Loughborough University | School of the Arts, English and Drama

Digital laser-dyeing: coloration and patterning techniques for polyester textiles

Doctoral Thesis (PhD)

Kerri Akiwowo

September 2015

Abstract

This research explored a ‘Digital Laser Dye’ (DLD) patterning process as an alternative coloration method within a textile design practice context. An interdisciplinary framework employed to carry out the study involved Optical Engineering, Dyeing Chemistry, Textile Design and Industry Interaction through collaboration with the Society of Dyers and Colourists. In doing so, combined creative, scientific and technical methods facilitated design innovation.

Standardized polyester (PET) knitted jersey and plain, woven fabrics were modified with CO_2 laser technology in order to engineer dye onto the fabric with high-resolution graphics. The work considered the aesthetic possibilities, production opportunities and environmental potential of the process compared to traditional and existing surface design techniques. Laser-dyed patterns were generated by a digital dyeing technique involving CAD, laser technology and dye practices to enable textile coloration and patterning. An understanding of energy density was used to define the tone of a dye in terms of colour depth in relation to the textile. In doing so, a system for calibrating levels of colour against laser energy in order to build a tonal image was found. Central to the investigation was the consideration of the laser beam spot as a dots-per-inch tool, drawing on the principles used in digital printing processes. It was therefore possible to utilise the beam as an image making instrument for modifying textile fibres with controlled laser energy.

Qualitative approaches employed enabled data gathering to incorporate verbal and written dialogue based on first-hand interactions. Documented notes encompassed individual thought and expression which facilitated the ability to reflect when engaged in practical activity. As such, tacit knowledge and ‘designerly’ intuition, which is implicit by nature, informed extended design experiments and the thematic documentation of samples towards a textile design collection. Quantitative measurement and analysis of the outcomes alongside creative exploration aided both a tacit understanding of, and ability to control processing parameters. This enabled repeatability of results parallel to design development and has established the potential to commercially apply the technique. Sportswear and intimate apparel prototypes produced in the study suggest suitable markets for processing polyester garments in this way.

Keywords: Textile design, CO_2 Laser Technology, Polyester fabrics, Surface modification, Laser-dye patterning, Textile coloration, Digital dyeing, On-demand processing

Acknowledgements

This is to thank everyone who made this journey possible.

Most especially, my supervisors: Dr Faith Kane, Prof John Tyrer, Dr George Weaver and Mr Andrew Filarowski (Society of Dyers and Colourists); together with funding body, Arts and Humanities Research Council (AHRC Collaborative Doctoral Award Studentship); Ian Smith (Coloursmith Ltd.) and Peter Crews (Crystal Martin Knitwear).

I am also thankful to a number of others, for your time, assistance, patience, encouragement, advice and kindness: Dr Marion Arnold; Emma Nadin; Karen Skorski; Lewis Jones; Nick Goffin; Matthew Broughton; Peter Wileman; David Britton; Mark Capers; Claire Lerpiniere; Kerry Walton; Dr Janette Matthews; Dr Rachel Philpott; Dr Nithikul Nimkulrat; Dr David Kerr; Dr David Worrall; David Morris, Kate Riley, Dr Mark Evans and Prof J.R. Campbell.

Not forgetting my husband, family, friends and RCCG Cornerstone Parish Loughborough, for your love, support and prayers throughout.

I am truly grateful to you all.

Thank you.

Table of Contents

List of Tables and Figures

Chapter 1: Introduction

1.1 Overview

This research considers a digital dyeing technique termed ‘Digital laser-dye’. The technique was explored as a new coloration method for textile design. As the term laser-dye suggests, the process involved laser technology and dyeing practices. Standardized polyester (PET) knitted jersey and plain, woven fabrics were modified with CO_2 lasers in order to graphically engineer dye onto the fabric surface as well as sportswear garments. Patterns were generated by combining CAD, laser technology and dye methods. As such, laser technology was investigated as a method to modify surface fibres for dyeing in order to generate tonally varied high-resolution patterns on to the textiles, defined as laser-dye patterning. The work considered the aesthetic possibilities, production opportunities and ecological potential of the process as an innovative surface design technique for textiles.

Traditional textile design and coloration methods facilitate creativity when applying colour and pattern to fabric, as documented by Meller and Elffers (2002). Many textile designers and fabric producers embrace techniques based on conventions that are influenced by historical crafts, cultural references (Seivewright 2007) and current technology. Long-established processes such as textile dyeing, print and pattern making combined with advanced technologies like digital inkjet printing and laser technology provide opportunities for experimentation and innovation (Bowles and Isaac 2012, p.7, Clarke 2011, p.67 and Fish 2005, pp.81-90). This approach often leads to novel patterning for textile surfaces and new fabrication ideas. Laser technology in particular enables different effects to traditional and existing textile coloration/patterning techniques and production methods. Laser-dyeing explored in this research, combined textile dyeing with CAD technology. In doing so, the work suggests a new digital patterning approach for textiles with dyes.

Conventionally, the coloration of synthetic textiles places high demand on resources in processing such as energy and water use involving solvents, as documented by Shamey and Shim (2011). Typically, polymers like PET are difficult to dye especially to yield deep/dark shades. Laser technology, as a method to modify surface fibres for improved dyeing is a low energy, dry and efficient approach that does not involve chemicals. This in turn promotes sustainability for textile manufacture. The technology is therefore considered environmentally beneficial – an aspect also raised by Yip et al. (2002, p.78), Shahidi et al. (2013, p.42) and Wong (2003, p.114).

The effects of laser modification on the coloration properties of some synthetic fibres have been identified in previous academic studies such as Shahidi et al (2013), Nourbakhsh and Ebrahimi (2012), Bahtiyari (2011), Yip et al. (2002) and Kan (2008a and 2008b). In particular, polyester/PET and polyamide/PA materials that have been found to display improved dye uptake capability when modified by laser beam energy. However, knowledge is limited in terms of creative exploration of the research results. Additionally, previous work does not incorporate industrial procedures towards the commercial potential of techniques established. The digital laser-dye process studied therefore addressed textile design aspects.

An interdisciplinary approach was employed and positioned within the framework of textile design practice. Textile design practice was approached as a ‘T-shaped’ practitioner (Design Council 2010, p. 14) to facilitate ‘crossing over’ from one distinct specialist area – textile design – into other disciplines including chemistry and optical engineering together with industry involvement. The purpose of this approach was to enable design innovation through the creation of novel ideas alongside the ability to apply them through ensuring repeatability and transferability in a way that is commercially relevant in terms of production.

Through the approach taken, this research goes beyond current knowledge of laser-dye methods. It has enhanced design capability and commercial potential of combined laser/dye techniques through scientific understanding of the technology, experimental methods and procedures; commercial relevance of processes via industry involvement and integrated creative input from a textile design perspective. New knowledge generated by this work has led to an ability to control, specify and replicate novel surface effects as well as communicate the results through quantitative measurement and analysis and demonstrate the creative potential through design collections and prototype garments and garment sections.

1.2 Context

Current knowledge about laser modified textiles centres around synthetic fibres regarding the effect on dyeing properties as investigated by Yip et al. (2002); Kamel et al. (2012); Bahtiyari (2011); Lau et al. (1997); Shahidi et al. (2013), for example. These polymer materials are preferable due to their affinity with laser irradiation. A reaction enabled by exposure to the beam, changes their chemical bond composition affecting the dyeability of laser treated surface fibres. Consequently, this results in deeper colour strength due to increased dye absorption.

The use of laser technology in textile design and manufacture to achieve a range of creative goals has increased in recent years (Gabzdyl 2008, p.21-22 and Clarke 2011, pp.106-107, pp.130-131). At present, it is mainly used to cut and mark a range of textile materials for aesthetic effect. Designers and manufacturers have adopted laser processes to produce innovative materials that display the capability of the technology as a creative tool. In the textile industry, denim fabrics represent the vast majority of laser-etched goods (Lockman and Clayson 1996; and Ondogan et al. 2005). Laser cutting enables precise incisions with a variety of materials suitable for interior/exterior environments and the body, explored by Boontje (Clarke 2011, pp.106-107); and Hur (Mix A/W 2010/11, p.22 and Braddock Clarke and Harris 2012, p.54), for example. This digital process facilitates repeatable effects and enables production speed due to digital automation. As such, laser material process is considered efficient.

Within the textile design research communities, practitioners have used lasers to enhance the visual and tactile characteristics of cloth to create new structures and surfaces often by combining conventional textile techniques with laser processing. For example: Stoyel (1996 and 1999) explored laser technology to manipulate synthetic and natural fabrics for decorative surface effects in the form of patterns and textures; Kane (2008) has generated unique surface effects by integrating laser technology and nonwoven materials; Addrison (2009) and Bartlett (2006) began to combine surface modification methods with wet techniques; Goldsworthy (2009) employed laser technology as a creative environmental alternative to finish polyester substrates; Matthews (2011) has developed novel laser processes to form three-dimensional textiles; Schlaepfer et al. (Clarke 2011, pp.130-131) explored this technology as a tool for fine work to create laser embellished metalized fabrics; and Weedlun (2011) investigated laser-engraving techniques to create decorative dual colour appliqué textile designs.

1.3 Research problem: identifying and addressing gaps in current knowledge

Scientific and technical approaches rather than a design perspective currently dominate this laser/dye research area (Nourbakhsh and Ebrahimi 2012; Kan 2008). Investigation typically occurs in disciplines such as Textile Chemistry, Textile Engineering and Material Science, for example. In these research contexts, an inherent scientific language has led to sufficient know-how of common issues regarding experimental methods, materials, data handling and analysis. Investigation from within creative textile disciplines is apparent (Addrison 2009 and Bartlett 2006) but is less developed from a scientific or technical perspective. Therefore, design innovation and commercial relevance of a combined laser/dye process was limited. The potential was there but, the means to apply/extend/transfer techniques, methods, procedures and results is not evident. Although some creative insights are offered, artistic development through an in depth study of methods and techniques alongside consideration of commercial context were absent.

Both Addrison and Bartlett's work (2009 and 2006) further discussed in Chapter 2, reached a point that identified opportunities to achieve modified dye and pattern effects using the laser. However, the work was limited in terms of combining both creative and technical perspectives to achieve robust laser/dye processes for textile design and coloration development. In order to address such gap through this laser-dye study, a research question together with an aim and objectives facilitated focused in depth experimentation and steered developments.

Research question

How can a digital laser-dye process be developed in order to achieve new ways to colour and pattern polyester textiles for industry?

Aim

The aim of this research was therefore to:

- investigate a new digital laser-dye surface patterning method for textile design by exploring digital laser-dyeing as a transferable creative graphic approach for textile designing with dyes.

Objectives

In order to fulfill the research aim, the objectives of the work were to:

- explore a range of experimental parameters regarding fabric, laser machines/equipment and design aspects by employing different fabric structures, laser processing methods and design approaches involving CAD techniques;

- embed industry standard (ISO) methods and procedures into experimentation as well as incorporate ISO measurement and analysis including wash fastness, colour assessment and textile performance testing;

- identify the design possibilities of the process for specific markets by producing a specified range of prototypes that exploit the process in terms of textile design innovation and market potential; and

- develop an awareness of the environmental aspects identified in existing studies regarding laser modified textiles for improved dyeability, applicable to the digital laser-dye process in order to further understand the environmental advantages of processing fabric in this way.

Polyester fabrics were investigated in order to establish carbon dioxide (CO_2) laser technology as a precise digital laser-dyeing tool for textiles. CO_2 lasers are already used routinely within the textile industry enabling commercial exploitation of the research results. ISO dyes and dyeing procedures were employed to further facilitate the commercial relevance of the research and to develop techniques from previous studies (Addrison 2009; Bartlett 2006) in which these procedures were not evident.

The experimental results presented in this thesis are based on an approach that has been termed 'energy density'. This refers to the amount of power or joules/units of laser energy transferred to the fabric surface per cm^2 via beam delivery, represented as J/cm^2. Actual energy output released from the laser nozzle was used to modify fibre with different levels of laser surface treatment. To achieve specific laser-dye effects, energy parameters were investigated by employing controlled technical procedures with the laser in relation the scientific chemical/physical structural changes of the fibre. Interactions between laser beam energy and textile fibres were studied as a way of generating tonally varied dye uptake on the textile surface in the form of high resolution patterns that depict sharp graphic qualities and well-defined forms enabled by CAD technology. The overarching purpose of this approach was to identify the creative opportunities of the process in a way that was commercially relevant in terms of reproducibility - an important factor for industrial development.

Environmental aspects were also considered as to further understand the advantages of processing textiles in this way. Existing studies have already acknowledged certain environmental benefits regarding combined laser technology and dye approaches to some extent. This laser-dye research advances such discussion through integrated technical, scientific, design and industrial involvement. As such, an interdisciplinary approach considers environmental issues and impact of the process more broadly. These encompass different perspectives relating to textile manufacture. For instance:

- laser processing - which is a low energy, low resource approach that does not require water; and
- precision-dyeing - in the form of engineered digital patterns using a low liquor method and accurate dye quantities, and so minimum resources and minimum waste.

In doing so, environmental aspects that involves textile design and production have been identified.

1.4 Thesis content summary

A *Literature Review* discussion is presented across five key themes that position this research. The examination of existing studies encompasses the technical, scientific, design and environmental aspects of the project. The *Methodology* chapter discusses the methodology and methods used in the research, organised into two main parts – the interdisciplinary and collaborative framework for the study and the methods undertaken. A preliminary results chapter: *Laser-dyeing in this study*, sets out the parameters surrounding the laser-dye process explored in relation to textile type, laser processing issues, computer software matters and design attributes. The *Experimental results and discussion* chapter sets out the research findings whilst an *Analysis of results* evaluates this work. In the *Conclusion*, the research is summarised drawing on key findings and observations within the context of the study. This discussion is supported by *Further work* that considers development of a laser dye process beyond the scope of the doctoral project presented.

Chapter 2: Literature Review

2.1 Introduction

The digital laser-dye patterning process explored in this research involved interactions between textile fibres, laser beam and dyes. As such, this study considered the process as an alternative method for dyeing and patterning within a textile design context, from a textile designer's perspective. An interdisciplinary research framework was employed, which aimed to further understand and advance the capability of digital laser-dyeing in terms of design potential, environmental opportunities and the industrial relevance of processes involved. This to some extent, has been achieved in this study as outlined in Figure 1 and Figure 2, which focus on: the 'Creative potential', 'Application' and 'Manufacture' aspects, also discussed in Chapter 8: *Further work*. The work is relevant to current knowledge concerning laser modified textiles and the effect on dyeing properties such as that generated by Yip et al. (2002), Kamel et al. (2012), Shahidi et al. (2013), Bahtiyari 2011, Kan (2008a and 2008b), Lau et al. (1997), Bartlett (2006) and Addrison (2009), for example.

Laser modified synthetic materials are a central focus of existing research in this field such as polyester (PET) and polyamide (PA), for example. This is due to their compositional affinity with heat irradiation induced by interaction with the laser beam. A chemical reaction between fibre and laser is able to alter fibre properties and encourage an increased dye uptake effect. As such, this capability is considered beneficial in this study as a new textile coloration approach relevant to design innovation and sustainable textile development. Current literature suggests this (Addrison 2009; Bartlett 2006) however, investigation that evidences development of these ideas from this perspective is limited. Overall, existing knowledge focuses mainly on the scientific and technical aspects. Creative and industrial development of combined laser/dye textile processing are not evident. Therefore, this laser-dye research explored the creative development, industrial relevance and environmental potential of processes involved from a textile design perspective. In doing so, knowledge in this field has been advanced by engaging with the creative, technical, scientific and industrial aspects of the work in parallel.

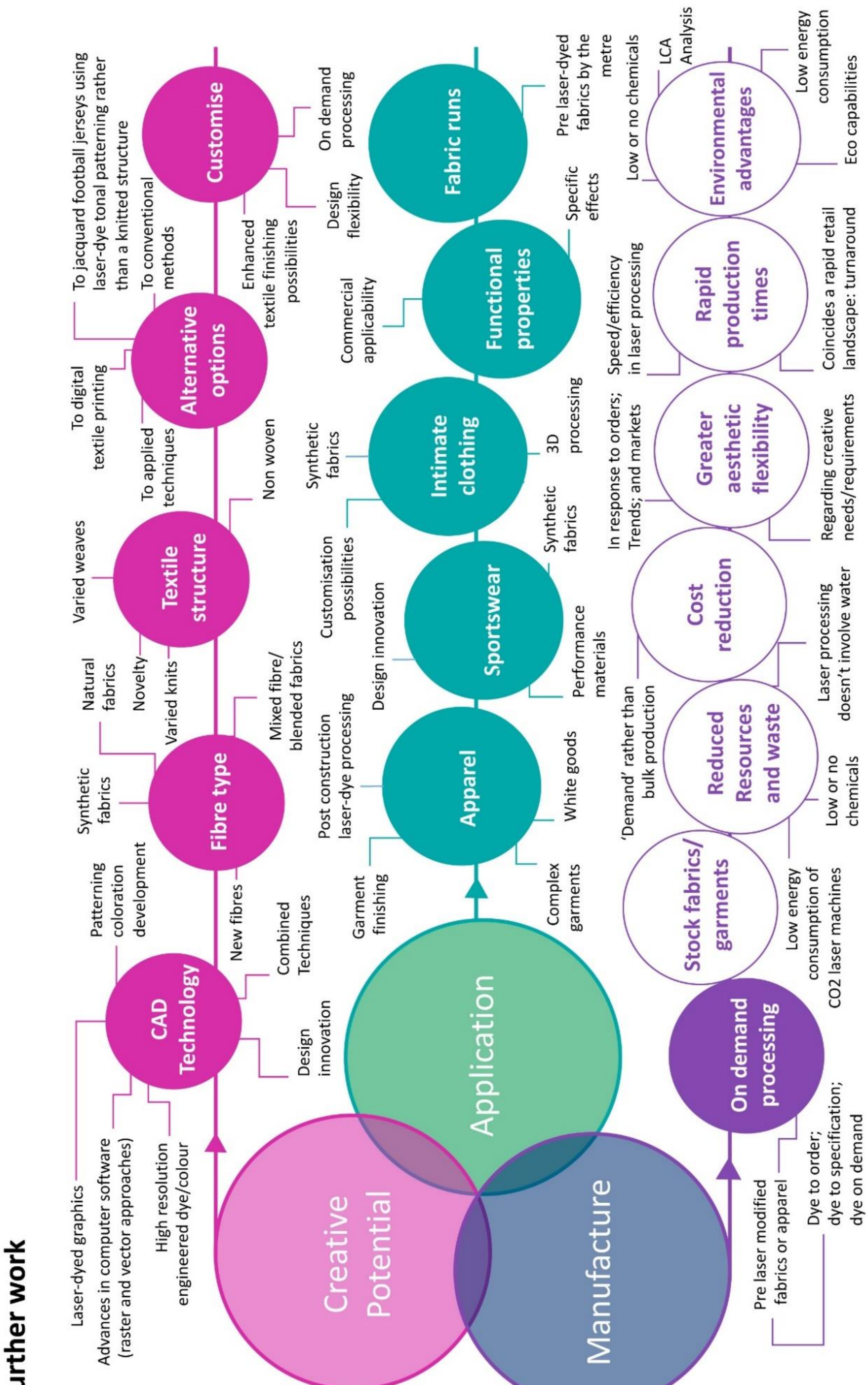


Figure 1: Diagram identifying 3 main areas for further work beyond this doctoral study

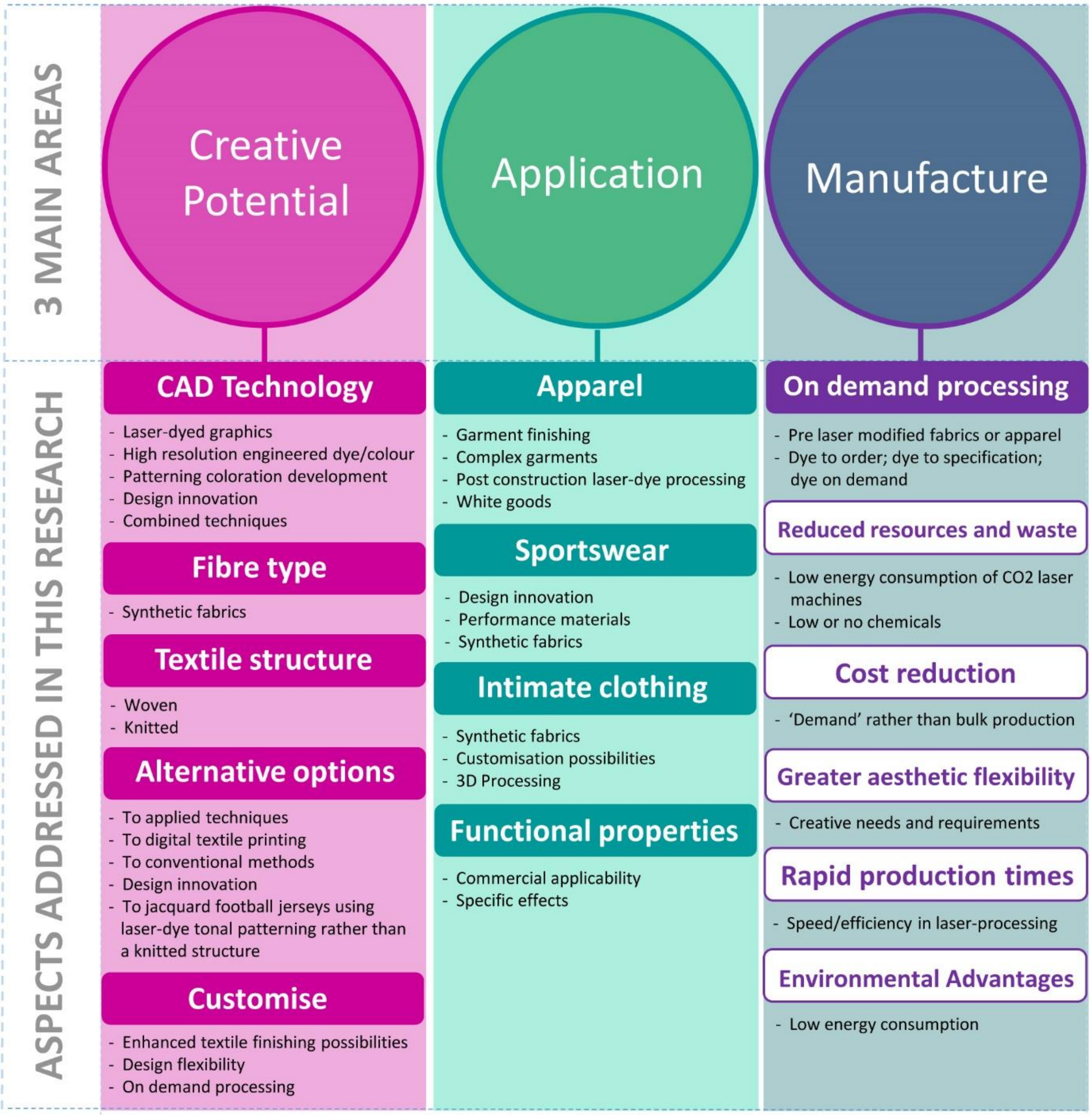


Figure 2: A delineation of aspects specifically addressed in this research in relation to Figure 1 (3 main areas for further work)

This literature review discussion is organised across five overarching themes fundamental to the ideas and issues that position this research, summarised in Table 1: *Dye-fibre interactions*; *Textile coloration methods*: *dyed patterns*; *Laser processing in textile design and research*; *Laser-dye processing: laser, fibre and dye interactions*; and *Environmental considerations for textile dyeing: a sustainable approach*. These themes define the scope for the review and relate to the creative, scientific, technical, environmental and industrial aspects of the research. This digital laser-dye study identifies gaps in existing literature and discusses the opportunities and limitations for laser/dye textile processing relevant to the research.

Theme	Background	Rationale
1 **Dye-fibre interactions**	Textile dyeing – a chemical reaction between dye molecules and yarn fibres to enable dye uptake in the form of coloured fabric (Fibres, dyes and uptake capability).	To identify, understand and discuss important issues associated with dyeing textile fibres. Most especially, synthetic polyester (PET) materials in terms of: dye/fibre compatibility; dyeing methods; and industry (ISO) standard procedures.
2 **Textile coloration methods: dyed patterns**	Creative methods and techniques used to generate artistic textile effects/surfaces with dyes; A focus on: colour, pattern and surface appearance.	To discuss current/traditional/established textile processes that relate to the digital laser-dye process: Applied techniques: devoré and its relevance to laser-dye; and Technological developments: digital dye methods.
3 **Laser processing in Textile design and research**	Laser technology has been widely used by designers, researchers and manufacturers to mark and cut textiles in order to achieve a range of aesthetic effects. Dye removal techniques for denim fabrics/clothing represents vast exploitation of the technology in this field. An early example of laser processed textiles that utilised cutting methods is airbag manufacturing in the 1970's and 1980's to improve production.	To discuss ways in which laser technology has been used as an enabling tool for creative textile applications and production goals. Typically to enhance or facilitate specific design/technical outcomes as with the digital laser-dye process. Existing knowledge from scientific and technical perspectives regarding laser modified textile and the effect on dyeability is limited in terms of creative exploration of the research results.
4 **Laser/dye processing: laser, fibre and dye interactions**	Synthetic materials such as polyester (PET) and polyamide (PA) have been found to display improved dye uptake capability when modified by laser beam energy. Such investigation has been studied in scientific and technical textile fields such as Textile Chemistry, Textile Engineering and Material Science, for example.	To explore and discuss current understanding of the process in terms of the dyeability of laser modified synthetic fibres based on existing knowledge. . This information facilitated a greater understanding of the digital laser dye process in terms of the scientific and technical aspects attributed to physical and chemical interaction of PET and PA fibres.
5 **Environmental considerations for textile dyeing: a sustainable approach**	Laser technology, as a method to modify surface fibres for improved dyeing is a low energy, dry and efficient approach that does not involve chemicals. This in turn promotes sustainability for textile manufacture. The technology is therefore considered environmentally beneficial.	To further understand the environmental opportunities of the digital laser-dye process linked to textile design and production aspects based on dyeing procedures, equipment and technological advancements.

Table 1: Literature review themes

2.2 Dye-fibre interactions

In this research, the term 'dye-fibre' denotes textile dyeing – a chemical reaction between dye molecules and yarn fibres to enable dye uptake in the form of coloured fabric. The purpose of this discussion is to identify issues associated with dyeing textile fibres, in particular synthetic polyester (PET) materials, relevant to this study. These include: dye/fibre compatibility; dyeing methods; and industry (ISO) standard coloration procedures.

2.2.1 Fibres, dyes and uptake

Dye/fibre compatibility as detailed in Table 2, is determined by dye class and fibre type related to the technology of textile properties as discussed by Taylor (1990, 3rd ed.) and Kendall (2001, pp.10-21). The fundamental principles outlined are also applicable to textile printing methods, including hand and traditional screen techniques explored by Fish (2005); and digital methods examined by Bowles and Isaac (2012, 2nd ed.) and Braddock Clarke and Harris 2012), for example. Both approaches require dyes in order to transfer colour, pattern, imagery and graphic elements onto fabric.

DYES / FIBRES	Cellulosic	Cotton	Linen	Jute	Hemp	Regenerated Cellulosic	Viscose Rayon	Lyocell	Acetate	Protein	Silk	Wool	Alpaca	Cashmere	Angora	Synthetic	Polyester	Nylon	Acrylic; Modacrylic	Spandex
Basic dye				•																
Disperse									•								•		•	•
Acid											•	•	•	•	•			•		•
Reactive		•	•	•	•		•	•												
Direct		•	•	•	•		•	•												

Fibres/dyes are not exhaustive

Table 2: Dye/fibre compatibility

Polyethylene terephthalate (PET) (Figure 3) or 'Polyester' is a manufactured synthetic polymer fibre formed entirely by chemical synthesis, as described by and Elsasser (2005, p. 14) and Taylor (1990, 3rd ed., p.36). Filament fibres are extruded through the process of melt spinning to produce yarns. These yarns are constructed to form textiles such as woven and knitted fabrics. PET typically requires high temperatures for dyeing compared to other synthetic polymers such as polyamide/nylon or natural fibres like cotton, for example. This is due to a higher glass transition temperature (T_g) of 130°C compared to polyamide for instance, which is 47°C. During T_g, the physical properties of a material alter in response to temperature and trigger structural change. This enables the dyes to adhere to the fabric more readily - molecules permeate textile fibres and auxiliaries used in the dyeing process encourage good dye uptake (previously discussed in section 1.2. and also in section 2.5).

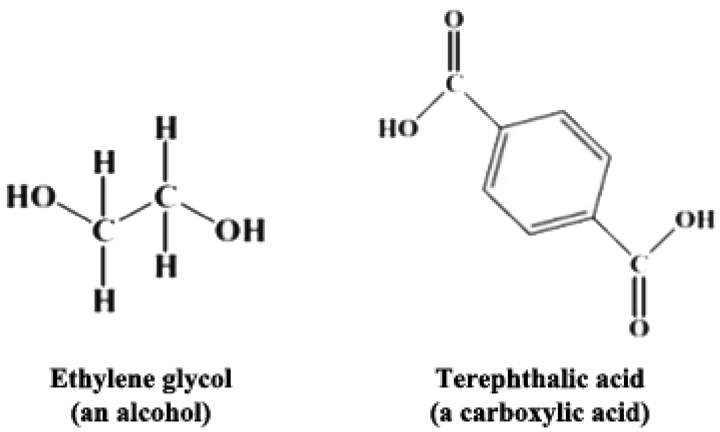


Figure 3: Starting compounds for the manufacture of PET fibre (Shamey and Shim 2011, p. 98)

In their assessment of key issues for polyester dyeing, Shamey and Shim (2011, p. 105) comment, ‘several approaches have been attempted to improve the dyeability of polyester…’ They explain difficulties in dye uptake of PET are attributed to the manufacturing conditions and processing history of fibres related to the preparation, fabric construction, dyeing procedures and finishing stages of fibre production. Factors such as level dyeing, shade reproducibility and colour fastness further discussed by Shamey and Shim (2011, pp. 127-128, 133), were essential to the laser-dye process explored in this research. These issues are relevant to industry requirements for commercial textile goods. Discussing colour consistency, Elsasser (2005, p.180) writes, ‘The textile colorist is challenged constantly to achieve a level color or uniform color…’ Further explaining, ‘The textile buyer, whether purchasing in a personal or professional capacity, should examine products for consistent color’ (ibid). Issues concerning quality and stability of the laser-dye process from an industrial perspective were taken into consideration in terms of the visual appearance and functional performance aspects of the resulting digital laser-dyed fabrics.

Visual colour analysis is related to colour perception based on how the human eye sees and interprets colour. Colour perception tests such as the *Ishihara* and *Farnsworth-Munsell 100 Hue* tests provide statistical analysis and graphical evidence of an individual’s ability to translate colour. In their discussion about *Visual perception and other phenomena* (2008), the Society of Dyers and Colourists (SDC) comment, ‘For the majority of people, and certainly for designers, it is colour, tone and shape as a visual experience that is important.’ This notion relates to how colours appear to an individual, connected to emotion and meaning. These ideologies are further explored by Norman (2004) who, within a design context, attributes human responses to ‘the meaning of things’ as an emotional response based on visceral, behavioural and reflective characteristics. Design and Emotion Society (designandemotion.org 2014) seek to raise issues and facilitate dialogue among practitioners, researchers and industry about ‘the involvement of emotional experience’ in design, particularly product design.

The PET woven and knitted fabrics explored in this research were dyed with disperse dyes in line with current practice. The study addressed issues relating to challenges in the coloration of polyester. This was achieved by exploring laser technology as a method to modify surface fibres with graphic patterns prior to dyeing for improved uptake capability and engineered tonal dye distribution. Laser-dye methods enabled improved depth of shade, increased colour strength and enhanced the design possibilities of PET fibres in terms of innovation. Colour analysis of the resulting laser-dyed fabrics was carried out using quantitative approach. In doing so, visual effects can be reliably communicated and repeated (further discussed in Chapter 5).

2.3 Textile coloration methods: dyed patterns

The aim of this section is to identify and discuss current, traditional and established textile processes that relate to and inform the digital laser-dye process explored. In this discussion, textile coloration methods that produce dyed patterns have been examined.

Textile printing and dyeing enables dyed patterns and surface designs on fabric as presented by Fish (2005, pp.101-118) and Kendall (2001). Meller and Elffers (2002) document a long history of applied techniques and craft-based approaches. These include ancient **Block printing** with carved wooden blocks (Figure 4), **Gravure printing** dye transfer methods, **Batik** wax resist techniques (Figure 5), **Indigo Shibori** resist dyeing and **Silk-painting** using both hand and screen methods which demonstrate creative skills and processes in order to produce specific textile designs and effects. Today, such craft techniques are associated with traditional forms of cloth patterning in contemporary textile production. For example, textile designer and researcher Emma Ronald (2012) explored the use of hand block printed fabrics produced in Western India for modern global markets. At the international textile trade show *Indigo* held in Paris (September 2014) where textile producers source fresh designs for their forthcoming collections, hand painted fabrics were featured for Autumn/Winter 2015/2016, as reported by World Global Style Network (WGSN) (www.wgsn.com 2014).


Figure 4 (Right): A 19th-century wood block with fine pattern (Hobson 1961, 2nd ed., p. 32a.)
Figure 5 (Left): Batik pattern, France 1888 (Meller and Joost 2002 p. 367)

Colour possibilities for textiles relates to both historical and modern coloration developments. In 1856, Chemist William Henry Perkin produced the first synthetic dye – ‘Mauveine' (SDC 2007), now more commonly known as mauve. This advancement largely impacted fashion trends at the time. The colour was unique and both production time and costs were reduced compared to previous methods. By the early 20th century, digital inkjet printing technology, capable of printing textile dyes emerged, as documented by Bowles and Isaac (2012, 2nd ed.). This technology became an innovative, efficient and ecological alternative to traditional textile printing methods of 'colouring' fabric such as roller, stencil and screen practices (ibid. pp.168-171). Ongoing developments in this field continue to impact surface pattern approaches and textile trends today as Clarke (2011) and Quinn (2013) demonstrate.

Hand and digital dye techniques were relevant to this study regarding the creative and conceptual aspects of the work. Laser-dye processing has been explored as an image-making tool through combined pattern and colour coloration approaches towards textile design development. In doing so, the work has identified new ways to process fabric with tonal digital patterns using a dyeing approach rather than textile printing. Laser and CAD technologies facilitated a technical understanding of the process which can be controlled and effects repeated in order to achieve replicable results as well as specify and determine new aesthetic outcomes. As such, textile design innovation is supported by an in depth knowledge of the technical, scientific and creative aspects involved associated with laser issues, fibre modification, dyeing and surface appearance.

2.3.1 Devoré and its relevance to laser-dye patterning

Devoré is a traditional surface technique used in textile design to generate patterns and creative effects through the removal of fibres from the textile structure using a chemical 'burn out' paste before or after the dyeing stage. Fabrics used for the process are typically constructed using two different fibre types within the warp and weft of a woven or knitted textile. The effect of this process is the revealing of the base cloth or mesh where the original face has been destroyed. Once treated, the fabric becomes visually enhanced through dyeing with a single shade and cross-dyeing that involves two or more dyes/shades. During the process, patterning is enhanced as colour is added to the cloth - shade differences emerge during dyeing causing variable tones that are emphasised by contrasting fibres and dye uptake capability per fibre type (Figure 6). Handle and drape characteristics also alter, determined by the level of devoré treatment applied. In terms of design, approaches such as layering colour, image based textures, ombré patterns and gradient effects are possible, as with the tonal capabilities in the laser-dye tonal process (presented in Chapter 5).

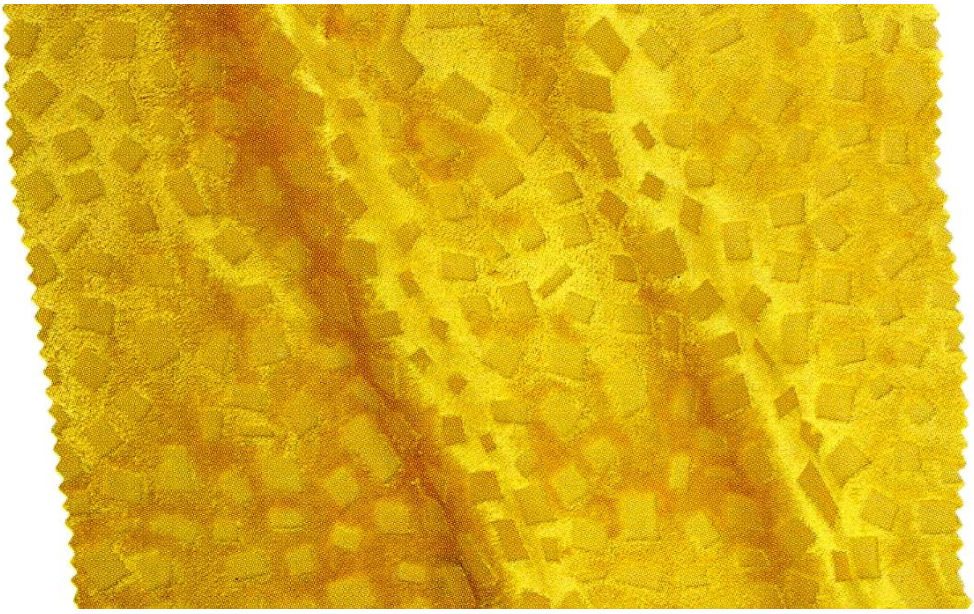


Figure 6: Devore velvet dyed a single shade – silk/viscose revealing fabric mesh (silk) via square pattern (Kendall 2001, p. 137)

Devoré has been compared to laser techniques in previous studies such as Janet Stoyel's investigation, *Laser and Devoré* (Miraftab and Horrocks 2007, pp. 210-215). Although she remarks on the attractiveness of textile products treated by the process commenting, fabrics are '…so very beautiful, desirable and costly' (ibid. p.213) adding, 'effects resemble lace, creating textiles with different degrees of translucency, transparency and opacity' (op cit. p.210). However, Stoyel proposes laser surface abrasion methods as an environmental alternative for decorative burn away textile effects that does not involve harsh chemicals and pollutants attributed to the devoré process arguing, '…not only does the process generate chemical and colour waste, it also generates large quantities of fibrous sludge' (ibid. pp. 210). In doing so, Stoyel has acknowledged the environmental advantages of a laser approach to textile design, relevant to the laser-dye process explored in this research. Therefore, laser-dyeing can be compared to devoré from environmental and aesthetic perspectives.

Digital laser-dyeing enables dual surface qualities as with devoré techniques. However, unlike conventionally dyed devoré fabrics, an extensive range of shade depths of a dye/colour can be achieved with digital laser-dyeing through an ability to control and determine mechanical aspects involved. In doing so, tonally engineered graphic patterns were created by variable dye uptake in relation to specific areas of a design. This is not possible with a devoré approach. The absence of chemicals and water in laser processing, low energy use attributed to CO_2 lasers, along with ISO dyeing procedures and lower liquor ratios explored in this research relate to the environmental aspects of the process associated with sustainable textile production. Factors include minimum resources, pollutants and waste.

2.3.2 Technological developments: digital dye methods

This section is about existing and relevant knowledge regarding digital dye methods used in textile design. Approaches carried out in this digital laser-dye research are covered in the Methodology chapter (Chapter 3).

In digital printing, dyes are controllably transferred to fabric via jetting and deposition of fluid onto a range of materials - textiles, films and other substrates, as studied by the Inkjet Research Centre (IRC, Est. 2005), University of Cambridge, Institute for Manufacturing. In addition, for synthetic fabrics, sublimation methods allow disperse dyes to be ink jetted onto paper and heat-transferred (fixed) to the fabric with combined heat and pressure, further described by Karanikas et al. (2012, p.3) who studied disperse inkjet inks with active agents for application on polyester and polyamide fibres.

Designs are generated by a computerised interface between design files and graphic data for printing. Steaming fixes dyes for other fabric types such as cotton or silk for example. A pre-treatment applied to the fabric before printing aids this process.

Digital technology developments such as inkjet printing for textiles and CAD software/hardware devices have encouraged design innovation. Since the late 20th century, technological advancement has aided the creation of diverse novel patterns and experimental colour (Figure 7) influenced by a digital approach to design, as discussed by Sandy Black, Professor of Fashion and Textile Design and Technology at London College of Fashion in *Textiles and new technology 2010* (O' Mahony and Braddock 2010, pp. 24-29). For example, Bowles and Isaac (2012, 2nd ed., p. 7) comment '…Designers are able to work with thousands of colours and create designs with a high level of detail' by using a digital approach.

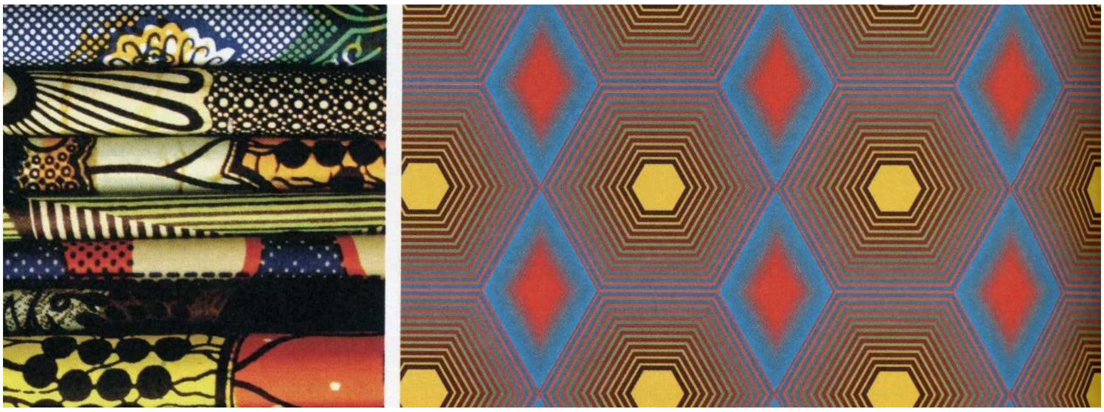


Figure 7: Digital textile print (right) by Emamoke Ukeleghe showcasing 'a new contemporary ethnicity' alongside traditional hand-dyed batik fabrics (left) (Bowles and Isaac 2012, 2nd ed., p. 44)

Design practices and creative opportunities have broadened with advancements in digital printing. Bowles and Isaac (ibid.) argue, 'Working in a digital environment, designers are afforded more time to experiment, explore and create, while manufacturing technologies offer innovative printing solutions'. An ability to generate new design concepts or merge digital and traditional approaches gives designers increased freedom and individuality. A combination of hand and high-tech methods is therefore favourable in this field. Alternatively, Clarke (2011, p. 67) argues that some '…aesthetic qualities can only be achieved outside the computer', only with hand methods. So, in order to consider how digital and hand methods may be utilised simultaneously, Fish (2005, pp. 81-90) explored the combination of old and new approaches through her study into *Designing and printing textiles*. Techniques identified include scanning original artwork for digital manipulation, finishing fabrics with laser methods, overprinting with screen printing processes and embellished handcrafted qualities (Bowles and Isaac 2012, 2nd ed., p. 7). Clarke (2011, pp. 67-68) discusses 'a new digital vernacular' created by this technology. In particular, he refers to enhanced possibilities in terms of quality and experimentation within CAD and digital printing.

From an environmental perspective, digital textile printing has a reduced impact compared to conventional textile printing methods as described by Bowles and Isaac (2012, 2nd ed., p. 178). They argue (ibid), '…a more sustainable future will be possible if this production method is adopted over others'. Design specification, executed through a highly specified and controllable approach minimises waste in the process - dyes are transferred to the fabric within specific boundaries; colour/pattern is digitally engineered on to the cloth; and printing is performed on demand. Waste is therefore limited in terms of unused or discarded resources and materials. Processing time reduces with digital textile printing, compared to conventional textile printing methods. Automation enables increased production capacity at faster speeds and lower costs. It is therefore considered a more efficient approach to achieve patterned fabric with dyes. Provost (1994, p. 36) has identified factors such as speed of response and short delivery times in a discussion about sustained development of print markets in the 21st century. Similarly, Karanikas et al. (2012, p. 1) comment that the increasing use of CAD systems '…eliminate the costly and time consuming process of screen-making…drastically reducing the production cost' of printed fabrics. This rapid turnaround is particularly beneficial on a commercial scale relevant to revenue and changing design trends in fashion or interiors, for example.

In this laser-dye study, hand drawn elements were modified with computerised tools to form patterns and create experimental textile designs. As with digital textile printing, laser-dyeing enabled engineered patterns with dyes by integrating CAD approaches in order to determine tonal distribution of the dye using precision graphic dyeing. This process is enabled by fibre/laser/dye interactions – laser beam energy modifies fibres which increases their dye uptake capability. Compared to digital printing whereby dyes rest on the textile surface/structure, with laser dyeing, fibres are actually dyed. This offers advantages of the process in terms of dye stability and longevity of design contrary to fading, associated with printed fabrics for example. In terms of aesthetics, as described by Cresswell (2002, 2nd ed., pp. 85-87), the design results of laser-dye fabrics assumed both digital and traditional characteristics. Surface patterns were generated with a range of shade depths facilitating both gradient and textural effects (as demonstrated in Chapter 5).

2.4 Laser processing in textile design and research

This section discusses different approaches to laser processing undertaken within a textile design and research community. Descriptions about how the technology may be understood in this environment are offered and a range of approaches, methods and experimental techniques adopted by designers and manufacturers are presented and explained.

Laser processing in textiles can be referred to as the denaturing of fibres through laser beam interaction by:

1. **Controlled laser etching**
   For example, dye removal denim methods that utilise a surface etching/marking approach have been well documented and demonstrate an efficient and environmental alternative to traditional surface abrasion procedures. These include bleaching and stonewashing approaches that are time consuming and involve the use of chemicals. Lockman and Clayson (1996), Ondogan et al. (2005) and Ortiz-Morales et al. (2003) for example, have explored engineered fading effects with graphic designs for denim clothing and fashion items using a laser etching approach (Figure 8); and

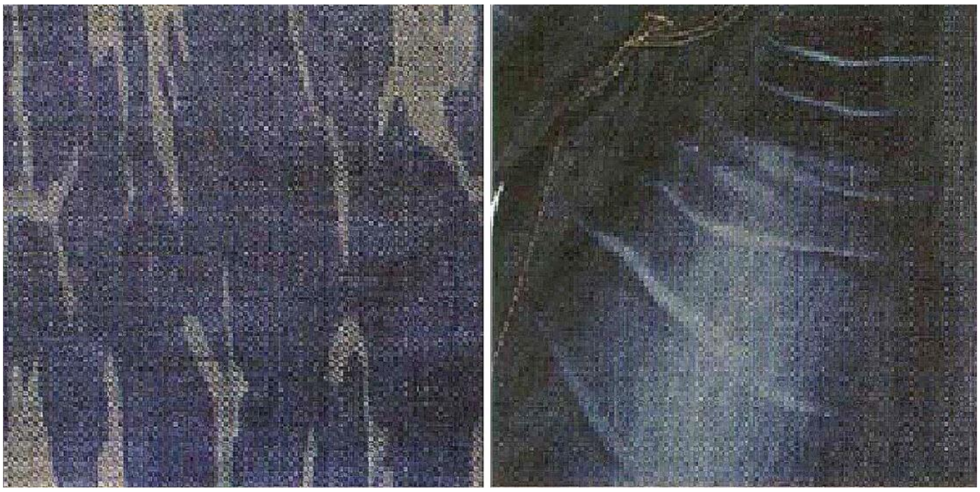


Figure 8: Laser etched denim trousers (Ondogan et al. 2005, p. 634)

2. **Increased power density for cutting**
   Whilst laser etching interacts with surface fibres, laser cutting interrupts the textile structure by a subtractive method to remove sections of the fabric according to the design/CAD file. This process is described by Babenko and Tychinskii (1973) in relation to gas-jet cutting with CO_2 lasers; Bamforth et al. (2006) who studied CO_2 lasers to cut nylon lace; and Walker (1998, pp. 29-31) who explained industrial

developments in automotive airbag manufacturing in the 1970’s and 1980’s. During this period, CO_2 lasers were used to cut airbag materials accurately with a clean edge and multiple layers could be cut simultaneously. Consequently, the technology overcame difficulties in the production process.

Early adoption of laser technology for textile materials in the 1970’s and 1980s’, recorded by Babenko and Tychinskii (1973) and Walker (1998, pp. 29-31) presented manufacturers with a solution to process fibres with precision without mechanical contact. High power capability of the technology facilitated speed and volume in production. Variable processing powers enabled cutting and/or marking applicable to different substrates and products. Laser methods offered a controlled approach to denature fibres according to design and specification.

In recent years, the use of laser technology in both textile design and manufacture has increased as Steen (2005), Gabzdyl (2008) and Clarke (2011) document. In these environments, lasers have been used to achieve a range of creative goals. A slow uptake of laser technology by the design community can be linked to the absence of the technology in education institutions such as schools and colleges, for example. Therefore, exploitation of the technology was most apparent in the garment industry where this technological development was financially afforded.

In fashion design, laser approaches have given designers the opportunity to explore new ways to advance fashion fabrics. Most commonly, precision laser cutting methods have been used to separate fabric elements to form novel textile structures (Figure 9) or reveal otherwise hidden layers (Figure 10).

Figure 9: Laser-cut garment detail by Jakob Schlaepfer (Braddock Clarke and Harris 2012, p. 160)

Figure 10: Laser-cut garment by Miucci Prada, A/W 2008 (Braddock Clarke and Harris 2012, p. 160)

Textile designers such as Janet Stoyel (1996; 1999), Savithri Bartlett (2006), Kate Goldsworthy (2009), Jenny Addrison (2009) and Janette Matthews (2011) have explored laser technology in their creative practice, expanded upon in section 2.4.1 of this chapter. In this community, the technology has aided creative development of concepts that propose alternative textile processes and techniques involving cutting, etching and manipulation effects.

Effects of laser modification on the coloration properties of fibres in academic studies focus on dye uptake. For example, Kan (2008a and 2008b), Lau et al. (1997) and Bahtiyari (2011). As such, current knowledge is principally approached from a scientific perspective such as Shahidi et al. (2013), Nourbakhsh and Ebrahimi (2012) and Kamel et al. (2012). Therefore, creative development is limited in this field. Industrial development and a commercial understanding of processes, methods and techniques involved are also underdeveloped. It is therefore possible to identify gaps in existing knowledge regarding laser-dye approaches. In this research however, the technology was used to investigate a laser-dye process that combined laser processing and textile dyeing with creativity and industrial involvement towards design innovation. In doing so, this study represents advancement in the textile community from a design perspective.

2.4.1 Laser techniques for textile design: a creative agenda

2.4.1.1 Laser techniques: cutting; etching; engraving; marking; pleating; pre-processing; and sintering.

Designers and manufacturers have adopted laser processes to produce innovative materials that display capability of the technology as a creative precision digital tool. Currently in textile design, laser technology is mainly used to cut and mark a range of textile materials for aesthetic effect.

For example, Schlaepfer et al. (Clarke 2011, pp. 130-131) have explored laser technology as a tool for fine work to create laser embellished metalized fabrics; Stoyel (1996; 1999, Miraftab and Horrocks 2007) explored the technology to manipulate synthetic and natural fabrics for decorative effects. Laser cut holes and surface experiments were considered an alternative environmental approach to traditional textile techniques such as devoré screen-printing methods and lace making; Goldsworthy (2009) also embedded environmental design principles by employing laser technology as a creative approach to finishing or 'upcycling' (i.e. repurposing to a higher value) synthetic textiles; Kane (2008; 2010) generated unique surface effects by integrating laser technology and nonwoven materials; Matthews (2009; 2011) was concerned with textile manufacture methods and has developed three laser processes (laser-assisted template pleating, laser pre-processing and laser sintering) to form novel 3D textile structures and surfaces; Weedlun (2011) studied 'laser engraving' techniques to create decorative dual colour appliqué textile designs. Author of the research, Wallace (Seymour 2010, p. 116-119 and Quinn 2013, pp. 266-267) used laser etching to re-image performance fabrics and propose new garment concepts; Sara Robertson (2010) also employed *Laser etching to enhance liquid crystal colour-change on textiles.*

In terms of precision processing—an advantage of the technology, Matthews (2009; 2011) as the designer, was able to control/specify results through the process of decision-making (further discussed in the Methodology Chapter (3) of this thesis). An ability to apply appropriate creative and technical parameters was based on the necessary knowledge of processes involved gained through practical investigation in order to understand and determine the outcomes (Figure 11).

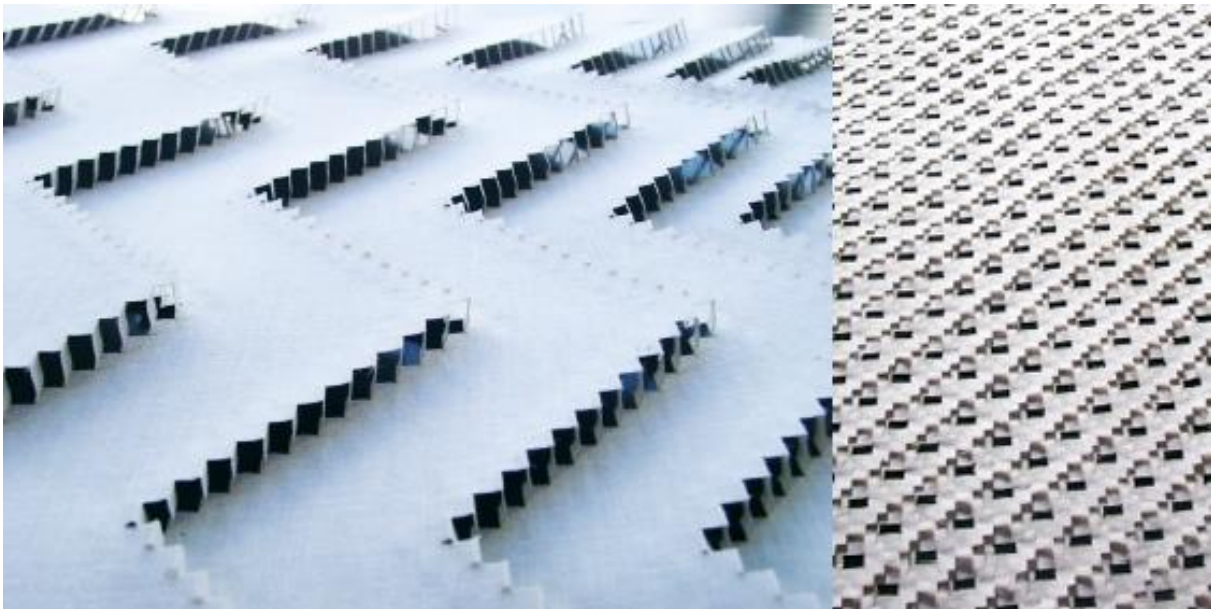


Figure 11: Laser-formed 3D textile structures by Matthews (2009)

Matthews (2009, p.3) described the role of ‘intervention’ as a practitioner within the context of the study by asking, ‘Where should an intervention be made to achieve a desired outcome?’ (ibid) A technically rigorous approach adopted, explored how a ‘happy accident’ could be recognised and replicated during the experimental design process. Systematic trials were carried out involving a range of laser parameters. The purpose of this approach was to methodically document creative effects in a way that was both qualitative and quantitative. Being able to influence and manipulate creative, scientific and technical parameters was essential to reliability and repeatability goals of the work. An experimental design approach aided the development of novel and precise 3D effects.

In contrast, Goldsworthy (2009) emphasised creativity rather than the technical aspects involved in laser finishing polyester substrates commenting, ‘…I spent very little time testing the parameters of power and speed for the material I was exploring. I did look closely at the type of mark that could be achieved with various fabric constructions and weight’ (ibid., p. 11). According to Goldsworthy, this approach was adopted due to a prior knowledge of materials and processes. Hi-tech laser data was articulated through design outputs inspired by traditional crafts (Op cit., pp. 9-16) (Figure 12).

Goldsworthy (2009) and Stoyel (1996; 1999, Miraftab and Horrocks 2007) explored lasers to address ecological textile design issues. In these studies, laser methods were considered as an environmental alternative to traditional textile design approaches.

Figure 12: Laser-finished textile samples by Goldsworthy, (2009, p.13)

Stoyel (Miraftab and Horrocks 2007, p. 213) described the technology as a ‘responsible futuristic devoré effect’ (previously discussed in section 2.3.1 of this chapter), highlighting the absence of chemicals, waste products and pollutants associated with this method. Similarly, Goldsworthy (2009, p. 2) explained, decorative laser finished substrates exclude the use of additional adhesives and stitching or ‘a mix of materials from different metabolisms’. Mono-material factors embedded into the work promoted ‘Cradle-to-Cradle’ lifecycle design principles as discussed by McDonough and Braungart (2002). This approach to textile design therefore fulfilled the recyclability objective of the project enhanced by laser processing methods. Therefore, minimal resources and the absence of coatings, encouraged environmental textile design. In addition, CO_2 lasers employed encouraged low energy consumption—a known feature with this laser type compared to other laser systems such as Nd:YAG or Excimer, for example. Comparatively, CO_2 laser methods were used in this laser-dye research regarding environmental considerations of a laser-dye process investigated such as low energy consumption and absence of water and chemicals in processing, low liquor ratios and accurate dye quantities based on industry standard dyeing procedures. The potential for dyeing synthetic fabrics such as polyester at lower temperatures than the current industrial standard of 130-140˚C, due to the increased dye uptake capability of laser modified fibres can also be considered.

2.4.1.2 Surface patterning and dyeing approaches

Textile Designer Jenny Addrison (2009), explored *Laser surface modification of woven structures for dyeing* at Loughborough University (LU). This study made use of different departments at LU including the School of Art, Department of Chemistry and Department of Materials. Therefore, this was probably one of the first attempts to approach textile design in a scientific way in terms of experimental rigour regarding methods, procedures and results, underpinned by a creative perspective, akin to this interdisciplinary laser-dye research. Bartlett's (2006) study*, Laser and textiles: an exploration into laser dye-fibre interaction and the process of technology transfer* also linked across departments at LU – the Art School and Wolfson School of Mechanical and Manufacturing Engineering as well as collaboration within the fashion industry. This work combined laser technology and dyeing to some extent however, investigation was limited in terms of experimental and creative exploration of the laser-dye process and the research results.

Bartlett (2006) was concerned with how experimental results of textile surface explorations with the laser might be applied in commercial garment production. Therefore, collaboration with haute couture fashion designers was embedded into the research framework. A CO_2 laser was used to char the surface of different natural fabrics including cotton/denim via a laser etching method similar to Stoyel (1996; 1999; Miraftab and Horrocks 2007), Lockman and Clayson (1996) and Ondogan et al. (2005). The aim of this approach was to generate a range of damage levels in order to aid the creation of images with a raster halftone CAD method. The results of such investigation was demonstrated by a range of laser etched fabrics and denim garments. This work also presented a method for staining (rather than dyeing) fabrics. Some experiments were carried out with polyamide fabrics using Nd:YAG and Ruby laser systems and disperse dyes via hand and manual procedures. To observe dye uptake, fabrics were first placed in a solution and laser treated whilst the sample was wet. In doing so, a few test samples of the results demonstrate the feasibility of the process. However, these initial results were not explored further from a scientific, technical and creative understanding of the process and so did not include a sizable range of laser processing parameters, microscopy or design development demonstrating artistic input for textiles or potential application within a fashion and garment production context. It was assumed uptake capability was based on dye absorption of a particular dye/shade in response to an energy dependant function such as heating, caused by laser beam interaction (Bartlett 2006, p.205), also influenced by time and temperature, suggesting results could be improved by applying a longer pulse of laser energy (ibid., p.221). An attempt to analyse fabrics is presented in the study with tear and tensile strength tests undertaken.

Prior to Bartlett's study (2006), laser-dyeing methods were already established. Although some work was done by Bartlett, the conclusions of her pulsed laser work were not sustained with any detailed experimental work. No attempt was made to quantify or systematically investigate any of the basic control parameters necessary to optimise the laser, nor describe an image density method in terms of shade depth against energy density. Design development with imagery was therefore limited. No micrography documented means there is no evidence that seeks to investigate the mechanism for enhanced dye uptake or analyse dye performance. Similarly, no comprehensive analysis of the results has been provided regarding laser treated and performance tested fabrics. For example, washability and durability aspects have not been discussed. As such, the results are non-transferrable/non-repeatable methods, procedures and results, as well as issues with the accuracy of outcomes. Instead, an initial set of findings have been reported within a limited experimental scope of the project. Earlier studies however, such as Lau et al. (1997) and Yip et al. (2002) for example, (further discussed in section 2.5 of this chapter), evidences scientific and technical investigation regarding combined laser/dye methods. These studies report quantitative analysis of the results and are therefore reliable in a way that is not evident in Bartlett's work.

Addrison's investigation combined laser and dyeing methods in order to explore colour and pattern with differential dye uptake techniques. Cotton, polyester and poly/cotton commercially available woven fabrics and dyes (rather than industry standard dyes) were employed. Using a CO_2 laser bed system to etch fabrics, an experimental approach was pursued in order to understand interactions between the laser beam, textile fibres and dyeing. As with traditional devoré methods (previously discussed in this chapter), also explored by Stoyel (1996), dual fibre poly/cotton fabrics enabled multi shade effects demonstrated by bold geometric designs achieved with a CAD approach (Figure 13).

Commenting on the results Addrison (2009, p.7) remarked, 'Devoré only allows for one additional colour yet by laser etching, numerous shades can be produced'. Quantitative data was obtained through microscopy, spectroscopy reflectance testing and dye absorption measurements. This information steered creative development and facilitated an understanding of the opportunities and limitations of combined laser/textile/dye processes for textile design within the scope of the project. Results of the study provided the platform for the start of this research surrounding the digital laser-dye process. As such, this work aimed to explore laser technology as a creative graphic patterning tool via digital coloration methods for polyester fabrics and apparel, relevant to industry.

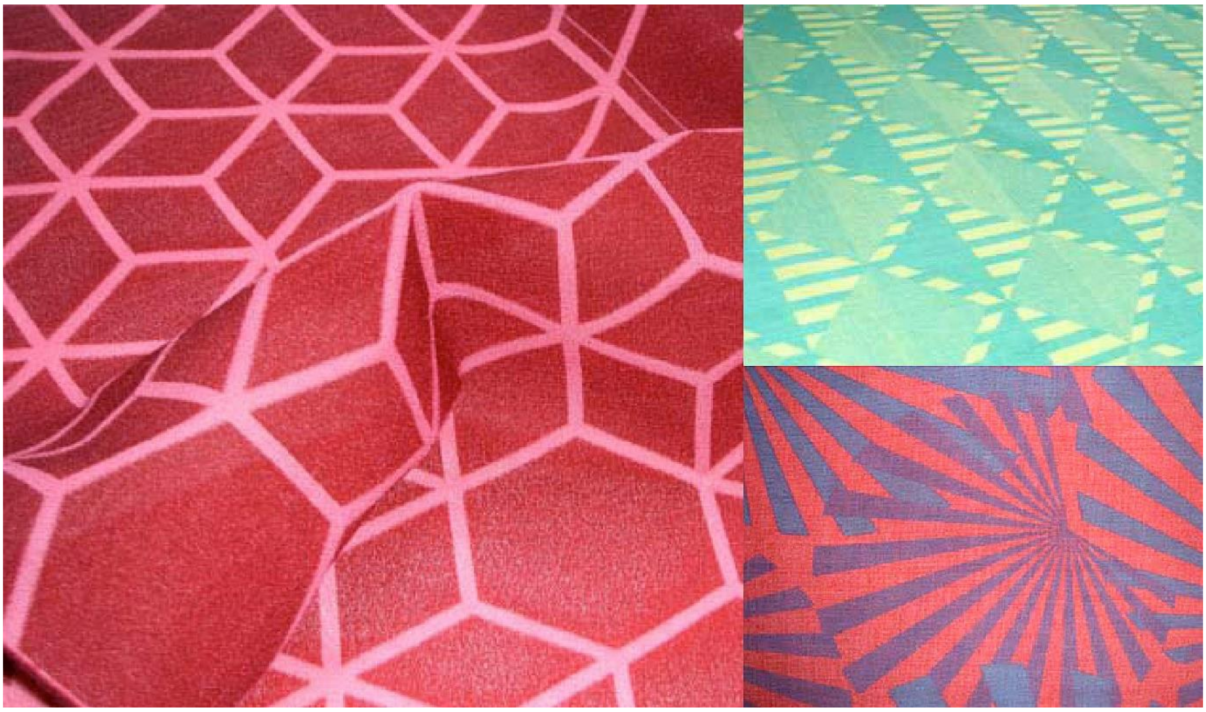


Figure 13: Laser textile patterns – 'cross-dyed' poly/cotton (Addrison 2009)

The aforementioned studies (Bartlett 2006 and Addrison 2009) demonstrate the significance of laser processing as a creative tool for textile design.

Laser-dyeing discussed in this thesis focused on fibre modification fused with dyeing in order to initiate new graphics within a textile design context. This work demonstrates a thorough understanding of a method for generating a range of tones with one shade using a digital patterning approach. A scientific and technical experimental approach relevant to industry standards enabled rigor and the communication of techniques and procedures involved. Other studies such as Bartlett (2006) for example, do not do this in terms of the creative opportunities of a laser/dye approach.

2.5 Laser modified synthetic textiles: fibre, laser and dye interactions

The aim of this section is to explore, discuss and summarise current scientific understanding of the laser-dye process in relation to polyester textile materials. The effects of laser modification (or irradiation) on surface fibres are explained in relation different laser types/systems. These include structural, physical and chemical changes and the relevance to dyeing properties, described as ‘dyeability’.

2.5.1 Polyester (PET) fibres

Laser irradiation causes structural surface changes to PET materials. As such, the process induces modification to textile fibres. It is known that this reaction enables increased dye uptake capability compared untreated/dyed polyester, as explored by Shamey and Shim (2011).

Researchers have studied laser modified polyester using a UV excimer laser approach able to deliver energy via pulsed beam i.e. the number of repeated pulses applied at different wavelengths. The work of Bahners and Schollmeyer (1989) and Kesting et al. (1990) represent early studies in this field regarding laser modified PET textile fibres, rather than films or other polymeric materials commonly explored at the time.

In UV excimer laser processing, ‘fluence’ describes the amount of energy distributed over an area (e.g. mJ/cm^2 or J/cm^2) known as ‘Energy density’. Bahners et al. (1993, p.13) explain ‘It is well known, that the existence of a threshold fluence is a main characteristic of UV-laser induced ablation of polymer surfaces’. Wong et al. (2003, p.114) further explain, ‘…changes to the surface morphology of PET fibres were found in relation to the laser energy applied.

2.5.1.1 Laser modified PET fibres: Structural surface changes

The surface morphology of laser irradiated PET textile fibres has been widely researched. Some of these studies include: Bahners and Schollmeyer (1989), Kesting et al. (1990), Bahners et al. (1993), Lau et al. (1997), Wong et al. (2003), Yip et al. (2002), Kan (2008b), Nourbakhsh and Ebrahimi (2012), and Kamel et al. (2012), for example.

As a highly absorbing polymer, both the physical and chemical properties of polyester are affected during fibre-laser interaction, as documented by Kan (2008b). Yip et al. (2002, p.151) explain, '…laser treatment on certain polymer materials can be categorised into two groups' – above ablation threshold or 'high fluence' and below ablation threshold or 'low fluence'.

The morphological configuration of the modified surface has been commonly referred to as periodic 'roll-like' ripple structures, as documented by Kesting et al. (1990), for example. Kan (2008, pp.115-116) reported high fluence irradiation caused the polyester surface to become 'sufficiently' rough (Figure 14) compared to the untreated material (Figure 15). As such, this method encouraged trapped air between the solid and liquid interface preventing water penetration (Figure 16). Lau et al. (1997, p.526) discussed such effect saying, 'According to surface physics, the unwettability of a hydrophobic material is enhanced by surface roughening'. Wettability decreased with high fluence irradiation causing an increase in wetting time. Bahners et al. (1993, p.12) also documented a higher number of laser pulses applied to the fibre increased the depth of structure yielding coarser modification. Bahners and Schollmeyer (1989, p.1884) further described this effect as 'a strong thermal contribution to laser-material interaction'.

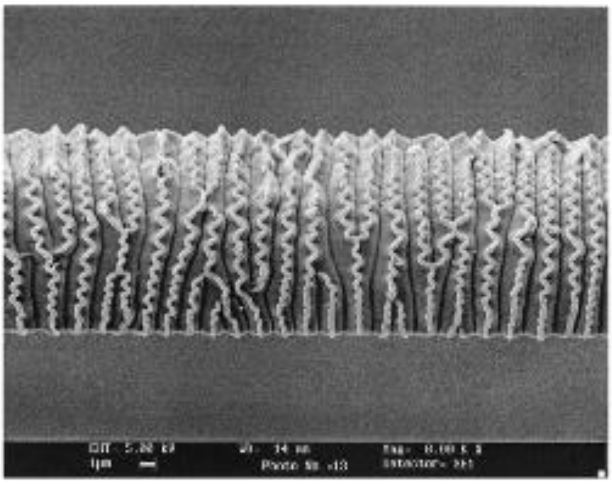
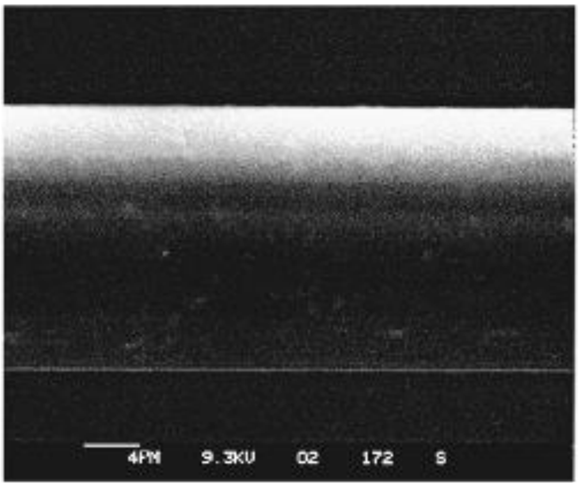



Figure 14: (Left) Surface structure of laser treated polyester under high fluence (Kan 2008b, p.115)
Figure 15: (Right) Surface structure of untreated polyester (Kan 2008b, p.115)

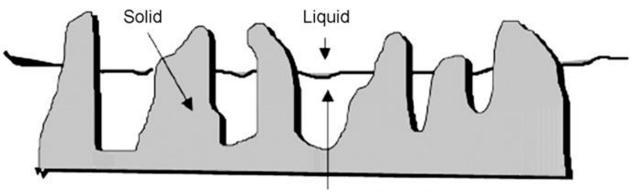


Figure 16: The effect of surface roughness on wetting (Kan 2008b p.118)

Low fluence formed sub-micron structures without deposited surface debris. Nanometric (tiny) sized ripples indicated structural surface modification was reduced (Figure 17). Nourbakhsh and Ebrahimi (2012, p.3), Kamel et al. (2012, p.2) and (Kan 2008b, p.116) reported such finding. The effect of a low fluence approach is therefore of ‘greater practical importance’ (Kan 2008, p.116) in terms of functionality and applicability of the laser process for textile goods, for example. According to Kan (2008b, pp.115-116), air could not be trapped between ripples using a low fluence approach due to ripple size constraints denoting micrometre structures on the fibre surface. Both wetting and dyeing time reduced based on minimised structural change to fibres. These results suggest opportunities for dyeing polyester regarding uptake capability in terms of reduced dyeing cycles for polyester coloration, relevant to this laser-dye research.

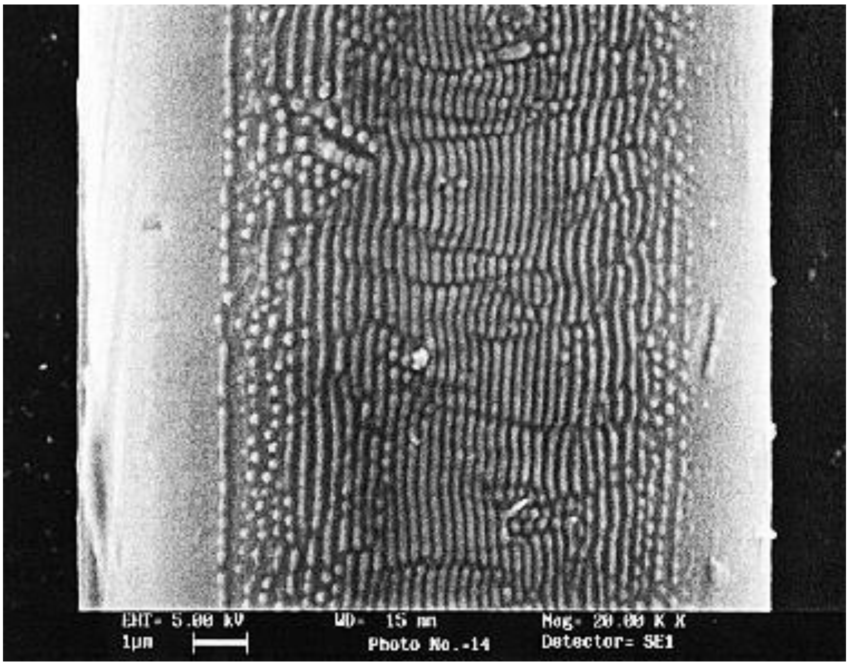


Figure 17: Surface structure of laser treated polyester under low fluence (Kan 2008b, p.116)

In terms of the impact of laser treatment on the properties of the fabric, Kesting et al. (1990, p.326) indicated an ability to influence fibre characteristics by controlled surface modification by using a UV excimer laser. These include wetting ad adsorption abilities, for example. Lau et al. (1997, pp.14-15), Nourbakhsh and Ebrahimi (2012, p.1) and Kesting et al. (1990, p.326) discussed the potential to design/alter the optical appearance of polyester fibres due to a change in lustre or reflective ‘glossiness’. Similarly, Bahners and Schollmeyer (1989, p.1884) described a loss of ‘birefringence’ (or optical characteristics) following modification.

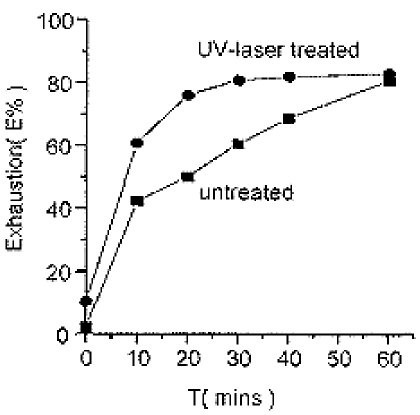
Kamel et al. (2012) explored the process as a method for improving properties of woven polyester fabrics, particularly dyeability (further discussed in section 2.5.1.2 of this chapter).

Tensile strength and colourfast properties were also indicated in the study based on laser modification. However, unlike this laser-dye research (as presented and discussed in Chapter 5), detailed investigation regarding textile performance was not evident and therefore limited regarding these aspects of the study. Kan (2008b) documented a more extensive investigation in this area compared to Kamel et al. (2012) by using PET fibres, yarns and fabrics, rather than one type of substrate. Discussion and results by Kan (ibid) included fibre weight and diameter, tensile strength and elongation, yarn abrasion, bending, surface lustre, air permeability and crystallinity.

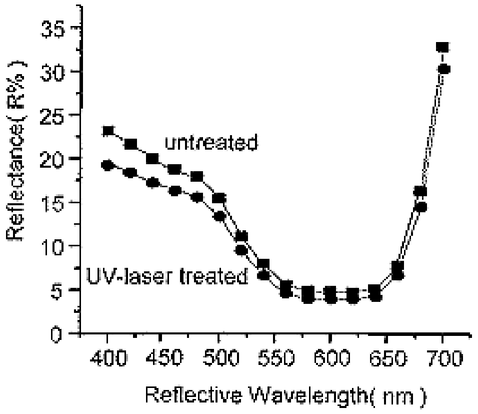
2.5.1.2 Dyeability studies

Dye uptake capability of PET fibres increases when modified by laser energy, as discussed previously. Lau et al. (1997) and Kamel et al. (2012) have carried out dyeability studies with UV excimer laser treated woven polyester fabrics. Samples were dyed at 130°C for 60 minutes, as studied by Lau et al. (1997) and at different temperatures (70°C -100°C), between 5-90 minute intervals, as Kamel et al. (2012) explored, and therefore below glass transition of 130°C T_g, typically required for polyester coloration according to industry standards. In both studies, conventional disperse dyes were used. Exhaust dyeing methods were carried out in order to understand the rate of dye adsorption against laser modification, compared to untreated fabrics. Adsorption levels were quantified using colour reflectance methods via spectrophotometer as documented by Lau et al. (1997) and K/S measurements to explain colour yield, described by Kamel et al. (2012).

According to Lau et al. (1997, p.527), laser treatment quickened the dyeing process and produced ‘deeper dyeing’ in a shorter time than the untreated fabric (Figure 18). It was argued that the laser etching process caused large molecular chains of the PET fibres to break and form smaller molecules during fibre-laser interaction (ibid). It was therefore concluded that dyeability was improved by laser treatment due to the increase of the overall surface area as a result of UV excimer irradiation. These findings suggest a more permeable substrate for he dyes as a result of laser induced morphology, further supported by statistical/visual reflectance colour data (Figure 19). Laser treated samples yielded lower values attributed to darker shade depths and therefore lower reflective characteristics, which can be understood.



(a)



(b)

Figure 18 (Left): Exhaustion rate of laser treated and untreated dyed polyester samples (Lau et al. 1997, p. 526)

Figure 19 (Right): Colour reflectance of laser treated and untreated dyed polyester samples (ibid)

Kamel et al. 2012 suggested increased dye uptake was proportional to beam exposure time and dyeing time. Uptake levels were defined by plotting ‘colour intensity’ against ‘dyeing time’ in relation to fibre/laser interactions over different time durations. Results showed that the dyeing behaviour of laser treated PET was enhanced compared to untreated samples. Notably, longer beam exposure and dyeing times produced an increased depth of shade, as Kamel et al. (ibid, pp.3-4) explained. Therefore, K/S colour yield was higher for laser irradiated samples. However, treated samples with a longer beam exposure time such as 10 minutes, produced lower K/S than 1 or 5 minutes for instance, as illustrated in Figure 20. These results can be attributed to a darkening (rather than a brightening) of colour caused by greater/longer fibre/laser interaction.

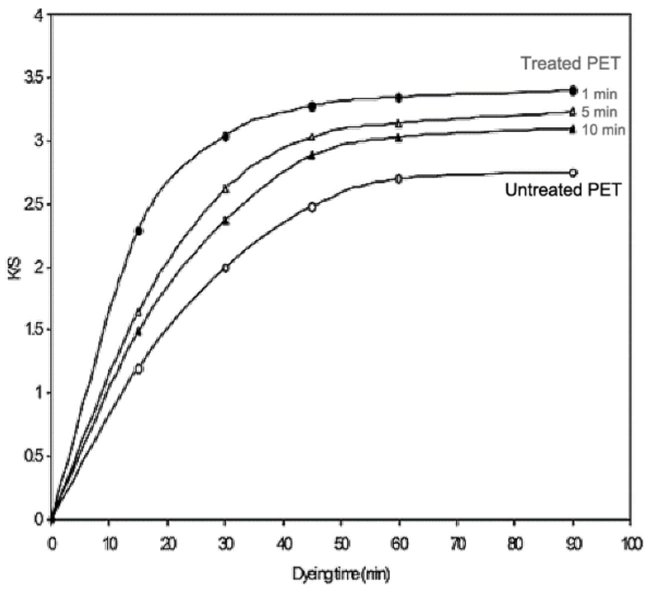


Figure 20: Dyeability of CW laser treated PET fabric at different exposure times (Kamel et al. 2012, p. 4)

The study (Kamel et al. 2012) therefore suggests dye-to-fibre penetration leading to increased uptake was proportional to both beam exposure time and dyeing time. It was concluded that pre-treatment with laser irradiation improved the dyeability of PET fibres.

The aforementioned studies offer some insight regarding the molecular change of PET textile fibres induced solely by excimer laser irradiation. Dyeability research provided further knowledge of dye uptake capability post laser treatment. However, the scope for combining laser processing and textile coloration methods is limited for polyester compared to polyamide (PA) synthetic materials (further discussed in section 2.5.2). Therefore, this digital laser-dye research has addressed some of gaps in existing knowledge. An ability to understand, calculate, determine and repeat energy density parameters in relation to colour density based on the dyeability of laser modified polyester has been achieved in this study. In doing so, a controllable laser processing approach to tonally engineer dye on to polyester textile surfaces with digital patterns was found.

2.5.2 Polyamide (PA) fibres

Polyamide (PA) textile fibres are commercially known as Nylon - Nylon 6 and Nylon 6,6 based the molecular composition of polymer chains (Figure 21). As with PET fibres, molecular structural changes also occur during laser processing. This effect is caused by the breakage of the amide linkages in the molecular structure and the formation of free amino groups as described by Bahtiyari (2011, p.115). Therefore, laser modified PA fibres adhere more readily to the dyeing process than untreated fibres causing increased uptake capability.

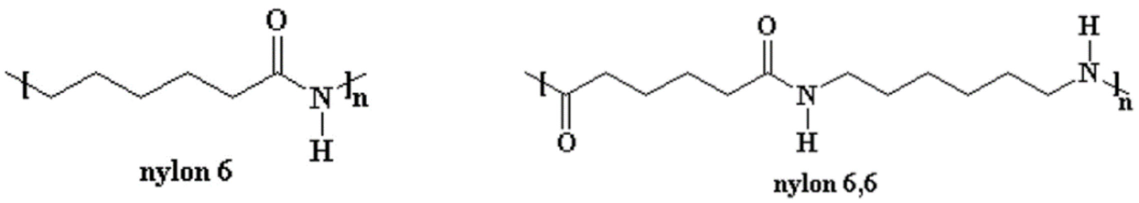


Figure 21: Nylon 6 and 6,6 (http://www.pslc.ws/macrog/images /six12. gif) [Accessed: 09/08/13]

In existing laser studies involving PA fibres, both UV excimer and CO_2 laser systems have been explored. Dyeability studies in this area evidence different dyes such as acid, disperse and reactive dyes along with other processing parameters. The aim of these studies was to observe the effect of variable uptake in relation to laser modification on both knitted and woven textiles.

2.5.2.1 *Laser modified PA fibres: Structural surface changes*

Laser modified polyamide has been studied by Yip et al. (2002), Shahidi et al. (2013), Bahtiyari (2011), Bahners (1993) and Nourbakhsh and Ebrahimi (2012). Plain woven fabrics and knitted structures were explored in these studies. The effects on dyeing were also investigated (Yip et al. 2002; Shahidi et al. 2013; Bahtiyari 2011), further discussed in section *2.5.2.2*.

Yip et al. (2002, p.152) reported on the morphological and chemical modifications of laser treated fibres commenting, 'Today, pulsed UV laser is one of the most commonly used non-contact treatment techniques in modifying surface properties of polymers physically as well as chemically' (Yip et al. 2002, p.73). Sub-micrometre sized structures formed on the fibre surface with low fluence methods had significant effects on wetting and dyeing properties of woven PA fabrics. Therefore, hydrophilic properties were improved with a low fluence, rather than high fluence approach, similarly described by Shahidi et al. (2013, p.42). This method was considered most appropriate in terms of practicality. As with laser modified PET fibres, ripple like structures were formed with PA textiles. Bahners et al. (1993, p.12) argued, 'The resulting surface properties may have an important impact on processing, as they can affect technical properties of synthetic and even natural fibres…' e.g. wetting. They further explained that surface changes to UV excimer laser irradiated PA (nylon 6,6) and PET fibres were dependent on parameters such as the range of fluences and material constants i.e. the type of substrate, for example.

Yip et al. (2002) further explored the effects on dyeing properties with PA (nylon 6) plain woven fabrics using a UV excimer laser. As with PET fibres treated by UV excimer laser, they also report ripple-like structures regarding PA materials describing them as '…strictly perpendicular to the stress direction of the fibre' (ibid. p.73). These results are similarly documented by Shahidi et al. (2013, p.42) who have studied surface modification of polyamide to improve PA fibre properties for dyeing using UV excimer laser. They comment (ibid.), '…the change in coloration closely corresponds with the ripple-like structures and the changes in chemical properties induced by laser treatment'. Therefore, fibre modification is possible by the deliberate change in composition or structure, as described (ibid. p.33). Bahtiyari (2011, p.115) further discussed 'the change of macromolecular structure' to improve dyeability using polyamide knitted fabrics and a CO_2 laser system. A decrease in the crystallinity (polymeric molecular order) of PA fibres led to a greater affinity for dye uptake in disperse dyeing (ibid. p.116). Bahtiyari (2011, p.17) argued that this was due to an amorphous (formless) morphological change induced by higher laser intensities, as reported in the study.

2.5.2.2 *Dyeability studies*

With conventional coloration methods, synthetic textile polymers are typically difficult to dye as they require high temperatures and more resources in the dyeing process such as energy usage, chemicals and auxiliaries. Therefore, laser methods that improve dye uptake capability are beneficial to this field. Nourbakhsh and Ebrahimi (2012, p.1) explained PA (and PET) fibres are characteristically hydrophobic without laser treatment. In textile processing however, dyeing, printing and finishing are largely based on wet treatments (ibid). With a laser approach, surface modification improved fibre characteristics such as adhesion, wetting and the penetration of dyes into fibres. This interaction counteracted the hydrophobic tendencies of synthetic fibres.

Shahidi et al. (2013, p.42) studied the surface modification of plain knitted polyamide via UV excimer laser as a method for improving dyeabilty; Yip et al. (2002) explored the effects on dyeing with laser modified knitted PA fabrics, also with a UV excimer system; Bahtiyari (2011) studied knitted PA using a CO_2 laser. In the study (Bahtiyari 2011, pp.115-116), improved dyeability was further attributed to 'the change of macromolecular structure' - a decrease in the crystallinity (polymeric molecular order) of PA fibres leading to a greater affinity for dye uptake in disperse dyeing.

Commercially available acid, reactive and disperse dyes were used in each of the studies (Yip et al. 2002; Shahidi et al. 2013; Bahtiyari 2011). Yip et al. (2002) carried out dye bath exhaustion and spectral reflectance data methods in order to observe dye uptake. Dye exhaustion (%) was measured against time (mins) for all dye baths and spectral values (R %) against wavelength (nm) for dyed samples. Shahidi et al. (2013) also examined dye bath exhaustion to compare untreated and laser treated samples. Bahtiyari (2011) studied the effect of laser exposure on the colour yields (*K/S*) using a laboratory dyeing machine and spectroscopy measurements, also carried out in this digital laser-dye research, further discussed in Chapter 5 of this thesis.

In acid dyeing experiments, Yip et al. (2002, p.77) and Shahidi et al. (2013, p.43) reported a faster rate of dye exhaustion with laser treated samples compared to untreated (Figure 22).

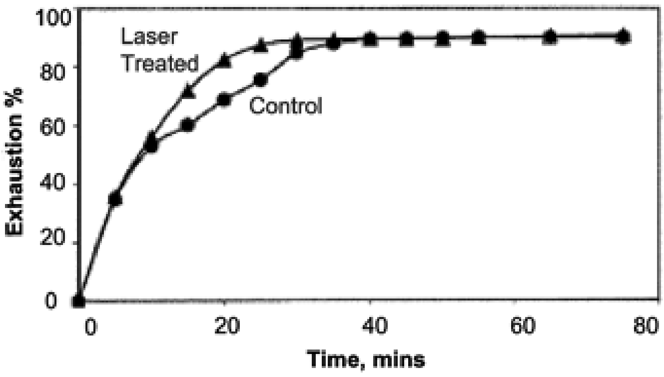


Figure 22: Exhaustion rate in acid bath – laser treated and control PA fabric samples (Shahidi et al. 2013, p.43)

Both studies documented equilibrium (sameness) was reached between treated and untreated sample over a shorter dyeing time in contrast to other dye baths containing different dye types. A change in molecular structure/bonds to laser modified fibres accelerated acid dye adsorption consequently decreasing the equilibrium time reached.

Bahtiyari (2011, p.15) investigated three types of acid dye – fast acid, milling and levelling dyes (as well as disperse and reactive dyes). A notable increase was recorded with milling type acid dyes with controlled parameters using CO_2 laser in pulsed mode. Consequently, *K/S* colour yield values were significantly higher, indicating deeper dyeing (Figure 23). Shade changes were also described in terms of CIE *L* a* b** colour measurements (L*: lightness, *a**: redness and greenness, *b**: yellowness and blueness values). Acid milling dyes produced lower K/S % yield at higher intensities. This can be attributed to significant deeper dyeing caused by notably darker, rather than brighter shades, as previously discussed. With fast acid and levelling dyes a more linear/steady increase in colour yield was reported in relation to results higher laser intensities against colour yield. This can also be said for reactive dyeing experiments. Samples dyed with disperse dyes report the lowest *K/S* colour yield indicating the fabric was only stained and not dyed, therefore producing paler shades.

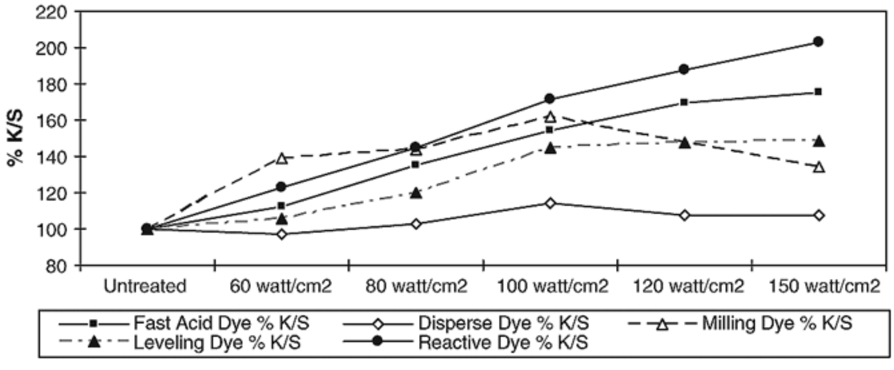


Figure 23: %KS of treated and untreated fabrics (Bahtiyari 2011, p.115)

Steeper exhaustion curves were documented by Shahidi et al. (2013, p.43) and Yip et al. (2002, p.77) for disperse dyeing. This result was determined by fibre/dye capability. In both studies, ‘No significant change’ (ibid) was recorded between laser treated and untreated samples in the first 40 minutes of dyeing, also reported by Bahtiyari (2011, p.115). After this time, Yip et al. (op. cit) documented increased dye absorption with treated fabrics. However, Bahtiyari (2011, p.115) did not report this. Instead, Bahtiyari (ibid.) explained, ‘It is well known that disperse dyeing is unrelated with the macromolecular structure of fibres and that generally the change in fibre crystallinity does not affect the disperse dyeing of polyamide’. Yip et al. (2002, p.78) suggested that laser irradiation increases overall dye uptake of PA fibres in disperse dyeing due to an increased surface area. However, based on these studies (Yip et al. 2002; Bahtiyari 2011; Shahidi et al. 2013), it is thought that the rate of exhaustion is not significantly altered by laser treatment in acid dyeing.

In contrast to acid and disperse dyes, both the rate of exhaustion and the total amount of dye absorption increased throughout dyeing with reactive dyes. These results are documented by Yip et al. (2002, pp.77-78), Bahtiyari (2011, p. 115) and Shahidi et al. (2013, pp.42-43). Referring to laser treated fabrics, Shahidi et al. (ibid.) commented, ‘…darker shades are obtainable using only the usual amounts of dyestuffs’. Yip et al. (op cit.) reported that these results are due to ‘an increase in the number of end groups…’ This effect of the treated fibre therefore led to accelerated dyeing and greater overall dye uptake.

In general, regarding exhaustion, results in each of the aforementioned dyeability studies revealed laser treated samples absorb more dye overall or at the point of equilibrium (where applicable). Therefore, deeper shade depths were achieved compared to the untreated control samples. Yip et al. (2002, p.78) explained, ‘The shade improvement by laser treatment can be attributed to scattered reflection from the roughed fibre surface’. Findings were further supported by lower spectral reflectance results for all laser modified/dyed samples. For example, Yip et al. (2002, p.77) reported higher spectral values for untreated samples. On the principle of colour physics as described by Itten (1970, pp.15-16), this result can be expected due to lighter/paler shade depths typically attributed to untreated fabrics compared to laser modified samples. Paler shade depths exhibit higher reflectance compared to darker depths as with treated samples. Modified fabrics have higher absorbance and lower reflectance values due to a ‘deeper dyeing’ effect.

This literature review discussion acknowledges greater experimentation carried out with PA compared to PET synthetic fibres, in this research field. Therefore, the digital laser-dye investigation presented extends current knowledge regarding laser modified polyester in terms of the approach and the development of processes. The work has been carried out in a way that is also relevant to other polymer fibres including polyamide as well as natural and multi-fibre fabrics. Based on a rigorous experimental framework explored, applicable to textiles, methods and techniques can be repeated and adjusted in relation to a specific fibre/fabric type. Consequently, experimental laser parameters were assessed in terms of performance and functional properties using ISO procedures in order to further understand the effects of laser treatment. This approach supported industrial applicability of processes regarding commercial relevance of new knowledge generated and consideration for the potential development of aspects studied beyond this doctoral project.

2.6 Environmental considerations for textile dyeing

Ecotextile (2011) reported approximately 54 million tonnes of textile fibres are processed each year, which requires 1 million tonnes of dyes and 7 million tonnes of other chemicals; A report by Janet Rodie of *Textile World* (2012) said, '…according to some estimates, 60 million metric tons of textiles are dyed each year at the rate of 100 litres of water per kilogram of material, which translates to some 6 trillion litres of water…'; In a study on textile colour application, Aspland (2000, p. 201) discussed some of the processes involved in dyeing along with the technical and commercial problems traditionally associated with this industry such as excess global dye and chemical capacity, international sourcing and pricing pressures; Clarke (2011, p. 32) described industrial dye processes in terms of resource usage and dye-contaminated water treatments. From a product perspective, Clarke (ibid) explained, 'consumers are now more environmentally aware and want to see evidence on textile goods of low impacting manufacturing methods used'.

2.6.1 Advancing textile dyeing approaches

Factors such as wastewater, energy-saving, chemical reduction, molecular dye composition, processing time and equipment, for example are relevant to the textile community. Industrial corporations such as *Clariant*, *DyStar* and *Huntsman*, for example contribute to developments in the textile coloration industry. In addition, *DyeCoo* textile systems engineers commercially developed a waterless dyeing technology in 2009. This system uses CO_2 gas, high pressure and temperatures instead of water. The process is also known as Supercritical Fluid Dyeing Technology earlier described by Bach et al. (2002). More recently, global sportswear brands *Nike* and *Adidas*, along with home furnishings retailer *IKEA* have incorporated this technology into their product lines. The adoption for this trend (Rogers 1962), highlights the significance and interest in innovative coloration procedures within this sector.

Other advances in textile dyeing have been described by *Cloth Market,* 2011 (Fibre2Fashion 2012). These developments include Plasma – the chemical status of a substance in its gaseous phase. Plasma methods are currently used as a surface treatment to structurally alter textile fibres in order to increase dye uptake during dyeing such as synthetic textiles. Secondly, Electrical Chemical Process Technology initiates chemical reactions using electrical energy beneficial for processing efficiency. This approach replaces traditional aid agents in direct chemical reactions. With colour reduction processes, direct electrochemical methods eliminate reducing agents normally used. The value of wastewater is also reduced, therefore lowering the cost of wastewater treatment, as discussed by Khouni et al. (2011) and Kong and Wu (2008).

Global Industry Analysts Inc. (2011) explained that environmental concerns in the textile industry surrounding dyes called for a change in 'product mix'. This referred to the types of compounds and substances used to form dye molecules. It was discussed that an increase in the banning of certain dyes on a global scale could lead to a demand for eco-friendly textile chemicals from textile manufacturers. 'Development in technical expertise and achievement in R&D activities are expected to bring about new dyeing technologies in the industry' (ibid). On this subject, *New Cloth Market* 2011 (Fibre2Fashion 2012) also remarked:

> *The industry is desperately in the need of newer and very efficient dyeing/finishing and functional treatments of textiles. There is growing awareness and readiness to adapt new perspective on industrial upgradation of Cleaner Production Programme, such new technologies help enterprises achieve green production and cost reduction at the same time. Green Production has become necessary for enterprises under the upgrade and transformation policy. Therefore there is an urgent need to promote new technologies in textile dyeing and finishing, injecting new thoughts to the industry.*

In this digital laser-dye research, environmental opportunities of the process have been acknowledged such as no water or chemicals in laser processing, low energy usage associated with CO_2 lasers, low liqour dyeing ratio's and reduced dye quantities via industry standard dyeing procedures; and the potential to dye synthetic fabrics at lower temperatures than current conventional requirements. The work is commercially relevant based on design ideas, experimental procedures and project goals embedded into the research framework. These considerations were supported by the aims and objectives of the study. In general, methods and approaches that promote low-waste, resource-efficient principles towards sound environmental textile practice are considered important in this field. Therefore, the potential environmental benefits proposed by this work positions development of a laser-dye process as significant to the textile coloration industry.

2.7 Conclusion

The laser-dye process explored in this research is concerned with alternative methods for dyeing and patterning in textile design and coloration which suggest ecological advantages. This literature review has discussed the capability of laser modification approaches for fibres based on existing studies within this field and in relation to the scope of this research. In particular, the effect of dye uptake, textile processing methods and design innovation regarding combined laser processing and textile dyeing techniques. A platform for the creative potential, environmental opportunities and commercial significance of a laser-dye approach has been discussed. This was achieved by identifying gaps, opportunities and limitations in relation to the current body of knowledge and attributing subsequent advancements in this field to this doctoral study, as summarised below

Although conventional coloration practices enable creative input when applying colour/pattern to cloth, procedures usually require harsh substances and/or intensive resources to achieve particular aesthetic effects. By comparison, digital textile printing does however offer greater environmental benefits as discussed by Bowles and Isaac (2012, 2nd ed., p. 178). Advantages of this technology are mainly associated with less dye and material wastage due to printing on demand via engineered precision. However, related factors such as pre/after treatments and additional processing stages e.g. steaming and washing typically involved in production and finishing do limit the environmental potential of this technological approach.

By contrast, in terms of the opportunities presented by the digital laser-dye process, this surface coloration approach may be seen as an environmental alternative to traditional and existing textile patterning techniques. This is due to the relatively low energy output of lasers and the absence of water and chemicals in laser processing as discussed by Yip et al. (2002, p.78) and Wong (2003, p.114). Shahidi et al. (2013, p.42) commented, '…the excimer laser modification process has a high industrial potential, as it is an environmentally friendly dry process not involving any of the solvents required for a wet chemical process'. This can also be said for fibre-laser interactions achieved with other laser systems such as Carbon Dioxide (CO_2) for example, used in this research. The increased uptake capability of laser modified synthetic fibres explored in this research field highlights the potential to reduce dyeing temperatures of polyester textiles and other manmade materials. In doing so, energy, time and possibly production costs may be further reduced. Therefore, laser methods for modifying the surface of synthetic textiles to improve dye uptake via patterning are advantageous in the textile coloration sector.

Existing literature concerning laser surface methods for textiles is dominated by synthetic materials due to their affinity with the irradiation process, as previously discussed (section 1.5) and to investigate the effect of laser modification on textile fibres to improve dyeability. Contributions to this body of knowledge regarding polyester (PET) include Kan (2008a and 2008b); Bahners et al. (1993); Lau et al. (1997); Nourbakhsh and Ebrahimi (2012) and Kamel (2012), for example. Other studies that explore laser modified polyamide (PA) include Bahners et al. (1993); Shahidi et al. 2013 and Yip et al 2002, for example, using mainly a UV excimer laser approach. However, greater experimentation in this field has been carried out with PA substrates with both UV excimer and CO_2 laser systems. As such, in this area, varied experimental parameters were studied relating to dyes, methods and assessment procedures. Such knowledge has provided a more in depth understanding of the effect laser modification on PA fibres in a way that is not evident regarding PET/laser modification studies. Although some variable parameters have been explored in PET dyeability studies such as dyeing temperatures and times for example, the scope of overall experimentation in terms of scale and depth is relatively small compared to PA studies. Therefore, investigation with polyester demonstrates some limitations attributed to approach and methods. Overall, existing literature affirms that the laser does increase dye uptake capability of synthetic textile fibres.

A lack of design development of the results and industrial contribution towards combined laser and textile coloration methods has been identified in both areas (PET and PA). This indicates the absence of creative knowledge and input regarding coloration and surface design opportunities. In addition, the use of conventional fabrics, dyeing methods and dyes rather than industrial approaches in terms of equipment, dyeing profiles, dye type, fabrics and testing suggests minimal understanding in terms of potential application of laser-dye techniques that relate to practicality and commercial potential addressed in this laser-dye research (further discussed in Chapters 5 and 6). Such information is relevant for textile design and textile processing in terms of product identification based on suitability, manufacture and finishing, for example. However, by approaching this work as a textile designer, this research addresses some of these gaps and has therefore advanced knowledge in this field.

Commercially, the CO_2 laser is more accessible than UV excimer systems however, is not widely investigated based on current literature, particularly with PET fibres. Therefore, in this doctoral study, a CO_2 laser was used to investigate the modification of PET woven and knitted fabrics, thus expanding knowledge in this field. Combined laser, fibre and dye interactions were explored from a textile design perspective within an interdisciplinary framework including creative, scientific, technical aspects integrated with industrial input. This involved the use of industry standard (ISO) dyes, dyeing profiles, dyeing equipment, specification fabrics and ISO measurement and analysis procedures, as well as consultation through collaboration with Society of Dyers and Colourists (SDC). As such, this involvement facilitated the acquisition of industry specific knowledge relevant to development of the laser-dye process and its potential application in a commercial textile environment.

From an environmental perspective, conventional methods for dyeing synthetic fibres such as polyester demand significant energy consumption. These polymers are dyed at high temperatures to reach glass transition (T_g) phase so that dyes fully permeate fibres. The increased uptake capability of laser modified synthetic fibres explored in this research field highlights the potential to reduce dyeing temperatures of polyester textiles and other manmade materials. In doing so, energy, time and possibly production costs may be further reduced. Therefore, laser methods for modifying the surface of synthetic textiles to improve dye uptake are advantageous in textile coloration and surface design sectors. In this research, a low energy approach was undertaken, encouraged by the employment of CO_2 lasers. Low resource methods were employed using industry procedures for sample dyeing with an infra-red dyeing machine. This enabled low liquor ratios by sufficient agitation and temperatures under ISO procedures in line with both the environmental considerations and commercial relevance of the work.

In this digital laser-dye study, creative development of the processes and techniques explored were enabled by a practice-led interdisciplinary approach. This development is relevant to advances in surface design and textile coloration procedures influenced by the authors experience and expertise in pattern and print textile design practice. Essentially, laser energy was used to digitally mark textile fibres in a way that generated patterns on the fabric surface via laser beam. Laser processing methods employed enabled controlled exploration of dye/colour density or shade depth in relation to energy density parameters. Therefore, an approach for the engineered application of preferential tonal dye uptake on a single polymer cloth – polyester woven and knitted fabrics, has been achieved. Creative, experimental (scientific) and industrial textile dyeing procedures were carried out in this work. An ability to specify and replicate a digital dye-on-demand coloration approach with high-resolution graphics is presented in this thesis discussion. Such practice is not possible using conventional hand and applied dyeing methods whereby accuracy and repeatable results are more difficult to achieve. Interrelated CAD/CAM laser processing and textile dyeing approaches explored in this study facilitated development of a digital laser-dye process investigated, both technically and creatively. As such, two main laser/dye techniques have been identified in this research – Fibre Laser Dye (FLD) and Fibre Dye Laser (FDL) interactions, further discussed in Chapter 5 of this thesis.

Chapter 3: Methodology

This chapter identifies the methodology and methods used in the research. It sets out the overarching ideas and approaches employed in order to contextualise the wok, summarised in Figure 24. This framework facilitated the scientific, technical and creative aspects of the project, as explained in Table 3, related to laser-processing, dyeing and the analysis of textile fibres.

Divided into two parts, 'Part 1' of this chapter describes the Methodology undertaken and 'Part 2' describes the Methods applied. The study is an interdisciplinary collaborative investigation linking academia and industry. The work is positioned in a practice-led, design research environment and has been approached from a textile design perspective as a practitioner. Therefore, a practice-led methodology was employed. This model (explained in Figure 24) steered the acquisition of new knowledge surrounding a new digital laser-dye process. The study combined quantitative and qualitative methods referred to as a 'mixed method' approach (Creswell 1994), as outlined in Figure 24 and further defined in Part 2 of this discussion (Table 5). The methods described assisted the creative focus of the inquiry centred on development of digital laser-dyeing techniques for textiles.

Aspects of the research	Description
Scientific	Quantitative experimental methods, data handing (based on precision, mathematical or computational approaches), measurement and analysis involving methodological statistical procedures that can be repeated and graphically presented or explained; approaches include: structured experiments (relating to laser processing, CAD, dyeing and testing), ISO dyeing procedures, digital microscopy (fibre/surface analysis), colour assessment and ISO textile performance tests.
Technical	Experimentation involving a range of varied processing parameters required in order to explore digital laser-dye techniques attributed to laser machines and associated equipment (e.g. laser power meters), computer software: laser and CAD related, infrared dye machine/dye profiles and elements of fibre and colour analysis such as equipment, settings and computer software e.g. microscopes, reflectance spectrophotometry and ISO performance testing machines.
Creative	Design practice based on artistic input, encompassing discipline specific skills and an awareness of creative elements. This involved being experimentally engaged scientifically, technically and creatively as to identify and exploit opportunities presented by the laser-dye process from a textile design perspective by focusing on colour and pattern surface development; creative aspects represent a qualitative approach that embodies individual thought (intuition and tacit knowledge) and expression which aids design innovation.

Table 3: Descriptions for the Scientific, Technical and Creative aspects of the research

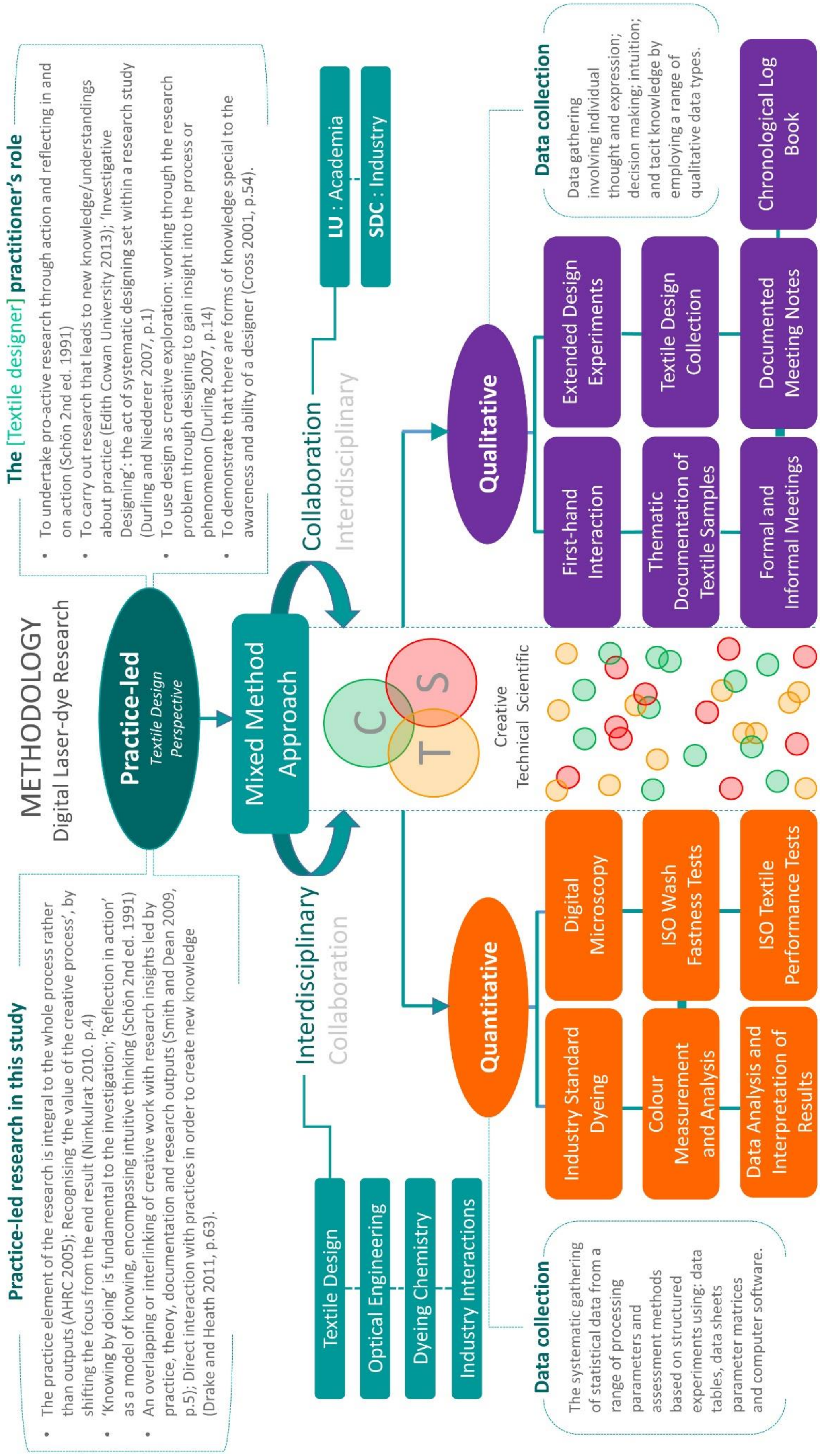


Figure 24: Practice-led methodology: a 'mixed method' research approach

An interdisciplinary approach undertaken describes the crossing over into different disciplines and departments within academia (Loughborough University) from the standpoint of a textile designer in order to carry out the study. Collaboration in this work describes the partnership with an industry organisation, Society of Dyers and Colourists (SDC) that facilitated considerations for commercial potential of the digital laser-dye process. A combined interdisciplinary collaborative approach employed for this research is defined and further contextualised in this chapter. Textile design practice, Design research and Design context are also described in relation to the scope of this study which establishes the creative underpinning of the work.

3.1 Part 1: Methodology: a practice-led approach

This section discusses the main approaches used to carry out this investigation within a practice-led methodological framework, set out in Figure 24. Malins et al. (1995, pp. 2-3) describe the relative infancy of formal research in creative disciplines such as Design [compared to a long established history in scientific fields for instance], explaining that 'designers have sought methodologies which reflect their particular discipline-specific expertise'. Consequently, Malins et al. (1995, p. 3) argue that this has led to approaches such as 'practice-led' research, for example. In this manner, the researcher/practitioner assumes 'a pro-active research model involving practitioners researching through action and reflecting in action', as defined by Schön (2nd ed. 1991). Gray and Malins (2004, p. 17) acknowledge that the research process is more important than the product . Aspects relevant to this 'research practitioner' approach are further discussed by in *Visualizing Research: A Guide to the Research Process in Art and Design* (Gray and Malins 2004). Additionally, Malins et al. (1995, p. 3) explain that in the practice-led model, 'the researcher/practitioner is central to the inquiry as is the context in which the research is taking place'. Similarly, these ideas regarding practice-led research are shared by Drake and Heath (2011, p. 63); Smith and Dean (2009, p. 9); AHRC (2005); and (Nimkulrat 2010, p. 4), for example.

Interdisciplinary and collaborative issues surrounding design and research have also been described in this section, in the context of this study. Practice-led research and Textile design practice are defined in relation to this investigation and the design context for the work is explained, as to understand the creative element of the inquiry. This discussion pertains to textile design via the DLD process explored.

3.1.1 Interdisciplinary approaches in design research

In this research, interdisciplinary describes the coming together or crossing over of diverse disciplines from a textile design perspective in order to carry out the laser-dye investigation.

Also termed multi-disciplinary, this approach refers to the involvement of two or more distinctly different fields. An interdisciplinary approach to research supports the acquisition of diverse knowledge and enables different areas of learning to be opened up. Problems and solutions are investigated and developed holistically in varied environments with people who have different viewpoints, expertise, skills, expectations and field specific language in relation to their 'unique' training.

A shift towards ‘developing tomorrow’s designer’s’, through interdisciplinary or multi-disciplinary activity in UK universities is said to equip design students with the necessary mix of skills recognised by employers (Design Council 2010, p. 16). Therefore considered a requirement for interdisciplinarity. The knowledge gained through such activity enhances the discipline specific attributes of the designer and cultivates a deeper understanding and interaction with aspects relating to business, science, technology, engineering and manufacture, for example.

Kees Dorst (2006, p.18) argues, ‘It has become almost impossible for a single designer to possess all the necessary knowledge and skills to develop complicated design’. The nature of design practice is that it combines different things. It is ‘multifaceted’, bringing together historical references, technological innovations, production techniques and process, as described by Clarke (2011, p. 7). Such variety means designers rarely work alone. They are likely to interact with other designers, cross disciplines or communicate with manufacturers, textile mills or technologists, for example. The purpose of working in this way is to test or realise ideas and facilitate production. This approach is essential for design development and application.

The intention of the interdisciplinary approach untaken in this research was an attempt to advance knowledge by combining methods, characteristics and attributes from each field – textile design, optical engineering, dyeing chemistry and industry standard procedures, underpinned by creativity. The process of doing research in this way is a less traditional approach than that commonly relating to just a single discipline. Instead, a lateral and more fluid structure was adopted, further explained by Rhoten (2004, p. 6). Such ‘fluidity’ is also discussed by Drake and Heath (2011, p. 61). Referring to research practitioners, they discuss ‘…spaces created through the interaction of several ‘contexts’, which inevitably interact with each other’. This structure encouraged essential crossover in thinking, discourse and action towards generating new knowledge and creating a platform for innovation entailing project meetings, one-to-one discussions and discipline specific structured experimentation (in both academic and industrial environments) . Interdisciplinary methods facilitate the ability to approach a problem or subject in a more holistic way. It is said that exposure to multi-disciplinary team working leads to ‘…a more holistic outlook to problem solving and a better capacity to influence people and negotiate change’, as discussed by Baily and Smith (Design Council 2010, p. 31). Multiple aspects were embedded and addressed as a whole body within this research.

The reciprocal nature of interdisciplinary studies enables inclusivity of different areas of knowledge, method, skills and techniques towards well rounded mutually informed results and rich discussion. This can lead to an efficient framework that embodies variety. Therefore, sufficient understanding of the subject or problem is essential to the research process. From a designer's perspective, Dorst (2006, p.109) refers to the varied attributes contributing to the design process as a 'combination of intelligences – linguistic, logical/mathematical, spatial, musical, bodily/kinaesthetic and personal'. As such, design is a natural site for interdisciplinary work and the knowledge of the designer draws on many aspects. This type of knowledge is as Cross (1999, p. 5) writes, 'Design knowledge resides firstly in *people*: in designers especially'. He explains, '…there are forms of knowledge peculiar to the awareness and ability of a designer' (ibid.).

In this study, an interdisciplinary approach was necessary in order to interact with multiple disciplines. This led to the production of different types of information and a deeper subject knowledge not obtainable within a limited single discipline approach (i.e. Textile Design; Engineering; and Chemistry). In doing so, knowledge inherent to one field, adopted or enhanced by other fields presented a valuable standpoint for originality and advancement, also discussed by Katz and Martin (1997, p. 2). This process of knowledge transfer is key to innovation – the ability to share, understand and apply new knowledge and best practice. Diverse skills, knowledge and experience(s) are considered important attributes of such interdisciplinary activity. These ideas have been explored and discussed by the Design Council (2010) - Temple (Design Council, p .9) argues, 'The economic goal of generating more wealth from new science demands multi-disciplinary teams of designers, engineers and technologists designing around the needs of customers'. Papanek (1984, 2nd ed., Preface x) also writes, 'Design must become an innovative, highly creative, cross-disciplinary tool responsive to the true needs of men'. Similarly in 1947, textile designer, *Anni Albers on designing* (Albers 1962, 2nd ed., p. 2) commented, '…we find two distinct points of departure: the scientific and technological, and the artistic. Too often these approaches arrive at separate results instead of a single, all-inclusive form that embodies our needs: the need for the functioning of a thing *and* the need for appearance that responds to our sense of form'.

The interdisciplinary approach within this research included both qualitative and quantitative methods previously described (Figure 24) and are further discussed in Part 2 of this chapter. Similar to this approach, Cross (2001) examines the relationship between design and science in his study, *Designerly Ways of Knowing: Design Discipline Versus Design Science*. He discusses the growth of scientific design process and design methods in the 1960's. Evidence of such could be linked to the invention of laser technology in 1960, for example – '…the application of novel, scientific, and computational methods…' (Cross 2001, p.49). Cross identifies the reemergence of 'design-science' matters (also discussed by Dorst 2006, p. 204). This term may also be considered relevant to this laser-dye research. Cross (ibid.) further acknowledges the shift towards methodological approaches, publication themes and dialogue within this territory.

In this study, an interdisciplinary approach was necessary in order to interact with multiple disciplines within Loughborough University in collaboration with industrial project partner, SDC. As such, this led to the production of information and deeper subject knowledge not obtainable within a limited single discipline approach (i.e. Textile Design; Engineering; Chemistry; and Industry). In doing so, knowledge inherent to one field, adopted or enhanced by other fields presented a valuable standpoint for originality and advancement.

The effectiveness of interdisciplinary interactions was dependent on building workable relationships with people – project members, technical staff and other doctoral researchers in different departments (School of the Arts, Wolfson School of Mechanical and Manufacturing Engineering; Department of Chemistry; and Society of Dyers and Colourists). Initially, this platform for interaction proposed a dynamic that was not yet fully known or understood, described by Smith and Dean (2009, p. 42) as '…uncertain relationships surrounding human and physical structures and systems'. However, project progression was considered a discernable factor in which to evaluate the efficiency of day-to-day working relationships between disciplines and in relation to the experiences of the researcher. From a researcher perspective, communication and learned behaviour(s) became a key aspect of the research process, enabled by practical engagement within different environments. An awareness and understanding of discipline/environment specific issues has been demonstrated by this study through the transfer and exchange of first-hand knowledge (i.e. information, know-how, experience and skills) gained by interacting with people, machines, equipment, varied data types, textual information and specific vocabulary. This in turn, aided effective communication and project development.

In terms of collaboration, some of the challenges of the process can be attributed to communication aspects such as keeping partner(s) up-to-date at all stages of the work to affirm their involvement; or the location/distance between parties involved regarding logistics and the frequency of first-hand interactions, for example. Equally, the advantages of a collaborative approach carried out in this study, bridged the gap between academia and industry in order to understand and apply the commercial requirements for industry standard textile coloration procedures and ISO colour measurement and analysis regarding the digital laser-dye process investigated. These factors were fundamental to the research and are discussed further in the next section.

3.1.2 Collaborative approaches in design research

In this research, a collaborative approach describes a partnership between the researcher/ textile design practitioner (academia) and industrial organisation, the Society of Dyers and Colourists (SDC). The collaborative elements involved hands-on experimental assistance and training provided by the SDC, industry standard resources and methods such as fabrics, equipment and facilities, together with a mutual exchange of knowledge, skill and expertise by both parties through various modes of interaction, in relation to the laser-dye process explored.

Collaborative approaches involve more than one contributor to the research process regarding inputs and outputs. The researcher(s), academic institution(s) or industrial partner(s) for example, collectively contribute to the body of work as a team. Katz and Martin (1997, p. 7) define research collaboration as 'the working together of researchers to achieve the common goal of producing new scientific knowledge'. This suggests that the coming together essence of collaboration and '…making sensible connections' as described by Gray and Malins (2004, p. 21) is fundamental to advancement and originality. The expectation is that each participant will have something unique to contribute and add value towards the anticipated outcomes. Teamwork in some capacity is therefore understood. This dynamic encourages vibrancy and diversity in discussion and problem solving towards project development (further described by Dorst 2006, p. 15 and Papanek 1984, 2nd ed., p. 5).

Research collaboration forms a joint effort towards project development. Such an approach could be defined from a 'mono' or 'inter' disciplinary position (as with this study) through 'examination of other fields' (Gray and Malins 2004 p. 21). The motivation for collaboration may be an individual or collective agenda to gain knowledge in a specific area. Other reasons may be to facilitate project aims and strengthen the research process in terms of rigor, embarked on in this research. This might be achieved within an advisory or consultancy framework through some form of active participation to fulfill particular goals or criterion of the project.

The McKinsey definition of 'T-shaped people' discussed by the Design Council (2010, p. 14) provides a description for progression towards collaboration across disciplines of fields. Figure 25 illustrates how the T-shaped model was applied in this research. The vertical bar represents in-depth, 'deep' specialist skill and knowledge whilst the horizontal bar represents a 'broad' standpoint and refers to the ability to apply knowledge across situations whilst develop a combination of skills. Based on this understanding, textile design was the starting point in this interdisciplinary study. From this perspective, it was important to acquire different skills and adapt to new environments through experiential involvement. This transition was also supported by those associated with the project. Each possessing high-level, expert knowledge of their discipline matched with the ability to share details through informed dialogue which facilitated project development. It was crucial that these details were mutually understood within the team to enable effective exchange of subject specific knowledge including discipline specific language/terms and principles. Communication and transparency is therefore an essential factor in collaboration and the process of knowledge transfer between disciplines/environments. The necessary knowledge and expertise of distinct fields was readily available and a platform for the exchange and implementation of skills, ideas and resources was established regarding this study, further discussed in Part 2 of this chapter.

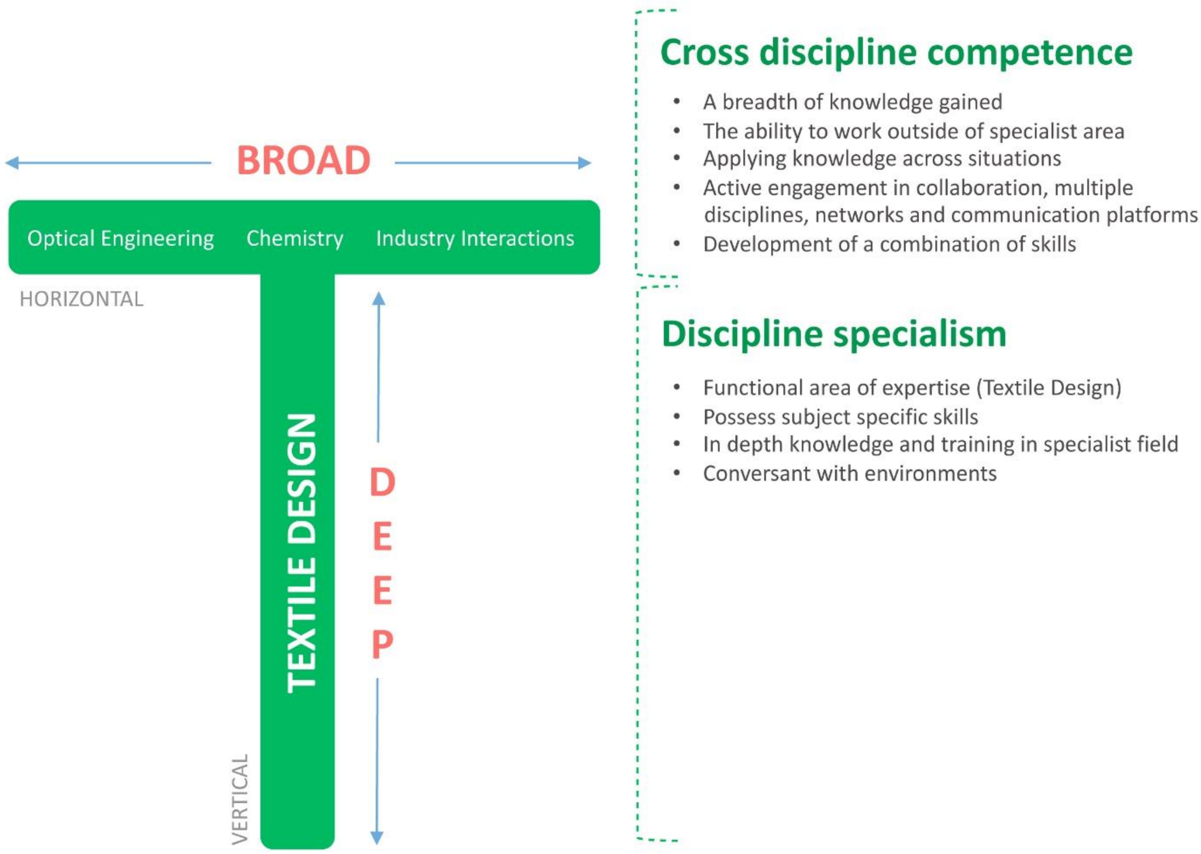


Figure 25: 'T-shaped' model used in this research

3.1.3 Defining practice-led research relevant to this study

Practice-led research describes the ‘practice’ element of the research as ‘integral to the whole research process or processes rather than outputs’ (AHRC 2005). This notion is also described by textile artist, designer and researcher Nimkulrat (2010, p .4) arguing ‘…the value of the creative process’ by shifting the focus from the end result. Similarly, in their discussion about ‘the research process’ from a practitioner’s perspective, Gray and Malins (2004, p. 17) explain ‘the process is more important than the product’.

As a practitioner carrying out this research, the ‘knowing by doing’ was fundamental to the investigation encouraged by the intention to reflect in action, as described by Schön (2nd ed., 1991) He discusses ‘reflection-in-action’ as a model of knowing that encompasses intuitive thinking. Therefore, the ‘knowing how’ component of the work was validated through practice/action/doing. Such first-hand involvement steered developments and varied knowledge types were generated by this experiential approach. The process of learning in this way created new knowledge that was established through direct interaction with practices, as explained by Drake and Heath (2011, p. 63). The ‘practice’ element led this inquiry and so practical knowledge (through hands-on experimentation) was attained.

From a design perspective, the need to be actively and experimentally engaged is essential to the research process – ‘Research is about investigation’ (Seivewright 2007, p. 14) and ‘…it is an ongoing process (Fish 2005, p. 25). In her discussion about working with materials, textile designer Albers comments, ‘Free experimentation here can result in the fulfillment of an inner urge to give form and to give permanence to ideas…’ (Albers 1962, p.51) Such engagement by the research practitioner involves creative intuition, implicit behavior and tacit knowledge when experimenting, sampling, designing and documenting research processes. Harrison (1978, p. 13) writes, ‘…to make something may be to do something that is informed by thought, reflection, knowledge and speculation may have its outcome in doing’.

Brenda Laurel (2003, p. 39) describes design research as ‘inherently paradoxical’ saying, it is both imaginative and empirical. She explains designers engage in creative exploration in the process of designing through risk taking, speculation and discovery for specific applications. Dorst (2006, p. 16) argues that this process can also be seen as learning to gain understanding. He describes design as a process of going through ‘learning cycles’ – propose-experiment-learn. ‘Design (As) Research’ however, defined by Laurel (2003, p. 82) describes designers undertaking research through their own creative practice. This research addresses a larger set of questions that form an extended inquiry. At this point in the shift from design to design research, the role of the designer is to bring the two processes together – design and research to form 'design research'. This bridging together consists of an interrelated paradigm in which to carry out the investigation (also discussed by Cross 1999, p. 5). An overlapping or interlinking of creative work with research insights led by practice, theory, documentation and research outputs, discussed by Smith and Dean (2009, p. 5) suggests an inherent identity of practice-led research. This is further examined within the context of this study in Section 3.1.4 and Part 2: 3.2 of this chapter.

3.1.4 Textile design practice in this study

In this research, textile design practice involved five main characteristics that underpinned the creative approach employed to carry out the work, identified in Figure 26 and further discussed in this section. Collectively, each attribute facilitated design development of the digital laser-dye process investigated.

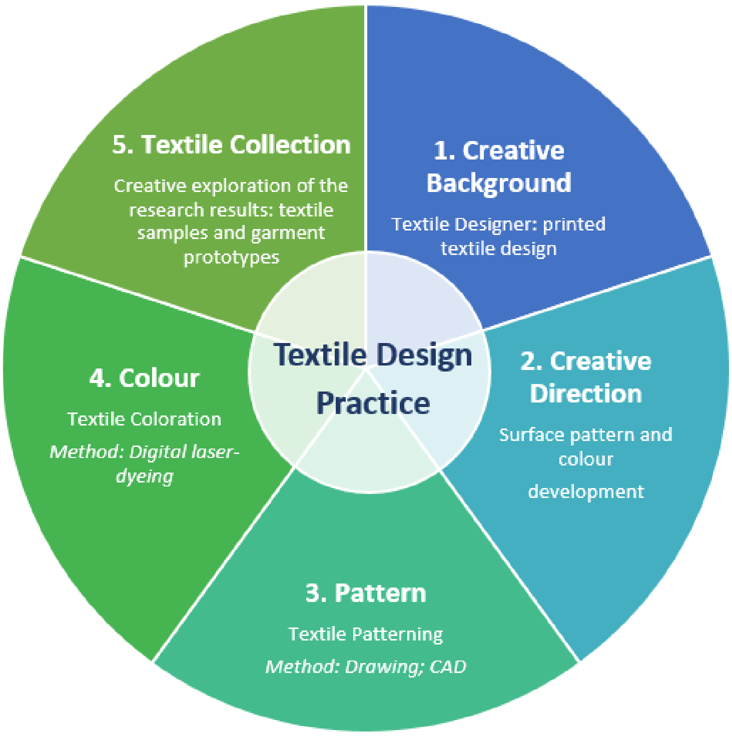


Figure 26: Diagram of textile design practice in this study detailing 5 main characteristics of the work

3.1.4.1 Creative background as a textile designer relevant to this research

In this digital laser-dye research, textile design practice was approached as a 'T-shaped' practitioner (Design Council 2010, p. 14), previously discussed in section 3.1.2 of this chapter.

The author of the research's background and training is in traditional art and design education, moving towards 'Textile Design' as an undergraduate at Chelsea College of Art and Design and 'Design for Textile Futures' as a postgraduate at Central Saint Martins, United Kingdom (both University of the Arts London), further discussed in Sections 3.1.4.2 and 3.1.4.3 of this chapter. Professional experience as a textile dye technician and a textile design lecturer in higher education institutions (HEI's), further establishes the author's affiliation with textile design practices.

Principally, as a textile design practitioner, previous work (prior to this doctoral study) focused on an engagement with creative practices such as drawing, screen-printing and making, for example. This was achieved through the exploration of textile processes and techniques based on acquired 'deep' discipline specific knowledge and accompanying skills - those gained through training in the aforementioned design education environments, combined with 'designerly' intuition and tacit capability. In *Ideas in the making: Practice in Theory*, Shreeve (1998, p. 42) describes tacit knowledge from a [craft] textiles perspective as, '…personal knowledge held by the individual such as: intuition, hunches, ways of doing things, a knack, awareness, and skilled performance.' Therefore, as a practitioner, scientific and technical rigor are not fundamental to generating textile samples or products. Artefacts embody and disseminate artistic qualities and fundamentally, creative adeptness generated by means of practical knowledge, creative ability and insight, which foretells a practitioner, rather than a clear research approach. To further understand some of the differences between design practice and practitioner research, Table 4 provides a diagnostic summary of literature studies (previously discussed in Chapter 2: *Literature Review*), which highlights characteristics, themes, ideas and issues associated with each approach, in relation to the context of the work relevant to this research. Where a black dot appears on Table 4, the principle standpoint of the study is indicated. Likewise, where there is a grey dot, both design practice and practitioner research are relevant to the study, with the black dot indicating the principle standpoint and the grey dot indicating the secondary. In such a case, some amount of crossover is comprehended. This DLD research can be considered in the same way, approached from a textile design perspective. Referring to Table 4, insights into design practice based on a practitioner rather than a research approach include: Knowing by doing; and Reflection in action (Schön 1991, 2nd ed.); Forms of knowledge special to the awareness and ability of the designer (Cross 2001); and Making/doing/practice informed by thought, reflection, knowledge and speculation (Harrison 1978).

Title of study	Design Practice	Practitioner Research	Author(s)	Date of study	Context	Notes
Research Review: Practice-led Research in Arts Design and Architecture		●	AHRC	2005	Research is integral to the whole research process rather than outputs – A definition of research	
Material inspiration: From practice-led research to craft art education	○	●	Nimkulrat, N.	2010	Practitioner research and creative education	
The Reflective Practitioner: How Professionals Think in Action	●	○	Schon, D.	1991, 2nd ed.	Knowing by doing; Reflection in action	
Practice-Led Research, Research-Led Practice in the Creative Arts		●	Smith and Dean	2009	Doing research as a practitioner; Practice informed by research	
Practitioner Research at Doctoral Level: Developing coherent research methodologies		●	Drake and Heath	2011	PhD research methodologies for practitioners	
Research methodologies for the creative arts and humanities		●	Edith Cowen University	2013	Doing practice-led research; Research methodologies	
The benefits and limits of investigative designing	○	●	Durling, D.	2007	Systematic designing set within a research study; Working through the research problem through designing	
Designerly ways of knowing: Design discipline versus design science	●		Cross, N.	2001	Forms of knowledge special to the awareness and ability of a designer	
Design research: A disciplined conversation		●	Cross, N.	1999	Design knowledge resides in people - designers peculiar to their awareness and ability	
Appropriate Research Methodologies for Artists, Designers & Craftspersons: Research as a Learning Process	○	●	Malins, Gray and Bunnell	1995	The infancy of formal research in creative disciplines compared to scientific fields; designers seeking new methodologies leading to the inception of 'practice-led' for example	
Visualizing Research: A Guide to the Research Process in Art and Design		●	Gray and Malins	2004	A 'research practitioner' approach; different perspectives/methods	
Understanding design: 175 reflections on being a designer	●		Kees Dorst	2006	Characteristics of design and being a designer	
Interdisciplinary Research: Trend or Tradition		●	Rhoten	2004	Interdisciplinary research as a lateral, more fluid approach unlike a single discipline traditional research process	The 'T-shaped' person concept
Multi-disciplinary Design Education in the UK, Report and Recommendations from the Multi-disciplinary Design Network			Bailey and Smith (Design Council)	2010	Multidisciplinary design education facilitates the ability to approach a subject in a more holistic way	
Multi-disciplinary Design Education in the UK, Report and Recommendations from the Multi-disciplinary Design Network	●		Temple (Design Council)	2010	Economic perspective on multidisciplinary design: more wealth can be generated by mixed teams of designers; engineers and technologists responsive to customer needs	Cross ref. with Papanek 1984, 2nd ed.
Research Design: Qualitative & Quantitative Approaches		●	Creswell, J.	1994	A research approach that combines methods and styles – qualitative and quantitative to aid a better understanding of a concept tested or explored	
Design for the real world: Human ecology and social change	●		Papanek, V.	1984, 2nd ed.	Design as a tool which should be innovative, highly creative, cross-disciplinary and respond to the true needs of men	Cross ref. with Temple (Design Council 2010)
Anni Albers: On Designing	●		Albers, A.	1962, 2nd ed.	Scientific and Technological, and the Artistic aspects should be an all-inclusive approach in design that embodies and responds to our needs – both functional and aesthetic	Holistic design approach (Cross and Papanek)
What is research collaboration?		●	Katz and Martin	1997	Research collaboration: working together to produce new scientific knowledge	
Making and Thinking: a Study of Intelligent Activities	●		Harrison	1978	Making/Doing/Practice, informed by thought, reflection, knowledge and speculation	
Design Research: Methods and perspectives		●	Laurel, B.	2003	Design (As) Research - Designers undertaking research in their own creative practice. This addresses a larger set of questions to form an extended inquiry	

KEY

● Principle standpoint

○ Secondary standpoint

Table 4: Diagnostic summary of design practice and design practitioner literature studies

Within 'design as a discipline', as described by Cross (2001, p.53), parallels between designers can sometimes be identified, as described by the Design Council (2005). However, 'different designers manage the process of design in different ways' (ibid). Figure 27 shows a 'Double diamond' system used to summarise the phases of work undertaken in this interdisciplinary design research.

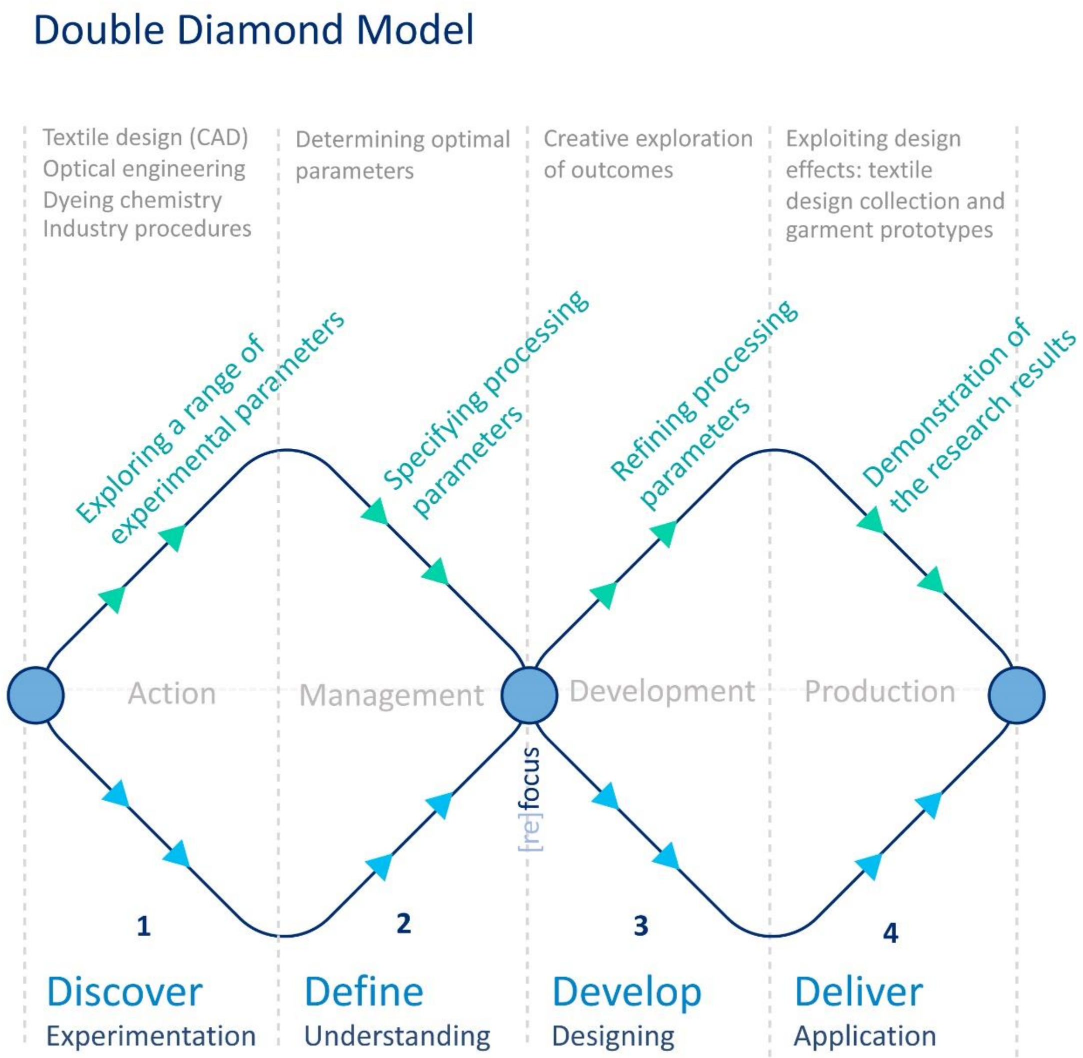


Figure 27: A ‘Double Diamond’ model summarising the work phases adopted in this research

This illustration has been adapted from the double diamond model generated by the Design Council (2005) used to refer to the different design phases carried out by designers in general. However, Figure 27 sets out the practical work phases attributed to this research. Here, the double diamond structure has been divided into four main quadrants – 1: *Discover* which represents the transition from a single discipline (Textile Design) to a broader platform of discovery by embarking on new discipline specific experimental parameters in addition to textile design, through action; 2: *Define* describes an understanding gained through experimentation in order to specify and determine processing parameters based on the ability to harvest and manage optimal results leading to focused structured experiments; 3: *Develop* builds on the ability to specify parameters by creative exploration of the research results via a range of artistic coloration/patterning approaches, and therefore refining the processing parameters through design development; and 4: *Deliver* concentrates on demonstrating the creative outcomes by exploiting the design effects achieved with the digital laser-dye process through the production of a textile design collection and garment prototypes.

3.1.4.2 Creative direction: patterning

The author of the research's principal area as a designer is printed textile design. A preoccupation with surface pattern and colour (Figure 28) connects previous work - *Motion Response Sportswear*, 2007 (Quinn 2013, pp. 266-273; San Martin 2010, pp. 62-65; Wallace, In: MADE 2009, pp. 28-30; Seymour 2008, pp. 43-44), *Garment ID*, 2008 (Quinn 2013, pp. 266-273; Seymour 2010, pp. 116-119) and this study. The aim of the project to investigate textile patterning through coloration techniques therefore utilises existing specialist knowledge and skills. This research broadens the scope for exploration towards new methods and techniques in textile coloration and pattern creation, particularly with laser processing.

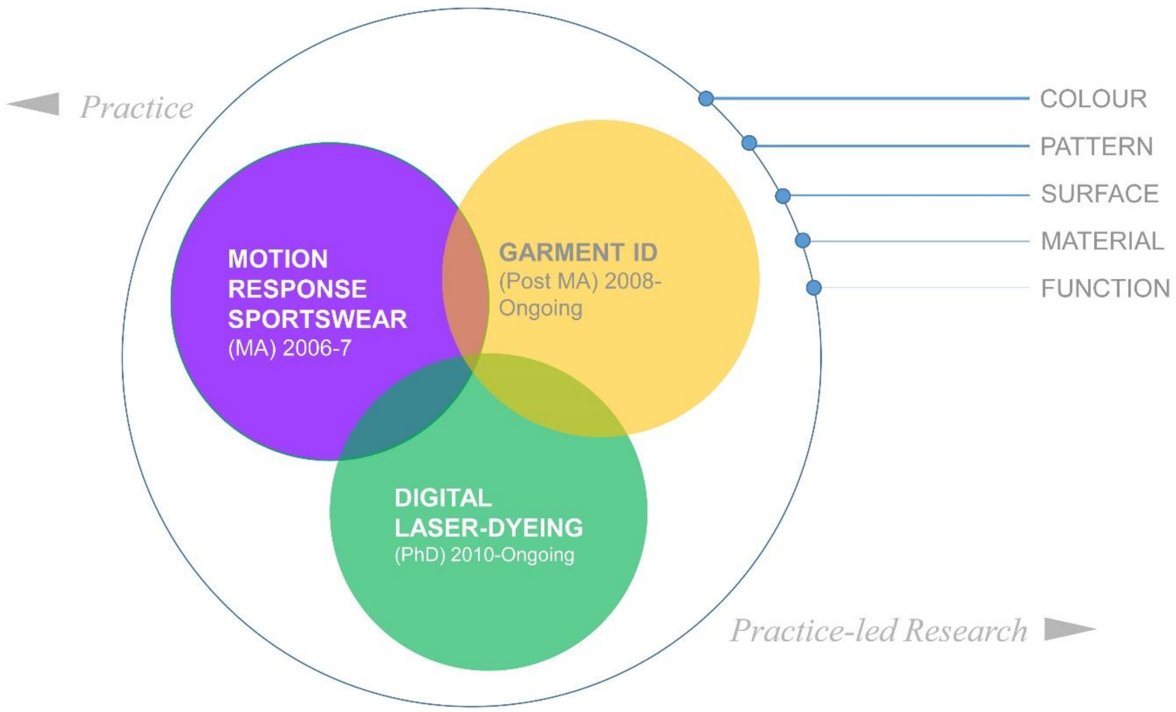


Figure 28: Design elements that connect previous projects and this research

In this study, pattern development was approached in a way that is typically inherent to many designers, using a systematic creative investigation process of looking, collecting and documenting. This has usually involved the production of imagery, photography, image-making and in some cases film. The initial research forms a larger body of work whereby annotation and personal discourse occurs and the two entities are intertwined. Sketchbooks, folders and other creative/annotated diaries such as logbooks record this process. Ideas and themes are explored and developed, leading to the process of designing. This process is described by Papanek (1984, 2nd ed., p. 3) as ‘The planning and patterning of any act, toward a desired, foreseeable end’. In this manner, patterns may emerge from developmental drawings and/or photography, motifs or computer aided design (CAD) input to produce final designs.

In this research, the drawing process included the study of organic and naturalistic forms and structures based on observational mark-making studies. By preference as a textile designer, biological plant and animal imagery typically formed the starting point and the basis of initial creative and scientific inspiration. In terms of the intended aesthetic of this artistic approach to surface design, the process aided the ‘…shaping of forms and colours into entities…’ such as patterns and repeat designs for example, as described by Papanek (1984, 2nd ed., p. 22). As such, these elements relate to visual appearance in terms of as shape, tone and composition (discussed further in Part 2: Section 3.2.3.1 of this chapter). Monochromatic drawings assisted computational photographic scanning to enable subsequent pattern development using CAD software using a greyscale approach (further discussed in chapters 4 and 5). Combined hand drawings and CAD methods using Adobe Photoshop and Adobe Illustrator CAD software facilitated the development of patterns towards final designs. This approach aided the laser-dye patterning process as the operating software for the laser enabled graphic elements to interpreted via laser beam or ‘spot’ utilised as an image creation tool in this research, as discussed in chapters 4 and 5. As such, this system for designing further supported a pre-existing ability to digitally create and manipulate imagery as a textile designer specialising in print and surface pattern. Tonal capability of the laser-process in terms of the dye uptake behaviour on laser modified PET textiles, visually enhanced the structural characteristics of laser-dyed patterns. This was achieved by exploring varying surface effects such as gradient designs, shade depth shifts and novel pattern compositions in order maximize the visual impact of the digital laser-dye process on the fabric surface. The design process consisted of three overarching stages to assist the creative development, as described in Figure 29.

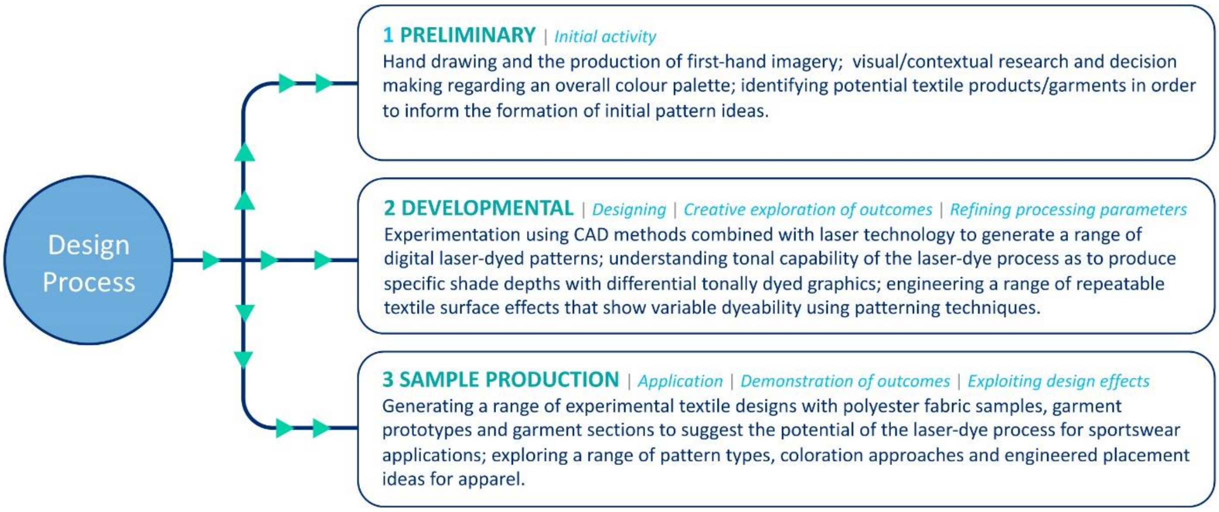


Figure 29: The design process: 3 overarching stages

These stages were relevant to different aspects of design practice associated with the creative background and personal interests of the author of this research; the creative direction for the work; textile patterning and coloration approaches; and the development of a textile design fabric/garment collection, further explained in this chapter (Section 3.1; Figure 26).

3.1.4.3 Considering colour

The role of colour in this study was imperative to the project primarily concerned with the coloration of textile fibres. Colour has been approached both creatively and scientifically in this research. Its significance was apparent throughout the investigation relevant to each phase of the design process. Therefore, inquiry into colour occurred at the Preliminary, Developmental and Sample Production stages of the study (Figure 29).

In the Preliminary stage, colour was attributed to visual inspiration and collated materials using a generalised approach. These namely consisted of images, artifacts and industrial interaction with the SDC. Visual and physical aids and references were used including books, websites, creative journals, textile samples and industry materials.

In the Developmental stage, greater consideration was given to how the preliminary exploration of colour would influence further progression. An ongoing qualitative cycle termed ‘categorization-reflection-application’ in this study fed design development, with colour aspects embedded into the inquiry. Initial colour investigation in the preliminary stage stimulated the production of evolving ideas, design themes and focused experimentation relevant to the creative goals and design context of the study regarding innovative textiles for sports apparel (Figure 30).

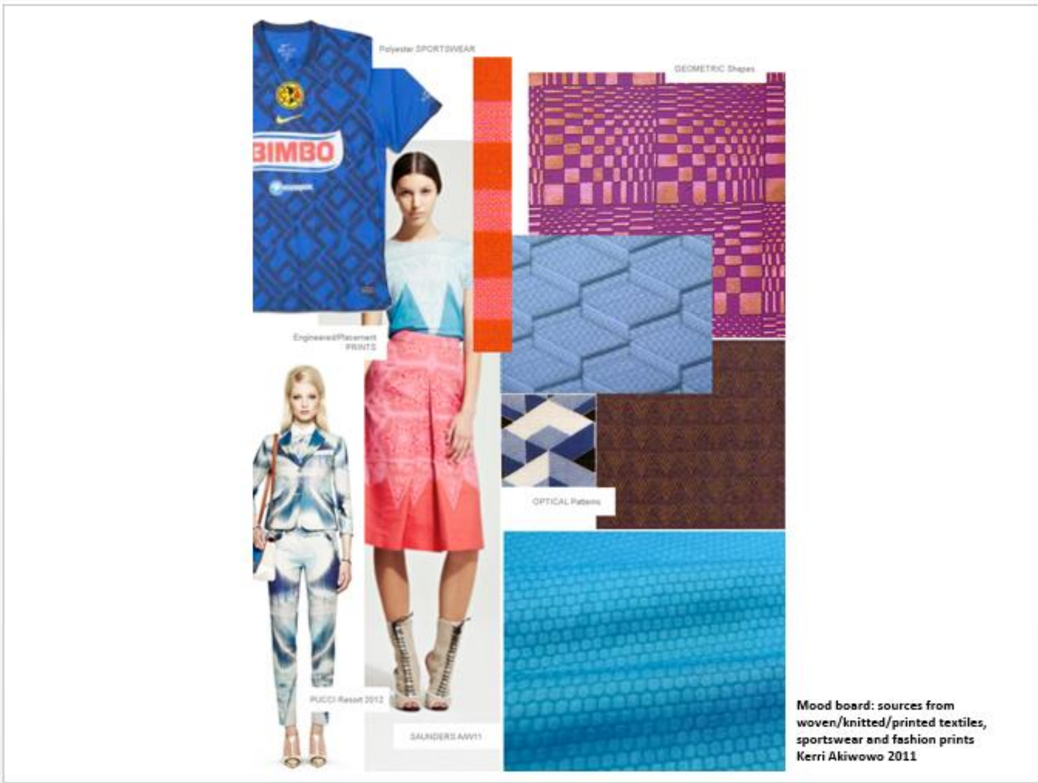


Figure 30: Visual research and inspiration demonstrating evolving ideas, design themes, creative goals and the design context for the work (Mood board pages constructed by Kerri Akiwowo 2011)

The Sample Production stage involving a textile design collection and prototype garments and garment sections considered the potential commercial opportunities of the laser-dye process (beyond the scope of this study). A commercially applicable colour palette was integrated into the inquiry. Namely, 'Lenzing textile fibres 'Sportswear Trend for Spring/Summer 2013', consisting of 10 Pantone® colours with six colour-ways (smarthouseidea.com 2012) (Figure 31). Pantone® is a commercially recognised colour matching system used to communicate colour in graphic arts communities professionally and globally. By relating to the system, this study indicates how aspects of laser-dye colour development may be conducted in the future within a wider textile design context.

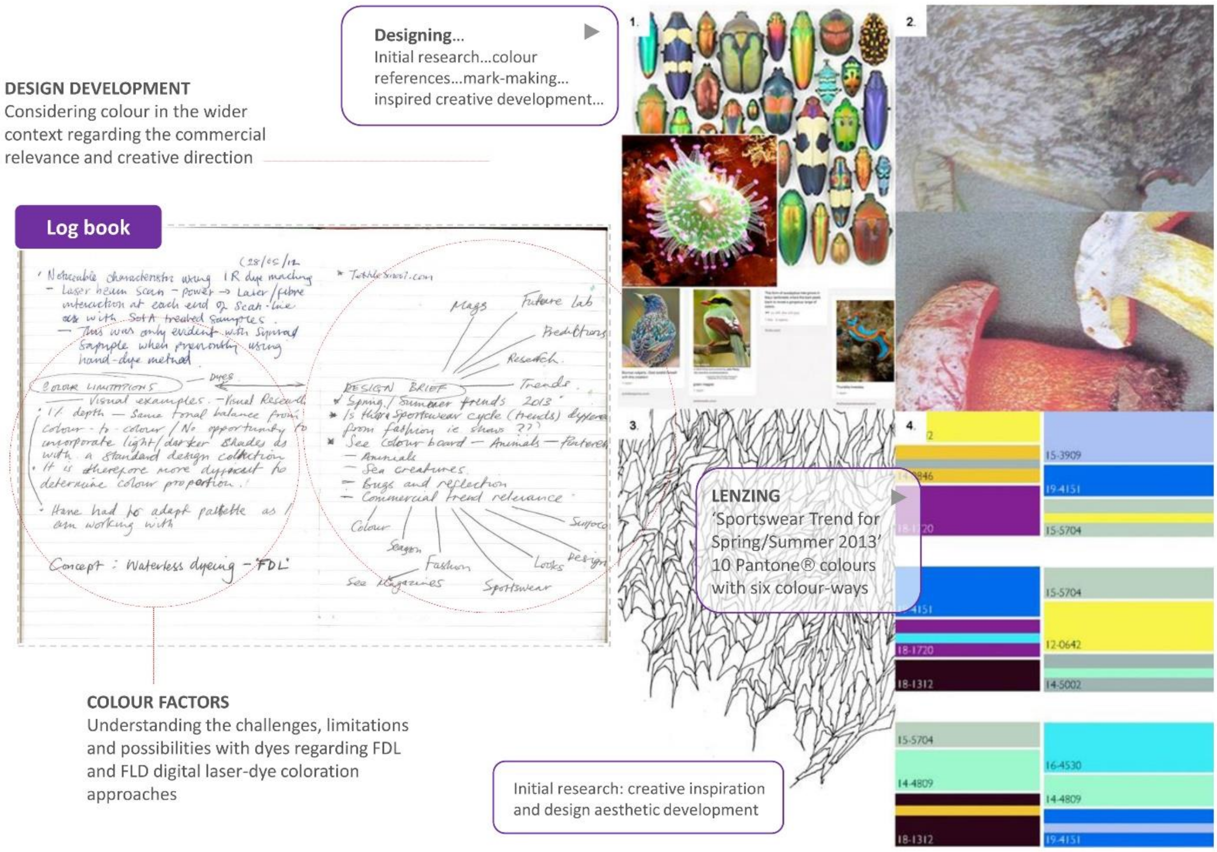


Figure 31: Colour development: considering creative aspects, process capability of DLD approaches explored and the commercial opportunities

3.1.5 Design context

The design context for the research set out in this section discusses the significance of the digital laser-dye process in terms of synthetic materials and potential product application; textile design and patterning opportunities; and the environmental design considerations for the work.

3.1.5.1 A material-led approach: synthetic fibres

Polyester (PET) fibres were the main focus of this study due to their affinity to laser modification, supported by existing studies in this research field. Two standardised polyester fabrics were used in this investigation – one plain weave and one knitted jersey, as detailed below. This variant facilitated the transferability goals of the laser-dye process in terms of exploring the feasibility of consistent processing parameters between the two fabric structures and identifying where individually specified parameters needed to be applied based on the difference (further discussed in chapter 5).

- **Woven polyester** - supplied by project partners, SDC
  Fibre: 100% polyester; Type: staple fibre; Condition: un-dyed; Construction: 1/1 plain weave, warp: 23,5 per cm, Weft: 20,5 per cm; Yarn: warp – 7,5tex Z 1000 X 2 S 800, R 15 tex; weft – 20 tex S 800
- **Knitted polyester** - supplied by Crystal Martin, International apparel manufacturers
  Fibre: 97% polyester/3% elastine; Type: jersey knit; Name: BILLY; Condition: piece dyed off-white; Width: 150cm; Structure: 28 gauge single jersey, 17Dex 180 gm per sqm2, 57 courses – 3cm, 49 wales – 3cm

Potential applications of the digital laser-dye process for sportswear apparel which is widely manufactured from PET (and other synthetic materials), have been considered in this work, in relation to the author of this research's previous textile design practice and interests. From a functional perspective, performance materials are mostly manmade substrates due to properties such as durability (higher than average wear and tear), wicking (quick drying), resistance to light and weather elements, for example. The link between synthetic PET materials and sports clothing explored in this research is further discussed in Chapter 5 of this thesis which presents and discusses the research results.

3.1.5.2 Textile design: patterning

This study is positioned within a coloration context for surface patterning with dyes. As described, digital laser-processing enables patterning from computer-aided design to laser modified textile fibres. Great precision and intricacy was achievable due to the high-resolution capability of the laser beam via raster scanning methods. High resolution relates to a 'dots per inch' (DPI) understanding used in printing processes to describe the sharpness or blurriness of an image that can be appropriated with such approach. This helps to explain the laser beam spot as an image creation tool. Vector CAD/laser scanning approaches were also explored in this study. Both methods are further explained in Chapter 5.

The laser-dye process offers the possibility to have tonal colour characteristics embedded into the design concept and final product. Preliminary sketchbook drawings and developmental studies were manipulated and refined to form patterns, which reflect a particular aesthetic direction in relation to the ideas which informed the construction of designs (previously discussed in section 3.1.4.2 of this chapter). These included tonal gradated colour (from light-to-dark/dark-to-light) to represent the human body in motion such as during sport; and repeated stylised cell-like structures inspired by biological and botanical bonds, structures and linkages found in nature, human and animal biology. This purposeful approach as a designer is described by Papanek (1984, 2nd ed., p. 5) as imposing our intent through the order and arrangement of shape, size and alignment toward aesthetic value and the satisfaction of outcomes.

In addition, creative exploration in this study references woven jacquard effects within a sportswear context such as football jerseys, for example. Experimentation within these design parameters facilitated logical exploitation of a laser-dye process appropriate to the scope of this study.

3.1.5.3 Environmental considerations in relation to design

The environmental opportunities of a laser-dye process were considered in this research which influenced the design approach to colour and pattern relating to the appearance of colour through tonal difference. The ability to adopt low dye quantity methods identified opportunities to limit effluent/waste water and reduce resources. As such, less dye produced lower percentage depths and a lighter coloured base cloth. Colour became less saturated reducing ‘relative purity’ as Horning (2005, p. 28) explains. The textile therefore appeared visibly lighter as a paler shade was exhibited. In terms of a textile design collection, this approach facilitated further tonal variety such as two-toned effects between untreated and laser-dyed areas. This enabled greater creative opportunity as a designer. Normally, a textile design collection will intentionally emphasise or understate the effect of certain colours. A combination of colours in a colour palette or colour-way show harmony/contrast, proportion and depth i.e. value: hue or saturation differences.

Despite using minimal dye in some experiments during this study, compared to standard quantities required, the patterning element of the design remained distinct. This was due to the increased dye uptake characteristic of the laser-dye process. The visual contrast of the laser-dyed fabric, between the untreated base cloth and laser pattern in some results demonstrated improved aesthetic design qualities, identified in the design development stages. This discovery indicates how exploring reduced dye quantities can combine both environmental and creative principles towards sustainable design concepts in textile production. Thus, identifying a distinct environmental design opportunity for laser-dye methods and techniques, explored in this research.

3.1.6 Summary

This section discusses the key characteristics of the practice-led research methodology employed in this study. These have been defined as: *Interdisciplinary approaches in design research* which sets out the context for the work undertaken in relation to the multidisciplinary nature of the project; *Collaborative approaches in design research* which further contextualises the environment for the work based on the collaboration with industrial partner, the SDC; *Defining practice-led research relevant to this study* outlines the attributes of the approach applied; *Textile design practice in this study* discusses the relevance of the author of the research's creative background in printed textiles and surface design, corresponding with the patterning/coloration design direction of the project from a textile design perspective; and *Design context* identifies the relevance and significance of the research in terms of synthetic materials and potential product application with a focus on sportswear, surface design in terms of patterning/coloration and the design considerations for the environmental opportunities of the digital laser-dye process relevant to both textile production and creativity.

The following section describes experimental methods carried out regarding the practice-led methodology employed.

3.2 Part 2: Methods

Part 2 of this chapter sets out the methods used to carry out the investigation in relation to the research methodology applied, as discussed previously in Part 1 of this chapter (section 3.1). Combined methods employed in this research, also referred to as a mixed method approach are explained in order to ascertain how both quantitative and qualitative aspects were managed. In this section, the quantitative and qualitative methods used have been defined and further described within the context of this work.

3.2.1 Combining quantitative and qualitative methods in this study: a mixed method approach

The interdisciplinary framework of this project established the platform for combining both quantitative and qualitative research methods. This involved textile design, optical engineering, dyeing chemistry and industry Interaction. Such arrangement allowed the creative, technical and scientific aspects of the work to be addressed through a collaborative approach, in that partners involved from each area contributed to discussions and the direction of the work. The diversity and distinction between disciplines required an essential crossover in methods as to pursue the investigation holistically (Design Council 2010, p. 31). This combination of methodologies mixes methods by linking paradigms and utilising varied approaches in a way that aids a more rigorous grasp of the inquiry, unobtainable with a limited single discipline approach.

Creswell (1994, p. 174) describes ‘within methods’ and ‘between methods’ as a way of identifying how combined quantitative and qualitative styles may be understood. He explains a ‘within methods’ approach might consist of different kinds of quantitative data collection strategies (or a single methodology) such as a survey and experiment, for example. In the ‘between methods’ approach, both qualitative and quantitative data collection procedures are involved such as a survey and in-depth interviews, for example. Based on this notion, a ‘between methods’ approach best describes this study. Combined quantitative and qualitative data collection procedures explored included scientific, technical and creative experimentation, personal and collaborative thought and discussion (recorded in note form), verbal/written feedback based on the exchange and analysis of outcomes within a multi-disciplined project team, from a textile design perspective. This intersecting based on a single discipline starting point highlights the multi-layered character of the study. Overlapping issues commonly emerged during the experimental, reflective, formal and informal discussion (project meetings and one-to-one exchange) phases of the work. Such crossing over presented its own challenges when considering the organisation of results. Thematic documentation (outlined in section 3.2.1.1) in particular became challenging due to the holistic inclusive nature of the project.

3.2.1.1 Summary of methods used in this study

The quantitative and qualitative methods used in the research are summarised in Table 5. This information defines the work carried out in relation to specific practices. In doing so, a mixed method research approach is demonstrated in this work.

Textile Design Research | Mixed Method Approach		Method	Description of method
	Quantitative	Industry standard (ISO) dyeing	Employing certified ISO procedures based on calculated measurements and quantities, specific procedures, ISO equipment dyes and dye profiles to enable accuracy, repeatability and replicable results.
	Quantitative	Digital microscopy	Undertaking fibre analysis to gain a scientific understanding of the physical impact of laser modification to textile fibres in relation to the chemical effect on dye uptake capability through micrography.
	Quantitative	Colour measurement and analysis	To quantify and reliably communicate tonal colour of laser-dyed fabrics using ISO procedures: Reflectance Spectroscopy; CIE Lab Colour Model; Delta E Colour Difference, Wash fastness tests and additional digital methods such as Grey Level computer software.
	Quantitative	ISO Textile performance tests	Textile testing to further understand the physical impact of laser modification to textile fibres in relation to potential development of the laser-dye process for textile products and applications including: Tensile Strength, Tear Resistance, Bursting and Dimensional Stability tests.
	Quantitative	Data analysis / interpretation of results	The presentation and discussion of experimental results that embody statistics in the form of calculated numerical values, figures and variables displayed as: results tables, graphs and diagrams
	Qualitative	First-hand interactions	Experiential contact with people and equipment in different environments/places – practical and observational involvement e.g. inductions, training, experiments and discussion.
	Qualitative	Extended design experiments	Using results obtained in initial structured experiments and selecting specific aspects for further creative exploration e.g. tonal density of a pattern or area of a design.
	Qualitative	Thematic documentation of textile samples	Categorised sampling to facilitate the development of different knowledge types (processing parameters and machine characteristics, anomalies, software issues and CAD aspects) in relation to design concepts regarding pattern/colour development, novel surface effects and aesthetics.
	Qualitative	Chronological log book	Personal/dated records of practical experiments with hand written and drawn information relating to experimental preparation, actual experimental activity (data collection) and reflective notes.
	Qualitative	Textile design collection	Creative exploitation of digital laser-dye processing parameters by generating a range of textile samples and garment prototypes that demonstrate the artistic aspects of the work and potential product applications.
	Qualitative	Formal / Informal meetings	Engaging in group meetings and one-to-one discussions with project partners and associates to aid knowledge exchange through the contribution of ideas and expertise towards project development.
	Qualitative	Documented meeting notes	Maintaining dated log books with written entries and additional meetings notes to facilitate reflection before/during/after practical action; Recognising the value of recorded verbal dialogue to inform decision making and progression.

Table 5: Quantitative and qualitative 'mixed methods' used in this research

3.2.2 Defining quantitative research methodology in relation to this study

Quantitative research methods are concerned with systematic experimental data collection i.e. surveys and experiments and the quantifiable explanation of results and observations based on statistical analysis. Wolberg (2010, pp. 1-2) explains, key phases of quantitative experiments can be defined as ‘Design’ (equipment, layout and setup), ‘Execution’ (the physical process of obtaining data), ‘Data Analysis’ (details, values, variables and numbers) and ‘Interpretation’ (a function of what one hopes to accomplish). Findings are generalised through objective evidence in order to eliminate bias. Variables are measured and displayed graphically and numerically using tables, graphs, charts and alike. Quantitative approaches are characteristically scientific, therefore controlled, precise, logical and repeatable in the form of mathematical or computational models, methods and techniques. Validity and reliability of results is therefore important here, as Creswell (1994, p. 116) describes.

Different types of quantitative data collection procedures were carried out in this study relating to optical engineering, dyeing chemistry or colour measurement and analysis aspects of the work. Structured laboratory experiments provided an environment for specific tasks such as focused technical, scientific or design experiments centred on thematic documentation, as explained in Table 5. First-hand technical, scientific and creative data was therefore generated. Such data included both statistical and visual information such as data sheets with physical fabric samples, results tables, graphs, diagrams, digital microscopic images and computerized measurements. Procedures carried out using a quantitative approach related to technical, mechanical and scientific aspects of the work associated with laser-processing, textile fibre analysis, coloration chemistry (dyes and dyeing laser modified textiles), industry standard (ISO) colour measurement and analysis and textile performance testing. Each of these areas led to the numerical and graphical representation of different data types. Overall, this work is underpinned by design from the perspective of a textile designer that considered the creative potential of the digital laser-dye process in terms of colour/pattern surface effects and textile/product application opportunities. The procedures undertaken were essentially steered by both creative and validity considerations for textile coloration/patterning and production. In doing so, this approach enabled repeatability of results, controllable parameters, specified designs and knowledge about the functional capabilities of laser-dyed fabrics through ISO textile performance tests carried out.

3.2.3 Defining qualitative research methodology in relation to this study

Qualitative research methods allow the process of ‘data gathering’ to encompass individual thought and expression rather than adhering to a tried and tested scientific framework, as explained by Smith and Dean (2009, p. 4). Creswell (1994, p .145) writes, ‘The qualitative researcher is the primary instrument for data collection and analysis’. In this manner, data is mediated through this ‘human’ instrument, also discussed by Davies (2007, pp. 135-167). Process and meaning characterise qualitative methods associated with experiential involvement as to know and understand the ‘how’ and ‘why’ of a situation or problem (Schön, 2nd ed., 1991). This approach facilitates first-hand interaction, participation and observation with people, machines and objects, as in this study. Evidence and analysis or procedures undertaken are descriptive, allowing subjectivity, and understanding is attained through words i.e. discussion, interviews, documents and annotated journals for example, along with visual materials such as images and other artefacts rather than statistics, as with quantitative approaches. Inherently, qualitative methods are concerned with value and quality. Therefore, data collection procedures essentially involve collecting information through interaction, observations, interviews, documents and visual materials (further explained by Creswell 1994, p. 148).

In this study qualitative data collection occurred through experiential involvement. First-hand investigation of the DLD laser-dye process encompassed direct interaction with varied disciplines, people, equipment, procedures, methods, techniques and environments – regarding laboratories in industry and academia: which facilitated creative intuition and tacit knowledge in the production of visual results and the process of decision making; formal and informal discussions through project meetings that enabled a verbal exchange of expertise and face-to-face dialogue. This approach was undertaken in order to gain comprehensive practical knowledge, as discussed by Schön, (2nd ed., 1991) and steer developments. Such interaction was also carried out on a collaborative level with project partners, SDC as a prerequisite of the inquiry. Project development was further aided by reflection after doing (ibid). This method took the form of descriptive and discursive dialogue on a collaborative level in team/one-to-one meetings whereby thoughts were verbalised and opinions were exchanged and documented in log books and meeting notes/minutes. Additionally, personal innate questioning, recorded thoughts and written analysis of outcomes (logbooks short reports) also facilitated reflection before/during/after practice in this study. Dorst (2006, p.15) refers to such as ‘pose-search-generate-test’ in attempt to identify varied stages in problem solving.

An emphasis on ‘subjectivity’ attributed to qualitative methods complimented the author of the research’s creative and interpretative background as a textile designer. Individual thought and expression occurred through design and the technical related aspects of the work regarding fabric samples and design development. Intuition and implicit decision-making happened on an immediate level in the process of practical investigation. Schön (1991, 2nd ed., p. 49) writes, ‘our knowing is ordinarily tacit, implicit in our patterns of action and in our feel for the stuff with which we are dealing’. Based on this idea, a pre-existing knowledge of creative elements such as form, scale, colour and composition, aided coloration/patterning development of the digital laser-dye process explored. Similarly, Papanek writes, ‘Design is the conscious and intuitive effort to impose meaningful order’ (1984, 2nd ed., p. 4). Therefore, familiarity with some factors such as a physical understanding of textile materials and CAD techniques for example, also contributed to a ‘spontaneous, intuitive performance’ (Schön 1991, 2nd ed., p. 49).

The qualitative research methods undertaken in this study enabled the data gathering of non-quantitative data types. Specific methods employed (First-hand interaction; Formal and informal meetings; Documented meeting notes; Chronological log books; Thematic documentation of textile samples; Extended design experiments; and a Textile design collection) encompassed individual thought and expression, decision making, intuition and tacit knowledge. As such, these methods were not concerned with numerical approaches, systematic data gathering or statistical analysis. Instead, the qualitative methods investigated in this research facilitated engagement with the project from the human-centered standpoint of the researcher to enable: verbal communications with people; shared knowledge through conversational exchange; mobility within different environments; recorded notes/minutes in written and electronic forms; a reflective approach to analysing technical results for creative purposes; categorisation of textile samples to build an understanding of the DLD process from a design perspective; and design development by identifying specific parameters for further investigation in order to enhance the quality and appearance of specific patterns and surface effects. The scope of the qualitative work carried out is considered appropriate for the DLD investigation presented in this thesis. In terms of the limitations of the qualitative methods employed, for example, it is noted that design analysis of the results such as focus groups comprising other designers to gain further creative insights; semi-structured interviews with production or retail experts regarding the on-demand aspects of the work; or an exhibition of designs – textile samples and garments, in order to harness feedback based on observations of practical elements, does not exist. These approaches are considered relevant beyond the scope of this doctoral study.

3.2.4 Flow of work conducted using mixed methods

Figure 32 demonstrates the flow of work conducted in this research regarding the digital laser-dye process and in relation both qualitative and quantitative methods carried out, as previously described in Table 5. Three digital laser-dye approaches were identified and explored in this study – Fibre-laser (FL) involving the textile and laser only; Fibre-laser-dye (FLD) whereby fabrics were laser treated first then dyed; and Fibre-dye-laser (FDL) which denotes fibres/fabrics were dyed first then laser modified (each approach is further discussed in chapters 4 and 5 of this thesis). This work flow of the laser-dye process (Figure 32) outlines how practical work happened in terms of the sequence in which specific activities occurred corresponding with each of the approaches explored (FL/FLD/FDL).

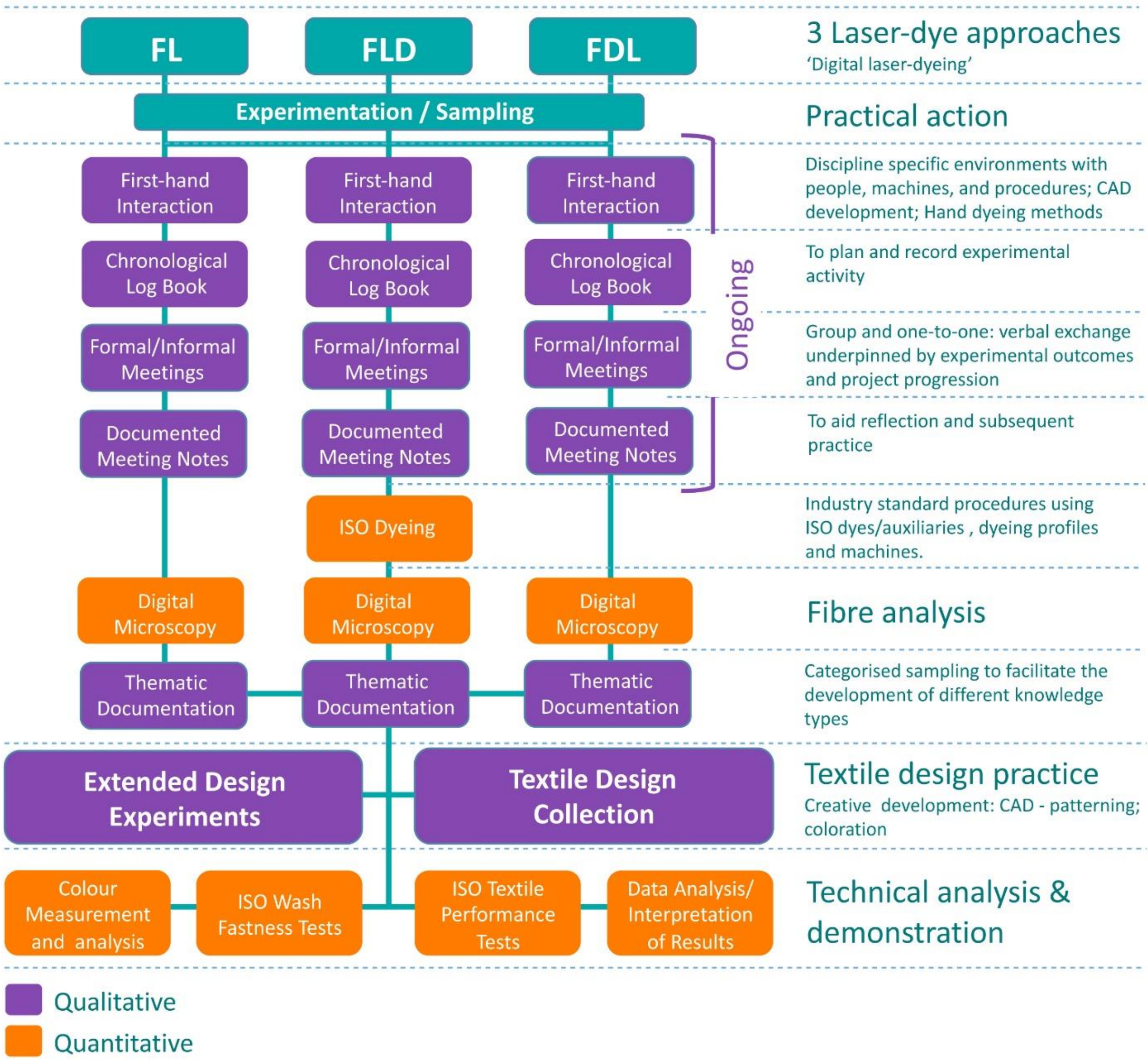


Figure 32: Flow of work using mixed methods

3.3 Conclusion

In this chapter, the methodology and methods employed in the research are discussed over two distinct sections (Part 1: Methodology: a practice-led approach; and Part 2: Methods). In Part 1, the interdisciplinary and collaborative approach of the study is explained within the context of this research: practice-led design research from a textile design perspective. Relevant key issues are drawn out of the discussion including: the purpose and value of doing interdisciplinary and collaborative research which facilitated well-rounded knowledge in terms of skill and ability by incorporating creative, scientific, technical and industry aspects. This section aimed to describe how such approach facilitated the acquisition of new knowledge through multi-disciplinary activity and collaborative industry interaction. Explanation is given as to how aspects of the framework relate to one another in order to contextualise the work, and present the research process. Part 2 describes specific research methods assigned to the study related to the methodology and reflects the design research approach as a textile designer. Qualitative and quantitative methods have been discussed and the significance of combining the two approaches (mixed methods) within this research is explained in relation to the interdisciplinary nature of the investigation. A range of methods are identified in the discussion attributed to particular aspects of the study.

The appointment of specific disciplines informed the methodology that aimed to ensure that the research question, aim and objectives were appropriately and adequately explored. The perspective of the researcher has been clearly defined contextualising the approach. Chapters 4 and 5 detail the work conducted and the discussion of results obtained.

Chapter 4: Digital laser-dyeing in this study: experimental work conducted

This chapter sets out the experimental work conducted in order to achieve digital laser-dyeing in this research. In doing so, the discussion outlines the fundamental parameters explored. These essentially underpin the experimental investigation presented in Chapter 5 – *Experiments and discussion of results*.

The laser-dye process studied involved textile coloration methods and textile design. The process prompted physical and chemical interactions between fibre, laser and dye. Under laser beam exposure, textile fibres changed their structure dependant on fibre type. As such, this effect altered dye uptake behaviour of PET fibres explored. A fibre-laser process and two laser-dye processes have been identified in this research in relation to three different experimental phases of the investigation outlined in Figure 33.

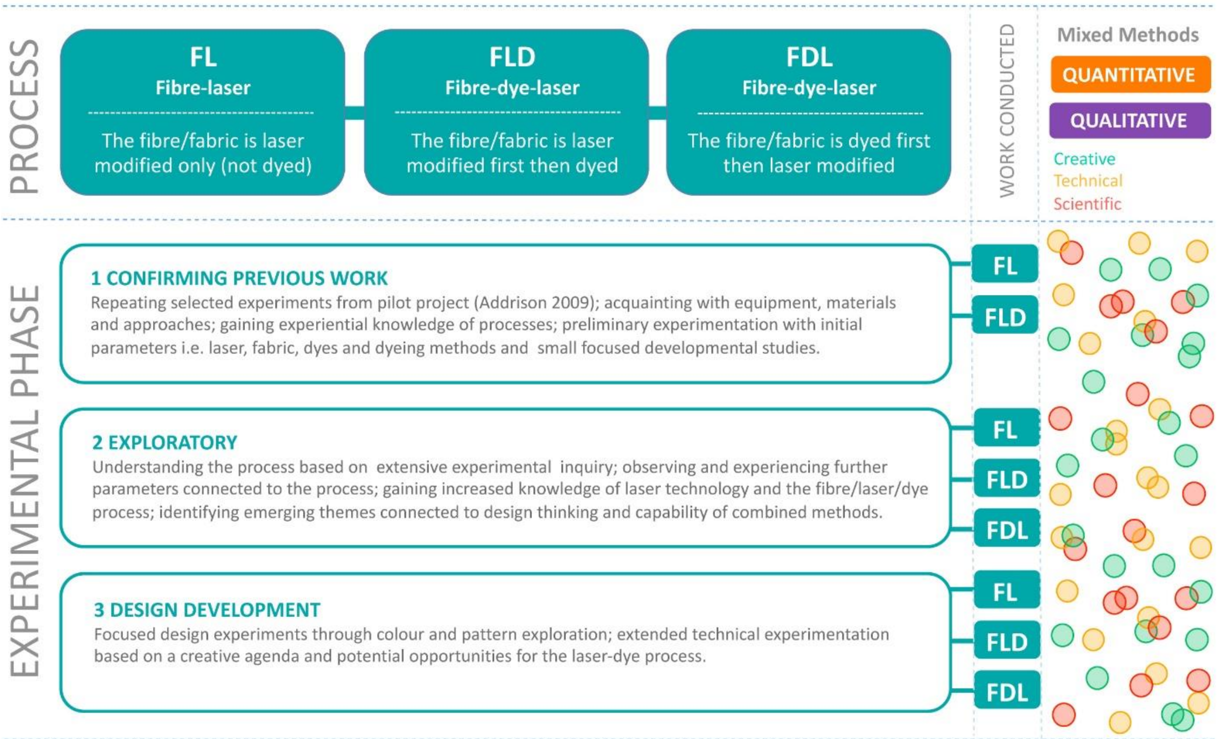


Figure 33: Digital laser-dye processes and experimental phases in relation to the work conducted

Initial experimentations involved interactions between the fibre and laser only, referred to as ‘FL: Fibre-laser’ in this study. In doing so, sufficient preliminary understanding of the relationship between the textile fibres and laser irradiation was attained prior to dye explorations. Each process is further discussed in Chapter 5 of this thesis (*Experiments and discussion of results*).

In this study, new knowledge has been generated in terms of approach, methods, techniques and evidence both creative and technical outputs. Therefore, the interdisciplinary research presented in this thesis is transferrable, as the work can be applied and further developed within an industrial environment. Controllability of processing parameters explored facilitate the potential to transfer the laser-dye process effectively by providing key principles and technical information needed such as energy density for example, which is associated with power output, velocity, beam characteristics, laser scanning and CAD aspects. Design/experimental results were developed through textile patterning and surface design approaches. The purpose of this was to explore the creative opportunities of the process in a way that is commercially relevant. Optimal experimental parameters have been identified in this research through rigorous practical investigation, further discussed in Chapter 5 which sets out and discusses the experimental results achieved.

4.1 Parameters

In this section, the experimental parameters used to conduct the research relating to all stages of the work, involving qualitative and quantitative methods (Figure 34), are presented and discussed. These include: Textile fibres (relevant to all work phases); Laser issues (machines, beam characteristics, power, velocity processing variables and CAD technology); Dyes, Dyeing methods, Design issues (CAD/Patterning/Coloration) and Micrography used as an analysis technique. Experimentation facilitated the technical, scientific and creative elements of the study combined with commercially relevant aspects associated with the laser-dye process investigated. This inquiry provided a context for structured quantitative approaches in relation to ongoing qualitative methods, which underpins experimental activity. The specific qualitative elements of the research are outlined in Figure 35.

The ability to control and specify variable parameters to determine particular aesthetic surface effects achieved, whilst retain fibre stability, advances knowledge in this research field. Consequently, such effort presses towards establishing the laser-dye process as a viable creative tool in a textile design and coloration context. This knowledge is relevant to processing, production and application opportunities within the textile sector.

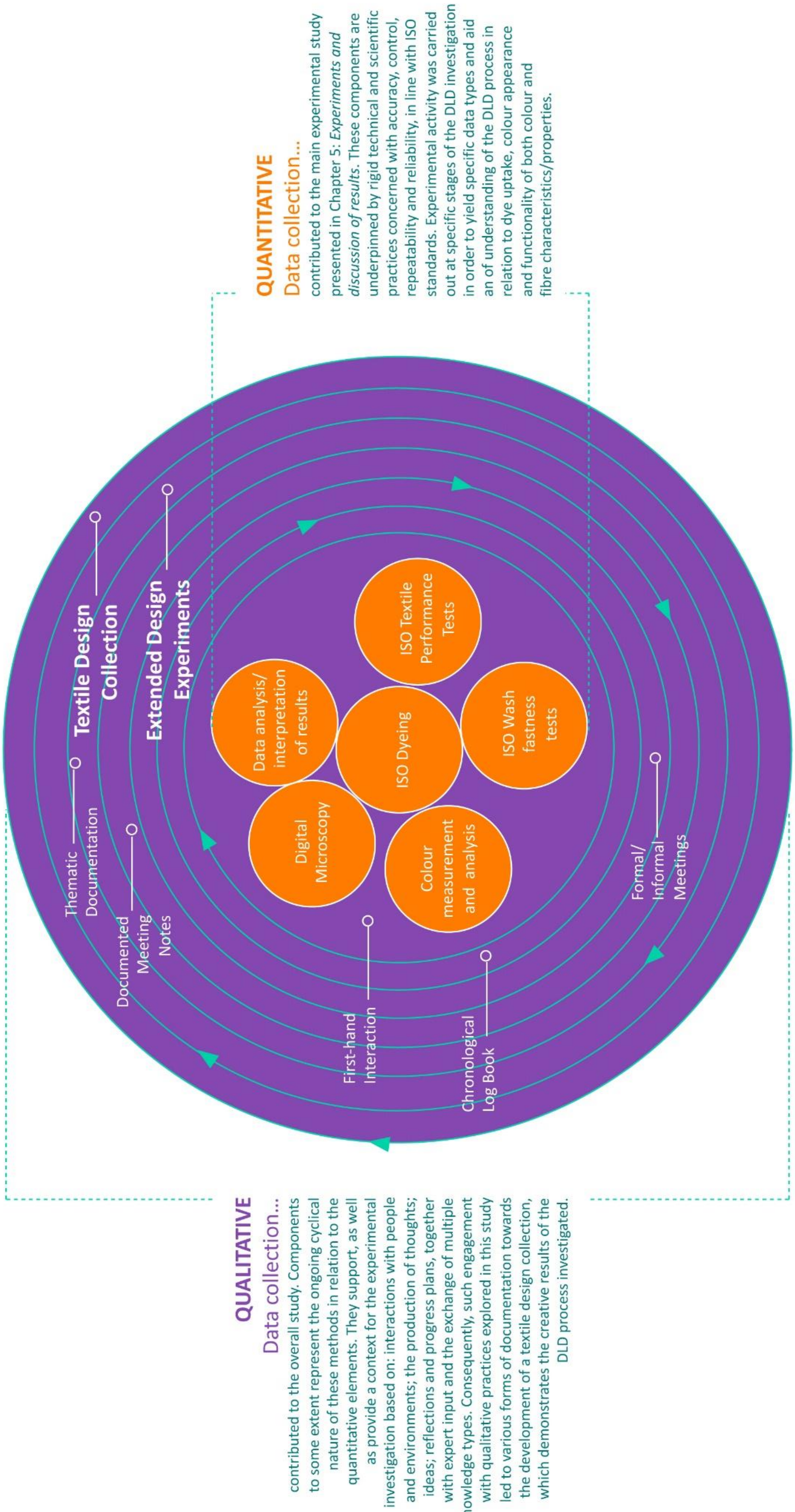


Figure 34: Qualitative and quantitative methods undertaken in relation to experimental study

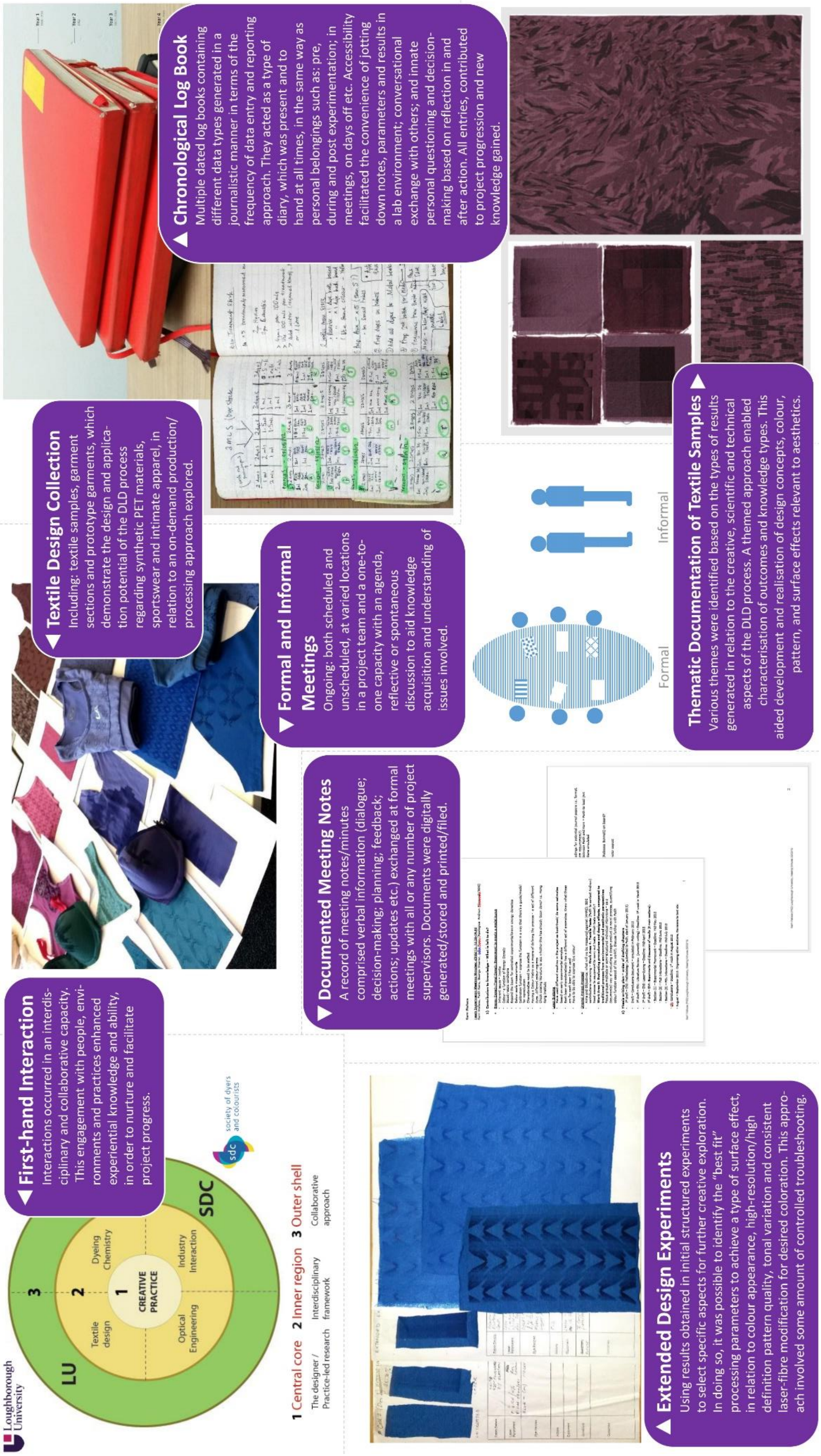


Figure 35: The specific qualitative elements of the research in relation quantitative aspects

4.1.1 Textile fibres

A range of textile fibres were explored for initial experimentation, as listed in Table 6. The fabrics employed were sourced from a commercial supplier, Whaleys Bradford Ltd. A range of textiles, including polyester fabrics were supplied by industrial project partner, SDC and a polyester knitted fabric was supplied by Crystal Martin apparel manufacturer. Focused progression was carried out with polyester specification woven (SDC) and knitted (Crystal Martin) fabrics. The significance of using specification fabrics supplied by industry supported the realisation of consistent and repeatable outcomes based on known reliable details per fabric/batch related to fibre composition, construction and finishing, as outlined in Table 6. This approach responded to the commercial relevance of the work associated with repeatability of the laser-dye process explored in terms of control and consistent outcomes. In doing so, specific knowledge regarding the substrates employed enabled a focused understanding about the effect of various processing variables and parameter modifications. This made it possible to understand the effect of the DLD process more clearly. An important benefit of this, was the ability to isolate and identify outcomes in order to determine specific replicable effects. Such factors are more difficult to attain with ‘shop bought’ textiles whereby specification information concerning fibres, construction and production are often unreliable and/or untraceable through commercial retailers. In terms of textile coloration and patterning approaches, some of the disadvantages of sourcing fabrics in this way may lead to inconsistencies in dye uptake (shade variability) and surface anomalies in terms of creative/design effects due to unknown differences between batches, for example.

Fabric	Supplier	Composition	Construction
Cotton Satin Medium White	*Whaleys Ltd.*	100% Cotton	**Weave**
Batiste Cotton White	*Whaleys Ltd.*	100% Cotton	**Weave**
Polycotton Duvet White	*Whaleys Ltd.*	50% Polyester, 50% Cotton	**Weave**
Polycotton A4079 Optic White	*Whaleys Ltd.*	65% Polyester, 35% Cotton	**Weave**
Polyester Chiffon White	*Whaleys Ltd.*	100% Polyester	**Weave**
Polyester Satin Kent White	*Whaleys Ltd.*	100% Polyester	**Weave**
Cotton Lawn	*SDC*	100% Cotton (undyed)	**1/1 Plain Weave**: Warp: 32 per cm; Weft: 33 per cm; Yarn: Warp/Weft: 15 tex Z 590
Cotton Drill	*SDC*	100% Cotton (undyed)	--/--
Cotton Limbrick	*SDC*	100% Cotton (undyed)	**1/1 Plain Weave**: Warp: 35 per cm, Weft: 31 per cm; Yarn: Warp: 16,5 tex 820; Weft: 14 tex 900
Viscose Rayon		Viscose Rayon (undyed)	1/1 Plain Weave: Warp: 28 per cm, Weft: 22 per cm; Yarn: Warp: 20 tex 740, Weft: 33 tex 700
Wool (Australian Merino)	*SDC*	Pure wool (undyed) *Fat content: 0.5 ± 0,2 %*	**1/1 Plain Weave**: Warp: 210 ± 5 per 10cm, Weft: 180 ± 5 per 10cm; Weaving without sizing; Yarn: 15,6 tex x 2 worsted, Spin twist: 620 t/m, Yarn twist: 600 t/m, Fat content of yarn: 0,6 ± 0,2 % (emulsified groundnut oiling agent)
Polyester	*SDC*	Polyester staple fibre (undyed)	**1/1/ Plain Weave**: Warp: 23,5 per cm, Weft 20,5 per cm; Yarn: Warp: 7,5tex Z 1000 X 2 S 800; R 15 tex, Weft: 20 tex S 800
Polyamide	*SDC*	Polyamide staple fibre (Nylon 6.6), (undyed)	**1/1 Plain Weave**: Warp: 17,5 per cm; Yarn: Warp: 10tex Z700 X 2 S 600; R20tex, Weft: 20tex Z 700
Polyester	*Crystal Martin*	97% Polyester, 3% Elastine (piece dyed off-white)	**Single Jersey Knit**: 28 gauge, 17Dex 180 gm per sqm2; 57 courses, – 3cm, 49 wales – 3cm

Table 6: Textile fibres used for experimental sampling in this research

Polyester (PET) woven and knitted fabrics were selected for further in depth study regarding potential product application within a sportswear design context acknowledged in this study (further discussed in Chapter 5 and Chapter 7 in terms of design development and further work). As a synthetic textile material commonly used in sports clothing due to advantageous performance/functional properties (i.e. fast wicking, light weight and durability), polyester was identified as appropriate for this work. This progression with PET textiles addressed gaps in existing literature surrounding laser modified textiles polyester fibres and dye uptake capability as discussed in the *Literature Review* (Chapter 2).

4.1.2 Laser issues: machinery; processing parameters; and CAD technology

Laser technology is 'Light Amplification by Stimulated Emission of Radiation' (LASER). A laser is a device that emits light through electromagnetic radiation in an electrically powered wavelength energy frequency delivered by beam, also called irradiation. Optical Engineering describes the function of light (laser beam) used for a specific activity such as cutting or etching textiles, for example, using laser methods. A laser beam is characteristically narrow/tiny such as 0.1mm – 0.3mm when focused, typically used for textile processing. Lasers are also a relatively low power source. However, the increased energy density of a focused beam capable with high power industrial laser machines is intense enough to cut, etch and weld metals.

There are various types of industrial laser such as Carbon Dioxide (CO^2), Carbon Monoxide (CO), Nd:YAG, Ultraviolet (UV) Excimer, Diode and Fibre lasers, for example. The differences between these laser types relate to beam delivery systems whereby optics, mirrors and lenses are used to guide the beam controlled by computer software, further discussed by Matthews (2011, p. 91); variations in the wavelength in terms of size, attributed to particular applications/laser types and whether it functions as a continuous or pulsed wavelength of light (or both) in processing. An ultraviolet excimer laser is one example that characteristically operates at a UV electromagnetic field and therefore has a shorter wavelength frequency, usually in pulsed mode; assisted gases (CO^2 and CO) which aid the thermal reaction and remove unwanted debris and deposits (Matthews, p. 93), or solid state lasers such as Nd:YAG or Diode systems that use a solid medium such glass or crystals to assist interaction between the substrate and laser beam rather than gas. Alternatively, fibre lasers use rare earth solid elements such as naturally occurring metals and minerals; operating power (watts); and cost (purchasing and running) are also differentiating factors between laser types. CO^2 lasers are commercially available and tend to cost less than other lasers. Industrially, they are used in textile processing as described in the Literature Review (Chapter 2; Section 2.4). Laser markers are also commonly used to inscribe consumable dates on food packaging, for example. So, by employing CO^2 lasers for this research, the commercial potential and industrial considerations for the laser-dye process have been supported.

Three Carbon Dioxide (CO^2) laser machines (Table 7) were used in this study to confirm the transferability of the laser-dye process. Factors included calibration in terms of power output and energy density in order to produce repeatable patterning/coloration surface effects. The main difference between the two main laser types explored in this research is the difference in beam delivery systems, as detailed in Table 7. All machines operated with continuous wave (CW) power regarding laser beam delivery, opposed to pulsed energy mode (distinctive of UV excimer and Nd:YAG lasers, for example). Therefore, the wavelength emission of each system was 10,600 nanometres (nm) or 10.6 microns (µm), typical of CO^2 lasers. Each laser system embodied a set of factors and characteristics attributed to the machine type such as computer software aspects, beam related issues and power/energy. Therefore, variables between machines are have been acknowledged in this research. So, in the process of discovery, machine specific as well as system specific experimental approaches were adopted to aid the repeatability goals of the laser-dye process regarding fibre, laser and dye interactions.

CO^2 Laser system	Power (W)	Computer Software	Machine location (Dpt.)	Sampling stage
Laser bed *(Flat bed cutter used for etching in this study)* The laser is directed around the bed by a nozzle; the nozzle is taken to the location where the textile is taped into position on the bed	58	**ApS-Ethos** An integrated database enables designs to be stored and utilised for vector or raster processing. Design files can be assigned to a specific material setting i.e. 'Polyester' from a list of material types in addition to selected numerical parameters.	School of the Arts	*(1) Confirming previous work* *(2)Exploratory* *(3)Design development*
Synrad laser marker A galvanometer mirror driven system used for etching/marking textiles in this study; the beam is directed by oscillating mirrors	10 60	**WinMark Pro** Enables mark files to be created. These files can include a variety of design 'objects' and graphics to generate images such as shapes, lines, text and image-based functions/modes, in addition to imported CAD elements. The software supports incremental and changing laser parameters.	Wolfson School of Mechanical and Manufacturing Engineering	*(2)Exploratory* *(3) Design development*

Table 7: CO^2 Lasers used in this research

Parameters relating to the following issues were studied in order to manage this:

- Laser beam
- Laser processing power
- Laser power measurement and calibration
- Dyes and dyeing
- Design issues: CAD/Patterning/Coloration
- Micrography: an analysis technique of parameters explored

In doing so, a thorough understanding of the laser technology and associated parameters relevant to the project was gained. This facilitated the acquisition of in depth technical knowledge fundamental to the fibre/laser/dye investigation. The ability to identify all relevant issues connected to laser material processing for polyester fabrics, particularly for coloration/patterning via CAD approach in order to laser modify PET textile surfaces with tonal graphics was crucial to this study. Sufficient comprehension of aspects and procedures linked to both laser and CAD technologies, and how these impact the fibre/laser/dye process was paramount. This level of awareness enabled a logical and methodical technical framework to adequately carry out the subsequent inquiry.

4.1.2.1 Laser beam

In this research, 'Fibre-laser' (FL) interaction refers to the point where contact is made between the textile fibre, i.e. polyester and the laser beam demonstrated in Figure 36, further discussed in Chapter 5 – *Experiments and discussion of results*. Figure 37 is an image of a double page log book entry, which roughly illustrates some of the thinking and problem solving, regarding laser beam behaviour and laser scanning when processing fabric in this way.

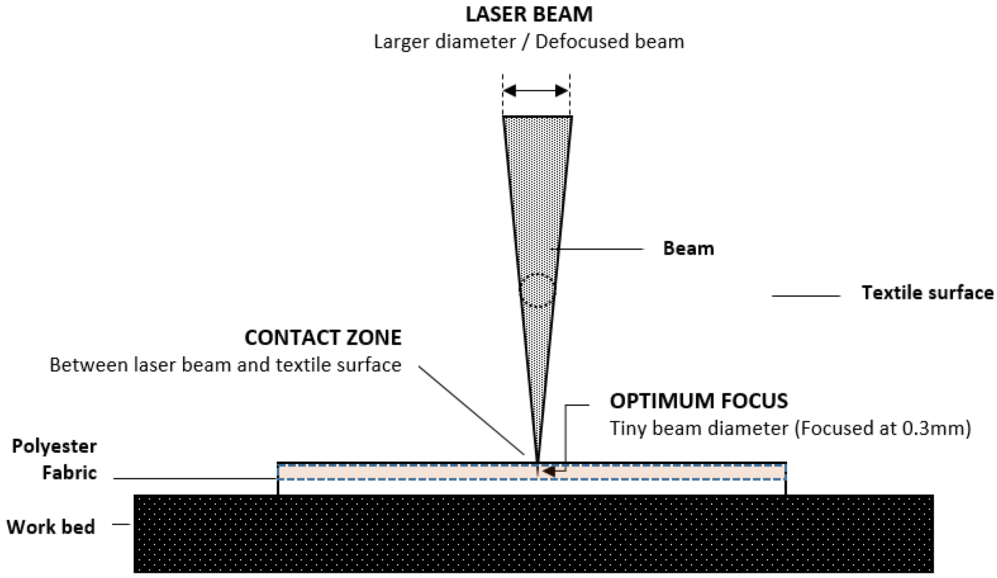


Figure 36: Fibre-laser interaction

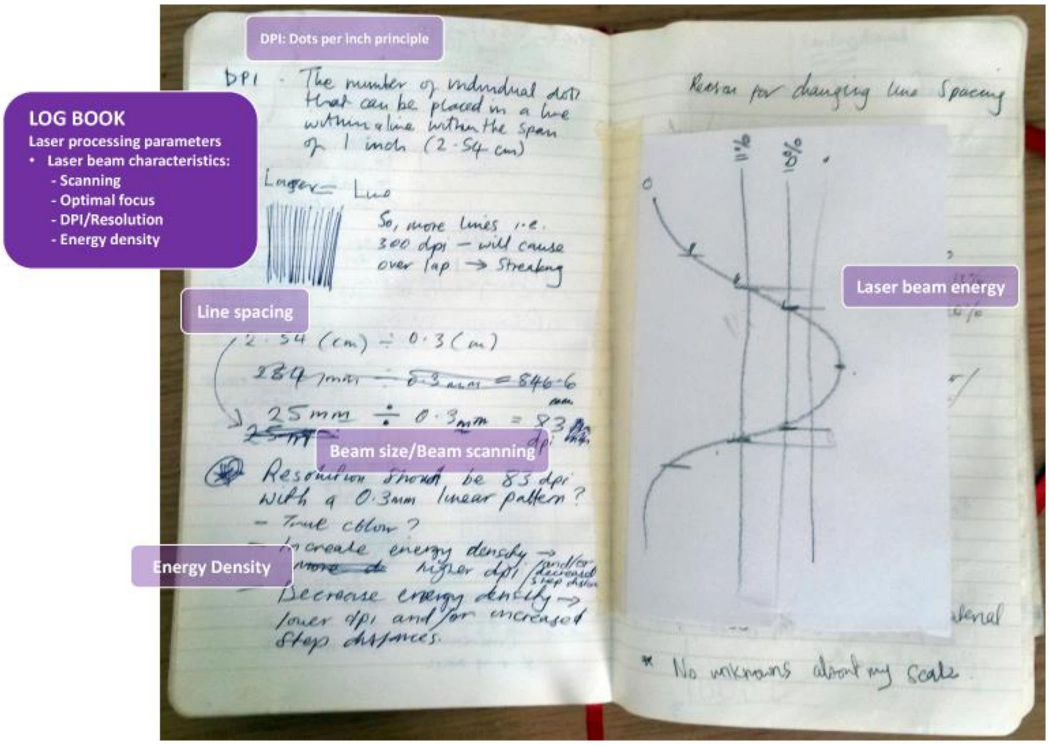


Figure 37: Log book: Problem solving in relation to beam behaviour and laser scanning

Figure 38 shows documented meetings notes generated from supervision minutes. This conversational exchange facilitated further understanding and knowledge acquisition regarding laser beam characteristics such as: beam delivery systems; beam interaction with textile fibres; and beam scanning, for example.

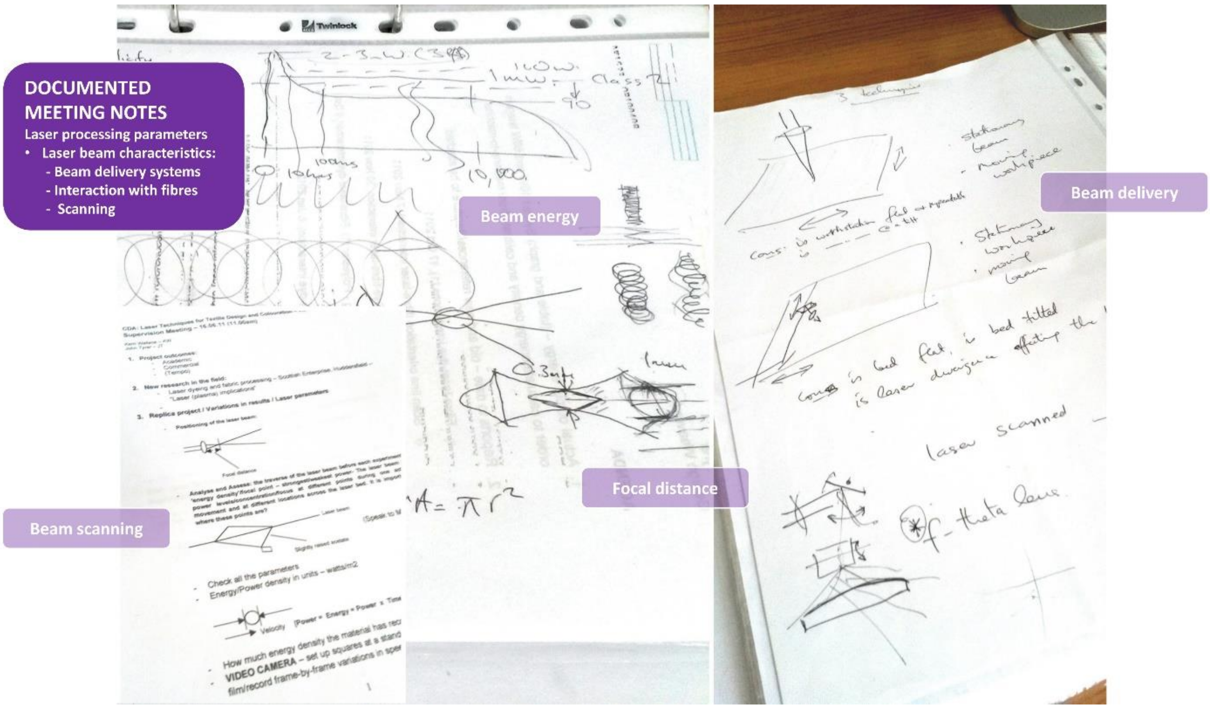


Figure 38: Documented meeting notes generated from supervision minutes: laser beam characteristics

Through this interaction between the fibre and laser, laser irradiation alters the structure of the synthetic PET textile fibre. This energy is delivered via laser the beam by continuous wavelength activity. As such, this interaction can be controlled by computer software to achieve various alterations to the fIbre at the molecular level. Resulting, essentially in a visible change to the textile surface, ranging from a cut to a mark. In this research two laser marking methods, facilitated by CAD were explored – raster and vector:

- **Raster fill** - a series of closely spaced parallel scanning paths via laser beam mark (etch) to surface fibres creating a filled pattern or shape on the textile in relation to the design, computer software and CAD file.

- **Vector line-pattern fill** – a pattern, shape or block was pre-filled with a series of repeated vector lines (or paths) with a specified distance between each line to create an all-over laser marked area on the textile.

Essentially, both approaches were investigated in attempt to identify ‘best practice’ for laser-processing textile fibres with graphics in terms of consistent flat colour/dye uptake with even/level laser energy, in relation to laser-dye treated areas of the fabric. Each method induced a physical and chemical change to the textile impacting the appearance and performance of fibres. However, visual effects differed due to the procedures carried out. These differences along with results are further discussed in Chapter 5.

Fundamental laser beam characteristics were observed in this study relevant to each laser machine employed. The purpose of such was to identify optimal parameters for effective exploration of the laser-dye process. These are outlined in Table 8.

Laser beam parameters	
Spot size	Denotes the diameter of the laser beam actually marking the fibre/fabric during fibre-laser interaction. The spot size is determined by **Focal distance** and influences the **Resolution** of the graphic marked on to the textile and is also relevant to yarn size/diameter within a textile structure.
Focal distance	Height / distance between beam output and fabric surface which determines the beam focus and optimal focus. This also influences marking **Resolution** based on the **Spot size**.
Resolution	Based on 'dots per inch' (dpi) for marking via the laser beam. This defines the 'sharpness' or the 'blurriness' of the mark/image. A larger dpi produces a sharper graphic representation.
Scan direction	Determines whether the marking of a raster image is performed with horizontal or vertical scanning. The laser beam therefore travels in a specific direction in relation to the fibre axis and orientation of the fabric structure i.e. weave or knit**.**

Table 8: Laser beam parameters observed relevant to this study

In a laser system, the beam has an optimum field of focus which is the optimal location or focal position for processing (Figure 39) This is where the beam/spot size is at its tiniest and therefore considered most effective in relation to the work piece. In terms of fabric and textile design, this may enable a cut or surface marking with graphics and other creative effects facilitated by CAD technology. By carrying out 'burn prints' in this research, detection of the optimal focus area for processing fabrics was enabled. Burn print refers to a test method that involved firing the laser beam multiple times into a material such as acrylic or light sensitive paper in order to measure the beam size and determine the shortest diameter in order to find the optimal focus (Figure 39).

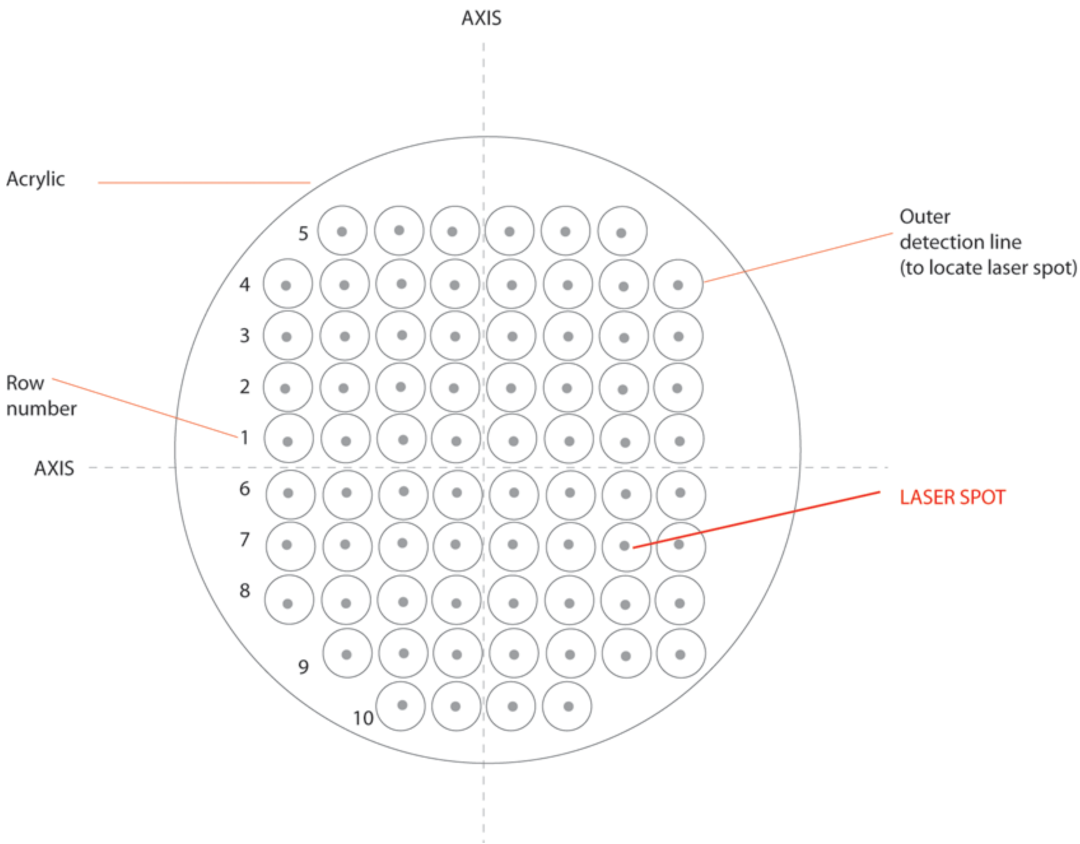


Figure 39: Burn print in a circular piece of acrylic showing the layout of multiple laser spots

In doing so, an understanding of the highest/sharpest resolution (further described in Table 8) processing area was known. This knowledge was beneficial for exploring the laser-dye process in terms of patterning regarding image/surface quality. Two test approaches were used in this study - one for each Synrad laser marking machine (both paper and acrylic methods). The significance of test results related to the fibre-laser interaction between fabric and laser in terms of achieving consistency across the textile surface through even or level laser scanning. Therefore, understanding the impact of laser beam variables was necessary to this investigation to enable satisfactory or exemplary outcomes both technically and creatively. Burn print tests carried out in this research are further discussed in *APPENDIX 1* of this thesis.

4.1.2.2 Laser processing power

In this research, practical inquiry identified that several factors contributed to the amount of laser power/energy used to process fibres, outlined in Table 9. In stages one and two of experimental sampling – ‘Confirming previous work’ and in the early ‘Exploratory’ phase, perceptions were made about laser technology as a tool. It was assumed that by selecting the power (%) value in the computer program (for all three laser machines) in relation to the operational power assigned to a particular machine, this would determine the exact amount of laser power output/energy density processing the fabric. However, this ‘face-value’ approach was not rigorous, nor was it reliable. Table 10 shows the values for the 60 Watt Synrad laser marker machine. ‘Selected power (%)’ obtained via computer software is shown against ‘Actual power output (W)’ gained by using a laser power meter. By acquiring this data, an informed and reliable method for processing fabric with accurate and repeatable laser energies was attained.

Laser power parameters	
Operational power	Energy (in Watts) assigned to a particular machine by the manufacturer.
Computer power selection	Processing power controlled by a computer software power function to specify a power percentage value e.g. 1-100% of a 10 Watt laser machine.
Actual power output	The known amount of actual energy exiting the nozzle of the machine via laser beam output, measured using a laser power meter.
Energy density	The amount of energy used over a space per unit volume which is the power + dwelling time e.g. Joules per centimetre squared (J/cm^2) applied to the fabric surface dependent on the mark/design/size, laser beam diameter and scanning velocity in relation to contributing factors described above.

Table 9: Laser power parameters observed in this study

Selected Power (%)	Actual Power Output (W)
5	0.2
6	0.9
7	1.8
8	2.75
9	3.7
10	4.5
11	5.6
12	6.9
13	8.1
14	8.9
15	9.6

Table 10: Data for the 60W Synrad laser marker showing selected power (%) via computer software against actual power output (W) measured using a laser power meter

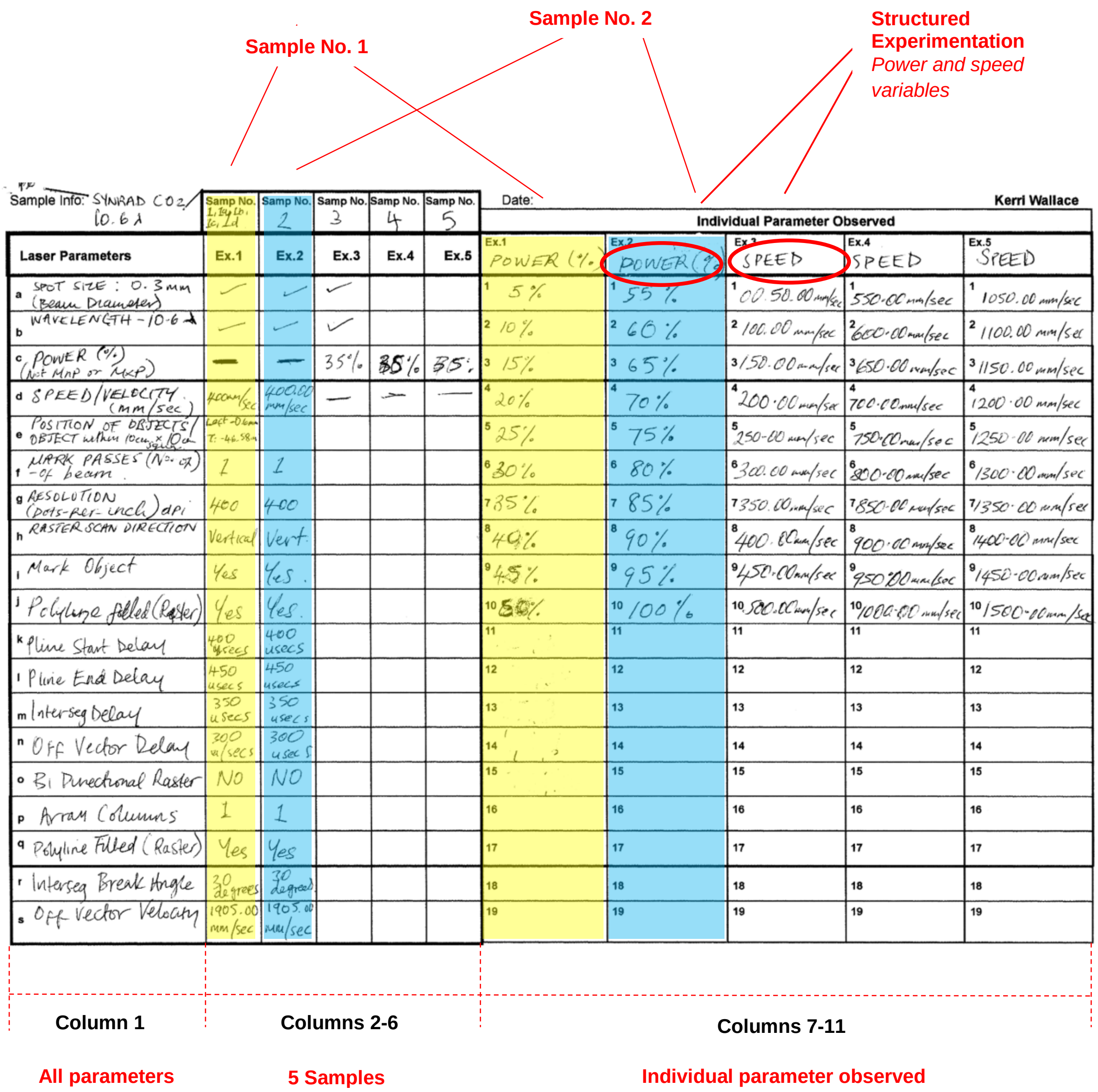
Further understanding of the technology regarding characteristics of the laser and the validity and/or transferability of computer software functions was gained through practical study.

Regarding laser aspects, knowledge obtained related to ‘power drop-off’ which occurs over time associated with the age of the machine, and that which occurs between the point of switching on the machine and subsequent use; and ‘inertia’ which refers to the tendency of a laser machine to change speed during processing causing varying levels of modification and so inconsistent surface effects. In terms of the computer software, factors included ‘functions’ which differed between laser systems. In some instances, specific features were attributed to a particular machine so experimental results were not a characteristic of the technology. Instead, these results were a function of the software; ‘data input’ enabled the user to specify processing values such as power, for example. However, the accuracy of some features was unreliable, hence the need to measure actual power output with a laser power meter, independently of the laser machine(s); and ‘software versions’ such as updates which impacted aspects of this research in the initial exploratory stages of the work. As such, irreversible settings during installation altered previous software parameters.

First-hand experience revealed the importance of knowing and being able to control these issues rather than relying on ‘given’ data containing unknown anomalies. Such aspects were relevant to the creative and repeatability objectives of the project. The ability to determine and reproduce specific effects with specific fabrics whilst retaining fibre stability with subtle fibre modification levels and minimal fibre damage, was essential in establishing the laser-dye process for textile patterning and coloration. ‘Know-how’ (further discussed in Chapter 2: *Methodology*) was attained by identifying optimum processing parameters through methodical experimental practice directly related to individual laser machines, fibre type, fabric construction, dyes and dyeing methods.

Experimental practice carried out in terms of laser processing power required a systematic approach to obtaining data during sampling based on multiple parameters that influenced laser energy such as machine/software features, selected power and speed/velocity.

Table 11 is an example of one type of data collection table matrix created within this study to facilitate focused structured experimentation with the CO_2 10W Synrad laser marker. All laser parameters associated with the laser computer software for the machine are listed in the first column – 1, (rows a-s). Columns 2-6 identify five experimental samples studied, numbered 1-5, in relation to the laser parameters in the first column. The next 5 columns (7-11) state the different numerical values of an ‘individual parameter observed’ for each of the five samples, which was either selected power or speed (velocity).



Sample Info: SYNRAD CO2 / 10.6 λ — Date: — Kerri Wallace

	Laser Parameters	Samp No. 1, 1a, 1b, 1c, 1d — Ex.1	Samp No. 2 — Ex.2	Samp No. 3 — Ex.3	Samp No. 4 — Ex.4	Samp No. 5 — Ex.5	Individual Parameter Observed — Ex.1 POWER (%)	Ex.2 POWER (%)	Ex.3 SPEED	Ex.4 SPEED	Ex.5 SPEED
a	SPOT SIZE : 0.3mm (Beam Diameter)	✓	✓	✓			1 5%	1 55%	1 00.50.00 mm/sec	1 550.00 mm/sec	1 1050.00 mm/sec
b	WAVELENGTH - 10.6 λ	✓	✓	✓			2 10%	2 60%	2 100.00 mm/sec	2 600.00 mm/sec	2 1100.00 mm/sec
c	POWER (%) (Not MnP or MxP)	—	—	35%	35%	35%	3 15%	3 65%	3 150.00 mm/sec	3 650.00 mm/sec	3 1150.00 mm/sec
d	SPEED/VELOCITY (mm/sec)	400mm/sec	400.00 mm/sec	—	—	—	4 20%	4 70%	4 200.00 mm/sec	4 700.00 mm/sec	4 1200.00 mm/sec
e	POSITION OF OBJECTS/OBJECT within 10cm x 10cm square	Left -0.6mm T: -46.58mm					5 25%	5 75%	5 250.00 mm/sec	5 750.00 mm/sec	5 1250.00 mm/sec
f	MARK PASSES (No. of) - of beam	1	1				6 30%	6 80%	6 300.00 mm/sec	6 800.00 mm/sec	6 1300.00 mm/sec
g	RESOLUTION (Dots-per-inch) dpi	400	400				7 35%	7 85%	7 350.00 mm/sec	7 850.00 mm/sec	7 1350.00 mm/sec
h	RASTER SCAN DIRECTION	Vertical	Vert.				8 40%	8 90%	8 400.00 mm/sec	8 900.00 mm/sec	8 1400.00 mm/sec
i	Mark Object	Yes	Yes.				9 45%	9 95%	9 450.00 mm/sec	9 950.00 mm/sec	9 1450.00 mm/sec
j	Polyline filled (Raster)	Yes	Yes.				10 50%	10 100%	10 500.00 mm/sec	10 1000.00 mm/sec	10 1500.00 mm/sec
k	Pline Start Delay	400 usecs	400 usecs				11	11	11	11	11
l	Pline End Delay	450 usecs	450 usecs				12	12	12	12	12
m	Interseg Delay	350 usecs	350 usecs				13	13	13	13	13
n	Off Vector Delay	300 u/secs	300 usecs				14	14	14	14	14
o	Bi Directional Raster	NO	NO				15	15	15	15	15
p	Array Columns	1	1				16	16	16	16	16
q	Polyline Filled (Raster)	Yes	Yes				17	17	17	17	17
r	Interseg Break Angle	30 degrees	30 degrees				18	18	18	18	18
s	Off Vector Velocity	1905.00 mm/sec	1905.00 mm/sec				19	19	19	19	19

Table 11: Data collection table matrix for the 10W Synrad laser marker showing laser and experimental parameters investigated

Figure 40 visualises one configuration of multiple velocity parameters (mm/sec) explored in relation to a ‘laser-fibre’ treated woven polyester textile sample, using the 10W Synrad laser marker. A constant power value of 35% was selected via computer software to process all 10 test squares with variable speed parameters of 550.00 mm/sec – 1000.00 mm/sec (increasing by 50.00 per square). The resulting laser modified fabric indicates some form of treatment has taken place due to tension differences across the fabric. However, incremental subtleties between each parameter generated little distinction overall, prior to the dyeing stage. The benefit of this result was the ability to understand that the fabric was not processed with too much power due to the lack of obvious fibre deterioration or significant visual damage to the textile structure. The effect of these variables led to a range of dye uptake levels as a result of differential energy across the fabric, influenced by different processing speeds.

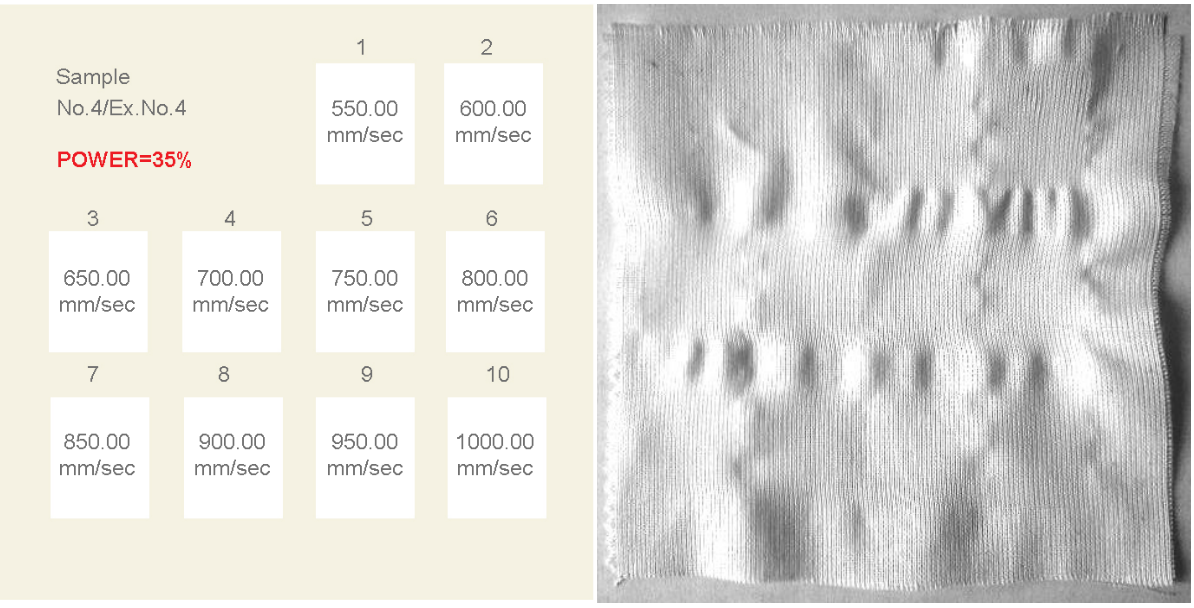


Figure 40: Configuration of laser parameters explored using the CO2 10W Synrad laser marker (left); and the resulting woven polyester woven fabric sample (right)

4.1.2.3 Laser power measurement and calibration

Power output was measured with a laser power meter in order to quantitatively know the actual amount of energy leaving the nozzle via laser beam of a marking system, rather than a belt driven laser bed machine. This experimental method was carried out with both CO_2 laser marking machines used in this study – Synrad 10W (Figure 41) and 60W. The laser marker machines were employed for further exploratory and design development work in this research due to the reliability of the machines and operating computer software. Over time, these aspects of the technology were less reliable with the 58W laser bed system initially explored. First-hand data obtained provided a reliable set of statistics for experimental investigation. This information aided understanding of exactly how much of a computer specified power (%) value was being used in Watts, during laser processing fabrics in relation to parameters explored and effects achieved. It was also deemed necessary to undertake this kind of inquiry in order to establish the transferability of the laser-dye process across multiple laser machines used in the research for replicable effects. The ability to calibrate power output from one machine to another was essential to the repeatability of outcomes based on known energy density. These outcomes were related to specific visual/design effects and physical modifications achieved on the fabric surface through both technical and creative input.

This approach also informed the potential applicability of processes beyond the scope of this PhD project such as within an industrial environment using different CO_2 lasers, for example. Therefore, controllable consistency of results based on a method for acquiring actual power output was paramount in this study. These considerations were important for the commercial relevance of the investigation outlined in the research questions, aims and objectives.

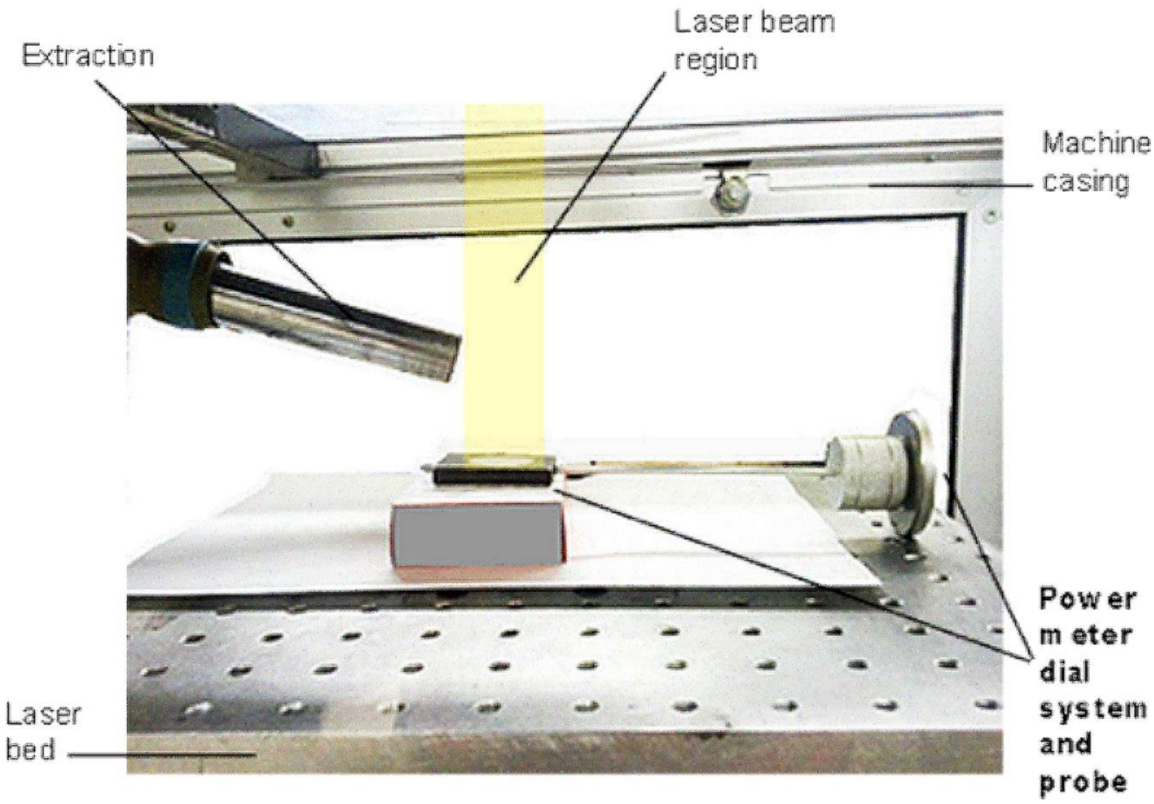


Figure 41: Measuring power output of CO2 Synrad 10W laser marker

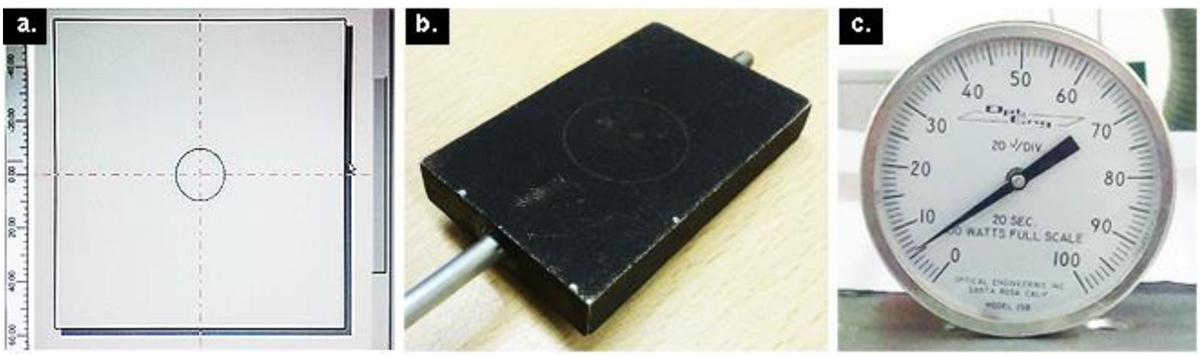


Figure 42: Computer screen/central spot (a); 10-100W Power meter probe (b); and gauge (c)

To carry out the laser power measurement method, the laser beam was fired in order to start marking the probe with a spot lase duration of 1000.0 milliseconds (ms) at 20 mark passes totalling 20 secs/20000 ms (Figure 42). This procedure activated the gauge providing a quantitative reading for actual power output within the parameters and computer controls explored. A digital power meter system also used in this study enabled greater accuracy of results (Figure 43).

Figure 43: Digital laser power meter – 0-10W Coherent LM10 Probe

4.1.2.4 Dyes and dyeing

Two main approaches to dyeing fabrics were carried out in this research. Namely, traditional hand methods and ISO procedures summarised in Table 12.

	Hand method	ISO method
Dyes	Commercially available workshop dyes from LU supplied by Midland Dykem: *Disperse dyes* Dispersol Scarlet B200% Dispersol Cetyl Blue BN 125% *Direct dyes* Chlorantine Fast Scarlet 4B 150% Solphenyl Blue 3RL	Industry standard dyes from SDC supplied by ITOCHU Group: *Disperse / Dispersol / Itosperse dyes* Yellow 3G Yellow Brown SERL 150% Rubine CGL 150% Red 2BE 200% Blue 3RL 150% Navy CD2G 200%
Auxiliaries	Acetic Acid – *Disperse dyeing* For ensuring the correct pH of a dye bath Salt/Sodium Chloride – *Direct dyeing* Increases exhaustion and dye aggregation	Acetic Acid – *Disperse dyeing* For ensuring the correct pH of a dye bath of 4.5 Itosolt mend – levelling agent 0.5% For uniform dyeing Itoquest LJ3-12 – cheatling agent 0.5% Helps with impurities in the water LJ550 dispersing agent 0.5% So dyes do not agglomerate
Dyeing* *Dye profiles detailed in *APPENDIX 4*	Open-air dye bath Max. Temperature capable – 98°C Variable temperatures explored Manual stirring High liquor ratios Tap water	Enclosed automated infra-red dyeing system Max. Temperature - 140°C Programmable dye profiles Prepared dye solutions Constant agitation Low liquor ratios Deionised water
Equipment	Heat source: Bunsen burner; Gas hob Digital weighing scales Metal dye vessels Plastic measuring containers Hand held thermometer Wooden stirring sticks Metal spatulas	Infrared sample dyeing machine Multiple metal beakers (batch) Digital weighing scales Glassware and measuring vessels In-built temperature regulation Metal spatulas Pipettes
Environment	Traditional textile dyeing workshop (School of Art, LU)	Standard chemistry lab (Chemistry Dpt., LU)
Other Procedures	FDL: Fibre-dye-laser hand methods *(Further explained in Chapter 4)*	Reduction clear after-treatment Necessary to remove un-dyed dyes from the fabric surface

Table 12: Summary of dye methods

In stage 1 of this research – 'Confirming previous work', commercially available workshop dyes and hand dyeing methods were used to carry out experiments. This approach was adopted in order to repeat the results parameters previously achieved (Addrison 2009).

During stages 2 (Exploratory) and 3 (Design development), industry standard (ISO) dyeing procedures were adopted essential for establishing the commercial potential of the laser-dye process. The methods were deemed necessary to establish transferability and repeatability aspects linked to reproduction in terms of specification and the control of parameters involved leading to colour quality (level dyeing), shade consistency between batches and the stability/wash fastness of dyes on laser-dyed fabrics, further implemented through ISO colour measurement and analysis. Hand methods (carried out in stage 1 and at the start of stage 2) do not enable this accuracy, nor do they meet the necessary requirements for ISO textile coloration. Therefore, ISO dyes, dyeing equipment, dyeing profiles, measurement and analysis procedures have been conducted in this work, in collaboration with the SDC (See Table 12) in order to move the process forward and gain a clearer understanding of its potential as a viable design tool for industry.

Colour development was embedded into the design development aspect of the work linked to creativity and commercial awareness of textile trends. Therefore, a ‘Colour Library’ was created and catalogued within the investigation consisting of an initial shade range of dyed fabric swatches (Figure 44). Each swatch was precision dyed using ISO dyes and procedures therefore yielding a particular shade. Using this methodical approach shades could be replicated. The Colour Library produced in this study became a useful reference point for proceeding experimentation. From a textile design perspective, such resource encouraged creative freedom and authority through the ability to select certain shades and create colour palettes and colour ways.

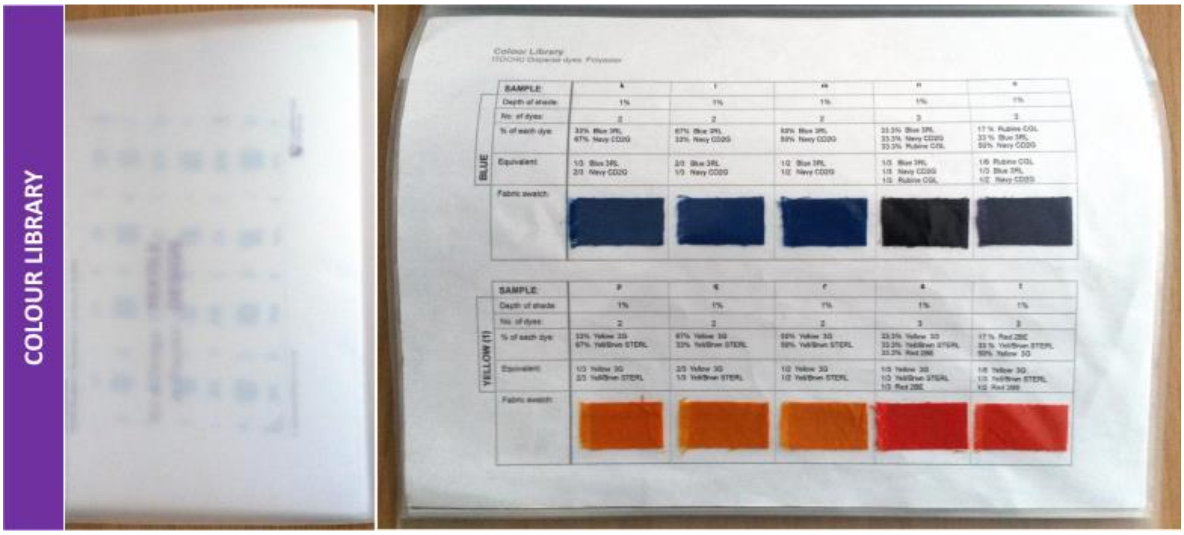


Figure 44: Colour Library with precision dyed PET fabric swatches

4.1.2.5 Design issues: CAD/Patterning/Coloration

Fundamentally, laser-dyeing was investigated in this research to understand the potential of the process as a viable creative tool for textile coloration and textile design. As discussed, the technical and scientific aspects embedded into this practical interdisciplinary study were underpinned by a creative perspective. Certain factors influenced the process of textile designing in this study concerning the development of pattern and colour onto fabrics in terms of dye uptake and patterning. These factors are categorised by the areas indicated below (further discussed in Chapter 5 within the context of the work) and have been summarised in Table 13 which outlines the associated design issues:

- **Computer Aided Design (CAD)** – involving both design and laser processing digital systems.
- **Default effects** – the ability to discern between novel visual effects attributed to specific laser machines and computer software or outcomes determined directly by the laser-dye process including anomalies and system differences.
- **Colour onto cloth –** qualitative and quantitative assessment through visual observations associated with creative intuition and expertise (as discussed in the Methodology/Chapter 3) and statistical analysis of laser-dyed fabrics via ISO colour measurement and analysis methods.

	CAD	Default effects	Colour onto cloth
Design Issues	***Digital considerations***: Creating graphics – raster and vector approaches Handling and preserving graphics between designing and laser-processing stages; combining multiple methods and techniques Image modes/formats i.e. Greyscale; Halftone Resolution (dpi) issues in relation to the laser beam	***Software***: Type/Model/Make Versions and updates System differences – functions, tools and methods System errors Anomalies as a product of specific tools or features: Inconsistencies between machines; Novelty opposed to fundamental technical factors File conversion File compatibility File type/extension(s)	***Dyes and dyeing***: Commercial workshop dyes and hand dyeing methods; ISO dyes, dyeing profiles and procedures *Dye uptake:* Levelling – shade consistency Accuracy and repeatability – coloration and design *Colour perception:* Intuitive visual assessment of results regarding creative effects and overall designs Initial reflectance spectroscopy measurements (LU) *ISO Colour measurement and analysis:* Reflectance Spectrophotometry (SDC); Wash fastness tests (SDC)

Table 13: Summary of design issues

4.1.2.6 Micrography

In order to assess the effect of laser modified/laser-dyed PET in this study, micrography was employed as an analysis technique for untreated and laser treated fibres/fabrics based on a range of experimental parameters explored. This microanalysis method facilitated close view observations (x10.100; x20; x40 magnification) capable of capturing digital photographic micrographs due to the microscope being linked to the computer software used to operate the equipment. Such in depth visual information facilitated a greater understanding about the effect of fibre/laser/dye interactions at fibre, yarn and textile/structural level in terms of surface changes and dye uptake behaviour. By using this apparatus, it was possible to view captured microscopic images on screen and to store these images digitally. Calibration between the microscope and the software enabled accurate digital measurements to be obtained, viewed and stored, such as the diameter of individual yarn fibres and the size/area of a laser-dye treated section of fabric, for example (further discussed in Chapter 5).

4.2 Conclusion

In this chapter, the experimental parameters employed in this digital laser-dye research have been presented and discussed in relation to the three main processes explored – Fibre-laser (FL); Fibre-laser-dye (FLD); and Fibre-dye-laser (FDL), which embody the qualitative and quantitative methods investigated. Initially, a range of different fabrics were used, before focusing on woven and knitted polyester fabrics, suitable for potential sportswear applications. This discussion is relevant to all three phases of work conducted – ‘Confirming previous work’; ‘Exploratory’; and ‘Design Development’. In doing so, this experimental framework which describes the fundamental parameters, methods and techniques carried out have been identified and further explained. These encompass the combined technical, scientific and creative aspects of the work in relation to the interdisciplinary research approach undertaken. Therefore, aspects relevant to Textile fibres; Laser issues (machines, beam characteristics, power, velocity processing variables and CAD technology); Dyes, Dyeing methods, Design issues (CAD/Patterning/Coloration) and Micrography, used as an analysis technique for the parameters explored, underpin this practical investigation. As such, this work provides an informed background to Chapter 5 of this thesis – *Experiments and discussion of results*.

Chapter 5: Experiments and discussion of results

This chapter sets out the experimental findings of this research in relation to the three phases of the work, previously discussed in Chapter 4 – Confirming previous work; Exploratory and Design development. Relevant issues regarding the laser-dye process have been identified and discussed. This work explored laser modification, textile coloration and patterning methods towards the development of a combined laser-dye process. Structured experiments were carried out within an interdisciplinary experimental framework using a practice-led research methodology, based on first-hand interactions with people and different environments – machines, procedures and alike, as outlined in Chapter 4. The data obtained relates to the creative, technical, scientific and industrial aspects of the study, summarised in Figure 45. Fundamentally, this knowledge relates to the opportunities and limitations of laser-dye methods for textile design and coloration. Three main approaches to digitally laser-dye polyester textiles using combined coloration and patterning techniques were identified and explored in this study presented in this chapter. They consist of one preliminary approach to laser modification and two laser-dye approaches, previously described (Chapter 4):

- Fibre-laser (FL) - involving the textile and laser only
- Fibre-laser-dye (FLD) - fabrics were laser treated first then dyed
- Fibre-dye-laser (FDL) - fibres were dyed first then laser modified

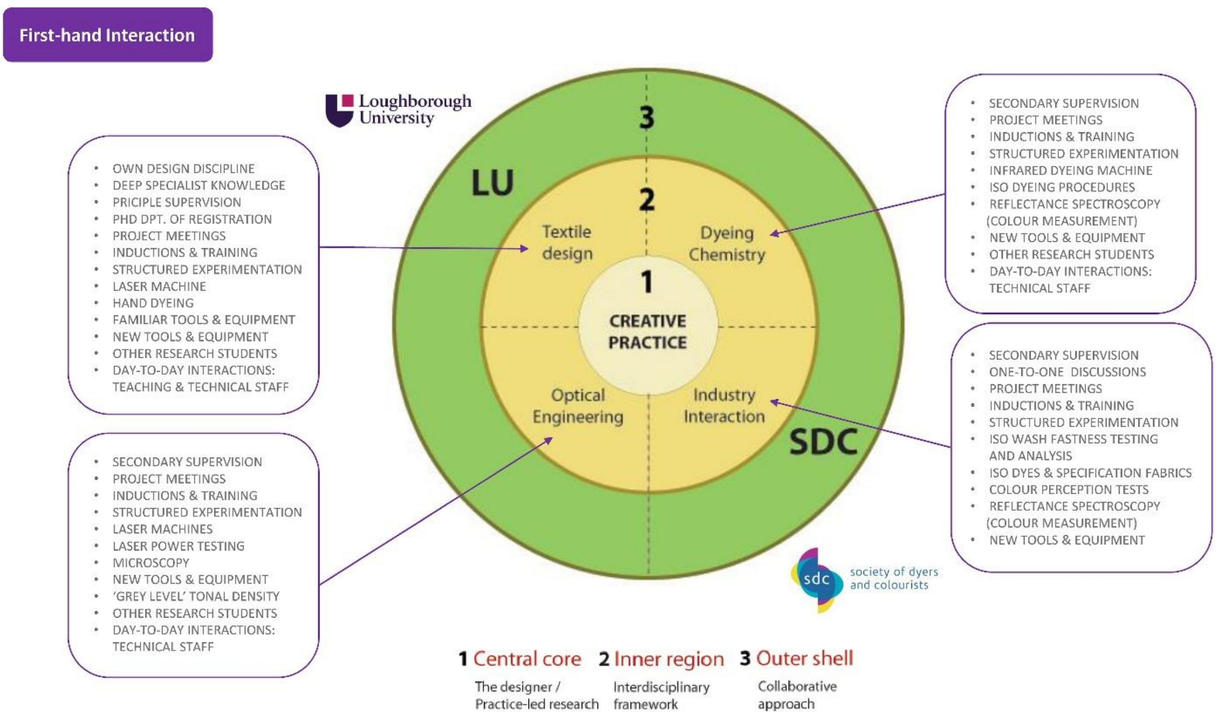


Figure 45: First-hand interaction carried out in this research

5.1 FL: Fibre-laser interactions

Fibre-laser experiments involved interactions between fibre and laser only. This element of the investigation aided understanding of issues concerning laser-modified textiles for dyeing. The work was carried out with a range woven textiles and fibre types – both commercial and industry specification fabrics including one knitted fabric (listed in Chapter 4; Table 6). Three CO_2 laser machines (Chapter 4; Table 7) were used to modify fibres by generating several test patterns on textile samples. Experiments were initially carried out with a CO_2 58W laser bed system operating at 53.6W (approx.) at full power. Further work was conducted using a CO_2 10W laser marker operating at 7W (approx.) full power. The power drop-off identified with each machine can be attributed to the age of both lasers typically producing a decline in operating power over time. It is also a normal tendency for laser machines to decrease in power output to some extent after a few minutes of turning on the equipment. A CO_2 60W laser marker was employed for procedural investigation. This machine operated at 97W full power, as it was new at the time of experimentation. Such issues regarding variable laser power per machine are therefore acknowledged in this research and are further discussed in this chapter.

Structured experimentation focused on specific parameters. Laser treated fibres were observed visually, by eye and through computational microanalysis methods as explained in Chapter 4 (Section 4.1.2.6) and discussed later in this Chapter, in relation to the results presented. Untreated fibres were also micro-analysed for comparison in terms the visual/physical impact of laser modification. This analytical approach was carried out in order to sufficiently understand the effects of a fibre/laser process on the modified textile surface. Outcomes facilitated further practical study regarding combined fibre/laser/dye interactions. Relevant experimental samples were generated relevant to phase 1 (Confirming previous work) and phase 2 (Exploratory) of this study.

5.1.1 Experimental approach

This section documents and discusses a raster laser beam scanning method used to modify fabrics. This process involved exploring a range of grey tones i.e. percentages of black, generated in Adobe Photoshop CAD software. The three main processing parameters investigated were - Greyscale (% of black), Power (% of energy in Watts) and Velocity (cm/sec). Machine features and characteristics as well as orientation of the cloth and textile structure were also taken into consideration.

A grid-like formula composed of multiple squares for raster scanning enabled several test patterns on the textile surface. This approach facilitated processing parameter specification shown in Figure 46.

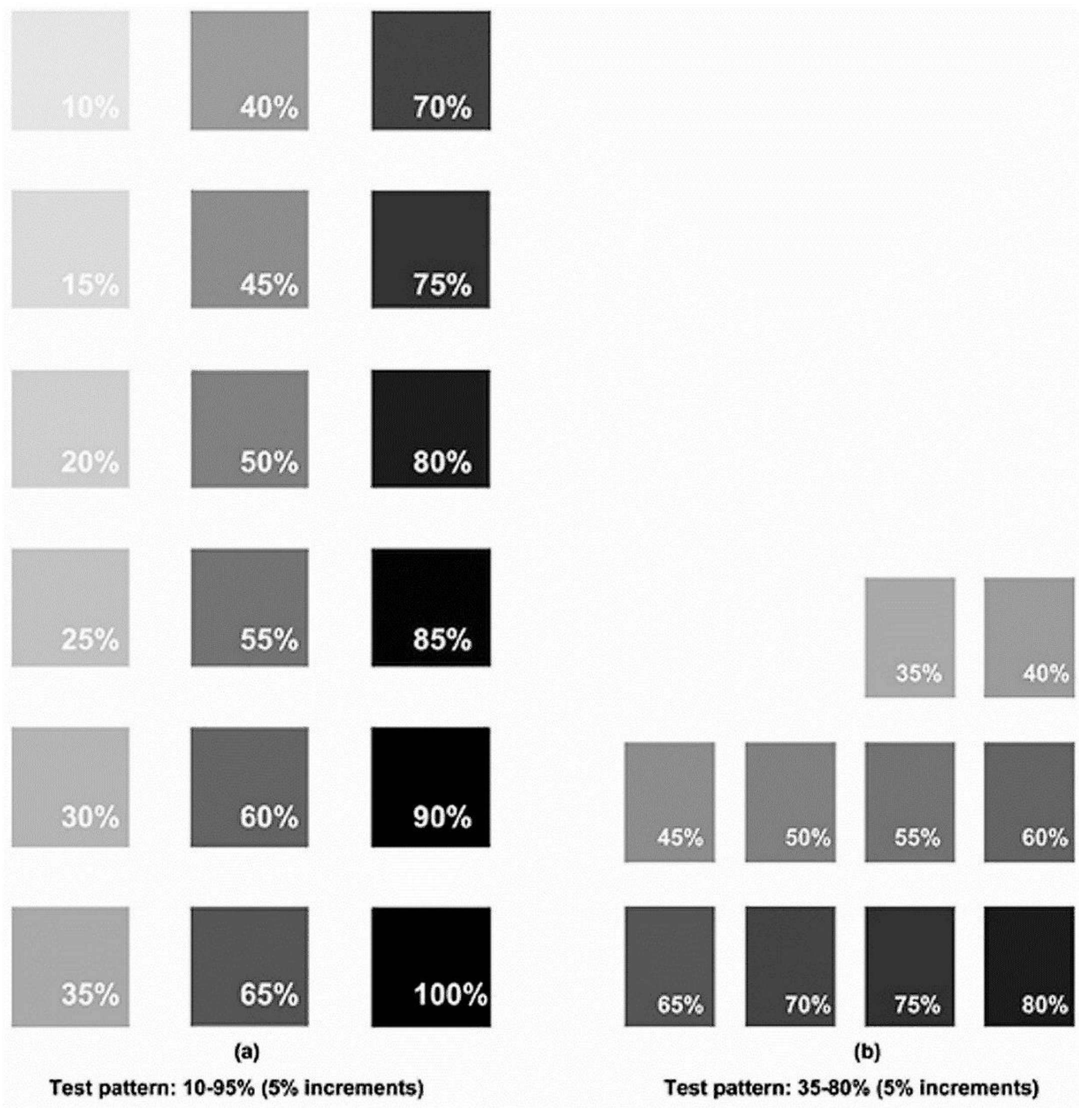


Figure 46: Greyscale test patterns generated via CAD (x2)

A methodical approach such as this could therefore be repeated or adjusted during sample production. Effectively, the higher the percentage (%) of black/grey tone within the greyscale, abbreviated to "GS" in this study, the greater amount of laser power treated the fabric. Increased interaction between the beam and textile fibres induced higher levels of modification to fibres. In comparison, paler greys i.e. lower % of black (or GS%) induced lower modification and subtler surface effects based on reduced fibre-laser interaction. In this research, such phenomenon is described as variations in energy density. This definition refers to the amount of power used to process textile fibres understood as the amount of units i.e. Joules (J) of energy over a certain area or space per cm^2. This is a new more specific approach to textile design research using lasers and a significant aspect of the methodology, not evidenced by Bartlett (2006) or Addrison (2009), for example. Equation 1 sets out the appropriate calculations.

[1] Total energy (J) = [2] Power (watts) x [3] Time (sec)

$$\text{[5] Energy density } (J/cm^2) = \frac{\text{Total amount of energy (J)}}{\text{[4] Laser treated area } (cm^2)}$$

1 Total Energy
UNIT MEASUREMENT
A unit of energy in Joules

2 Power
LASER SETTING
Refers to operational power attributed to the laser machine or a percentage of operational power by selecting a value (1-100%) via laser computer software

3 Time
VELOCITY SETTING
The speed/time taken for the laser beam to scan an area/design (cm2) in seconds

4 Laser treated area (cm2)
SIZE OF DESIGN/SPACE
The size of the processing area. This alters the time taken (sec) and energy density (J/cm2) between designs/effects in relation to the size of the design or sample and the level of detail and intricacy embedded into a CAD file. However, once specified, time/velocity and laser power settings remain constant and are not affected by the above mentioned factors.

5 Energy Density
ACTUAL ENERGY USAGE PER DESIGN
This calculation provides the specific amount of energy used to process an effect, design or pattern – a known value based on operational/percentage of selected power (watts), the processing time taken (sec) and the size of the laser scanned area (cm2). This value aids repeatability and transferability of the laser-dye process. Once known, the value can be reapplied or employed to use for different CO2 lasers with different operational power, in order to achieve replicable outcomes.

Equation 1: Energy equations and definitions in relation to this study (Kerri Akiwowo 2015)

Varying grey tones, combined with specified power and velocity values, controlled the amount of energy leaving the nozzle of the laser via laser beam in relation to actual power output (previously discussed in Chapter 4). An alternative raster approach explored in this research used only a single grey tone/GS % and varied the energy density between test patterns by altering power and velocity parameters only, rather than all three parameters (greyscale, power and velocity). Different levels of fibre modification were also achieved with this method. As such, these results support the technical and creative flexibility of the fibre-laser process. The digital approach employed supports specification aspects in terms of determining varied surface effects based on tonality.

5.1.2 Experiments and outcomes

This section focuses on the experiments carried out and the results achieved in relation phases 1 and 2 of the research, involving the confirmation of previous work and further exploratory investigation. In doing so, experimentation with commercial and industry standard (ISO) fabrics is presented and discussed.

5.1.2.1 Experimentation with commercial fabrics

During phase 1 of the investigation, the aim of experimentation was to confirm previous work and gain first-hand understanding of the fibre-laser (FL) process by using commercially available fabrics sourced from Whaleys (Bradford). In order to do so, poly/cotton and cotton woven varieties were employed. Repeating and developing selected experiments facilitated knowledge acquisition. 'Poly/cotton Duvet Optic White' (50% Polyester, 50% Cotton) fabric were explored to mirror previous fabric parameters using a CO_2 58W laser bed system (Figure 47). Power features attributed to this machine included a Minimum power (MnP), Maximum power (MxP) and (%) function, specific to the laser, whereby a numerical value was inputted for each. MnP describes the 'starting up' and 'slowing down' behaviour during beam scanning at the beginning and end of processing. MxP describes activity in between the start and finish whereby power output is the greatest. Factors that may affect consistent energy output during laser processing could relate to inertia – speed variables whilst scanning, the substrate/fabric not being flat or temporarily secured into position, beam focus/defocus and data within the CAD file, for example. Regarding this particular laser machine actual power output and energy density in relation to processing parameters was calculated by using data which included operational output energy linked to the machine, a % of energy (watts) selected via computer software based on maximum/minimum power and the size of a laser treated area (cm^2). This information was adequate for procedural experimentation.

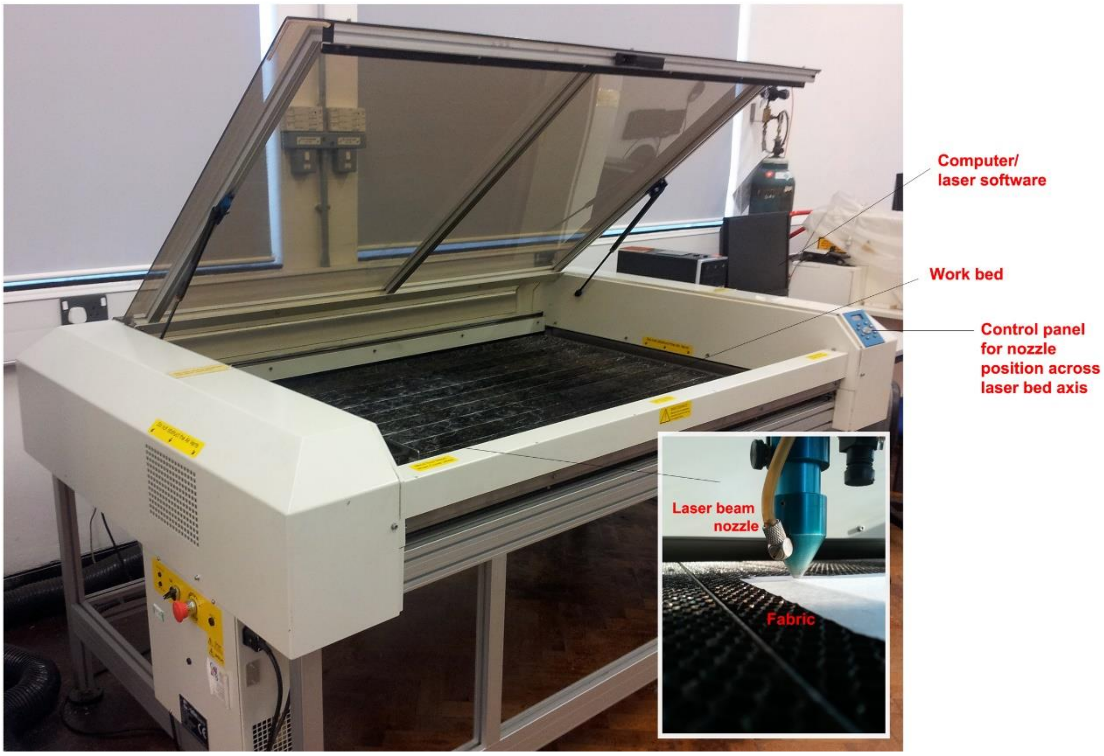


Figure 47: 58W CO2 Laser bed system

Greyscale (GS) test patterns were generated via CAD in increments of GS: 5% per square ranging from GS: 10-95% to produce 18 laser-marked squares on to the poly/cotton (Figure 48). This procedure was conducted to discern the damage threshold of the fabric detected by visibly different modification levels (Figure 49). Power and velocity combinations were investigated to confirm optimum processing parameters for this particular fabric.

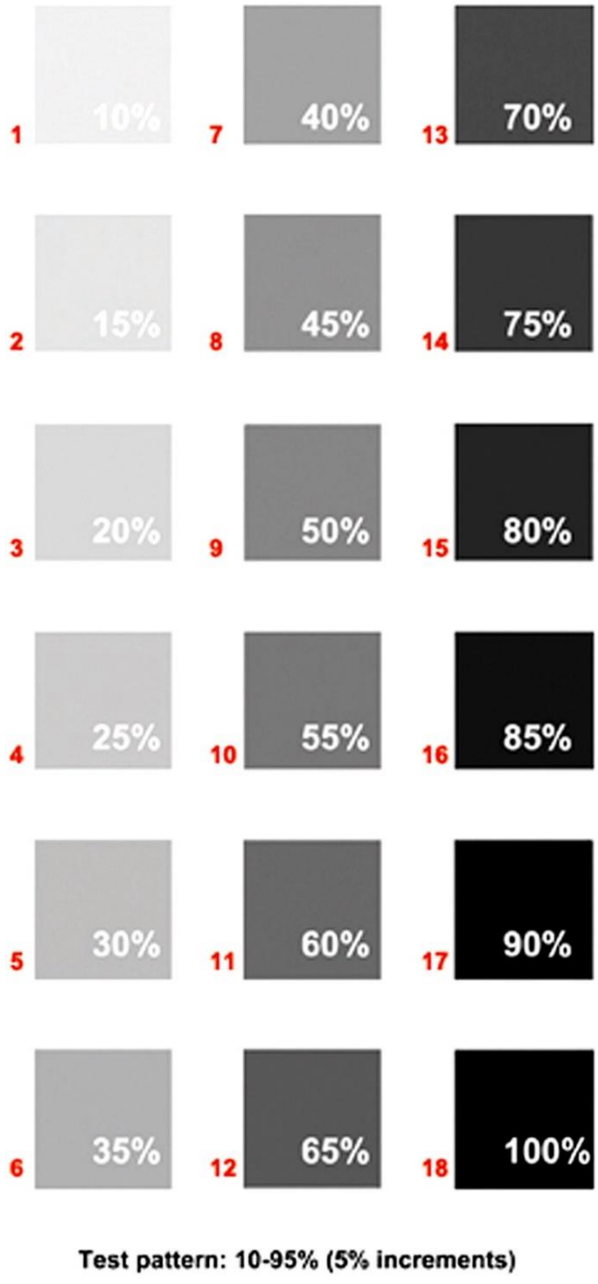
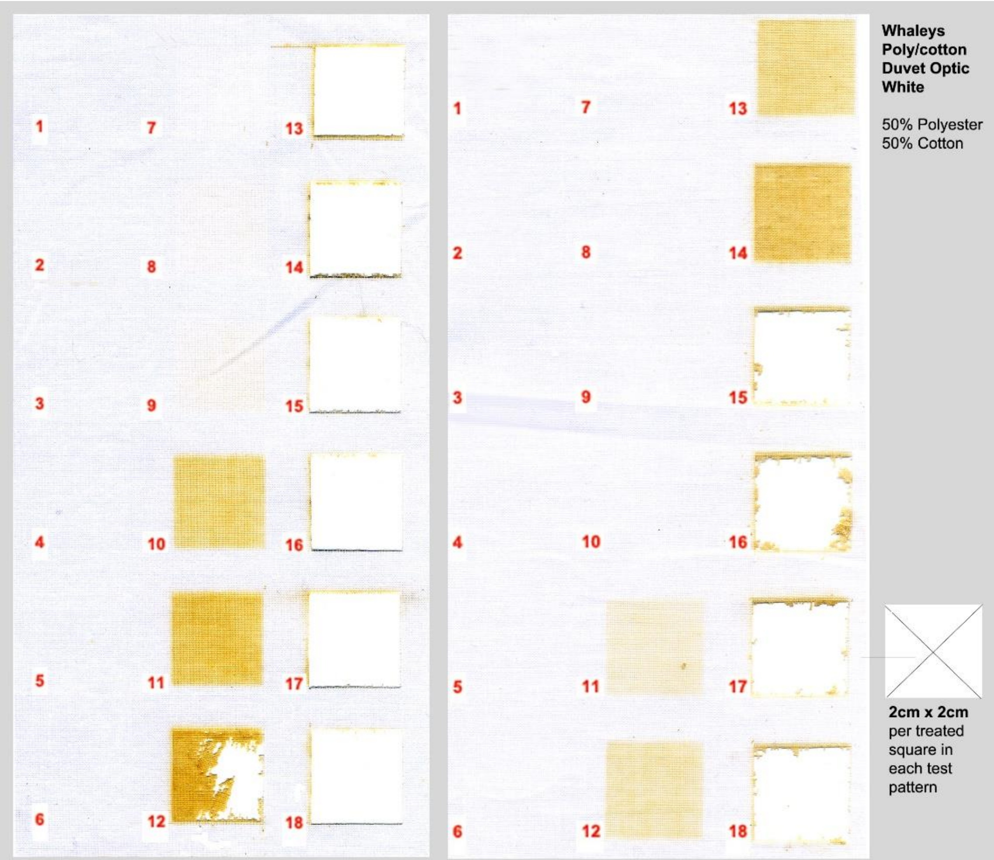


Figure 48: CAD generated test pattern showing 18 grey shades



Sample 4b	
Maximum Power (MxP)	60% (32.2W)
Minimum Power (MnP)	3% (1.6W)
Velocity (V)	60 cm/sec
Energy Density (J/cm²)	966 J/cm²

Sample 9a	
Maximum Power (MxP)	16% (8.6W)
Minimum Power (MnP)	3% (1.6W)
Velocity (V)	40 cm/sec
Energy Density (J/cm²)	172 J/cm²

Figure 49: Laser modified poly/cotton samples (4b) and (9a) with a 18 greyscale test pattern

Fabric samples 4b and 9a (Figure 49) were modified with different laser parameters:

1. **Sample 4b**:
   Max. Power (MxP): 60%; Min. Power: 3% (MnP); Velocity (V): 60cm/sec
2. **Sample 9a**:
   Max. Power (MxP): 16%; Min. Power (MnP): 3%; Velocity (V): 40cm/sec

Power (MxP/MnP) stated above, refers to a % of 53.6W leaving the nozzle via laser beam. Velocity indicates beam scanning (cm) per second (sec) applicable to all 4cm^2 laser modified squares within the test pattern greyscale grid. When using the CO_2 (58W/53.6W) laser bed system, % processing power was calculated by using the maximum power value in this research. Minimum % power value remained constant at 3% as the lowest possible value achievable controlled by the laser software. It was therefore approximated that a MxP of 60% translated to 32.2W laser energy in sample 4b with a MnP of 1.6W at 3%. A MxP of 16% was equal to 8.6W in sample 9a (with the same MnP as sample 4b), approximately four times less.

In both samples, a GS % tonal difference was determined by eventual processing power leading to variable fibre modification within test grids.

Subtle-to-extreme surface fibre damage can be seen in both samples (Figure 49). Test squares either exhibit some degree of discoloured surface charring – an effect typically associated with cotton fibres and natural fabrics rather than synthetic materials, partially remaining weakened fibres or total fibre disintegration. At the lower greyscale spectrum of GS: 10-35% (squares 1-6) little or no fibre-laser interaction was detected as the fabric appeared untreated. Therefore energy density at these parameters minimalised fibre/laser interaction. Modification was not noticeably detectable by eye with lower energy. Microscopy did however reveal that a greyscale shade of 35% was capable of inducing some level of fibre-laser interaction, identified in Figure 50.

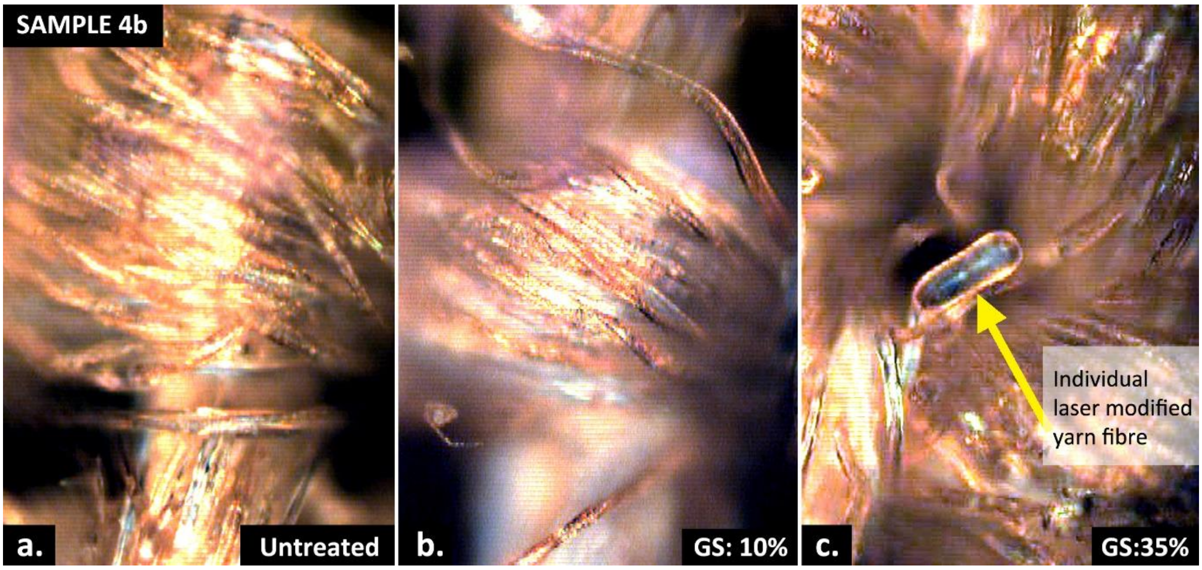


Figure 50: Laser treated woven poly/cotton (50%/50%) sample (4b) viewed at x20 magnification

This was detectable by a change in shape of an individual polyester yarn fibre (Figure 50/c). The laser-induced area of the yarn became swollen and formless. At higher energy parameters influence by a higher greyscale %, deeper fibre modification occurred. Both samples (4b and 9a) show the effect of too much processing energy. Increased interaction lead to fibres becoming brittle, recognised by distinct surface charring in the form of brown discolouration of varying levels. Significant interaction caused complete damage and so a separation of fibres from the fabric structure as shown in treated squares 13-18/sample 4b (Figure 49), for example.

Sample 4b shows 11 out of 18 laser treated squares are intact (1-11). Three of which are only subtly visible (7-9), two distinctly charred (10 and 11), one with partially disintegrated/remaining fibres (12) and six with extreme damage therefore maximum fibre degeneration (13-18). By comparison, sample 9a shows 14 out of 18 squares intact (1-12), four distinctly charred (11-14) and four with significant damage (15-18) and so lesser overall modification due to a lower energy density determined by a reduce MxP value, which can be expected.

Generally, results revealed that the % of grey affects actual laser energy output. It was therefore possible to manipulate energy density via grey shade variables in order to produce a range of surface effects. This combined function involving CAD and laser processing was explored further in this research. A method for designing digital graphic patterns specifically for laser-dye processing textiles using a greyscale/raster approach has been identified in a way that is quantifiable and therefore repeatable. As such, this work initiates new knowledge that is not evidenced in previous research (Addrison 2009 and Bartlett 2006). Therefore, this approach presents an advantage for the creative potential of a fibre/laser process on a commercial scale in terms of consistency in production. Such procedure is relevant to textile manufacture and product application suggesting a repeatable and reliable approach (further discussed in sections 5.2 and 5.3 of this chapter).

By carrying out extended design experiments using a patterning approach (Figure 51), the creative potential of a FL approach are demonstrated from a textile design perspective. Variable test patterns previously presented and discussed, enabled controllability of the FL process using multiple squares within a grid system to identify optimal fibre-laser modification levels and fibre damage threshold, in relation to increased energy density. The inquiry facilitated a mechanical understanding about interactions between fibre and laser based on specific processing parameters. As such, this knowledge made it possible to isolate the ‘best’ or suitable parameters to investigate FL surface effects using graphic ‘images’ via a raster approach. Whaleys woven poly/cotton (50%:50%) was explored at this stage in the research. A fragmented repeat pattern was employed, relevant to previous work and patterning practices investigated as a textile design practitioner (Figure 51). Small structures reference organic and naturalistic forms based on the aesthetic preferences of the author of the research such as irregular grids, cell frameworks and animalistic membranes, for example. Based on a small-scale patterning approach to FL processing, which utilises multiple individual laser modified elements/shapes to form an all over repeat design, it is considered that fibre damage was reduced as a result of minimal interaction, which can be understood. Therefore, it is reasonable to suggest that energy density distribution across the design, was lessened by this creative approach to surface patterning using a fibre-laser process explored.

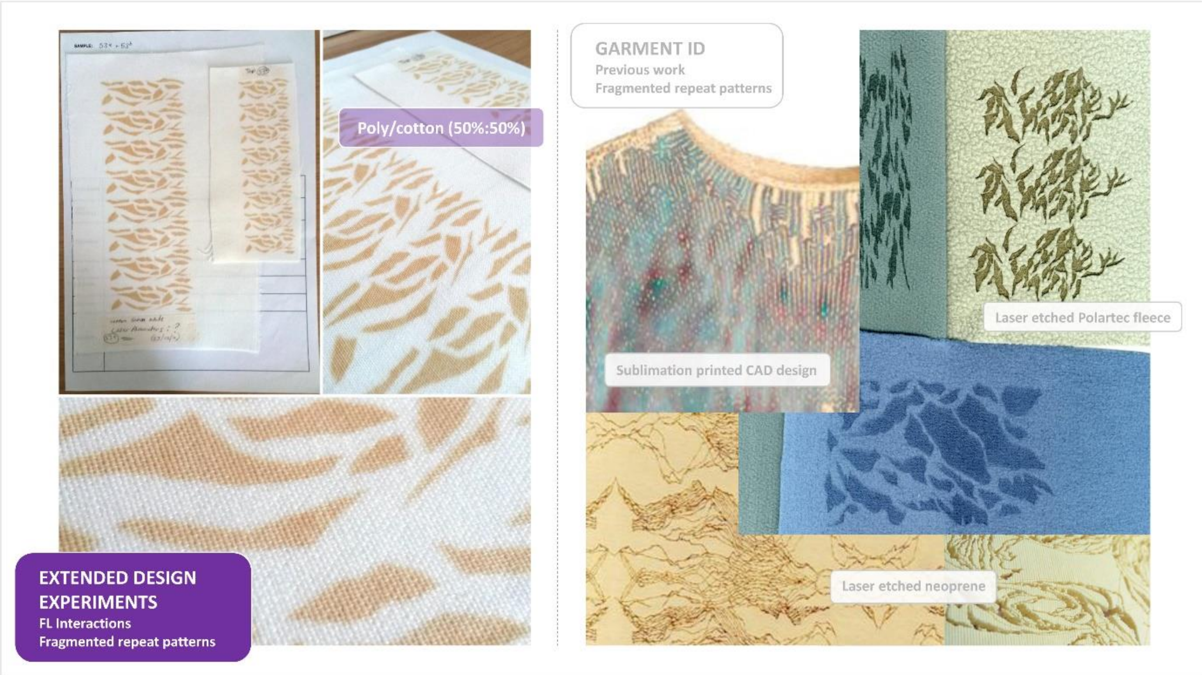


Figure 51: Extended design experiments using a patterning approach in relation to previous work: Woven poly/cotton (50%: 50%) sample (left); Garment ID textile design collection (right)

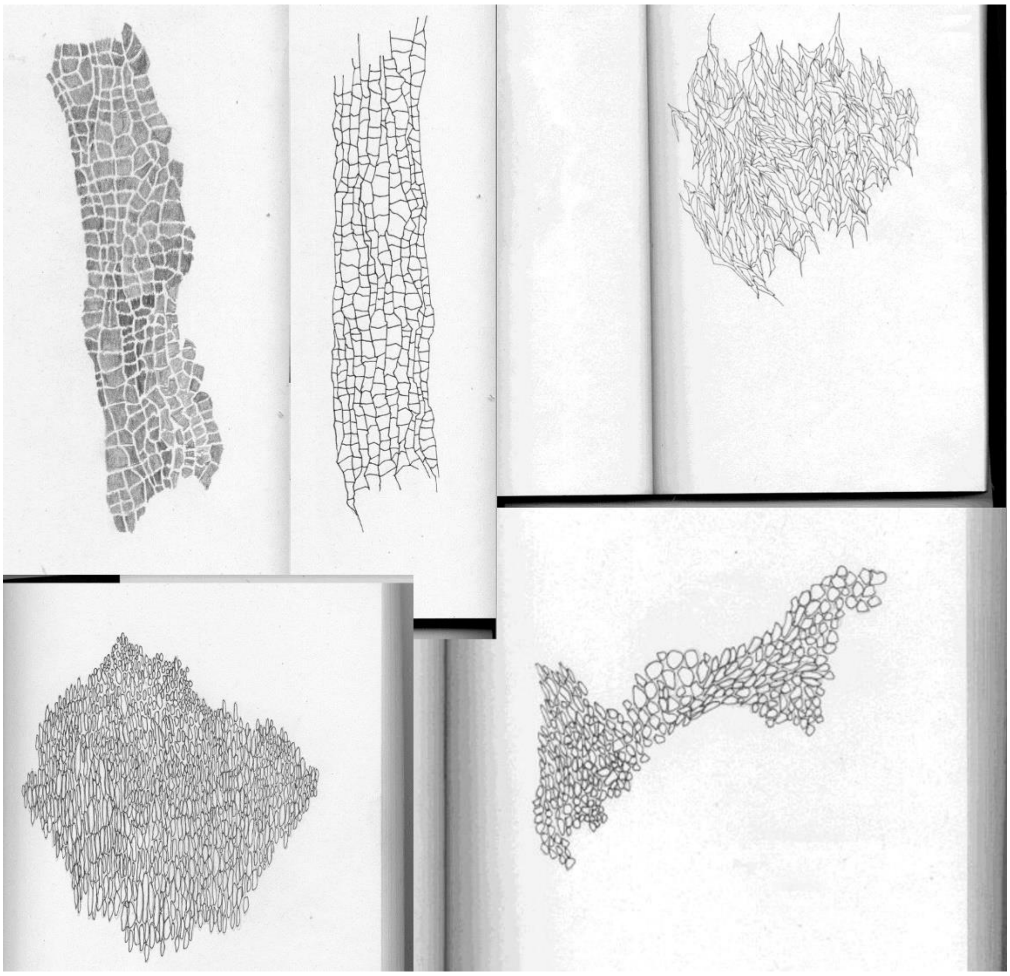


Figure 52: Drawings of organic and naturalistic forms

Overall, results of this confirmatory experimentation were often different compared to previous work such as the threshold point of fibre-laser interaction regarding specific parameters. In some experiments, more or less interaction occurred between the fibre and laser. It is thought that factors such as different fabric batches i.e. structural variations, differences in the day/time/year between experiments, 'unique' CAD files and software updates for instance, may have constituted these inconsistencies. Such issues probe the question of repeatability and the robustness of the fibre/laser process. Therefore, these aspects have been addressed in this research and are further discussed in this chapter demonstrated by a new process that is a more robust approach and contributes new knowledge to this field regarding textiles/lasers. Structured experiments and consistent parameters were employed in terms of specification fabrics, machines, methods and techniques.

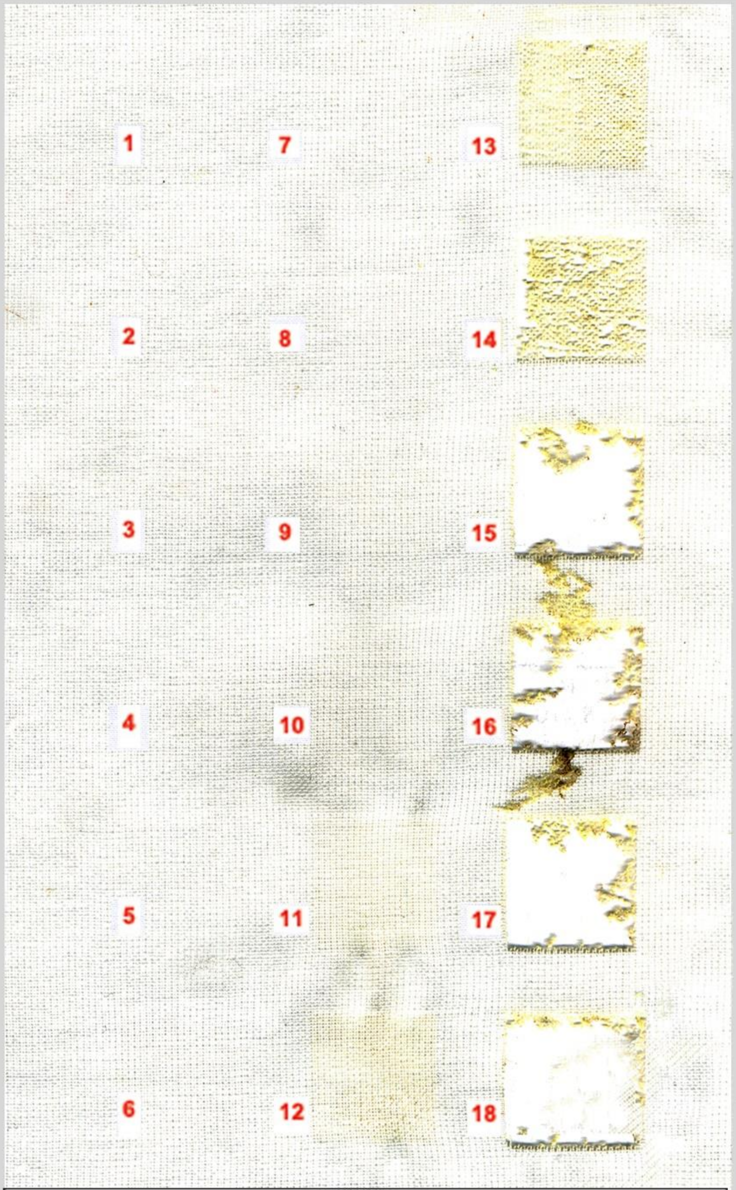
5.1.2.2 Experimentation with industry standard (ISO) fabrics

In this research, industry standard fabrics supplied by SDC and Crystal Martin were employed, introducing further insight in this field concerning lasers and textiles. Previous academic studies such as Kan (2008a; 2008b) and Shahidi et al. (2013) for example, as well as textile design research such as Bartlett (2006) and Addrison (2009) does not do this (as discussed in Chapter 2). In these studies, only commercial fabrics have been used. By using ISO fabrics undertaken in this research, detailed specification for each textile was made available. This entailed information about the characteristic of the fabric, composition and construction, staining properties etc. All of which were important to the practical inquiry from a design research approach and in relation to the repeatability goals of the study. Access to this information aided reliability of experimental work and results. Factors were constant between fabric batches as all fabrics were produced to identical specification. This practice is required at industry level regarding textile manufacture. Therefore, such procedure supported the commercial relevance of this study outlined in the research questions, aims and objectives.

Experimental work progressed from exploration with a broad range of different textiles/fibres to one fibre type – polyester (PET). The purpose for doing so was to steer and focus the investigation in response to the current body of knowledge in this field which is limited regarding PET fabrics. Gaps in existing knowledge have been identified in this thesis discussion (as argued in Chapter 2). Two PET ISO fabrics were employed in this study. One plain woven – 100% polyester and the other a jersey knitted fabric containing 97% polyester and 3% elastine.

Experimentation with ISO polyester explored interaction levels between the laser beam and textile surface fibres. Variable laser parameters and greyscale % were investigated as with commercial fabrics. CO_2 laser bed (58W) and two laser markers (10W and 60W) were employed, broadening the scope of this investigation relevant to the wider research field.

Firstly, a greyscale test pattern with 18 levels of grey (GS: 10-95%) was repeated to modify the woven polyester - sample 6 (Figure 53). Identical laser parameters to those in sample 9a (discussed in section 4.1.2) were applied. Results revealed at an increased % of grey (GS: 70-95%, squares 13-18) there was distinct deterioration of the fabric. Fibres became hardened and fragile separating from the woven structure. At GS: 60-65% (squares 11 and 12) fibres were visibly damaged exhibiting significant change to the textile surface becoming hard and rough. This region was therefore considered the threshold within these parameters. High levels of fibre-laser interaction increased the melting effect of laser irradiated synthetic yarns at these parameters caused by heat absorption. GS: 40-55% (squares 7 and 10) were only barely visibly treated with slight noticeable surface change (Figure 54). At GS: 10-35% (squares 1-6) there was no visible interaction and the fabric appeared undamaged, as there was no fibre discolouration or breakage. When viewed at x20 magnification, laser treated region GS: 35% revealed some interaction similar to the aforementioned polycotton fabric (Figure 49). There was an increased melting effect attributed to the synthetic PET substrate. Individual yarn fibres became less ordered exhibiting a build-up of ‘bubbling’ upon laser beam exposure. At GS: 10%, no noticeable change was detected when compared to untreated fibres. It was understood that an energy density of 0.7 J/cm^2 applied when processing square 6/GS: 35% was sufficient enough to initiate onset FL interaction. This was confirmed by microscopic analysis of surface fibres (Figure 55).



Sample 6	
Maximum Power (MxP)	16% (8.6W)
Minimum Power (MnP)	3% (1.6W)
Velocity (V)	40 cm/sec

Figure 53: Laser treated ISO woven polyester with an 18 shade greyscale

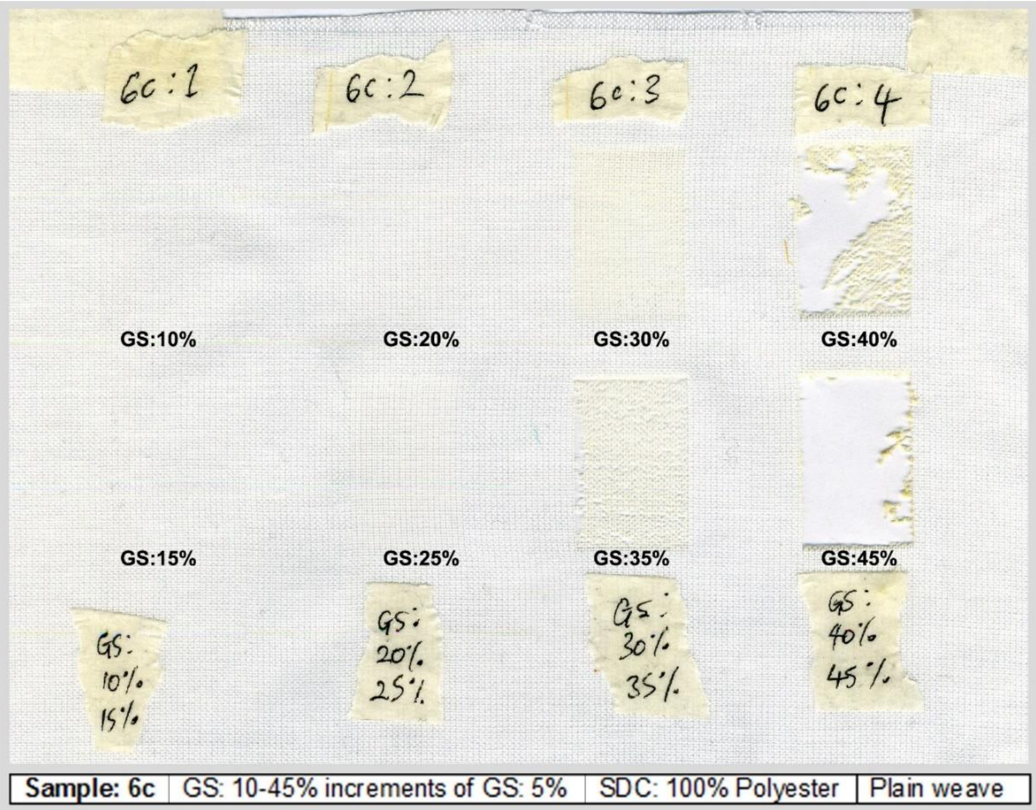


Figure 54: Laser treated ISO woven polyester with a reduced range of 8 greys

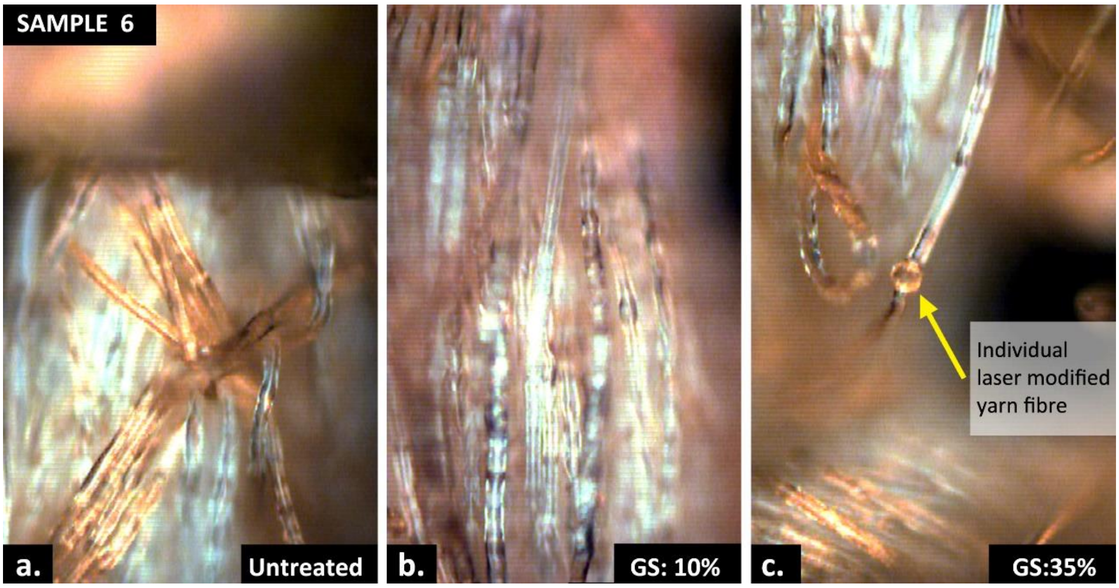


Figure 55: Laser treated SDC polyester treated sample 6 viewed at x20 magnification

Unlike the charring affect demonstrated with the polycotton fabric previously described (section 5.1.2.1), polyester fibres melt when exposed to laser beam. This reaction is attributed to the innate thermal properties of man-made synthetic polymers i.e. PET and PA, for example, based on absorption of the laser beam.

The experiment provided an instant gauge for where onset interaction may occur as well as the damage threshold of this particular fabric regarding specific laser parameters – processing power (actual output), energy density and the % of grey. Surface effects immediately indicated those parameter combinations that were not suitable for modifying fibres due to extreme fibre deterioration or significant surface damage. Therefore, procedural experimentation was carried out with selected parameters from sample 6. This entailed fewer grey levels (GS: 10-45%) to form greater focused study by further structured investigation – sample 6c (Figure 55). This sample is a concise indication of effects form minimum to maximum fibre-laser interaction based on greyscale in relation to specified laser parameters explored.

Test patterns explored incremental variable parameters in order to gain a deeper understanding of the fibre/laser process. This approach was relevant to both the technical and creative aspects of the study from a textile design perspective. Such methodology is not common in textile design as a discipline. Therefore, this investigation was underpinned by interdisciplinary inquiry encompassing a range of procedures, techniques and skills from design, chemistry and engineering disciplines together with industrial collaboration with the SDC.

Having established a set of usable laser parameters whilst exploring woven polyester, the same or similar parameters were initially applied to the ISO polyester knitted jersey fabric (3% elastine). This was considered logical to pursue procedural investigation in a focused and methodical manner concerning different fabrics. Experimentation between laser machines was achievable by the process of calibration with regards to energy density previously discussed. Although the structure of each textile differed (Figure 56), their fibre content i.e. PET was largely the same. It was therefore possible to some extent speculate the potential laser modified effects based on prior knowledge of a similar textile material.

Developmental experiments with the knitted polyester fabric provided a concise range of preliminary parameters that did not adversely damage fibres during the laser modification process. Although not visually noticeable by eye, at the lowest GS of 50% with an energy density of 0.05 J/cm^2, micrography revealed that some fibre-laser interaction had occurred. This result was also true for each GS% value applied to the test samples. Through this study, further understanding about the subtlety of laser surface modification achievable through incremental parameter variables was gained. This knowledge aided experimental development. Earlier explorations with both poly/cotton commercial fabric and the industrial woven polyester facilitated the ability make decisions about on-going experimental investigations.

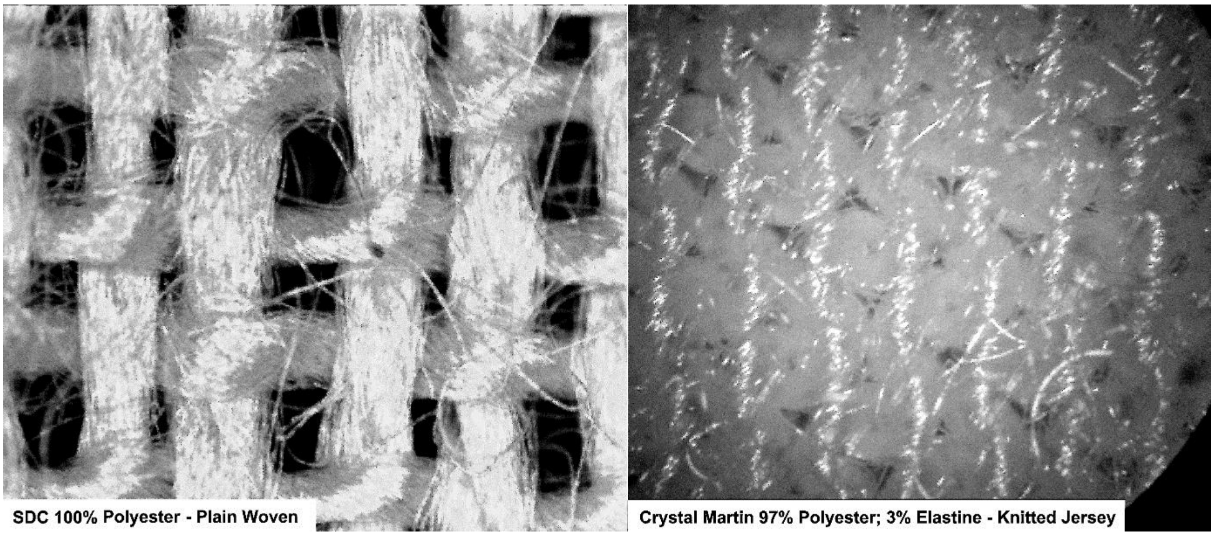


Figure 56: Structure of untreated woven (a) and knitted (b) polyester at 10.100x magnification

All three CO_2 lasers were employed regarding fibre-laser interactions – 58W bed system, 10W and 60W laser markers. So, it was important to be able to apply the same energy density for modifying fabrics between machines in order to repeat surface effects. Calibrating actual energy output for each machine ensured that the energy density for processing was the same across samples in relation to specific parameters explored. Repeatability was achieved by calculating the % of energy required (Watts) to induce a specific effect or level of fibre modification per machine, in relation to laser energy. Actual power output measurements were conducted for each laser marking system using laser power meter equipment, as discussed in Chapter 4. Calculations were applied in relation to the laser bed system (as previously discussed). Based on these findings, the appropriate numerical value(s) via the laser computer software were inputted for processing fabrics. In doing so, parallels in energy density were applied to fabrics when using any one of the three lasers (also discussed in Chapter 4 of this thesis). This approach was continued for further experimentations with both woven and knitted polyester materials in this study.

5.1.3 Conclusion

In this research, a ‘Fibre-laser’ (FL) approach to laser marking fabrics via raster scanning directly in relation to greyscale (GS) tonal depth i.e. a % of black generated in CAD software has been investigated. This method demonstrates that it is possible to determine different levels of fibre modification/energy output by applying greyscale variables. Anomalies and inconsistencies in the results during phase 1 - confirming previous work, produced variants to some extent. It was therefore necessary to address this issue by developing the fibre-laser process in a way that could be quantified, controlled and repeated to ensure valid outcomes.

By employing ISO specification fabrics in the exploratory phase (2) of the work, along with the ability to understand the process in terms of energy density, a more reliable method for processing fabric in this way was realised. These issues are relevant to the commercial opportunities of combined fibre/laser/dye processes explored regarding textile development. This scientific approach to textile design, coloration and patterning relevant to industry has not been investigated in other ‘lasers and textiles’ design studies or related academic research. As such, the results indicate new knowledge.

5.2 FLD: Fibre-laser-dye interactions

The fibre-laser-dye (FLD) interaction explored in this research describes a method whereby the fibre/fabric has been laser modified/treated first then dyed. This section documents and discusses the approaches undertaken, experiments carried out and results achieved and moves on from the previous section by involving dyes/dyeing by way of a coloration and patterning approach from a textile design perspective. This work addresses the design issues, opportunities, limitations and associated characteristics based on the digital laser-dye process such as: the laser beam and scanning; computer software and digital files; axis issues; engineered colour/pattern and on demand processing; and energy density in relation to tonal density regarding a range of surface effects (sections 5.2.1; 5.2.2). The results of quantitative colour measurement and analysis of laser-dyed samples are also presented and discussed (section 5.2.3). In doing so, an approach to reliably assess and communicate colour was employed by using methods such as: reflectance spectroscopy and industry standard spectrophotometry; CIE L*a*b* colour model, also used in industry; computational grey level system; and ISO wash fastness testing (section 5.2.4). ISO textile performance tests were carried out on laser dyed fabrics and the results are also presented and discussed (section 5.2.5). The purpose of such investigation was to further understand the impact of the process on polyester woven and knitted fabrics in relation to potential product application regarding digitally laser-dyed textile goods. Tests undertaken include: tensile strength; tear resistance; burst strength; and dimensional stability.

Experimentation was initially carried out with hand-dyeing methods. Further investigations involved an industrial infra-red sample dyeing machine. Both raster and vector laser scanning approaches/modes were employed in relation to the CAD software. Default effects, anomalies and corrective methods have been studied to address the reliability goals of a laser-dye process. Experimental progression explored dye uptake capability and design development through sampling and garment prototyping.

5.2.1 Laser beam scanning and patterning

In this section, the relationship between beam scanning and patterning regarding the FLD process is discussed, in relation to three key aspects:

- Beam characteristics
- Laser software/file conversion
- Axis issues

This discussion highlights aspects that are fundamental to processing PET textiles in this way in terms of achieving high quality surface modification with graphics and consistent tonal dye uptake.

5.2.1.1 *Beam characteristics*

The raster scanning laser method is capable of importing CAD files in the form of shapes, patterns and other design elements (as discussed in Chapter 4) into the laser computer software for processing. Digital monochromatic greyscale design features attributed to both the laser and CAD software facilitated the creation of graphics/patterns (Figure 57) on the textile surface through tonally varied dye uptake. Factors described in this section have been identified as significant to the quality i.e. evenness and consistency of laser marking/dye uptake in relation to the laser beam and machine characteristics, also referred to in Figure 58.

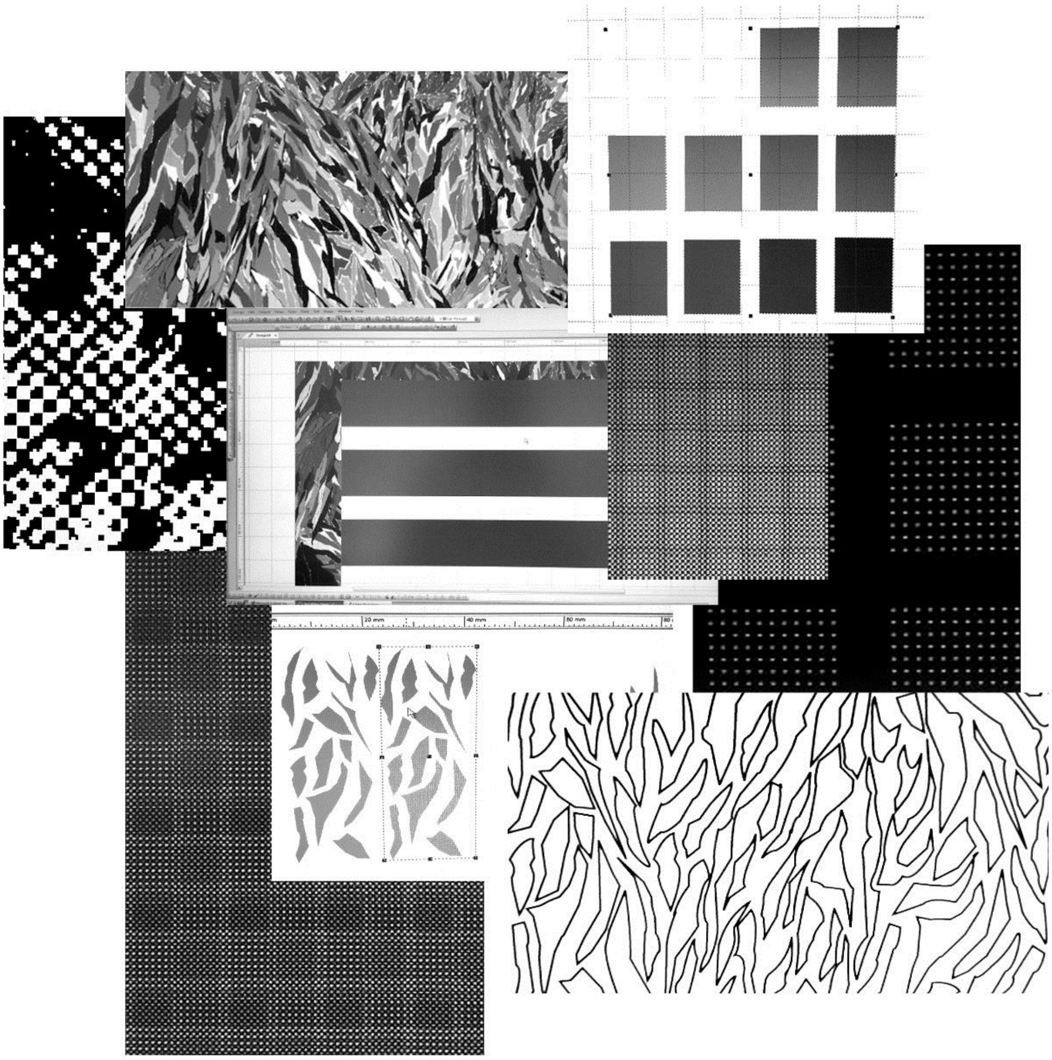


Figure 57: Digital monochromatic greyscale graphics/patterns enabled by laser and CAD software

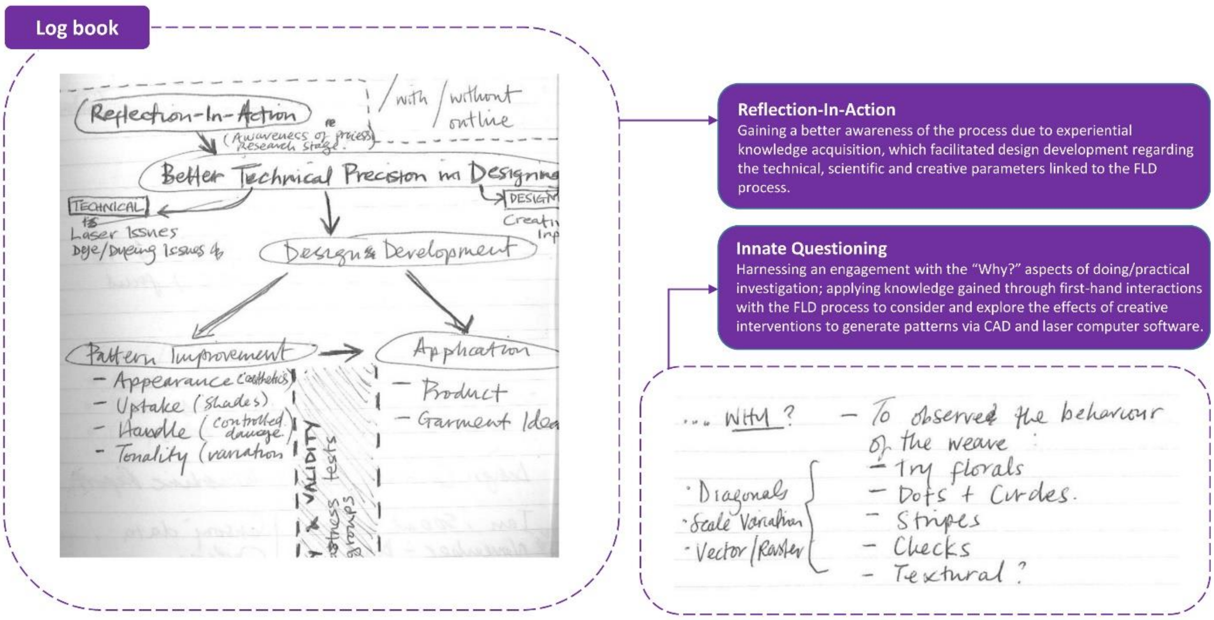


Figure 58: Log book: containing reflective thinking regarding the laser marking and dye uptake factors regarding surface effects and design development

As discussed in Chapter 4 (section 4.1.2) finding the optimal field of focus within a specific area regarding a laser marker system in relation to the work piece i.e. the fabric sample was important in order to determine sharpness of image (resolution). For example, achieving the most prominent results within a 200mm x 200mm area/piece of fabric. The belt driven laser bed system is a larger machine and optimal focus is aided by the automated position of the nozzle, requiring minimal manual height adjustment. However, a laser marker system is typically smaller and the beam is directed by moving mirrors, as previously discussed. Therefore, notable manual input is required in terms of finding the optimal focal height for acceptable beam delivery in order to modify the fabric satisfactorily with graphics. Once the optimal field of focus was found using the laser marker, scanning beyond this region reduced image quality shown in Figure 59. This was due to a larger depth of field as the laser beam spot size increased, in turn decreasing beam focus and producing blurry graphic quality. Based on this characteristic of the laser marker system, it is noted in this research that the size of the work piece such as a fabric sample, fabric length or garment, in relation the type of laser marked design can influence the visual appearance of such a mechanical trait based on size/area/space. In relation to these considerations, it is also acknowledged that the scale, composition, pattern style and dye shade can either emphasise or minimalise this effect. Therefore, from a textile design perspective, different pattern types were explored in this study which considered such aspects through the creation of all over and repeated tonal patterns Figure 60.

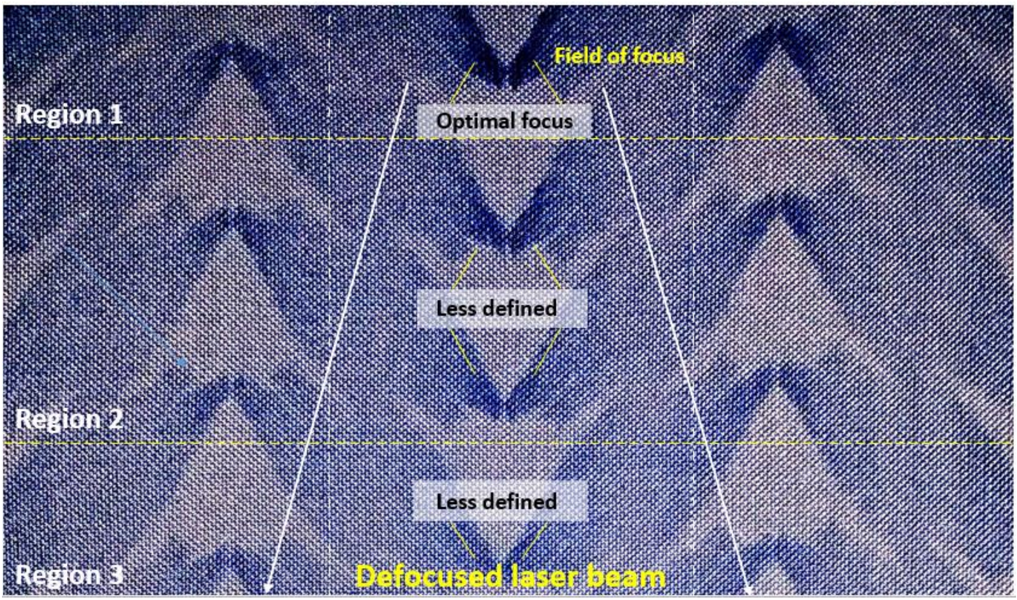


Figure 59: FLD processed woven PET sample showing reduced sharpness due to defocused beam

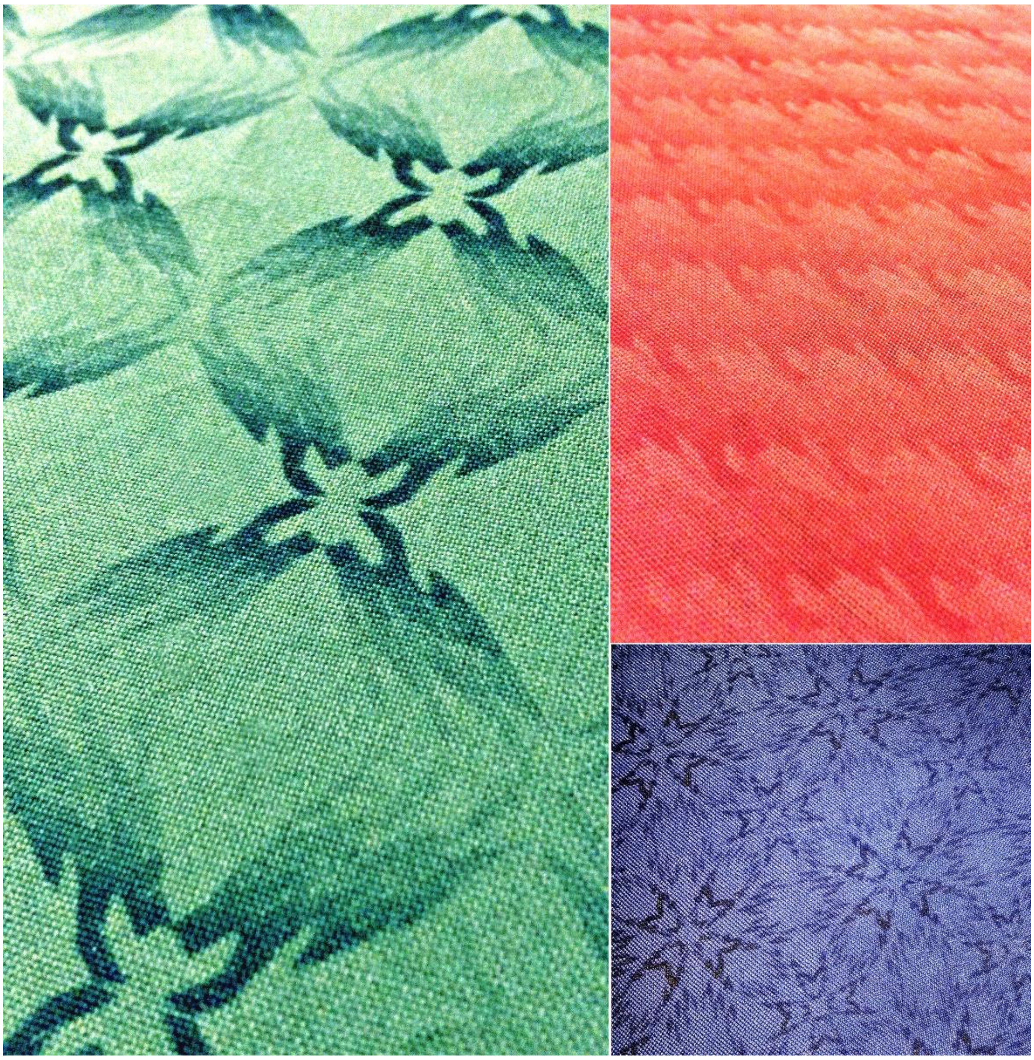


Figure 60: FLD processed woven PET fabrics demonstrating different pattern types explored

Essentially, the raster method induced closely spaced beam scanning in order to fill an area (as discussed in Chapter 4). This encouraged some degree of beam overlap when processing fabrics as the space between each scan was smaller than the beam spot size (Figure 61). Irregular surface modification occurred due to some fibres being treated twice (Figure 62). Consequently, a visible streaking effect emerged as a result of repeated fibre/laser interaction. In areas where flat even colour was intended, a stripy surface emerged instead. Where streaking did occur, this caused some interference to patterns, altering the appearance of designs. In terms of achieving flat shades without patterns, the effect was eliminated using a vector scanning approach, discussed in the next section (5.2.2).

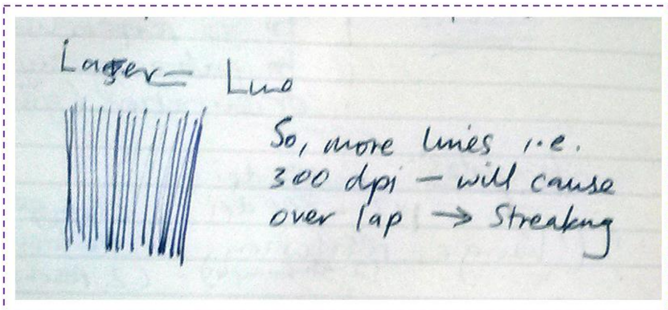


Figure 61: Log book note: Laser beam scanning causing beam overlap leading to a 'streaking' effect

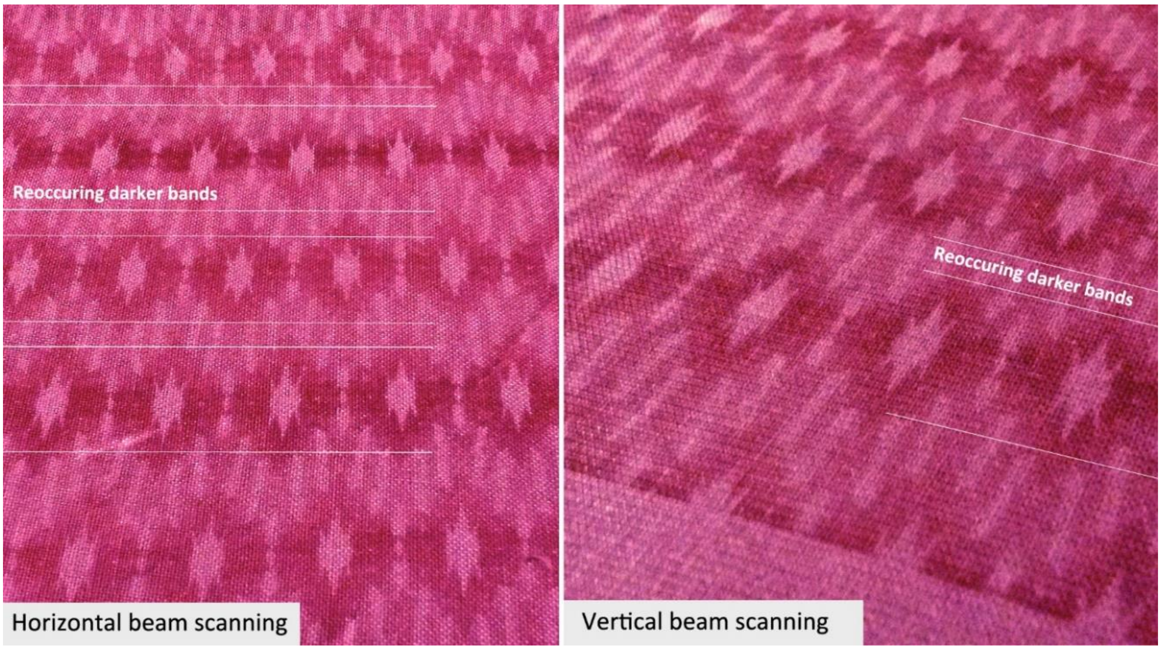


Figure 62: Visible overlapping 'streaking' effect as a result of beam overlap during scanning

Speed changes during processing known as 'inertia' typically occurs as a laser beam traverses across a bed during beam scanning. In this study, a raster method emphasised this characteristic due to a slowing down motion at the start and end of each scan when filling a shape (Figure 63).

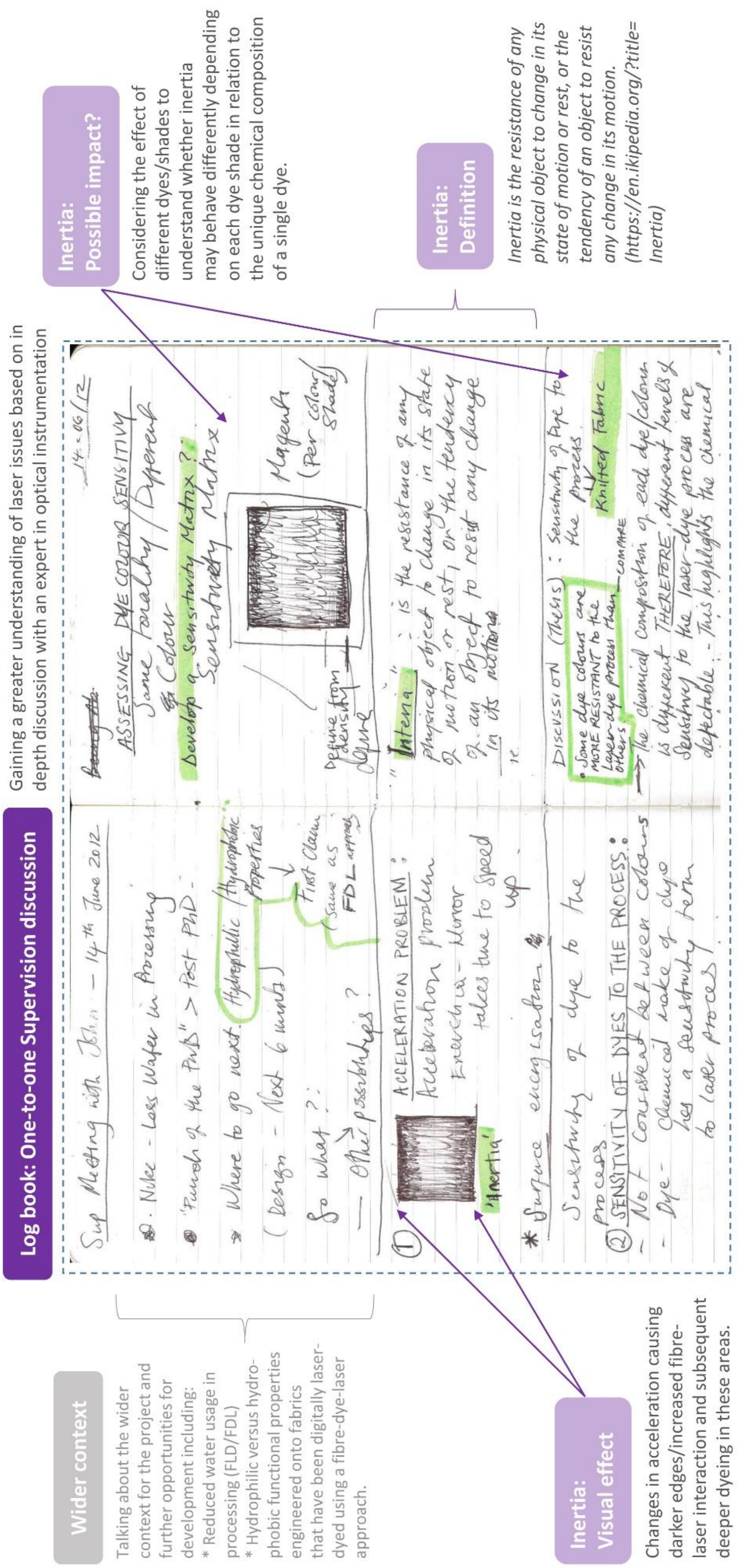


Figure 63: Log book pages: Supervision meeting regarding ‘inertia’ laser issue

Although it is understood that this effect can be controlled to some extent with some laser systems, in this research, inertia produced regions with darker edges of a pattern due to increased fibre modification and dye uptake caused by slower beam scanning (Figure 64). Overall appearance of the pattern was uneven, as well as experimentation with flat all-over colour, noticeable by surface irregularities (Figure 65).

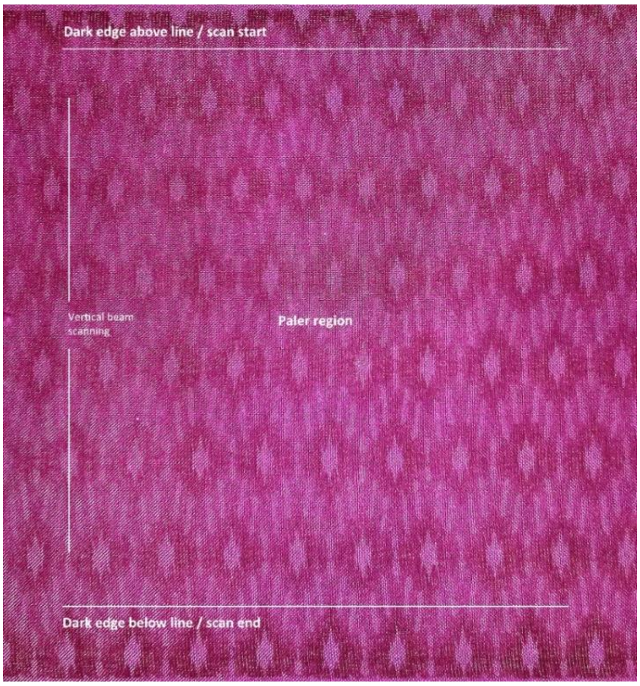


Figure 64: FLD patterned fabric sample showing inertia leading to darker edges (woven PET)

Figure 65: FLD fabric sample (no pattern) showing darker edges due to inertia (woven PET)

5.2.1.2 Laser software and file conversion

Importing a CAD file involved converting an original graphic to an image-based mode in the laser marking software (WinMark Pro) appropriate for raster scanning via laser beam. A ‘Colour reduction method’ was employed to do so. This computer software feature was relevant to both CO_2 laser markers used in this research (10W and 60W). Both ‘Greyscale’ and ‘Halftone’ colour reduction options were explored deemed suitable in relation to the CAD files created based on patterns formed from varying percentages of black, referred to as Greyscale or GS% in this study.

Having investigated a greyscale approach for generating patterns with CAD technology using varied % black, selecting a greyscale laser scanning mode via laser software seemed logical for marking. However, results were unpredictable in this mode and therefore unreliable. Laser-dyed samples processed in this way, did not depict a ‘true’ representation of designed patterns or creative effects when laser marked on the fabric surface as demonstrated in Figure 66. Although repeated experiments were carried out in this mode, with similar results each time, no definitive reason for such occurrence was found. Therefore, these results may suggest a technical incompatibility between the systems for generating greys created via CAD: Adobe Photoshop, and the greyscale colour reduction system embedded into the WinMark Pro laser software. However, such explanation cannot be concluded.

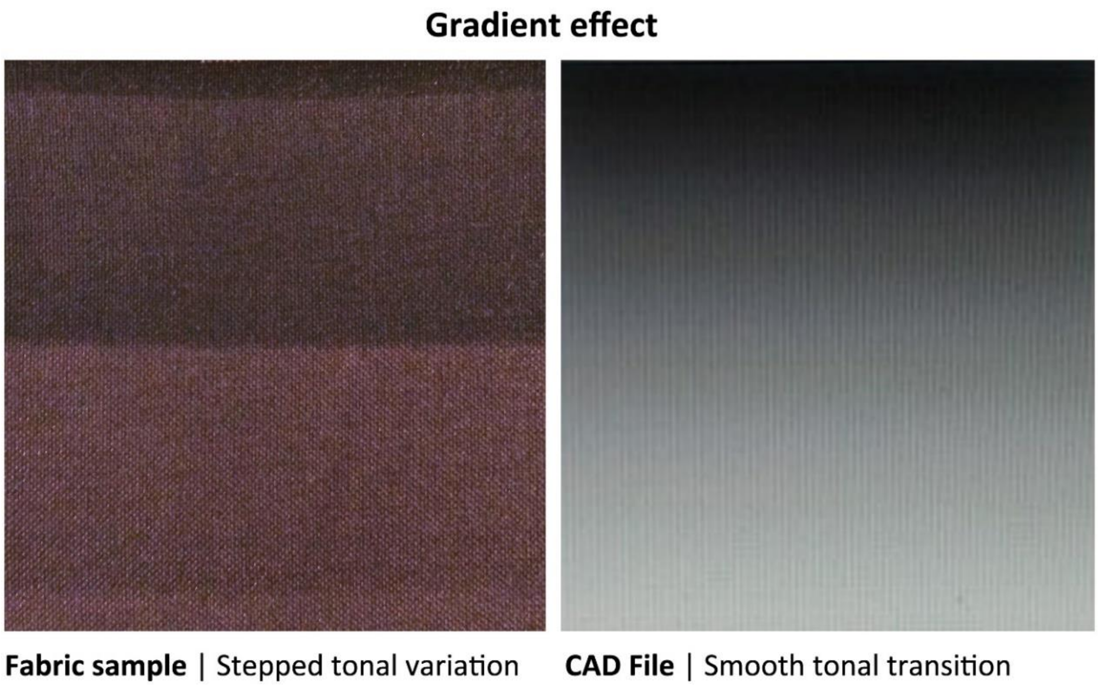


Figure 66: Fabric sample (left) processed with 'Greyscale' Colour reduction mode via WinMark Pro laser marking software showing misrepresentation of the true pattern alongside original file (right)

Due to the unknown anomalies of the results produced using a greyscale colour reduction mode, attributed to the laser software, a halftone colour reduction method, also an option/feature for processing substrates was adopted for further experimentation instead (Figure 67).

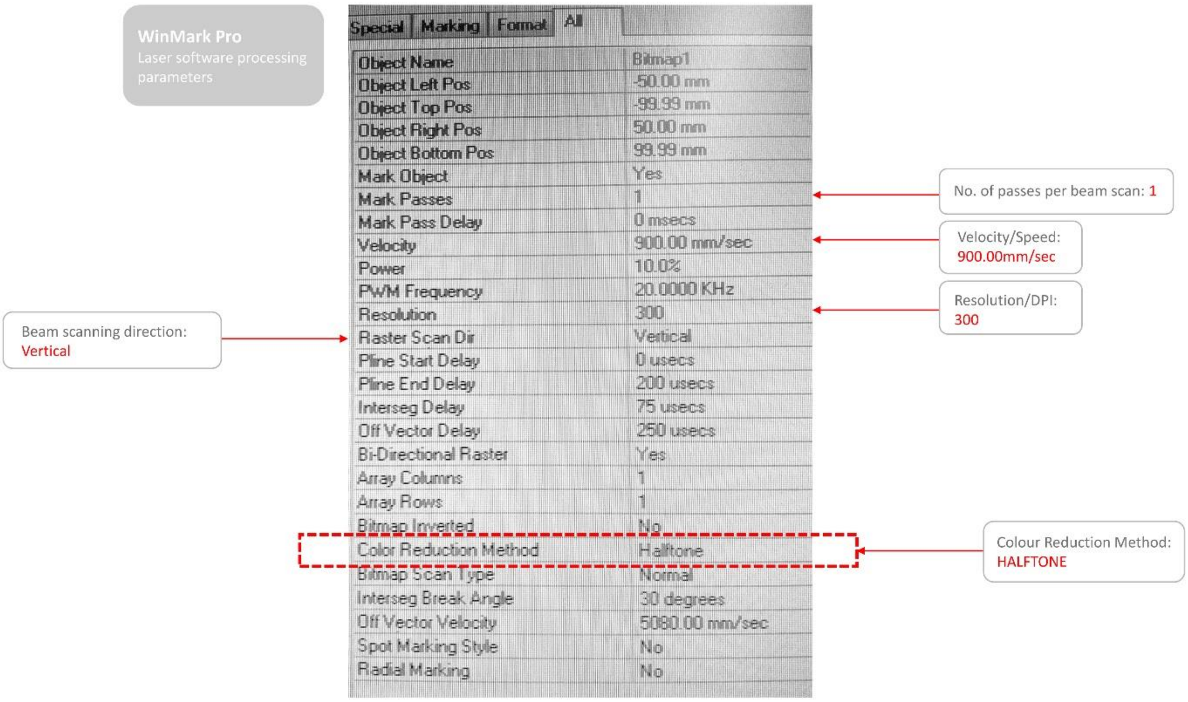


Figure 67: WinMark Pro laser software processing parameters showing: 'Halftone' colour reduction mode

Traditionally, halftone is an image-based approach typically used in printing production to separate an image into different colours in order to eventually build the final printed image usually made of four key colours (C – Cyan, M – Magenta, Y – Yellow and K – Black). In this research, the halftone colour reduction method converted CAD designs created with multiple greys (GS %) into multiple halftone grids consisting of areas of black and white pixels. Each grid differed depending on the percentage of black representing the section of a pattern. Therefore, each percentage generated a unique halftone grid (Figure 68).

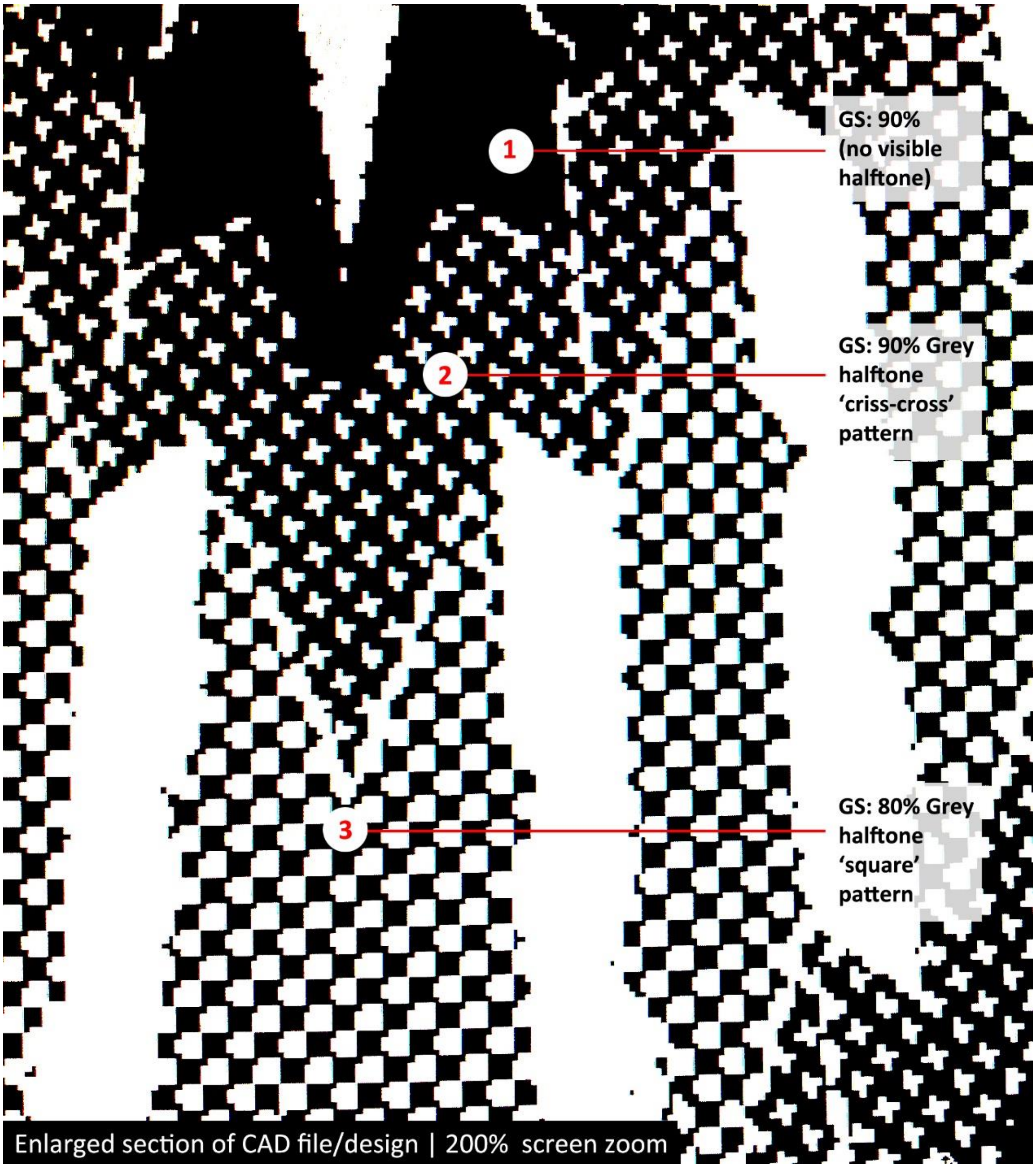


Figure 68: Halftone reduction CAD file - pixelated grids based on different GS% in a pattern/design

The black element of the grid represented the GS% value. For example, a 60% greyscale tone contained a 60% black and 40% white pixelated grid. This value also translated to 60% of a selected power value (1-100 %) applied via laser software for processing, also connected to actual power output in watts e.g. 60% of 4.5W of processing energy = 2.7W. Likewise, a 70% grey tone represented a unique halftone pixelated grid containing 70% black and 30% white and so on. Therefore, based on this colour reduction method attributed to the laser operating software (WinMark Pro), each design/pattern was laser processed with a combination of different energy densities distinguished in this way. This method influenced beam scanning action which produced variable tonal distribution on the fabric surface through the dyeing stage of the FLD process.

Employing a halftone method provided better understanding as to how energy density distribution may be understood using greyscale techniques. This practice for generating graphics on a textile surface combined both CAD and laser software features in a logical, transferrable manner. Such capability supports identification of a laser beam as a creative tool with industrial potential concerning textile design and coloration production processes. The ‘halftone’ method explored produced replicable results compared to the aforementioned unpredictability of a ‘greyscale’ colour reduction. Both options were available with the laser marker systems via WinMark Pro laser processing software.

5.2.1.3 Axis issues

In this study, beam scanning was explored in both vertical (y-axis) and horizontal (x-axis) directions using the raster method. This was made possible by the laser software in which the laser beam interacted with the fabric/work piece and therefore a direction for processing could be selected. Experimental study revealed that results differed on the modified fabric depending on vertical or horizontal scanning despite all other parameters remaining the same. Outcomes also showed that this effect was influenced by fabric structure (e.g. a woven fabric with vertical warp yarns and horizontal weft yarns) in relation to orientation of the fabric on the laser bed in terms of whether the vertical warp yarns were aligned with vertical beam scanning, for example, or otherwise.

Regarding the FLD method, horizontal beam scanning with woven polyester induced greater interaction (Figure 69) between the beam and fabric compared to a vertical action (Figure 70). The laser beam therefore moved from right-to-left in zig-zag motion, horizontally across vertical warp yarns parallel to weft yarns during rastering/filling a pattern. This action increased fibre damage. Comparatively, fibre damage was reduced with vertical scanning.

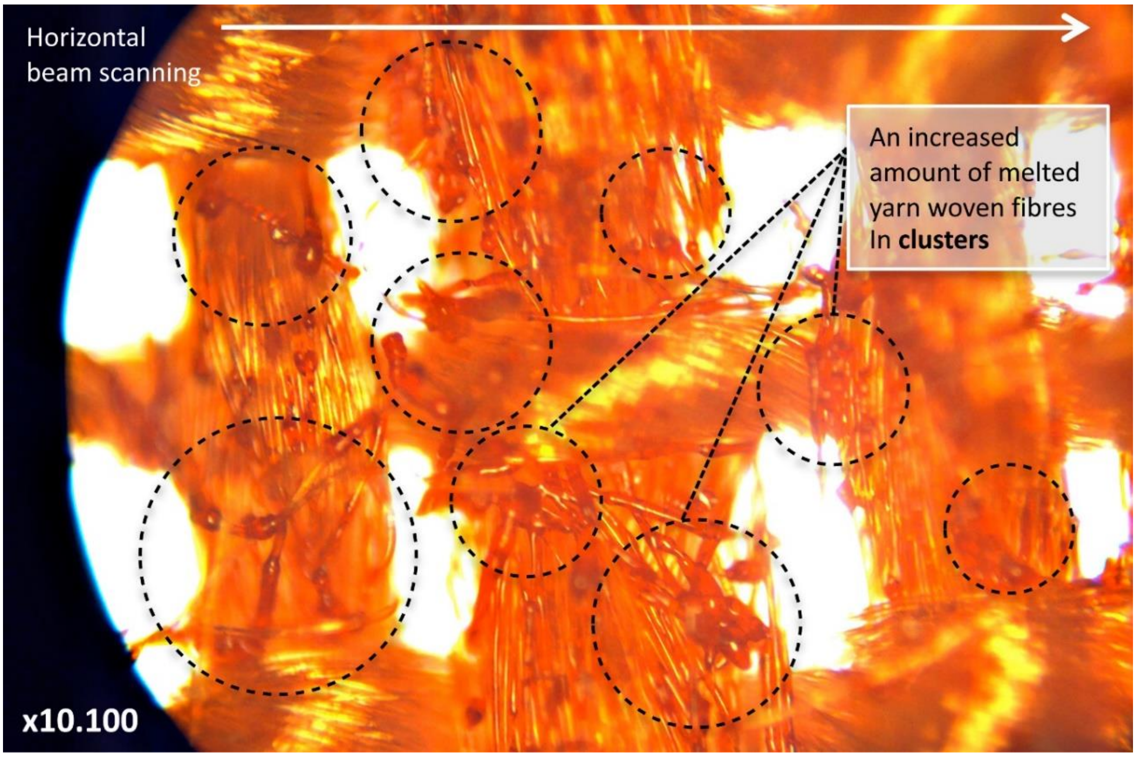


Figure 69: Horizontal beam scanning showing increased fibre damage with woven PET sample

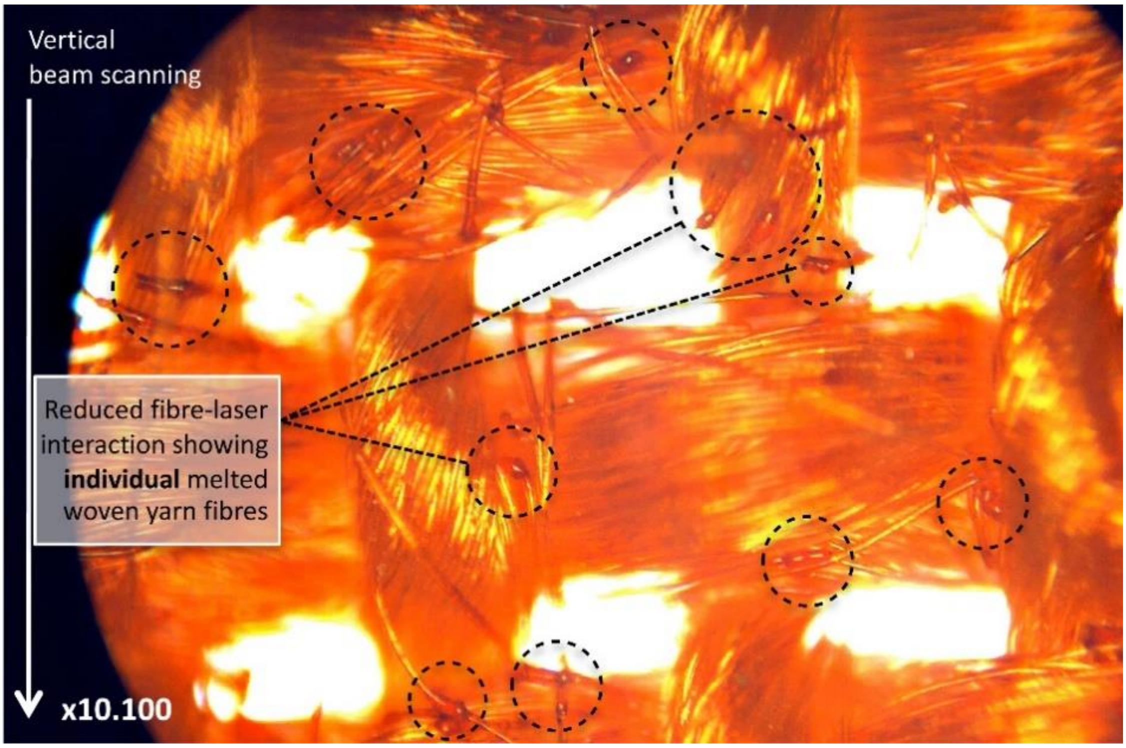


Figure 70: Vertical beam scanning showing reduced fibre damage with woven PET sample

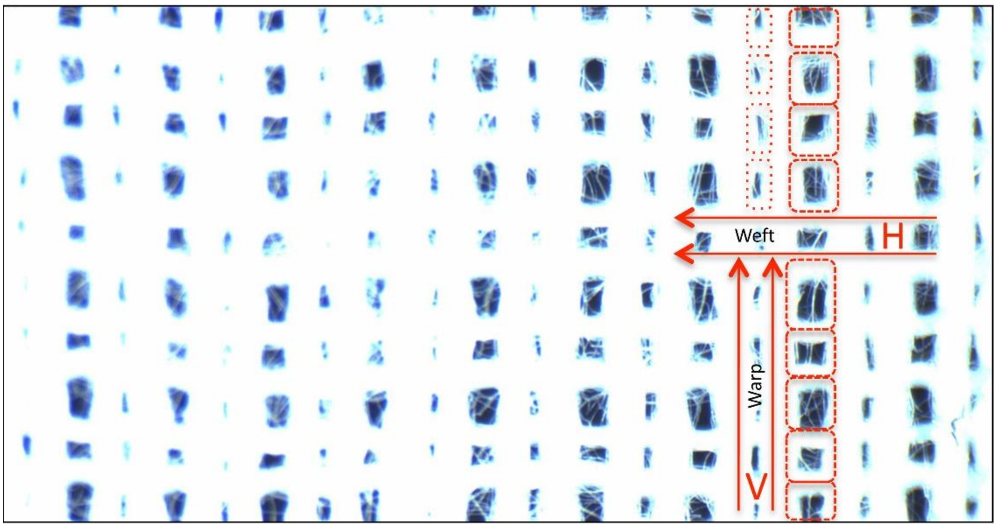


Figure 71: Woven PET fabric structure showing spacing of warp yarns and weft yarns (x5 mag.)

With vertical scanning, both the beam and warp fibres assumed the same direction during processing, along the y-axis. Microscopic analysis showed that within the interlacing woven structure (Figure 71) there were larger gaps between every two vertical warp yarns and every two horizontal weft yarns. This meant that during processing, the rate of interaction between fibre and the laser beam was less frequent at specific points due to the spacing. Where individual yarns were more closely spaced together, beam/fibre contact frequency increased encouraging fibre damage. Therefore, vertical beam scanning along a vertical warp was considered optimal enabling a subtler, controllable and more suitable approach for processing based on the yarn configuration parallel to beam scanning direction. In doing so, woven polyester textile fibres were not adversely degenerated and a more even surface colour/patterning was achieved.

In terms of design, the image quality of surface graphics altered dependent on more or less interaction between fibre and laser beam. The impact of this influenced the aesthetics of test samples, especially dye uptake variability on the textile surface. So, understanding the relationship between all axis' related issues in a way that both enhanced and stabilised results was significant to the combined fibre-laser-dye technique investigated.

Vertical scanning was also explored using knitted polyester jersey fabric, also known as a weft knit. This type of structure has vertical columns, called 'wales' revealed on the fabric face and horizontal rows on the back, called 'courses'. The beam scanned vertically, back-and-forth in a zig-zig motion along the vertical wales of the knitted textile structure during raster processing. So, both the orientation of the fabric and laser beam assumed the y-axis.

Investigating vertical scanning with a knitted polyester fabric in the same way as the woven polyester enabled exploration of the transferability potential of the laser-dye process for different fabric structures. Practical inquiry revealed that retaining this parameter as a constant for two fabric types formed of the same fibre was feasible in most cases. Exceptions concerned specific designs whereby surface depiction of an image was unsatisfactory in areas. This occurrence was relevant to both woven and knitted polyester fabrics. Therefore, this study also acknowledges that individual patterns can improve or lower the quality of modification/graphic representation specifically linked to design aspects such as scale, composition and the overall construction of graphics in relation to axis/beam scanning issues. In such instances, uneven laser modification to fibres became evident through irregular dye uptake leading to an 'interrupted' pattern (Figure 72) - an issue separate to an inertia effect previously discussed.

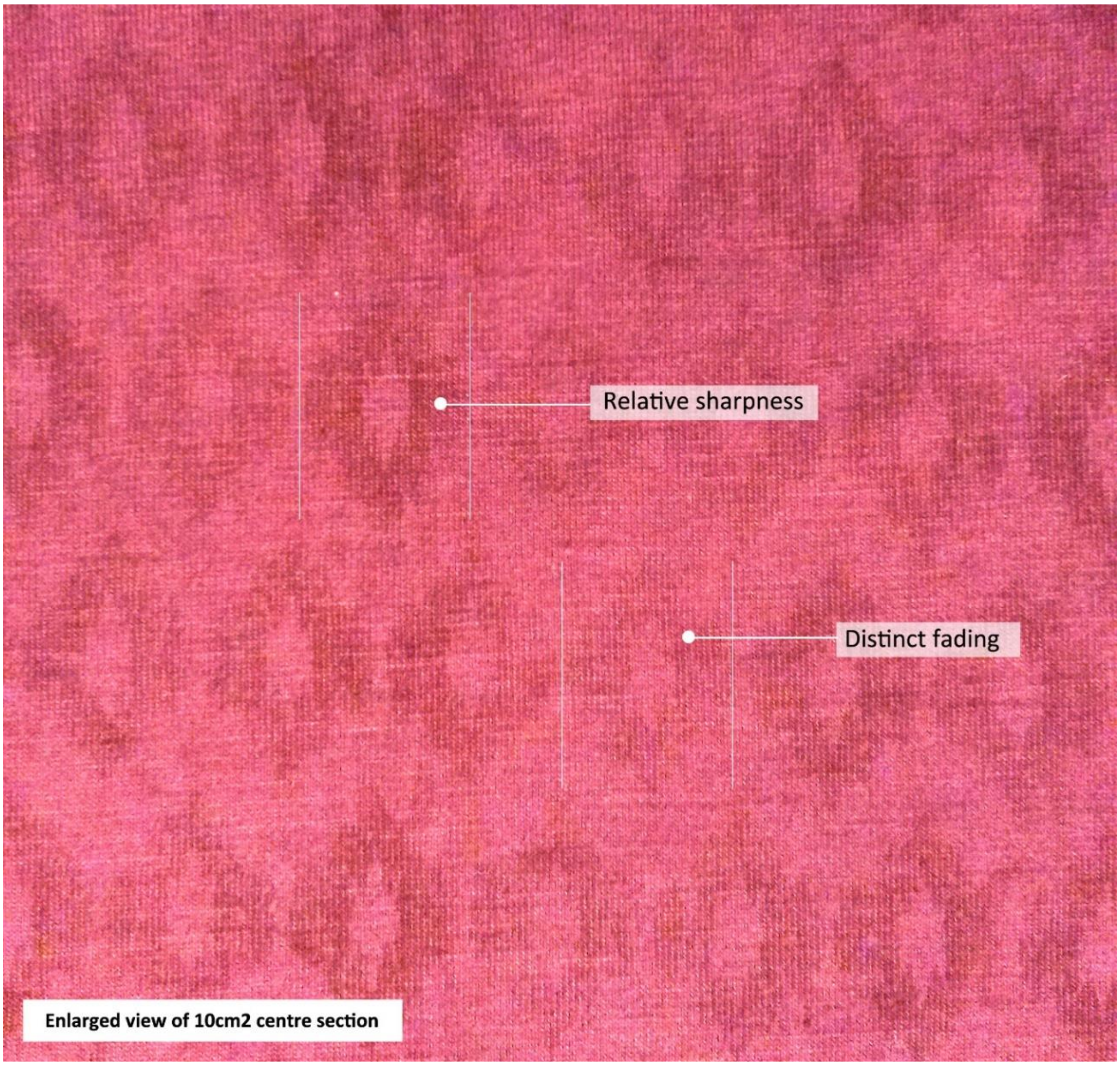
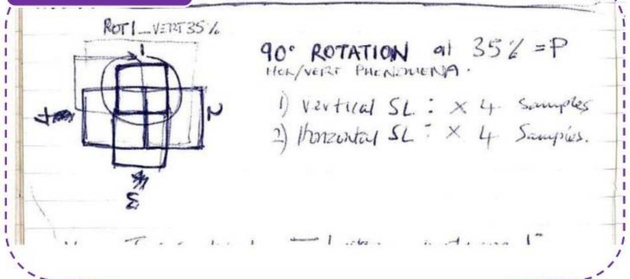


Figure 72: Vertically scanned pattern showing some interruption of image on the laser-dyed PET knit

It was therefore necessary to conduct further axis study with woven and knitted PET fabrics. Test samples were laser scanned using a specific pattern with the fabric orientation at a different angle/axis per experiment. As such, fabrics were rotated and processed vertically, horizontally and diagonally along warp and weft yarns, in relation to a specific pattern (Figure 73 and Figure 74). The purpose of this inquiry was to understand how certain axis combinations may alter image quality, essentially to improve the evenness of fibre modification and achieve the best possible result in terms of high graphic definition and tonality. The results demonstrate varied surface effects in terms of tonal distribution and pattern resolution. This proves that axis factors can affect visual qualities in relation to pattern type and/or textile structure and may be used as a method to control the digital laser-dye process in order to steer anticipated outcomes. As such, this approach supports the ‘on-demand’ characteristic of a laser-dye process both technically and creatively concerning textile design, coloration methods and surface effects.

Log book



Planning

Illustrative preparation and accompanying notes generated in advance of practical activity provided a useful step-by-step guide to follow during experimentation.

Above
Details some of the initial planning prior to carrying out structured axis experiments regarding the position of the fabric on the laser bed through 4 rotations at 90°.

Opposite
Further details some of the axis parameters regarding a specific pattern/design with woven PET. Parameter combinations consider the orientation of warp and weft yarns, the design, beam scanning direction and the position of the fabric on the laser bed.

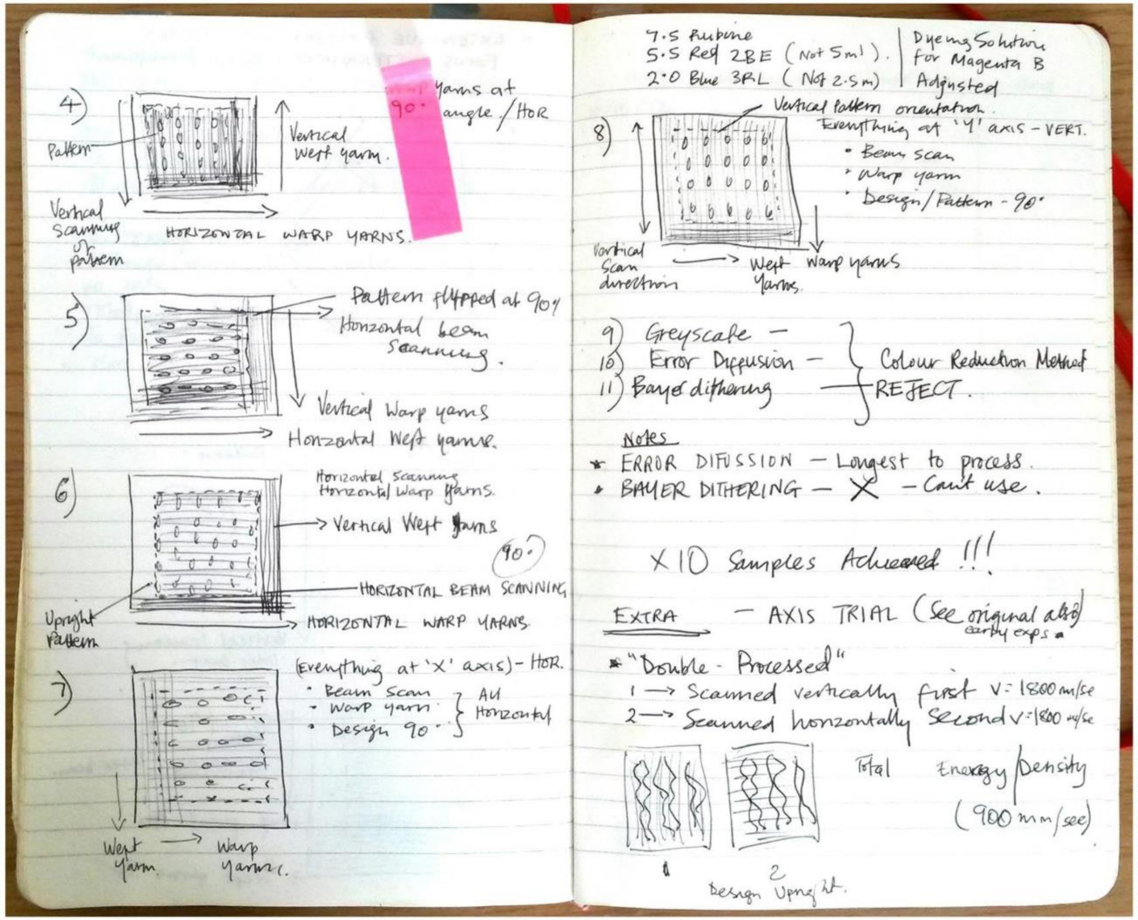
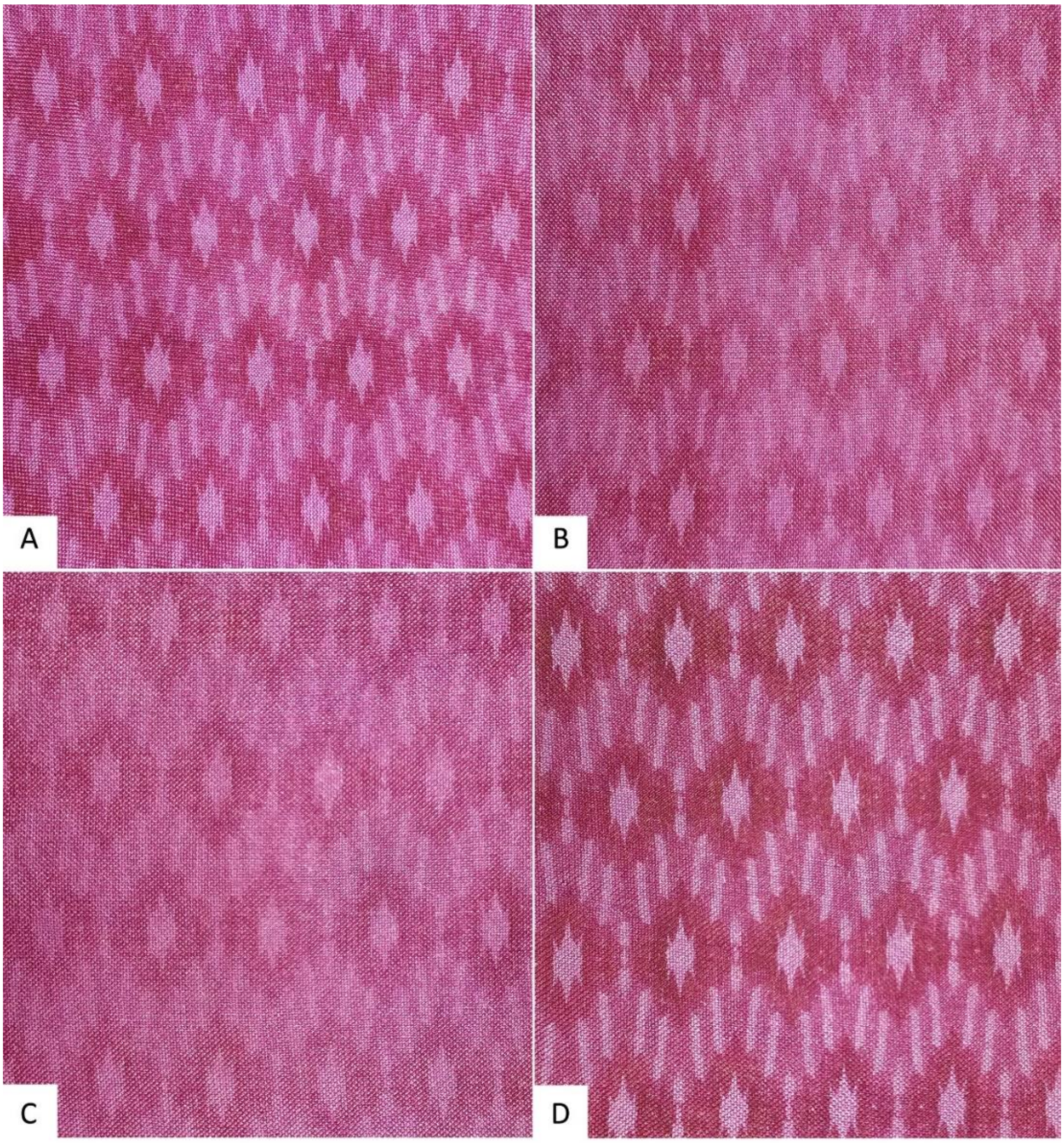


Figure 73: Log book: documenting plans for experimental activity regarding 'Axis Trials'



A Rotated left at a 45 degree angle | warp and weft yarns assumed a 45 degree angle | vertical scanning
B Rotated left at a 90 degree angle | horizontal warp yarns; vertical weft yarns | vertical scanning
C Rotated left at a 90 degree angle | vertical weft yarns; vertical weft yarns | pattern rotated 90 degrees left | horizontal scanning
D No rotation | vertival warp yarns | horizontal weft yarns | vertical scanning

Figure 74: Axis experiment (woven PET): one pattern scanned at different fabric axes with same energy density

The laser beam diameter i.e. spot size in relation to the diameter of an individual yarn uncovered additional axis factors to consider. The research identified a relationship between the two (Figure 75). On-going experimentation with both woven and knitted polyester fabrics revealed reoccurring ‘moiré’ patterns on the surface of laser-dyed textile samples. In physics, a moiré effect (as discussed by Bassett et al. 1958; Rong and Kuiper (1993) is created when two identical linear patterns – one set overlaying another, generate a new pattern as the sets of lines are rotated at varying degrees of each other (Figure 76). Visually, results appear similar to optical illusions, interference grids or lattice patterns.

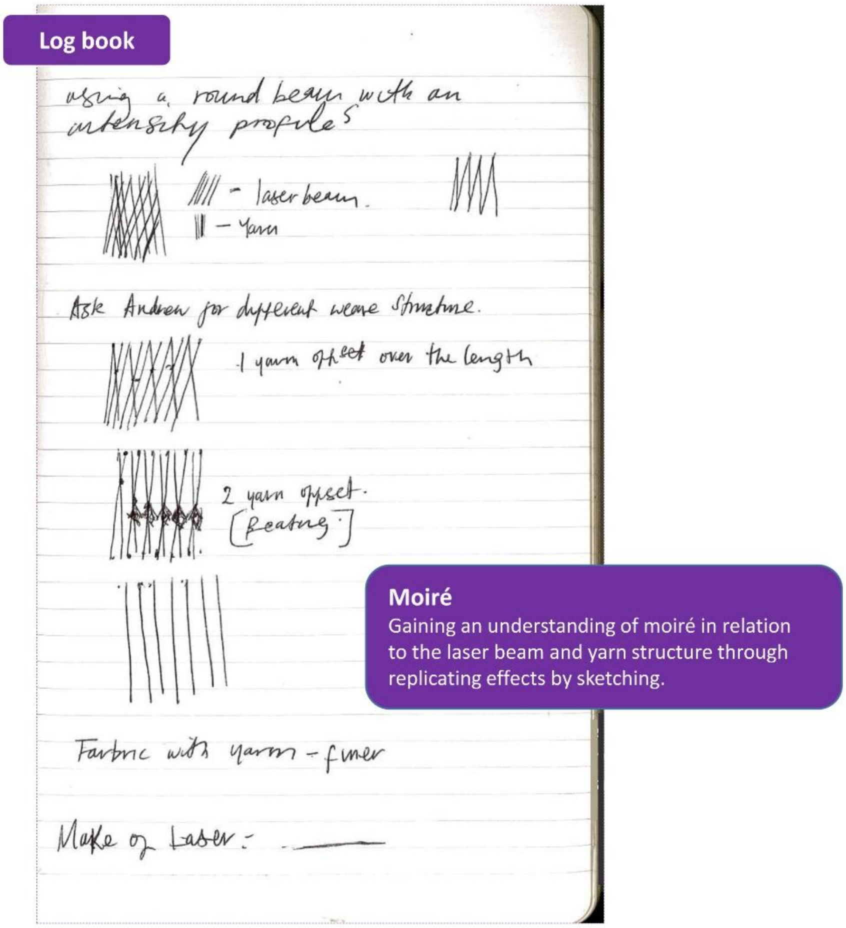


Figure 75: Logbook: understanding moiré effects through sketching

Figure 76: Moiré pattern caused by identical linear patterns overlaying at a slight angle (bowiestie.wordpress.com 2010)

In textile design, moiré is a traditional wavy ‘watered’ pattern Figure 77. It may be applied as a surface effect with print based techniques, formed in weaving by altering yarn tensions or by calendaring that involves folding and passing the fabric through rollers at high temperatures.

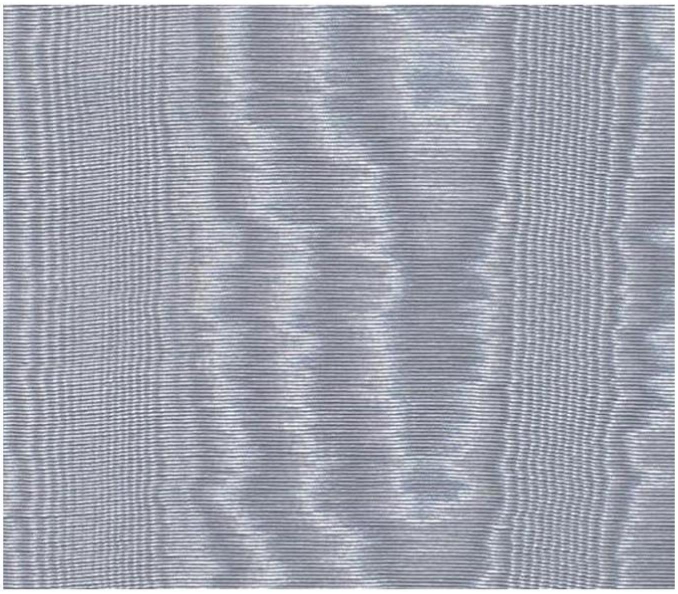


Figure 77: Watered silk textile design (nickyskye.blogspot.co.uk 2012)

In this study, axis misalignment between two near identical linear factors – laser beam scanning (i.e. vertically back and forth in a zig zag motion) and an individual woven yarn triggered this effect (Figure 78).

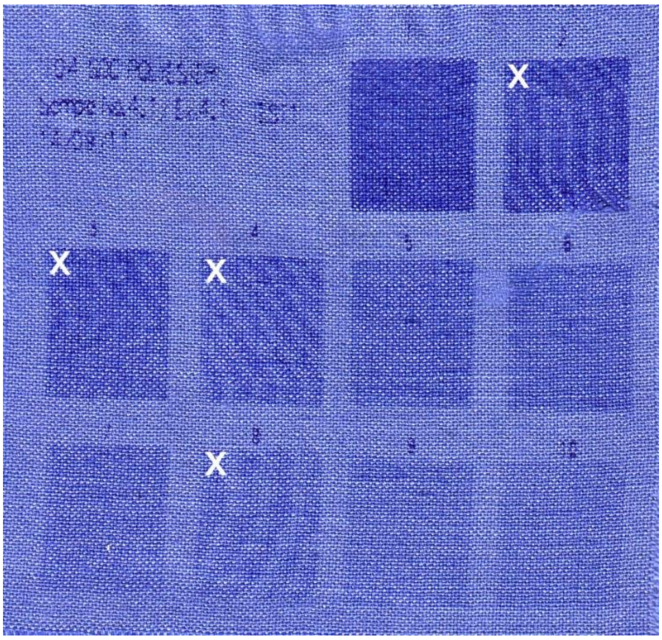


Figure 78: Examples of moiré surface effects generated in this research with woven PET

Each yarn was measured and compared. Results showed a minute difference in diameter size by approximately 21 microns (Figure 79). Size similarity confirmed that a slight axis misalignment between the two encouraged/facilitated emerging moiré patterns on the textile surface, illustrated in Figure 80.

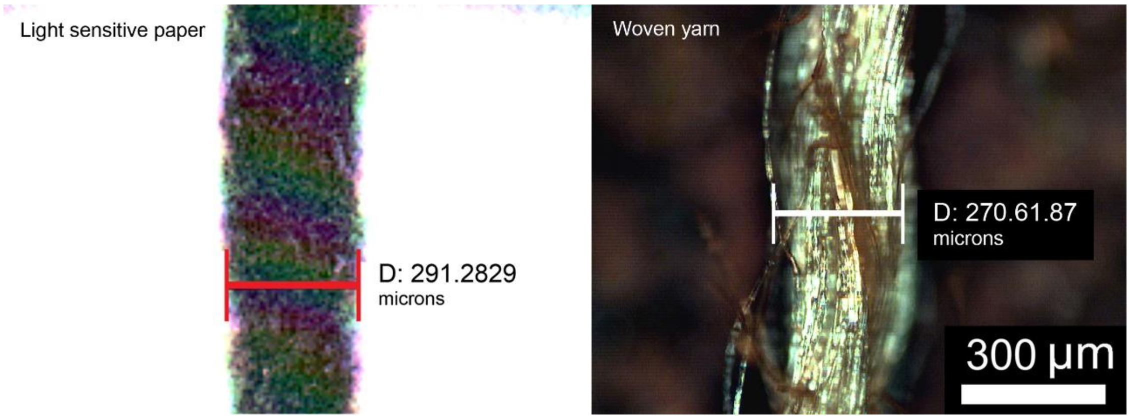


Figure 79: Laser beam scan with Synrad 60W Laser (left), Individual woven polyester yarn (right), x10.100 magnification

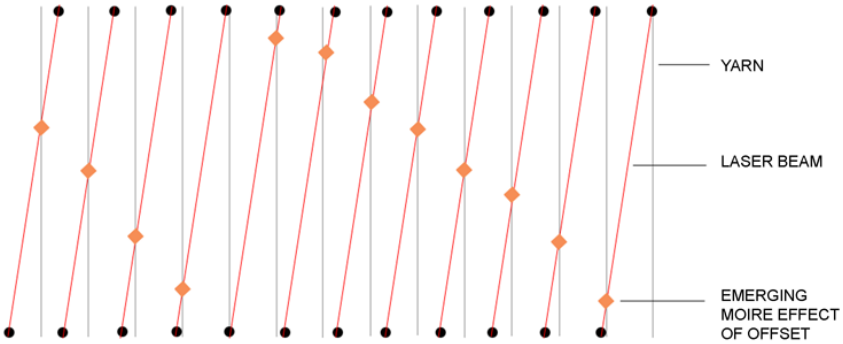


Figure 80: Diagram demonstrating emerging moiré effect

By defocusing the laser beam, spot size increased eliminating moiré patterns. Through manual adjustment, it was possible to alter beam diameter, essentially altering the focus (previously discussed in section 5.2.1.1 of this chapter). By raising the height of the nozzle (bed system) or lowering the laser bed (marker system), a greater distance was created between the beam delivery/output and the work piece/fabric. As such, this caused the beam to become less narrow but expand in diameter instead, enabling fibre-laser interaction with a larger surface area of an individual yarn through enlargement of the beam. Various heights for defocusing the laser beam were explored using the laser bed system therefore the colour reduction file conversion was not relevant here, as with the marker system. Level dye uptake was produced per parameter with a single grey tone rather than applying multiple greys (GS *%) (*Figure 81).

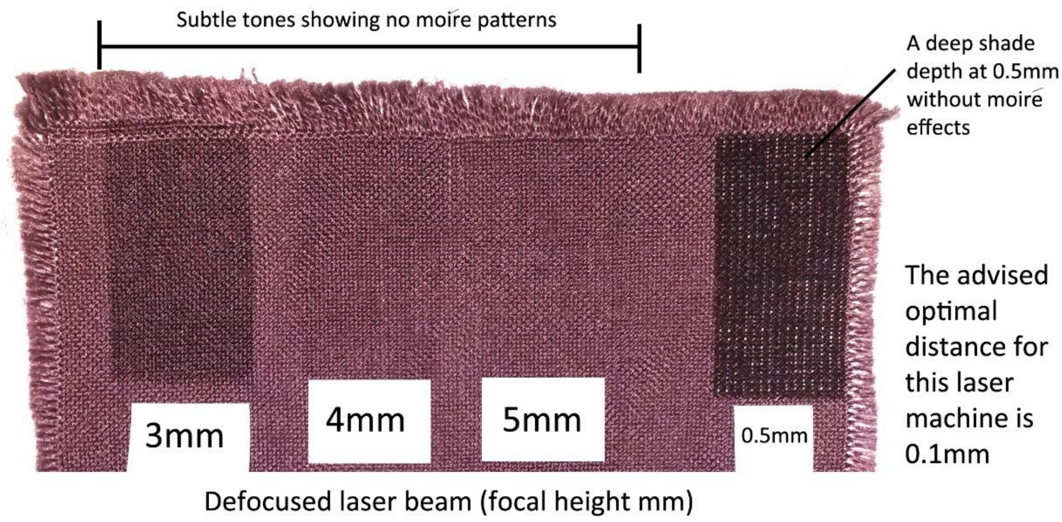


Figure 81: Defocusing the laser beam with woven PET to eliminate moiré effects (laser bed system)

Each laser-modified test area exhibited different tonal dye uptake. Difference in spot size in relation to nozzle height difference explains this variation instead of a greyscale (%) approach. The closer laser beam output was to the fabric surface, the narrower beam diameter leading to a greater, more intense energy density during processing. Therefore, increased interaction between beam and fibres was induced enabling deeper dyeing. The further away the beam output was from the fabric, the larger the spot size producing weaker dye uptake due to lower energy density. In the experiment shown in

Figure *81*, incremental height parameters were explored including 0.5mm, 3mm, 4mm and 5mm. This approach initiated gradual tonal variability. As such, this research explored an alternative method for achieving tonal variety with a single dye by defocusing the laser beam using a hands on approach to manually alter energy density. As such, this method may be pursued creatively to achieve varied shade depths with patterns similar to greyscale techniques. The technology can be considered as a tool that enables dye uptake flexibility with graphics. This approach may also be employed as a practice that allows the manual control of fibre damage by minimalising laser irradiation. The method that can be repeated or adjusted for optimisation in relation to specific materials. For some substrates, such an approach may be more advantageous in terms of controllability in processing, instead of the more automated method with predetermined 'grey' parameters embedded into the digital file.

Moiré patterns developed in a similar way with the knitted polyester fabric (Figure 82) using both laser bed and marker systems, applying vertical beam scanning.

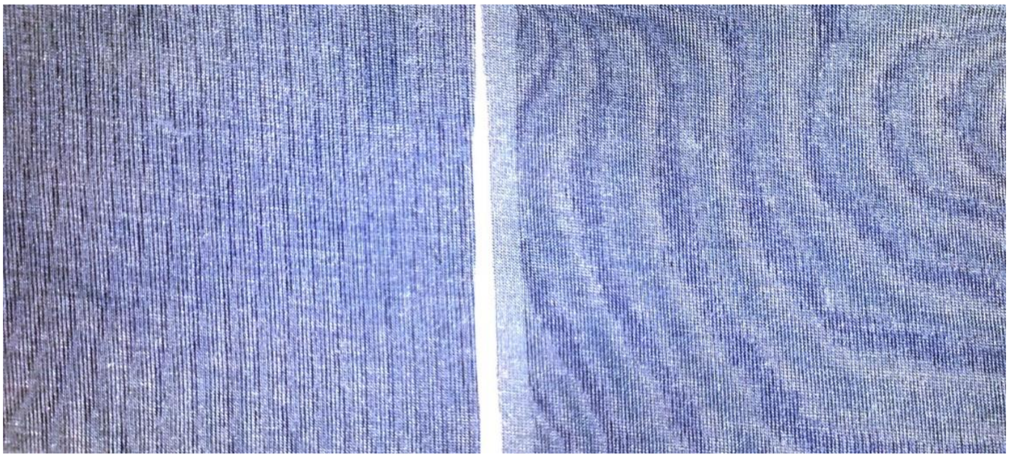


Figure 82: Moiré pattern on knitted PET textile surface

Results were influenced by yarn size (Figure 83), which was smaller/narrower than an individual woven yarn as well as the optimal laser diameter of 0.3mm; and the interlooping textile structure, in relation the axis issues during processing. In an attempt to process the whole surface of a knitted PET sample with an all over flat tone (no pattern), moiré patterns emerged instead. These results suggested that the multiple axis parameters (beam scanning direction; textile structure; yarn size; and orientation/alignment of the fabric positioned for processing), triggered moiré effects. It is understood that a focal beam spot size (0.3mm) scanned across multiple 'wavy' yarns in which each yarn measured a shorter diameter than the beam. The crossing over of the beam and yarns encouraged moiré effects. As with the woven PET, by defocusing the beam to increase beam diameter, moiré pattern were eliminated or minimalised. This was achieved by using the marker system (10W Synrad Laser) by manually lowering the bed/work piece.

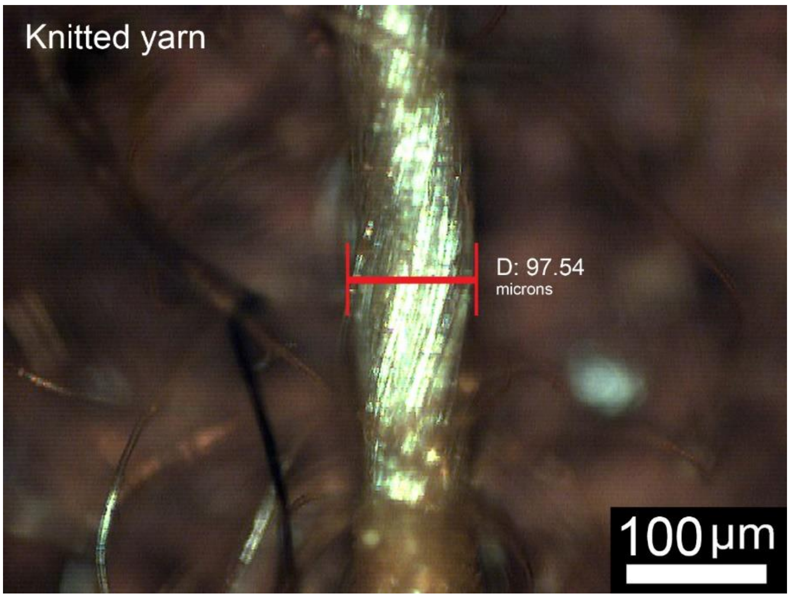


Figure 83: Micrograph of individual yarn taken from knitted PET fabric (x10.100 magnification)

The goal to remove the reoccurring moiré effect was based on trying to achieve flat/level/even all over flat dye shades with the FLD process rather than a pattern only approach. In terms of textile coloration, the ability to alter the shade depth of a fabric, in relation to specific laser-dye parameters supports the 'on-demand' considerations of the laser-dye process applicable to industrial textile production and commercial aspects such dyed-to-order stock fabrics, for example. Additional parameters such as variable power and velocity combinations were also explored to dissuade moiré patterns. In doing so, optimal processing parameters were identified for both woven and knitted polyester. In terms of design development, it is however noted in this research that the link between moiré patterns traditionally used in textile design and the ability to reproduce moiré patterns through the fibre-laser-dye process identifies a potential design feature for further exploration. The aesthetic qualities of experimental results suggest this. As such, the patterning potential of the laser-dye process was enhanced and creativity combined traditional textile design elements and advanced textile methods. This type of investigation regarding design development of laser-dye processing for textiles is not evident in existing studies (Addrison 2009 and Bartlett 2006).

Further experimentation with a vector rather than raster beam scanning (filling) approach was carried out to investigate whether it was possible to achieve even/level tonal colour without specified graphic patterns or moiré effects, discussed in the next section (5.2.2.2). In doing so, a viable method for producing flat variable shade depths on the fabric surface via the FLD method has been identified in this study.

In this section laser beam scanning and patterning has been discussed, in relation to beam characteristics; laser software/file conversion and axis issues. Based on the results presented, it was found that in order to achieve high quality surface modification with graphics and consistent tonal uptake, controllability and an understanding of parameters relating to these key issues was essential to effective FLD processing for the PET textiles explored. Using a raster approach, establishing the optimum field of focus for modifying a specific area (cm^2) with pattern(s) was necessary to achieve sharpness of image; Laser software influenced the conversion of patterns from CAD files to digital patterns suitable for modifying surface fibres with high resolution graphics. Procedures for doing so were heavily determined by the laser software. By exploring a range of experimental parameters associated with 'colour reduction' methods (from grey-to-halftone), a better understanding of energy density distribution when laser processing greyscale patterns was gained; Axis issues presented a range of further processing parameters related to laser beam scanning and patterning. For example, scanning in different directions (vertical and horizontal) produced varying levels of fibre-laser interaction, influencing dye uptake and pattern/surface quality of laser-dyed fabrics. Some patterns were more favourable to a particular scanning direction for optimum results. Similarly, some designs preferred the fabric to be rotated/placed at an angle on the bed to assume diagonal scanning across warp and weft yarns. Laser beam spot size in relation to yarn diameter influenced the appearance of dye uptake triggering a moiré patterning effect. However, by defocusing the beam, such patterns were controllably eliminated or reduced. From a creative perspective, the ability to repeat/specify moiré patterns was also considered beneficial in this research regarding the design development and aesthetic aspects of the work.

Overall, this inquiry has identified significant processing issues for the PET fabrics explored regarding the FLD process.

5.2.2 Engineered colour and pattern: textile design issues and coloration development

This section documents and discusses how colour and pattern was engineered onto the PET woven and knitted fabrics employed in this study via the FLD process and in relation to textile design issues and coloration development considered in this work. The results of experimental investigation are presented and discussed across two key issues relating to textile structure and energy density:

- Considering textile structure: on demand laser processing parameters
- Energy density versus tonal density

In doing so, this discussion identifies the processing parameters, experimental methods and techniques studied. These include parameter adjustments in relation to a specific textile structure (woven or knitted) such as variable velocities and the employment of a vector beam scanning approach (as discussed in Chapter 4, section 4.1.2.1), rather than the previously discussed raster method (section 5.2.1).

5.2.2.1 Considering textile structure: on demand laser processing parameters

In order to achieve high quality patterns through level dye uptake with both woven and knitted polyester, it was necessary to tailor procedures to suit each textile type. Woven and knitted PET fabric samples processed with the same laser/dye parameters were compared in terms of visual appearance. Structural differences between the knit and weave produced varying results on the fabric surface. Inherent bulk properties of the knitted polyester meant a greater or denser fabric mass compared the lighter plain, woven fabric. Laser-dyed samples were observed from a combined technical and design perspective. Aspects included sharpness of pattern, consistent dye uptake and even tonal distribution. Results revealed that an increase in energy density was required to sufficiently laser modify the knitted polyester compared to the woven polyester. This was achieved at slower velocities. Slower processing facilitated greater interaction between the knitted textile and laser beam. Such approach compensated for existing bulk characteristics of the knitted polyester.

Differences in fabric structure initiated an on demand approach. Although parameters were marginally different between the two fabric constructions, the impact of on demand processing was significant to the quality of results regarding pattern/colour definition i.e. resolution/sharpness and tonal variation, linked to technical capability and aesthetics.

Additional parameter adjustments were pursued for specific patterns by carrying out further ‘Extended Design Experiments’ (Figure 84).

Figure 84: Extended design experiments

Such experiments combined variable greyscale percentages with variable velocity parameters to ensure optimum results in terms of well-defined tonal patterning. The process for making such decisions was intuitive based on a firm knowledge of the laser-dye process and a sufficient understanding of how to alter (reduce or increase) energy density. Aesthetically, designs were enhanced by the distinct tonal distribution of a dye determined by textile design input – the creation of patterns and design effects such gradient colour. It was therefore important to carefully monitor patterning per experiment/pattern/design/sample and adjust parameters where necessary. In doing so, adjustable characteristics of the laser-dye process were further realised and appropriately managed for design development.

In the dyeing stages, identical procedures were carried out for both fabrics (knitted and woven polyester) appropriate to the weight of samples. It was not necessary to make any further adjustments in relation to differences in fabric structure.

5.2.2.2 Energy density versus tonal density

Vector scanning was adopted in addition to the raster method explored. In doing so, a controllable system to laser mark fabrics for dyeing was undertaken in this research. Repeated horizontal vector lines were created in *Adobe Illustrator* CAD software to form linear grid-like patterns or blocks as illustrated in Figure 85. Specifying the accurate and consistent distance between each line formed individual grids. This approach for laser processing textiles was better suited to laser beam scanning compared to a raster fill approach using a greyscale (GS%) method via *Adobe Photoshop* CAD software.

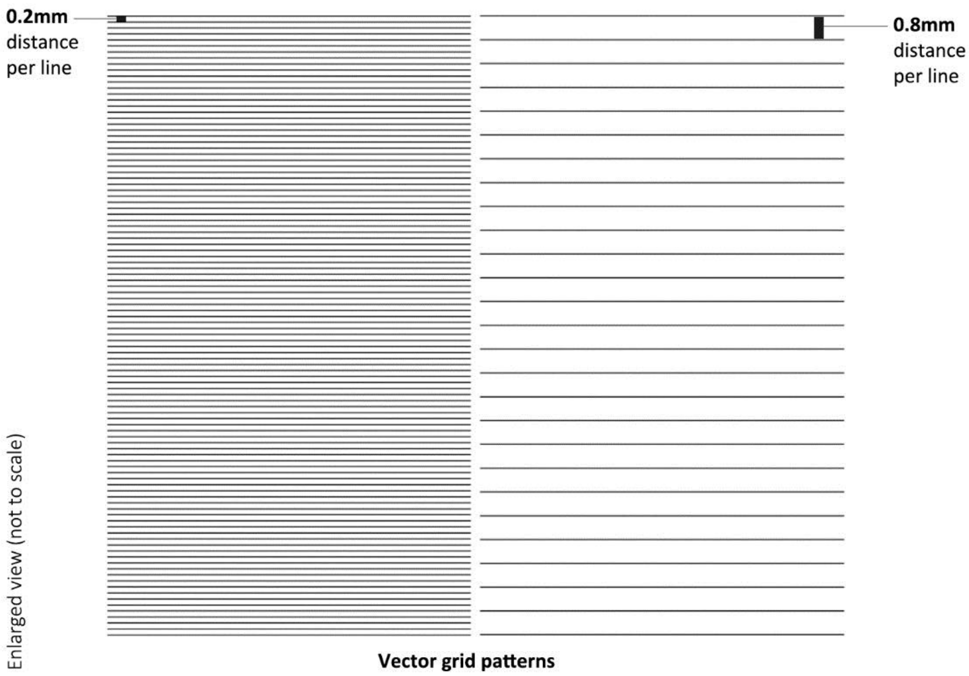


Figure 85: Vector generated linear grid patterns

The vector method explored, enabled consistent beam scanning in relation to a specified grid pattern. Creating sets of linear vector grids provided a path or a type of ‘blueprint’ for the beam to follow different to relative beam scanning automation associated with raster methods. Vector lines were prepared using CAD software appropriate for vector-based artwork and compatible with the laser software. Three methods for doing so were explored – a ‘wobble’ function of the laser software, *AlphaCAD* software and with *Adobe Illustrator* graphic design software. This approach facilitated the diameter of the laser beam or ‘spot size’ (as described in Chapter 4, section 4.1.2.1; Table 8). Therefore, beam overlap was investigated in a controlled manner to determine even dye uptake on the textile surface. Similarly, elimination of visible beam overlap was also achieved. Energy density (as defined in section 5.1.1 of this chapter and in Equation 1), was influenced by the orientation of repeating vector lines in a grid. Distances shorter than the beam width activated overlap causing greater fibre/laser interaction and deeper dyeing. Longer distances (larger gaps) discouraged this effect, reducing laser processing energy, resulting in weaker dye uptake and subtler surface effects. Experimentation with incremental parameter differences produced a relatively large tonal range, more so than with raster greyscale methods. This indicates that the method showed a greater affinity to the laser-dye process than the raster scanning approach.

Where optimal beam spot size and vector line spacing distance measured the same (0.3mm), an optimum tonal density was identified and understood (Figure 86).

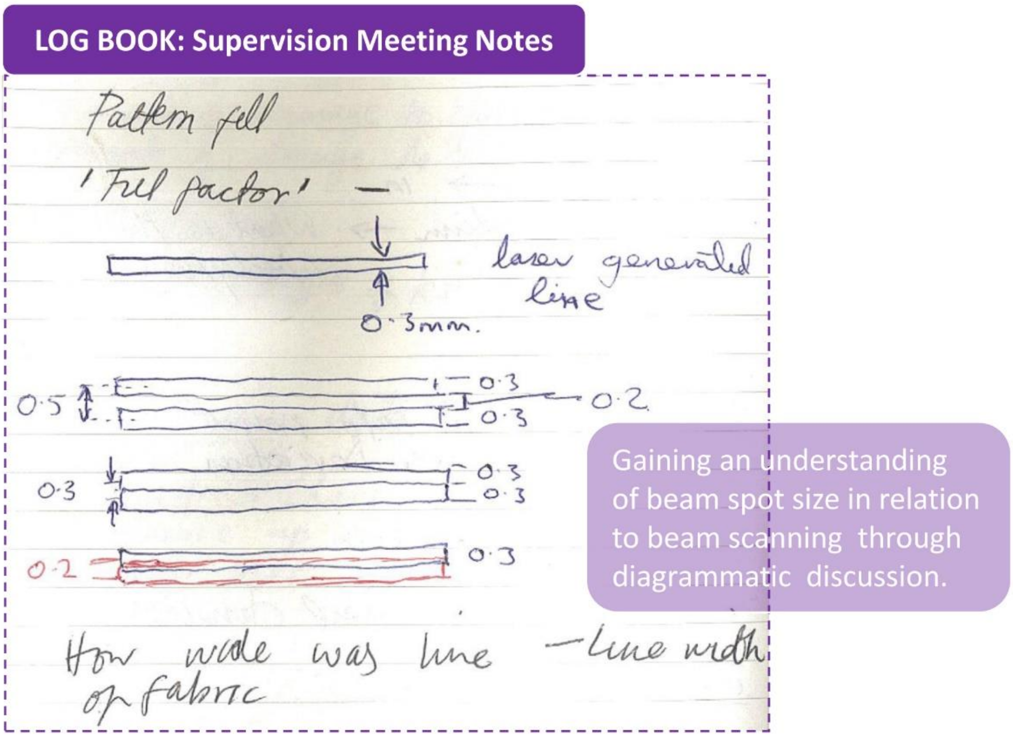


Figure 86: Log book notes - beam spot size versus vector line spacing

In this study, tonal density is defined as the shade depth of a dye. This parameter combination did not allow for either a gap or overlap between each beam scan. The result was considered the truest depth of shade in relation to a dye and the most appropriate energy density for level dyeing via the laser-dye technique in question. Systematic fabric colour charts were generated with both knitted and polyester showing a controllable and repeatable tonal range capable with a single dye shade such as Figure 87, for example. A chart of 25 tones was created by slight differences in line spacing per vector grid ($9cm^2$), starting at 0.2mm (1) and increasing by 0.01mm per grid to 0.44mm (25). This determined energy density variability during laser scanning whilst all other parameters remained constant such as velocity and power output.

An identical experiment on paper revealed each vector pattern. Figure 88 shows grids 0.21mm, 0.3mm and 0.44mm), comparable to the laser treated fabric (Figure 87).

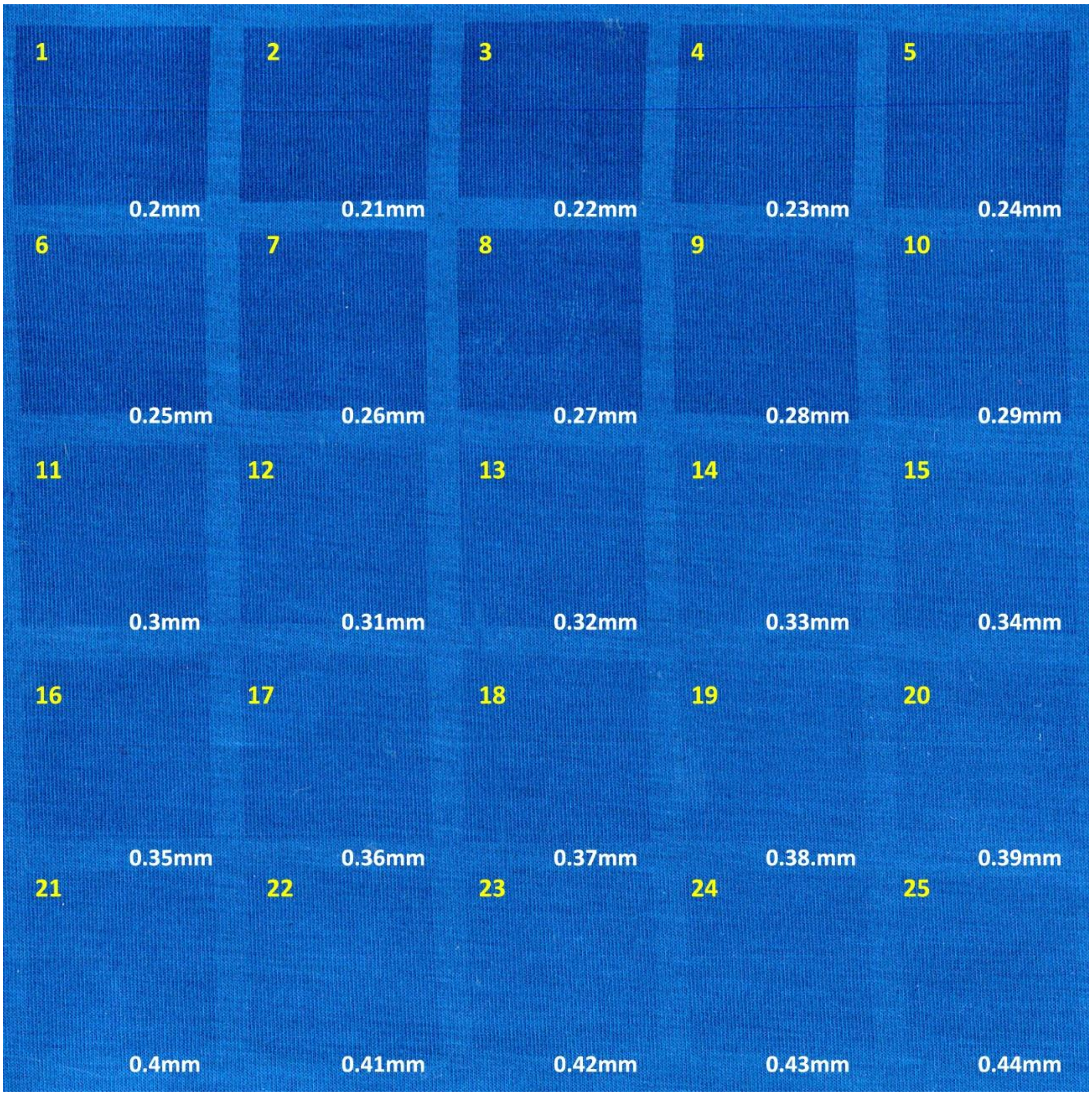


Figure 87: Laser-dyed tonal colour chart: knitted polyester fabric sample

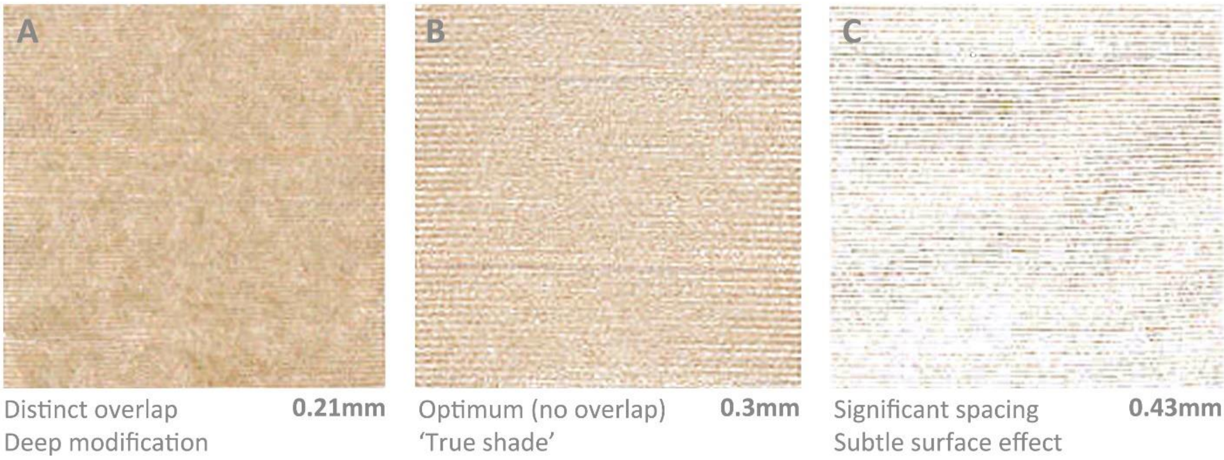


Figure 88: Laser marked vector grids on paper

A line spacing distance of 0.3mm (11/B) was the same as the optimum focal diameter of the laser beam for modifying the fabric. With both at 0.3mm, an overlap was avoided and so identified as the optimum depth of shade regarding dye uptake. Instead, energy output was most evenly distributed across the textile surface (Figure 89) unlike grids 0.21mm and 0.43mm, for example. At 0.21mm, a distance less than 0.3mm, induced greater interaction between fibre and laser beam encouraging deeper dyeing due to beam overlap. Significant spacing with a 0.43mm grid reduced interaction as the laser beam scanned the fabric less times as a result of larger gaps between individual vector lines. Therefore, overall energy density was reduced producing subtler surface effects due to less fibre modification and dye uptake.

Figure 89: Diagram showing the position of a 0.3mm laser line vector grid

Outcomes of the vector approach demonstrate the dexterity of the laser-dye process as a coloration and patterning tool for textiles. Figure 90 is a visual synopsis of the tonal colour chart in Figure 87 that represents the tonal range achieved.

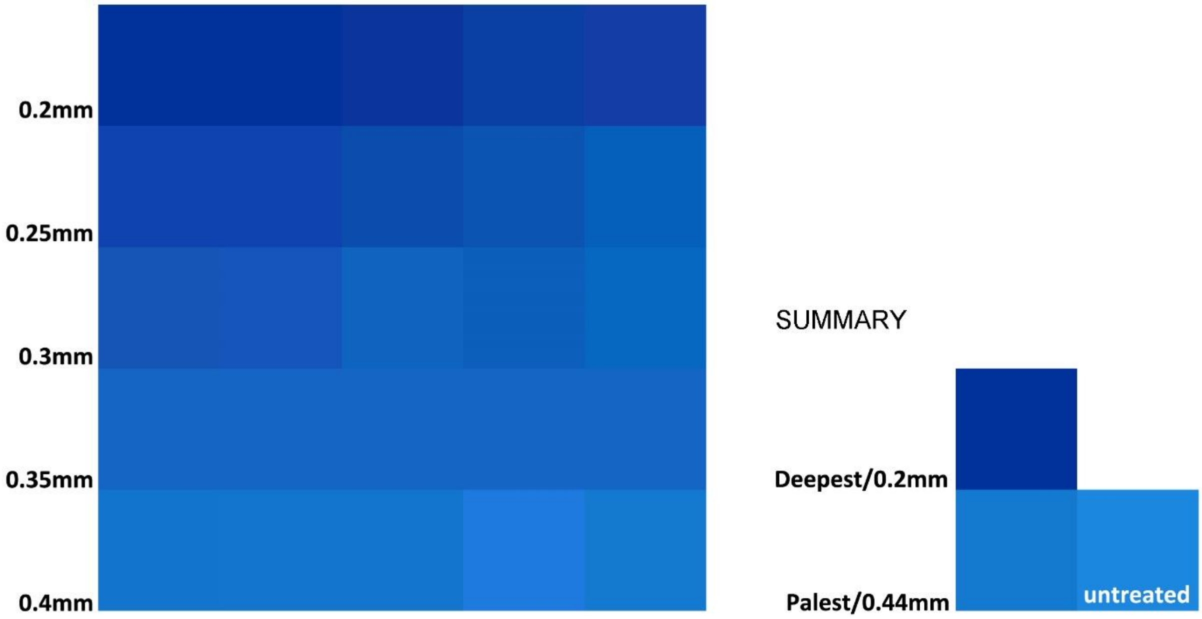


Figure 90: Visual synopsis of the tonal colour chart fabric sample (See Figure 87)

Generally, there was a correlation between line space distance and colour intensity. When looking downward along the chart at vector grids 1 (0.2mm), 6 (0.25mm), 11 (0.3mm), 16 (0.35mm) and 21 (0.4mm), tonal density decreases. This is understandable based on the arrangement of each linear pattern as discussed previously. Therefore, a method for plotting energy density against tonal density has been identified in this research. Table 14 shows the calibration values attributed to the fabric sample (Figure 87) in relation to the laser processing parameters explored based on 4.5W of beam power. Vector line space (mm), Total energy (J) and Energy density (J/cm^2) are given in relation to each 9cm^2 laser-dyed area of fabric (1-25 tones). Once calculated, the differences in energy density were small although the visual effects on fabric were distinguishable between different parameters. Therefore, the energy density column shown in Table 14 demonstrates that multiple grids yielded the same J/cm^2 numerical value.

Grid	**Vector line space** (mm)	**Total energy** (J)	**Energy density** (J/cm^2)
1	0.2	1.8	0.2
2	0.21	1.8	0.2
3	0.22	1.4	0.16 (0.2)
4	0.23	1.4	0.16 (0.2)
5	0.24	1.4	0.15 (0.2)
6	0.25	0.9	0.1
7	0.26	0.9	0.1
8	0.27	0.9	0.1
9	0.28	0.9	0.1
10	0.29	0.9	0.1
11	**0.3**	**0.9**	**0.1**
12	0.31	0.9	0.1
13	0.32	0.5	0.06 (0.1)
14	0.33	0.5	0.06 (0.1)
15	0.34	0.5	0.06 (0.1)
16	0.35	0.5	0.06 (0.1)
17	0.36	0.5	0.06 (0.1)
18	0.37	0.5	0.06 (0.1)
19	0.38	0.5	0.06 (0.1)
20	0.39	0.5	0.06 (0.1)
21	0.4	0.5	0.06 (0.1)
22	0.41	0.5	0.06 (0.1)
23	0.42	0.5	0.06 (0.1)
24	0.43	0.5	0.06 (0.1)
25	0/44	0.5	0.06 (0.1)

Table 14: Calibration values

Energy density values show an overall decline from grid 1-25 as expected. The rate of change reflected marginal line space parameters. Although 25 vector line distances (mm) were explored, a slight difference per grid induced little variable energy across the fabric sample of mainly 0.2 and 0.1 J/cm^2. Grid ‘11’ indicates the optimum parameter combination in relation to laser beam diameter. It is therefore acknowledged that tonal variance achieved was largely dependent on vector line spacing due to subtle differences in laser power between grids patterns. However, the greatest difference in energy density was recorded between 0.2 J/cm^2 (1) and 0.06 J/cm^2 (25), which can be understood. Data was configured both visually and numerically to show the relationship between a specific vector grid, tonal density and energy density, demonstrated by Figure 91 and Figure 92.

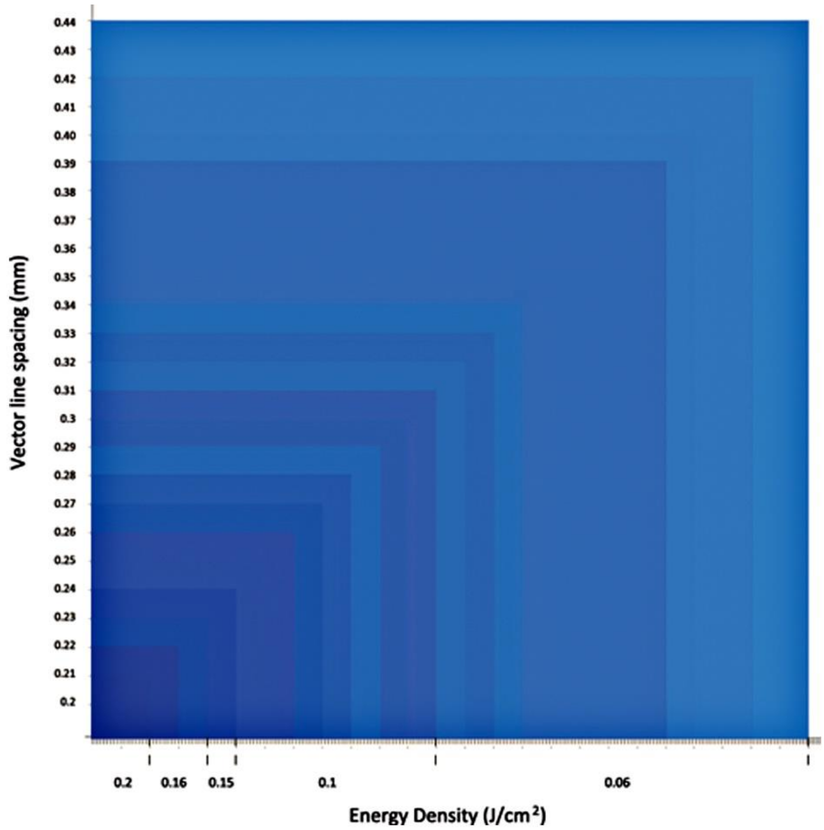


Figure 91: Colour configured data: Energy density/Vector line spacing parameters

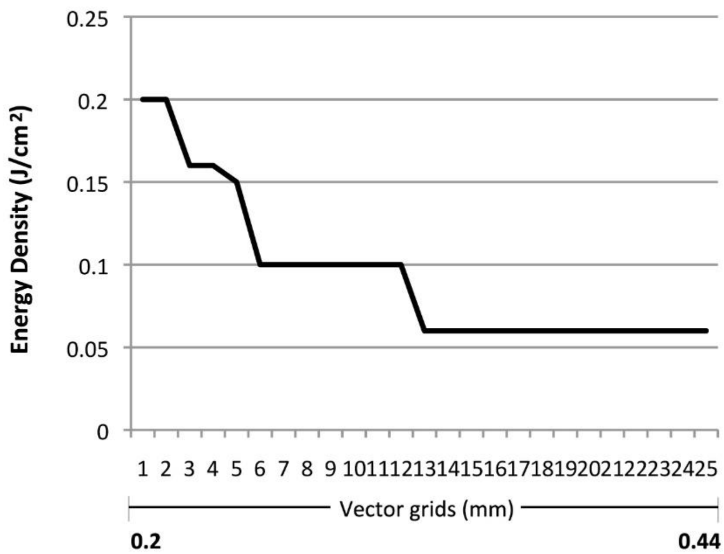


Figure 92: Diagram showing an energy density decline as line spacing increases per vector grid

Visual, physical and digital colour information (i.e. tonally laser-dyed fabrics samples/charts, computer aided design and numerical parameters, colour diagrams and data tables, also recorded in logbooks (Figure 93)) related to specific vector grids, linked to specific laser energy densities, in order to produce specific tones/depths of shade generated in this research, may be considered a type of 'know-how guide' for laser processing textiles in this way relevant to different dyes, shades and materials. Hence the significance of the fabric colour chart demonstrated in Figure 87.

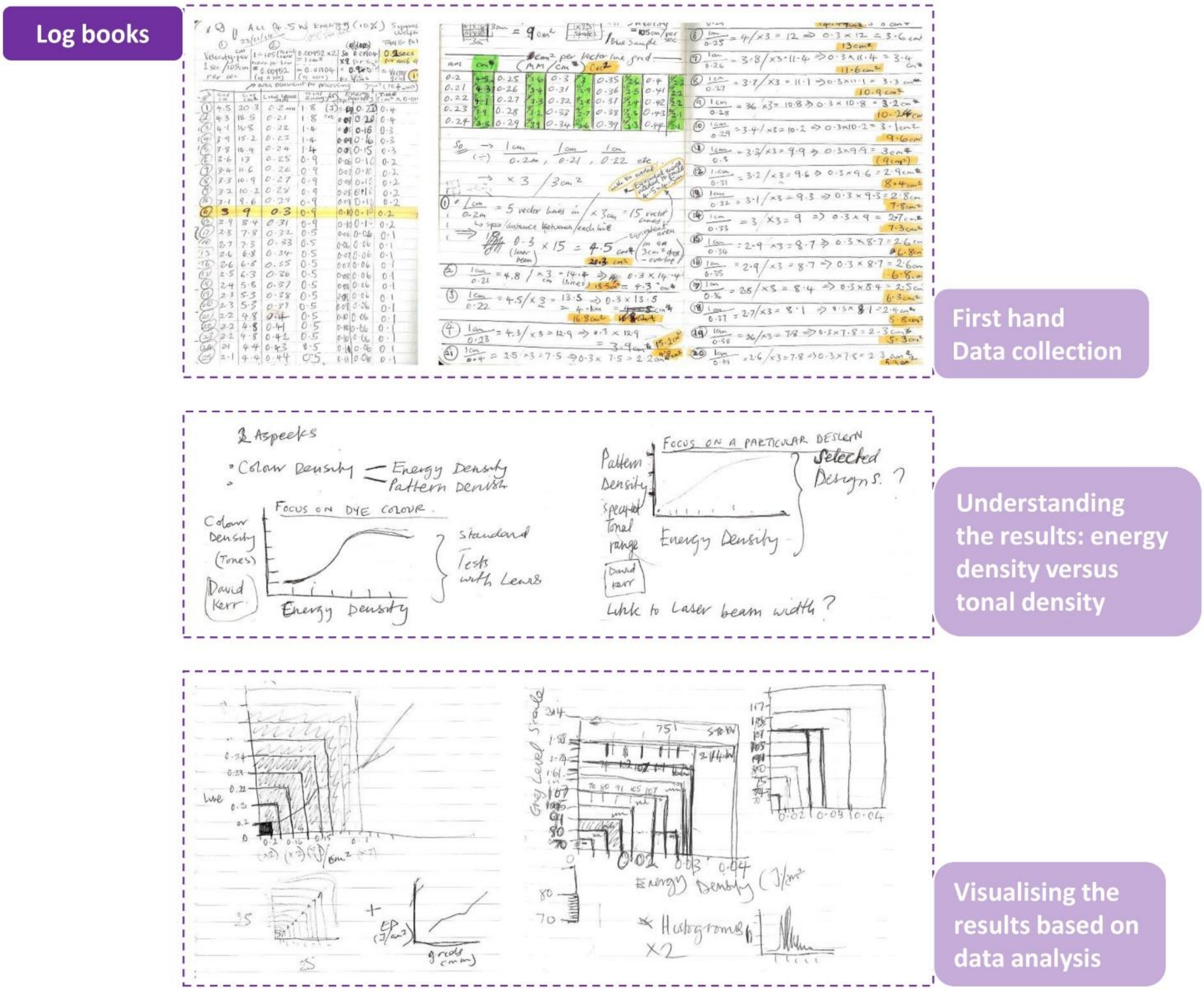


Figure 93: Laser energy density/tonal density information recorded in log books

Greatest tonal variability is seen at 0.1 J/cm^2, between 0.24-0.3mm (Figure 91). This can be attributed to an almost definite repeating stripe effect occurring on the fabric surface through marginal but distinct beam overlap at a micro level. The linear grids in this range move closer to optimum distance of 0.3mm, which also sits in an optimal energy density of 0.1 J/cm^2. The importance of control and accuracy of the process for repeatable outcomes is emphasised here, largely dependent on line spacing. At polar ends however: >0.2 and <0.06 J/cm^2 for example, deeper dyeing caused by extreme beam overlap and pale dye uptake due to significant spacing resulted in reduced tonal variation separate from identified optimum energy density. Therefore, marginal line space difference became less fundamental to consistency at these parameters and some level of flexibility was enabled. Such factors are useful when considering design and production issues regarding creative development and transferability of procedures between machines and/or software in terms of calibration. By changing laser parameters such as velocity and percentage of processing power in conjunction with vector grids, variability has been explored in this study in order to alter and determine the appearance of colour and pattern.

The vector approach facilitated accuracy and stability of the laser-dye process by eliminating surface anomalies caused by variable energy densities evident in raster scanning. This significantly impacted dye uptake across larger treated areas containing little or no pattern i.e. all-over flat colour. Experiments focused on the process potential as an on demand coloration tool concerned with level uptake and depth of shade variability. This compares to conventional textile dyeing processes that typically use more or less dye quantities to determine shade depth i.e. 0.5%, 1%, 1.5%, 2% dye and so on. With a laser-dye approach however, it was possible to specify tonal range by function of specific laser parameters demonstrated in this study rather than by adjusting dye quantities. Dye uptake was determined by laser modification to textile surface fibres not by varied dye amounts. Therefore, dyeing was manipulated via laser technology to produce tonal variation on the fabric surface in a single dye bath. An ability to achieve ‘deep dyeing’ without increasing dye quantities and by reducing the amount of dye required e.g. for a 0.5% depth of shade/tone, highlights the potential for laser-dye approaches as an environmental friendly alternative to conventional methods by suggesting that the impact of laser processing textiles in this way could facilitate reduced dye quantities. Creatively, the process enhances design flexibility in terms of the vast range of tones possible to create varied effects through both pattern and colour development. This encourages new experimental surface effects for textiles with dyes (
Figure *94*).

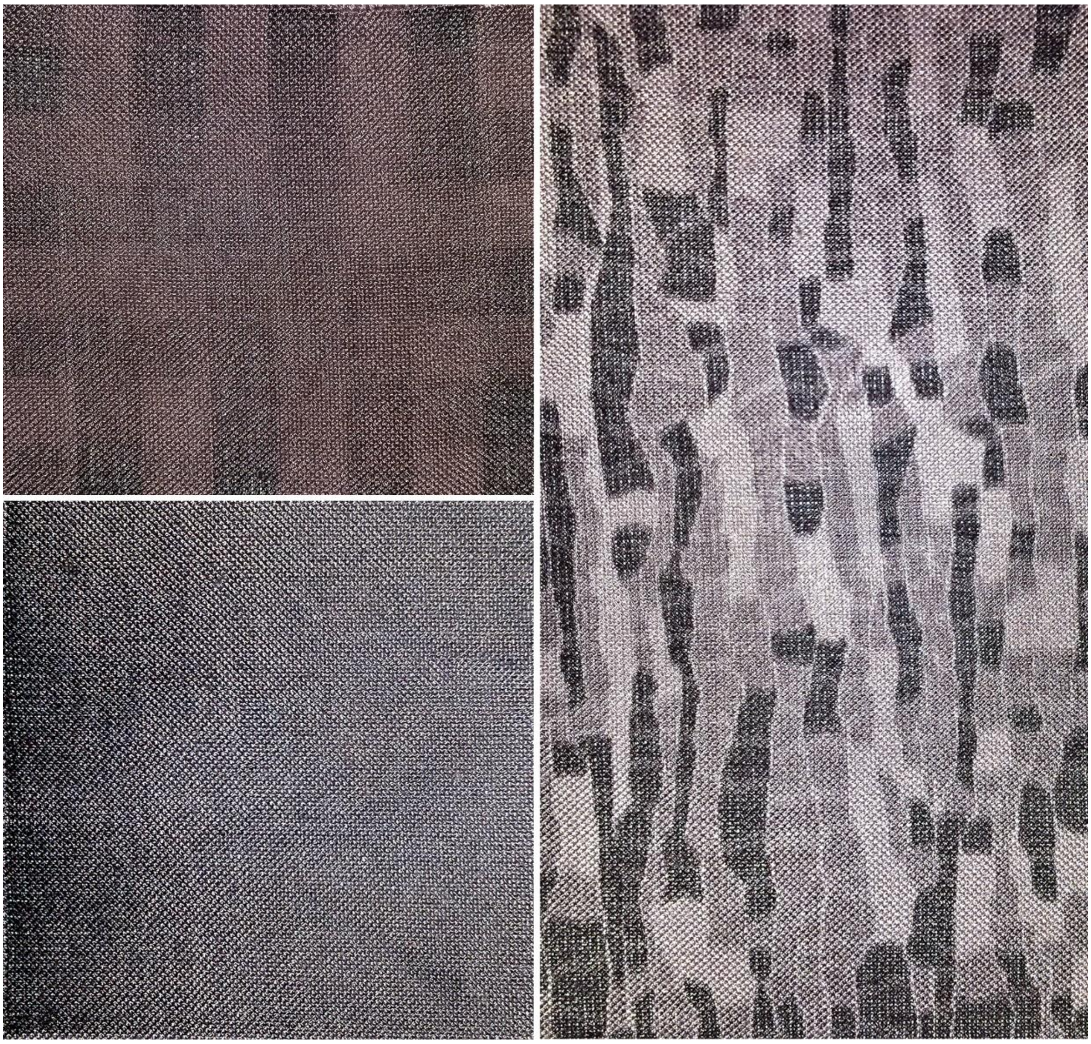


Figure 94: Experimental laser-dyed surface effects

A formula for quantifying colour in relation to the laser-dye process was achieved in this study by calibrating energy density with tonal density by using a vector CAD approach to determine laser beam scanning and dye uptake capability. This scientific approach supports the reliability and transferrable goals of the work regarding innovative textile coloration methods relevant to industrial procedures and requirements. Such methods may also be considered a guide for controlling and categorising fibre damage caused by extreme energy density by instead, providing a system for generating a larger tonal range based on incremental differences and subtle shifts in depth of shade. Essentially, increased dye uptake signifies increased denaturing of fibres. Therefore, colour may also be considered a damage analysis tool capable of visually indicating optimal modification levels in relation to structural fibre/fabrics changes induced by the laser beam during processing. Textile performance tests were carried out in this research in order to further investigate and understand the impact of the laser-dye process on the physical properties of woven and knitted PET fabrics studied. These results are presented and discussed in section 5.2.5 of this chapter.

5.2.3 Quantifying colour: measurement and analysis

In line with the aims of this study to embed industry standard (ISO) methods and procedures into experimentation and confirm the industrial relevance of the laser-dye process, in order to fulfil these aims, the objectives of the research were to incorporate ISO measurement and analysis including wash fastness and colour assessment. The rationale for doing so was to acquire an in depth rigorous scientific and technical understanding of procedures involved and results achieved through quantitative analysis. The methods used to do so were:

- **Reflectance Spectroscopy (RS)** – to measure the reflection and absorption properties of laser-dyed and untreated fabrics within a visible wavelength spectrum of 400 to 700 nm;
- **CIELAB (CIE *L*a*b**) colour model –** for quantifying colour, applicable to industry standards. This system does not actually measure colour but colour difference (Delta E); and
- The '**Grey Level**' method used as a numerical technique for defining colour density.

The purpose of this approach was to investigate the scope for quantifying colour and the potential to definitively discuss tonal density in relation to the laser-dye process. This was perceived to support the transferability/commercialisation of the process in terms of the ability to reliably communicate the research results. By quantifying and visualising colour in this way, further understanding of optimal laser modification parameters in terms of processing energy and dye uptake was gained. These findings relate to the appearance of colour on laser-dyed fabrics.

In order to discuss the results in relation to specific processes/treatments, five categories were used to define fabric samples/test specimens, outlined in Table 15.

	Process/Treatment	**Definition of fabric**
1	**Untreated**	Original fabric as received for the supplier; control specimen; no laser modification; undyed
2	**Undyed**	Laser modified (treated); not dyed
3	**Dyed/Not treated**	Fabric has was dyed only; not laser modified
4	**Laser-dyed**	Laser modified and dyed (no pattern)
5	**Laser-dyed/patterned**	Laser modified and dyed with pattern (stated where necessary to make the distinction between laser dyed samples treated with or without pattern)

Table 15: Fabric sample categories

5.2.3.1 Reflectance Spectroscopy (RS)

Non-patterned knitted polyester samples treated with the same laser parameters and dyed with different dyes/shades were tested. Laser energy density was controlled by a tonal greyscale (GS %) raster approach, as previously discussed. GS: 70% was used to modify fabrics unless stated otherwise. For example, GS: 100% was also applied, where applicable as a variable processing energy density for comparison. Higher GS% induced deeper dye uptake due to increased laser energy. All other laser parameters between samples were constant. Dyed, laser modified and untreated knitted polyester samples were compared. Five different dye shades created in this study, were assessed and samples were organised into batches. Tested fabrics included GS% and depth of shade (DOS %) variables as stated. Where DOS is unsaid, fabrics were dyed at 1%.

Based on physics, whereby darker surfaces are more absorbent than pale objects which reflect more light, it was anticipated that there would be a linear trend between treated and untreated fabrics. The deeper dyeing effect caused by laser treatment produced darker shades therefore lower reflectance values were expected here. However, analysis of samples per shade batch yielded results that challenged this principle.

Figures 95-101 show the results graphs of RS tests carried out. In general, only a marginal difference can be seen between treated and untreated fabrics with little difference in reflectance curves. Exceptions to this are Figure 96 and Figure 100 which revealed greater difference. Most notably, higher reflectance rates were recorded with laser-modified fabrics - seen distinctly in

Figure 95 and Figure 100. The reverse effect, which is expected based on the deeper dyeing effect of the laser-dye process was recorded in Figure 97, showing a small difference and marginally in Figure 96 and Figure 99 report results of samples modified at GS:70% and GS:100% respectively. In Figure 96, as would be expected, lower processing energy (GS: 70%) yielded greater reflectance due to paler dye uptake. However, a difference in trend seen between 400-500 nm (Figure 96) showing decreasing reflectance (%) for the GS: 70% specimen and increasing reflectance (%) for the GS: 100% specimen, to some extent suggests that variable laser energy densities can affect the optical properties of a dye/fabric surface differently. At approximately 425 nm, which is the dominant wavelength region (nm) for deep blues, a sharp 10% reflectance increase from 30-40%, was recorded for the lesser treated sample (GS: 70%) whilst a sharp 13% (approximately) reflectance decrease was recorded for GS: 100% which was laser modified with more energy. This behaviour may indicate some anomalies on the fabric surface attributed to irregular laser processing or some non-uniformity in the dyeing for example, regarding these particular fabrics. These explanations were not conclusive however. Overall, the results demonstrate a change in laser energy caused a shift in the colour quality or hue of a dye/shade, as understood. Consequently, reflectance/absorption properties of laser-dyed fabrics adjusted according to the corresponding visible wavelength spectrum.

Comparatively, samples in Figure 99, were dyed at 0.5% DoS. The highest overall reflectance peaks at approximately 475 nm in relation to the dominant wavelength/dye shade. Although the curves are near identical (Figure 99), the greatest difference was recorded with the GS: 100% between 425-440 nm, not with fabric specimen GS: 70%, as in Figure 96. It may be concluded that increased laser energy altered the spectral characteristics of the dye. Therefore, a more assertive result in this wavelength range was yielded compared to a paler shade due to weaker dye uptake. This rationale may also apply to other results obtained whereby the laser modified sample produced a higher reflectance rate compared to the untreated fabric e.g.

Figure *95*. It is however acknowledged in this discussion, that such explanation is not definitive.

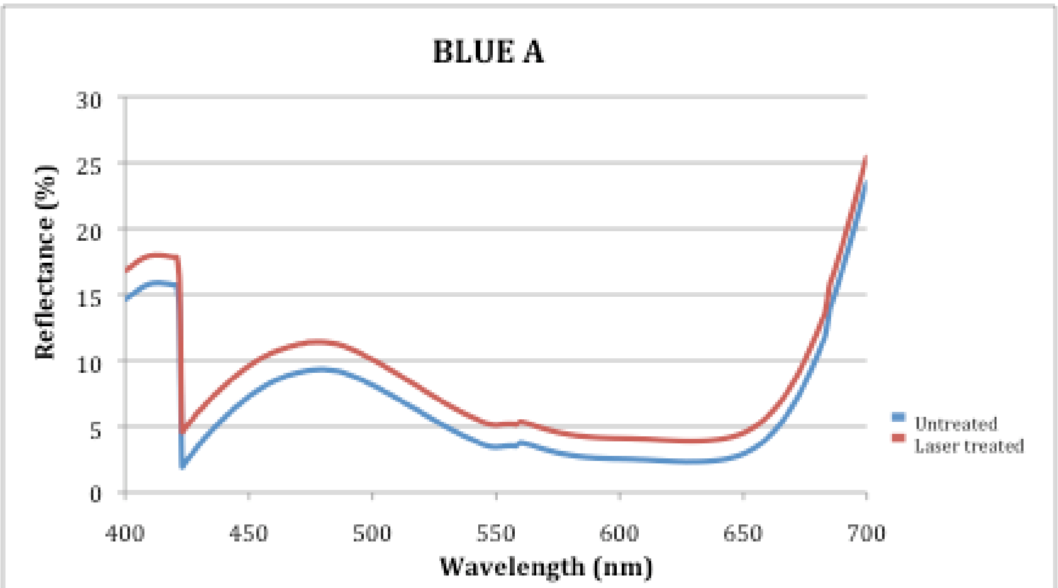


Figure 95: Reflectance/Batch 1: Blue - Laser treated: GS: 70% (*Blue A*) and untreated fabrics

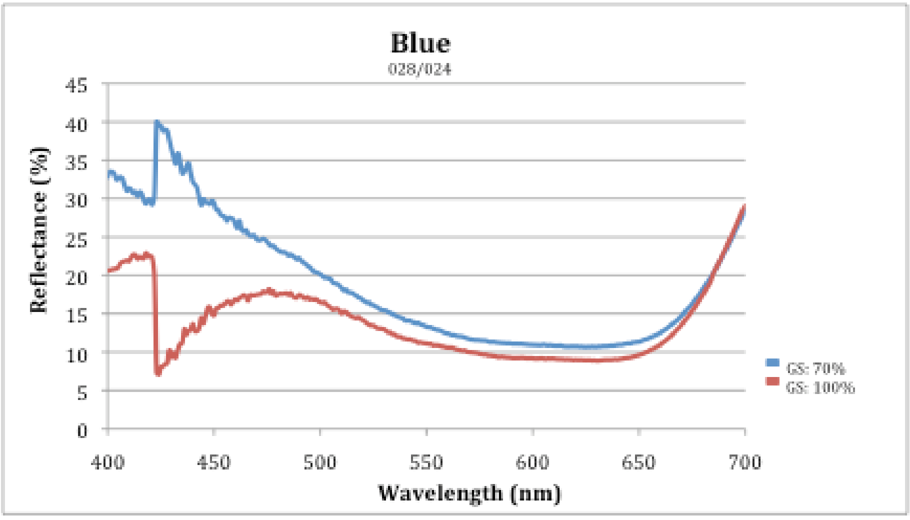


Figure 96: Reflectance/Batch 1: Blue - Laser-dyed fabrics: GS: 70% and GS: 100% (*Blue*)

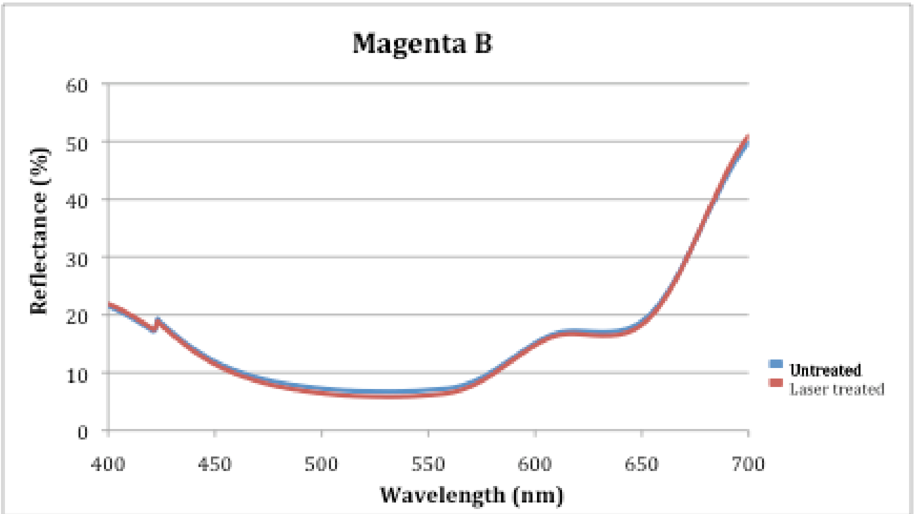


Figure 97: Reflectance/Batch 2: Magenta - Laser treated and untreated fabrics: GS: 70% (*Magenta B*)

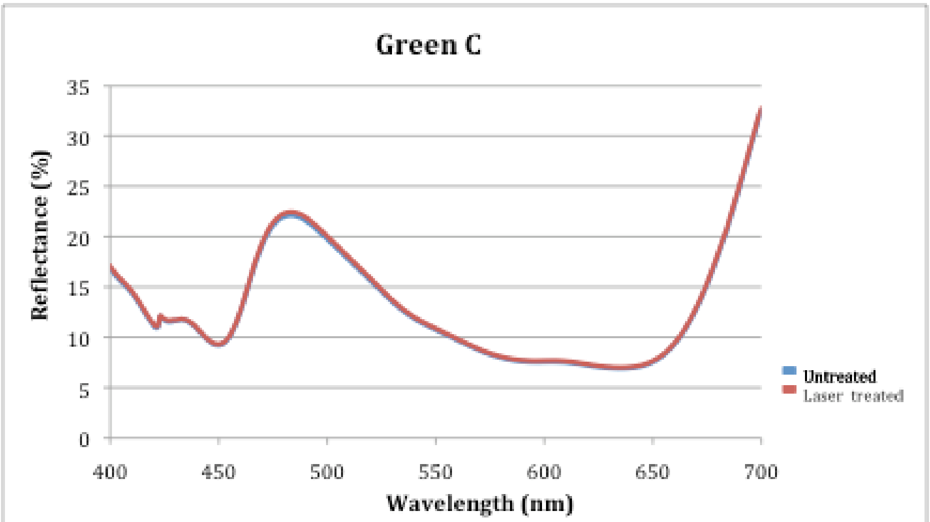


Figure 98: Reflectance/Batch 3: Green - Laser treated and untreated fabrics: GS: 70% (*Green C*)

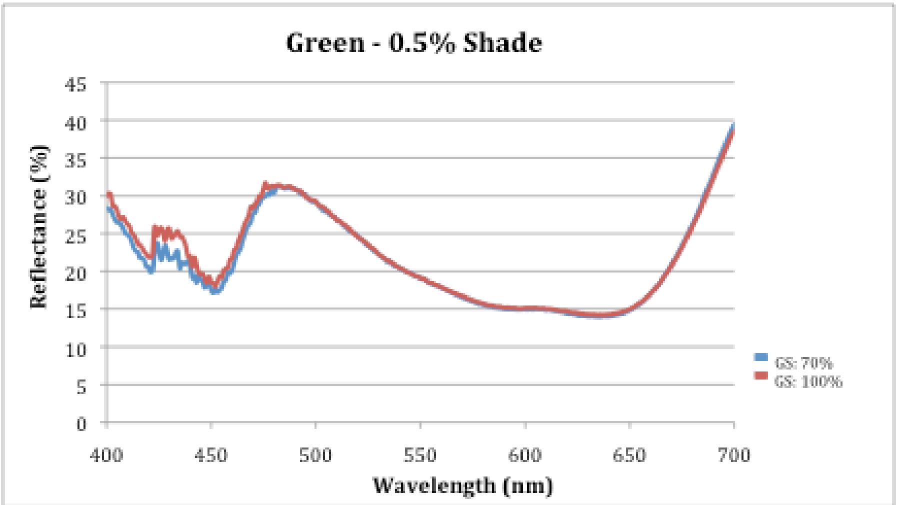


Figure 99: Reflectance/Batch 3: Green - Laser-dyed fabrics: GS: 70% and GS: 100% (*Green 0.5%*)

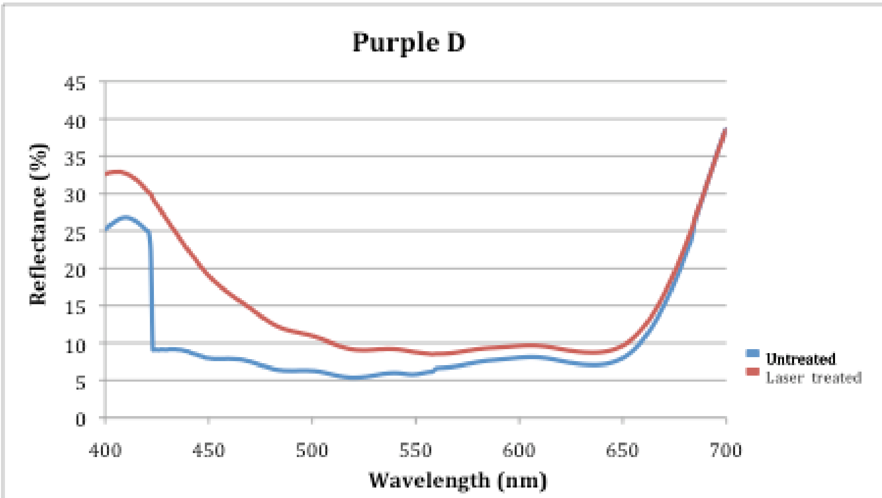


Figure 100: Reflectance/Batch 4: Purple - Laser treated and untreated fabrics: GS: 70% (*Purple D*)

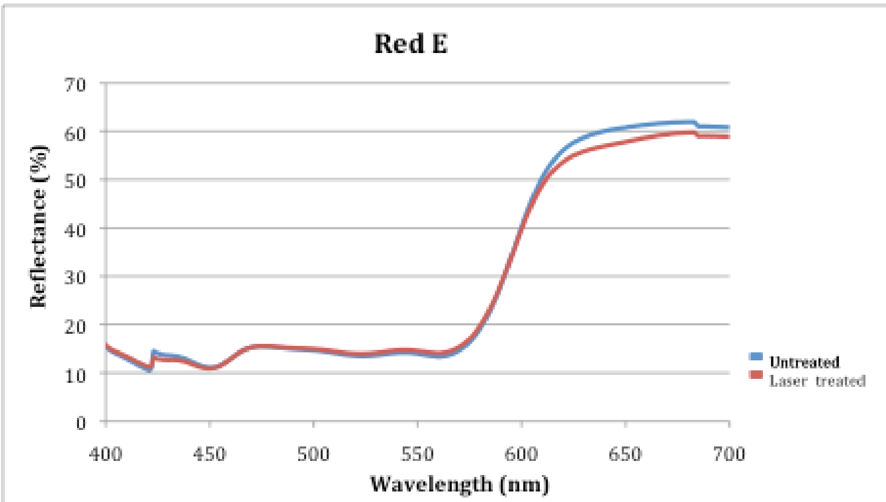


Figure 101: Reflectance for Batch 5: Red E - Laser-dyed fabrics: GS: 70% and GS: 100% (*Red E*)

An overall linear trend was not found based on the results obtained from RS tests undertaken in this research. Outcomes do however show that the laser-dye method can influence the reflectance and absorbance properties of a fabric. This approach to some extent enabled quantitative analysis of colour and colour change in relation to the process explored. In doing so, further understanding about effect and impact of laser-dyeing using PET textiles was gained. As such, the results can be scientifically analysed, understood and communicated through digital/numerical measurements. This approach aids the reliability goals of the work.

*5.2.3.2 CIELAB/CIE L*a*b* Colour Model*

Distinct differences between laser-modified and untreated fabric samples were recorded using the CIELAB (CIE *L*a*b**) colour model. Samples dyed with a 0.5% shade and at 1% were assessed for comparison (Figure 102). L*a*b* colour values were measured - *L** = lightness – darkness, *a** = redness – greenness *b** = yellowness – blueness (Figure 103). In the model, a* and b* simulate how the signals are transported to the brain. These values are converted to Hue and Chroma to define colour in 'L*C*H* space' (L*/Lightness; C*/Chroma; H* /Hue).

Figure 102: Fabric samples used in reflectance testing (Batch: *Green C*)

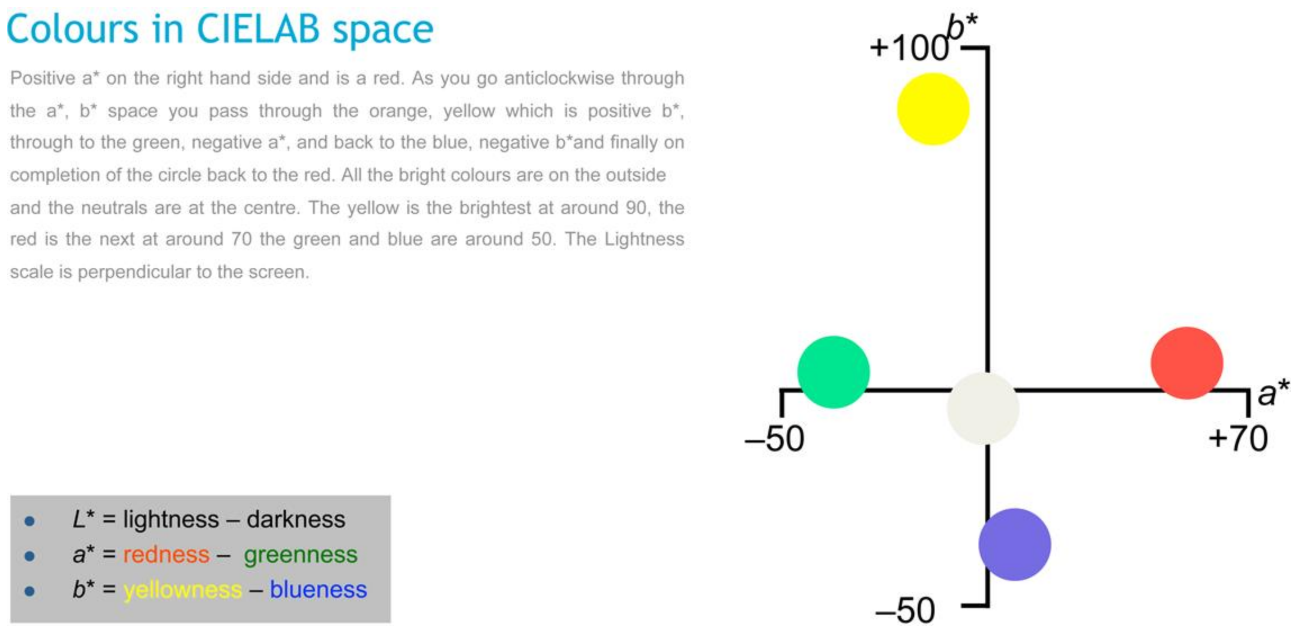


Figure 103: CIELAB (CIE L*a*b*) colour model, SDC, 2013

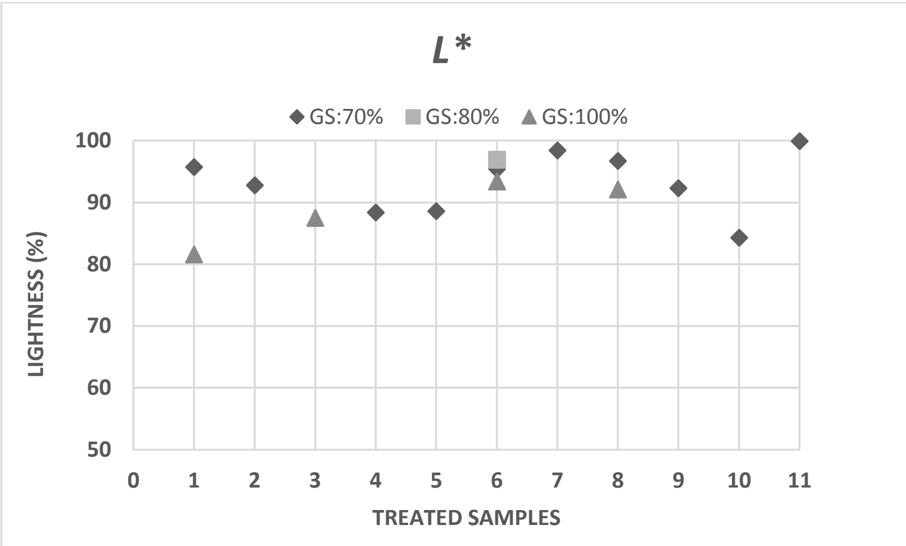
Delta E assessment based on the L*C*H* colour model, quantified total colour difference between fabrics by the analysis of each sample. The total colour difference between samples in a batch and/or the standard is ∆E. It is a single number that is calculated from the difference in lightness, the difference in chroma and the difference in hue (∆L*, ∆C* and ∆H*). CMC is the metric used to measure Delta. In this research, a ratio of 2:1 (CMC) was applied, commonly used for acceptability, required by industry standards.

Table 16 documents the *L** - Lightness value of each fabric sample per batch including the depth of shade (DoS %) at which samples were dyed. Each batch comprised a range of variable samples including DoS% (Depth of Shade) and tonal density GS% (Greyscale) differences along with standard untreated specimens. Fabrics were defined by five categories in relation to their processing parameters – 1) **Standard/Std.** - Dyed/Not Treated; 2) **GS: 70%**' - Laser-dyed; 3) **GS: 80%**' - Laser-dyed; 4) **GS: 100%**' - Laser-dyed; 5) **Undyed** (treated and not treated).

Sample / BATCH		DOS % 1	DOS % 0.5	Std.	GS: 70%	GS: 80%	GS: 100%	Lightness *L**
1	**BLUE A**	x						**35.70**
2		x						**34.18**
3		x						**29.14**
4			x					**44.55**
5	**GREEN C**	x						**39.51**
6		x						**36.67**
7		x						**34.57**
8			x					**46.50**
9			x					**41.33**
10			x					**48.56**
11	**MAGENTA B**	x						**33.98**
12		x						**30.04**
13			x					**40.62**
14	**PURPLE D**	x						**36.26**
15		x						**32.11**
16			x					**44.71**
17	**RED E**	x						**51.82**
18		x						**49.46**
19		x						**48.38**
20			x					**56.17**
28		x						**50.95**
29		x						**50.21**
21	**DRK. BLUE-PURPLE**	x						**30.49**
22		x						**29.99**
23			x					**40.23**
24	**LT. ORANGE-YELLOW**	x						**58.80**
25		x						**56.90**
26		x						**54.17**
27			x					**64.89**
30	**GREY-GREEN**	x						**33.19**
31		x						**30.62**
32			x					**42.74**
33	**AUBERGINE**	x						**33.58**
34		x						**28.31**
35		x						**40.67**
36	**UNDYED:Trtd**				x			**93.96**
37	**Not Trtd**							**94.07**

Table 16: CIELAB Lightness (L*) values per sample type

Samples that were 'dyed/not treated' produced higher *L** values compared to treated fabrics as expected. Similarly, untreated fabrics dyed with 0.5% depth of shade also produced higher *L** values than those dyed with 1%. Figure 104 shows that in general, 1% DoS fabrics modified at GS: 70% yielded the smallest % difference in lightness compared to the standard (dyed/not treated) specimen. GS: 100% specimens yielded lower *L**% due to increased fibre-laser interaction and so increased dye uptake, therefore a darker shade. Exceptions to this trend can be seen with Sample 6/RED E, whereby GS: 80% produced a higher *L** value than GS: 70%. This result was simply attributed to marginal experimental deviation. Overall, results were influenced by tonal difference due to variable energy density applied when laser processing the fabrics. Deeper dyeing as a result of increased laser modification, yielded reduced *L** values. Likewise, less fibre-laser interaction produced greater lightness. A lower *L*%* was recorded for all laser treated samples compared the standard specimen. This outcome further demonstrates the impact of the laser-dye process in relation to colour. Laser-dyeing enables increased dye uptake capability compared to untreated fabrics due to the interaction between fibres and laser beam energy which changes the fibre structure through the irradiation process. This in turn, induces a deeper dyeing effect to laser modified fabrics.



Treated Sample	
1	BLUE A
2	GREEN C[a] (1% DOS)
3	GREEN C [b] (0.5% DOS)
4	MAGENTA B
5	PURPLE D
6	RED E
7	DARK BLUE-PURPLE
8	LT. ORANGE-YELLOW
9	GREY-GREEN
10	AUBERGINE
11	UNDYED

Figure 104: Lightness (L*) graph showing different values for treated fabric samples

Table 17: Samples in numerical order

Hue and Chroma values for dyed and treated fabrics were plotted in L*C*H* lab space by converting *a** and *b** (*L*a*b**) shown in Figure 105 and Table 19. This method identified the quality of a colour, determined by its dominant wavelength (hue), as well as intensity (chroma). Starting at positive *a** as 0°/360° - red, moving anticlockwise 90° - yellow, to 180°- green and 270° - blue. Chroma is the distance from the centre where intensity is weakest/neutral to where the colour is plotted further away, therefore stronger/brighter. Chroma is calculated from *a** and *b** coordinates. This assessment provided a definitive reliable language for describing colour change regarding a laser-dye process in a way that is transferrable and relevant to the textile industry.

Table 19 reports ‘a’ and ‘b’ values regarding hue and chroma for each specimen per batch (previously identified in Table 16), Figure 105/Table 18 represents this data. Laser/dye processing laser parameters applied determined a unique position for fabric samples quantified in L*C*H* lab space. Each cluster is relative to a measure of metarmerism associated with dye/shade and dominant wavelength. Batches 5 and 7 yielded high chroma and distinct hue seen in the outer circle(s). Undyed samples/batch 10 yielded the lowest hue and chroma data as expected, along with batches 8 and 9 each positioned around the central region.

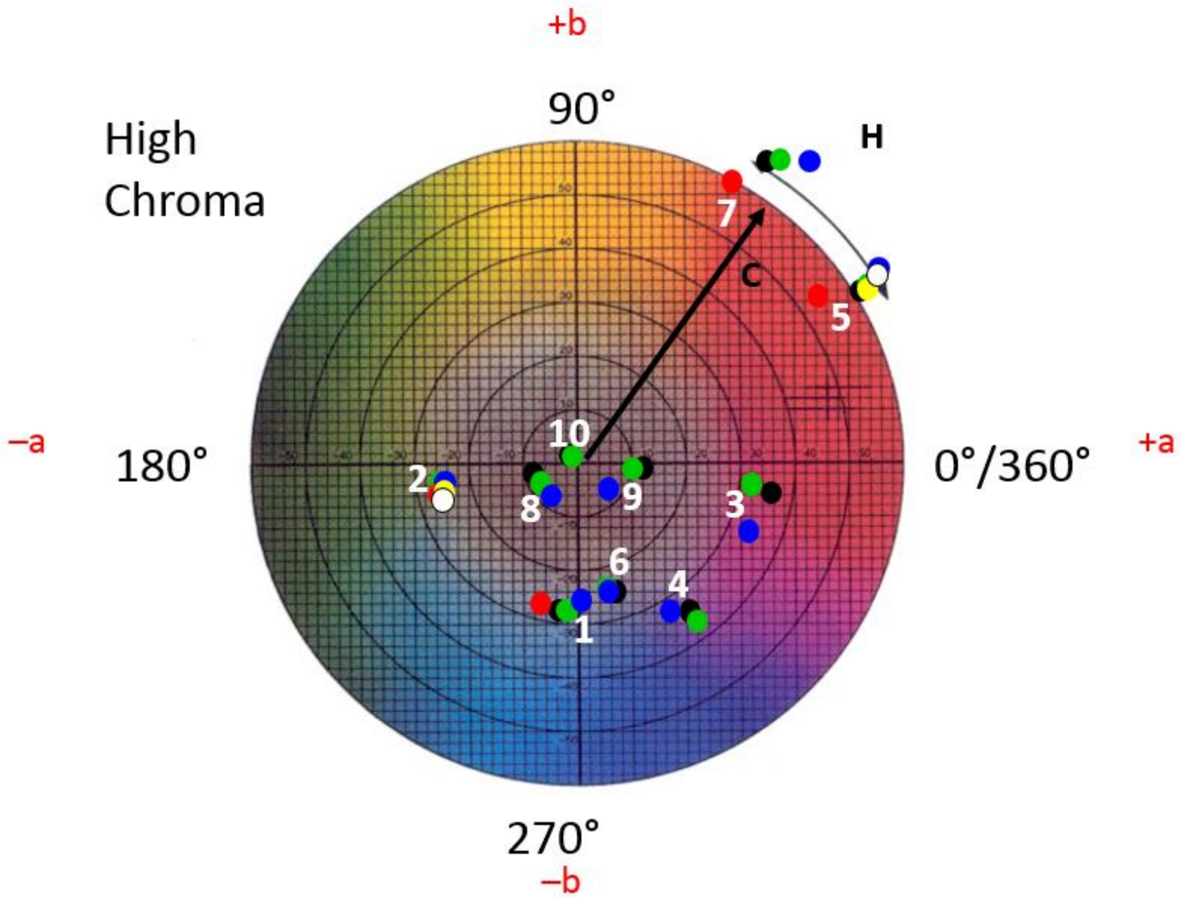


Figure 105: Fabric samples quantified in L*C*H* lab space

	SAMPLE BATCH	SPECIMEN
1	BLUE A	● Std
2	GREEN C	● 2
3	MAGENTA B	● 3
4	PURPLE D	● 4
5	RED E	● 5
6	DRK. BLUE-PURPLE	○ 6
7	LT. ORANGE-YELLOW	
8	GREY-GREEN	
9	AUBERGINE	
10	UNDYED	

Sample Batch		Specimen	HUE / CHROMA a	HUE / CHROMA b
1	BLUE A	Std	-3.61	-27.96
2		2	-2.53	-27.35
3		3	0.10	-25.86
4		4	-5.05	-26.81
5	GREEN C	Std	-22.51	-5.13
6		2	-22.61	-5.61
7		3	21.39	-6.35
8		4	-24.61	-1.15
9		5	-24.97	-3.62
10		6	-23.33	1.03
11	MAGENTA B	Std	32.15	-7.94
12		2	29.32	-4.84
13		3	27.87	-12.15
14	PURPLE D	Std	16.24	-27.60
15		2	18.04	-29.97
16		3	14.99	-26.91
17	RED E	Std	50.36	31.52
18		2	51.06	32.17
19		3	53.76	35.12
20		4	42.20	29.70
28		5	50.97	31.54
29		6	53.13	34.09
21	DRK. BLUE-	Std	6.66	-22.58
22	PURPLE	2	5.90	-22.66
23		3	5.96	-22.71
24	LT. ORANGE-	Std	33.50	54.69
25	YELLOW	2	35.02	55.05
26		3	39.79	55.31
27		4	26.57	51.42
30	GREY-	Std	-8.21	-7.01
31	GREEN	2	-7.21	-5.55
32		3	-8.33	-5.69
33	AUBERGINE	Std	12.60	-1.57
34		2	10.56	-1.20
35		3	6.09	5.38
36	UNDYED:Trtd	2	-0.59	2.17
37	Not Trtd	Std	-0.54	2.08

Table 18: Key - CIE Lab Space (left)

Table 19: Hue and Chroma values per batch/specimen (right)

The total colour difference between the batch and the standard (1% DoS; Not treated) is Delta E (ΔE). It is a single number calculated from the difference in lightness, the difference in chroma and the difference in hue – ΔL*, ΔC* and ΔH* recorded in Table 20. These results shows Lightness (ΔL*) consistently in the negative (-). This simply indicates a darkening of the colour, due laser treatment which can be understood. No correlation can be seen for how Chroma (ΔC*) moved demonstrated in the graph (Figure 107). The Hue (ΔH*) appeared to always move the same direction for all samples generating positive (+) ΔE, rather than negative numerical values. This trend confirmed laser-dyeing enhanced coloration which triggered greater dominance in colour appearance, signified by the increased quality of the hue, as discussed previously.

	Sample BATCH	DOS % 1	DOS % 0.5	Std.	GS: 70%	GS: 80%	GS: 100%	Delta E (ΔE) ΔL*	ΔC*	ΔH*
1	BLUE A	x								
2		x						-1.52	-0.72	1.01
3		x						-6.56	-2.33	3.57
4			x					8.85	-0.91	1.60
5	GREEN C	x								
6		x						-2.84	0.21	0.45
7		x						-4.95	-0.77	1.46
8			x					-2.06	1.29	0.06
9			x					-7.23	1.88	2.43
10			x							
11	MAGENTA B	x								
12		x						-3.95	-3.40	2.47
13			x					6.64	-2.72	5.35
14	PURPLE D	x								
15		x						-4.15	2.96	0.33
16			x					8.45	-1.22	0.75
17	RED E	x								
18		x						-2.36	0.94	0.17
19		x						-3.44	4.80	1.20
20			x					4.36	-7.80	2.98
28		x								
29		x						-0.74	3.18	1.01
21	DRK. BLUE-PURPLE	x								
22		x						-0.50	-0.12	0.76
23			x					9.74	-0.07	0.71
24	LT. ORANGE-YELLOW	x								
25		x						-1.90	1.12	1.10
26		x						-4.63	4.00	4.90
27			x					6.09	-6.25	4.43
30	GREY-GREEN	x								
31		x						-2.58	-1.70	0.50
32			x					9.55	-0.71	1.11
33	AUBERGINE	x								
34		x						-5.28	-2.07	0.12
35		x								
36	UNDYED:Trtd	---	---					-0.11	0.10	0.02
37	Not Trtd	---	---							

Samples:

Standard (Std) – Dyed/Not Treated

Laser-dyed (Treated)

Table 20: Delta E data

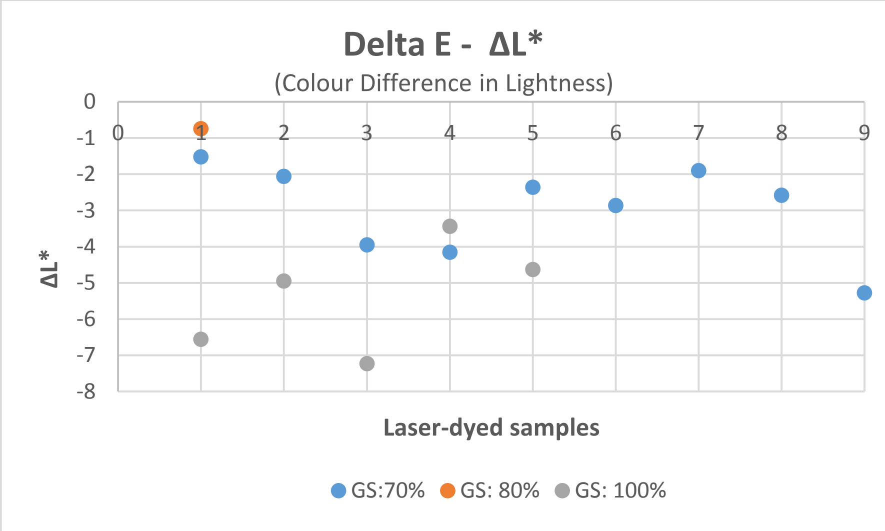


Figure 106: Delta E Colour difference: Lightness results (ΔL*)

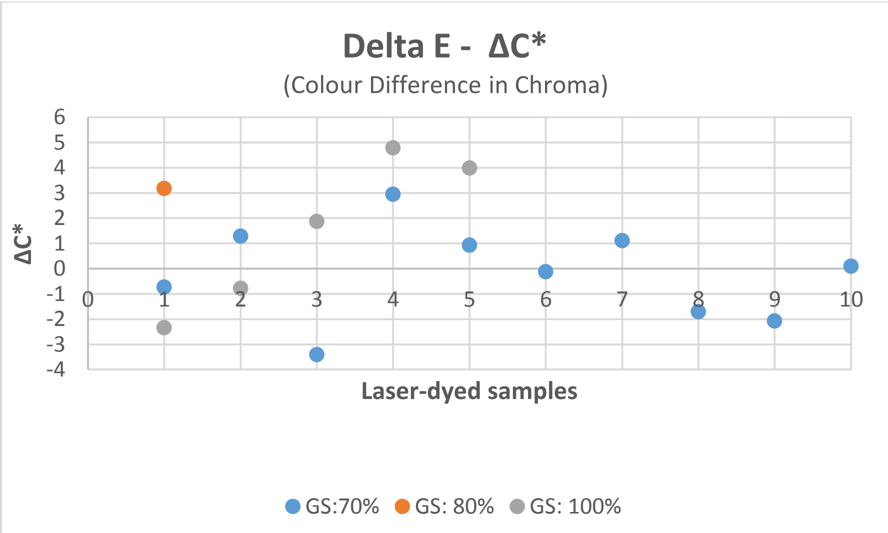


Figure 107: Delta E Colour difference: Chroma results (ΔC*)

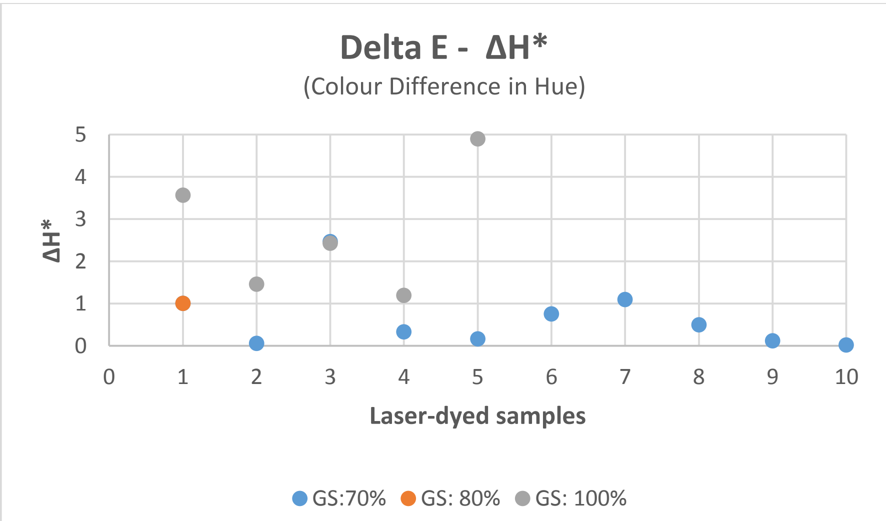


Figure 108: Delta E Colour difference: Hue results (ΔH*)

Quantitative data obtained using the CIELAB colour model provided further knowledge about the impact of laser modification on dye uptake in relation to the specified laser/dye processing parameters explored. This type of scientific interrogation and analysis of colour concerning a combined laser and dye process does not exist in current textile/laser studies.

5.2.3.3 Grey Level method

A Grey Level (GL) method for defining colour density was explored in this research. This approach was adopted with the attempt to statistically describe tonal density variations of laser-dyed fabrics by process of colour-to-grey computational calibration. To do so, a measurement of grey within a scale of 0-255 was employed to calculate tonal variation of laser-dyed fabrics. In this scale, 0 = Black and 255 = White (Figure 109). This model made it possible to plot colour density against numerical tonal data based on laser/dyeing parameters explored. In doing so, a quantitative representation of dye uptake variability in relation to laser modification was given in a logical manner.

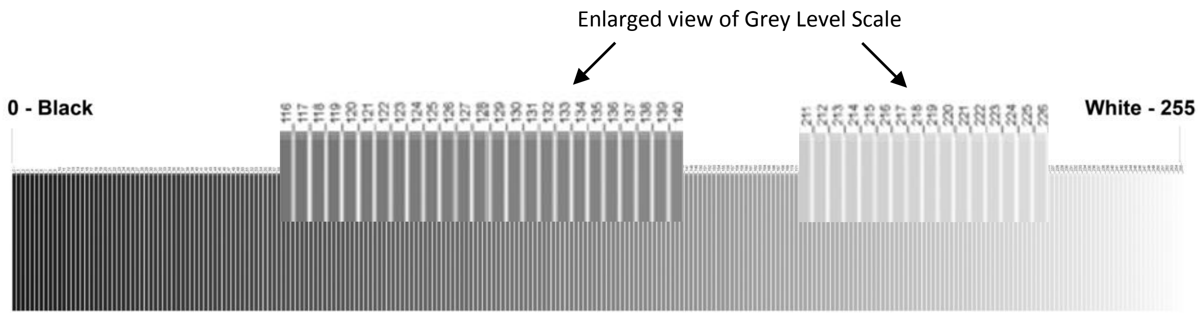


Figure 109: Grey Level scale

Using *Vision Assistant* computer software, a still video image of fabric samples was captured in grey (black/white) with standard lighting conditions using a white fluorescent tube. *Image Pro* software measured brightness based on a grey level represented statistically and graphically.

Figure 110 shows the digital design file containing a range of grey tones (GS %) which form an all over repeat design. Figure 111 is a grey still image of a laser-dyed gradated textile pattern – a knitted polyester fabric sample with inset image of the dyed fabric.

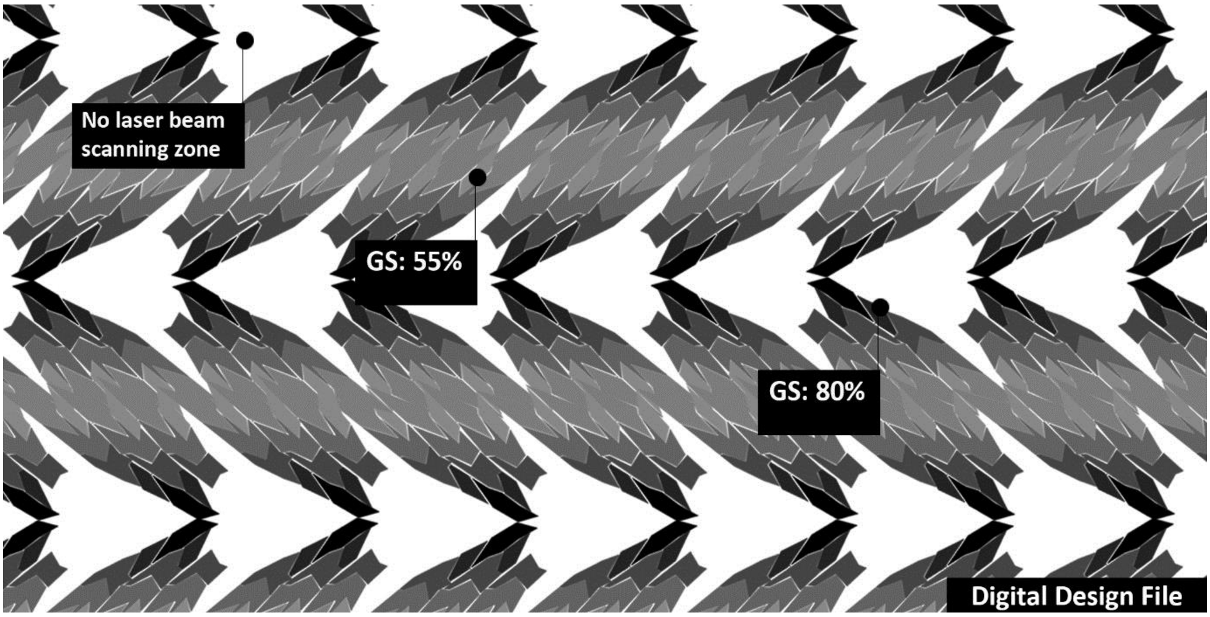


Figure 110: Digital design file with a range of grey tones (GS %) which form an all over repeat design

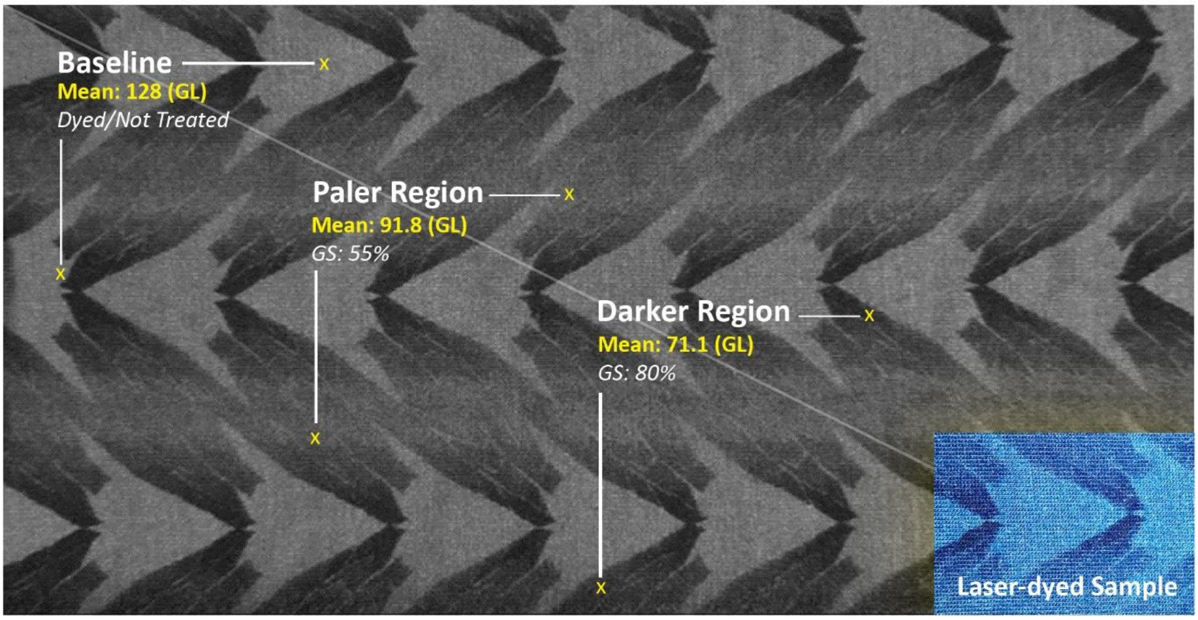


Figure 111: Grey still image: knitted polyester laser-dyed textile design; inset showing the dyed fabric

Measurements were taken by first locating the baseline region – the dyed/not treated fabric (see Figure 111). Table 21 documents results of laser-dyed/patterned regions in paler and darker areas of the treated fabric, together with baseline data. Figure 112, Figure 113 and Figure 114 are histograms for each region.

	Grey Level		
	Baseline	**Paler Region**	**Darker Region**
Mean	**128.3**	**91.8**	**71.1**
Std Dev	17.6	16.3	7.1
Min	93	61	57
Max	183	134	92
Sum	12318	8810	6827

Table 21: Grey Level data for laser-dyed/patterned fabric sample

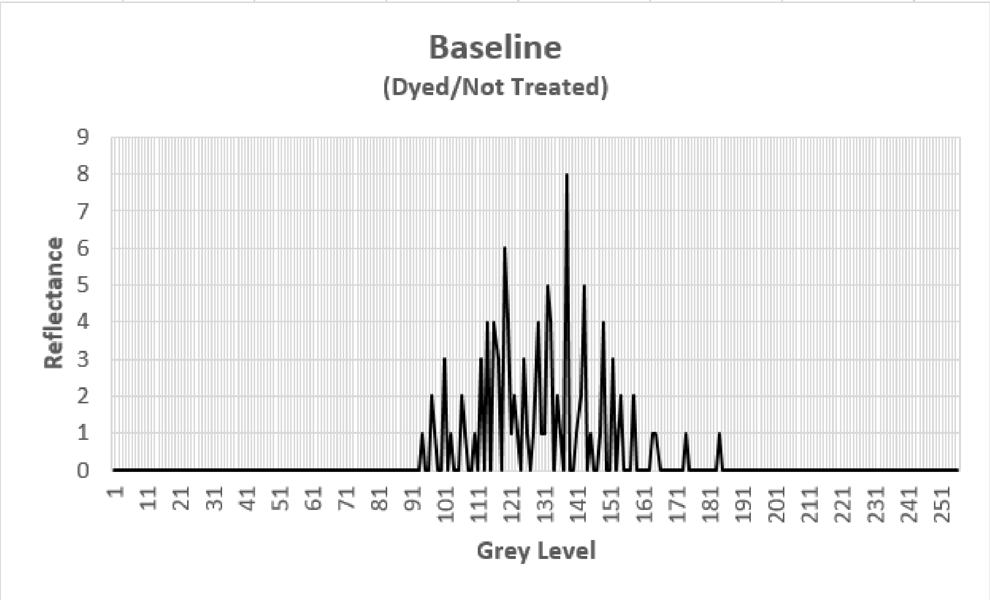


Figure 112: Grey Level Histogram: Baseline

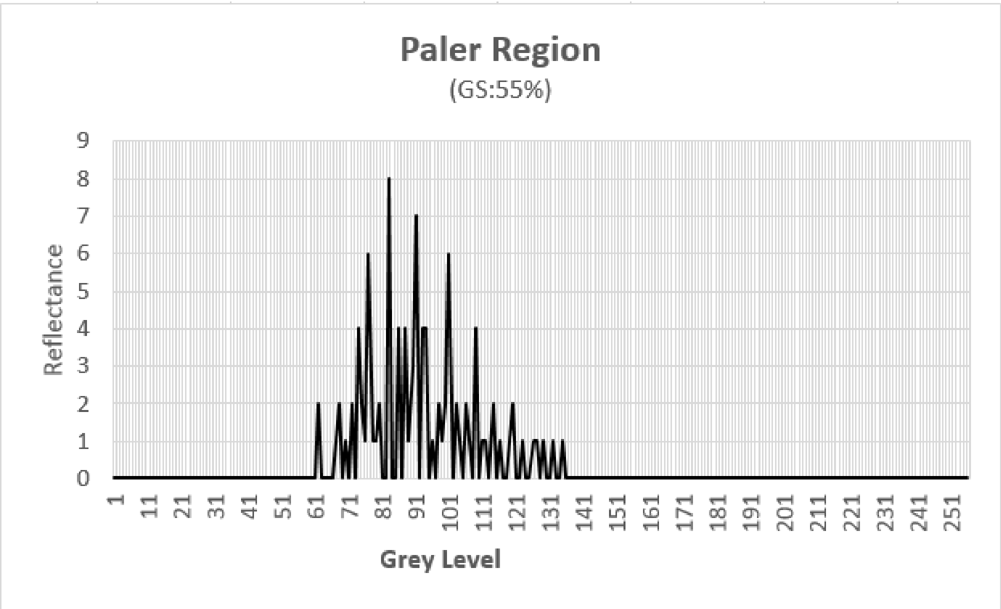


Figure 113: Grey Level Histogram of fabric sample: Paler Region (*GS: 55%*)

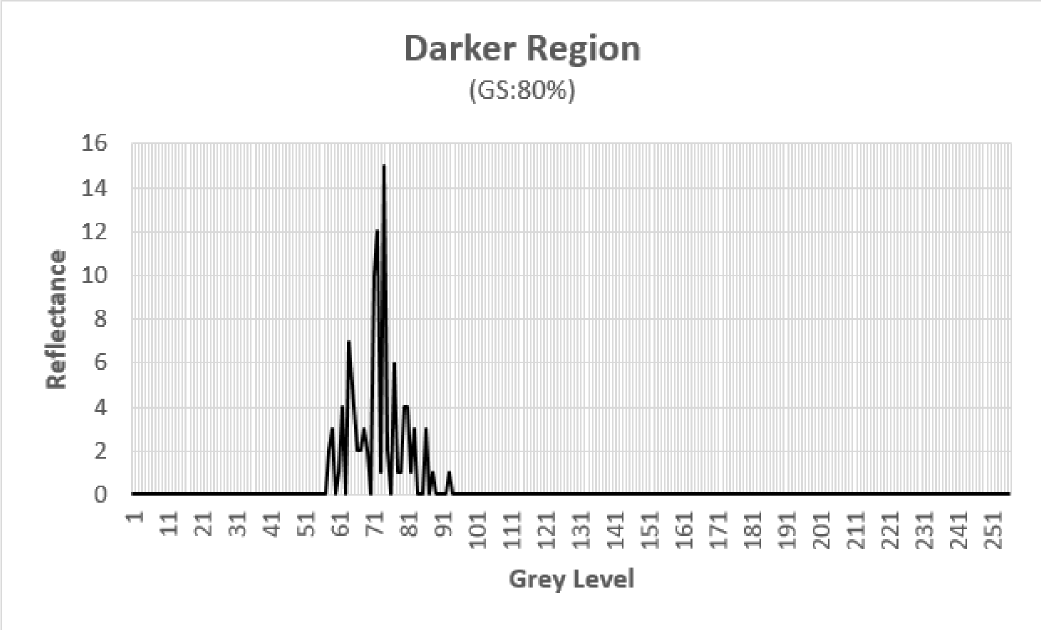


Figure 114: Grey Level Histogram of fabric sample: Darker Region (*GS: 80%*)

Numerical data provided a *mean* grey level measurement for each region, along with the maximum/minimum values in relation to reflectance (%). Results confirmed the baseline region was the palest. The dyed/not treated fabric produced a mean of 128 (GL), peaking at 141 at 8% reflectance (Figure 112). A result of 91 was recorded in the paler region, reaching 81 also at 8% (Figure 113). A result of 71 was recorded in the darker region, achieving 76 at 15% (Figure 114). These results show a decline in the grey level relative to the laser-dye process. Laser treated areas exhibited lower results than the baseline due to increased dye uptake of modified fibres. Results varied between paler and darker regions of the treated fabric based on different laser processing parameters applied.

As the pattern became darker, a lower GL was recorded, closer to zero/black. Paler areas yielded higher results closer to 255/white. This outcome was understandable based on the increased dye uptake phenomenon attributed to the DLD process.

A Grey Level approach provides a system for plotting colour density against statistical tonal data in relation to a laser-dye process explored. Therefore, a method for quantifying dye uptake based on specific laser modification parameters can be communicated. This procedure supports the repeatability of outcomes that can be adopted if using different laser machines, fabrics and/or dyes such as by designers and in industry, for example because designs can be statistically assessed.

The approach also suggests it is possible to calibrate a grey level (GL) measurement system with a greyscale (GS) computer software method for raster scanning explored in this research. By combining these processes, surface tonality directly linked to laser energy may be achieved in a way that can be quantified from the outset, at the pattern development stage. This model would enable design specification in order to arrive at predictable surface effects through controlled, systematic 'Grey' procedures. In this manner, creativity and production would be effectively linked.

5.2.4 ISO wash fastness tests and assessment

Industry standard (ISO) wash fastness tests were carried out on laser-dyed and untreated fabrics samples for comparison. The purpose of this investigation was to find out whether laser-modified fibres had acceptably absorbed dyes in a stable manner with little or no residue (wash-off). This was validated by commercial textile coloration requirements. After washing, 'Change in colour' and 'Assessment of staining' were recorded. Results obtained provided summative data about the robustness of a laser-dye process explored relevant to conventional dyeing methods. Such information enabled further understanding about the potential of the process for commercial use.

5.2.4.1 Textile samples

A range of knitted polyester samples with different finishes/treatments were tested for wash fastness. These included fabrics dyed with different shades; laser-dyed samples that were modified all over without pattern(s) but processed with varied laser parameters; and a range of laser-dye/patterned fabrics. Test specimens consisted of 1% and 0.5% depth of shade (DoS). Samples were organised into 11 shade batches arranged by their dominant hue/colour (Figure 115). Each batch comprised varied fabrics processed differently. The combined amount of samples tested equalled 39 specimens. The batches were distributed over three wash cycles and included a minimum of one laser-dyed (with and without pattern) and one untreated (standard/control) fabric per batch.

Figure 115: Wash fastness samples (x39 specimens) for testing arranged into batches by shade

5.2.4.2 Procedure

ISO standard - BS EN ISO 105- CO6/B2S:2010 was used. Specimens were washed with a Roaches Washtech machine. Each sample was cut to 4cm x 10cm and machine sewn to an SDC 'multifibre DW test fabric' (Figure 116) with the same dimensions.

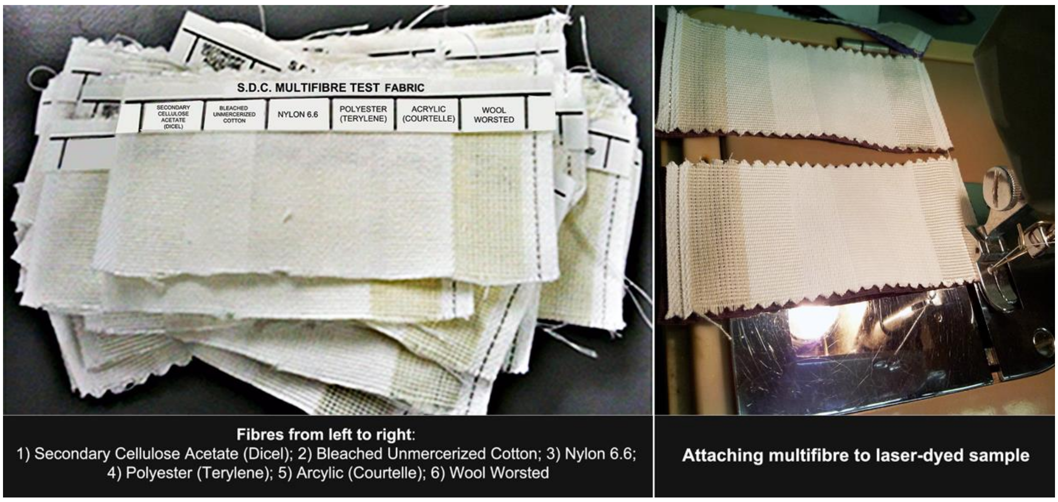


Figure 116: SDC Multifibre DW; Prepared for wash fastness tests

Individual samples were held in separate beakers with the measured liquor containing metal beads to aid agitation, indicated in Figure 117. Once washed, fabrics were rinsed, spun and air-dried prior to colour measurement and analysis. A VeriVide light cabinet model: CAC 150 was used to observe any residual dye on the multifibre sample.

Figure 117: Individual beakers and Washtech machine

Multifibre test fabrics were assessed using D65 artificial daylight. Observations were made per batch to gain a generalised indication of fastness and in relation to a blank non-tested (standard/control) multifibre for comparison with the original appearance (Figure 118).

Figure 118: Fabrics assessed inside light cabinet for wash fastness by batch and per specimen

The grey scale for assessing change in colour complies with ISO 105-A02. The grey scale for assessing staining complies with ISO 105-A03, shown in Figure 119.

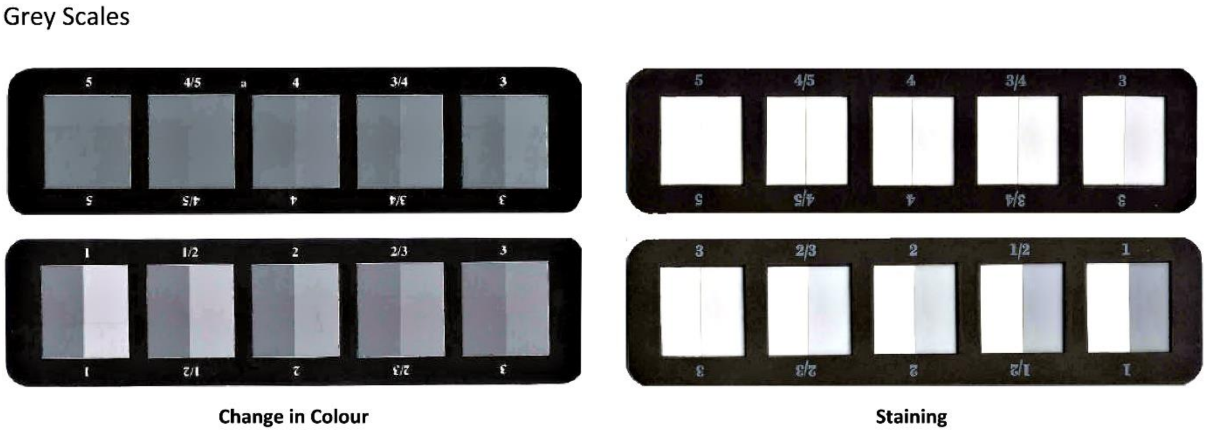


Figure 119: ISO Grey scales for assessing Change in Colour and Staining
(TLF Leather Technology Ltd. 2004, pp. 3-4)

Each grey scale has nine pairs: values – 5, 4-5, 4, 3-4, 3, 2-3, 2, 1-2, 1. 5 is the best rating signifying no visible change regarding change in colour or staining. 1 is the worst rating meaning significant visual change in both assessments. A minimum value of 4 is deemed acceptable for apparel applications according to industry standards. All nine values contain a portion of optimal value 5 which is Grey for *Change in Colour* and White for *Staining*. Value 5 has a 100% portion shown as a tonally even square. The rest have 50% of optimal Grey or White respectively. The other 50% indicates a value of visual change i.e. contrast. So, all ratings below 5 are equally divided by two different tones.

Results were obtained by isolating a small area of the fabric and blank multifibre against an isolated greyscale rating. To assess Change in Colour, a single measurement was observed across the batch. Each fibre was observed in turn to assess Staining. A total of seven results were obtained per fabric sample.

5.2.4.2 Results

Table 22 and Figure 120 document wash fastness test results carried out. Sample categories comprised:

- **Dyed/Not Treated – 1% Shade**: Dyed only (standard)
- **Dyed/Not Treated – 0.5% Shade**: Dyed only (standard)
- **Laser-dyed: Greyscale (GS): 100% - 1% Shade**: All over raster scanning with 100% grey tone generated via CAD (flat colour/no pattern)
- **Laser-dyed: Greyscale (GS): 70% - 1% Shade**: All over raster scanning with 70% grey tone generated via CAD (flat colour/no pattern)

- **Laser-dyed/patterned – 1% Shade**: Laser modified repeat design (CAD/raster)
- **Laser-dyed/patterned – 0.5%**: Laser modified repeat design (CAD/raster)

A high rate of wash fastness was recorded. Out of 273 results obtained:

- **161** results yielded a rating of *5*
- **100** results yielded a rating of *4-5*
- **9** results yielded a rating of *4*
- **3** results yielded a rating of *3-4.*

Generalisations across batches revealed excellent fastness in batches 6/Red (samples 20-23) and 10/Purple (samples 33-35), with a rating of *5* throughout regarding assessment of staining. Comparatively, such results were not recorded in batch 3/Lt. Orange/Yellow (samples 9-12) where a rating of *4-5* was predominant. These results may simply be attributed to the fastness of each dye compound opposed to laser treatment. All 39 samples yielded a result of *4-5* concerning change in colour, therefore reporting very good wash fastness. Patterned samples dyed at 0.5% DoS produced a marked change in colour of *3-4*. In consultation with the SDC, it was agreed fabric samples dyed with shade depth less than 1% would not undergo after-treatment post dyeing as such process would affect the shade and appearance of colour. Therefore, these results implied loose dye particles remained on the fabric limiting wash fastness, which is understood.

Overall, results indicate stability of the laser-dye process explored in this study. Outcomes therefore suggest as a textile coloration approach, digital laser-dyeing is technically robust in terms of wash fastness.

			Sample	Change in Colour	Assessment of Staining: Acetate	Cotton	Nylon 6.6	Polyester	Acrylic	Wool
			DES 1 / COLL1: DRK BLUE/PUR							
C1:S1	1	1	Not Trtd - 1% Shade	4-5	5	5	4-5	5	5	5
C1:S1	2	2	GS: 70% - 1% Shade	4-5	5	5	4-5	5	5	5
C1:S1	3	3	Patterned - 1% Shade	4-5	5	5	4-5	5	5	5
C1:S1	4	4	Not Trtd - 0.5% Shade	4-5	5	5	4-5	5	5	5
C1:S1	5	5	Patterned - 0.5% Shade	4-5	4	4-5	3-4	4	4-5	5
			DES 5 / COLL1: AUBERGINE							
C1:S2	6	1	Not Trtd - 1% Shade	4-5	5	5	4-5	5	5	5
C1:S2	7	2	GS: 70% - 1% Shade	4-5	5	5	4-5	5	5	5
C1:S2	8	3	Patterned - 1% Shade	4-5	5	5	4-5	5	5	5
			DES 3 / COLL1: LT. ORNG/YELL							
C1:S3	9	1	Not Trtd - 1% Shade	4-5	4-5	4-5	4	4-5	4-5	4-5
C1:S3	10	2	GS: 70% - 1% Shade	4-5	4-5	4-5	4	4-5	4-5	4-5
C1:S3	11	3	GS: 100% - 1% Shade	4-5	4-5	4-5	4	4-5	4-5	4-5
C1:S3	12	4	Patterned - 1% Shade	4-5	4-5	4-5	4	4-5	4-5	4-5
			DES 4 / COLL1: GREY-GREEN							
C1:S4	13	1	Not Trtd - 1% Shade	4-5	5	5	4-5	5	5	5
C1:S4	14	2	GS: 70% - 1% Shade	4-5	5	5	4-5	5	5	5
C1:S4	15	3	Patterned - 1% Shade	4-5	5	5	4-5	5	5	5
			DES 1 / COLL2: BLUE							
C2:S5	16	1	Not Trtd - 1% Shade	4-5	5	4-5	4-5	4-5	5	5
C2:S5	17	2	GS: 70% - 1% Shade	4-5*	5	5	4-5	4-5	5	5
C2:S5	18	3	GS: 100% - 1% Shade	4-5**	5	5	4-5	5	5	5
C2:S5	19	4	Patterned - 1% Shade	4-5	5	5	4-5	5	5	5
			DES 5 / COLL2: RED							
C2:S6	20	1	Not Trtd - 1% Shade	4-5	5	5	5	5	5	5
C2:S6	21	2	GS: 70% - 1% Shade	4-5	5	5	5	5	5	5
C2:S6	22	3	GS: 100% - 1% Shade	4-5	5	5	5	5	5	5
C2:S6	23	4	Patterned - 1% Shade	4-5	5	5	5	5	5	5
			DES 2 / COLL2: MAGENTA							
C2:S7	24	1	Not Trtd - 1% Shade	4-5	4-5	5	4-5	5	5	5
C2:S7	25	2	GS: 70% - 1% Shade	4-5	4-5	5	4-5	5	5	5
C2:S7	26	3	Patterned - 1% Shade	4-5	4-5	5	4-5	5	5	5
C2:S7	27	4	Not Trtd - 0.5% Shade	4-5	4-5	5	4-5	5	5	5
C2:S7	28	5	Patterned - 0.5% Shade	4-5	3-4	4-5	3-4	4	4-5	4-5
			DES 3 / COLL2: GREEN							
C2:S8	29	1	Not Trtd - 1% Shade	4-5	5	5	5	5	5	5
C2:S8	30	2	GS: 70% - 1% Shade	4-5	5	5	5	5	5	5
			DES 3 / COLL1: RED							
C3:S9	31	1	Patterned - 1% Shade	4-5	4-5	5	5	5	5	5
C3:S9	32	2	Patterned - 0.5% Shade	4-5	4	4-5*	4	4-5	5	5
			DES 4 / COLL2: PURPLE							
C3:S10	33	1	Not Trtd - 1% Shade	4-5	5	5	5	5	5	5
C3:S10	34	2	GS: 70% - 1% Shade	4-5	5	5	5	5	5	5
C3:S10	35	3	Patterned - 1% Shade	4-5	5	5	5	5	5	5
			DES 3 / COLL2: GREEN							
C3:S11	36	1	GS: 100% - 1% Shade	4-5	4-5	5	4-5	5	5	5
C3:S11	37	2	Patterned - 1% Shade	4-5	4-5	5	*4-5	5	5	5
C3:S11	38	3	Not Trtd - 0.5% Shade	4-5	4-5	5	4-5	5	5	5
C3:S11	39	4	Patterned - 0.5% Shade	4-5	4-5	5	4-5	5	5	5

Ratings	
(orange)	5
(green)	4-5
(red)	4
(yellow)	3-4

Key	
Red	Industry Standard assessment are
*/**	No official assessment for result
C:S	Cycle:Set

Table 22: Wash fastness test results table

Figure 120: Wash fastness test results graph

5.2.5 ISO Textile performance tests

ISO tests were undertaken on treated fabrics to assess the mechanical performance of laser modified fabrics. Both woven and knitted polyester samples were tested as appropriate, outlined in Table 23. Modified samples were processed with varied laser parameters generated using the raster/greyscale/CAD approach. Untreated fabrics were tested to identify any differences between the two sample types.

Textile Performance Test	Standard (ISO)	Fabric samples tested
Tensile Strength *Determination of maximum force and elongation at maximum force using the strip method*	**BS EN ISO 13934-1: 1999 Part 1: Woven fabrics only**	**Woven polyester** Untreated warp and weft; Laser-dyed/patterned warp and weft
Tear Resistance *Determination of tear force using ballistic pendulum method*	**BS EN ISO 13937-1: 2000 Part 1: Woven and knitted fabrics**	**Woven and knitted polyester** Untreated warp and weft; Laser-dyed/patterned warp and weft
Burst Strength *Pneumatic method for determination of bursting strength and bursting distension*	**BS EN ISO 13938-2: 1999 Part 2: Knitted fabrics only**	**Knitted polyester** Untreated; Laser-dyed all over tonal colour (varying energy densities); Laser-dyed/patterned
Dimensional Stability *Preparation, marking and measuring of fabric specimens and garments in tests for determination of dimensional change; Domestic washing and drying procedures for textile testing*	**BS EN ISO 3759: 1995 and BS EN ISO 6330: 2001: Woven and knitted fabrics**	**Woven and knitted polyester** Untreated; Laser-dyed/patterned

Table 23: Textile performance tests carried out in the study

Data collection occurred in log books (e.g. Figure 121) through first-hand interaction with ISO test methods. The data was later analysed and visualised in order to understand and discuss the DLD process in relation to the performance characteristics of PET woven and knitted fabrics.

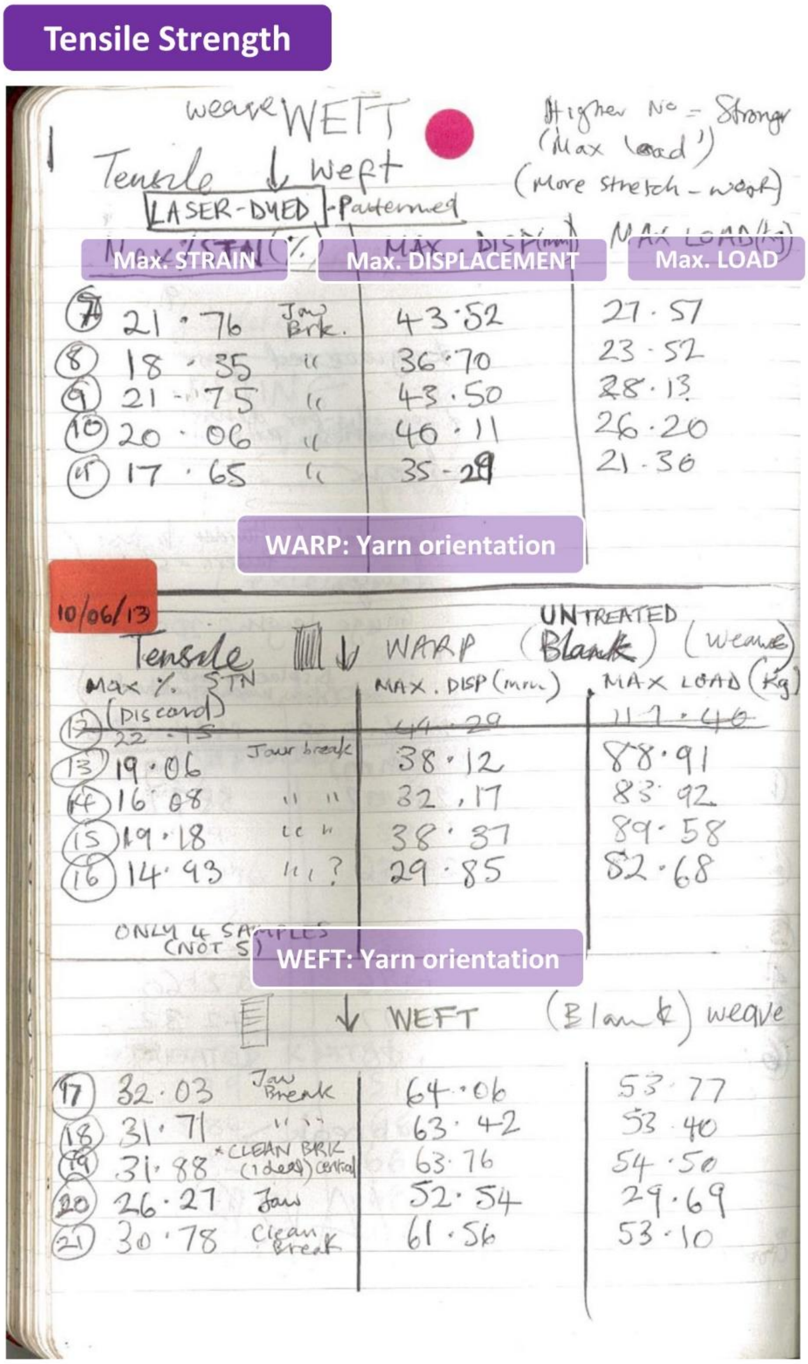


Figure 121: Tensile Strength - Example of data collection for test specimens recorded in log books

5.2.5.1 Tensile Strength

Two different laser-patterns were tested:

- Type A – an all over structured repeat design (Figure 122)
- Type B - an all over (non-repeating) textural design (Figure 123)

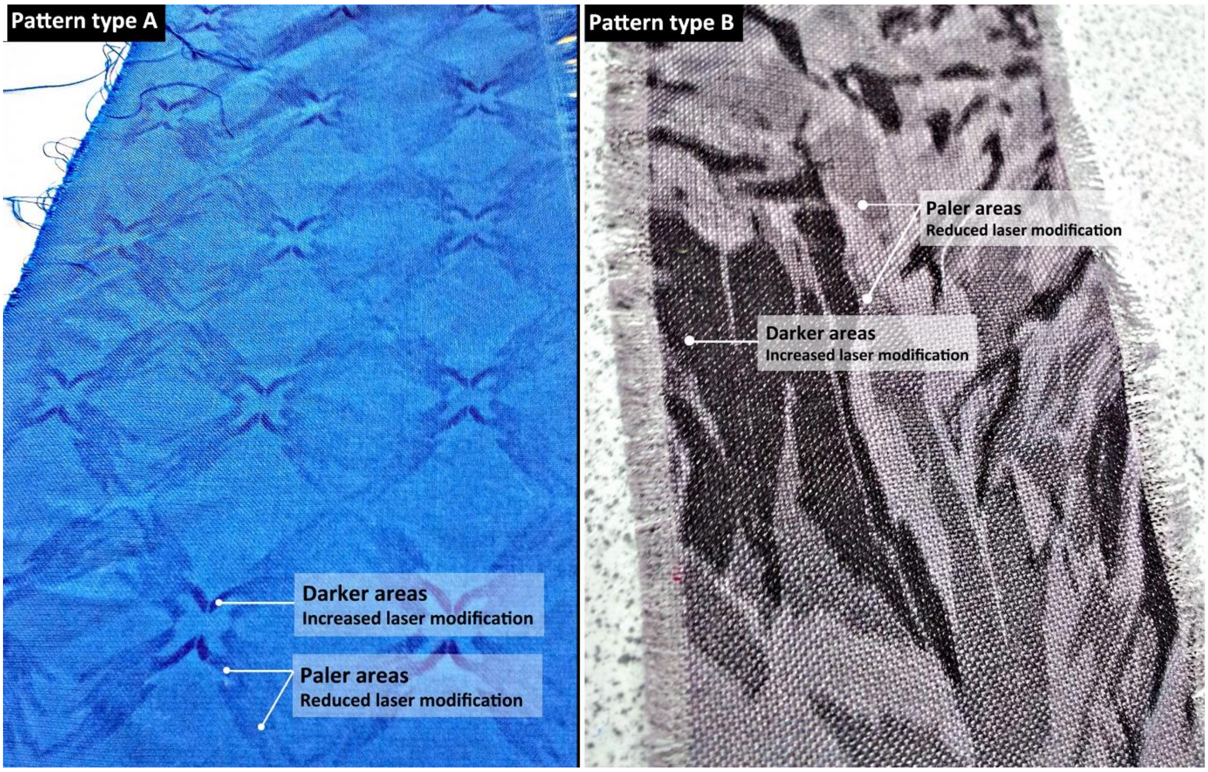


Figure 122: (Left) Tensile Strength test: Pattern Type A – an all over structured repeat design
Figure 123: (Right) Tensile Strength test: Pattern Type B - an all over (non-repeating) textural design

Each pattern type contained differential tonality due to specified variable energy density parameters embedded in to the design. More tests were carried out on pattern type A based on preference in terms of the design aesthetic, the amount of laser modified fabric generated for each pattern type and for functional reasons. By anticipating where the highest result would be yielded in relation to pattern composition and laser modification levels, pattern A was considered most suitable. Pattern type A possesses small areas of increased laser modification identified by darker shades due to deeper dyeing distributed in a regular repeated sequence across the fabric. This tonal distribution indicates minimal and confined denaturing of fibres. In comparison, pattern type B has larger, broader areas of increased fibre-laser interaction represented by bold laser-dyed engineered shapes. Subtler areas in both pattern types signify reduced fibre/laser interaction and paler dye uptake.

Tests specimens included vertical warp and weft fabrics. Results therefore indicated the impact of laser modification to textile fibres in relation to textile structure and orientation of the woven cloth. Performance data reported Maximum Strain (%), Maximum Displacement (mm) i.e. stretching and Maximum Load (Kg). Warp and weft results were obtained for pattern type A and weft only for pattern type B based on the amount treated fabric available. Both warp and weft, untreated (not laser modified, dyed or patterned) samples were tested. Table 24 documents data obtained.

		WARP								WEFT							
TENSILE STRENGTH MEASUREMENTS		Test Specimens					MEAN	STD. DEV.	STD ERR.	Test Specimens					MEAN	STD. DEV.	STD ERR.
		1	2	3	4	5				1	2	3	4	5			
Pattern A	Max. Load (Kg)	38.8	45.0	37.6	42.3	47.6	*42.0*	*4.0*	*1.8*	27.6	23.5	28.1	26.2	21.3	*25.0*	*2.9*	*1.3*
	Max.Strain (%)	13.0	14.8	12.4	13.9	15.4	*14.0*	*1.2*	*0.6*	21.8	18.4	21.8	20.1	17.7	*20.0*	*1.9*	*0.9*
	Max. Disp. (mm)	26.0	29.6	24.8	27.8	30.8	*28.0*	*2.5*	*1.1*	43.5	36.7	43.5	40.1	35.3	*40.0*	*3.8*	*1.7*
Pattern B	Max. Load (Kg)	40.0	33.2	40.9	47.7	36.0	*40.0*	*5.5*	*2.6*								
	Max.Strain (%)	8.7	8.4	8.7	9.6	7.9	*8.7*	*0.5*	*0.3*								
	Max. Disp. (mm)	17.4	16.8	17.4	19.2	15.8	*17.0*	*1.2*	*0.6*								
Untreated	Max. Load (Kg)	88.9	83.9	89.6	82.7		*86.0*	*3.5*	*1.6*	53.8	53.4	54.4	29.7	53.1	*49.0*	*11.0*	*4.8*
	Max.Strain (%)	19.1	16.1	19.2	14.9		*17.0*	*2.1*	*1.0*	32.0	31.7	31.9	26.3	30.8	*31.0*	*2.4*	*1.1*
	Max. Disp. (mm)	38.1	32.2	38.4	29.9		*35.0*	*4.3*	*1.9*	64.1	63.4	63.8	52.5	61.6	*61.0*	*4.9*	*2.2*

Table 24: Tensile strength test results

Graphs show the relationship between in results:

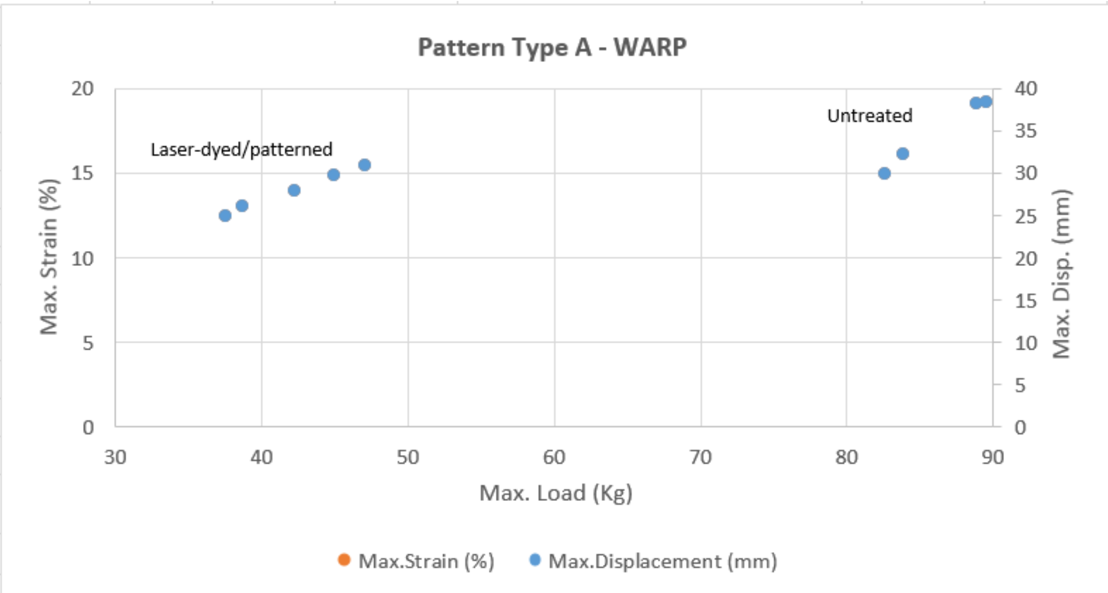


Figure 124: Tensile Strength results graph: WARP - Pattern Type A and Untreated fabric

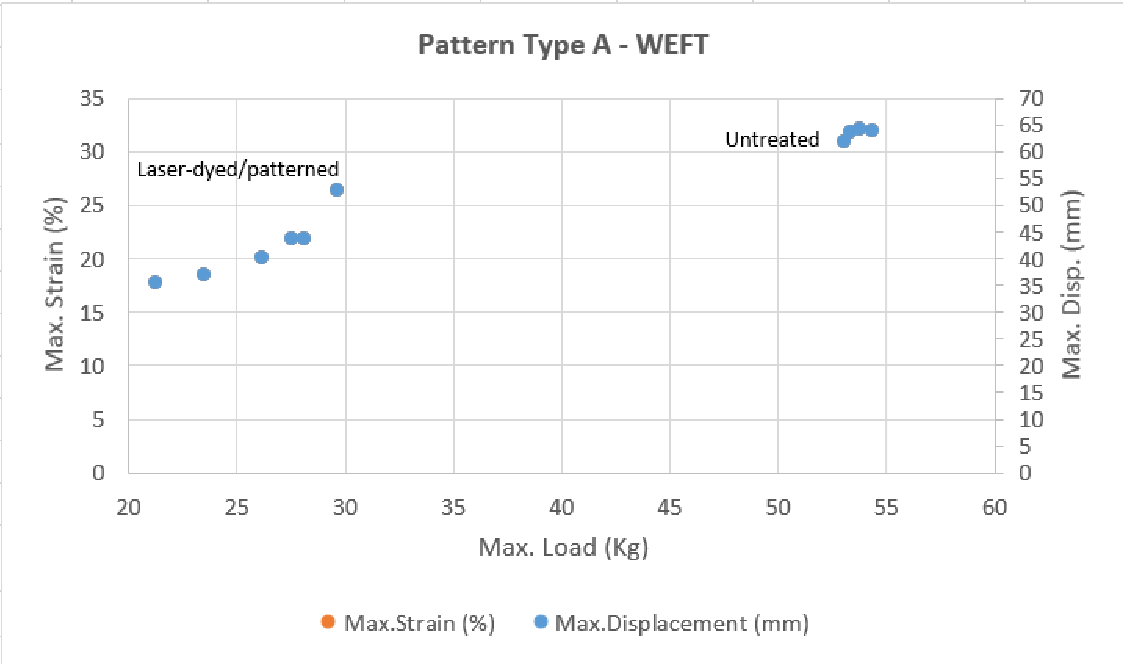


Figure 125: Tensile Strength results graph: WEFT - Pattern Type A and Untreated fabric

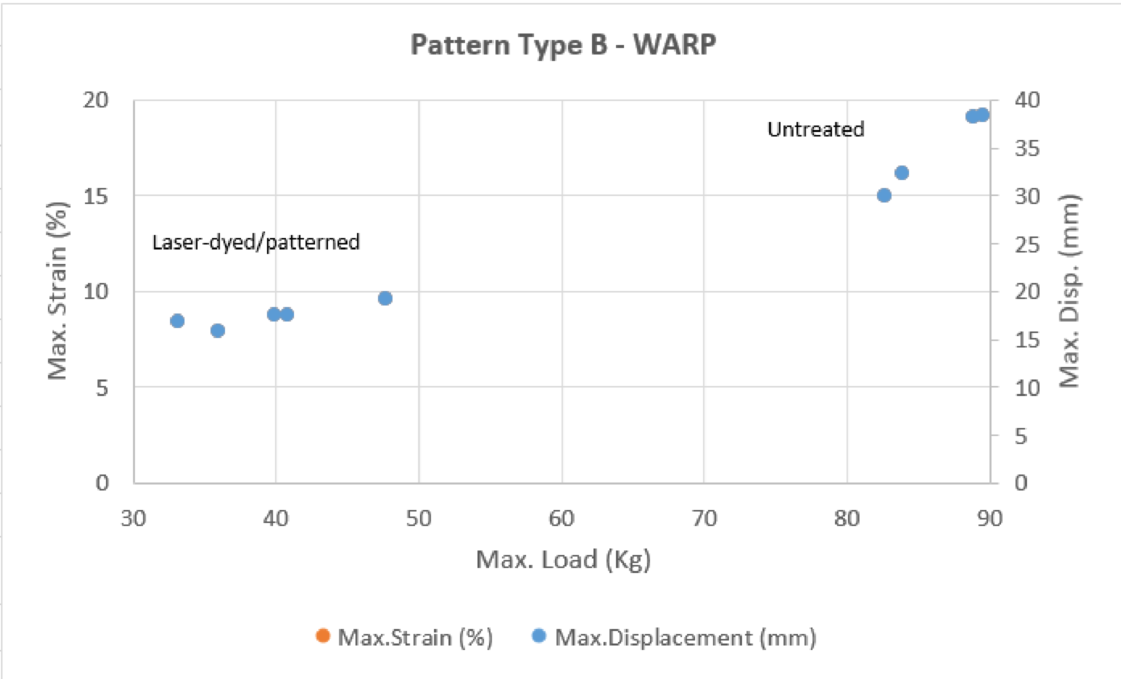


Figure 126: Tensile Strength results graph: WARP - Pattern Type B and Untreated fabric

Strain (%) was proportionate to double the rate of Displacement (mm) in relation to Load (Kg). A correlation in results was identified here. This can be seen for all samples – warp and weft, pattern type A and B as well as untreated fabrics. Pattern Type A warp samples (Figure 124) yielded greater tensile strength than Pattern Type B (Figure 126). This can be attributed to lesser laser modification and so reduced fibre degeneration. Weft specimens (Figure 125) reported higher strain/displacement compared to warp samples. Such results were expected due to the stretch capability of weft fabrics linked to woven textiles in general. Overall, untreated specimens produced greater tensile strength and results were higher across all measurements, demonstrated in each graph. This research however, identifies how laser fibre damage can be controlled and minimalised to retain textile strength.

Figure 127 shows the kind of damage that occurred for each sample type, termed ‘jaw break’. Typically, jaw break is a horizontal tear across the secimen as with the untreated sample. However, laser-dyed samples showed breakage in areas of increased laser modification relative to the pattern. This can be understood due to more fibre damage in tonally darker areas causing greater weakness.

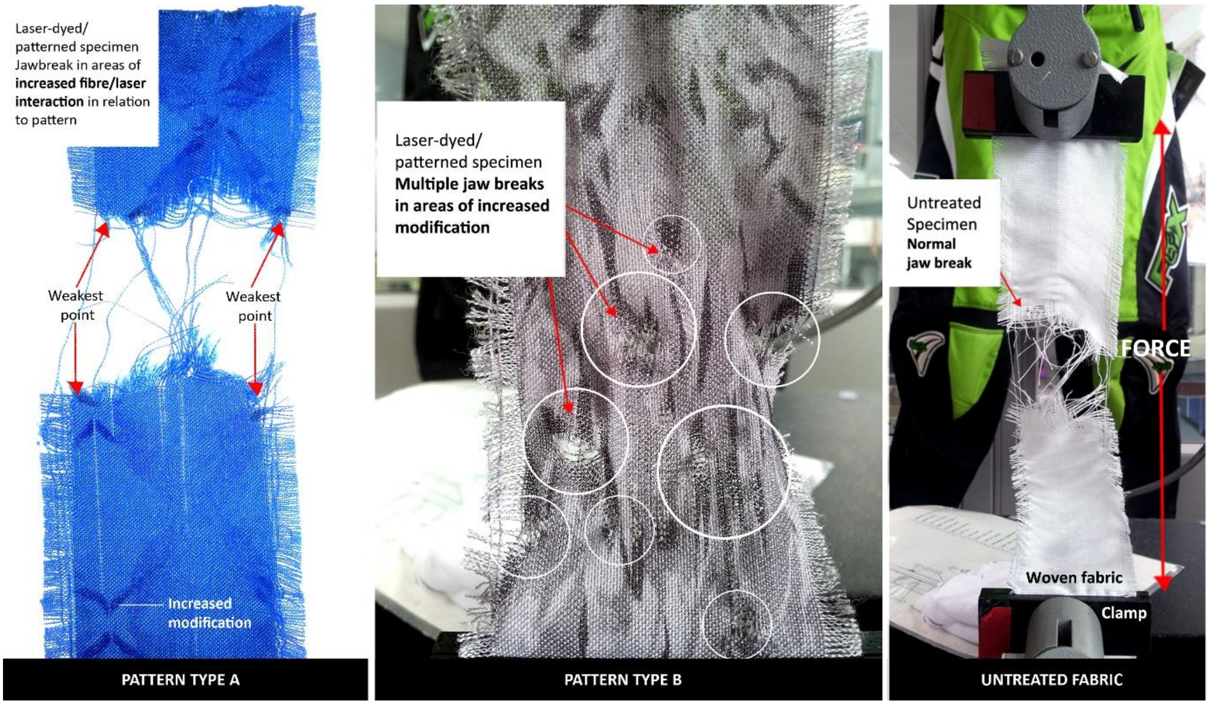
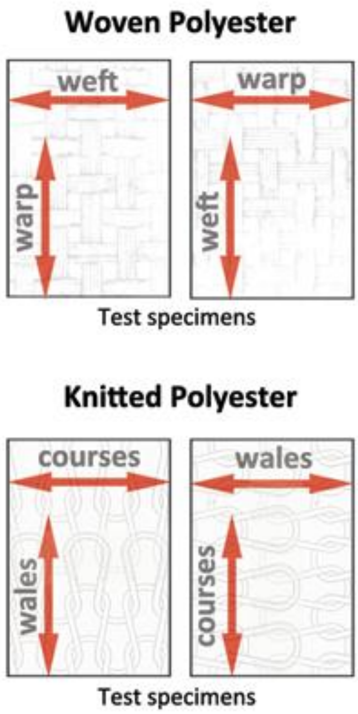


Figure 127: Tensile strength tests showing jaw break: Pattern Type A, B and Untreated specimen

5.2.5.2 Tear Resistance

In this study, woven and knitted polyester fabrics were tested for tear resistance. Samples included laser-dyed/patterned and untreated/non-patterned specimens. One pattern type was tested – ‘laser-dyed/patterned’ all over repeat Pattern type A, as in Figure 122. Performance was recorded in both directions of the sample – warp (vertical) and weft (horizontal) test specimens for plain woven samples and wales (vertical) and courses (horizontal) for knitted jersey samples, shown in Figure 128. ‘The tear force is qualified as “across warp” or “across weft" according to whether the tear is made across the warp (warp threads are torn) or weft (weft threads are torn) respectively' (BS EN ISO 13937-1:2000, p.5). Tear resistance was determined by force measured in newtons (N). Table 25 documents the results.



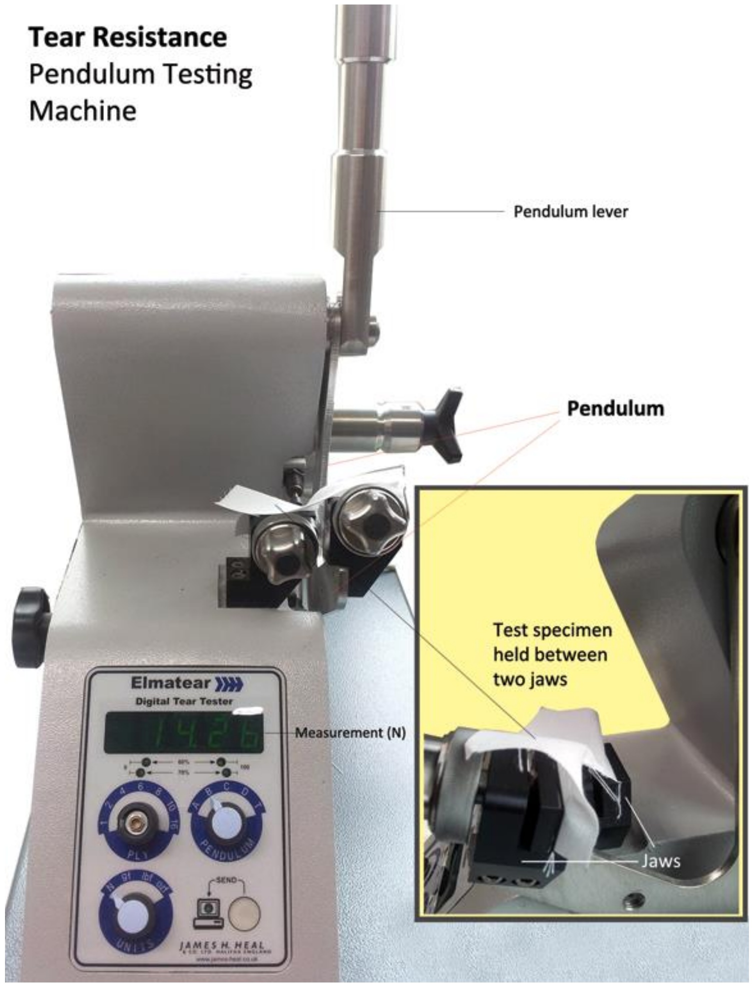


Figure 128: Tear Resistance specimens - woven and knitted polyester fabrics (Left)

Figure 129: Tear Resistance Pendulum Testing Machine; Inset: Test Specimen (Right)

		WARP/WALES								WEFT/COURSES							
		Test Specimens **(N)**					MEAN	STD. DEV.	STD ERR.	Test Specimens **(N)**					MEAN	STD. DEV.	STD ERR.
		1	2	3	4	5				1	2	3	4	5			
WOVEN	Laser-dyed/patterned	9.9	15.3	15.1	14.3	15.1	13.9	2.3	1.0	12.1	14.19	14.5	13.3	10.6	13.0	1.6	0.7
	Untreated	14.5	14.2	14.5	14.3	14.8	14.4	0.2	0.1	14.5	14.4	14.4	14.5	14.5	15.0	0.1	0.1
KNITTED	Laser-dyed/patterned	16.4	15.9	16.6	6.7	2.8	11.7	6.5	2.9	3.9	5.1	9.8	9.1	9.0	7.4	2.7	1.2
	Untreated	7.4	3.9	7.1	7.8	5.0	6.2	1.7	1.0	8.7	11.1	10.7	11.1	10.6	11.0	1.0	0.4

Table 25: Tear Resistance Results - woven and knitted polyester fabric samples

Results graphs (Figure 130 and Figure 131) provide an overview of performance per textile type.

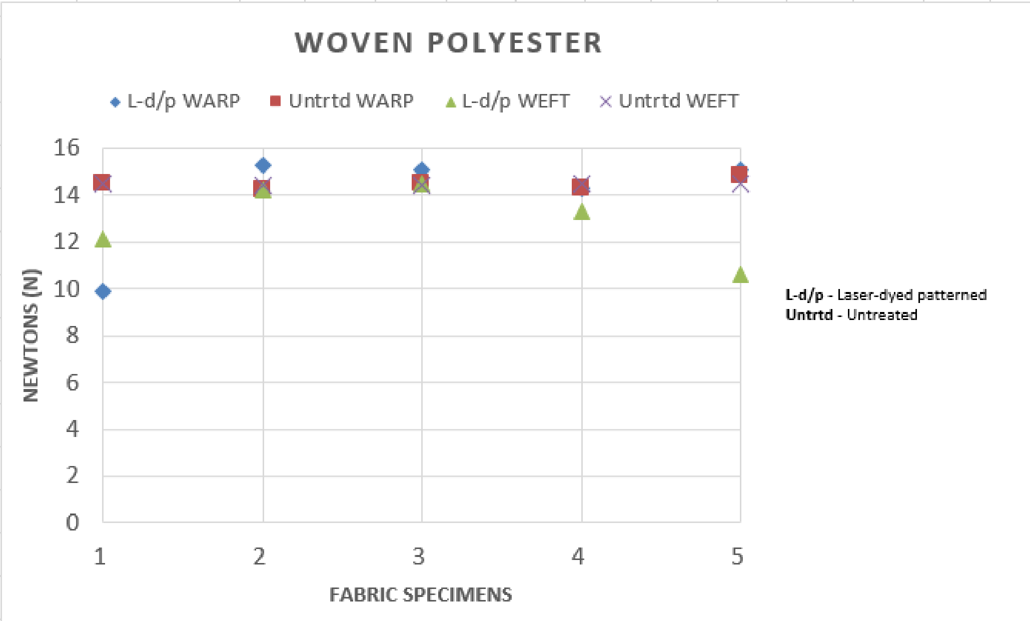


Figure 130: Tear Resistance results graph: Woven polyester

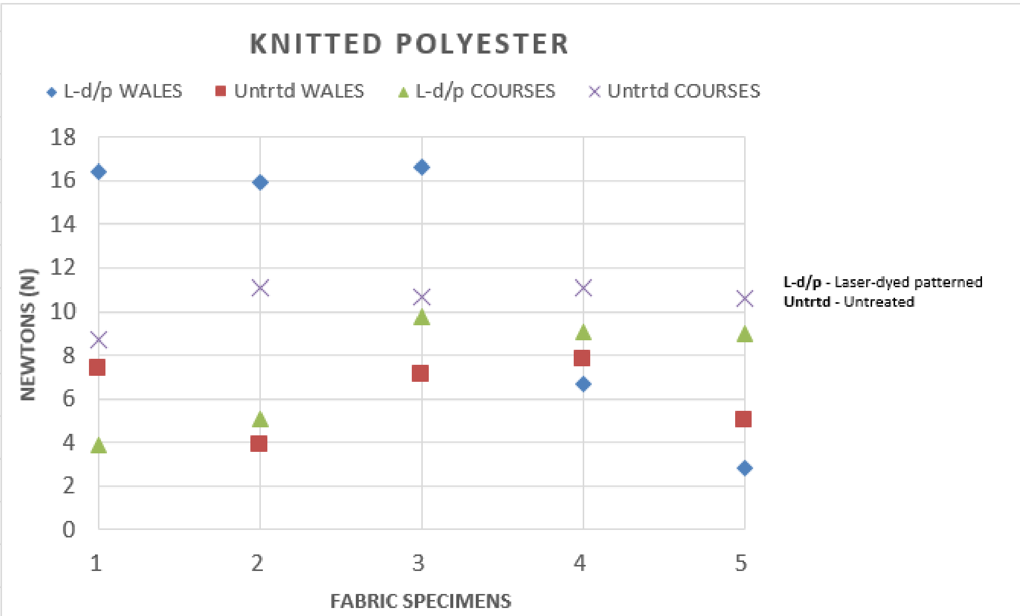


Figure 131: Tear Resistance results graph: Knitted polyester

Figure 130 (untreated warp and weft specimens) report near identical results (14N an 15N), higher than Laser-dyed/patterned weft specimens. Untreated knitted samples seen in Figure 131 and Table 25 documents relatively low standard deviation in general. Increased variability between treated specimens, particularly Laser-dyed/patterned 'wales' specimens, was also noted which can be attributed to positioning of the laser-dyed pattern per sample. Overall, untreated fabrics yielded better tear resistance regarding both ‘wales’ and ‘courses’. This result was anticipated, as it is known that laser modification weakens textile fibres. Therefore, the implications or limitations of the laser-dye process suggest that textiles processed in this way are more susceptible to tearing. It is therefore considered that extremely low laser energy densities/ subtle tonal coloration effects would be most appropriate in order to increase tear resistance.

5.2.5.3 Bursting

Bursting strength tests were carried out with knitted fabrics, according the standard. They included laser-dyed/patterned and all-over laser-dyed/non-patterned modified fabrics. An untreated/non-patterned sample was tested for comparison. Results were recorded using a bursting strength tester machine (Figure 132) which measured performance in Kilopascals (kPa): Pressure, Millimetres (mm): Extension and Seconds (s): Time taken, per test. Each sample was subject to a surge of pressure until threshold i.e. bursting, as demonstrated in Figure 133. Table 26 documents the outcomes.

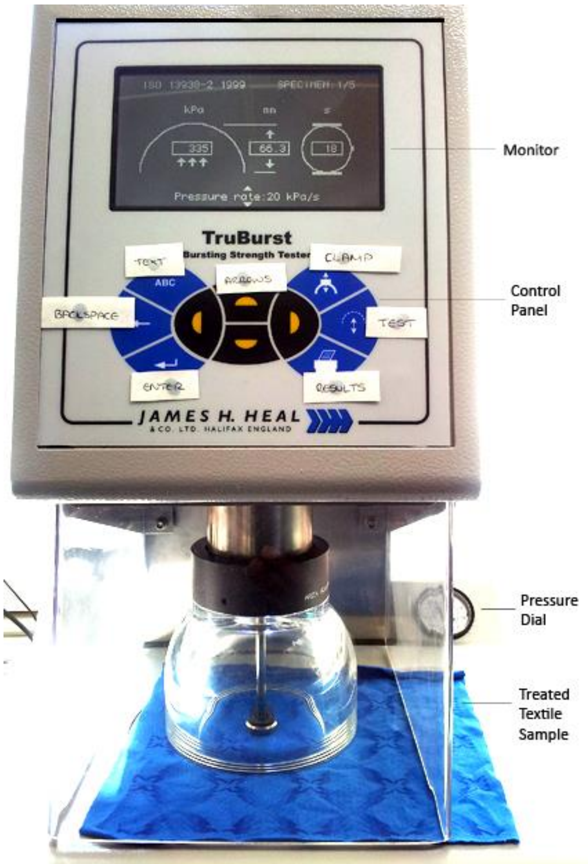
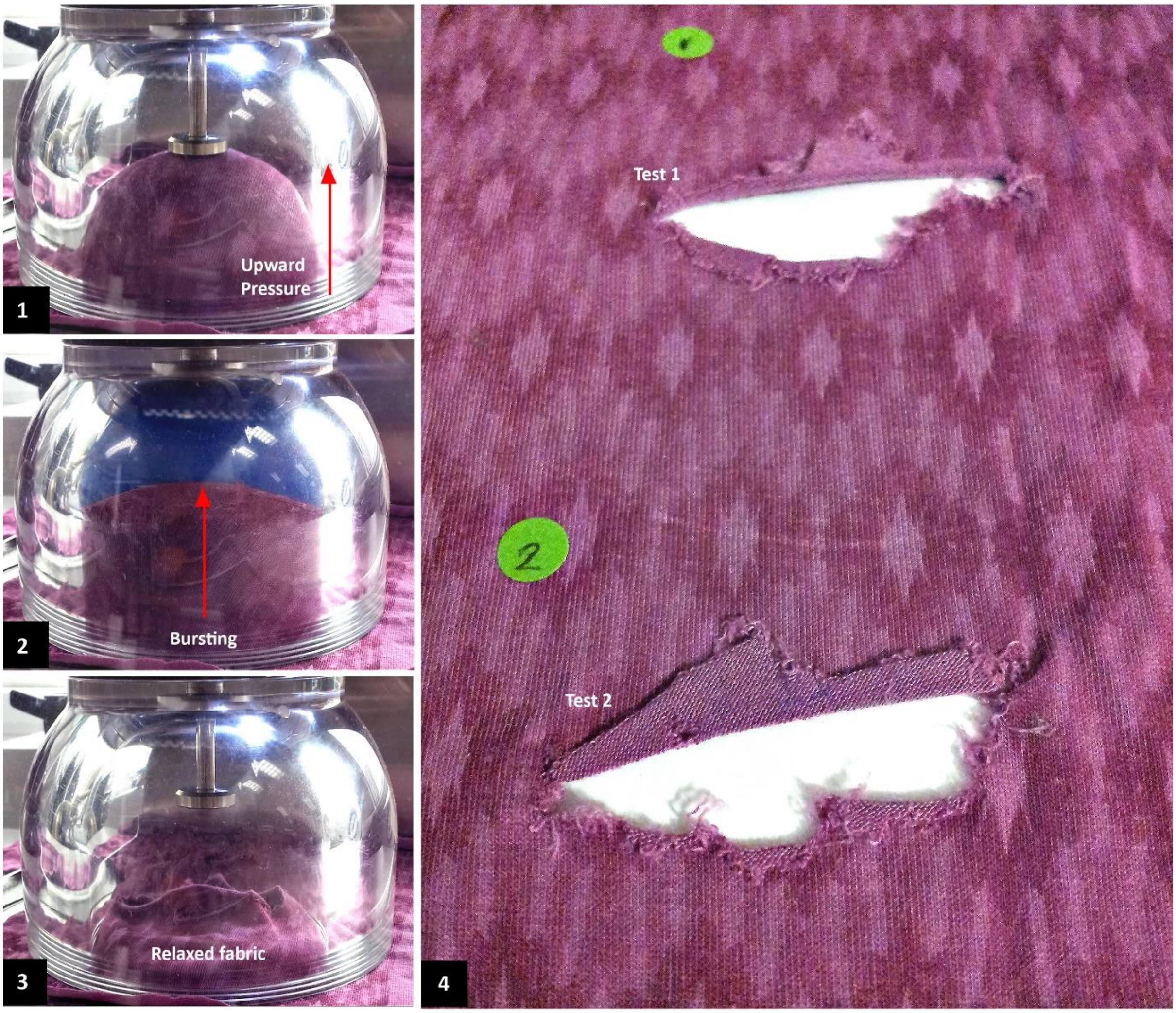


Figure 132: Bursting Strength Tester Machine



1. Laser-dyed textile sample subject to a surge of air pressure during test; 2. Bursting threshold - fibre breakage, 3. Relaxed fabric after testing; 4. Tested sample

Figure 133: Bursting Strength testing

Test results set out in Table 26 and Figure 134 show the untreated sample (1) had the greatest bursting strength compared to laser treated fabrics, both laser-dyed/patterned and laser-dyed/ non-patterned (samples 2-12). Although only a marginal difference in extension (mm) and time taken (s) was recorded, threshold pressure (kPa) was distinctly higher. Variable strength amongst laser-dyed/patterned samples (3-9) can be attributed to a difference in processing and design parameters such as tonality/energy density and pattern composition. Amongst non-patterned samples (10-12), a decline in bursting strength correlated with increased laser modification, which was understood. Sample 10 – GS: 70%, yielded greater performance compared to sample 12 – GS: 90%, processed with more laser beam energy. Performance measured confirmed a known denaturing effect of textile fibres due to laser modification.

		Bursting Strength															
		kPa					mm					s					
	Test Samples	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
1	Untreated	299.0	384.0	412.0	370.0	335.0	51.3	66.4	66.4	66.2	66.3	19.0	20.0	21.0	20.0	18.0	*x5 tests according to ISO Standard*
	Mean	360.0					63.3					19.6					
	Std Dev	44.0					6.7					1.1					
	Std Error	19.7					3.0					1.0					
2	Laser-dyed/patterned	179.0	176.0	202.0	155.0	137.0	37.5	38.2	39.7	36.1	36.4	10.0	10.0	11.0	9.0	8.0	*x5 tests according to ISO Standard*
	Mean	169.8					37.6					9.6					
	Std Dev	24.8					1.5					1.1					
	Std Error	11.1					1.0					1.0					
3	Laser-dyed/patterned (F)	157.0	156.0				35.8	36.1				9.0	9.0				*Subsequent Laser-dyed/patterned samples*
	Mean	156.5					36.0					9.0					
	Std Dev	1.0					0.2					0					
	Std Error	0.3					0.1					0					
4	Laser-dyed/patterned (G)	236.0	270.0				41.0	42.6				13.0	15.0				
	Mean	253.0					41.8					14.0					
	Std Dev	24.0					1.1					1.4					
	Std Error	10.8					1.0					1.0					
5	Laser-dyed/patterned (H)	171.0	216.0				38.3	39.7				10.0	12.0				
	Mean	194.0					39.7					11.0					
	Std Dev	31.8					2.0					1.4					
	Std Error	14.2					1.0					1.0					
6	Laser-dyed/patterned (I)	155.0	157.0				35.6	35.6				9.0	9.0				
	Mean	156.0					35.6					9.0					
	Std Dev	1.4					0					0					
	Std Error	0.6					0					0					
7	Laser-dyed/patterned (J)	239.0	155.0				43.9	38.4				13.0	11.0				
	Mean	197.0					41.1					12.0					
	Std Dev	59.4					3.9					1.4					
	Std Error	26.6					1.7					0.6					
8	Laser-dyed/patterned (K)	291.0	217.0				66.6	39.5				15.0	13.0				
	Mean	254.0					53.1					14.0					
	Std Dev	52.3					19.2					1.4					
	Std Error	23.4					8.6					1.0					
9	Laser-dyed/patterned (L)	195.0	197.0				38.6	37.5				11.0	11.0				
	Mean	196.0					38.1					11.0					
	Std Dev	1.4					1.0					0					
	Std Error	0.6					0.3					0					
10	GS:70%	257.0	282.0	237.0			43.5	66.6	43.3			16.0	15.0	13.0			*All-over raster scanning: variable parameters*
	Mean	258.7					51.1					14.7					
	Std Dev	22.6					13.4					1.5					
	Std Error	10.1					6.0					1.0					
11	GS:80%	235.0	242.0	237.0			42.3	41.8	41.2			13.0	13.0	13.0			
	Mean	238.8					41.8					13.0					
	Std Dev	3.6					1.0					0					
	Std Error	1.6					0.2					0					
12	GS:90%	198.0	172.0	177.0			37.2	34.2	35.4			11.0	10.0	11.0			
	Mean	182.3					35.6					10.3					
	Std Dev	13.8					1.5					0.6					
	Std Error	6.2					0.7					0.3					

Table 26: Bursting strength test results: Knitted polyester samples

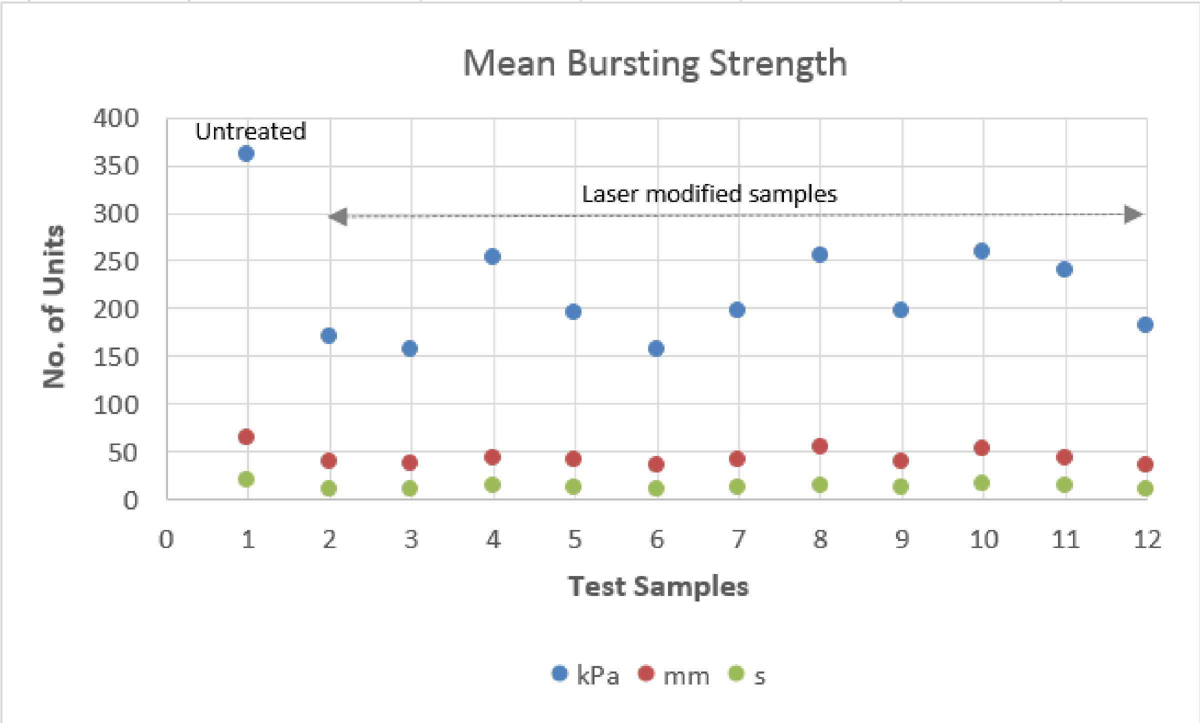


Figure 134: Bursting strength results graph

5.2.5.4 *Dimensional Stability*

Tests for dimensional stability were carried out in this research according to the standard (outlined in Table 23). The purpose of such assessment was to understand the effect of a laser-dye process explored, if any, in relation to domestic washing and drying textile procedures in terms of shrinkage or stretching. In order to determine dimensional change, treated and untreated woven and knitted fabric specimens were prepared for testing. This involved measuring, marking and sewing each sample as demonstrated in Figure 135. Following washing and drying procedures undertaken, markings were re-measured. Results showed no dimensional change. The distance between points recorded for all samples remained the same after testing. Outcomes therefore suggest a laser-dye textile coloration process investigated does not impact the dimensional stability of modified woven and knitted polyester fabrics.

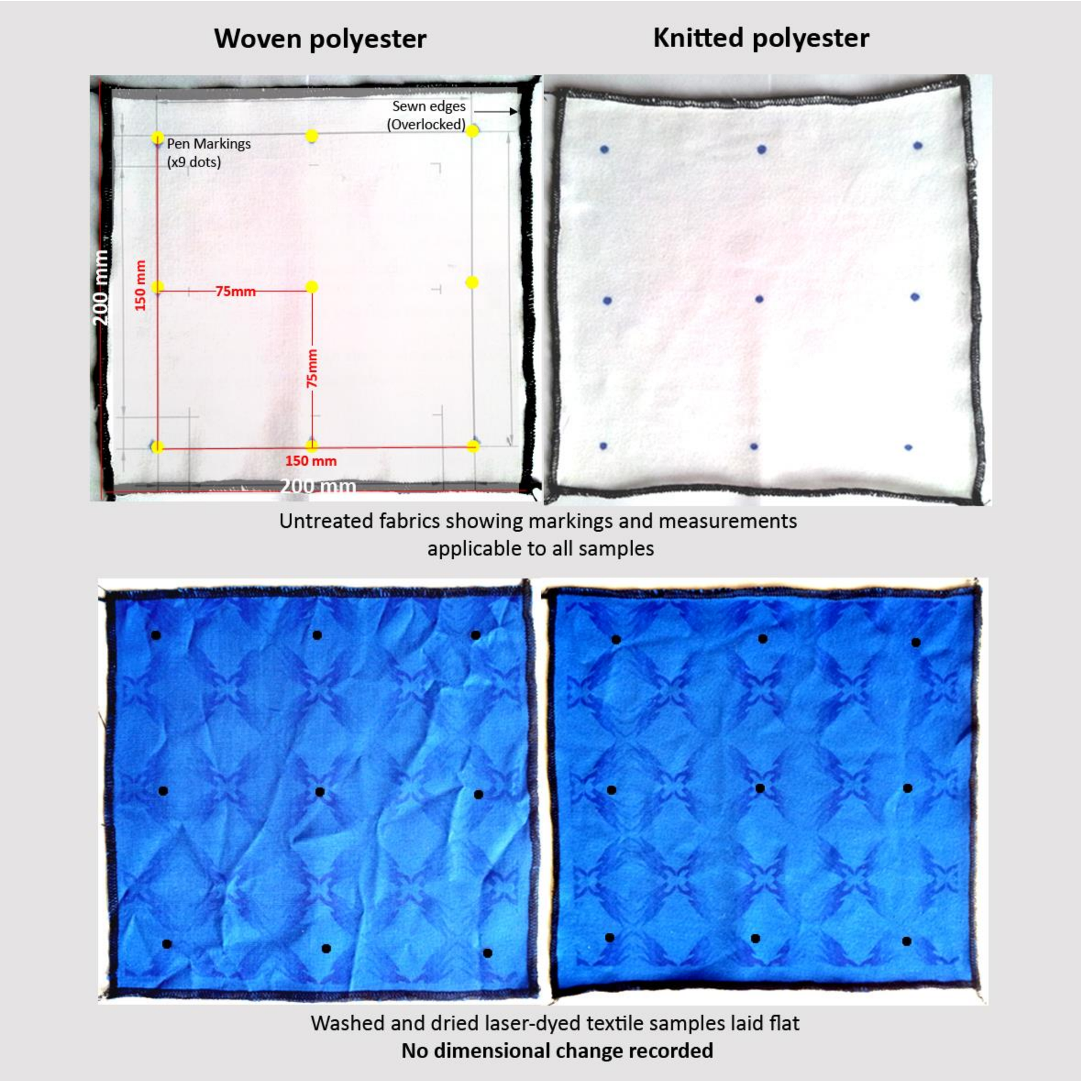


Figure 135: Samples tested for dimensional stability

To summarise, four different types of ISO performance tests were carried out (Tensile Strength; Tear Resistance; Bursting; and Dimensional Stability) on laser-dyed, laser-dyed/patterned and untreated knitted and woven PET fabrics. In doing so, the results mainly confirmed that laser processing (PET) textiles in this way denatures surface fibres. In particular, where laser energy density was increased or significant. Overall, in areas where the fabric was minimally laser modified to produce subtler tones/shades, higher textile performance was recorded. By comparison, untreated specimens yielded the highest properties, which was anticipated. However, regarding dimensional stability, no dimensional change was recorded. Therefore, these results indicate that the laser-dye process does not affect fabric structure in relation to shrinkage or stretching, as previously discussed. The benefits of this in terms of application means that factors such as drape and sizing regarding apparel for example, would not be affected when garments are laundered, relevant to woven and knitted polyester fabrics.

5.2.6 Textile design development

In this research, laser technology has been investigated as a digital precision dyeing tool for textiles. The process is capable of achieving tonally varied dye uptake via high resolution graphics, not possible with conventional dyeing. Combined laser and dyeing methods determined specified repeatable surface effects. An ability to understand and control laser-dye processing parameters and quantitatively interpret the outcomes, already discussed in this chapter, aided design development as demonstrated in this section.

By focusing on the following areas: ‘High resolution graphics for textile patterning’; and ‘Prototype garments: Surface design and 3D processing’, it was possible to explore the potential of the DLD process from a textile design perspective, as a practitioner. In this manner, the planning and development of specified creative effects in the form of gradient repeat CAD patterns, which considered colour, scale, composition and tonal distribution of the dye was investigated using PET woven and knitted fabrics. Potential application of the designs (patterns/surface effects) for textile products have been proposed by employing PET sportswear garments, garment sections and intimate apparel items. This enabled the relationship between pattern and garment to be explored such as placement considerations (Figure 136), for example, as well as capability of DLD processing three-dimensional, constructed and finished garments.

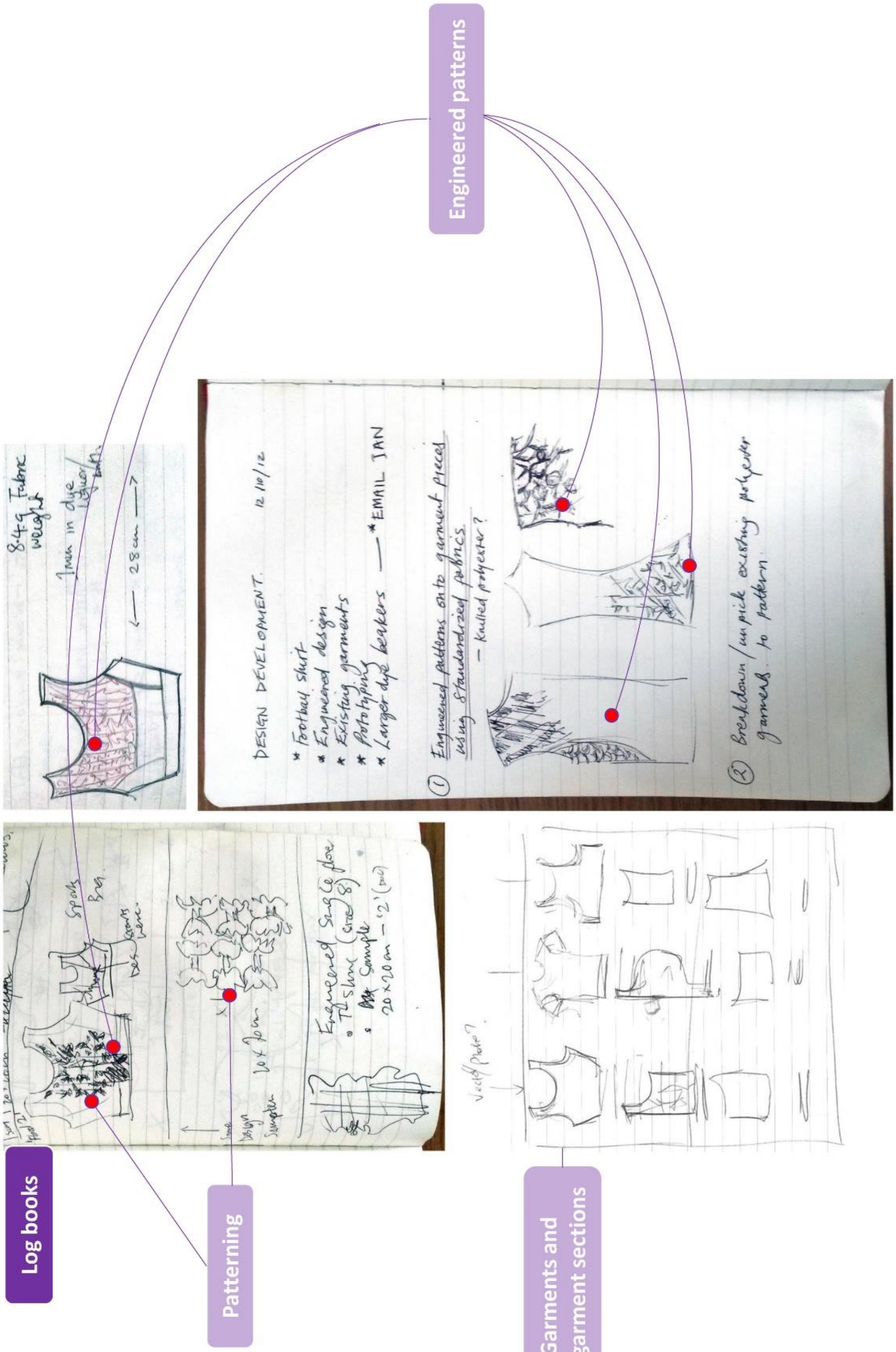


Figure 136: Planning for patterning: garment prototypes

5.2.6.1 High resolution graphics for textile patterning

The digital laser-dye process undertaken in this study involved both laser technology and computer aided design (CAD) methods. This relationship facilitated textile coloration and patterning. The laser beam (spot) was considered in the same way as a dots-per-inch principle used in printing processes. It was therefore possible to utilise the beam as an ‘image-making’ instrument for modifying textile fibres with controlled laser energy. Resolution capability was determined by laser and design parameters such as spot size, beam scanning and software issues (previously discussed). This enabled sharp consistent pattern depiction demonstrated through engineered tonal dye uptake.

A monochromatic ‘Greyscale’ (GS) design approach was investigated in the development of graphics (further discussed in sections 4.1 and 4.2 of this chapter). Percentages of black (grey) in the form of engineered repeat patterns were initiated by CAD data and creative input, illustrated in Figure 137. This technique facilitated controlled variable power output in laser processing. Such was achieved with a raster scanning method based on ‘filling in’ generated by the laser beam. Each GS% influenced a different energy density. When combined with specified laser parameters, this system determined differential dye uptake based on variable fibre modification.

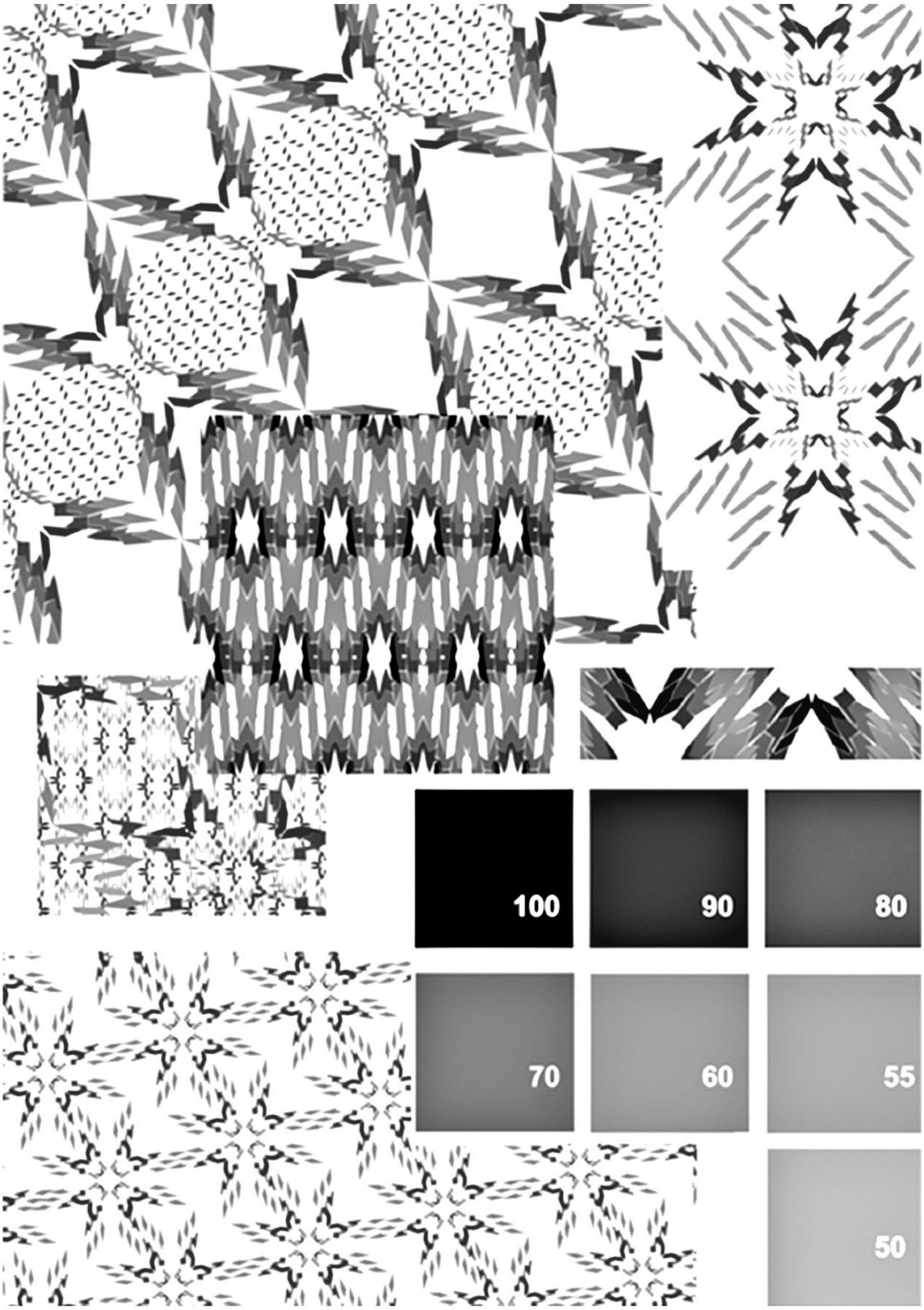


Figure 137: Greyscale CAD patterns and design parameters

Figure 138*:* is a screen image showing how a greyscale CAD design is converted to halftone via laser software for raster scanning. Each GS% generates a unique halftone which alters the energy density of the laser beam during processing enabling alternate fibre modification levels.

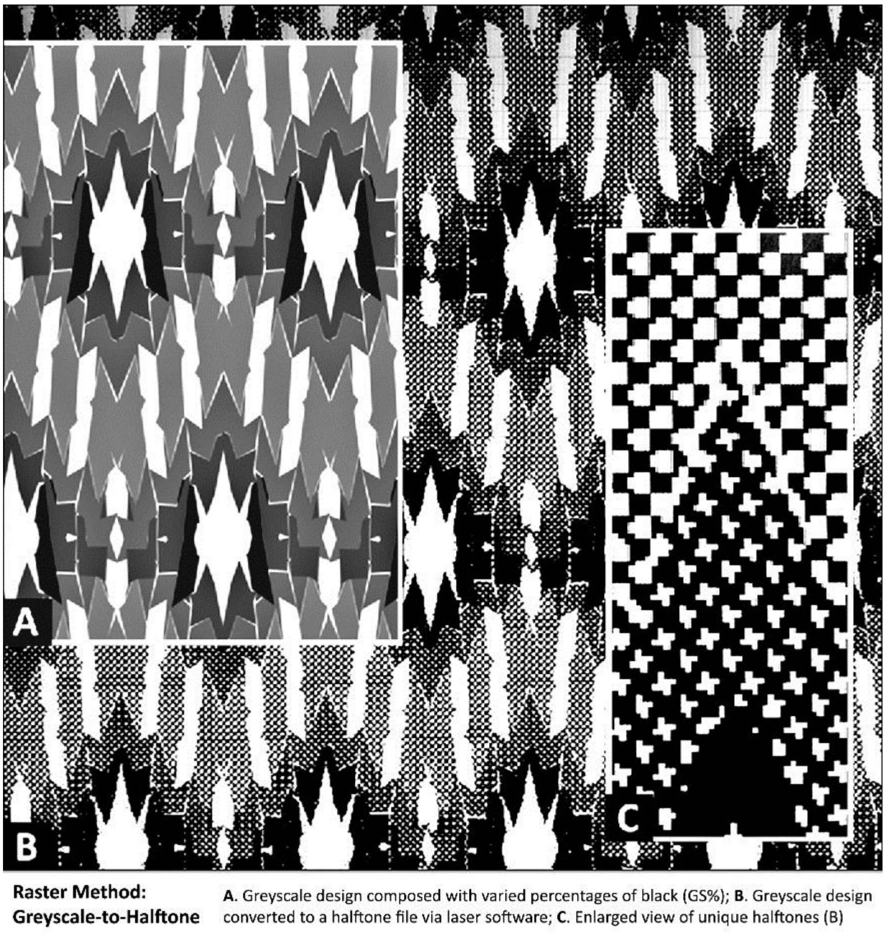


Figure 138*:* Greyscale design (not to scale): monitor image showing conversion to halftone mode (100% view: 50mm x 60mm section of a 200mm x 200mm design/fabric sample

An understanding of actual power output in relation to design information and processing parameters made it possible to digitally calibrate data to produce repeatable effects. Sufficient knowledge of a laser-dye process meant that outcomes could be manipulated in terms of surface quality and colour appearance. Similarly, Figure 140 simulates how the design may be constructed using a vector method discussed in section 5.2.2.2 of this chapter. A unique linear grid pattern was created for each component of the design motif to engineer differential energy density. The single motif was repeated to emulate the original pattern. However, this vector approach for creating patterns, rather than isolated blocks of colour, was challenging in terms of computer software compatibility for preparing patterns in this way. More complex linear vector grids, as in Figure 140, did not adequately modify the fabric surface when laser scanned, depicting only vague areas of the pattern and insufficient representation of designs. Although several attempts were carried out, including simpler designs, the results were the same. Digitally, this suggests the computer software has some way to go in terms of laser-dye patterning with vector CAD methods rather than a raster approach.

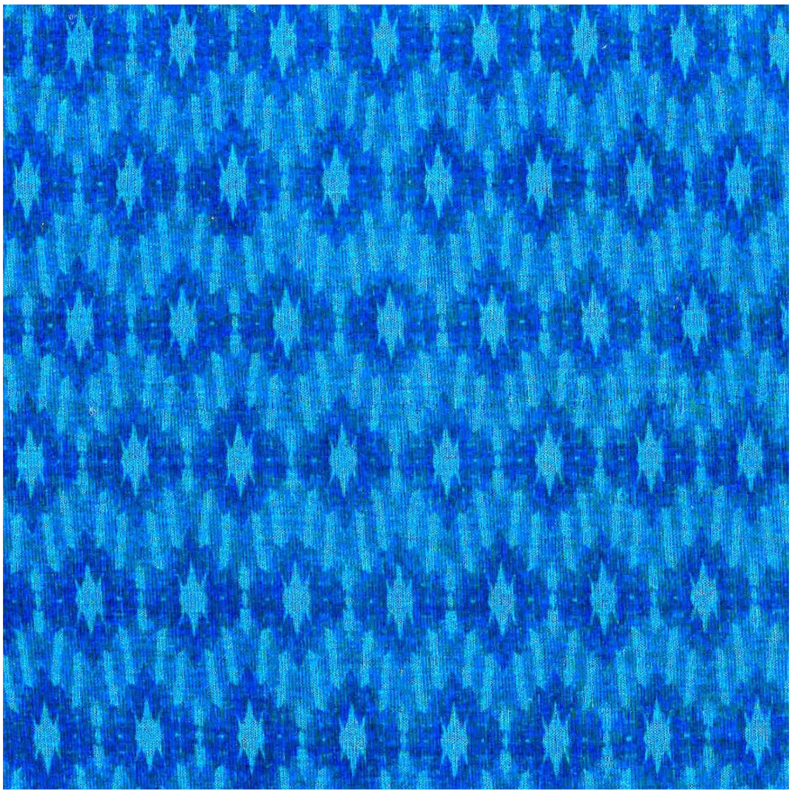


Figure 139: Laser-dyed knitted polyester textile sample: greyscale method

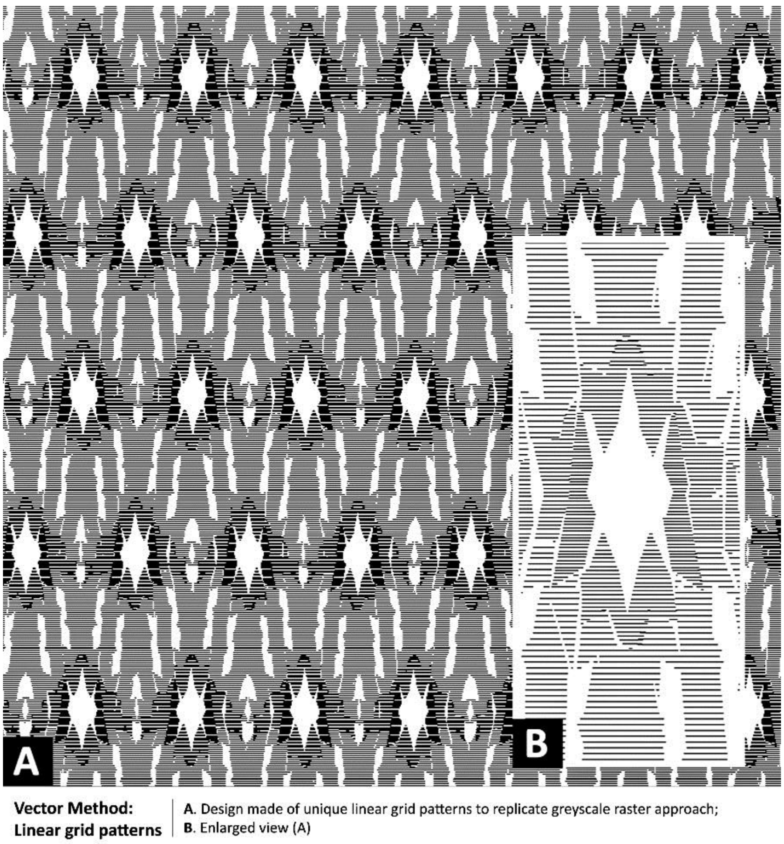


Figure 140: Vector generated pattern

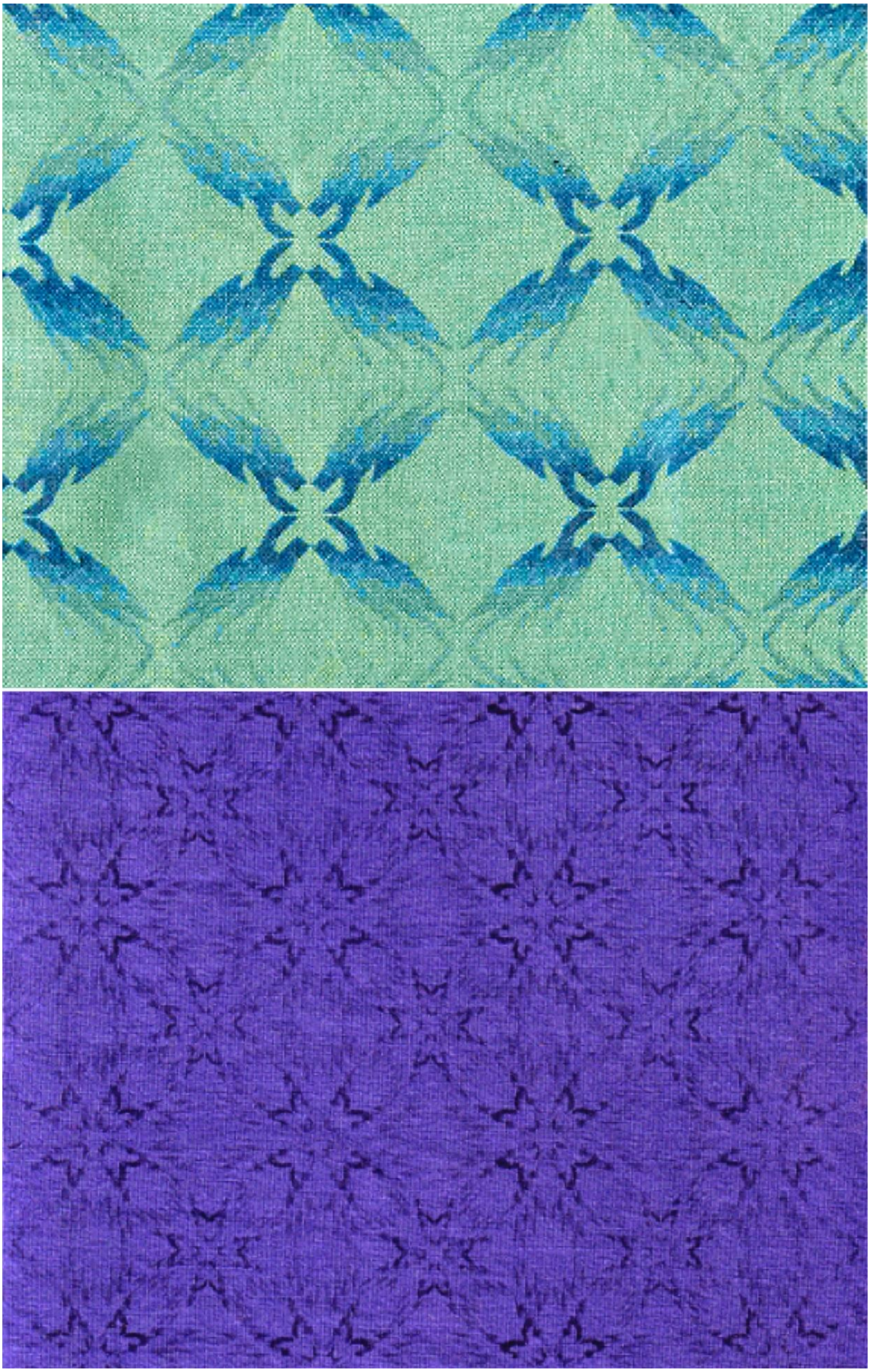


Figure 141: Laser-dyed woven (above) and knitted (below) PET textile samples generated using a raster approach: Engineered repeat patterns

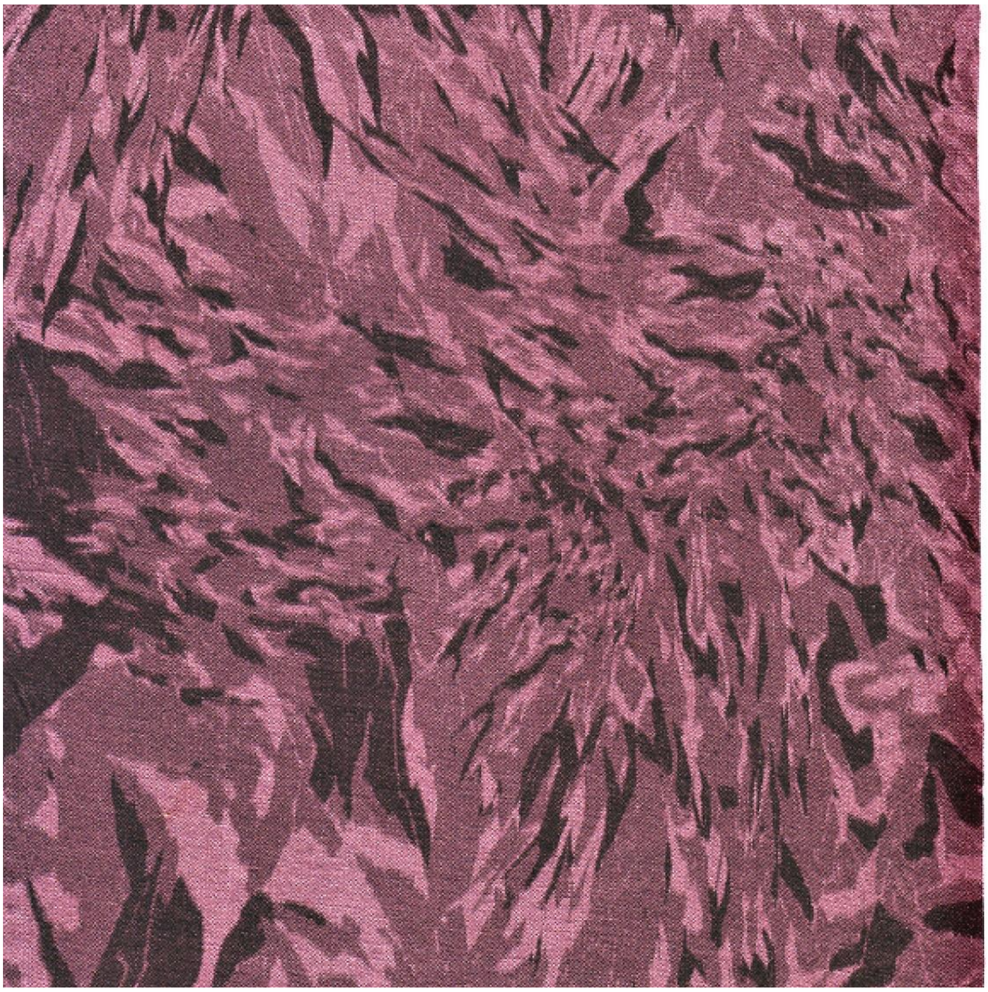


Figure 142: Laser-dyed textile sample generated using a raster approach: engineered textural pattern

5.2.6.2 Prototype garments: Surface design and 3D processing

Prototype garments and ideas were developed in this study to demonstrate the potential of the laser-dye process for commercial textile applications. Experimentation with knitted polyester fabrics inspired a sportswear and intimate apparel direction influenced by complex garment design, fit and customisation aspects linked to the potential to consider digital laser dyeing as an on demand process for garment coloration and finishing. Five undyed/non-coloured polyester garment types were investigated: 1) *PUMA* Sports bra; 2) *LA Gear* Bra top; 3) *Closer with Evie* Bra; 4) *Crystal Martin Fabric* Sports bra pattern; 5) *TITLE* Bra top, seen in Figure 143. Each one with a polyester/elastane fibre composition.

Different approaches were adopted for processing each garment type such as the whole garment, deconstruction and two-dimensional methods. This variety aided a better understanding of the opportunities and limitations associated with laser-dyeing for commercial apparel items. Figure 144 documents the experimental results.

Figure 143: Five undyed/non-coloured polyester (with elastine) garment types

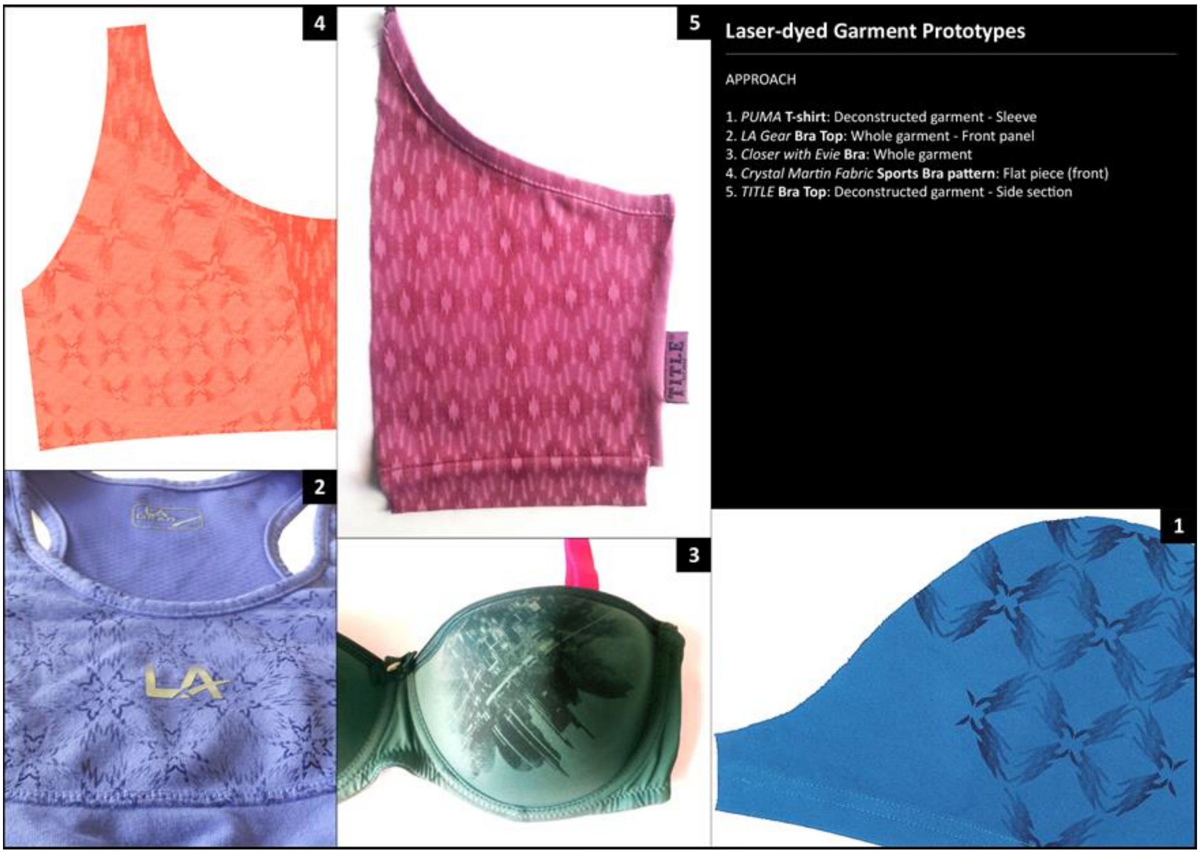


Figure 144: Laser-dyed garment prototypes

Experimentation presented opportunities for processing finished garments including three-dimensional clothing. The laser beam was able to scan across seams, stitching and three-dimensions whilst retain high-resolution graphics and tonal definition, demonstrated in Figure 145. This is not achievable in conventional image-based coloration approaches with finished garments such as digital and screen-printing methods and garment dyeing procedures, for example.

Figure 145: Laser-dyed finished garments and 3D clothing - construction and surface

This work proposes a 'Digital Demand Laser Dyeing' (DDLD) system for textiles relevant to industrial manufacture and commercial goods. Investigation has facilitated considerations for textile design and apparel development in terms of post-processing methods. The laser-dye process explored promotes a novelty market through an on demand design approach and customisation possibilities demonstrated in Figure 146, Figure 147 and Figure 148.

Production times from fabric-to-finished garment could be reduced, eliminating the need for multiple stages and excess resources in the chain. Instead, such goods may be laser manufactured in bulk or small batches in advance and dye finished on demand in response to orders, trends, markets etc. For example, the potential to utilise laser-dyeing for stock garments such as 'white goods' could largely impact retail environments Figure 149. In turn, this would also reduce waste resources and manufacturing costs due to a 'demand' approach, whilst enabling greater aesthetic flexibility.

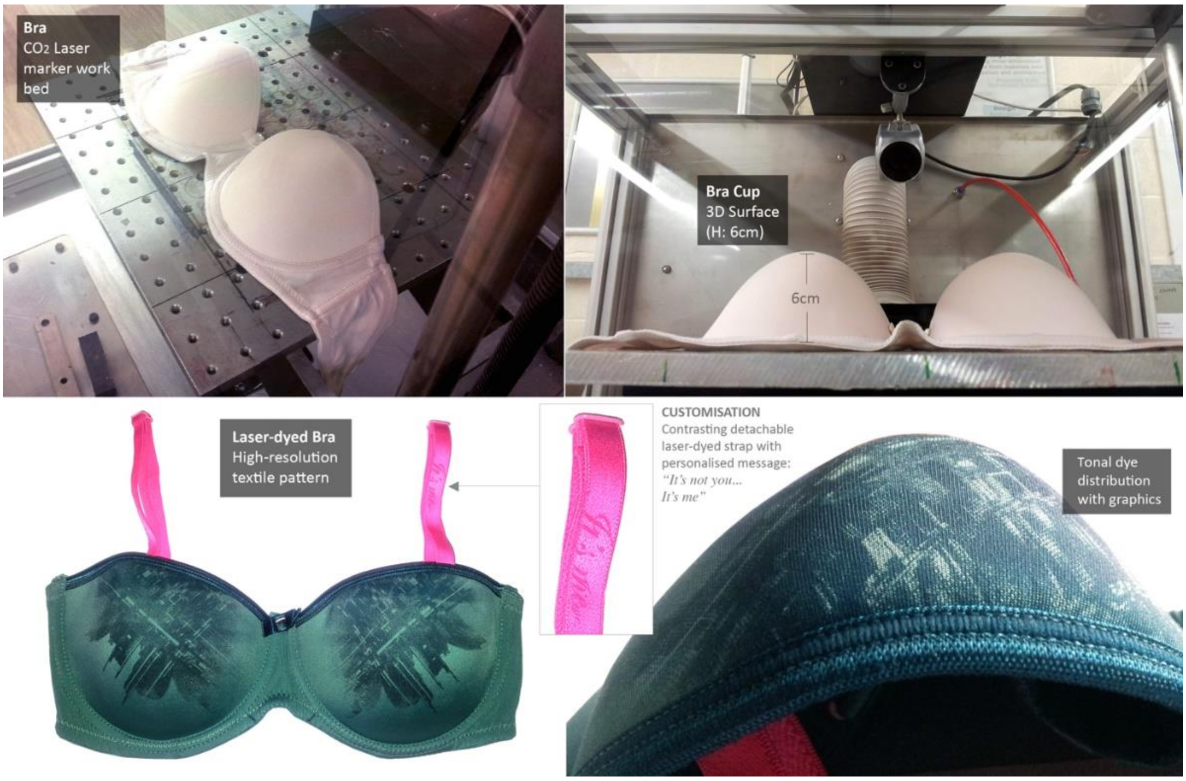


Figure 146: An 'on demand' design approach and customisation possibilities

Figure 147: Close up of bra demonstrating an on demand customisation approach

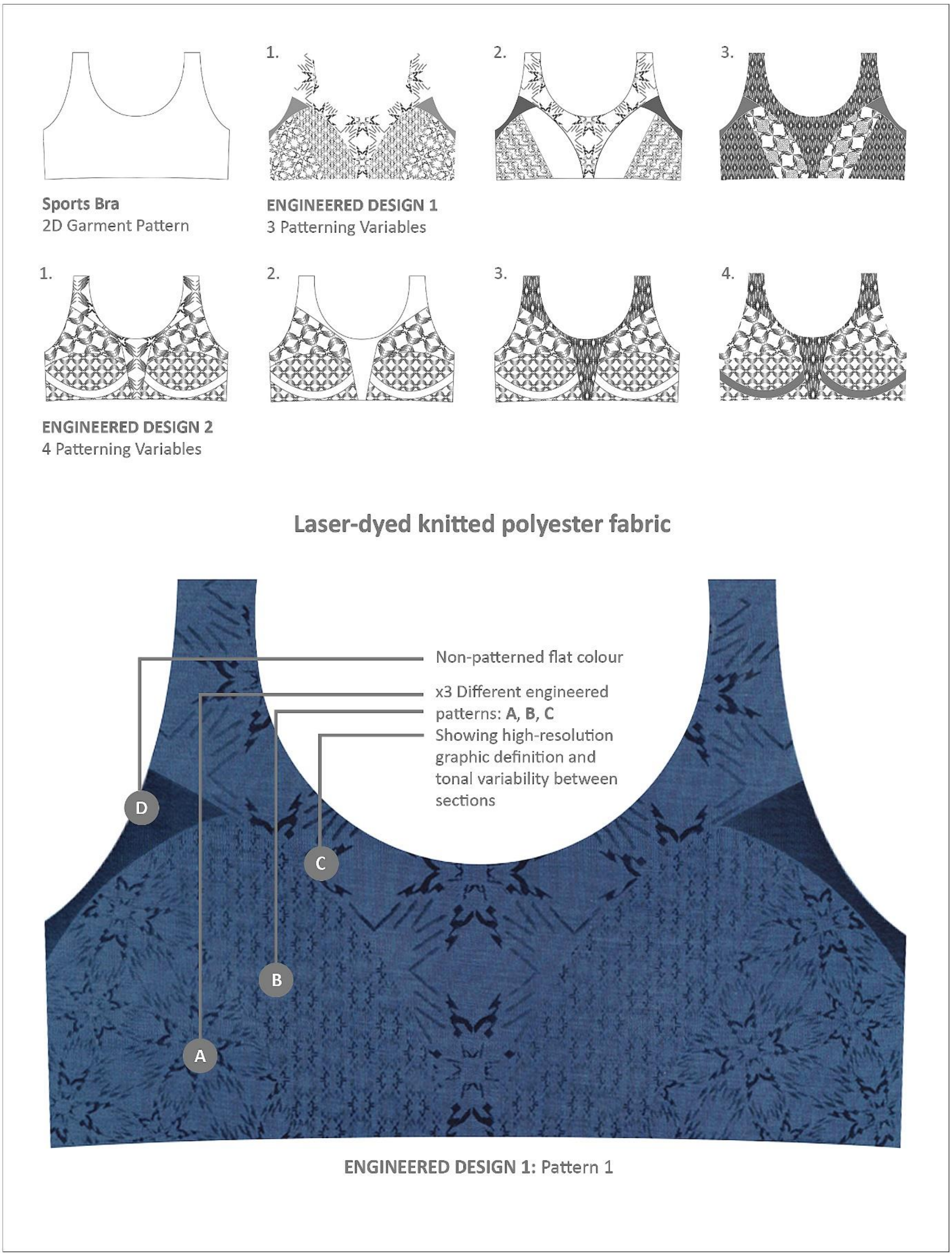


Figure 148: An on demand design approach and customisation possibilities

Figure 149: Laser-dyed 'White goods' (white garments)

5.2.7 Conclusion

In this section, ‘Fibre-laser-dye’ interactions (FLD) have been discussed. This approach moves on from the ‘Fibre-laser’ (FL) method discussed in the previous section (5.1) based on the use of dyes/dyeing and further experimental development relating to the scientific, technical and creative aspects of the work including: laser beam scanning and patterning issues; engineered colour and pattern in relation to textile design and coloration development; quantifying colour through measurement and analysis; ISO wash-fastness testing and assessment; ISO textile performance tests; and textile design development.

Through this investigation based on the FLD approach, it was found that an ability to control the laser beam in terms of optimal focus and scanning direction for example, along with an understanding of beam characteristics and associated processing parameters, was pertinent to exploiting the FLD process effectively. As such, this practical knowledge enabled precision graphics with CAD patterns and consistent dye uptake. Processing issues such as beam spot size, axis considerations regarding beam scanning and fabric position and software/file conversion have been identified as significant to achieving acceptable effects.

An ability to engineer colour and pattern in a way that can be quantified has been achieved by exploring a vector formula to produce even shades and notable tonal variability of a single dye shade. By systematically calibrating energy density with tonal density in relation to vector parameters employed (measured linear vector grids), controllability of the process was enabled. These findings therefore build on the repeatability, reliability and transferrable goals of the work, relevant to commercial potential of the FLD process.

To quantify colour in relation to a range laser-dyed textile samples generated, colour measurement and analysis procedures were carried out (Reflectance Spectroscopy (RS), CIEL*a*b* Colour Model and Grey Level approaches). RS results indicated that laser-dyeing does alter the reflectance and absorbance properties of fabrics due to colour change induced by fibre-laser interaction. By adopting the CIEL*a*b* colour model used in industry to quantitative understand and communicate colour. Lightness (L*), Chroma (C*) and Hue (H*) colour values were statistically and visually defined in L*C*H* space. Within this approach, it was also possible to assess Delta E (Δ) colour difference. Therefore, differences in chroma and hue values between laser-dyed and untreated fabrics was statistically defined. Delta E results aided further understanding about the coloration effects of the FLD process of the fabric surface through an ability to measure tonal change/difference by comparing samples numerically in relation to specific processing parameters. The Grey Level methods further supported calibration aspects of the FLD process by plotting (tonal) colour density against numerical 'grey' data in order to quantify dye uptake and reliably communicate the results.

ISO wash fastness testing and assessment carried out provided and understanding about the stability of fibre-laser-dyeing in terms of dye adsorption/wash-off. In this study, it was found that FLD as a textile coloration/patterning method was mostly 'good' (rated: 4-5) or 'very good' (rated: 5) in terms of colour change and assessment of staining. Therefore minimal or no dye wash-off (residue) was recorded for most test specimens. Further interrogation regarding the impact of the process explored by employing industry standard testing as achieved through ISO textile performance tests undertaken (Tensile strength, Tear resistance, Burst strength, and Dimensional stability). It was found that the process did not affect dimensional change when domestically washed/laundered. Overall the results confirmed that the fibre-laser (FL) interaction element of the FLD process does denature surface fibres. However, controllability of processing parameters identified in this research can minimalise this effect in order to maximise textile functionality.

In terms of textile design development, the FLD process explored enabled digital precision dyeing for textiles through tonal dye uptake and high resolution graphics. Experimental patterns were created using a raster scanning approach. This involved percentages of black (Grey/GS %) that were engineered to form shapes generated via CAD software (Adobe Photoshop) and converted to halftone digital files applicable to the laser software (WinMark Pro). Monochromatic gradient repeat designs were created in order to exploit the tonal capability of the FLD process. This investigation initiated an on demand approach for processing sportswear and intimated apparent in this way, relevant to PET textiles commonly used for such garment types. In particular, an ability to laser scan three-dimensional and uneven or non-uniform surfaces such as seams, joins and top-stitching for example, emphasises the on demand potential o the process as garments can be digitally laser-dye finished via FLD approach post construction. Therefore, a ‘Digital Demand Laser Dyeing’ (DDLD) system has been proposed by this research, relevant to industrial manufacture and commercial goods.

Scientific interrogation and analysis of colour carried out in this research does not exist in current laser/textile studies. This can also be said for in depth ISO wash fastness and textile performance testing, also documented in this work. Additionally, the ability to achieve precise high resolution tonal patterns/graphics with a single dye shade using conventional dyeing methods is not possible. Therefore, these findings contribute new knowledge to combined textile and laser academic studies regarding PET textiles as well as textile design practices more widely in terms of creative dyeing and patterning textile coloration techniques.

5.3 FDL: Fibre-dye-laser interactions

The fibre-dye-laser (FDL) method explored in this research denotes processes in which dyes were in some way applied to PET textile fibres prior to laser processing rather than afterwards, as described in the previous section (5.2) regarding the fibre-laser-dye (FLD) approach. In this manner, laser energy was examined as an additive procedure to activate the dyeing of pre-applied dyes. Experimentation involved hand-dyeing and hand application approaches such as brushing the dye solution onto the fabric surface, for example. Dye uptake capability and design potential of the process in relation to specified laser-dye parameters were investigated. As with the FLD process, CO_2 laser marking systems were used in this inquiry – both 10W and 60W Synrad laser machines, as detailed previously in chapter 4 (section 4.1.2; Table 7), together with workshop and industry standard dyes, also previously outlined in chapter 4 (section 4.1.2.4; Table 12). FDL interactions explored in this research suggests an alternative approach to digital laser-dyeing PET with patterns and artistic surface effects, relevant to the design development phase (3) of the work, as defined in Chapter 4; Figure 33. This includes colour and pattern exploration; extended technical experimentation based on a creative agenda; and potential opportunities for the laser-dye process. This section therefore documents and discusses the experimental results obtained using this method.

5.3.1 Experimental approach

This section sets out the experimental approach undertaken to carry out the FDL inquiry, by identifying the methods, techniques and parameters adopted relating to fabric/fibre type, dyes, dyeing methods, laser processing parameters employed and the design development aspects of the work.

Plain woven ISO polyester (detailed in Chapter 4, Table 6; section 4.1.1) was used for all FDL experiments as this area of investigation was a preliminary exploration of the fibre-dye-laser process. Therefore, focused parameters were adopted in order to aid structured experimentation. Selected commercial workshop and industry standard dyes were employed using water and solvent based dye application approaches. Dye solutions were 'painted' on to the fabric surface by hand using a paint brush. A raster laser beam scanning approach was carried out (as described in chapter 4, section 4.1.2.1) in both vertical and horizontal directions with variable energy densities (ranging from 0.04-to-0.09 J/cm^2). Laser modification involved technical and creative aspects by exploring flat colour, gradient and patterns effects using a range of processing parameters. To further understand the results, microscopy was employed which enabled a scientific analysis of individual yarns and surface fibres.

FDL		
FIBRE	**Woven PET (SDC)**	
DYE **Class/shade**: **Application**:	**Commercial** Disperse Cetyl Blue BN 125%; Dispersol Scarlet Red B200% Dye + water solution | Hand painted on Dye + solvent solution | Hand painted on	**ISO** Disperse: Rubine CGL 150%; Blue 3RL 150%; Yellow 3G Dye + water solution | Hand painted on
LASER **Scanning:** **Modification:** **Energy densities**: **(J/cm^2)**	 Vertical; Horizontal Test blocks/grids; flat colour; gradient effects; patterning 0.04; 0.05; 0.06; 0.07; 0.08	 Vertical; Horizontal Patterning 0.06; 0.07; 0.09

Table 27: FDL summary of experimental approach undertaken

5.3.2 Experiments and outcomes

This section identifies the experiments undertaken and the results generated regarding phase 3 of the research which was focused on design development of the digital laser-dye process. Based on practical knowledge gained and the experimental findings obtained from phases 1 (Confirming previous work) and 2 (Exploratory) of this research regarding FL and FLD laser-dye approaches, three main themes were decided and employed to study the FDL method in a focused and logical manner:

- Tonal density
- Patterning
- Axis trials

Each theme was considered fundamental to the research, in line with key issues and aspects of the study regarding the coloration and patterning of PET textiles via laser-dye approach. This included the ability to generate variable shade depths; surface appearance in terms of design qualities using graphic forms; and dye uptake capability to essentially enhance the performance of dyes regarding the tonal distribution achievable with a single dye shade (identified with the FLD method, previously discussed in section 5.2 of this chapter); and also to ensure evenness, consistency and stable absorption relevant to commercial coloration requirements for textile goods, as measured with the fibre-laser-dye method in section 5.2 using ISO wash fastness testing and colour assessment procedures.

Due to the hand applied workshop approach explored within a preliminary capacity, ISO testing was not carried out on FDL fabric samples as the dyeing conditions employed did not comply with industry standard coloration requirements. So, microscopic analysis facilitated an adequate assessment of the initial research results using the FDL laser-dye method.

5.3.2.1 Tonal density

In order to generate tonal difference on the woven PET fabric with a single dye, a variable concentration approach was explored regarding the dye solution, combined with experimental laser parameters. Two methods were studied – water based solutions and solvent based solutions. However, an aqueous (aq) solution better describes the water based method as the solvent was the water. Each technique involved hand painting a liquid dye solution onto the fabric surface. Once completely dry, samples were laser modified post dye application. Each sample weighed 1g and measured approximately 10cmx10cm (10cm^2).

Water based solution experiments were carried out:

- Using a weak solution with a high water ratio which was gradually decreased, to create a more concentrated dye substance; and
- Producing gradient effects by increasing the water content during application creating a gradually weaker solution such as from light-to-dark.

Dispersol Scarlet B200% was used in dye solutions. For sample (a), 0.1 g of dye was mixed or ‘pasted out’ into 50mls of warm water. This was repeated with a lesser liquor ratio of 20mls of water for sample (b). For sample (c), three times the amount of dye (0.3g) was pasted with three drops of hot water using a pipette. Each dye solution was painted onto the fabric in a grid of 10 1.5cm x 2cm (3cm^2) blocks or test areas. One block per sample was laser modified with an energy density of 0.08 J/cm^2. Figure 150 demonstrates the results.

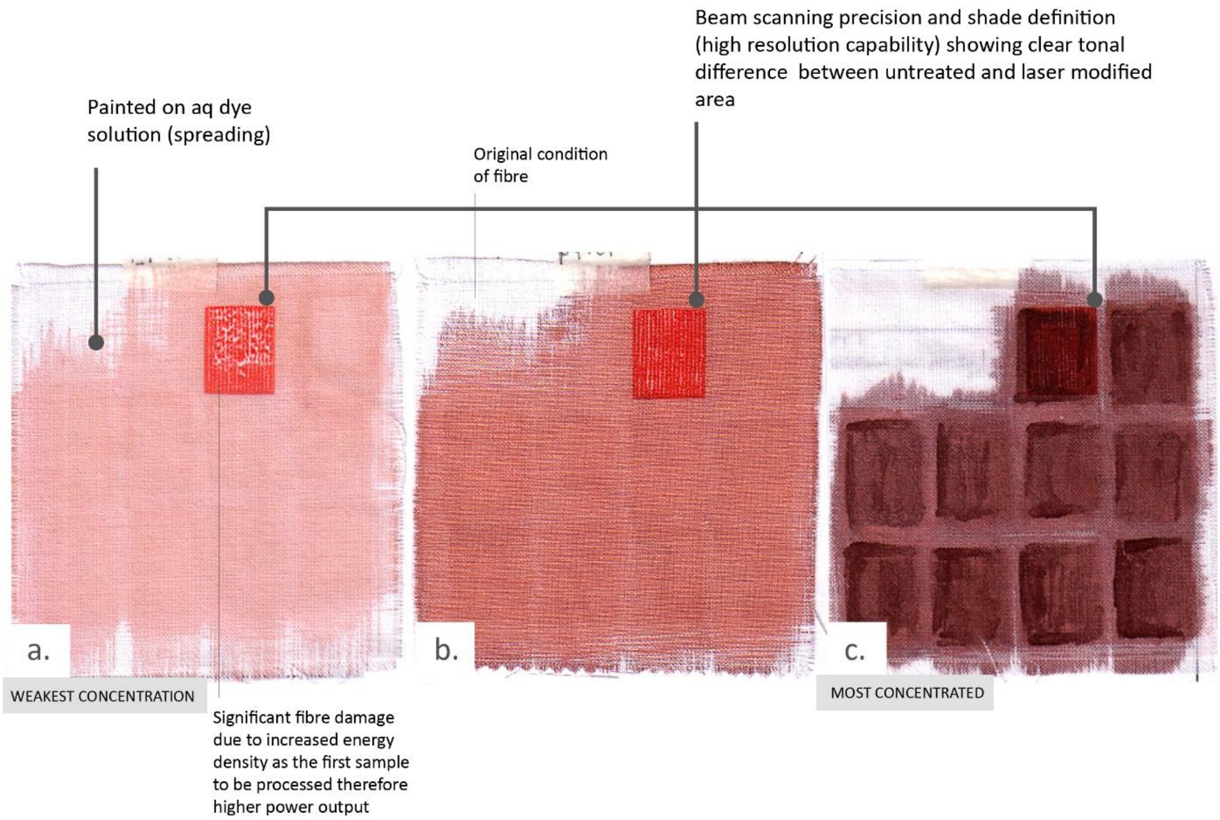


Figure 150: Laser modified blocks using a variable dye concentration water based approach

In terms of application, the dye solution spread across the fabric in all three samples, particularly in samples (a) and (b) where water ratios were higher. However, beam scanning precision facilitated shade definition through control of the process and high resolution capability of the laser. Results revealed processing power output was too much and so energy density parameters applied caused adverse fibre damage detected by the distinct hardening in the laser modified regions in all samples. However, as the first sample to be processed, sample (a) shows significant deterioration due to the increased power output characteristic of laser machines prior to power “drop-off”, as discussed previously. It is noted that his can be avoided by processing 1 or 2 preliminary samples before actual structured experimentation.

Tonally, a clear difference between untreated and laser modified areas can be seen in all samples. This outcome indicated that additive laser energy sufficiently heated the dye enough to trigger a reaction. Such interaction initiated textile coloration. The disperse dye was activated by the addition of beam energy turning the dull appearance of the dye to a brighter shade. Each shade reflects the dye solution applied to the fabric in terms of colour strength i.e. the Chroma, (previously discussed in section 5.2.3.2 of this chapter). For instance, sample (a) exhibited the palest scarlet red tone, relative to sample (b) which is more concentrated, therefore darker. Sample (c) yielded the deepest dyeing, which can be understood as a result of an increased dye quantity.

A gradient approach to investigate tonal variation was also explored. Figure 151 is an extract from a log book page which illustrates some of the initial planning for this method.

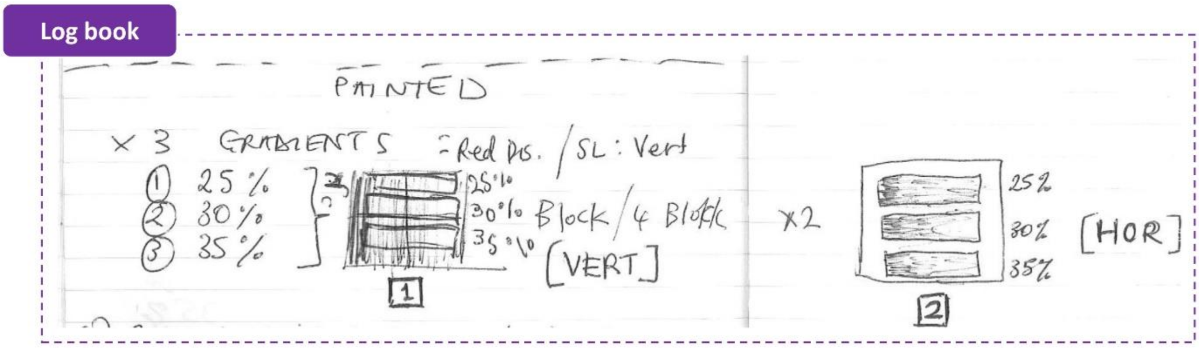


Figure 151: Log book extract demonstrating initial planning for a gradient approach

In doing so, 0.15g of dye was dissolved in hot water and applied to three samples using approximately 0.05g per fabric. The solution was brushed onto each sample from right to left of the fabric. Water was gradually added during application to produce an increasingly reduced dye concentration. A noticeably weaker solution was formed on the textile surface (Figure 152).

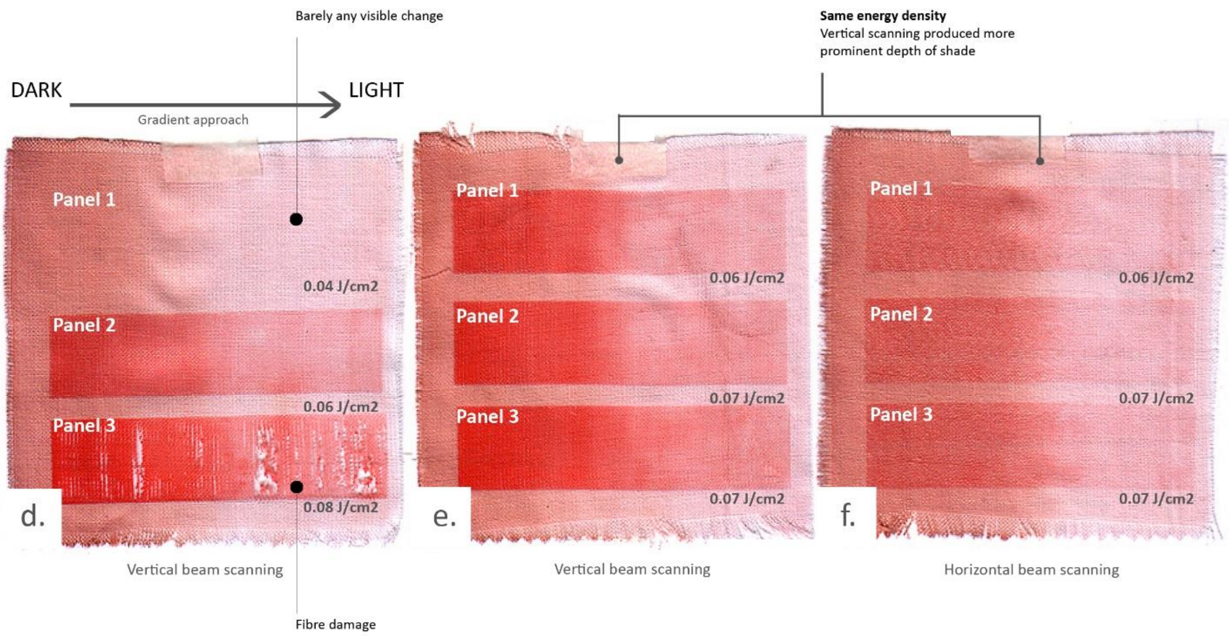


Figure 152: Gradient samples: laser modified panels with different energy densities

When dry, samples were laser modified. Sample (d) with three energy density parameters. Samples (e) and (f) were processed with the same two energy densities but raster scanned in different directions. These processing parameters are further described below as follows:

Sample:

- (d) – Vertical scanning: 0.04 J/cm^2, 0.06 J/cm^2, 0.08 J/cm^2
- (e) – Vertical scanning: 0.06 J/cm^2, 0.07 J/cm^2, 0.07 J/cm^2
- (f) – Horizontal scanning: 0.06 J/cm^2, 0.07 J/cm^2, 0.07 J/cm^2

Sample (d) showed the greatest difference in results between laser modified panels 1, 2 and 3. At 0.04 J/cm^2 (panel 1), there was barely any visible change. At 0.08 J/cm^2 (panel 3), processing power was too much causing fibre damage (Figure 153), previously discussed. An energy density of 0.06 J/cm^2 (panel 2), was sufficient enough to activate dyes without adversely affecting surface fibres (Figure 154).

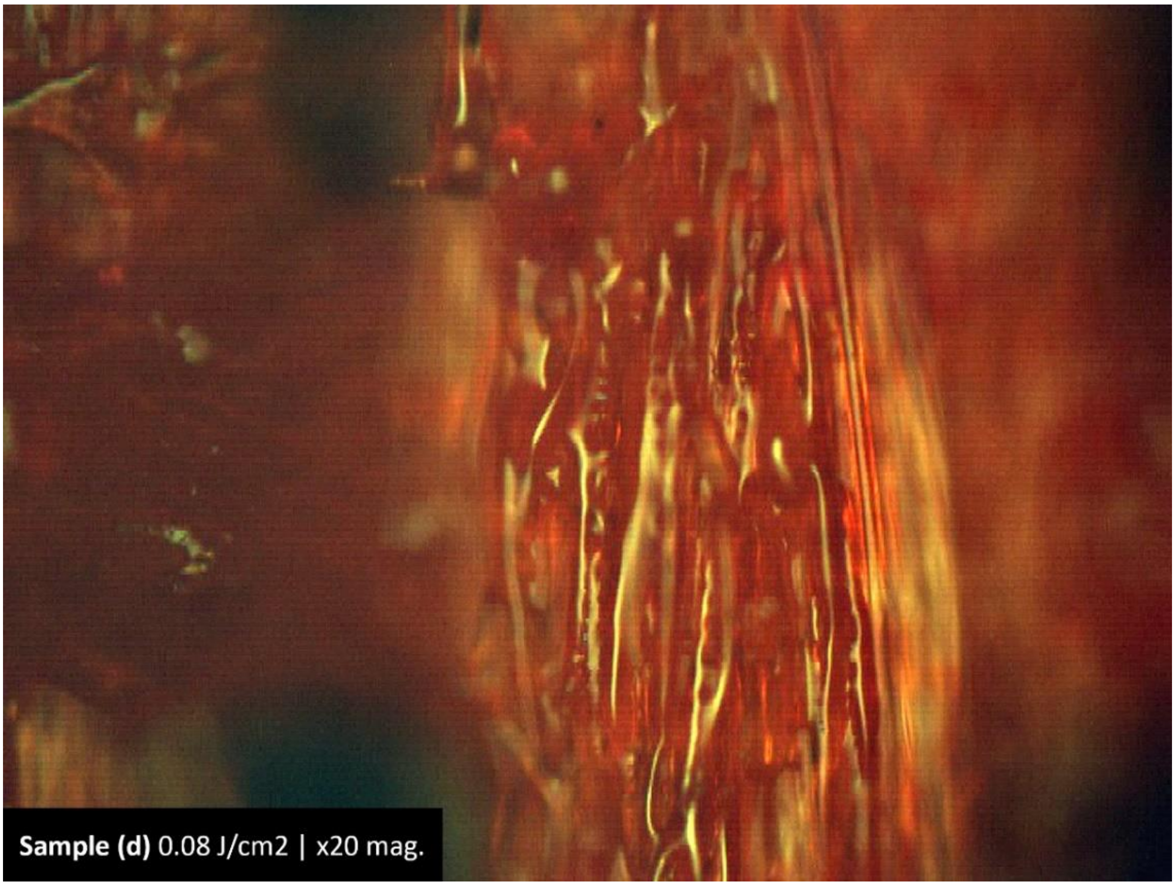


Figure 153: Sample (d): showing damaged fibres when processed with 0.08 J/cm2 energy density.

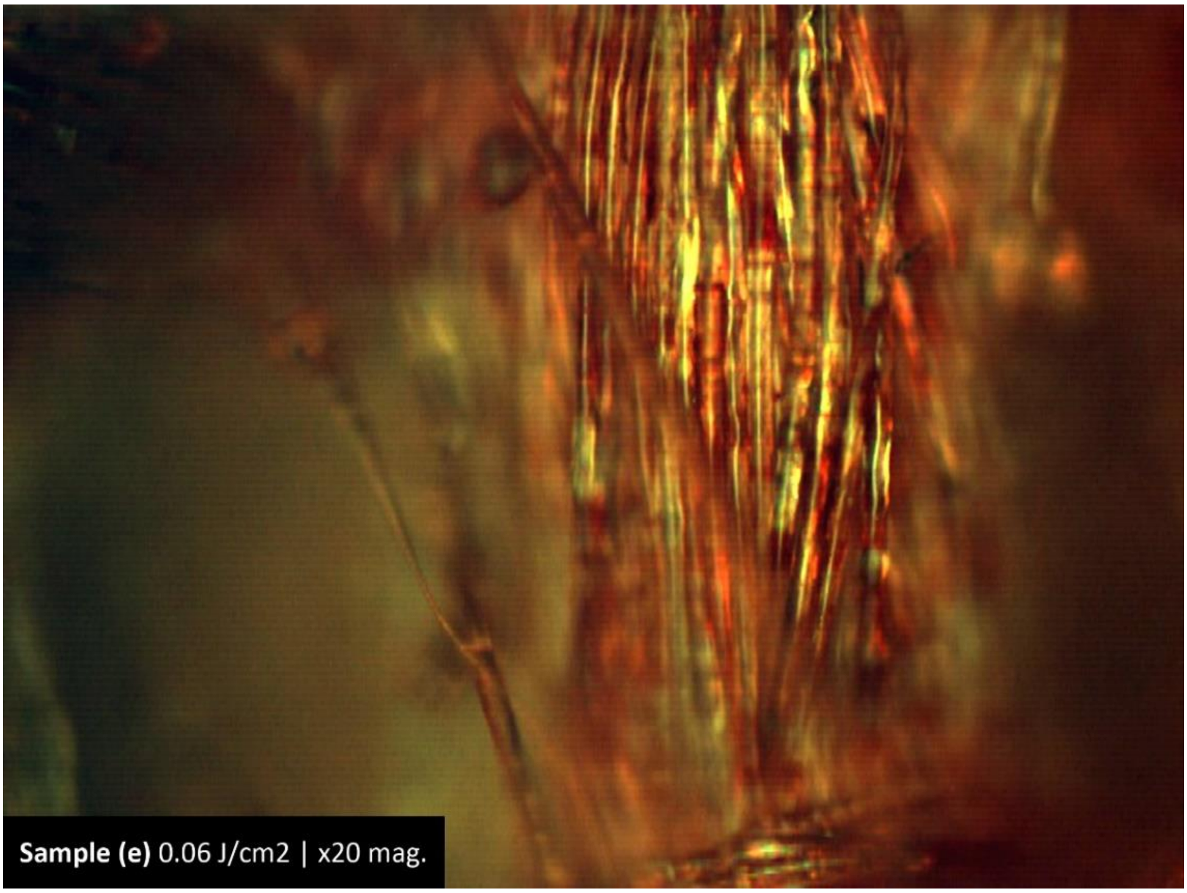


Figure 154: Sample (e): showing sufficient coloration without significant damage when processed with 0.06 J/cm2 energy density.

Samples (e) and (f) were noticeably dissimilar after laser treatment due to a difference in beam scanning direction. Vertical (sample e), rather than horizontal (sample f) processing yielded a more prominent gradated depth of shade (DoS %). Horizontal scanning produced a significantly subtler result. Therefore, vertical laser beam energy distributed across the fabric surface in this way was better suited to the weave structure/fibres for effective penetrative dye activation. An incremental energy difference between panel 1 (0.06 J/cm^2) and panels 2 and 3 (both 0.07 J/cm^2) produced a marginal difference in results, evidenced in samples (e) and (f).

Overall, results show that the water ratio in a dye solution does influence colour appearance of a laser-dyed fabric treated in this way. Therefore, shade variability can be achieved with a single dye/colour and dye amount. With this method, tonal difference is dependent on water quantities linked to laser processing/energy parameters. Potentially, such an approach could be used for bespoke textile coloration. Environmental considerations are also relevant in terms of resource consumption pertaining to dye and/or water usage. Laser energy as a catalyst for depth of shade, indicates it is possible to reduce both water and dye with a FDL process along with the processing stages for digital dyeing in this way.

Solvent based solutions involved:

- Combining dyes with solvents instead of a water. In doing so, three different solvents were investigated – Methanol, Ethanol and Acetone.

Using a solvent based approach, experiments were carried out on four woven PET fabric samples – two experiments using Disperse Cetyl Blue BN 125% for samples (g) and (h) and two using Dispersol Scarlet Red B200% for samples (i) and (j) (Figure 155). The difference in shade between the dyes provided a platform for comparison of the results obtained. In samples (g) and (i), 0.05g of dye was mixed with 2mls of Methanol and brushed onto the fabric within three 2cmx8.5cm ($17cm^2$) panels. Once dry, each panel was laser processed with different parameters, leaving a small area of the fabric untreated in order to compare with laser modified fibres afterwards. The laser parameters employed to carry out this experiment on samples (g) and (i) were as follows:

- Panel 1 – Vertical scanning: 0.07 J/cm^2
- Panel 2 – Horizontal scanning: 0.07 J/cm^2
- Panel 3 (i) – Vertical scanning: 0.06 J/cm^2; 3 (ii) – Horizontal scanning: 0.06 J/cm^2.

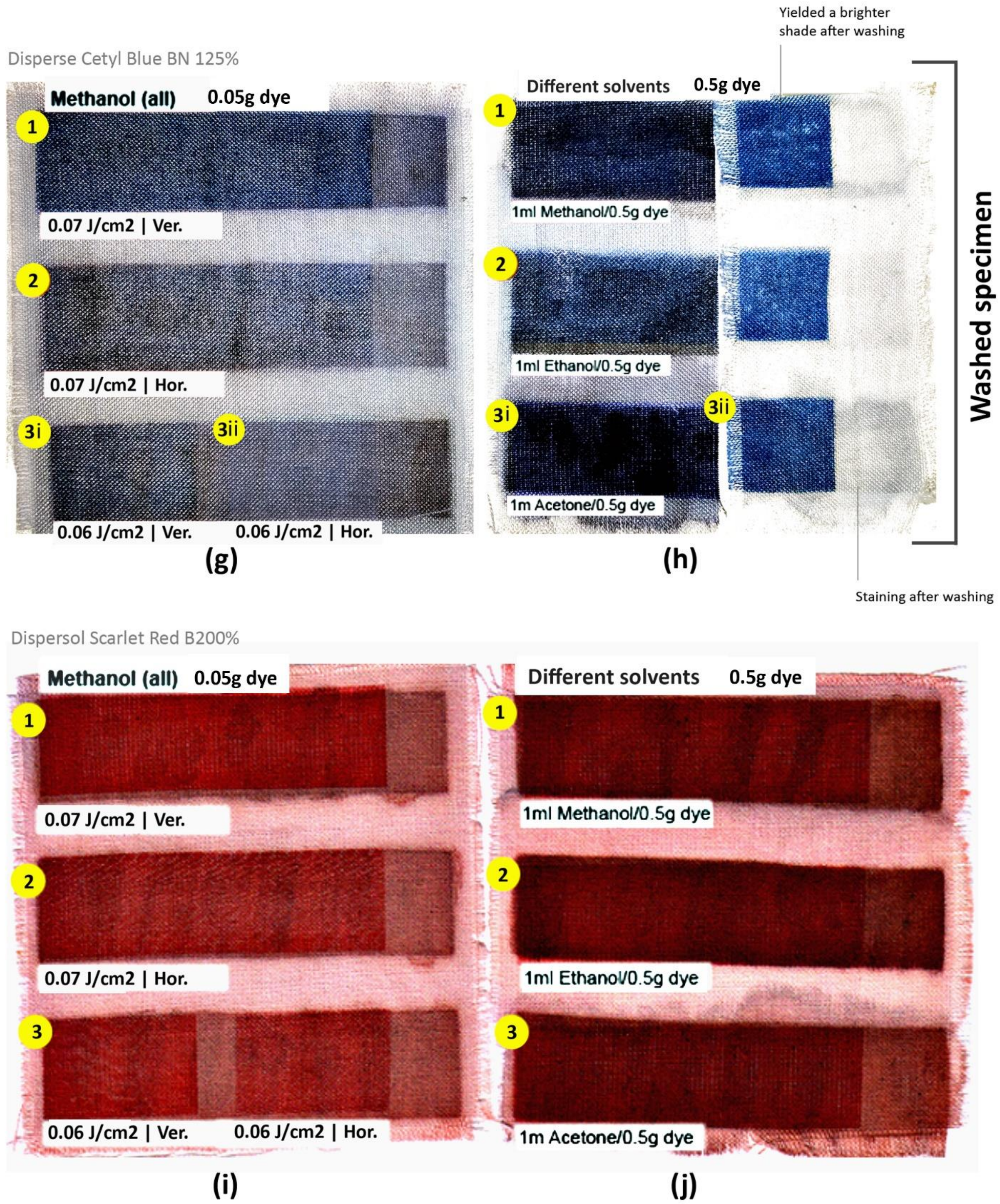


Figure 155: Solvent based samples

As with an aqueous solution, results show a difference in colour appearance between laser-dyed and untreated fibres. Brighter shades were yielded once modified. In both samples, panel 1 produced a more vivid effect compared to panel 2 due to vertical scanning. A lower energy density in panel 3 generated paler shades and a deeper colour in 3 (i), as expected.

In samples (h) and (j) three different solvents were investigated (Methanol, Ethanol and Acetone) in order to understand the effect this variation may have on dye uptake. Each solution contained 1ml of solvent and 0.5g of dye. All panels were vertically scanned with the same energy density of 0.07 J/cm^2. Individual dye solutions were brushed on to the fabric within a panel of 2cmx8.5cm (17cm^2). Laser modification occurred within an area of 2cmx7cm (14cm^2) per panel, leaving some of the area untreated. In both samples (h and j), panel 1 contained a methanol solution, panel 2 ethanol and panel 3 contained acetone. After processing, a section of the sample (j) was cut away, hand washed in warm (approximately 20°C) and hot tap water (approximately 50°C), then machine washed for 1 hour on a 40°C domestic cycle with household detergent.

Experimental results with solvents yielded deep coloration in all three test areas per sample (h and j). Colour appearance on the fabric surface was intense and distinctly more saturated than samples (g) and (i) and those explored with an aqueous solution. There were marginal differences in results between each solvent in both samples regarding tonal density. This variation can be attributed to the uneven application of the solution during the hand painting stage leading to some inconsistencies which can be understood regarding a manual, rather than machine-driven approach, as with the FLD method, previously discussed in this chapter (section 5.2)

The washed specimen from sample (j) generated the brightest results overall. A noticeable difference in colour appearance can be seen in Figure 155. Results suggest loose particles were removed from the surface during washing. Consequently, this ‘washing out’ revealed the level of dye uptake achieved aided by interaction with laser beam energy. The hand painted on dye in the untreated panel area was washed away in all three tests leaving some staining. It is also noted that washing significantly softened the fabric in treated and untreated areas compared to the unwashed specimen.

5.3.2.2 Patterning

To explore laser-dye patterning with the FDL method, two coloration techniques were investigated using a raster beam scanning approach (as discussed previously): 1) gradient effects; and 2) repeat designs.

Gradient effects made it possible to

- Convey gradual tonal variations, blended shades and colour shifts with patterns enhanced by the addition of laser energy to activate the ‘dyeing’ process and create novel surface effects;
- Generate gradient backgrounds or base effects to enable patterns to be generated later by specification such as on a Digital Demand Laser Dye (DDLD) basis, for example (as discussed in section 5.2.6.2 regarding the FLD method).

Using a gradient approach, two samples were generated – (k) and (l) (Figure 156). For each sample, 0.05g of Dispersol Scarlet Red B200% dye was dissolved in warm water and applied to the fabric from left-to-right, gradually diluting the solution strength by adding water. Different patterns were generated via laser beam with vertical scanning. Sample (k) was processed with an energy density of 0.06 J/cm^2 and 0.07 J/cm^2 for sample (l).

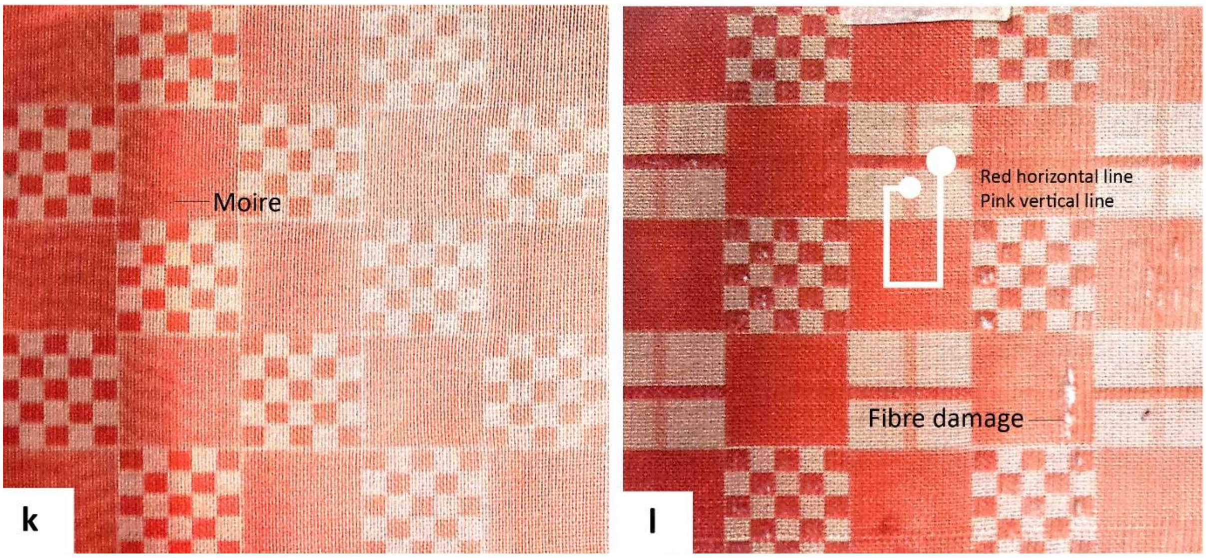


Figure 156: FDL samples: gradient pattern effects

The outcome of laser modification reflected dye application. A tonal gradient pattern was produced on the fabric surface. Modified areas were noticeably more vivid in colour appearance compared to untreated areas. At a higher energy density (sample l), depth of shade increased due to greater FDL interaction, which can be explained. However, at this power, fibres deteriorated causing breakage. So, although colour appeared deeper and brighter, these energy parameters were damaging to fibres. This affect was eliminated in sample (k) by reducing laser processing power. Consequently, a lower energy density resulted in a visible moire effect.

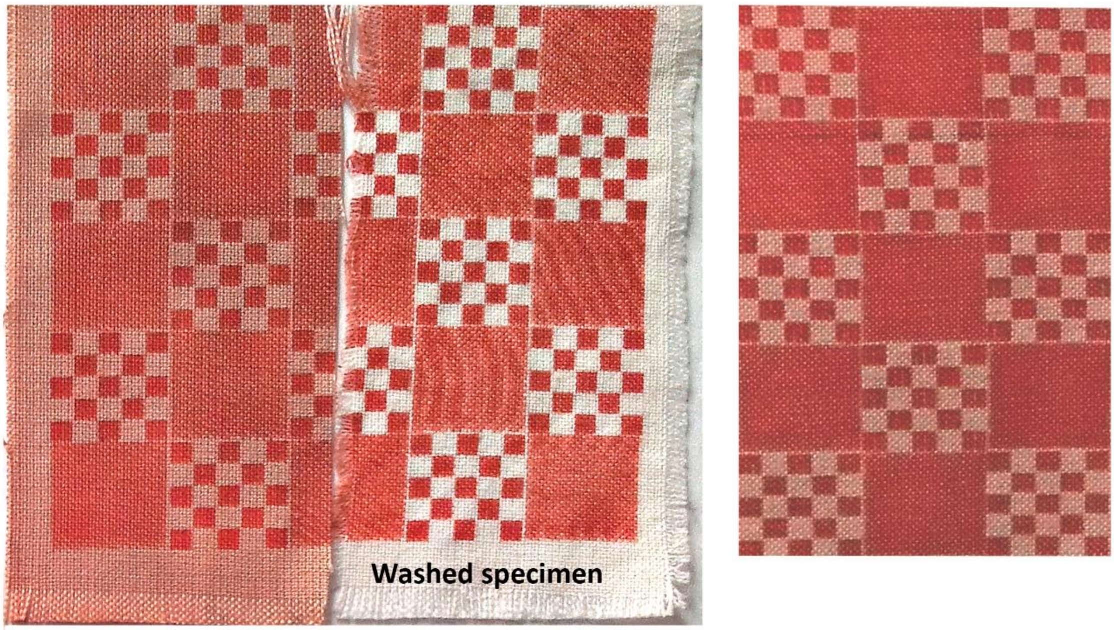
Beam energy distribution generated unintended tonal variability in sample (l). Where the vertical and horizontal bar cross, the vertical bar consistently remained darker across the entire pattern. Scanning vertically up and down the length of the sample produced minimalised fibre-laser interaction. This was due to a longer distance for the beam to travel at 8.5cm. Therefore, localised radiation was reduced. The horizontal bar had a shorter distance of 0.2cm and so localised radiation was more intense. This result suggests it is possible to manipulate and control shade/colour appearance through the considered design of a specific pattern.

Repeat designs made it possible to:

- Experiment with a range of repeat pattern types in order to further understand the processing parameters for laser-dyeing the woven PET fabric via FDL method. Gaining relevant practical and technical knowledge in order to facilitate design development;
- Employ both commercial workshop and ISO dyes to identify dye performance between the dye types in relation the FDL method in terms of colour appearance (Hue and Chroma) after processing, staining post washing, graphic capability regarding sharpness (resolution) and tonal contrasts within individual patterns;
- Explore the transferability of designs developed using the FLD method (documented in section 5.2.) regarding the CAD patterns generated and how these patterns may be translated with the FDL method.

Workshop and industry standard (ISO) dyes were applied to fabrics to achieve flat all over background colour. This approach provided the basis for repeat patterns to be laser modified on to the fabric surface. Dispersol Scarlet Red B200% dye was used for samples (m), (n) and (o). ISO disperse dyes, Rubine CGL 150%, Blue 3RL 150% and Yellow 3G were employed for samples (p), (q) and (r).

For samples (m) and (n) (Figure 157), 0.05g of dye was dissolved in warm water and painted on to the fabric. Once dry, patterns were laser marked on to the surface caused by the interaction between beam energy, dye molecules and textile fibres. The addition of laser power activated dyes which triggered the coloration process with engineered graphics. An energy density of 0.06 J/cm^2 was applied for processing sample (m) with horizontal beam scanning. Sample (n) was vertically scanned with an energy density of 0.07 J/cm^2. After modification, sample (m) was cut so that half the fabric could be washed to visually observe the appearance once washed in terms of depth of shade, brightness, even dye uptake and graphic qualities such as high resolution, for example. The specimen was machine washed on a 1 hour domestic cycle at 40°C with household detergent and air dried (Figure 157). Sample (o) (Figure 158) was coloured with 0.02g of dye applied to the fabric in the same way. A horizontal scanning approach was employed with an energy density of 0.07 J/cm^2.



(m) 0.06 J/cm2 Horizontal scanning (n) 0.07 J/cm2 Vertical scanning

Figure 157: FDL Repeat patterns including washed specimen

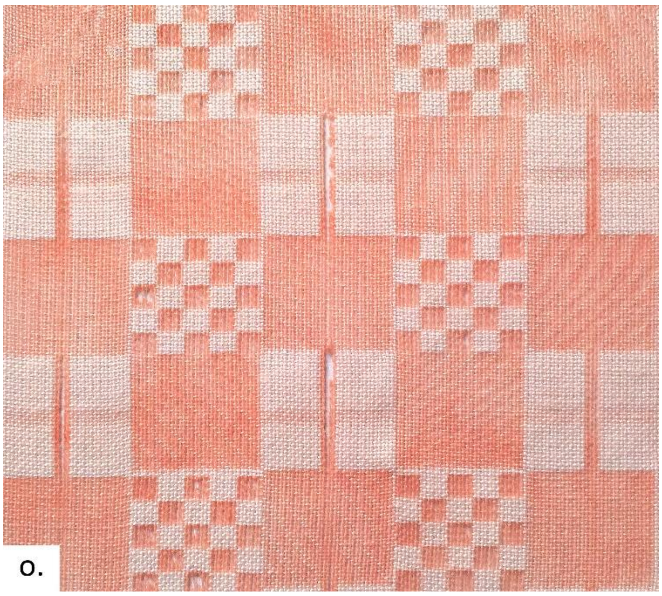


Figure 158: FDL Repeat pattern

High resolution graphics were achieved in samples (m), (n) and (o). Patterns appeared sharp and controlled. In terms of colour, results show a marginally higher processing power combined with vertical scanning produced a brighter and deeper red tone with sample (n) compared to (m). This effect can be linked to increased FDL interaction based on a higher energy density of 0.07 J/cm^2 rather than 0.06 J/cm^2. Sample (o) exhibited a distinctly weaker shade attributed to a reduced dye quantity which was understood.

Horizontal scanning applied to both samples (m) and (o) increased a previously explained moire effect, less visible with vertical scanning, demonstrated in sample (n). Moire patterns were emphasised in the washed specimen due to a contrast in colour between dyed and undyed fibres. Minimal staining was exhibited in untreated areas after washing, unlike an aforementioned solvent approach. Instead, much of the unabsorbed dye had washed away leaving an almost white fabric likened to its original condition. Results also show the washed fabric appeared brighter than the unwashed specimen in laser-dye/patterned areas.

For samples (p), and (q), 1g of ISO dye was dissolved with 3mls of water per sample then hand painted on to the fabric within a 10cm^2 (10cmx10cm) area. The same pattern was applied to both samples, each processed with an energy density of 0.09 J/cm^2 laser scanned vertically. Post modification, all samples were machine washed on a 1 hour domestic cycle at 40°C with household detergent and air dried. Post washing, visible staining can be seen where the fabric was not laser modified, opposite to the results obtained with workshop dyes, previously described. This indicates a difference in quality or robustness between the dyes which can be understood. High definition was achieved in modified areas due to increased dye uptake determined by laser parameters.

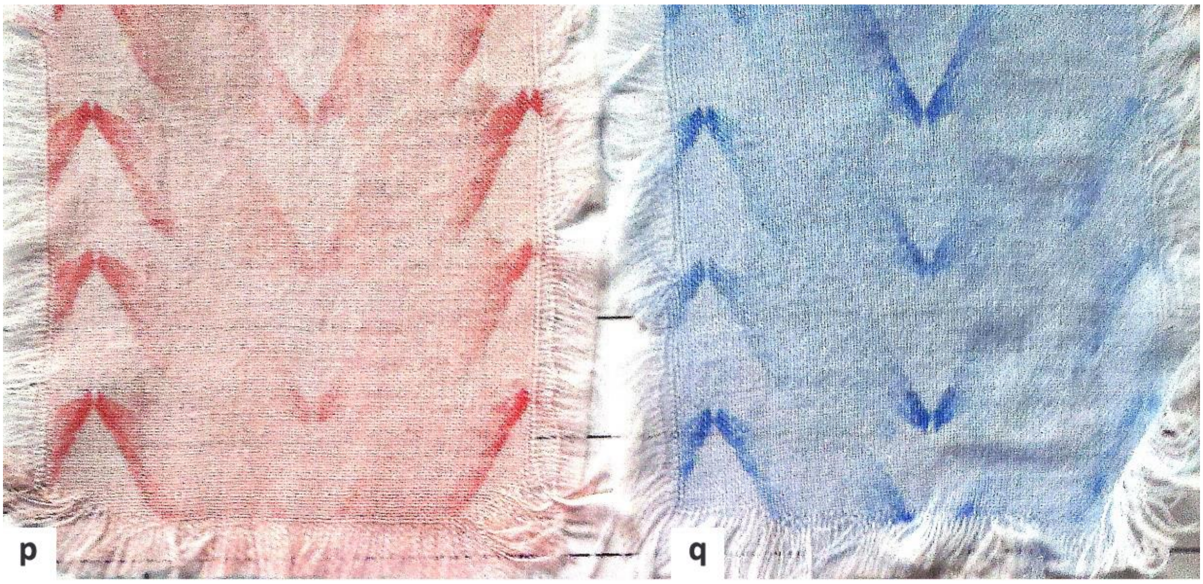


Figure 159: FDL Repeat patterns using industry standard dye

5.3.1.3 *Axis trials*

As with the aforementioned FLD method (section 5.2.1.3), axis issues in laser processing were also with the FDL method. The purpose of this investigation was to understand the impact on dye uptake capability as a result of variable angles at which the fabric was positioned and the laser bed, in relation to a constant vertical beam scan direction.

Five plain woven PET textile samples weighing 8.4g per sample and measuring approximately $28cm^2$, were individually submerged into a dye solution/bath each containing 1g of dye, 2mls of acetone and 100ml of tepid tap water. Fabric samples were manually agitated for 1 minute. Any excess solution was drained and each specimen was laser processed damp.

To modify the samples, five different angles for positioning the fabric were explored together with vertical beam scanning - 0˚, 5˚, 10˚, 15˚ and 20˚. Samples were therefore rotated accordingly. Three energy densities were applied per fabric using a greyscale raster method – 0.04 J/cm^2, 0.05 J/cm^2 and 0.06 J/cm^2 shown in Figure 160.

Results revealed the greatest dye uptake was achieved at 0˚ whereby vertical beam scanning direction and fabric orientation were parallel to one another, rather than at an angle. An energy density of 0.06 J/cm^2 yielded the deepest dyeing compared to 0.04 J/cm^2 which can be understood due to a greater processing power. Figure 160 demonstrates this outcome. By comparison, dye uptake was distinctly faint in samples - 5˚, 10˚, 15˚ and 20˚, showing marginal difference in results across experiments and between energy densities, per sample.

From these results, it can be concluded that based on the FDL method studied, the axis or orientation of a plain woven textile structure in relation the laser beam scanning direction does impact fibre modification and therefore influences dye uptake levels. When laser processed at an angle, energy density decreases causing reduced dye uptake. This indicated reduced interaction between fibre and laser beam within the parameters explored. A subtler surface effect was produced and tonal variability was far less pronounced.

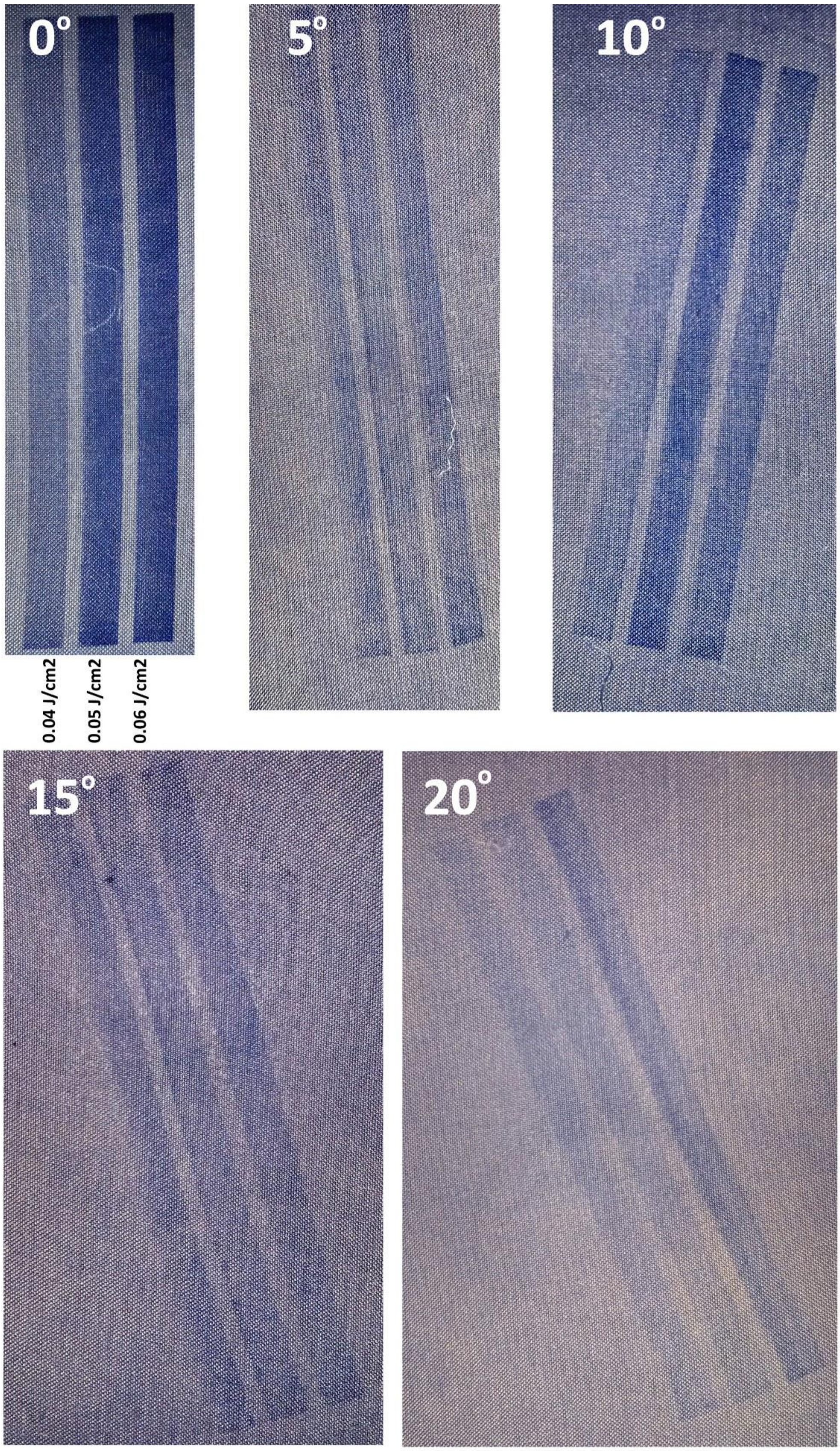


Figure 160: Axis experiments with woven PET samples laser modified at 0˚, 5˚, 10˚, 15˚ and 20˚

5.3.3 Conclusion

In this section, the experimental results of the FDL (fibre-dye-laser) digital laser-dye method explored in this research have been documented and discussed. The method follows on from the FLD (fibre-laser-dye) approach, previously discussed in section 5.2 and is in relation to the FL (fibre-laser) method set out in section 5.1. The FDL results and discussion presented corresponds to phase 3 of the research which focuses mainly on the 'Design development' aspects of the work through focused preliminary experimentation, relevant to phases 1 (Confirming previous work) and 2 (Exploratory) which also embed design development elements, as outlined in Chapter 4.

A foreknowledge of the laser processing issues gained during the FL and FLD stages of the research such as beam scanning characteristics and axis considerations for example, supported structured experimentation carried out with the FDL method in terms of a technical understanding of the parameters involved. However, in contrast to the FLD method that employed an infrared sample dyeing machine also used in industry, hand application of the dyes/solutions commanded a manual approach, not in line with industry textile coloration requirements due to a lack of precision, consistency and repeatability typically associated with hand methods. However, these factors are fundamental to an industrial approach and commercial textile production regarding coloration/patterning. Therefore, in this manner, the FDL method explored in this research is considered an initial study of the laser-dye process that is in an earlier stage of development compared to the FLD method investigated (section 5.2).

By investigating the FDL method for textile coloration/patterning in this study, it has been found in addition and alternatively to the FLD method, such an approach can also be adopted to digitally laser-dye PET (woven) textiles. As with the FLD method, the results demonstrate that it is possible to do so with graphic tonal patterns and novel surface effects aided by CAD technology combined with the addition of laser beam energy. The interaction between fibre, dye and laser enabled dyes to be fixed/absorbed into yarns via laser irradiation. Laser processing the pre-applied dye solution on the fabric activated the 'dyeing' process, causing dyes to readily adhere to fibres. The results of dye uptake were observed using microscopy to aid a scientific understanding of the process through detailed visual/computational data in order to perceive the impact of laser modification on woven PET dye stained surface fibres. In doing so, dye uptake behaviour was further understood by the ability to accurately see the spreading of dye particles on individual yarns.

Although ‘laser-dyeing’ which involves applying dyes to the fabric before laser processing is evident in an existing textile/laser study (Bartlett 2006), the exploration of such a technique has been minimally done and therefore the experimental outcomes are limited, as discussed previously (Chapter 2). Most notably, investigation into laser-dye patterning is not evidenced in the work. Therefore, the FDL method explored in this research as a preliminary study of the approach has contributed new knowledge to this field regarding ‘laser-dye’ textile coloration techniques. In particular the results achieved have advanced an understanding in this area regarding applying the dye to the fibre before laser processing, termed ‘fibre-dye-laser’ (FDL). This has been explored from a textile design perspective with a focus on coloration and patterning in order to enhance the design development potential of the digital FDL laser-dye process studied, relevant to the design and manufacture of textile goods.

Chapter 6: Analysis of results

In this chapter, an analysis of the research results presented in Chapter 5 (*Experiments and discussion of results*) concerning the digital laser-dye process are discussed. The experimental investigation involving qualitative and quantitative components is summarised and the key observations and findings of this study are set out. Additionally, the significance of the results have been described relevant to a textile/laser research field, textile design and textile manufacture.

6.1 Summary of experimental investigation

Central to the experimental investigation undertaken was the consideration of the laser beam spot as a dots-per-inch tool, drawing on the principles used in digital printing processes. It was therefore possible to utilise the beam as an image making instrument for modifying textile fibres with controlled laser energy in order to achieve digital graphics and level dye uptake. Tonal capability of the laser-dye process enhanced the appearance of patterns through an ability to achieve subtle, dramatic or gradient shifts and variable shade depths on the fabric surface. Embedded design data achieved with raster and vector CAD methods enabled this. These included: a greyscale (GS) approach involving specified percentages of black (i.e. a range of greys) in order to produce tonal variability; a greyscale-to-halftone approach which determined the eventual percentage of laser energy used to process a piece of fabric in relation to a specific halftone pattern, generated within the laser computer software; and a linear vector grid system by using specific line spacing measurements to create a precise scanning path for the laser beam to enable a range of controllable interaction levels between textile fibres and the laser.

Combined with the laser technology, the work discussed explored the technical parameters by which the process was essentially governed. Results demonstrate the design capability of the digital laser-dye approach explored through scientific understanding and integrated creative input towards replicable effects. This was achieved using a mixed method approach comprising qualitative and quantitative methods. Quantitatively, data collection involved the systematic gathering of statistical data from a range of processing parameters and assessment methods based on structured experiments using: data tables, data sheets, parameter matrices and computer software. Qualitatively, data gathering involved individual thought and expression; decision making; intuition; and tacit knowledge. Together, both approaches facilitated the creative, scientific and technical aspects of the work. In addition, further understanding about the process has been gained in terms of the functional properties associated with PET fibres and laser modified PET fabrics. Collectively, these findings support the commercial potential of the process and application opportunities. Sportswear prototypes produced in the study suggest a suitable market for processing polyester garments in this way supported by a body of experimental textile results regarding the design outputs achieved, documented and discussed in this thesis.

6.2 Observations and findings

6.2.1 An energy density approach

A quantifiable ‘energy density’ method to define the tone of a dye in terms of colour depth in relation to a particular fabric has been established in this research. In doing so, a system for calibrating levels of colour against laser energy in order to build tonal high resolution imaging was found. This system determined differential dye uptake based on variable fibre modification levels. It was therefore possible to plot energy density against the tonal density of colour/dye in order to generate specific patterns, designs and creative effects of the fabric surface. An ability to know, understand and manipulate energy output and distribution when processing a piece of fabric was fundamental to the laser-dye and design process. A mechanical know-how of methods enabled even, level dye uptake making it possible to create a range of tonal densities (patterns and effects) using a single dye colour in a way that could be repeated or altered by specification. This enabled creative exploration and freedom from a textile design perspective, which facilitated deep discipline specific knowledge and expertise relating to: types of creative effects, techniques, and styles; use of colour in terms of shade variability/tonality; and scale and composition concerning pattern, structure, form and orientation of a design or graphic component.

Energy density provided a ‘common language’ and quantitative procedure for the laser-dye process explored. As such, this understanding made it possible to achieve controlled, repeatable tonal colour range and pattern precision through combined CAD, laser technology, dye practices and analysis methods. An informed know-how of techniques aided reliability of the results parallel to design development and transferability and communication of the process/results through the use of charts, guides and tables for example, when using different CO_2 laser machines operating at different powers. Such knowledge has established the potential to commercially transfer the technique - a consideration relevant to the aims and objectives of the study regarding industrial development of the laser-dye process beyond the scope of this study.

6.2.2 Textile design, textile processing and apparel development

The interdisciplinary nature of the investigation facilitated textile design and apparel development. In doing so, the results of this study have identified: a system for tonally varied dye uptake with high-resolution graphics based on an energy density approach - a dexterous patterning tool that combines textile dyeing with CAD technology, integrating creative, technical and scientific methods in order to suggest new reliable and repeatable surface effects and designs; environmental potential of the laser-dye process in terms of a low energy, low resource approach requiring minimal or no chemicals, with the opportunity to reduce conventionally high temperatures at which synthetic textiles are currently dyed in order to achieve satisfactory depth of shade. From a textile design perspective, this opportunity may be applied to the development of sportswear for example, and other synthetic fabrics by using an innovative and environmental approach to textile design and coloration in this apparel sector; and new ways to process finished garments through combined patterning/coloration capabilities by means of laser marking/textile dyeing three-dimensional surfaces, proposing an 'on demand' post production approach relevant to industrial manufacture and commercial goods.

6.2.3 ISO Assessment: Colour analysis and textile performance

The ISO colour measurement and analysis procedures employed, such as reflectance spectroscopy and the CIELAB system set out and discussed in Chapter 5, further facilitated communication and transferability of the results. Colour data was configured both visually and numerically in relation to observations and assessments carried out on laser modified polyester fabrics. Findings encompassed microscopy, statistics, graphical and design interpretations of the results, based on a thorough examination of fibre, laser and dye interactions.

ISO wash fastness tests and textile performance tests examined the opportunities and limitations of the process in terms of coloration/patterning potential and functionality. This provided relevant information for industry in terms of textile processing and application. The outcomes of this assessment reported good dye-to-fibre adhesion achieved with laser-dyeing and therefore high levels of fastness, indicating dye stability. Performance tests affirmed controllability of the process pertaining to specific fibre modification intensities applied. A spectrum of variable surface effects tested yielded a range of textile performance data in relation to specific laser processing parameters i.e. designs, patterns and coloration techniques. As such, this information provides a useful basis for further work.

6.3 Significance of the results in this research field, for textile design and manufacture

A diverse range of interdisciplinary data types (qualitative and quantitative) have been generated regarding knitted and woven polyester textiles studied, relevant to several research fields and academic disciplines. This work has resulted from the rigorous textile design research approach adopted in order to carry out the investigation sufficiently, as discussed in Chapter 3 (*Methodology*). Experimental outcomes alongside creative exploration facilitated both a tacit understanding of, and ability to specify and control, laser-dye processing parameters towards particular surface effects. Therefore, laser technology can be considered as an alternative tool to traditional and existing textile patterning techniques and production methods.

In depth experimentation revealed opportunities for processing finished garments. The laser beam was able to scan across seams and stitching whilst retaining high-resolution graphic qualities and tonal definition. This is not achievable with conventional image-based dye/coloration approaches onto finished garments. For example, with digital printing processes, the flat fabric is printed by the metre and the garment is constructed after printing and fixing the dye to the fabric. In screen-printing, the bulkiness of a finished garment when laid flat interferes with application and evenness of the print due to an uneven surface. Garment dyeing typically involves total submersion of the item in a dye vat or equivalent dye container. These approaches do not facilitate patterning, focusing on coloration of the whole garment in a single even shade to achieve a uniform distribution of dye colour. As such, this research proposes an alternative digital laser-dye method for textiles relevant to industrial manufacture and commercial goods. The DLD process identifies potential as an ‘on demand’ coloration tool for textiles with customisation possibilities – an approach also considered relevant to the development of other fibres, textile structures and dyes.

Chapter 7: Conclusion

The work presented in this thesis is regarding a ‘digital laser-dye’ (DLD) process that was explored using a practice-led research approach and carried out from a textile design/practitioner perspective. This study was undertaken within an interdisciplinary framework integrating textile design, optical engineering, dyeing chemistry and collaborative industrial involvement with projects partners SDC, in order to understand the commercial potential of the techniques established and develop the means to transfer, apply and extend methods and procedures within an industry environment. The research results are also applicable to other textile designers, textile manufacturers and alike in terms of the ability to reliably communicate practices. In doing so, this facilitates the transferability of the process as an ‘on demand’ or ‘digital demand’ laser-dyeing approach relevant to textile production, textile goods and finishing procedures. As such, this work promotes textile design innovation by demonstrating new ways to process fabric with colour and pattern based on an in depth knowledge of the technical, scientific and creative aspects of the DLD process investigated.

CO_2 laser technology was investigated as a method to modify woven and knitted PET textiles with digital patterns in order to generate tonally varied high resolution graphics on the fabric surface when dyed. In doing so, ‘laser-dye patterning’ techniques were studied as an alternative coloration method to conventional approaches. The process combined laser processing, dyeing and CAD technology. This involved interactions between the laser beam, textile fibres, dyes and computer design software, suggesting a new digital patterning procedure for textiles. Therefore, in this research, laser-dyeing was studied to understand the potential of the process as a viable creative ‘image making’ tool for textile coloration and textile design development. In this manner, an approach for precision dyeing with graphics has been established, not possible with conventional dyeing/coloration methods. Instead, the digital laser-dye process can be likened to digital textile printing for example, based on the quality and intricacy of designs achievable due to the integration of CAD techniques. However, unlike digital printing whereby dyes sit on the textile surface, with laser-dyeing, the fibres are integrally dyed which was confirmed by carrying out microscopic analysis on treated fibres. This suggested the robustness of the process in terms of stable dye uptake, also supported by the results of ISO wash fastness tests carried out that were mostly rated 5 (*very good*) or 4 (*good*). Combined laser and CAD technologies facilitated a technical understanding of the process which can be controlled and surface effects repeated based on the ability to specify and determine aesthetic outcomes and produce replicable results.

The environmental opportunities of the digital laser-dye process regarding synthetic fabrics have also been considered and discussed in this thesis in relation to design considerations and potential production advantages of processing polyester textiles in this way, to some extent identified in existing textile/laser studies. These include: an ability to generate tonally distinct surface designs using reduced dye quantities and therefore less resources. This approach, which has been identified in this research, generated a pale base cloth whilst producing a deep saturated laser-dyed pattern comprising distinguishable variable shade depths and therefore a distinct graphic aesthetic; exploiting laser technology as an environmental alternative to traditional textile patterning techniques based on a low resource approach due to the low energy output of lasers and the absence of water and solvents in laser-processing; and the potential to reduce high temperatures at which synthetic PET fabrics are conventionally dyed due to the increased dye uptake capability of the process. As such, this could potentially reduce energy consumption and negate the demand for additional chemicals used in printing processes, for example. Together, this knowledge supports and develops an existing understanding of the environmental aspects associated with laser modified textiles for improved dyeability of synthetic materials. Potential development of the digital laser-dye from an environmental perspective is discussed in Chapter 8 of this thesis titled, *Further work*.

Through the investigation and development of textile coloration and patterning for PET fabrics, this study has advanced knowledge regarding the digital laser-dye process explored, relevant to textile/laser research fields, textile design communities and textile manufacture. Knitted and woven PET textiles as well as prototype sportswear garments, garment sections and intimate apparel items were studied in order to understand the capability of the process regarding different textile structures as well as potential applications of the process that considered the commercial relevance, product type, aesthetics and functionality. Therefore, in addition to the creative aspects of the work regarding textile design development and innovation in the creation of novel coloration/patterning techniques and surface effects, the inquiry was supported by technical analysis and the demonstration of these outcomes. This involved colour measurement and assessment including ISO procedures; ISO wash fastness tests; and ISO textile performance tests which led to data analysis and interpretation of the results. In this manner, the analysis also assisted further scientific understanding of the process such as quantifying colour in relation to laser-dyed/patterned fabrics and the impact of treated fabrics regarding the altered structural/functional properties of fibres. The interdisciplinary nature of this investigation therefore facilitated textile design and apparel development in relation to the digital laser-dye process explored.

Although the effects of laser modification on the coloration properties of some synthetic fibres have been identified in previous academic studies such as Shahidi et al (2013), Nourbakhsh and Ebrahimi (2012), Bahtiyari (2011), Yip et al. (2002) and Kan (2008), knowledge is limited in terms of creative exploration of the research results and the integration of industrial procedures regarding the commercial relevance and development of techniques established. Current textile/design literature (Addrison 2009; Bartlett 2006) suggests the potential for new textile coloration approaches based on combined laser-dye methods however, development of these ideas from a textile design perspective is minimal and therefore limited. So, based on the gaps identified in existing knowledge, this digital laser-dye study has enhanced the design capability and commercial relevance of the process through a scientific understanding of laser technology, embedding ISO dyeing and analysis procedures, an in depth knowledge of CAD methods and deep discipline specific know-how in order to modify and dye fabrics in this way. Essentially, integrated creative input was underpinned by a textile design approach towards textile design innovation. Design development and exploration was therefore integral to this study. Experimental methods and procedures employed combined quantitative and qualitative approaches (mixed methods) to: assist project progression within an interdisciplinary and collaborative capacity; facilitate creative development; and ensure reliability of the process in terms of replicable consistent effects and the transferability of methods involved. In doing so, the commercial potential of digital laser-dyeing as a new coloration and patterning possibility for PET textiles was investigated, enabled by industry involvement with project partners, SDC.

The research presented and discussed in this thesis has contributed new knowledge to the fields of laser material processing, textile engineering, textile coloration and textile design and CAD technology by:

1) Establishing a system for laser-dyed textiles, termed ‘digital laser-dye’, to enable tonally varied dye uptake with high-resolution graphics based on an energy density approach

An ability to control and determine energy density in order to achieve specific surface effects/shade depths has been established in this research. This was achieved with the laser machine and combined digital parameters regarding both laser and CAD software. As such, raster and vector methods for modifying surface fibres to generate tonally varied dye uptake were identified and explored. This area of contribution demonstrates an understanding of laser beam output energy, enabling the initiation and development of a dexterous patterning tool that combines laser technology, textile dyeing with CAD technology. The raster and vector approaches investigated and established facilitate pattern creation, enabling laser processing precision and consistent design results. In relation to this, the work presented in this thesis suggests new reliable and repeatable surface effects by integrating creative, technical and scientific methods. Variable tonal densities were generated with a single dye shade by way of controlled laser energy. In turn, design qualities were enhanced by high resolution laser-dyed textile patterns. Patterning capability was determined by an in depth knowledge of experimental parameters involved based on an interdisciplinary practice-led research approach. A method for calibrating tonal density i.e. shade depth (with graphics and flat colour) against laser energy density in relation to a specific fibre (PET) has been established. In doing so, a formula for quantifying colour in terms of generating laser-dye uptake variability was understood. This understanding relates to raster and vector laser processing approaches. The raster method involved different percentages of black (greyscale) and 'unique' halftone patterns which determined eventual energy density in relation to the actual power output. The vector method was based on being able to numerically specify the beam scanning path in relation to beam diameter using a precision grid system to create and calculate tonal variability.

2) Establishing digital laser-dyeing as a commercially relevant laser-dye patterning tool for textiles through industry standard (ISO) procedures, colour measurement and analysis and textile performance testing

ISO procedures and tests were undertaken in order to develop the commercial potential of the digital laser-dye process explored in line with current commercial requirements for textile coloration practices and manufacture. Collaboration with industrial project partner, the SDC enabled this. In doing so, technical analysis and demonstration of the research results was established. ISO standardized woven and knitted PET fabrics were explored which aided repeatability and reliable consistent results. ISO dyes, dyeing methods and equipment were employed in order to ensure practices undertaken aligned with current industry standards for textile coloration. ISO colour measurement and analysis procedures performed on laser-dye treated and untreated fabrics facilitated quantitative colour communication in relation to the process by obtaining industry relevant data types such as: Reflectance Spectrophotometer measurements; CIE LAB colour and Delta E colour difference values; Wash fastness tests indicated robustness of the laser-dye process according to industry requirements and compared to untreated fabrics such as dye stability/wash-off/staining and changes in depth of shade after washing were assessed. The wash fastness results yielded produced a significantly high proportion of acceptable outcomes in relation to commercial requirements for the production of textiles/goods. In addition, ISO textile performance tests were carried out on specific laser-dyed effects attributed to specific processing parameters. Test specimens included treated and untreated fabrics. This inquiry provided a greater understanding about the impact of laser processing fibres in this way through quantitative analysis of the test results. This work confirmed functionality linked to particular engineered laser-dyed patterns and effects explored.

3) Suggesting new ways to process finished garments by applying colour and pattern using the digital laser-dye process

The digital laser-dye process investigated proposes a new ‘on demand’ or ‘digital demand’ laser-dye approach to finish garments post production based on the ability to laser process/scan across complex construction details such as seams, stiches, joins, fastenings and uneven or irregular shapes and surfaces such as bras for example, demonstrated in this study. The work presented and discussed in this thesis identifies combined patterning and coloration capabilities by means of laser marking and dyeing 3D surfaces whilst retaining high-resolution graphic qualities and tonal definition. As such, this approach is relevant to industrial manufacture, commercial goods and considers the potential of a laser-dye process as an on demand coloration tool for textiles with customisation possibilities.

4) Demonstrating the design potential of the digital laser-dye process

A new digital laser-dye surface patterning method for textiles explored in this research begins to demonstrate the design potential for integrating aesthetics, science and technology based on an interdisciplinary approach within this field (Textile Design). As such, this practice-led investigation was underpinned by a textile design perspective contributing discipline specific knowledge and expertise relating to fabric and fibres, traditional textile techniques and processes; creative concepts; and experience as a print, pattern and surface textile designer based on a know-how of applied and CAD approaches. Pattern creation and the development of graphics was facilitated by design intuition, tacit and experiential knowledge executed through CAD approaches employed from a design practitioner standpoint. In doing so, a qualitative approach embedded insights, thinking, and decision-making as a textile designer. This facilitated the production of innovative textiles and garments, which exploit the capability of laser-dye techniques demonstrated through novel surface patterning and coloration effects with variable dye densities/shade depths.

A range of processing parameters were investigated enabling different design possibilities in relation to the fabric structure. A controlled experimental approach not only facilitated new creative effects, but aided variants, and therefore creative exploration of an outcome, achieved through adjusting individual parameters to determine levels of colour, sharpness of image and the overall aesthetic of a pattern. This design flexibility further supports the on demand and customisation potential of the process.

Quantitative procedures identified in this study including an energy density method, calibration systems, laser processing parameters, colour assessment and so on supports the transferability of information, results and practices involved. For example, colour data (graphs, charts, tables and diagrams) may be considered a type of 'know-how guide' and model for laser processing textiles in this way. Scientific approaches adopted enable communication and application of the digital laser-dye process in different environments, particularly relevant to commercial situations significant to this research. As such, an ability to replicate effects and achieve consistent results has been achieved. This work therefore demonstrates a rigorous laser-dye approach explored with PET textiles, also relevant to the coloration and patterning development of other fibres, textile structures, dye types and shades.

The following chapter, *Further work* (Chapter 8), discusses the potential of the process beyond this doctoral research.

Chapter 8: Further work

In this chapter, further work beyond the scope of this doctoral research has been identified. In order to contextualise the work proposed, further discussion falls into three areas, outlined in Figure 161.

1) Creative opportunities
2) Application
3) Manufacture

Between these areas, there is some crossover regarding aspects of the process in terms of common factors such as design innovation, which is most relevant to both the creative opportunities and application, along with synthetic fabrics, for example, which relates to all areas. As such, the reciprocal nature of the components identified are reflected in this discussion.

The creative opportunities presented by CAD technology facilitates the potential for broad investigation into laser-dyed graphics for textiles and clothing. Advances in computer software will aid pattern generation with vector methods, similar to the image-based capability of the raster approach identified in this research. Furthermore, computer software and digital interfaces which allow 'co-design' and 'co-creation' approaches in order to realise and obtain a product/garment also presents an area for development from an on demand customisation perspective relevant to technological advancements, consumer patterns and supply chains.

Using a DLD process, an ability to vary artistic impressions by way of shapes, structures, forms, gradients, symbols, moiré effects, text and so on, through high resolution engineered dye/colour and combined techniques demonstrates originality from a textile design perspective. Different fibre types such as alternative synthetic textiles and natural materials for example, as well as varied fabric structures suggest the potential for new experimental surface effects. A consideration also relevant to mixed fibre fabrics. As such, the capability of the process is favourable to customisation possibilities and on demand design potential for garments.

Further work

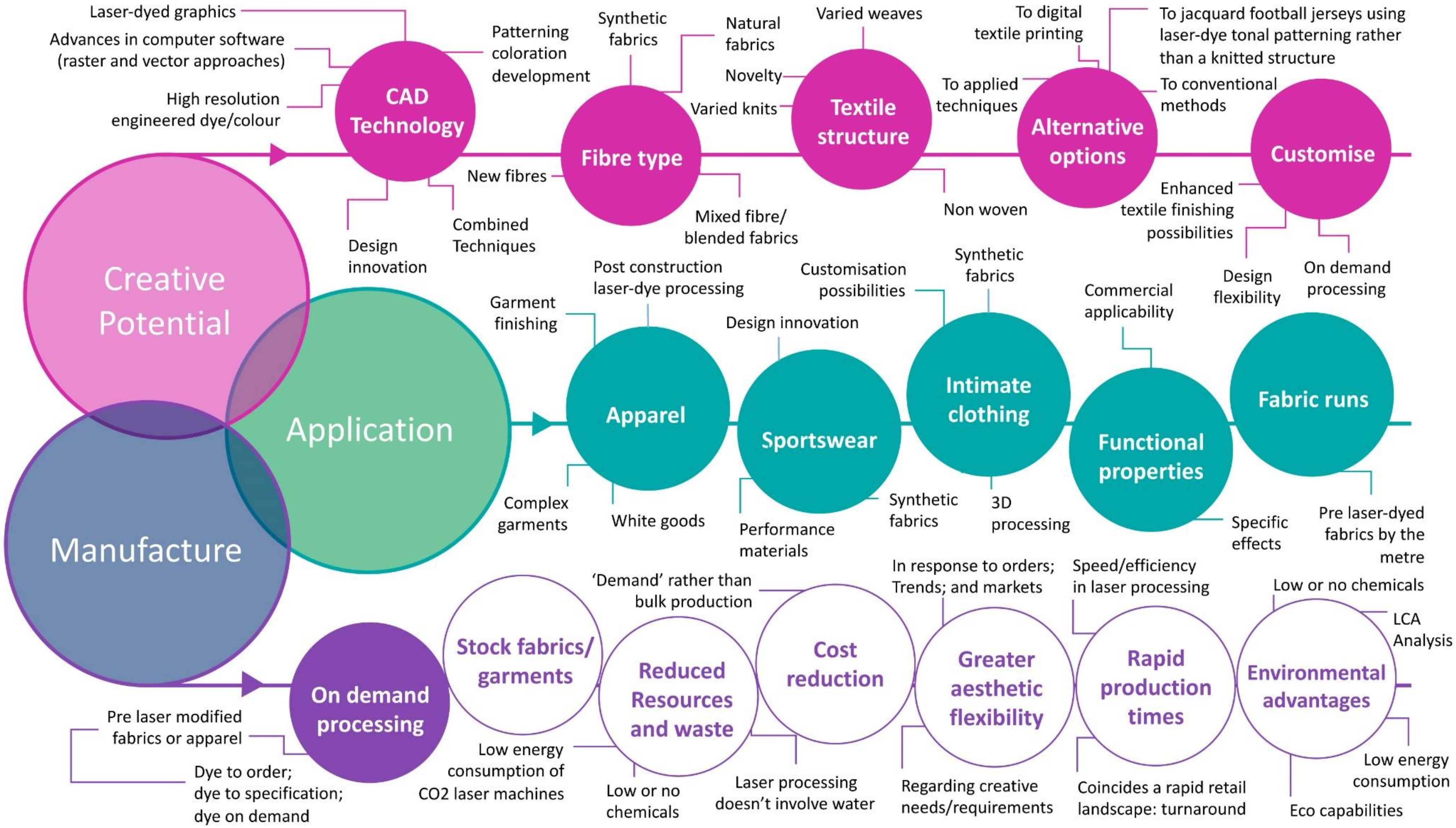


Figure 161: Diagram identifying 3 main areas for further work beyond this doctoral study

Similarly, this work proposes an alternative to woven or knitted jacquard stock fabrics, for example using a patterning surface design approach rather than structural methods for creating patterns. In this manner, the tonal distribution of colour at different densities/shade depths combined with high precision graphics enabled by the laser-dye process aids the production of intricate gradation patterns with woven or knitted textiles without the use of additional or separate yarns attributed to the jacquard process. Consequently, this approach eliminates yarns leading to less physical stock. It is therefore potentially more efficient than a traditional automated jacquard process that is typically resource intensive in fabric production to generate constructed textile patterns.

Compared to printing processes, laser-dyeing integrally dyes fibres rather sitting of the textile surface. This suggests digital laser-dyeing is a more robust coloration/patterning approach than textile printing, which further supports the suitability of the process for active/sportswear such as football jerseys, for example which are prone to extensive physical activity, bodily contact and wear. Laser processing is a low energy approach that does not require water or additional chemicals in dyeing as with screen printing methods. Additionally, fabrics do not require a pre-coating or steam/heat fixing, common to digital textile printing. Therefore, the laser-dye process is considered more efficient when compared to textile coloration and patterning printing approaches. In terms of application, textile products such as football jerseys for example, suggests a likely apparel sector suited to the laser-dye process.

In the long term, goods could be laser manufactured in bulk or small batches in advance of distribution to the market place such and retail or wholesale outlets and dye/finished on demand in response to orders, trends, markets etc. For example, the potential to utilise laser-dyeing for stock garments such as ‘white goods’ could largely impact retail environments. In turn, this would also reduce waste resources and manufacturing costs due to a ‘demand’ approach, whilst enabling greater aesthetic flexibility. Production times from fabric-to-finished garment could be reduced, eliminating the need for multiple stages and excess resources in the chain. Commercially, the process would respond to a rapid retail landscape where production turnaround needs to be fast. In addition, environmental advantages would aid production efficiency.

As with a white goods approach, the prospect of laser modifying runs of ‘white’ fabric with patterns prior to the dyeing stage advances textile coloration methods in this field. In such manner, ‘Dye to order’/‘Dye to specification’/‘Dye on demand’ principles are initiated. Subsequently, production efficiency is further encouraged in terms of increased speed and minimal fabric/dye waste for example, in response to creative needs and requirements.

By identifying types of clothing in order to develop the concept of laser-dyed finished garments, integrated performance testing would be possible to aid an understanding about the functional properties of a product in relation to the impact of a particular pattern/graphic/design. This type of assessment has the potential to extend the commercial applicability of the process, as previously discussed. Test results would provide quantitative analysis linked to specific laser/dyed effects and performance data would assist the identification of optimal laser-processing parameters to maintain acceptable functionality of a particular item or product type.

Environmentally, potential development lies in areas such as Life-cycle analysis (LCA). For instance, LCA may be adopted through an interrogation and assessment of process stages involved in digital laser-dyeing as to extend environmental capability of the process. Isolated analysis of energy usage, water, chemicals, waste, processing speed and so on, compared with conventional patterning approaches and workshop practices can be considered. Energy consumption attributed to the laser/dyeing equipment, along with other resources and production factors such as time and cost, as well as waste issues suggests relevant assessment areas. Results could indicate that the laser-dye methods and procedures employed need to be revised in order to achieve best environmental practice. In this way, an in depth ecological study surrounding lase/dye methods will advance knowledge in this field. Although existing studies acknowledge some potential environmental advantages of combined laser/dye/textile coloration processes, knowledge is limited due to under-exploration of ideas around the subject and limited real world application. Further work identified in this thesis therefore seeks to address this gap.

References

1. Addrison, J., (2009). Jenny Addrison, In: *Cutting Edge: Laser and Creativity Symposium, Loughborough University, School of the Arts, 2009.* Available: *http://www.*cuttingedgesymposium.com/pdf/jenny-addrison.pdf [October 30, 2015].

2. Addrison, J., (2009). *Laser surface modification of woven textile structure for dyeing*. Project Report [Unpublished]. Materials Research School Summer Bursary Project, Loughborough University, 1-18.
.
3. Albers, A., (1962). *Anni Albers: On Designing*. 2nd ed. Connecticut: Wesleyan University Press.

4. Arts & Humanities Research Council, (2005). 6 December 2005, 2005-last update, Research Review: Practice-led Research in Arts, Design and Architecture, AHRC's Definition of Research [Homepage of Arts & Humanities Research Council], [Online]. Available: http://aces.shu.ac.uk/ahrc/ahrcreview/resources/ahrcdefinition.html [July 28, 2011].

5. Aspland, J., (2000). Whither textile colour application research? Dyes and Pigments, 47(1–2), 201-206.

6. Babenko, V. and Tychinskii, V. (1973). Gas-Jet Laser Cutting (review).*Quantum Electronics*, *2*(5), 399-410.

7. Bach, E., Cleve, E. and Schollmeyer, E. (2002). Past, present and future of supercritical fluid dyeing technology–an overview. *Review of Progress in Coloration and Related Topics*, *32*(1), 88-102.

8. Bahners, T. and Schollmeyer, E. (1989). Morphological changes of the surface structure of polymers due to excimer laser radiation: A synergetic effect? *Journal of Applied Physics*, *66*(4), 1884-1886.

9. Bahners, T., Kesting, W. and Schollmeyer, E. (1993). Designing surface properties of textile fibers by UV-laser irradiation. *Applied Surface Science, 69*(1-4), 12-15.

10. Bahtiyari, M. (2011). Laser modification of polyamide fabrics. *Optics & Laser Technology, 43*(1), 114-118.

11. Bailey, M. and Smith, N., (2010). *Multi-disciplinary Design Education in the UK, Report and Recommendations from the Multi-disciplinary Design Network*, Design Council. http://www.designcouncil.org.uk/documents/documents/ourwork/mdnetwork/mdnetwork_finalreport.pdf [Online]. [September 1, 2012].

12. Bamforth, P., Williams, K. and Jackson, M.R., (2006). Edge quality optimisation for CO2 laser cutting of nylon textiles. *Applied Thermal Engineering, 26*(4), 403-412.

13. Bartlett, S., (2006). *Lasers and textiles: an exploration into laser dye-fibre interaction and the process of technology transfer.* Doctoral Thesis (PhD). United Kingdom: Loughborough University.

14. Bassett, G., Menter, J., and Pashley, D., (1958). Moiré patterns on electron micrographs, and their application to the study of dislocations in metals. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, *246*(1246), 345-368.

15. Bowiestie (2010). Moire patterns gifs. In: *Bowiestie* [Online]. Available: https://bowiestie.wordpress.com/2010/02/18/moire-pattern-gifs/ [December 26, 2014].

16. Bowles, M., and Isaac, C., (2012). *Digital Textile Design*. 2nd ed. London: Laurence King Publishing.

17. Braddock Clarke, S. and Harris, J., (2012). *Digital Visions for Fashion and Textiles: Made in Code.* New York: Thames and Hudson.

18. Clarke, S., (2011). *Textile Design: Portfolio Series.* London: Laurence King Publishing.

19. Creswell, J., (1994). *Research Design: Qualitative & Quantitative Approaches*, London: Sage.

20. Cresswell, L. (2002) *Textiles at the cutting edge*. 2nd ed. London: Forbes.

21. Cross, N. (1999). Design research: A disciplined conversation. *Design issues*, 5-10.

22. Cross, N. (2001). Designerly ways of knowing: Design discipline versus design science. *Design issues*, *17*(3), 49-55.

23. Davies, M. (2007) *Doing a successful research project: using qualitative and quantitative methods*. Basingstoke: Palgrave Macmillan.

24. Davies, O., (1979). *The design and analysis of industrial experiments*. 2nd ed., New York: Imperial Chemical Industries Ltd.

25. Design Council, (2005) *The Double Diamond design process*. [Online]. Available: http://www.designcouncil.org.uk/designprocess [January 5, 2013].

26. Design and Emotion, (2014) *The Design and Emotion Society* [Online]. Available: Homepage: http://designandemotion.org/ [October 1, 2014].

27. Dorst, K. (2006). *Understanding design: 175 reflections on being a designer*. Corte Madera: Gingko Press.

28. Drake, P. and Heath, L., (2011). *Practitioner Research at Doctoral Level: Developing coherent research methodologies.* Oxon: Routledge.

29. Durling, D. and Niedderer, K., (2007). The benefits and limits of investigative designing. In: *IASDR International Conference* [Online]. Available:

http://www.sd.polyu.edu.hk/iasdr/proceeding/papers/The%20Benefits%20and%20Limits%20of%20Investigative%20Designing%20%20%20.pdf [January 30, 2015].

30. Ecotextile. (2011). 6 January 2011, 2011-last update, Green Chemistry: Prevention is Better than Cure [Homepage of Ecotextile], [Online]. Available: http://www.ecotextile.com/2011010610923/materials-production-news/green-chemistry-prevention-is-better-than-cure.html [January 10, 2011].

31. Edith Cowan University, (2013). Research methodologies for the creative arts and humanities [Online]. Edith Cowan University. Available: http://ecu.au.libguides.com/content.php?pid=304691&sid=3085738 [January 22, 2015].

32. Elsasser, V., (2005). *Textiles: concepts and principles.* 2nd ed. New York: United States of America: Fairchild Publications, Inc.

33. Fish, J., (2005). *Designing and Printing Textiles.* England Wiltshire: Crowood Press.

34. Gabzdy, J., (2008). Materials Processing: Fibre lasers make their mark. *Nature Photonics,* (2), 21-23.

35. Gao, Z., Zhang, L. and Zhao, J. (2006). Application of laser technology in textile industry. *Journal of Textile Research*, *27(8)*, 117-120.

36. Global Colour Research Ltd., (2009) [Wall treatments: monochrome graphics]. *Mix. Color, trend and design magazine: International trends A/W 2010/11*, *3*(17), pp. 22.

37. Goldsworthy, K., (2009). Resurfaced: Using Laser Technology To Create Innovative Surface Finishes For Recyclable, Synthetic Textiles. In: *Cutting Edge: Laser and Creativity Symposium,* School of the Arts, Loughborough University. Kate Goldsworthy [Homepage of http://www.cuttingedgesymposium.com/20-minute-papers/kate-goldsworthy.html], [Online]. Available: http://www.cuttingedgesymposium.com/pdf/kate-goldsworthy-paper.pdf [January 25, 2011].

38. Gray, C. and Malins, J., (2004). *Visualizing Research: A guide to the research process in art and design*. Surrey: Ashgate Publishing Limited.

39. Harrison, A., (1978). *Making and Thinking: A Study of Intelligent Activities*. Sussex: The Harvester Press.

40. Hobson, J. (1961) *Dyed and printed fabrics*. 2nd ed. Leicester: Dryad Press.

41. Hornung, D. (2004) *Colour: a workshop for artists and designers*. London: Laurence King.

42. Hung, O., Song, L., Chan, C., Kan, C. and Yuen, C., (2011). Using artificial neural network to predict color properties of laser-treated 100% cotton fabric. *Fibers and Polymers*, *12*, 1069-1076.

43. Hung, O., Song, L., Chan, C., Kan, C. and Yuen, C. (2012). Predicting the laser-engraved color properties on cotton-spandex fabric by artificial neural network. *AATCC Review*, *12*(3), 57-63.

44. Itten, J. (1970) *The elements of color: a treatise on the color system of Johannes Itten, based on his book The art of color*. New York; Cincinnati: Van Nostrand Reinhold Company.

45. Karanikas, V., Nikolaidis, N. and Tsatsaroni, E. (2013). Disperse ink-jet inks with active agents: properties and application to polyester and polyamide fibers. *Textile Research Journal*, *83*(5), 450-461.

46. Katz, J. and Martin, B. (1997). What is research collaboration? *Research policy*, *26*(1), 1-18.

47. Kendall, T., (2001). *The Fabric & Yarn Dyer's Handbook.* London: Collins & Brown Limited.

48. Kesting, W., Bahners, T. and Schollmeyer, E. (1990). Controlled structuring of polymer surfaces by UV-laser irradiation. *Applied Surface Science*, *46*(1), 326-329.

49. Kamel, M., Raslan, W., Helmy, H. and Al-Ashkar, E., (2012). Improving Properties of Polyester and Cellulose Acetate Fabrics using Laser Irradiation. *Journal of Textile Science and Engineering*, (2), 117.

50. Kane, F., (2008). *Designing nonwovens: craft and industrial perspectives.* Doctoral Thesis (PhD). United Kingdom: Loughborough University.

51. Kane, F., (2009) Laser Patterned Nonwovens. In: *Cutting Edge, Lasers and Creativity Symposium*, School of the Arts, Loughborough University. Faith Kane [Homepage of http://cuttingedgesymposium.com/digital-posters/], [Online]. Available: http://www.cuttingedgesymposium.com/pdf/faith-kane.pdf [January 25, 2011].

52. Kan, C., (2008a). A study of laser treatment on polyester substrates. *Fibers and Polymers, 9*(2), 166-170.

53. Kan, C., (2008b). Impact on textile properties of polyester with laser. *Optics & Laser Technology, 40*(1), 113-119.

54. Kan, C., Yuen, C. and Cheng, C. (2010). Technical study of the effect of CO2 laser surface engraving on the colour properties of denim fabric.*Coloration Technology*, *126*(6), 365-371.

55. Khouni, I., Marrot, B., Moulin, P. and Ben Amar, R. (2011). Decolourization of the reconstituted textile effluent by different process treatments: Enzymatic catalysis, coagulation/flocculation and nanofiltration processes. *Desalination*, *268*(1), 27-37.

56. Kong, H. and Wu, H., (2008). Pretreatment of textile dyeing wastewater using an anoxic baffled reactor. *Bioresource technology, 99*(16), 7886-7891.

57. Laurel, B. (2003), *Design Research: Methods and Perspectives*, London: The MIT Press.

58. Lau, K., Chan, P., Yeung, K., Chan, K. and Gong, W., (1997). Surface properties of polyester fabrics induced by excimer laser processing. *Journal of Materials Processing Technology, 63*(1-3), 524-528.

59. Lockman, W. and Clayson, F., (1996). *Method for marking and fading textiles with lasers.* [Patent]. 8/444; 8/115.52; 8/115.53. United States: D06P 5/20.

60. Mahony, M., and Sarah Braddock, S., (2010). *Textiles and New Technology 2010*, London: Artemis London Limited.

61. Malins, J., Gray, C., and Bunnell, K. (1995). *Appropriate Research Methodologies for Artists, Designers and Craftpersons: Research as a Learning Process*. Gray's School of Art, Centre for Research in Art & Design [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.194.9364&rep=rep1&type=pdf [Accessed: January 15, 2015].

62. Matthews, J., (2009) Textile Design Research with/into Laser Processing. In: *Cutting Edge, Lasers and Creativity Symposium*, School of the Arts, Loughborough University. Janette Matthews [Homepage of http://cuttingedgesymposium.com/digital-posters/], [Online]. Available: http://cuttingedgesymposium.com/pdf/janette-matthews.pdf [January 25, 2011].

63. Matthews, J., (2011). *Textiles in Three Dimensions: An investigation into processes employing laser technology to form design-led three-dimensional textiles*. Doctoral Thesis (PhD). United Kingdom: Loughborough University.

64. McDonough, W. and Braungart, M. (2002), *Cradle to Cradle: Remaking the Way We Make Things*. 2nd ed. New York: North Point Press.

65. Meller, S. and Elffers, J., (2002). *Textile Designs: 200 Years of Patterns for Printed Fabrics arranged by Motif, Colour, Period and Design*. United Kingdom: Thames & Hudson.

66. New Cloth Market, (2011). *New technologies in textile dyeing and finishing*. Fibre2Fashion. [Online]. Available: http://www.fibre2fashion.com/industry-article/32/3181/new-technologies-in-textile-dyeing-and-finishing3.asp [June 1, 2012].

67. Nimkulrat, N. (2010). Material inspiration: From practice-led research to craft art education. *Craft Research*, *1*(1), 63-84.

68. Norman, D., (2004). *Emotional Design: Why we love (or hate) everyday things*, New York: Basic Books.

69. Nourbakhsh, S. and Ebrahimi, I. (2012). Different surface modification of poly (ethylene terephthalate) and polyamide 66 fibers by atmospheric air plasma discharge and laser treatment: Surface morphology and soil release behavior. *Journal of Textile Science and Engineering*, *2*(109), 2.

70. Ondogan, Z., Pamuk, O., Ondogan, E. and Ozguney, A., (2005). Improving the appearance of all textile products from clothing to home textile using laser technology. *Optics & Laser Technology,* 37(8), 631-637.

71. Ortiz-Morales, M., Poterasu, M., Acosta-Ortiz, S., Compean, I. and Hernandez-Alvarado, M., (2003). A comparison between characteristics of various laser-based denim fading processes. *Optics and Lasers in Engineering, 39*(1), 15.

72. Osing, J. and Shvets, I. (1998). Bulk defects in graphite observed with a scanning tunnelling microscope. *Surface science*, *417*(1), 145-150.

73. Papanek, V., (1985). *Design for the real world: human ecology and social change*, 2nd ed., London: Thames and Hudson.

74. Provost, J., (1994). Ink Jet Printing on Textiles. *Surface Coatings International, 77*(1), 36-71.

75. Quinn, B., (2013). *Textile Visionaries: Innovation and Sustainability in Textile Design*. London: Laurence King.

76. Rhoten, D., (2004). Interdisciplinary research: Trend or transition. *Items and Issues, 5*(1-2), 6-11.

77. Robertson, S., (2009). The use of laser etching to enhance liquid crystal colour-change on textiles. In: *Cutting Edge, Lasers and Creativity Symposium*, School of the Arts, Loughborough University. Sara Robertson [Homepage of http://cuttingedgesymposium.com/digital-posters/], [online]. Available: http://www.cuttingedgesymposium.com/pdf/sara-robertson.pdf [January 25, 2011].

78. Rodie, J., (2012). *Saving water a swimming poolful at a time*. [Online]. Textile World. Available: http://www.textileworld.com/Issues/2012/November-December/Features/Saving_Water_A_Swimming_Poolful_At_A_Time [August 1, 2013].

79. Rogers, E., (1962). *Diffusion of Innovations*. The Free Press. A Division of Simon & Schuster, Inc., (35), 267-299.

80. Ronald, E., (2012). *Patterns of Identity: hand block printed and resist-dyed textiles of rural Rajasthan*. Doctoral Thesis (PhD). United Kingdom: De Montfort University. Emma Ronald. Available: https://www.dora.dmu.ac.uk/handle/2086/8691 [Online], [October 29, 2014].

81. Rong, Z. Y., & Kuiper, P. (1993). Electronic effects in scanning tunneling microscopy: Moiré pattern on a graphite surface. *Physical Review B*, *48*(23), 17427.

82. Seivewright, S., (2007). *Basics Fashion Design 01: Research and Design.* Switzerland: AVA Publishing.

83. Seymour, S., (2010). *Functional Aesthetics: Visions in Fashionable Technology*, New York: Springer, 2010.

84. Schön, D., (1991). *The Reflective Practitioner: How Professionals Think in Action.* 2nd ed. New York: Basic Books.

85. Shahidi, S., Wiener, J. and Ghoranneviss, M., (2013). *Surface Modification Methods for Improving the Dyeability of Textile Fabrics.* InTech. Available: http://www.intechopen.com/books/eco-friendly-textile-dyeing-and-finishing/surface-modification-methods-for-improving-the-dyeability-of-textile-fabrics [Online], [June 12, 2014].

86. Shamey, R. and Shim, W., (2011). Assessment of key issues in the coloration of polyester. *Textile Progress, 43*(2), 97-153.

87. Smart House Idea (2012). *Lenzing Spring/Summer 2013 colour trends colour usage/polyvore sportswear* [Online]. Available: http://smarthouseidea.com/lenzing-spring-summer-2013-color-trends-color-usage-polyvore.htm [August 29, 2012].

88. Shreeve, A. (1998). Material Girls – Tacit Knowledge in Textile Crafts. In: Johnson, P. *Ideas in the making: Practice in Theory*. A resource for crafts contextual studies. London: Crafts Council. pp. 41-48.

89. Skye, N., (2012). Moire January 21st 2012. In: *Nickskye Meanderings* [Online]. Available: http://nickyskye.blogspot.co.uk/2012/01/moire-january-21th-2012.html [December 26, 2014].

90. Smith, H. and Dean, R., (2009). *Practice-Led Research, Research-Led Practice in the Creative Arts.* Edinburgh: Edinburgh University Press.

91. Society of Dyers and Colourists, (2008). *Communicating colour: theory, history, vocabulary*. Bradford: SDC Colour Experience.

92. Society of Dyers and Colourists, (2008). *Visual perception and other phenomena*. Bradford: SDC Colour Experience.

93. Society of Dyers and Colourists, (2007). *William Henry Perkin and the colour that changed the world*. Bradford: SDC Colour Experience.

94. Steen, W., (2003). *Laser Material Processing.* 3rd ed. London: Springer.

95. Stoyel, J., (1999). *Manufacture of textiles using ultra sound.* [Patent Application]. B3V V4BX, B4B B70D. United Kingdom: B26F 3/00, B23K 28/00.

96. Stoyel, J., (1996). *Method and apparatus for the manufacture of textiles.* [Patent Application]. B3V VLC V202 V221 V2. 31 V236 V255, B4B B70D. United Kingdom: B23K 26/08.

97. Stoyel, J. (2007) Laser and Devoré. In: Miraftab, M. and Horrocks, A. *Ecotextiles: The Way Forward For Sustainable Development In Textiles.* Cambridge: Woodhead Publishing, pp. 210-215

98. Taylor, M., (1990), Technology of Textile Properties, 3rd ed., London: Fobres Publications.

99. TLF Leather Technology Ltd. (2004), *Grey scales to measure the change in colour and staining instrumentially* [ISO Grey Scales]. [Online]. Available from: http://www.tfl.com/web/files/testmethodscolourfastness.pdf [3 March 2014].

100. Walker, R., (1998). Lasers: The cutting edge in industry. *Industrial Physicist 2*(4), 29-33.

101. Watkins, H. (2014). *Beautiful hand painted prints at Indigo*. [Online]. World Global Style Network (WGSN). Available http://wgsn.com/blogs/graphics/beautiful-hand-painted-prints-at-indigo [October 29, 2014].

102. Weedlun, P., (2011). *Appliqué having dual colour effect by laser engraving.* [Patent]. 428/3433; 216/40; 156/267. United States of America: B32B 7/12. 100. Wolberg, J. (2010). *Designing quantitative experiments: prediction analysis*. Berlin; London: Springer.

103. Wong, W., Chan, K., Yeung, K.W. and Lau, K., (2003). Surface structuring of poly(ethylene terephthalate) by UV excimer laser. *Journal of Materials Processing Technology, 132*(1–3), 114-118

104. Yip, J., Chan, K., Sin, K. and Lau, K., (2002). UV Excimer Laser modification of polyamide materials: effect on dyeing properties. *Materials Research Innovation, 6*(2), 73-78.

APPENDIX 1: **Burn prints carried out in this research**

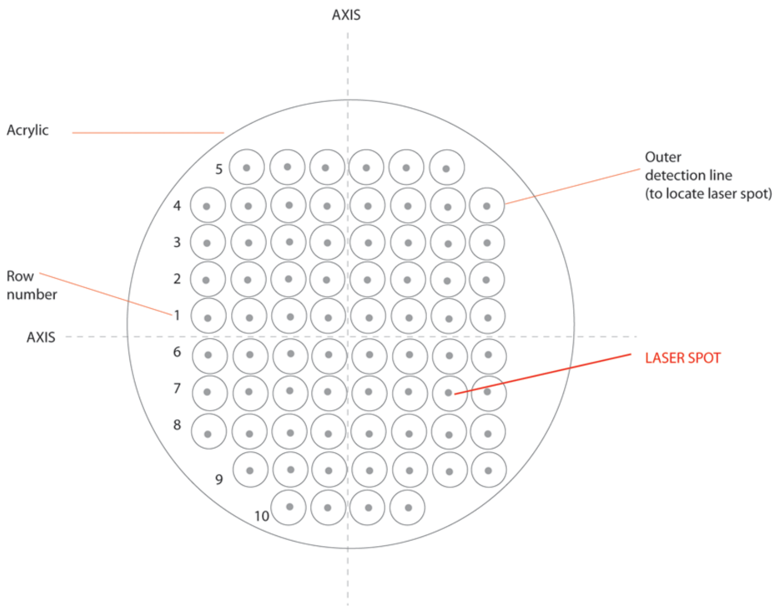
A burn-print is a technical exercise that enables the detection of optimum laser beam focus in relation to the work piece i.e. the fabric, by measuring the laser spot size in terms of diameter. As the laser beam travels away from the 'optimal focal point', the spot size is larger and therefore less focussed. Therefore, fibre-laser interaction reduces as a result of a lower energy density across the fabric surface. Generally, a burn-print helps to identify the location for maximum penetration of the laser beam in relation to the work piece and resolution of the marking such as a pattern or other graphic image.

Burn print experiment No.1

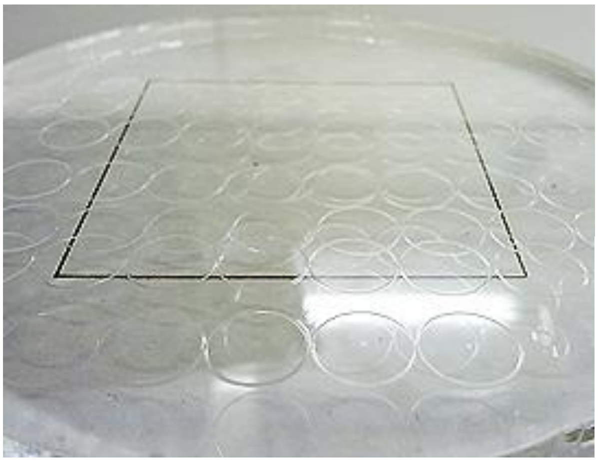
Equipment	**Materials**	**Laser**	**Computer program**	**Microscope**
	Acrylic	CO^2 Synrad 10 W *Spot size of beam: 0.3mm*	Image-Pro software	10.100x High magnification Nikon Optishot

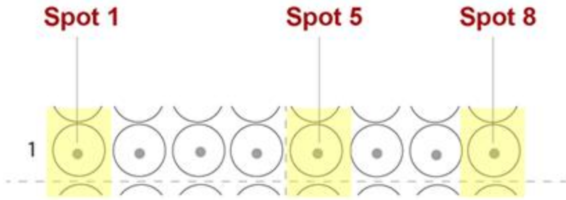
Table 1: Equipment used in burn print experiment no.1

A series of spots were arranged in rows using the laser computer software programme (a). These spots were set up to fire the laser beam into a piece of acrylic, approx. 10mm deep x 100mm in diameter. These dimensions conformed to the optimum laser marking area of the laser beam in relation to the machine. The purpose of doing this was to achieve a series of measurable laser formed spots to identify the optimal focus area of the laser beam relevant to the whole area of a 100mm x 100mm ($10cm^2$) fabric sample.



a. Burn print orientation: example showing layout of laser spots

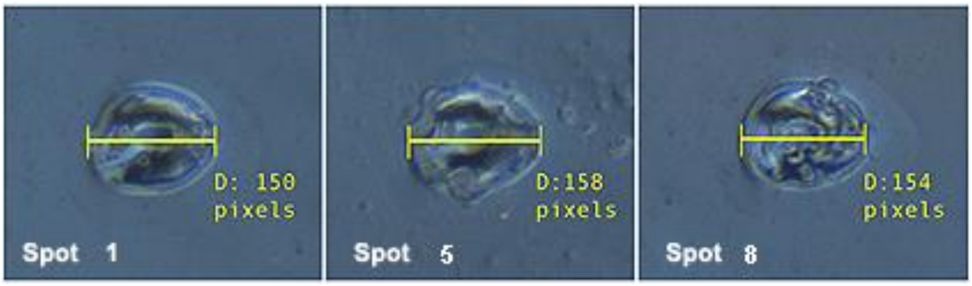




b. (Left) Orientation of burn print: laser spots fired on to acrylic specimen;
c. (Right) Row 1 of the acrylic burn print

Multiple rows/columns of spots were created across the vertical and horizontal axis of the acrylic (b). The purpose of doing so was to cover the same surface area for laser marking as with textile samples within an approximate 100cm x 100cm working space. By analysing the acrylic burn print using microscopy, variants in focal position of the laser beam when travelling across the entire fabric surface were identified.

A portion of the burn print was observed under the microscope (c) – Row 1, along the most centralised horizontal axis of the acrylic. Laser fired spots: 1, 5 and 8 were investigated.



d. Micrographs of acrylic burn print (x10.100) showing the number of pixels/diameter per spot

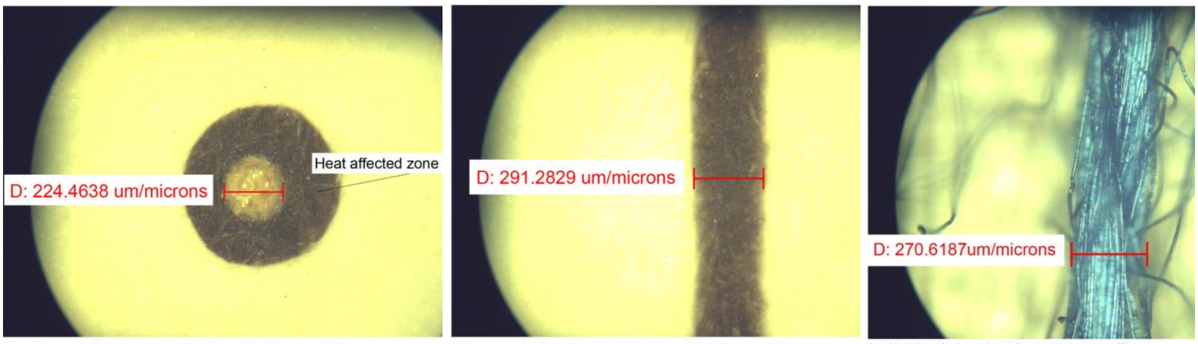
Each laser spot image was captured with the microscope at x10.100 high magnification (d).The *Measure* tool was used to provide data about the diameter of each spot in pixels. The results revealed spot 1 at the far left of the acrylic piece was the shortest at 150 pixels and therefore greater focus during beam scanning compared to spots 5 (central at 158 pixels) and 8 (far right at 154 pixels). Spot 5 identified the longest diameter and therefore the least focused area due to an elongated effect of the spot and the longest diameter. These results gave some insight into the earlier irregularities of laser treated polyester fabrics attributed to specific areas of laser scanned fibres/yarns. At this stage, it was acknowledged that a more proficient understanding of laser processing was required in order to sufficiently gain the necessary practical knowledge for development of the laser-dye process. Recommendations suggested that a burn print may needed to be carried out before every session of experiments to ensure the correct positioning of the fabric sample and improve the accuracy and consistency of results each time. Further tests were therefore also observed with the 60W Synrad laser marker system.

Experiment No.2

Equipment	Materials	Laser	Computer program	Microscope
	Dioptron light sensitive paper Polyester yarn	CO^2 Synrad 60W *Optimal focal distance: 370mm* *Spot size of beam: 0.3mm*	Image-Pro software	x10.100 High magnification Nikon Optishot

Table 2: Equipment used in burn print experiment no.2

A piece of Dioptron light sensitive paper capable of detecting the laser beam was used to acquire the spot size in relation to an individual polyester yarn from a woven textile sample (e). This purpose of this experiment was to understand how an individual laser scan line may affect the overall appearance of a laser processed fabric based individual yarn size. Therefore, the two were compared. Firstly, a laser spot was fired in to the paper followed by a laser line, both at an optimal height distance of 370mm from the work piece in order to determine a spot size of 0.3mm. Each result was measured and compared to the yarn measurement.



Spot mark fired onto Dioptron light sensitive paper | Line mark fired onto Dioptron light sensitive paper | Individual dyed polyester yarn fibre

e. Burn print of laser spot in Dioptron paper and polyester yarn at x10.100 magnification

Using a microscope (Table 2), results revealed very little difference between the average size of the laser spot (258µm) and the yarn (270µm). However, the laser line burn print measurement (291µm) was closer to the yarn measurement compared to the spot result. As such, this data and analysis was useful for creative and technical surface analysis of laser treated textile samples, as discussed in chapter 4.

APPENDIX 2: **Procedure for disperse dyeing carried out in this research**

Overview of approach

- *Stock solutions were used to carry out laboratory dyeing. 0.4 % stock solutions of the disperse dye were made for dyeing*
- *0.5% and 1.0% (shade depths) of dye were applied in relation to fabric weight*
- *ISO dyeing was carried out with a Coloursmith IR sample dyeing machine used in industry*
- *Dyeing profiles were based on those currently used in industry to dye polyester fabrics, set by the SDC*
- *Low liquor ratios (liquor/fabric weight) for example: 10:1; 9:1 and 1:7 were used.*

Step 1

A 0.4% stock solution was made by dissolving 2 gms of dye in 500 mls of water:

- 2 gms of dye was carefully weighed on a balance and transferred to a 100mls or 200mls glass beaker

- A little warm water was added and pasted up with the dye; more water was added to approximately 100 mls and poured carefully through a funnel into a graduated flask

- More water was used to clean out the beaker; this was also poured in to the flask until the beaker was clean

- The funnel was washed down to ensure that all the dye was in the flask; and finally, the flask was made up to the level indicated (on the flask).

Stock solution complete.

Step 2

Equation for working out the amount of stock solution required to apply 1% on the fabric is:

$$\textbf{mls require} = \frac{\textbf{\% depth x weight of fabric}}{\textbf{\% of stock solution}}$$

$$\text{e.g. mls required} = \frac{1.0\% \text{ x } 10 \text{ grms}}{0.4\%}$$

(The answer is 25 mls of the stock solution is required or 12.5mls for a 0.5% shade depth)

Step 3

The same equation was applied for auxiliaries:

$$\textbf{mls require} = \frac{\textbf{0.5\% auxiliary x weight of fabric}}{\textbf{\% of stock solution}}$$

Where 0.5% auxiliary was added on weight of fabric, based on the example equation given in Step 2, 12.5 mls was added on 10 mls from a 0.4% stock solution.
.

Step 4

To make up a dye bath/beaker, stock solutions were pipetted out of the graduated flask into a glass measuring beaker with water and made up to the required amount:

- Acetic acid was added to some experiments in order to reach pH 4.5 solution in line with current industry dyeing conditions for polyester textiles. However in this study, laser-dyeing was also effective with the absence of acetic acid.

- Dye solutions/baths were transferred to metal dyeing beakers including fabric sample then loaded and secured into the IR dye machine

- The following dye profile was programmed into the machine and used for dyeing all polyester fabric samples:

PROGRAM No 2	PROGRAM NAME - SDC POLY							
ROTATION					REVERSAL TIME		
Anti Clockwise		Clockwise			Anti Clockwise	Clockwise	
ON	20 RPM	ON	20 RPM		5 Minutes	5 Minutes	

STEP No	TARGET TEMP ºC	RATE OF RISE º/MIN	DWELL MIN & SECS	MESSAGE	STATUS
1	50	7.0	05.00		OFF
2	80	1.5	10.00		OFF
3	140	0.8	59.59		OFF
4	80	7.0	02.00		OFF
5	40	2.0	10.00	END	ON
6					OFF
7					OFF
8					OFF
9					OFF
10					OFF

Dyeing profile for PET fabrics (programmed on Infrared dye machine)

Step 5

After dyeing, samples were washed out using one of the following 4 methods:

1. Hand rinsed in a sink in cold running tap water for approximately 3-4 minutes and for a further 30 seconds-to-1 minute in hot tap water

2. Hand rinsed in a sink in cold running tap water for approximately 3-5 minutes and for a further 30 seconds-to-1 minute in hot tap water with mild fabric soap and then for another 1-2 minutes in cold water

3. After-treated to remove any unabsorbed dyes. This involved a heated diluted solution based reduction clear chemical process and further rinsing. A sodium hydrosulphite/hydroxide solution was used in this work, advised by the SDC. It was not necessary to after-treat fabrics dyed with pale shades due to minimal dye on the fibres from the outset.

4. Machine washed at 40°C or 60°C using a domestic appliance.

All samples were air-dried naturally.

APPENDIX 3: Publications

(By author of the research nee. Wallace)

Papers and Chapters

Akiwowo K. (2015) Garment ID: Textile Patterning Techniques for Functional Hybrid Clothing, In: Kane, F., Nimkulrat, N., and Walton, K., *Crafting Textiles in the Digital Age*, London: Bloomsbury Academic, pp. ---, ISBN 978-1472529060

Kane F., Akiwowo K., Tyrer J., Morgan L. Textile Design Research: from chemistry to craft towards sustainable innovation*,* In*: proceeding of European Academy of Design 11th International Conference: The Value of Design Research*, Paris Boulogne University, 21 Apr 2015 - 24 Apr 2015.

Kane F., Morgan L., Akiwowo K., Matthews J. and Tyrer J (2015) Proposing a digital laser-design supply service, In: *Proceedings of TechStyleLab Symposium*, Fashion School, Kent State University, Ohio, United States of America, January 29-30, 2015, pp. ---, ISBN ---.

Akiwowo K., Kane F., Tyrer J. and Filarowski, A. (2014) Digital Laser-dyeing for Polyester Fabrics, *Journal of Textile Design Research and Practice*, 2(2), 133 – 151, ISBN 978-147421797-2

Kane F., Akiwowo K., Morgan L., Matthews J. and Tyrer J (2014) Textile design research: from chemistry to craft towards design innovation, In: *Proceedings of Transition: Re-thinking Textiles and Surfaces Conference*, University of Huddersfield, United Kingdom, November 26-27, 2014, pp. ---, ISBN ---.

Kavanagh T., Wallace K., Kane F. and Matthews J. (2014) Developments in Design Led Textiles Research*,* In: *Proceedings of The 89th Textile Institute World Conference,* Wuhan, P. R. China, November 2-6, 2014, pp. ---, ISBN 978-1-84626-xxxx.

Wallace, K. (2009), Wear it Well: Wearable Display Technologies, In: Williams, K., *MADE: Materials and Design Exchange Magazine*, Issue 3.09, IOM Communications Ltd.: London, 28 - 30, ISSN 1753-2973.

Book Contributions

Quinn, B., (2013), *Textile Visionaries: Innovation and Sustainability in Textile Design*, Laurence King: London, 266 - 273.

San Martin, M., (2010), *Future Fashion: Innovative Materials and Technology*, MaoMao Publications: Barcelona, 62 - 65.

Seymour, S., (2010), *Functional Aesthetics: Visions in Fashionable Technology*, Springer-Verlag/Wien: New York/Austria, 116 - 119.

Seymour, S., (2008), *Fashionable Technology: The Intersection of Design, Science and Technology*, Springer-Verlag/Wien: New York/Austria, 43 - 44.