Engineering Doctorate

Innovation Report

The application of x-ray computed tomography in aerospace industry

by

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Abstract

In the 2015 report of 'The aerospace industry: statistics and policy', UK Government presents the aerospace industry as "*phenomenal success story*" with *"tremendous opportunities for growth*" (Rhodes, et al., 2015). The success of this sector depends on high efficiency and productivity levels while maintaining quality and satisfying market demands which request aircraft to stay safely in service for longer with reduced maintenance budgets. One of the strategic objectives of the aerospace companies is continuous improvement of the technologies and engineering capabilities. X-ray Computed Tomography (CT) is a growing Non-Destructive Evaluation (NDE) method with various applications in several sectors of industry. CT collects numerous radiographs that are then reconstructed to create a 3D model of the examined object. The results demonstrate the outer and inner structure of the part including any defects, altered densities and hidden constructions in the case of Additive Layer Manufacturing (ALM) parts.

Product development in the aerospace industry is a challenging task with significant risks that are handled by complex processes for quality control. The product development steps in this industry follow the products from concept to manufacturing and from service to disposal. This project examines the capabilities and limitations of CT in order to identify potential applications in this sector by considering all of the stages of development. Several case studies demonstrate its application in the research and development phase of composite design and machining selection as well as in the production phase with metrological and non-destructive evaluation applications. Finally, the application of CT in failure investigations and forensic examinations, close to the end of the life and disposal of the product was also considered. The results of these investigations demonstrate the possibilities of this technology as well as its limitations and led the sponsoring company to purchase a digital radiography system with CT capabilities.

The presented investigations answer the research question of '*How can CT be applicable in aerospace industry*?' by identifying the product development phases where CT is applicable. The developed innovative methods provide CT inspections and measurements while reducing human error. They identify the capabilities and limitations of this technology and develop improved scanning methods and standard operating procedures. This report summarises the results of these investigations that clearly demonstrate the potential applications of this technology as well as their limitations while it also introduces and demonstrates innovative methods to overcome these limitations. The innovation of this project is in the novel methods that allow this technology to be used in this industrial sector and provide the required results that are unobtainable with other NDT methods.

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1. Introduction

According to the latest ADS (Aerospace, Defence, Security and Space) industry facts report (Sinclair & Kearney, 2016), the UK government and industry are working together, investing in growth to attract global investment to the UK by supporting successful industrial strategies. This collaboration aims to improve productivity by encouraging investment of skills, technology and innovation by supporting Research and Development (R&D) while supporting exports by maximising opportunities, removing barriers and identifying growing markets. According to the same report, the UK aerospace sector's growth since 2010 reached 39% and it is the largest in Europe and the second one globally to the USA (Sinclair & Kearney, 2016). One of the strategic objectives of the aerospace companies is continuous improvement of the technologies and engineering capabilities (BAE Systems, 2014). In order to achieve this, continual improvements of the current systems are required while research for new methods and technologies is taking place. One of the new technologies considered is x-ray Computed Tomography (CT) that is a growing Non-Destructive Evaluation (NDE) method with various applications in several sectors of industry.

X-ray CT, which is an established technology, well known for its medical application, is gaining new interest due to its industrial applications. This technology collects numerous 2D radiographs that are then reconstructed to 3D models by using algorithms such as Filtered Back Projection (FBP) algorithm (Hsieh, 2009). The results of the reconstructions characterise the outer and inner structure of the part including any defects, altered densities and hidden constructions such as in the case of Additive Layer Manufacturing (ALM) parts. CT is used in several industries such as in food and automotive industries, and has some recent applications in aerospace industry as an NDE method (Copley, et al., 1994). This project was requested by one of the leading aerospace companies of UK to identify potential applications of the CT technology in their products life cycle.

In order to identify potential applications, the business requirements of the aerospace industry were determined by interviewing stakeholders of this industrial sector and categorising the requirements. The product development cycle was considered to recognise the stages where CT can be applicable. Next a series of case studies took place examining its capabilities and combining them with other methods such as image processing to create innovative novel methods that can sustain the high quality expected in the industrial sector. The results of the case studies demonstrate the capabilities of the technology as well as the limitations which are alleviated by combining different image processing methods. This report summarises the results of the different investigations and the potential applications of the CT technology in aerospace industry and demonstrate the impact of the work that led the company to purchase a digital radiography system with CT capabilities.

1.1 Engineering Doctorate

The Engineering Doctorate (EngD (International)) combines research with business and its main objective is to innovatively apply knowledge to the global engineering business. This research program provides the participants with: expert knowledge of an engineering and technology area and appreciation of industry and business culture. It also teaches them: project and programme management, excellent communication skills, teamwork and leadership skills, technical organisation, finance, project planning and control, application of knowledge and skills, solution solving and the possibility to develop society and business through research. These goals have been achieved in this project through a series of investigations and case studies that are included in the portfolio as different submissions.

The innovation report of an EngD needs to comprise the work covered in the portfolio in the context of the engineering business environment while summarising it. This report aims to declare the innovation of applying knowledge and demonstrate the novel methods created in the duration of the program. The application of the knowledge needs to be relevant to the global engineering business and provide improvements of technology or system. The improvements have to be applicable and affordable.

1.2 Guide of the submissions

The structure of this report was designed to assist the reader in understanding this technology and its potential applications in aerospace industry, by explaining the requirements of aerospace industry in Section 2. The methodology selected for this project is discussed in Section 3. The examination of the literature on CT is discussed in Section 4, so as to demonstrate the technology's capabilities. The case studies were separated into relevant chapters according to the stage of the product development with the three investigations into the machining of Carbon Fibre Reinforced Polymers (CFRPs) considered as part of R&D studies, and they are discussed in Section 5. The investigation of machining processes with the example of welding investigations is presented in Section 6 before the demonstration of a novel method which improves dimensional measurements in production for quality investigations discussed in Section 7. The last study of forensic and failure examinations is demonstrated in the Section 8 with a few examples. Finally, the findings of the project are summarised in the Section 9, highlighting the innovative novel methods applied and the potential improvements to aerospace industry when utilising CT.

All of the submissions were structured as independent reports providing all the necessary information for the understanding of the readers. This project initiated with reviewing the literature that led to the first submission, 'X-ray computed tomography in aerospace industry'. This submission covers the development of this technology that has led to the industrial applications, including information on the development of the designs, which improve quality of the results and reduce the exposure times and consequently the acquisition times. The industrial applications of this technology can be categorised into non-destructive and metrological investigations. This submission includes background information about non-destructive evaluations, metrology theory and aerospace industry.

The business requirements of aerospace industry for NDT methods were identified and evaluated through a series of interviews and meetings with three different aerospace companies and some of their suppliers and forensic examiners. The results and findings of the interviews have been provided in Submission 2: An investigation of the business requirements of aerospace industry for the utilisation of NDT methods and CT. In this investigation the business needs for quality inspections, as well as the potential applications of CT have been highlighted.

Submissions 3, 4 and 5 examine the application of CT in the investigation of machining carbon fibre reinforced polymers (CFRPs). This composite material has numerous applications in aerospace industry but any machining process is challenging because it breaks the fibres. These case studies consider different machining and cooling processes as part of the R&D investigations. The information gained from these case studies are utilised in the concept exploration stage of the concept creation phase and in the technology deployment stage of the development and qualification phase of the new product development process.

The next case study, submission 6, investigates the examinations of welded parts that are often examined for quality purposes in production in the aerospace industry with conventional radiography. The investigation compares the results of conventional radiography with the results achieved with digital radiography and CT. This case study demonstrates the application of CT in production environment and the manufacturing phase.

In the duration of this project several parts have been received by the industrial partner that demonstrated the need of the next two case studies, submissions 7 and 8. The majority of the parts received had metallic components which created systematic errors in the reconstructions of the scans and this demonstrates the need of a method to reduce beam hardening and scattered radiation. The investigation of scattered radiation has led to the novel combination of pre and post physical filtration of radiation, in order to reduce the scattered radiation and beam hardening effects and the metrological results are demonstrated in submission 7. The next submission arose due to requests received for failure and forensic examinations that demonstrated the need of such investigations with CT. The application of this technology is uniquely suitable for failure and forensic examinations since it provides information for the inner and outer geometries of the examined objects non-destructively, and it also assists in the identification of defects. The application of CT in metrological investigations demonstrates the applicability of this technology in quality inspections and the manufacturing phase while the failure and forensic examinations demonstrate its application and support in the operation phase and disposal phase that can even lead back to the concept creation phase.

As a result, the submissions demonstrate the application of CT in the aerospace industry, providing new methods of inspections by utilising image processing and volumetric analysis as well as a new radiation filtering method. Table 1 provides a portfolio plan as a suggested reading order of the portfolio while Figure 1 demonstrates the structure of the submissions as a diagram. The findings of the submissions are summarised in this innovation report as innovative application of knowledge in aerospace industry.

Table 1: Portfolio plan - Reading order of the portfolio

Submission No	Submission Name
1	X-ray computed tomography in aerospace industry
2	An investigation of the business requirements of aerospace industry for the utilisation of NDT methods and CT
3	CFRP inspection with x-ray CT: A new method of inspecting drilled holes in CFRPs
4	Inspection of milling CFRPs with x-ray CT
5	Inspection of CFRP/Ti6Al4V drilled holes using x-ray CT and image processing
6	Welding investigations with digital radiography with CT
7	Metrological investigation of scatter radiation reduction in CT
8	CT in forensic engineering and failure analysis

The structure of this innovation report does not follow the reading order of the submissions. The portfolio also includes post-module assignments from taught lessons, the personal profile, and published papers as well as this innovation report.

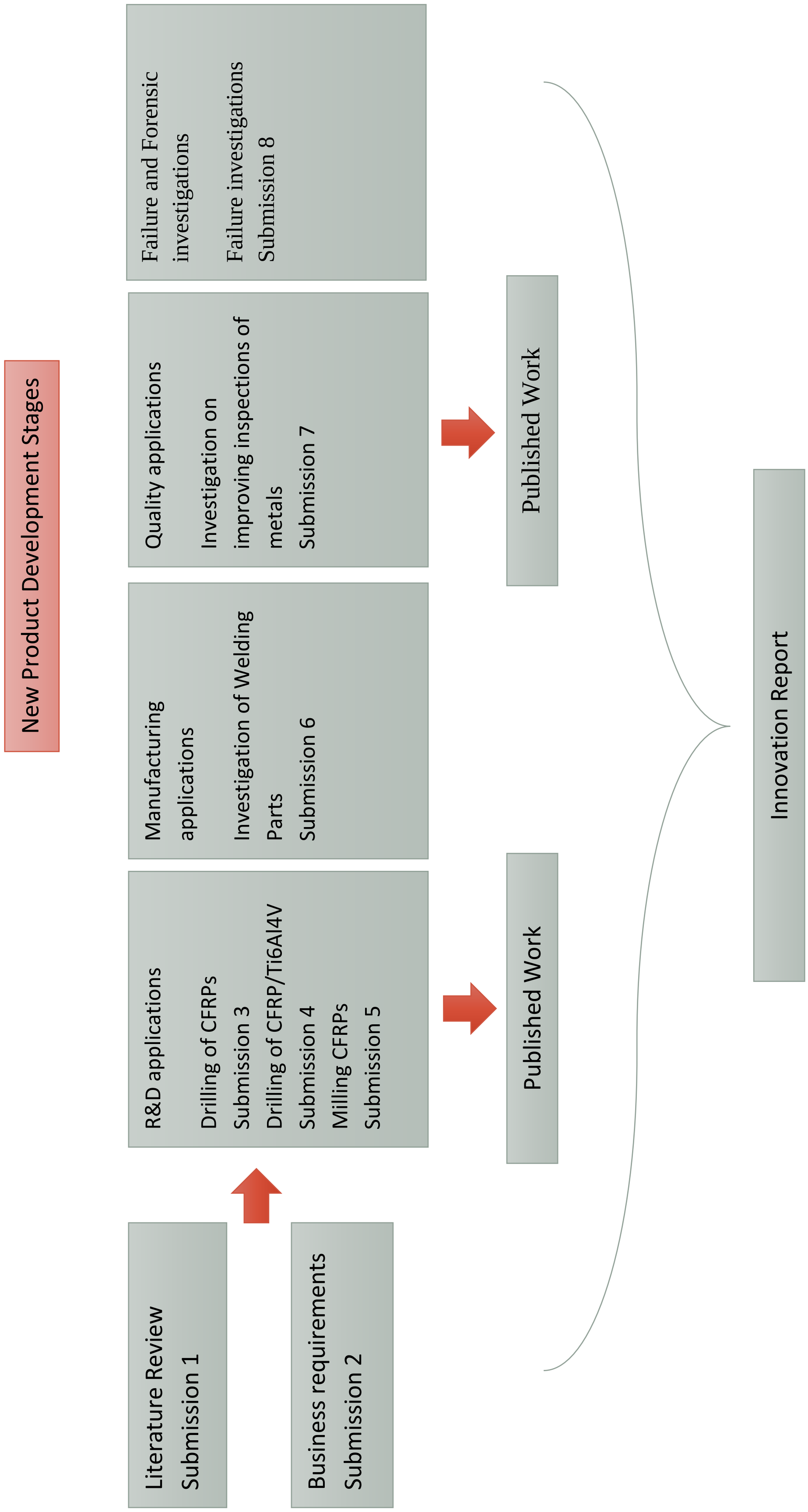

Figure 1: Portfolio plan and structure diagram

2. Aerospace industry, product development and inspection methods

The aerospace industry is one of the most successful sectors of UK manufacturing and it has been continually growing since it launched in 1908 (Central Office of Information, 1982). The UK Government presents the aerospace industry as a "*phenomenal success story*" with *"tremendous opportunities for growth*" while the UK has 17% of the global market according to an industry survey (Rhodes, et al., 2015). According to the latest government report in 2015, British Aerospace has significant turnover in the last decade with the total turnover of the industry in 2013 reaching £24.7 billion with £27.8 billion revenue and 0.9% economic output for the country in the same year. The sector provides 109,000 direct jobs and 120,000 indirect jobs while it has grown by 7.1% each year since 2008 and it is expected to continue growing at a rate of 6.8% over the next few years (Rhodes, et al., 2015).

The success of this sector depends on high efficiency and productivity levels while maintaining quality and market demands (Cantor, et al., 2001). The market requirements drive the industry towards aircraft that can stay safely in service for longer with reduced maintenance budgets. In order to ensure the required quality, several standards and guidelines have to be followed during design, production and maintenance and have to include quality tests of materials, so as to ensure the safety of the aircraft while the most serious threats of an aircraft's service life are corrosion and fatigue (Nikolaidis, et al., 2007).

2.1 New Product Development

Product development can be defined as *'the transformation of a market opportunity and a set of assumptions about product technology into a product available for sale'* (Krishnan & Ulrich, 2001). New Product Development (NPD) success depends on several areas such as marketing, organisations, operations management and engineering design that have to be considered in the duration of the project. Each area has different perspectives that need to be considered and will end up contributing to the success of the new product by providing a comprehensible and practical description of the product (Krishnan & Ulrich, 2001). The success of new products is determined by three key factors, product differentiation, early feasibility assessment and specification; and quality of NPD process and function (Cooper & Kleinschmidt, 1993).

NPD in the aerospace industry is a challenging task with significant risks that are handled by complex processes for quality control. The complexity of NPD is mainly due to the process of developing and certifying new technologies, the difficult nature of the products, the context of the value network where the products are developed and due to the disturbances in the development process (Kazerouni, et al., 2011).

According to the sponsoring company, the NPD phases for engineering products are: concept creation phase, development and qualification phase, manufacturing phase, supporting during operational phase and disposal phase. The development of services has different NPD phases: strategy phase, design phase, transition phase, delivery phase and termination phase. The NPD lifecycle for both products and services are demonstrated in Figure 2 to highlight that the name of the phases may be different but the stages are the same and that is also the case for all industries and companies as discussed by scholars and they only differentiate in the naming.

NDP starts with the *opportunity* that arises as a customer's need. In order to satisfy that need, different concepts are explored and developed in the stages *concept exploration* and *concept evolution*. During these stages, more information is gathered in order to select the requirements that will lead to a solution, which is represented in the stage *requirements and solution*. The concepts are then re-evaluated according to the latest information and the final requirements/specifications in the stage *solution realignment*. These stages are called concept development in academic texts.

The next stage is *technology deployment* or *supply chain design* and includes decisions about the technologies required for the production, the design of the production lines, materials and quality checks. Next, it is the product design, and in this phase the *preliminary design*, the *detailed design* and *qualification* take place. In these stages, the core concept has already been selected according to the customers' requirements and the final design of the product is developed including visual models and prototyping.

According to the academic texts (Krishnan & Ulrich, 2001), the last phase is production ramp-up and launch. The company's stages that take place in this phase are *implementation and integration*, *production and handover* and *support and upgrade*. The implementation and integration stage utilises the technology deployment and the final product design stages in order to prepare and improve the production processes and the final arrangements related to production. The production and handover stage cover test production, actual production and delivery, while support and upgrade cover the areas of customer support and improvements of the products, according to the customers' feedback. The only stages that are different from services are in production ramp-up and launch, the *deployment* and *operation and upgrade,* instead of *production and handover* and *support and upgrade*. The differences are due to the nature of the services, with deployment and operation representing the deliverance of the service, while the upgrade demonstrates the potential adjustments to the service based on feedback. The company adds another stage due to its industrial segment; the withdrawal and disposal that is required to be done by the company, by law. In the withdrawal and disposal stage the product needs to be returned to the company for disassembly and recycling (BAE Systems, 2014).

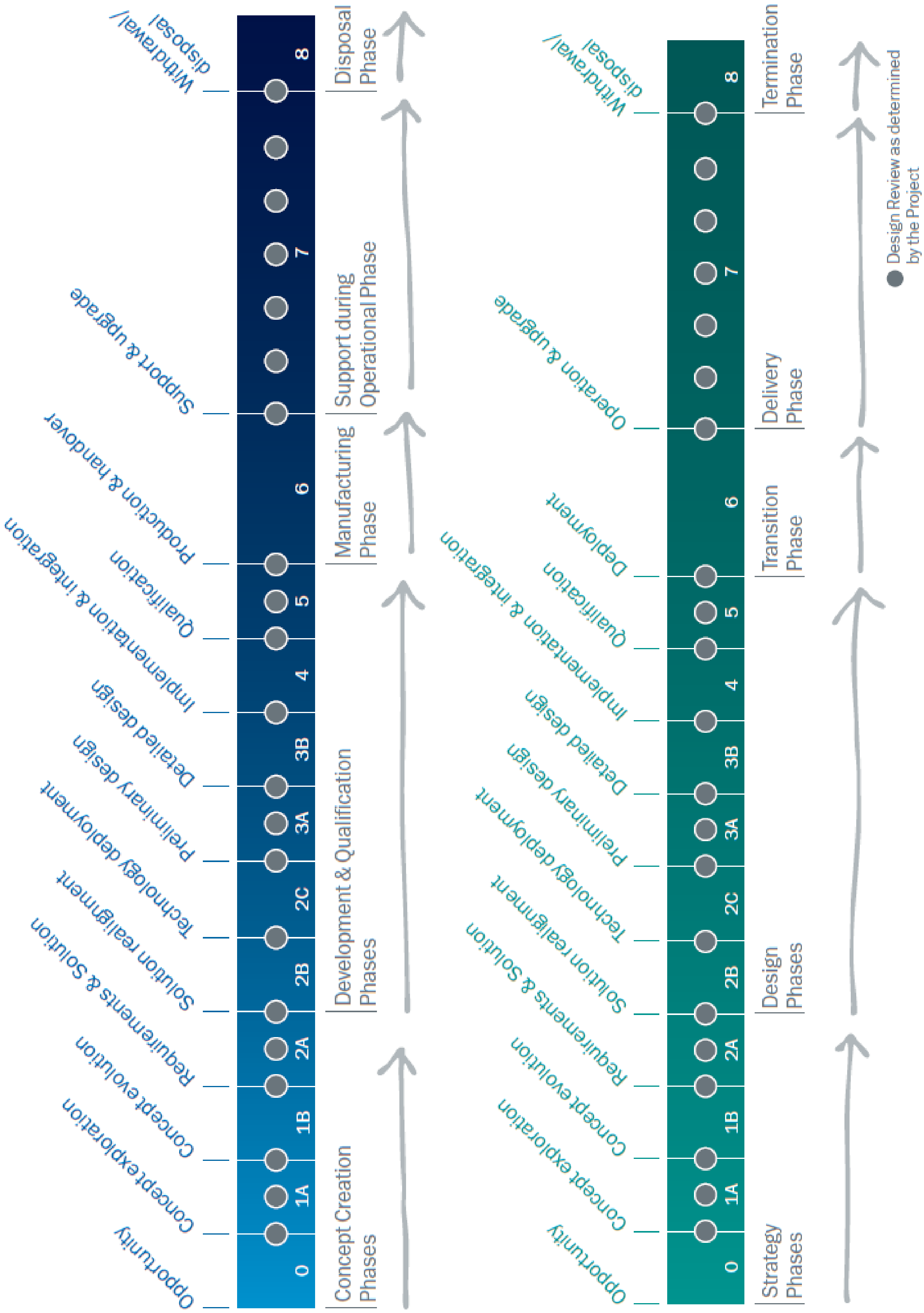

Figure 2: Project lifecycle of products and complex service lifecycle examples (BAE Systems, 2014)

2.2 Non-Destructive Evaluations and Metrology

Non-destructive tests and evaluations have numerous applications in the aerospace industry. Their development is partly due to the growing needs of the industry, while metrology is part of all industrial applications that takes place so as to follow designs and assemble parts together. These two areas are developed and applied according to the industrial requirements. This section provides an introduction to NDTs and metrology that are discussed in the applications of CT.

2.2.1 Non-destructive testing

The general definition of non-destructive testing is the examination of an object/specimen, which does not modify it or affect its utilisation in any way. These examinations aim to observe the object's characteristics, such as geometry, and to identify any defects such as absence or presence of material or discontinuities that should not be present (Hellier, 2003). Furthermore, the American Society of Non-destructive Testing (ASNT) define non-destructive evaluation to be *'the examination of an object with technology that does not affect the object's future usefulness*' (Shull, 2002). Non-destructive testing is not a new kind of examination, such as visual inspections, and it can give a first indication of quality (Shull, 2002; Hellier, 2003). NDT technologies have gained significant popularity during the last 35 years and consequently they have been developed to be used in the industry for the examination of raw materials before they are processed, materials during the manufacturing processes, finished products and products that are already in service (Hellier, 2003).

Due to the numerous different examinations and their utilisation, different terms were developed based on the specific application and the information gained from each one (Shull, 2002).

Table 2: Categories of Non-destructive Evaluation based on Shull, 2002

Non-destructive Testing (NDT)	is a general term that describes the actual test
Non-destructive Evalution (NDE)	is the most general term that describes the role of the test in the process
Non-destructive Examination (NDE)	usually describes tests that are not used in process control
Non-destructive Inspection (NDI)	is similar to non-destructive examination and is not used in process control
Non-destructive Characterisation (NDC)	is used to specify material properties
Non-destructive Sensing (NDS)	is using sensors to find information non-destructively and is the only term that does not ensure the object's future usefulness

Each NDT technique has its limitations that are known and considered before their selection (Hellier, 2003). Some of the most common non-destructive evaluation techniques are: acoustic emissions, electromagnetic testing method, leak testing methods, liquid penetrant tests, magnetic particle testing, neutron radiographic testing, radiographic testing method, thermal infrared testing method, ultrasonic testing, vibration analysis method, visual and optical testing (Mix, 2005).

Visual inspection is the oldest NDT method which can either be performed when the observer is consciously looking for defects and problematic areas, or unconsciously when the observer randomly notices something out of the ordinary. Visual inspection is the first method of filtering faulty or defective parts while the industrial examination requires specialised knowledge, training and experience in order to identify and categorise defects (NDT Resource Center, 2012; Singh, 2012).

Magnetic particle testing can detect discontinuities close to the surface and inclusions on the surface that are too small to be noticed by naked eye. It is limited to materials that have ferromagnetic properties. Magnetic particle testing utilises a magnetic field which create small magnetic poles at opposite sides of discontinuities and as a result magnetic particles are attracted more strongly on those sides and identify the discontinuities (NDT Resource Center, 2012; Singh, 2012).

Penetrant testing utilises liquid penetrant to cover the examined part and while the liquid is removed from the surface some remains are left in the opening of defects and re-emerge on application of a developer. This method exposes surface-opening discontinuities, highlighting even very small and tight imperfections and makes them easy to detect visually with either fluorescent or visible dye methods (NDT Resource Center, 2012; Singh, 2012).

Acoustic emission testing is based on the sound/signal emitted by a growing crack whilst it is loaded and which allows the identification of the positioning of the crack. Acoustic emission testing is used during proof testing in order to determine the growth of cracks during pressurisation (NDT Resource Center, 2012; Singh, 2012).

Pressure testing induces a pre-determined stress level in a test part to identify potential leaks by increasing the internal pressure and creating a pressure differential with ambient pressure (Singh, 2012).

Eddy current testing utilises an impedance coil and Fleming's law to create an alternating magnetic field which is projected into a conductive specimen that creates alternating eddy currents in the material. Lenz's law is then utilised to monitor the eddy currents in the material that are affected by any discontinuities that demonstrate changes in the chemical composition, crystal orientation and heat treatment hardness of the material. The type and thickness of the tested material are considered to select the appropriate frequency (NDT Resource Center, 2012; Singh, 2012).

Ultrasonic testing utilises high frequency sounds with low wavelengths so as to identify defects such as cracks, incomplete fusion, incomplete penetration, inclusions and porosity. A sound can travel through material in a given time with its velocity based on a function of the material's density, acoustic impedance and temperature (NDT Resource Center, 2012; Singh, 2012).

Radiography utilises x-rays or gamma rays that penetrate the examined part and reach the detector that converts the rays to 2D pictures that can be recorded on film, photosensitive paper or fluorescent screen. Some of the radiation produced by the x-ray tube will be absorbed by the material while the rest can be scattered or transmitted through the less dense material. A skilful inspector is required to interpret the findings after the radiographs are produced (Singh, 2012).

The thorough understanding of NDT methods is required to identify and examine the requirements of the aerospace industry, the limitations of currently utilised systems and any unresolved requirements. The combination of NDT limitations and unresolved requirements demonstrate the need of a new system.

2.2.2 Metrology

Metrology is the science of measuring and it is required in sciences as well as in everyday life (NPL, 2010). According to Lord Kelvin, '*When you measure what you are speaking about and express it in numbers, you know something about it, but when you cannot express it in numbers your knowledge is of a meagre and unsatisfactory kind…*'. The term Metrology is derived from the Greek words 'μετρώ' (metro) that means measuring and 'λόγος' (logos) that means talk and study. Metrology is defined as *'the science of measurement. Embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology'* (Bureau International des Poids et Mesures, 2004).

According to the National Physical Laboratory (NPL), *Scientific Metrology* is the science of measurement and includes the development of measurement standards (NPL, 2010). *Industrial Metrology* is the application of scientific metrology to manufacturing and other processes (NPL, 2010). *Legal Metrology* is the measurements that ensure fair trade, quality and consumer protection (NPL, 2010). The term of metrology may be considered recent; however, measuring is centuries' old and trading, ownership and science would have been impossible without it (NPL, 2010).

The quantities that are measured such as length, mass and time, are defined in science and the units that are used such as metre, kilogram and second, are chosen from the National Measurement Institutes (NMIs) nationally for each region, which work with the equivalent institutes in other countries. The NMIs also define, in corporation, the measurement standards (Czichos, 2011; NPL, 2010).

Even after the latest technological developments no measurement is perfect due to the limitation of the instrument and the operator who takes the measurements. Therefore, a series of terms are required so as to identify the limitations of each measurement. The limitations of any measurement can be defined by accuracy and error, precision, uncertainty and confidence level, trueness, bias, repeatability and reproducibility, and tolerance (NPL, 2010).

Accuracy is the closeness of the measured value and the true value that cannot be accurately determined. *Error* is the deviation between the measurement and the true value of the measurand and represents systematic and random errors. *Precision* represents the spread of the measurements taken under the same conditions and it can be used to apply corrections based on a known distance. *Uncertainty* of measurements is a non-negative parameter characterising the distribution of the measured values providing limits in which the true value lies. The *confidence level* of the measurements demonstrates the probability of the measurement to be accurate by examining the mean and standard deviation of the measurements and assuming a normal distribution. *Trueness* is the closeness of the average of measured values to the true value. *Bias* is the difference of the average of measured values and the true value and it represents the total systematic error of the measurements. *Tolerance* is the difference between the tolerance limits specified by the designer to ensure the best performance of the parts (Ramsey , et al., 2011; NPL, 2010).

Repeatability is the precision of the measurements taken under the same conditions, methods and equipment by the same operator of identical specimens. *Reproducibility* is the precision of the measurements taken under the same conditions and methods but different equipment and operators of identical specimens. *Repeatability and Reproducibility studies* demonstrate the capabilities of the methods and equipment to provide precise measurements (Ramsey , et al., 2011).

Metrological applications are essential in industry to ensure the viability of individual parts as well as the assemblies and products. The combination of NDT and dimensional measurements demonstrates the quality levels of the products. Hence, the recognition of importance of collecting reliable measurements is necessary.

2.3 Business requirements of NDTs and CT

The applications of NDT are increasing in the aerospace industry due to growing requirements of developing technologies and tighter quality specifications. New inspecting methods are being investigated in order to identify potential technologies that can fulfil these requirements. The sponsoring company showed interest in CT systems but due to the relatively limited applications of this technology in aerospace industry, there are concerns of its viability. In order to identify the business requirements a series of interviews of numerous stakeholders have taken place and the full findings can be found in Submission 2; 'An investigation of the business requirements of aerospace industry for the utilisation of NDT methods and CT'.

Findings

The aims of NDT investigations are to reduce costs of production and increase the life span of components. The aim of the NDT departments are to increase production by identifying optimum machining techniques and create new NDT inspection methods by even combining different methods to identify defects. All interviewees confirmed that the NDT systems currently utilised in the aerospace industry are:

- Ultrasonic testing, manual and automatic including laser ultrasonic tests
- Radiographic testing, conventional and digital
    - Two groups from different companies utilise CT for their inspections with one of them utilising it in production quality inspections as well.
- Magnetic particle testing
- Liquid penetrant testing – dye penetrant tests
- Electromagnetic testing – eddy current tests
- Visual testing

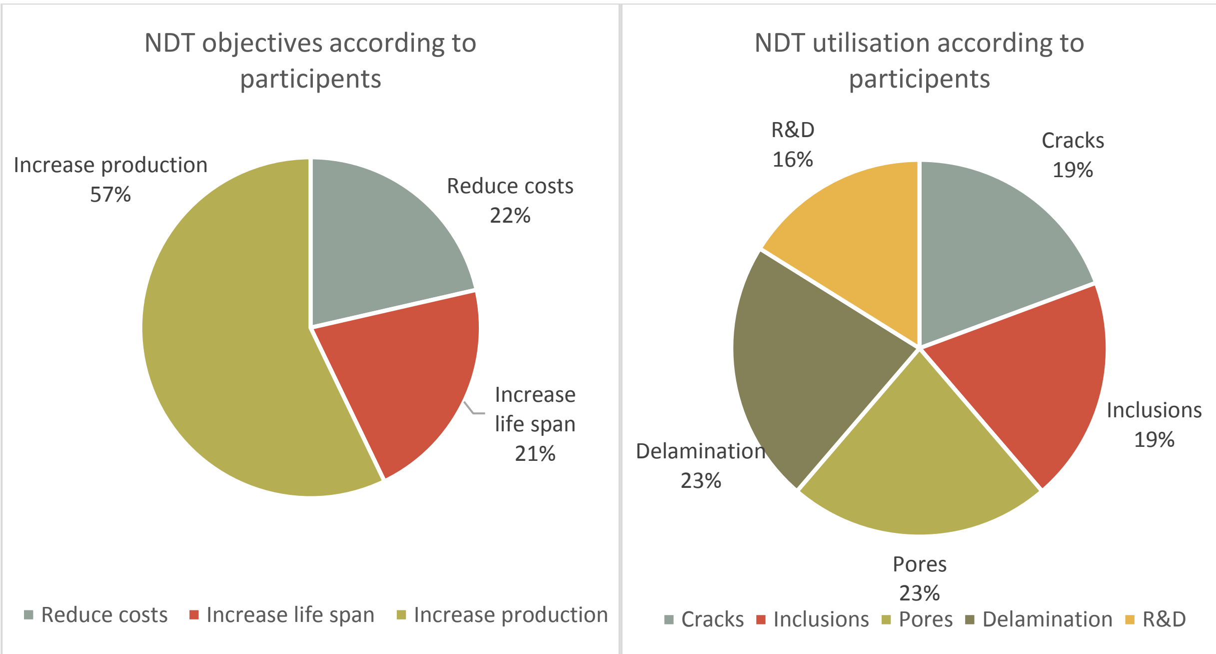

Figure 3: The results illustrated in piecharts are the percentage of participants who provided the same answers

According to the findings of this investigation, NDT inspections are used for quality assurance based on the requirements of national and international aviation authorities and organisations in production and in service inspections. The requirements of the inspections are the identification of defects and the documentation of their position and size in order to ensure the suitability of the parts to be used on aircraft. In production, NDTs are used as tests to determine whether a part passes or fails inspection and whether further investigation or re-work is required. The results of the production and in service inspections are conveyed in reports specifying the suitability of the components. NDTs are not often used as dimensional tools in production, even though non-destructive evaluations and metrology are interlinked. They may be used for research in:

- R&D investigations and in cases they need to provide measurements
- Characterisation of defects
- Demonstrate size, position and in some cases morphology of defects for failure investigations and R&D investigations

The results of this investigation demonstrate the NDT requirements of the aerospace industry and the ways that current systems are utilised. The variety of the different NDT methods was identified as well as the commonly examined materials, identified defect sizes and test duration expectations. The limitations of each technique lead to the combination of different methods to gain the required information while this is avoided in production because of the time restraints. The expected cost of the systems has been identified by receiving sporadic information from several participants. The quality level of the results is ensured by following aerospace standards, good practice guides and company procedures. Engineers are required to set up, analyse and evaluate the results and even though their involvement is necessary, it can lead to human errors. The limitations of the systems lead to unresolved requirements that have also been identified and demonstrate the potential applications of new developed NDTs such as CT. Submission 2 provides further information on the findings.

CT can provide answers to current investigations as well as unresolved requirements such as automated defect recognition and improved characterisation of defects when it is used with image processing. The identification of current NDTs limitations demonstrates where CT can be used. According to the findings, potential applications of this technology include inspections of CFRPs, failure analysis investigations – forensic engineering investigations, R&D investigations, production investigations and metrological investigations.

2.4 Research question and objectives

The interviews with the stakeholders brought to light the current NDT methods utilised in aerospace industry as well as the reasons and ways they are utilised, the production stages that they are needed in and their applications. The identification of business requirements of aerospace industry on NDT methods demonstrate the necessity of further analysis methods that provide more information than the systems currently available. Subsequently, the research question of this project is: *How can CT be applicable in the aerospace industry*?

In order to provide an answer to this question, three research objectives were selected by considering the business requirements and current applications of NDTs and CT.

- *Identification of NPD phases where CT can be applied in aerospace industry*
- *Identification of capabilities and limitations of CT technology*
- *Development of novel methods to provide CT inspections and measurements while minimising human error in the aerospace industry*
- *Development of improved scanning methods and standard operating procedures for the aerospace industry*

These objectives differ from the objectives discussed at the end of submission 1. The original objectives were revised and combined after the interviews and the identification of business requirements. The first two original objectives were the assessment of potential applications and the definition of requirements that both were achieved by the interviews and the business requirements study. The next three objectives of identification of capabilities and limitations of the technology, analysis of barriers and development of guidelines were reassessed in the last three current objectives while the revised objectives include the identification of NPD phases that CT can be applied in aerospace industry.

3. Methodology

In the previous chapters, it has been highlighted that the aerospace industry continually investigates ways of improving quality examinations such as NDT systems, and considers new technologies such as CT scanning. The business requirements have demonstrated the interest of the industry in evaluating new quality investigations for CFRP inspections, failure analysis and engineering forensic investigations, R&D investigations, quality investigations in production and metrological investigations. These areas cover a significant range of activities in the industry. In order to evaluate this technology in all of these areas, mixed and multimethod research are applied which indicate that different qualitative and quantitative methods are used in this research (Melvin, 2015).

Each study of this project utilises different methodologies according to its requirements and these methodologies are discussed in each submission. The business requirements are established through qualitative methods such as interviews and observations. The CT investigations mainly utilise quantitative methods since the data collected and analysed is based on grey-values representing the absorption levels of the radiation. The results can be represented qualitatively in images and videos to provide a better understanding of defects positioning. The combination of qualitative and quantitative research methods has been applied to provide a better understanding and demonstrate the findings.

3.1 Identifying the business requirements

The business requirements identify potential applications of CT and they are established by interviews with stakeholders who were identified with collaboration with the sponsoring company. All of the participants have experience in the application of NDTs in aerospace industry. People from five different organisations were interviewed. The subjects discussed in the semi-structured interviews were established through a detailed literature review on CT, NDTs and metrology. Semi-structured interviews utilise the dialogue as a knowledge producing means and allows further questioning after the participants responses so as the required information would be gained (Brinkmann, 2014). The interviewees were contacted and the interviews ran according to the ethical approval received by the University of Warwick. The results were qualitatively analysed and demonstrate the NDT requirements of aerospace industry and the ways that current systems are utilised.

The research question and objectives were finalised, having been based on the results of this investigation. The objective of CT technology's capabilities and limitations was established through further literature review discussed in Section 4. The identification of NPD stages where CT is applicable and the development of novel methods was established through a series of case studies, having been discussed in Sections 5, 6, 7 and 8.

3.2 Investigating CT applications

Different case studies had been run in order to gain a thorough understanding of the needs and to provide methods to resolve them. In order to provide a well formed solution to a general problem, a better understanding of individual issues may be required (Yin, 2014). In this project, the identification of CT application is required and to achieve this objective, case studies examined the reasons why CT is necessary instead of different NDT methods as well as developing methods to overcome the issues. The examination of different case studies also demonstrates the stages of the product development where CT is applicable. This methodology provides relevant information to answer the research question and objectives.

The selection of case studies was made according to the findings of the business requirements investigation, in Submission 2: An investigation of the business requirements of aerospace industry for the utilisation of NDT methods and CT. The results of this investigation demonstrate the need of a new NDT method that can provide information to develop new machining methods and techniques as part of R&D. This need was examined by Submissions 3, 4 and 5 and it is discussed in chapter 5. Another point from the business requirements is the utilisation of NDTs in production and it was examined in Submission 6 and it is discussed in chapter 6. Due to the limitations of CT, common reconstruction errors such as beam hardening and scattering radiation when scanning metallic parts affect the quality of the scans. Submission 7 examines the reduction of these errors by utilising a new radiation filtration method and it is presented in chapter 7. Submission 8 considers the application of CT in failure analysis and forensic engineering investigations and it is presented in chapter 8.

3.3 Limitations of the methodology

According to researchers (Yin, 2014), the limitation of a case study investigation is that it examines a particular problem at a specific time that may be overcome in time. However, the collection of case studies during this project, over a period of four years, as well as the increase of industrial examination requests received as people learned and understood this project; it demonstrates the necessity of this technology in aerospace industry that cannot be overcome by other available to the industry NDT methods. The next chapters provide the novel methods developed in order to achieve the successful application of CT in aerospace industry.

Another limitation of this methodology is the close collaboration of the sponsoring company which may have directed the case studies into the interests of one company. However, in the business requirements investigation, participants from five companies were interviewed and the selection of the case studies was achieved based on those results. Therefore, the selection of the case studies can be considered as representative to the needs of aerospace industry.

4. X-ray Computed Tomography in industry

Computed Tomography (CT) collects numerous radiographs that then are reconstructed to 3D models and it can provide precise data of the scanned object when optimum settings are selected. The data collected shows the inner and outer geometries of the part as well as any density irregularities and flaws. The application of CT for industrial applications was developed due to the growing need of quality inspection of complex engineering components (Sun, et al., 2012). CT's utilisation in aerospace industry is limited due to the high precision required for the measurements and the lack of international metrological standards. The association between x-rays, the development of CT and its applications are strongly linked with non-destructive testing in industry and metrology even though they are better known for their medical uses. This chapter aims to illuminate the nature of each subject to demonstrate their connection and CT's utilisation within the industry.

4.1 X-rays

X-rays are electromagnetic radiation with wavelength range of 30 pm to 30 nm and energy range of 100eV to 200keV (Muncaster, 1989; NASA, 2010). Electromagnetic waves, such as x-rays, light and gamma rays, travel through vacuum and the presence of any matter can affect them. The wavelength of x-rays is shorter than ultraviolet and longer than gamma rays and it is often measured in Ångström (Muncaster, 1989; Als-Nielsen & McMorrow, 2011).

Waves, including electromagnetic waves, transfer energy from one point to another without transferring any matter between the points (Muncaster, 1989). X-rays are waves of electromagnetic energy transferring energy through photons, similar to visual light, with the only difference being the amount of energy transferred in X-rays (Als-Nielsen & McMorrow, 2011).

There are two kinds of x-ray radiation, the continuous spectrum – bremsstrahlung, which accounts for approximately the 80-90% of the rays and the Characteristic radiation, which is approximately 10-20% of the rays. According to Clark (1955), the wavelength of the characteristic radiation depends on the atomic number of the emitting element of the source and this radiation is formed by electrons bounced to higher energy shell. Muncaster (1989) and Hetrich (2005) stated that electrons that lose all of their energy at once cause the characteristic radiation (Muncaster, 1989; Hertrich, 2005). The most common radiation, bremsstrahlung, is due to the loss of energy of the electrons when they are dropped from their shell (Clark, 1955; Hertrich, 2005). According to Clark (1955), bremsstrahlung radiation depends entirely on the voltage applied to the tube (Clark, 1955).

According to Compton and Allison (1963) and Bowers (1970), the two important characteristics that have to be defined in the production of x-rays are penetration and intensity. These two characteristics are used to 'measure' the x-rays. In practice, the level of penetration is determined by the power applied to create the x-rays and the tube current that determines the intensity. Besides, another important factor that has to be determined is the exposure time in radiation (Bowers, 1970).

4.2 X-ray CT

CT uses x-ray radiographs of a component, assembly or sample that then are reconstructed together to show the whole of the scanned object. The word tomography is derived from the Greek words 'τόμος' (tomos) that means slice or part and 'γραφή' (grapfy) that means 'write'. A similar word that is used in this field is Tomosynthesis that is also derived from the Greek world 'τόμος' (tomos) and 'σύνθεσις' (synthesis) that means 'to combine'. Both of these words highlight that CT combine and utilise the x-ray radiographs according to what is required to achieve. The images that are taken through the object's volume can be combined to illustrate tumours in medicine or defects in industry.

CT obtains information about the nature of material and position of features inside the body. This is achieved by producing specific cross section sinograms that are used to calculate the x-ray attenuation coefficient distribution which then is used in further computer processing to reconstruct the cross sections (Herman, 2009). Radiographs average the information of a 3D object in a 2D image and they cannot provide all the available information while CT utilises the radiographs to create a 3D model of the object (Copley, et al., 1994; Buzug, 2008).

Rotation in Cone-Beam Geometry

One of the most commonly utilised industrial CT layouts is demonstrated in Figure 4 with a cone-beam source that can penetrate a significant amount of volume of the scanned object. Such systems have a flat panel detector and fast computers and bandwidth that can transfer the data from the scanning unit to the reconstruction computer and reconstruct mathematical algorithms quickly.

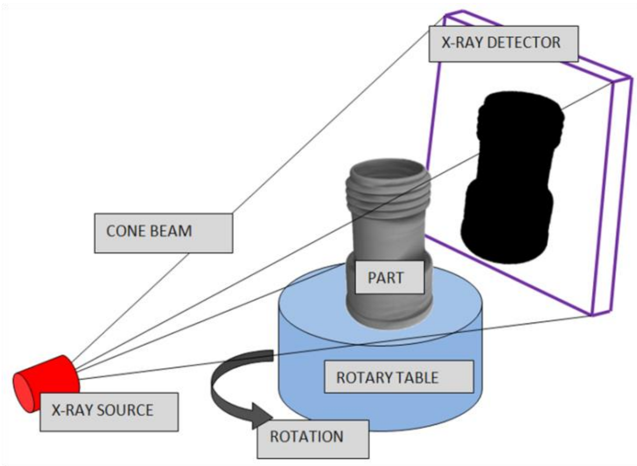

Figure 4: Cone beam CT system

4.3 Industrial x-ray CT

CT has another two major applications other than the medical; material analysis - examination and dimensional metrology (Kruth, et al., 2011). These applications of CT are primarily linked with industry and industrial applications, such as inspections, material investigations, research and development, design alteration and quality controls.

The reasons for the development of industrial CT are the same as for the medical CT, which is the ability of the system to provide useful and detailed information of the inner structure as well as the outside geometry of the scanned object more precisely than any other non - destructive technique. The exploration of CT for non-medical uses started at the end of the 1970s by using medical CT scanners (Copley, et al., 1994).

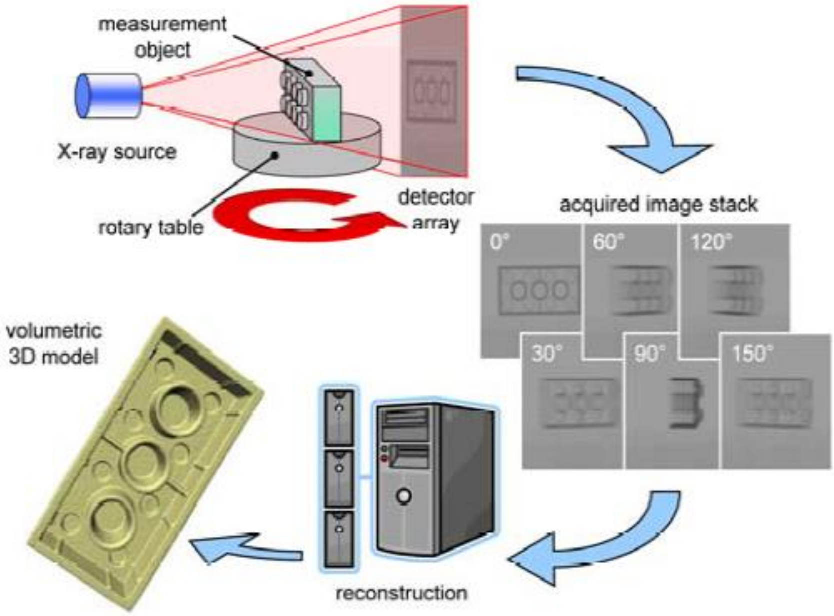

Figure 5: Basic Principle of Computed Tomography (Weckenmann, et al., 2007)

There are several industrial CT systems that have been developed as custom-built CT scanners and they are able to scan from 1mm up to 3m diameter objects. At the same time, there are CT systems that can produce x-ray energies from 5keV to 15MeV (Copley, et al., 1994). The selection of x-ray energy depends on the components' size and materials' properties (Welkenhuyzen, et al., 2009). Furthermore, there are numerous CT scanners, which are specialised for different purposes, such as portable scanners, rapid scanners and systems which can scan large volumes in a single scan (Copley, et al., 1994).

4.4 Equipment

Industrial CT systems consist of an x-ray source, a detector, a manipulator that rotates and moves the part between the source and the detector, a computer system that performs the required calculations for the reconstruction, shielding and cooling system (Copley, et al., 1994; Sun, et al., 2012; Kruth, et al., 2011).

4.4.1 X-ray source

X-rays are electromagnetic radiation that is emitted when electrons accelerate from cathode (filament) through the anode and hit the target in a vacuum tube. There are three different x-ray source types that are used in industrial CT characterised by their build; an electronic x-ray source, an isotope source or synchrotron source (Copley, et al., 1994; Kruth, et al., 2011).

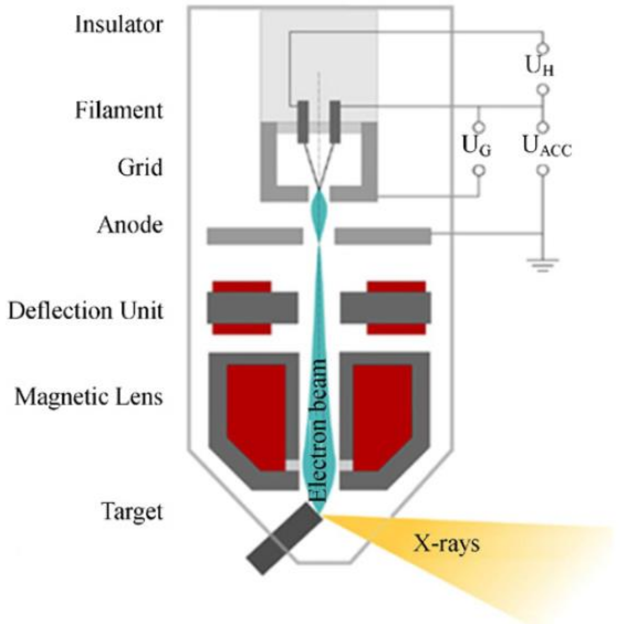

Figure 6: Typical X-ray Tube (Kruth, et al., 2011)

Electrically generated sources can be sub-divided to open tube/vacuum demountable x-ray sets, sealed tube constant potential x-ray sets and linear accelerators (BSI, 2011). X-ray sources can be categorised into direction or panoramic tubes as well as into unipolar or bipolar. Moreover, the output x-rays pass through a circular aperture or diaphragm for cone beam, or collimating plate for fan beam (Sun, et al., 2012).

Other tube characteristics are the focal spot size, flux and energy range (Copley, et al., 1994). Furthermore, the target of the source can be made from different materials that emit different x-ray spectra. The material of the target is selected according to the application of the CT and materials with high temperature resistance being preferable due to the nature of x-rays. It must be noted that only 1% of the energy generated in a tube is emitted as x-rays while the 99% of the remaining energy is released as heat (Sun, et al., 2012; Kruth, et al., 2011).

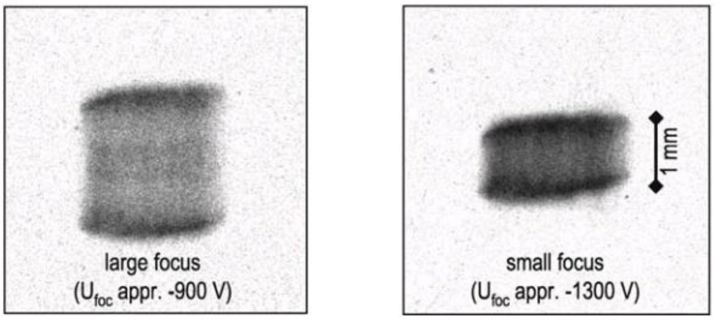

Figure 7: Spot Shape and Size of medical X-ray (Philips Medical Systems) (Buzug, 2008)

Isotope sources use radioactive isotopes and they are chosen when a single energy is required. Single energy rays are preferable when assembled or multi-material objects are scanned because it eliminates any beam hardening artefacts. Linear accelerator x-ray sources (LINAC) find application in industrial NDT or dimensional CT measurements. According to Kruth et al, nano-focus and micro-focus spots are produced by x-ray photon energies up to 250keV while mid-power CT commercial scanners with 450keV and 800keV tubes have been introduced to the market in the last few years (Kruth, et al., 2011) and a new micro-focus CT with 750keV will be introduced by mid-2017. In micro-resolution, synchrotron x-rays sources are preferable because the x-ray beam produced is well collimated and extremely intense. Synchrotron x-ray sources have limited beam diameter and tend to have a low keV of a few tens of keV voltage (Copley, et al., 1994; Kruth, et al., 2011).

4.4.2 Detectors

Even more consideration is given to the detectors used in industrial CT and radiography. The characterisation of the entire selection of detectors have been separated into two groups by ISO 15708 part 1, the ionisation detectors and scintillation detectors (Copley, et al., 1994; Sun, et al., 2012). Some x-ray detectors count single photons while others measure x-rays' energy, position and incidence time and others measure the count rate of total flux. The most suitable detectors for industrial CT and radiography are scintillation detectors that can provide measurements on energy range between 3keV and 10,000keV and energy resolving semiconductor detectors that can provide measurements on energy ranges between 1keV and 10,000keV (Thompson, et al., 2009).

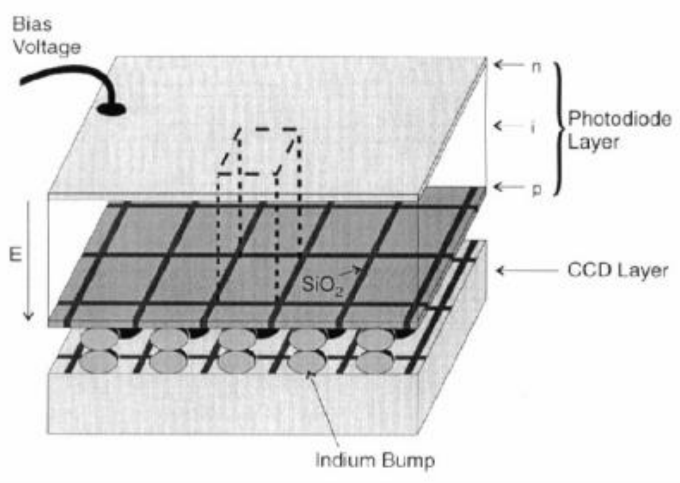

Figure 8: Schematic example of a hybrid detector (Yaffe & Rowlands, 1997)

Scintillation detectors use materials that convert the radiation to optical photons after they have been penetrated. Scintillation is produced when the radiation is absorbed by organic or inorganic scintillators, such as single crystals of sodium-activated caesium iodide CsI(Na), single crystals of thallium-activated sodium iodide NaI(Tl) or single crystals of bismuth germanate (BGO) (Thompson, et al., 2009; L'Annunziata, 2012).

4.4.3 Manipulation system

The importance of the manipulation system in a CT system lies on the kinematic system since it affects greatly the end-result of the reconstruction. In industrial systems, the object rotates around the central axis and the source and detector are stable during the acquisition (Kruth, et al., 2011; Sun, et al., 2012).

Systems with 2D flat panels do not need any vertical translation of the object in the duration of the scan while systems with linear detectors require the part to move vertically to the detector. The transition from stationary object and rotating source and detector to rotating object and stationary source and detector was made because this configuration is more stable with fewer variables and it allows the alteration of the magnification factor according to the object's size (Kruth, et al., 2011).

A basic kinematic system includes a turntable to rotate the part either stepwise or continuously, a horizontal translation that moves the part closer or further from the source according to its size, a horizontal translation that can move the component parallel to the source and detector and a vertical translation. The horizontal translation axis is used to position the part between the source and the detector and this position affects the magnification factor. The closer the part is to the source, the greater the magnification and therefore the greater the resolution. However, higher magnification can potentially cause blurrier radiographs due to the spot size, as shown in Figure 9 (Kruth, et al., 2011; Sun, et al., 2012).

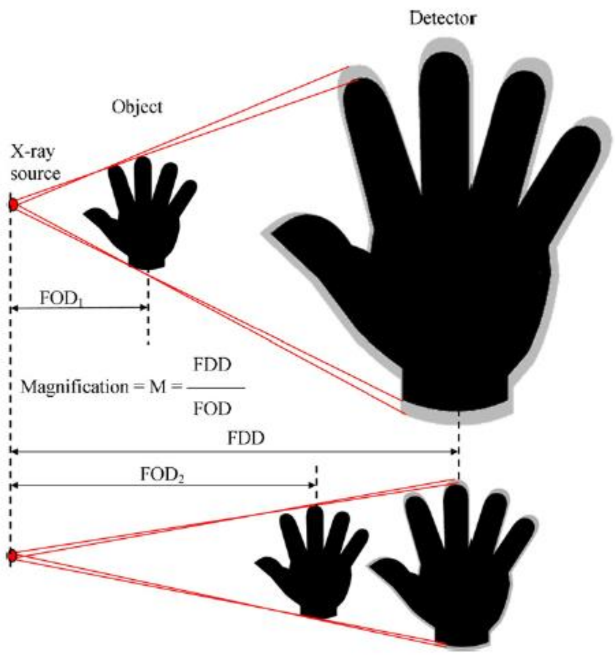

Figure 9: Magnification and blurriness effect created by the movement of the object between source and detector (Kruth, et al., 2011)

4.4.4 Computer hardware

The primary functions of CT are greatly affected by the capabilities of the computer systems that are used. The influenced functions are the user interface, device control and synchronisation, image reconstruction and image display, and analysis (Copley, et al., 1994). The functions of user interface, device control and synchronisation, and image display and analysis do not require intense computer capabilities while image reconstruction does (Copley, et al., 1994; Sun, et al., 2012).

After the end of a scan, the images are processed and reconstructed to transform the pixels to voxels that build the 3D model of the scanned part. This process tends to be time consuming and computing intensive. The parts of a computer that are critical to this process are the central processing unit (CPU), the random-access memory (RAM) and graphic cards. The process can be accelerated by the help of recently developed multi-core processors and advanced graphic cards with graphic processing units (GPUs) where a large amount of data and image decoding are required to be analysed. RAM is important when receiving the large amount of data (Sun, et al., 2012). Additionally, another important factor in computer hardware is the memory. Each scan usually requires 30 to 40GB and in many situations, the data is required to be kept for future reference and on-going analysis such as comparisons between components (Sun, et al., 2012).

The device control and synchronization function includes tasks such as setting up and interacting with the manipulation system. Likewise, it controls the x-ray source and handles the data acquisition. The image display and analysis function includes the real-time image acquisition that allows the operator to identify and select the optimum settings of the scan of each part. This function encloses the final analysis that may include defect analysis and CAD comparison to actual part. This process is computationally intensive as well (Copley, et al., 1994; Sun, et al., 2012).

4.4.5 Shielding

Even though x-rays can provide helpful data, radiation is dangerous and health and safety are important factors that have to be considered when handling a CT system. The shielding of a CT system has to be calculated according to beam power, workload, scatter and leakage. The most common material that is used for shielding of harmful radiation is lead due to its high density and atomic number. As the capabilities of a system in regards of x-ray energy increase, the thickness of lead has to be increased as well, to cover the shielding requirements (Sun, et al., 2012). Other common material for x-ray shielding is also concrete and steel.

4.4.6 Cooling system

In the production of x-rays, as discussed previously, the 99% of the energy emerges as heat. Due to this low efficiency of the process, excellent cooling systems are required for systems generating high power x-rays to prevent overheating of the systems. The significance of a cooling system in the configuration of CT lies on keeping the temperature of the system stable to minimise any instabilities caused by the thermal effects and minimise uncertainty. The cooling systems of industrial CT systems are separated to oil and water systems according to the energy of the x-ray source (Kruth, et al., 2011; Sun, et al., 2012).

4.4.7 The importance of the equipment

The effectiveness of industrial CT and its capabilities depend on the combination of the efficiency of the following individual systems, the x-ray source, detector, manipulator, computer hardware, shielding and cooling system. The scanner is affected by the level of interaction and combination of the individual systems. Each system affects the efficiency of the scanner as well as its applications and each one comes with its limitations that influence the metrological applications of the scanner. The individual systems are discussed here to demonstrate their significance and to identify their limitations which become the limitations of the scanner.

4.5 Data processing

In the CT process, there are two stages, the data acquisition and the data processing. The data processing is mainly the reconstruction of the acquired data and the analysis. The reconstruction of CT data is performed by mathematical algorithms that calculate the attenuation coefficient for each voxel. However, the results may suffer from systematic errors that may affect the quality of the results. Dimensional metrological analysis can be part of the data analysis if the right steps have been taken at the stage of data acquisition and only if systematic errors are not affecting the data.

4.5.1 Reconstruction

Reconstruction may be the most important part of the data processing and it is the most complicated process that takes place in the CT process. The reconstruction of the data converts the simple radiographs of the scanned part that are collected while the part rotates, to a 3D model that consists of all the data of the inner structure of the part (Sun, et al., 2012).The reconstruction of industrial CT is usually achieved by Filtered Back Projection (FBP) that its application is proven through Radon's *'linear integral transformation'* (Kruth, et al., 2011). In CT, Radon's transform calculates the projection of the sample by using the intensity of each pixel as a function of the attenuation coefficient and the distance the x-ray travels within the sample (Sun, et al., 2012).

The only input for the reconstruction is the intensity of each pixel that is found by the ‘grey value profiles’ that provide data of the inner structure of the part by the changes of their intensity (Sun, et al., 2012; Kruth, et al., 2011). The calculation of the projection is called back projection as shown in Figure 10. The procedure of calculating the inverse Radon transform can be achieved by different methods. The methods used to perform image reconstruction can be classified as (Kalender, 2011):

- Analytical reconstruction algorithms
- Series expansion methods / algebraic reconstruction
- Statistical reconstruction techniques

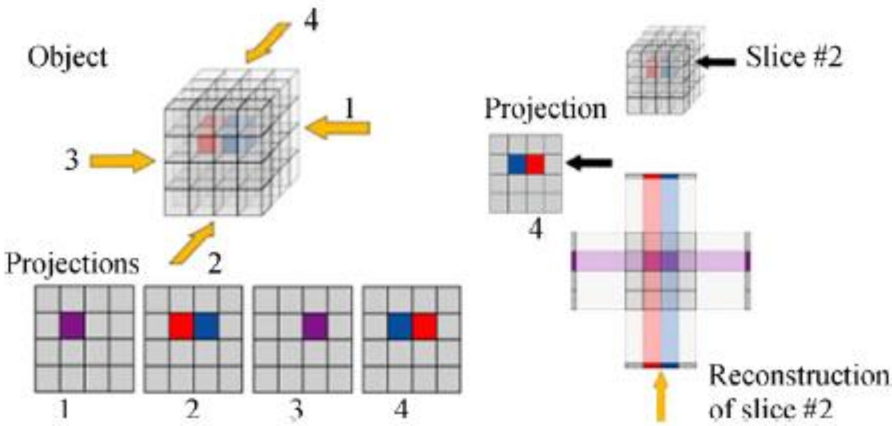

Figure 10: Example of back-projection reconstruction (Kruth, et al., 2011)

The reconstruction of the radiographs as well as the resolution is affected by the pixel size, the number of the detector’s pixels in x-direction and y-direction, or number of slices in systems with linear detector, the number of angular positions from which the radiographs are taken, the number of projection images for each angular position and the binning. At the end of the reconstruction process, the segmentation takes place to determine the edge or surface between the object and air or between different materials. The edge detection transforms the voxel data to surface data. This procedure is also called filtering and there are different types of filters. Systematic errors such as beam hardening, may affect greatly the edge detection by interacting with the true edges (Kalender, 2011; Sun, et al., 2012).

4.5.2 Cone beam reconstruction

The reconstruction of data collected in a cone-beam CT system differs slightly from the general reconstruction processes followed in medical CT even though they are based on the same mathematical models. There are numerous different variables that can affect the final models created by the reconstructions and have to be considered when evaluating any reconstruction algorithms to minimise potential systematic errors.

The algorithms can be either exact or non-exact. Exact algorithms are executed correctly when the data is noise free and all projections have all the required data. Non-exact algorithms are more flexible and able to calculate potentially missing data. Another important aspect that has to be considered is the x-ray vertex point that refers to the position of the x-ray source. According to some researchers, a scan cannot provide complete information for an object if there is not sufficient information for the vertex.

The main two categories of algorithms used in cone beam reconstruction are ‘analytic’ and ‘algebraic’. Algebraic algorithms are more time-consuming and require more computing power while analytic algorithms are considered more efficient because of their high reconstruction speed. The most common method in industrial computer tomography reconstruction is the convolution back projection that was developed by Feldkamp based on the algorithm used for medical fan beam CT systems and it assumes that the shape of x-ray source is a circle (Sun, et al., 2012).

4.5.3 Systematic errors

Due to uncertainties and fluctuations related with CT technology, systematic errors are common problems. The sources of these problems have been identified and methods to resolve or reduce the problems have been developed. According to ISO 15708 Part 1, an artefact is ‘*the discrepancy between the actual value of some physical property of an object and the map of that property generated by x-ray computer tomography imaging process*’ (ISO15708-1:2002, 2002).

Beam Hardening

One of the most common artefacts is beam hardening and this phenomenon is related to polychromatic x-ray beam. This artefact is caused due to a combination of the x-rays nature and the algorithms used in the reconstruction process. When the x-ray beam is produced not all photons have the same energy. The photons with lower energies cannot penetrate the scanned object. As a result, the mean energy of the beam increases (Barrett & Keat, 2004) and the external section of the object is penetrated by more rays than the centre while the reconstruction algorithms assume that the penetration of the object is homogeneous (Kruth, et al., 2011).

There are two common types of artefacts caused by beam hardening, the 'cupping' artefacts and the 'streak' artefacts. Three different methods can be used to correct or at least reduce as much as possible beam hardening, the pre-processing methods by filtering the radiation, post-processing methods by calculating and removing the artefact before reconstruction and the dual energy method that uses two x-ray beams to calculate the complete energy dependency (Kruth, et al., 2011).

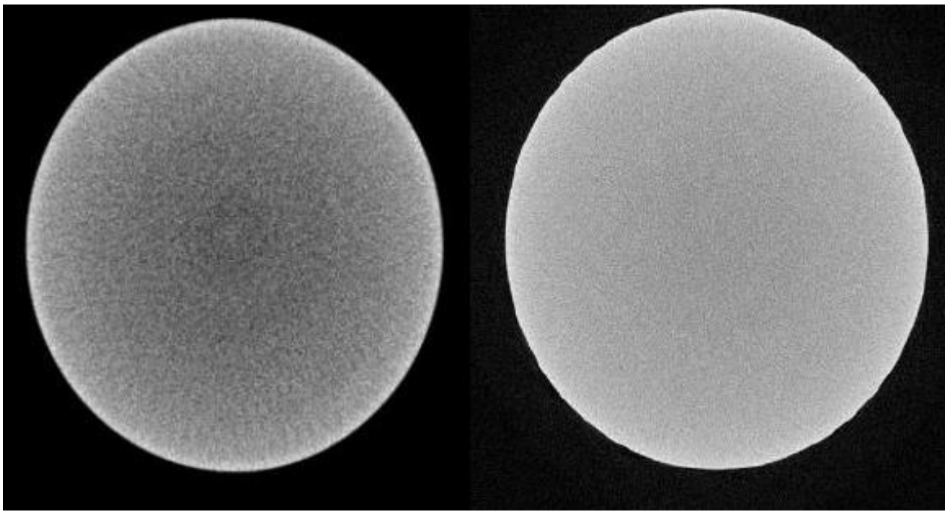

Figure 11: Beam Hardening Example given from Nikon Metrology (Sun, et al., 2012)

Ring Artefacts

Another very common CT systematic error is the ring artefacts that are caused by improper calibration of the detector. This artefact is caused by non-ideal or defective pixels that give higher or lower readings and cause rings of sharp contrast with the same centre as the centre of the rotation. This artefact can be resolved completely by the frequent calibration of the detector (Kruth, et al., 2011; Sun, et al., 2012).

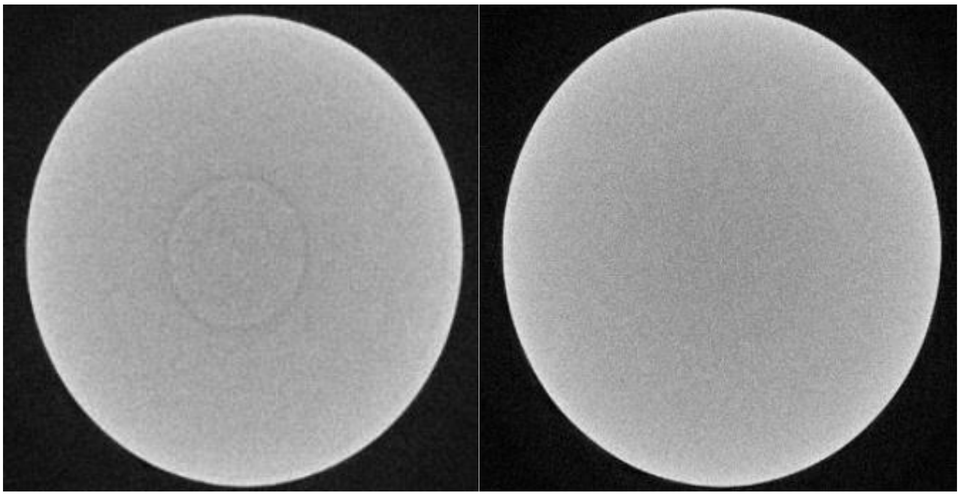

Figure 12: Example of Ring Artefact by Nikon Metrology (Sun, et al., 2012)

Beam Drift

This artefact is the only systematic error that is caused exclusively by the x-ray beam. It is caused due to the low-efficiency of the x-ray production and the high-temperatures that are produced. Due to these high-temperatures, the x-ray tube can undergo thermal expansion and therefore a beam drift can be produced. This problem can be resolved with a very good cooling system that ensures a stable temperature inside the tube (Sun, et al., 2012).

Scattering and Noise

Scattering is the artefact that can be characterised as a halo around the part and it is caused by deflection of x-rays inside the workpiece (Sun, et al., 2012). Noise is the variation of grey-values close to the correct value of each voxel and it is present in every scan. It can be generated by quantisation of the x-ray photons or other noise sources such as electronic noise of the detector, or because of amplification of signals (Sun, et al., 2012).

Other Artefacts

Other common systematic errors are aliasing artefacts, which are caused when the object extends beyond the field of view. Sampling artefacts are caused when the projections from different angular positions are limited. Noise can be caused by several factors including filtering, which is used to reduce beam hardening (Sun, et al., 2012).

The effect of systematic errors

The systematic errors discussed in this section affect the quality of the scans and considerably are a limitation of the technology. Optimum scanning settings can reduce their effect but they will always be related to CT scanning. A novel method of beam hardening and scattering reduction is discussed in later chapters.

4.6 Applications

Industrial Computed Tomography systems should meet three requirements simultaneously: high performance capability of the x-ray, good spatial resolution and short data acquisition time. When a system fulfils these requirements, its applications are broad and numerous (Izumi, et al., 1993). The application of material analysis and non-destructive testing (NDT) goes back to 1980s (Kruth, et al., 2011) and initially it was only used when other NDE methods failed (Copley, et al., 1994).

With CT, inaccessible internal features and structure of complex components can be studied in detail as well as it can examine cracks, voids and inclusions. In some applications, the results of CT are similar to those of radiography and ultrasonics. However, CT can provide detailed characterisation to assist in the investigation of systematic manufacturing defects (Copley, et al., 1994).

Metrological CT systems have four main functions in dimensional metrology. CT is the only available technology in the market that can measure inner or internal features in a non-destructive way. This technology can provide measurements of complex cast objects and additive manufacturing components that may have unreachable inner geometries. It can also measure entire assemblies and provide data for unforeseen parts (Kruth, et al., 2011; Sun, et al., 2012).

4.7 X-ray CT guidelines for metrological applications

This technology can be applied in non-destructive evaluations and as a metrological tool when strict procedures are followed to overcome a series of issues that can affect the precision of the data. The quality of the radiographs that are reconstructed are influenced by several factors as listed in Figure 13. The two factors that are more susceptive to errors are magnification and pixel size. The collected CT data has been proven to be possibly influenced by bi-directional repeatability of the system, radial run-out errors, the detector tilt and type and the movement of the spot size of the X-ray in the duration of a scan (Herman, 2009; Hsieh, 2009; Kruth, et al., 2011; Sun, et al., 2012).

- Source Current
- Source Voltage
- Type of Target
- Magnification
- Number of angular poses
- Exposure Time
- Number of projection images per pose
- Sensitivity of detector
- Binning
- Waiting time after turntable movement
- Number of positions along the Y-axis
- Use of filter plates
- CT strategy

Figure 13: Variables that affect CT radiographs

The reduction of systematic errors in CT data and its utilisation in metrological investigations can be achieved by following the recommendations provided by VDI/VDE 2630 Part 1.2; a guide to obtain dimensional measurements through CT (VDI/VDE, 2010). There are four different measuring procedures that can be used in CT scanning, ultimately leading to dimensional metrological results:

Type A
- Nominal/actual comparison based on nominal geometry

Type B
- Nominal/actual comparison based on reference measurements

Type C
- Analysis of size, shape and position tolerances and determination of compesating elements of ruled geometries and free shape surfaces

Type D
- Wall thickness analysis

Figure 14: VDI/VDE procedures to achieve CT metrological results.

The method most commonly used in this project is Type B that describes the procedure of how to make nominal/actual comparison between the scanned data and reference measurements. The utilisation of this method allows the reduction of measurement errors by rescaling the voxel size of the scans based on known threshold indented measurements. The reference measurements can be from the scanned part or a calibrated artefact that it is scanned at the same time with the part or prior and subsequent to the original scan (VDI/VDE, 2010).

All measuring techniques require to demonstrate traceability of the measurement instruments to the metre for useful interpretation of generated data. The CT measurements may be subject to absolute scale errors that correspond to the wrong voxel size. According to Lifton, et al. (2013), the measurement error in CT is mainly systematic. A measurement compensation can be made between the CT results and reference measurements so as to achieve the required scaling. The results are typically affected by less than 1 voxel size error which can be reduced with this method to less than 0.2 of the voxel size. The reference measurements are always by a traceable technique such as tactile Coordinate Measurement Machines (CMMs) and the uncertainty of the measurements drops from 2 voxels size to less than 0.3 of the voxel size (VDI/VDE, 2010; Lifton, et al., 2013).

4.8 Summary

In this chapter, CT technology is explained by discussing the theory, the individual systems that lead to a CT scanner, the data processing and reconstruction theory, the systematic errors and its applications. Each of these categories demonstrates the capabilities and limitations of such systems. The utilisation of cone beam layout leads to greatest magnification and better resolution as long as the spot size does not affect the unsharpness. The potential applications of CT scanning in aerospace industry are greatly influenced by the limitations of the technology. In the following chapters innovative methods are demonstrated in order to overcome these limitations.

5. The application of CT in research and development

Research and Development (R&D) is crucial for successful business and it is an important stage in NPD that leads to innovation which introduces new or improved products. Modern businesses require the innovation related to R&D in order to stay competitive since the exploitation of science and technology is critically required to identify new concepts of new products or to overcome current limitations. This phase of NPD considers all materials, technologies, designs and procedures in order to identify new improved ways that will benefit the company (Ganguly, 1999). The utilisation of technologies for which CT can provide information otherwise unreachable, about the materials and machining procedures. The evaluation of CT in R&D has been achieved by three case studies investigating CFRP machining technologies that are examining their effect on the materials.

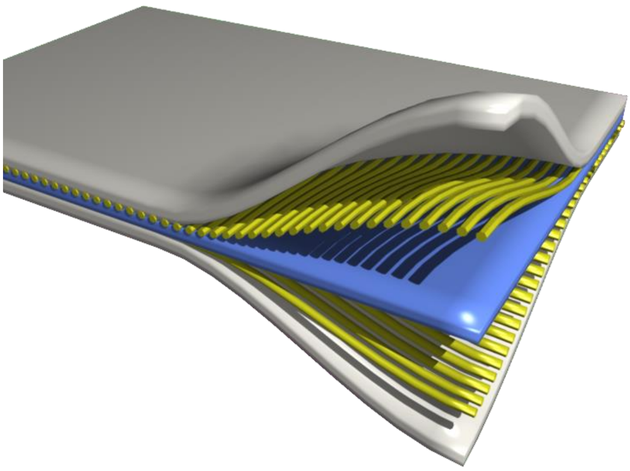
Figure 15: An example of orientation of fibres in a composite

Composite materials have been developed over the last two decades when materials with specific properties are required. They are formed by combining two or more distinct phases of more than one material using a reinforcement material to the matrix material, enhancing the properties of each distinct phase for particular applications (Adams & Cawley , 1988; Teti, 2002; Pejryd , et al., 2014; Grilo, et al., 2013). The applications of Carbon Fibre Reinforced Polymers (CFRPs) in aerospace and automotive industries are well known, such as fan cases, vanes and fan blades (Pejryd , et al., 2014). The mechanical and structural properties of CFRPs depend on the nature, orientation and bond of the fibres that are arranged in flat panels, sheets or a woven structure. The popularity of CFRPs in these industries is due to their advanced mechanical properties such as low specific weight, strength to weight ratio, durability, stiffness and density. These characteristics permit higher specific strength and stiffness in light structures while their high cost limits applications to cases when performance is the most important consideration. The greatest limitations of composites are their heterogeneity and heat sensitivity. They are also anisotropic and their material behaviour depends on diverse reinforcement and the matrix properties (Adams & Cawley , 1988; Teti, 2002; Grilo, et al., 2013; Grilo, et al., 2013; Persson, et al., 1997; Santhanakrishnan, et al., 1988; Davim & Reis , 2003; Makhdum, et al., 2012; Tsao & Hocheng, 2004; Abrate & Walton, 1992).

Machining CFRPs

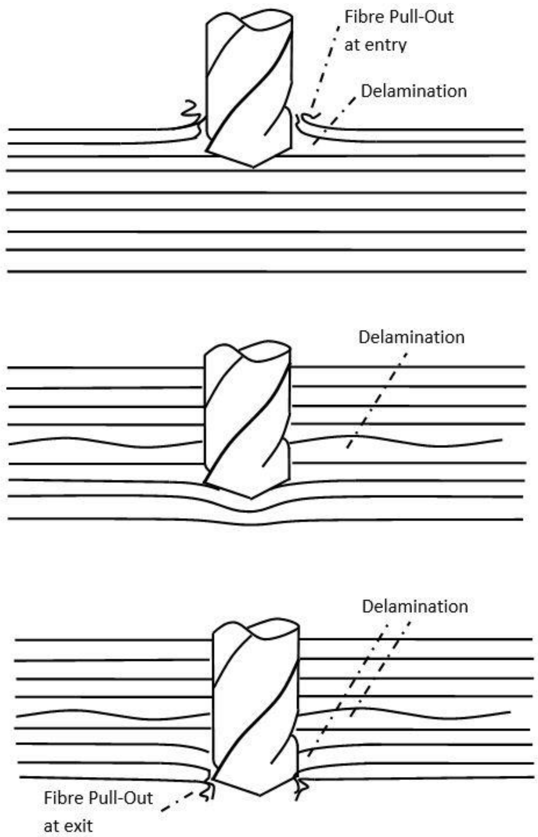

Figure 16: Machining may cause debounding, fibre pull out and delamination.

The selection of machining processes and tools has to be done according to the properties of the materials, tool wear mechanisms and the requirements of the application. The behaviour of the matrix material differs from the response of the reinforcement material while they are machined and both behaviours have to be considered before the selection of the machining process and tool. Due to difficulties faced when composites materials are machined, near-net shape processes are often applied to avoid any damage that would adversely affect their strength (Makhdum, et al., 2012; Tsao & Hocheng, 2004). However, some machining processes are unavoidable since mechanical fasteners are often required. The most common secondary machining is drilling and can cause fragmentation, burrs, interlaminar cracks, interfacial de-bounding, thermal damages and fibre pull-out, all of which can lead to delamination, as indicated in Figure 16 (Teti, 2002; Grilo, et al., 2013; Makhdum, et al., 2012; Abrate & Walton, 1992; Hocheng & Tsao, 2005).

Due to the numerous factors that affect the quality of drilled holes in CFRPs, several techniques were previously employed to assess the different results. Destructive methods such as sectioning can be applied by cutting part of a drilled hole to examine it, but as a result part of the hole is destroyed and some potentially useful data is lost. For this reason non-destructive test techniques are favoured to identify and study damages, defects and faults caused by the machining processes in CFRPs. Optical inspection with microscope is commonly used and the most common NDTs applied are radiography, ultrasonics and eddy-current testing (Davim, et al., 2007; Goeje & Wapenaar, 1992; Persson, et al., 1997). CT provides data of the entire part accurately and the results obtained can be examined automatically with little interaction from operators and as a result human error is reduced. CT data can also provide dimensional measurements when metrological procedures are followed. The following case studies were in cooperation with other research groups and assisted in the identification of optimum machining techniques and prove the beneficial application of CT in R&D.

5.1 CT investigations of drilled CFRPs

CT was applied as an NDT and a dimensional measuring technique in the investigation of CFRP holes. This case study assisted researchers to identify optimum machining techniques and machining settings in the drilling of CFRP by innovatively combining CT scanning, volumetric analysis and image processing to identify and measure defects. This method follows dimensional guidelines in order to provide accurate measurements.

Each part was CT scanned, the acquired data reconstructed, reviewed in two different inspection software packages and then analysed with image processing. The parts were measured with optical CMM so as to be used later for voxel rescaling. The optimum CT settings were selected to achieve the best possible acquisition of the data while ensuring maximum magnification that provided 15μm voxel size. The reconstructed data is represented by different grey values. A threshold selection is applied to include all the grey values of the material and it can be affected by CT artefacts. This selection is subjective and the threshold can affect the measurements of the 3D model. In order to overcome this issue, the CMM measurements were used as threshold independent measurement for the voxel rescaling which reduces the measurement error from 1% to 0.2% (Lifton, et al., 2013).

The image processing used a slice that was selected manually close to the entrance surface of the hole for the initial identification of the intended centre of the hole. The images were transformed to binary with the threshold utilising the Otsu method (Silva, et al., 2014). Image processing then utilised the Hough transform, to identify the edges of the machined markings with slope of 0° and 90° with two lines identified for each slot. The mid-points between the two edges of a horizontal slot (0°) and vertical slot (90°) give the y and x coordinates of the centre of the hole. Next, the code is run continuously through all the DICOM images to calculate the maximum and minimum radius, maximum and minimum diameter, circularity, positioning and the delamination close to the exit surface. The image processing reduces the human error and provides dimensional measurements of the hole that demonstrate any inclusions on the surface of the hole as well as delamination close to the exit surface.

The results of this investigation demonstrate the delaminated areas and provide accurate measurements of the defects depth. The results can be separated in morphological observations that demonstrate the issues graphically and quantitative results that are demonstrated in graphs. The two types of results can be combined to improve the understanding of the defects' formation and assist in the identification of the optimum machining technique and settings. A summary of the results follows while further information on the novel method and the results can be found in submission 3.

5.1.1 Morphological Observations

The morphology of the hole was considered to gain a general understanding of the defects. Figure 17 provides the reverse surface of the hole negating entry and exit layers with all the defects clearly shown. Protrusions in this view represent the defects, making it easier to qualitatively assess the surface of the hole.

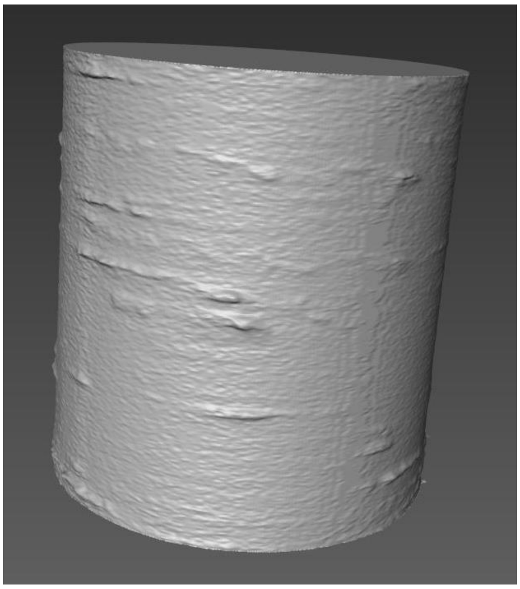

Figure 17: The reverse surface of the hole demonstrates the inclusions as protrusions.

The CT data was then examined as 2D images to identify the problematic areas, as shown in Figure 18. The 2D images are created from the 3D reconstructed data and they represent a slice of voxels.

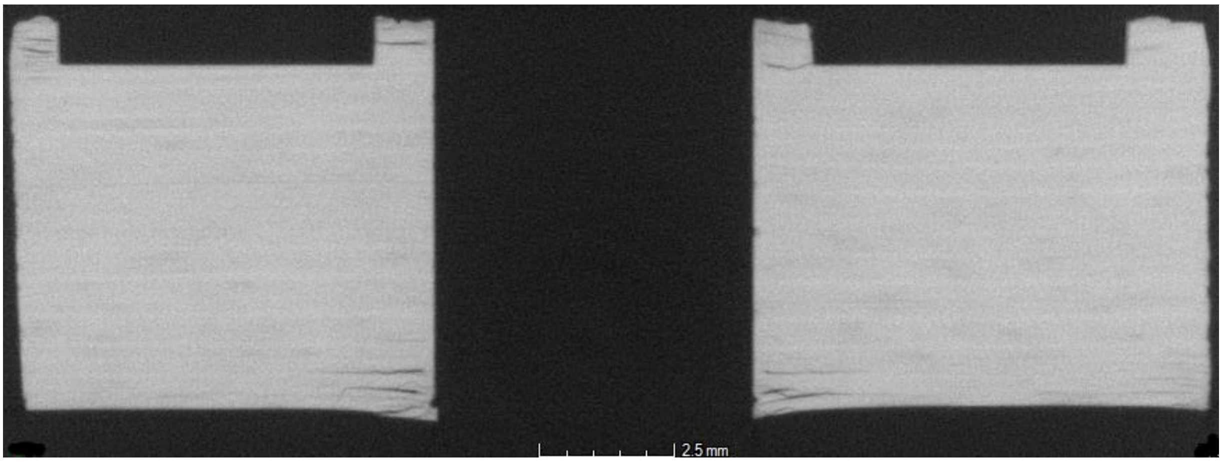

Figure 18: Delamination can be detected that is not connected to the wall but can still affect the quality of the part.

5.1.2 Quantitative Results

All of the quantitative results were calculated based on the intended centre. Calculation of radii has not previously been possible on a slice by slice basis, leading to a more meticulous evaluation of quality. The analysis of the results can provide information about every defect on the surface of the hole. The characterisation of defects as critical depends on the accepted tolerances of the values such as diameter, circularity and positioning.

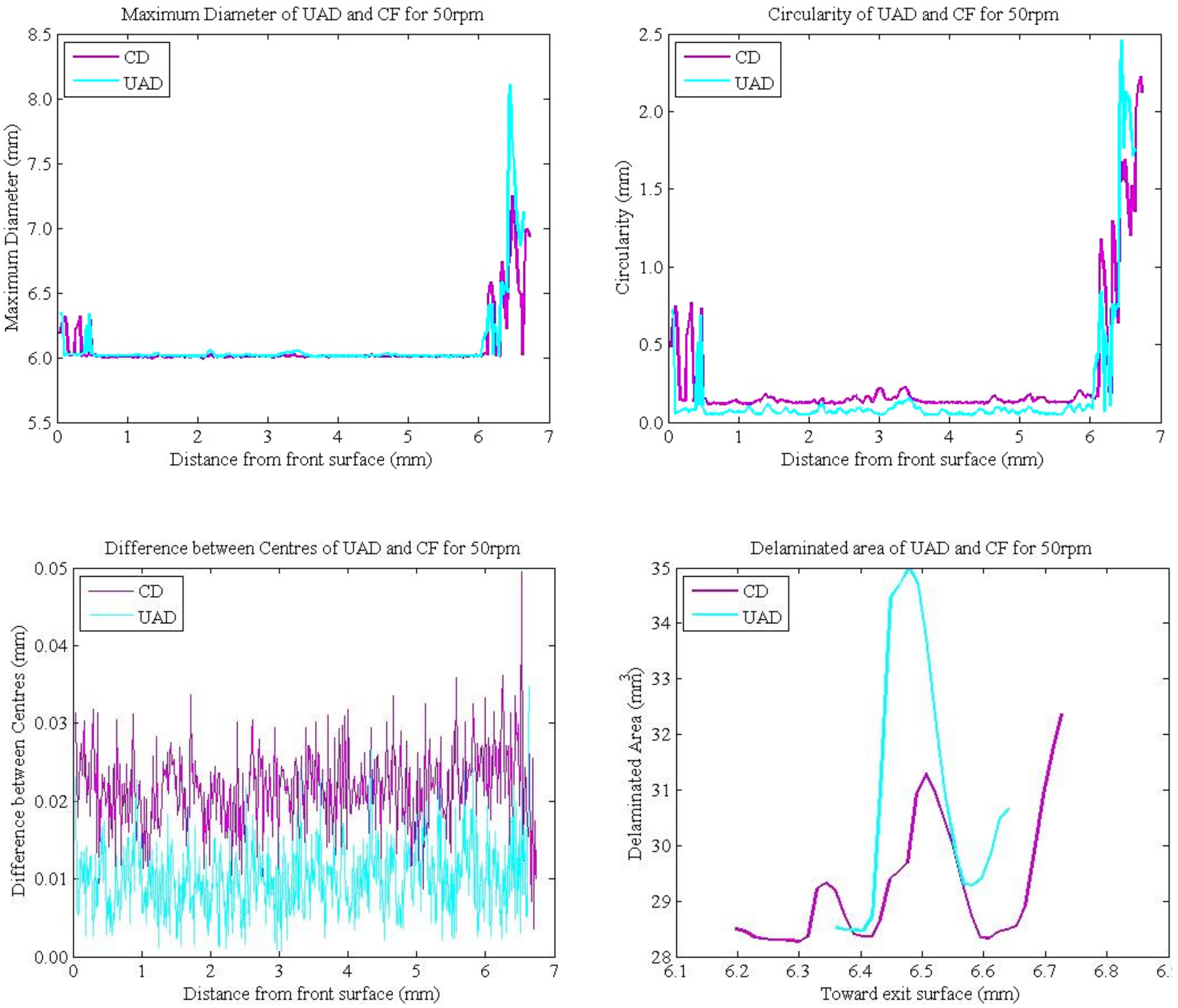

Figure 19: The results of this analysis can demonstrate differences between different machining processes and settings that assist in the identification of the optimum selection.

The results can demonstrate delaminated areas close to the entrance and exit surfaces and where tolerances are exceeded. This method also allows the identification of the exact point that a particular defect is detected and can be used for further examination of the slice. Patterns can be detected when experiments are repeated a sufficient number of times. The results can also demonstrate the growth of delaminated areas close to the exit surfaces.

A hole was digitally unravelled in Figure 20 from a cylinder to plane, providing a non-planar view. Here the radius is shown through 1440 discrete angular values throughout the length of the hole. The variation is immediately evident, with problematic areas readily identifiable. The degree of delamination is worse at the exit, interestingly variable through 360°. This is likely due to one region of CFRP being weaker than the other, but could also be indicative of minor misalignment of the drill from the orthogonal plane to the CFRP.

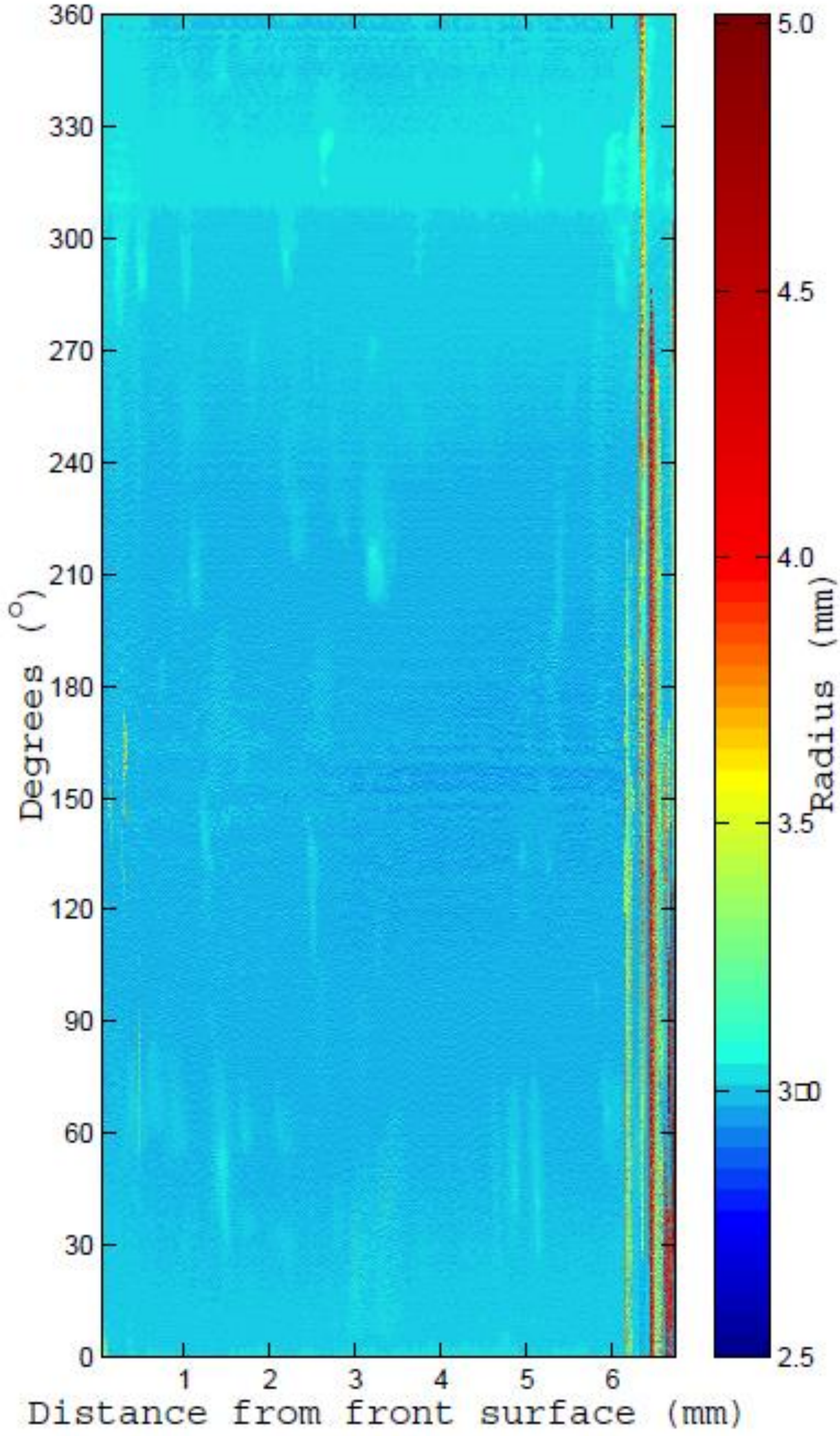

Figure 20: The hole was unravelled from a cylinder to plane. Each point represents a radius for a specific position on the periphery of the hole.

5.2 CT investigation of drilled CFRP/Ti6Al4V stack

An analysis method was developed for the investigation of drilling a stack of CFRP/Ti6Al4V, utilising CT scanning, volumetric analysis and image processing. This case study is part of an investigation which identifies optimum drilling methods and settings that will benefit an industrial production line. The combination of different materials and the significant difference of their atomic mass and structure introduce issues to the CT examination and image processing analysis that are identified and overcome by the developed method.

The combination of materials with significantly different atomic mass and structure introduces beam hardening and noise due to scattered radiation when CT scanning. These systematic errors affect the image quality and consequently the image processing. The analysis method utilised in this case study is similar to the method discussed in the previous case study. However, in order to reduce the effects of the systematic errors, physical radiation filtering that reduces the range of the spectrum of the x-rays is utilised as well as beam and noise reduction algorithms and methods that clear the images while preserving the edges of the represented parts. This novel combination of these methods overcomes the introduced systematic errors and provides inspection and dimensional measurements.

The joining of two or more materials prior to machining is chosen to avoid assembly difficulties. Titanium is widely used in the aerospace industry, for example, aircraft turbine and compressor blades and discs. Combining CFRPs with metals such as titanium and its alloys introduces more machining challenges due to its higher specific properties, significant formation and tool wear. Concentrated heat at the cutting edges results by low thermal conductivity of the material. As a result, the machining of titanium typically incurs high machining cost with high tool wear, decreased tool life and burrs on both entrance and exit surfaces of the holes (Isbilir & Ghassemieh, 2013; Kim & Ramulu, 2004; Brinksmeier & Janssen, 2002; Zhang, 2008; Dornfeld, et al., 1999; Feldshtein, 2011).

The combined issues caused by drilling these materials require the identification of the optimum machining settings for the specific combination of materials. This inspection method has been developed for examining different materials with significantly different atomic mass and structure. The evaluation of the quality of the holes is based on the internal damage of the materials, the circularity and centre deviation of the entire hole. CT scanning depends on a series of variables that are selected based on the scanned material, the capabilities of the CT system and the required resolution. In order to achieve optimum dimensional results, VDI/VDE 2630 Part 1.2 guidelines have been followed (VDI/VDE, 2010).

5.2.1 Method

Initially the stacks of CFRP/Ti6Al4V were CT scanned prior to the drilling, so as to ensure the quality of the joining with Hysol 9492. Then the part was scanned after the drilling to investigate the quality of the holes. Each hole was measured with optical CMM for voxel rescaling. Prior to the reconstruction of the 2D images, a beam hardening reduction algorithm with offset was used to minimise the effect of the error in the model (Kachelrieb, 2006). After the reconstruction of the images to a 3D model, each hole was aligned to the entrance surface. The DICOM images were exported in MATLAB. The Otsu method (Otsu, 1979) was used to identify the required threshold to convert the grey images to binary and the Hough transform was used to identify the lines of the markings and calculate the intended centre (Silva, et al., 2014). The Wiener filter was used to reduce the noise introduced and the Canny method was used to identify the edges that form the circle. A circular Hough transform was used to identify the circles and calculate the actual radius. Next, the code runs continually and calculates the maximum and minimum radius, maximum and minimum diameter, circularity, perimeter and positioning of the circle shown in every slide.

5.2.2 The quality of the results

Initially the joining of the two materials was visually examined prior to the drilling, as shown in Figure 21. The join includes glass particles with 0.3mm diameter to ensure homogenous thickness. The results show significant porosity in the join and the glass particles are easily identifiable from their higher density in comparison to the surrounding material.

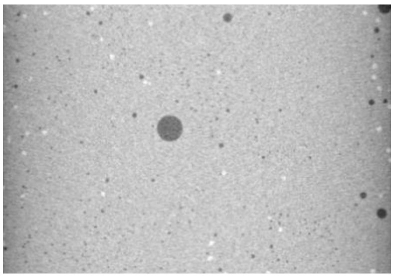

Figure 21: Visual examination of the join show extreme porosity.

The image analysis provided data on the maximum diameter and radius, the circularity, perimeter and positioning, that were used to compare two different drilling methods and the effect of the tool wear. The results demonstrate CFRP delamination, inclusions and small defects as well as the quality of the join that suffers significantly from porosity and the burrs created at the exit surface of the hole. The strength of the join cannot be known non-destructively but the porosity indicates its limitations and this method allows its examination which no other NDT can.

An example of the results is provided in Figure 22 demonstrating the results that indicate the similarities and differences between the two techniques. The first section of the hole that is drilled in the CFRP has more fluctuations in all measurements while the titanium section of the hole has nearly constant results in all measurements. The joining section exceeds tolerances due to the low strength of the joining material which was greatly affected by the machining process.

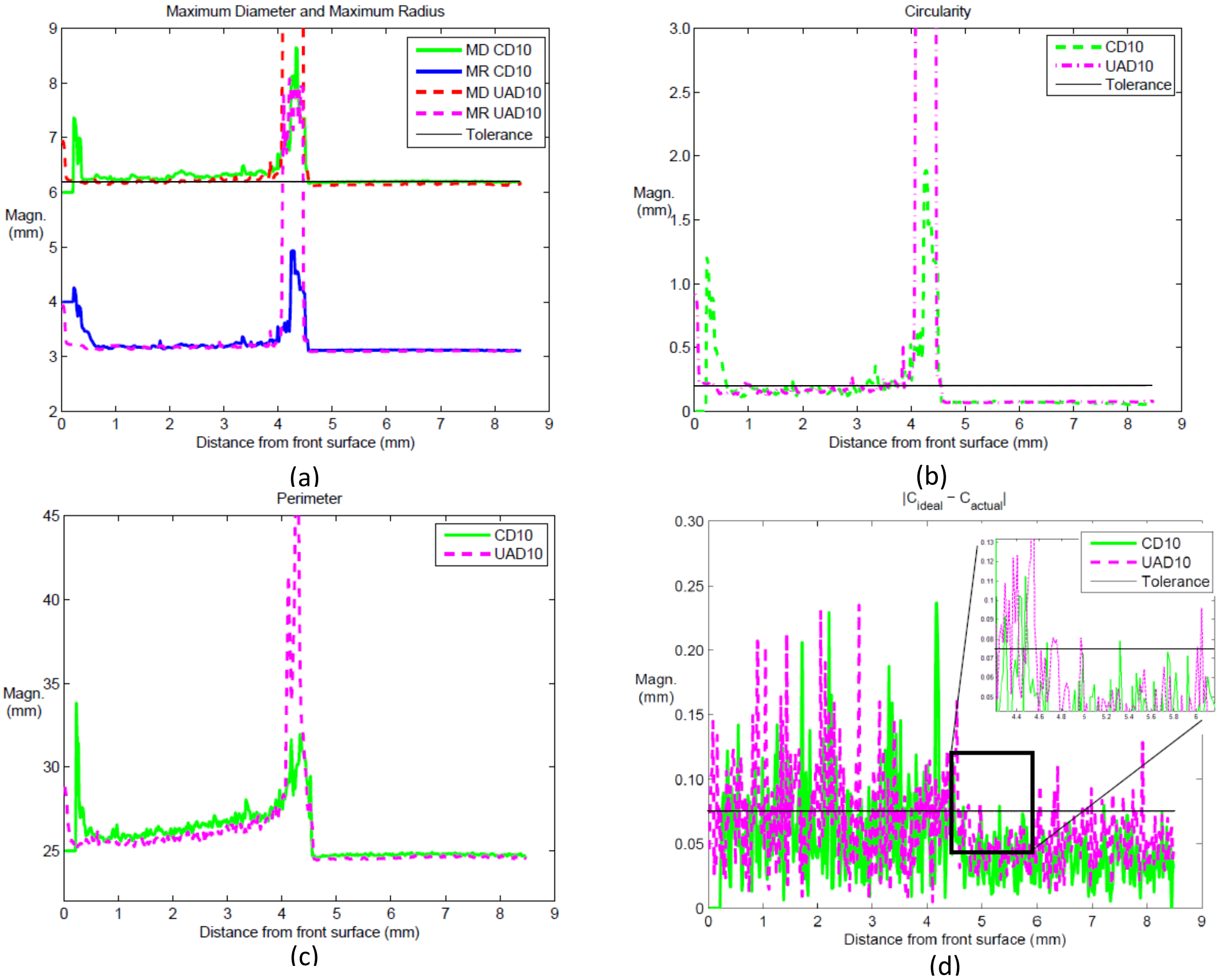

Figure 22: Example of the results of maximum diameter and radius per slide, circularity, perimeter and positioning.

The reduction of the beam hardening and noise created by scattered radiation is successful and these results demonstrate the capabilities of this method which has been created to provide inspection and dimensional measurements of joined materials with significantly different atomic number and structure. The results provide quality inspection of the holes and indicate the effect of tool wear that can be examined further with further studies. The information provided with this CT investigation would be unreachable with other NDT and destructive methods.

5.3 Milling of CFRPs and their CT investigations

The third investigation of the application of CT in R&D examines the quality inspection and dimensional analysis of milled CFRPs to assist in the development of the machining procedures of this composite and specifically the cooling method. This new method of studying and analysing milling CFRPs also combines CT, volumetric analysis and image processing. The two techniques can provide precise information of surface roughness and internal defects that are inaccessible by other non-destructive methods and destructive methods which destroy sections of the part that can also provide valuable data. The provided data from the combined methods demonstrate the surface roughness and identify the size and location of internal defects.

The most important factor for the cutting tool selection of milling CFRPs is the material selection of the tool, due to the characteristics of the fibres. The tool wear during machining CFRPs is due to the hardness of the carbon fibres (Teti, 2002). The selection of the cutting tool, includes its design (Figure 23) and material; it depends on the required milling process while in most cases high cutting speed with low to moderate feed rate per tooth is preferable for surface roughness. The fibre type and the fibre orientation of the part influence the machining results as well as the type of the polymer matrix, whether it is thermoset or thermoplastic material (Davim & Reiss, 2005; Pecat, et al., 2012; Wang, et al., 1995).

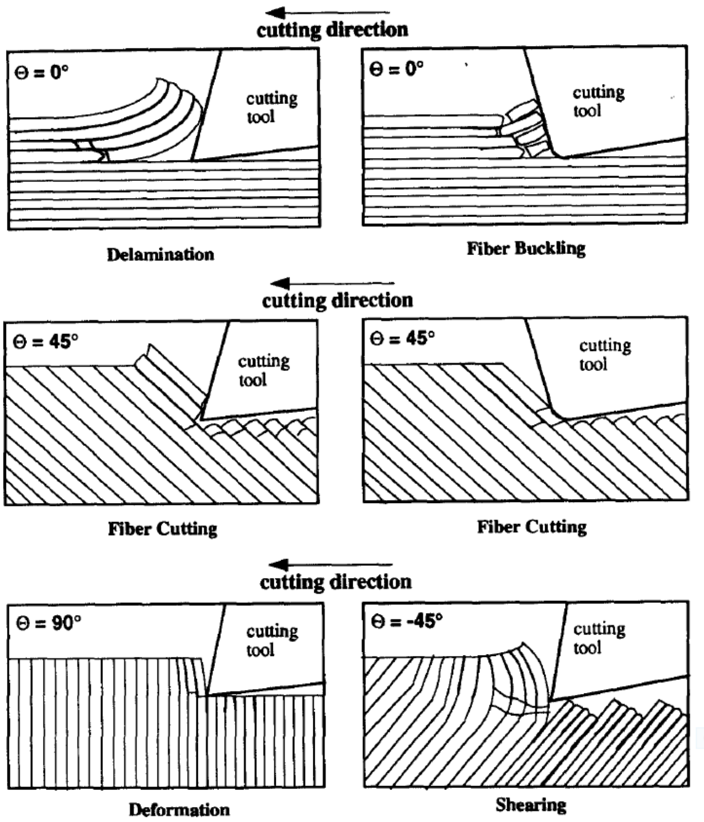

Figure 23: Cutting mechanisms in the orthogonal machining (Wang, et al., 1995)

All of the parts were CT scanned and one of their features was measured with optical CMM that was used for voxel rescaling. The acquired CT data was reconstructed with FBP, reviewed in inspection software and lastly analysed with image processing. Otsu method was used for threshold selection that transformed the images to binary. The edges of the part were identified, all the points of the edges are measured and the surface roughness was calculated. The inner delamination was examined by a different set of images and the code calculated the clusters of black pixels.

The fibre orientation of the milling surface was examined with volumetric analysis as shown in Figure 24, with the different angles highlighted with different colours. This analysis can examine the inner structure of the material and identify the orientation of the fibres. Figure 25 demonstrates the minimum values that provide the surface roughness for the entire surface. Figures 24 and 25 show a holistic representation of all of the analysed data with Figure 24 showing the side surface and Figure 25 showing the top surface. These figures illustrate the changes of depth in different colours for each surface.

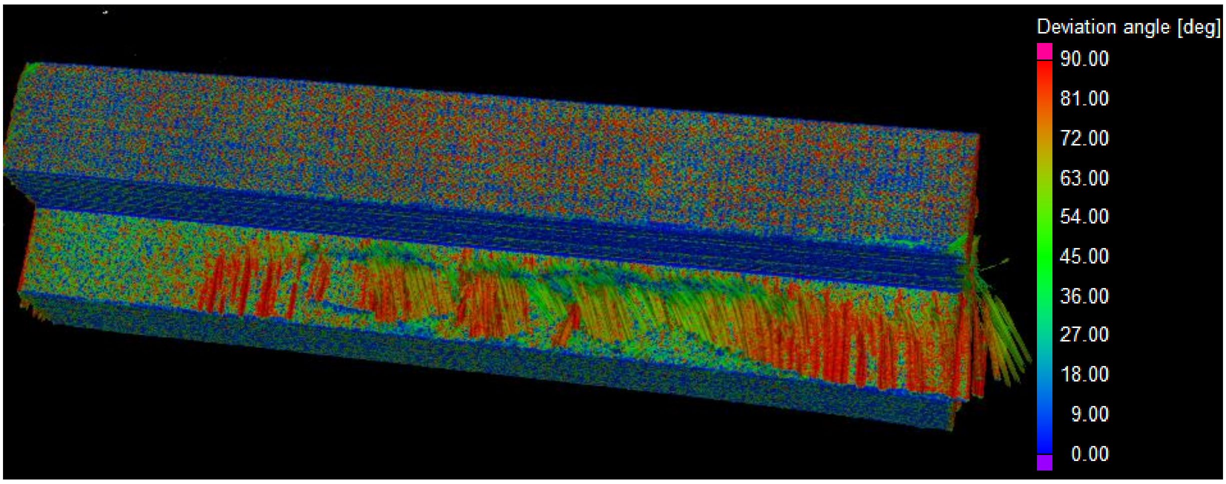

Figure 24: The orientation of the fibres are highlighted with different colours

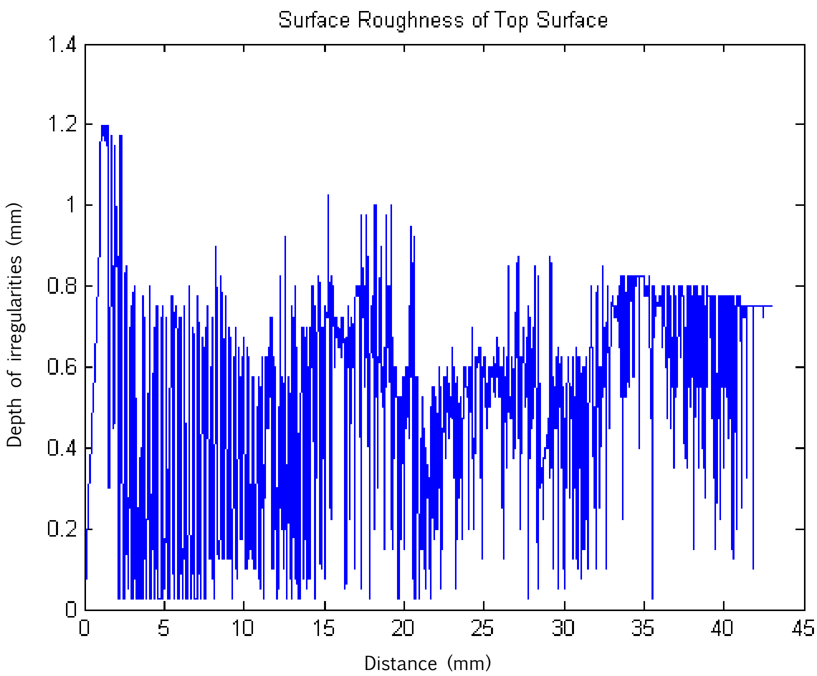

Figure 25: Maximum surface roughness of top surface. X-axis demonstrates the distance from the left side of the sample as demonstrated in Figure 22.

This analysis method provides volumetric results as qualitative images and quantitative measurements of the surface roughness without destroying the part. The surface roughness provided by this method includes the results of the entire surface that improves the understanding of the quality of the surface.

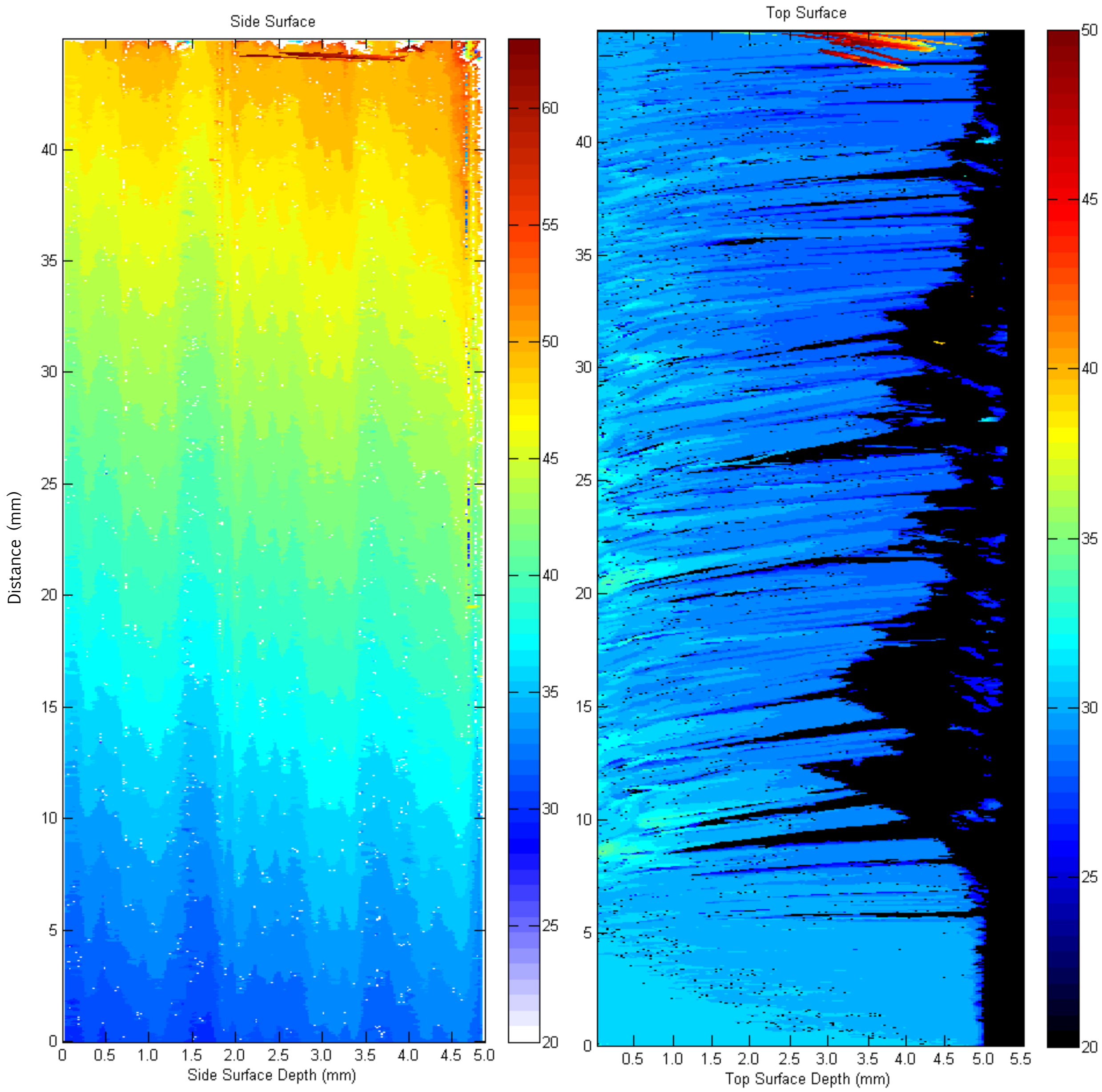

Figure 26: Side surface irregularities (left) and top surface irregularities (right). The surface measurements demonstrated in different colours are in mm and they are presented as in the colourmaps.

5.4 Summary

This chapter considers the application of CT in R&D by examining new machining techniques and settings for CFRPs. It covers three submissions and it examines the drilling and milling of CFRP and a combination of CFRP and titanium alloy join. These investigations demonstrate the utilisation of CT in R&D and the case studies are used as examples of potential future applications. The presented applications of CT utilise innovative examination methods that combine CT scanning and image processing. The investigation of the joined materials utilise a similar image processing method and specific CT settings, filtration and algorithms to minimise the effect of systematic errors, such as beam hardening without affecting resolution. The two of the three submissions were published in the International Journal of Advanced Manufacturing Technologies that demonstrates the impact of these methods to the industry. The results of the investigations also demonstrate the application of CT in this field of NPD.

6. CT investigations in aerospace manufacturing

The selection of manufacturing processes initiates in the design process with the chosen materials, sizes, shapes, finishes and tolerances influencing the selection. It is essential to select the most competitive combination during the designing process while designers should also consider the effect of their design to the manufacturing processes selection, while attempting to minimise costs and prevent production issues during this stage. The selection of competitive design considering Design for Manufacture (DFM) and Design for Assembly (DFA) can significantly reduce the costs in product development that are between 60% and 85% in later manufacturing stages to 5% and 7% in the early stages (Swift & Booker, 2013). The maximum simplification of the product structure is required in order to achieve the best manufacturing processes selection for a product, by eliminating or integrating parts with mating parts and considering material process combinations and joining technologies. Manufacturing processes are separated to casting/moulding, material removal and forming while joining processes are separated into welding, soldering and brazing, mechanical fastening and adhesive bonding. The selection of the manufacturing and joining processes is determined by the material selection, design requirements, economic considerations and quality requirements (Swift & Booker, 2013).

6.1 Welding joins and their NDT investigation

This case study takes into consideration the manufacturing processes and specifically due to minor difficulties developed in one of the welding production lines, the inspection of welds. Welding principles emerged at the end of the 19th century when the combination and storage of gases became available (Weman, 2012). The weldability of any metal is related to its microstructure and it is defined by the American Welding Society as *'the capacity of a material to be welded under fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactory in the intended service'*. Consequently, weldability covers the subjects of design, fabrication, fitness for service and even repair while describing the ability of fabricating a component by welding and for the component to perform as intended in its service environment (Lippold, 2015).

Welds have distinct microstructural regions that alter the properties of the materials. Each weld can be separated in the fusion zone and the heat affected zone (HAZ). The fusion can be subdivided to the composite region and the unmixed zone (UMZ) while the HAZ can be separated to partially melted zone (PMZ) and the true heat affected zone (T-HAZ). The metals' fabrication relates to the ability of the metal and the procedure to produce defect-free welds. Defects can be separated to those occurring due to the welding process and procedures and those associated with the material (Moore & Booth, 2015; Lippold, 2015).

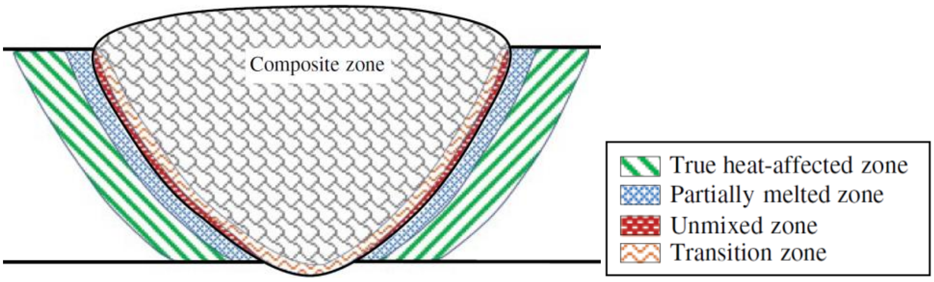

Figure 27: Schematic showing regions of a Fusion Weld (Lippold, 2015)

Welds are also related to several service related defects that may occur due to environmental or mechanical conditions. Service failures such as corrosion, fatigue, creep or complex combinations of all of these may also occur in defect free fabrications and can be unexpected and catastrophic. Methodologies preventing cracking and service failures can be developed after understanding the nature of the failure (Moore & Booth, 2015; Lippold, 2015). After the welding processes non-destructive tests (NDT) are often applied to identify defects without destroying the weld (Singh, 2012).

The most common defects in weldments are: HAZ cracking with thin, deep and open to the surface cracks; surface shrink cracks that are open to the surface and grow through the fusion and base metal; inclusions that can either be open to the surface or subsurface; lack of penetration that run from the root of the weld parallel to it and gas porosity that can be open to the surface or subsurface, clustered or scattered. Further defects related to manufacturing and service processes are burst, cold shuts, hot tears, micro shrinkage, unfused porosity, fillet cracks, grinding cracks, thread cracks, tubing cracks, hydrogen flake, lamination such as forgings, extrusions and rolled material, laps and seams and hydrogen embrittlement. Defects related to corrosion are intergranular corrosion and stress corrosion cracks (Singh, 2012).

The most common NDT methods to examine welds are visual inspection, radiography, magnetic particle testing, penetrant testing, ultrasonic testing, eddy current testing, leak testing and proof testing (Singh, 2012). The identification of the optimum selection of an NDT or a group of NDT methods is challenging due to the numerous different kinds of defects related to welds and the quality requirements of identifying and categorising them.

In this case study, conventional and digital radiography have been used to examine a series of welded pipes that are usually utilised as test specimens with numerous defects such as porosity and cracks, in comparison to CT that identifies all the defects. The objective of this case study is to demonstrate the suitability of digital radiography and CT in weld inspections demonstrating the identified defects and measuring the volume fraction of the porosity.

6.2 Conventional, digital radiography and CT of welds

The comparison between conventional and digital radiography demonstrated the superiority of conventional radiography in spatial resolution and contrast while digital radiography provided similar results. However, digital radiographs are faster, easier to be obtained and economical without utilising hazardous materials. The setup time and execution of conventional and digital radiography is the same while digital radiographs can be examined instantly on computer monitors.

The CT examination of welds may be considered as unrealistic in production due to the overwhelming number of weld examinations that are often required in a small amount of time and the time required for a CT scan. However, the examination of few welded parts that cannot be categorised with other NDT methods can be cost effective and avoid unnecessary scrapped parts due to lack of characterisation. The data analysis is volumetric and considers a specific number of voxels that can be selected either manually or automatically by selecting a grey value threshold to identify the pores or cracks. The selected defects can then be analysed to provide statistical data of the defects in the weld based on their volume. The results can be presented in a 3D volume for visualisation purposes.

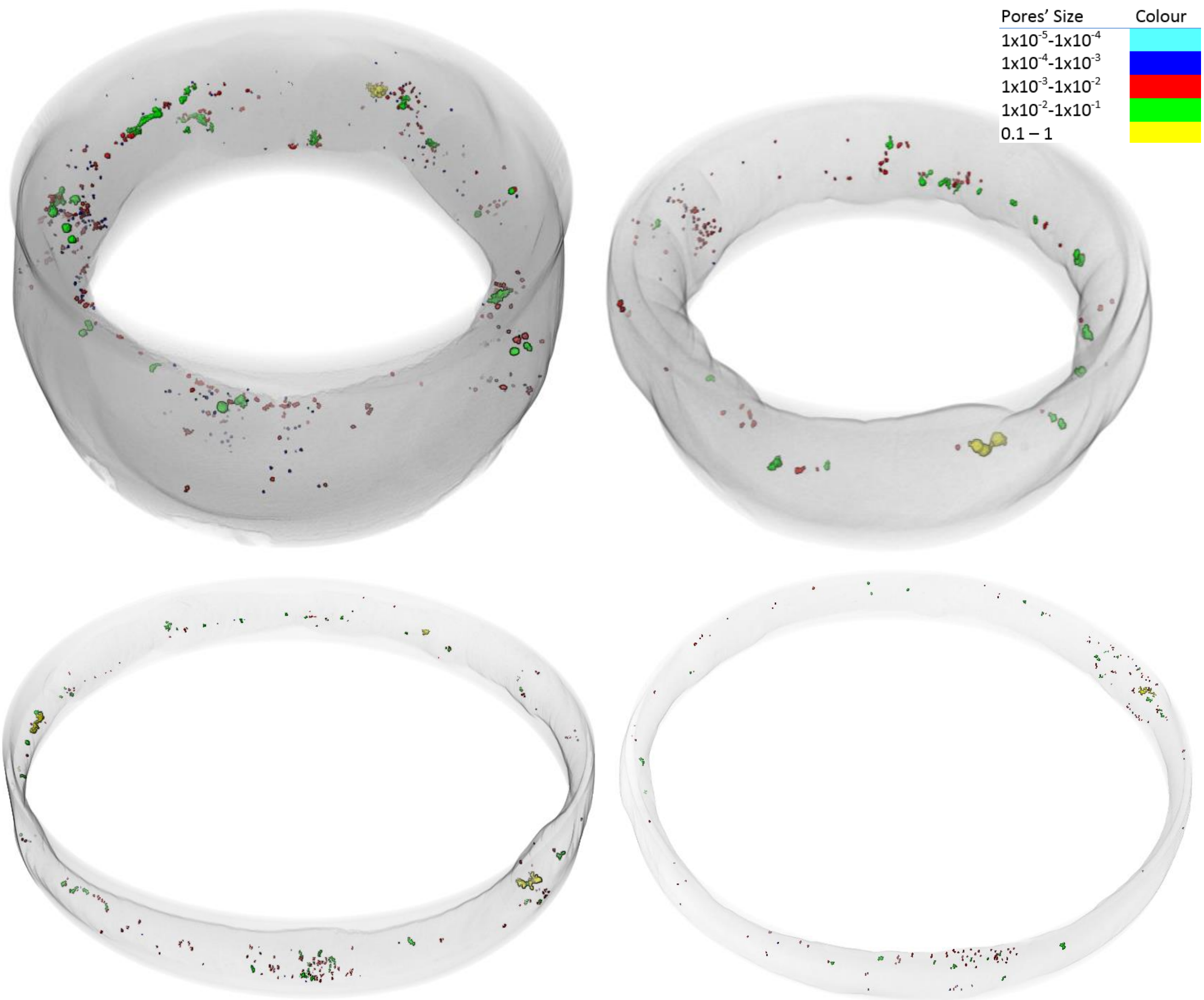

Figure 28: Examples of CT welds examinations demonstrating the different size of the defects in different colours

Figure 28 demonstrates an example of the CT results with porosity identified in different colours where each pore is categorised according to its volume and different colours demonstrate different sizes. The colouring of the different sizes is in a logarithmic scale. The results show the positioning of the pores as well as their size and morphology. Volume fractions can also be provided to demonstrate the strength of the weld. Conventional radiography identifies the positioning of the pores but it is unable to provide information of its size and morphology.

6.3 Defects that can be identified with CT investigations

The most common defect in welds is porosity but it is not the only reason of welds failures, with other important defects including delamination of the parts and weakness of the fusion area. Figure 29 demonstrates a case of delamination of the two parts with the two welded sheets separate. Figure 30 demonstrates weakness of the fusion around the porosity. This can be observed in CT scans in the changes of the grey values that demonstrate different atomic numbers. The changes highlight that the material around this porosity area has lower atomic number that indicates a weaken weld. These defects cannot be presented as easily as porosity in 3D while CT can identify them and present them in 2D images.

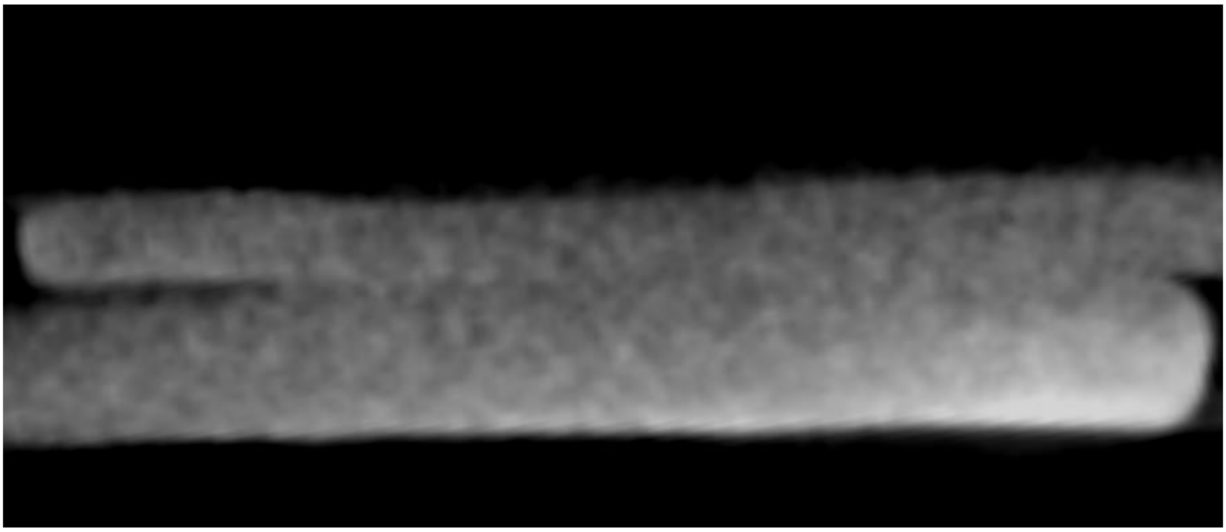

Figure 29: Delamination in a weld

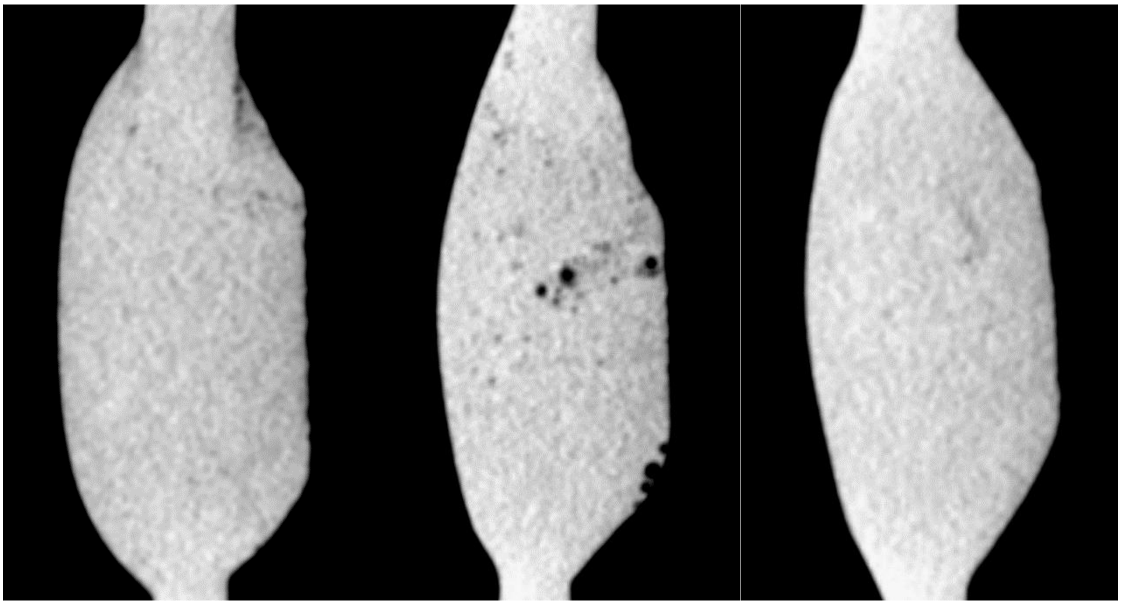

Figure 30: Weak fusion area

Figure 31: Examples of CT welds examination

CT provides significantly more information about the defects that allow the categorisation of the failures than conventional radiography, but it is time consuming and consequently CT examinations of metallic parts are avoided in production. However, it can be used in the development of new welding processes in order to ensure the quality of the welds and to provide data for training processes. CT may be used in production when other non-destructive techniques fail to characterise the defects and categorise the quality levels of the weldment. Currently, difficult to categorise weldments are either re-welded or scrapped. The application of CT can become time and cost effective by reducing the re-machined and scrapped parts and by providing volume fractions and better understanding of the defects.

6.4 Summary

This chapter examines the application of CT in production by demonstrating the results of one of the case studies which examines welds and compares the results of conventional and digital radiography with CT. The results provided by CT require longer examination and analysis times than any of the two types of radiography. An examination and the required analysis may take up to a day, although the results provide a better understanding of the position of the defects and the volume fraction of the defects that can determine the viability of a weld. CT scanning can be utilised when other NDTs fail to categorise joints and reduce re-machining time and scrapped parts. This case study demonstrates that CT is applicable in production as a system that provides unreachable for other NDTs information.

7. Metrological applications of CT in aerospace industry

All of the CT investigations in aerospace industry in this project are interlinked with metrology since all quality inspections need to demonstrate that any defects within a component have specific size/volume limits. In the previous chapters, the application of CT both in R&D and in production has been demonstrated. The results of these investigations have provided metrological measurements to categorise the defects. Currently, there are no official standards that provide guidelines to attain dimensional measurements with CT. The investigations of CFRPs discussed previously have demonstrated the comparison between CT and nominal measurements which leads to the conversion of the CT 3D models, according to traceable measurement procedures such as CMM (tactile and visual) as suggested in VDI/VDE 2630 guidelines

VDI/VDE 2630 Part 1.2 – Computed Tomography in dimensional metrology, Measurement procedure and comparability was published in June 2010 as a guide to obtain dimensional measurements with CT. These guidelines describe and discuss different measuring procedures and provide their advantages and limitations, as well as a comparison in order to assist CT users in choosing the right method for each application. The discussion about tactile procedures provides information about switching tactile sensors and measuring tactile sensors while the section about optical measuring procedures includes information about the scanning spot, image processing sensor, distance sensors, autofocus and laser spot sensors. Furthermore, it discusses the expected procedure followed in tomographic measuring procedures, so that it is possible for the results to be used in dimensional metrology. Part 1.2 also provides a comparison of these methods, by giving information about principal applications, as well as the uncertainty of measurements, technical and procedural details that include information about the typical measuring times of these methods. CT's common artefacts are also discussed as well as their effect on the measurements. VDI/VDE 2630 will expand to include guides and standards on the uncertainty of measurement, process qualification, calibration, contract and software systems used in computed tomography's metrological applications (VDI/VDE, 2010).

Numerous research projects examine x-ray CT applications in order to identify its limitations and develop methods to overcome them. For example, Lifton, et al. (2013), demonstrated that the voxel rescaling, suggested in VDI/VDE 2630 Part 1.2, reduces the dimensional measurement error from 1% to 0.2% voxel size (Lifton, et al., 2013). A new standard on CT, ISO 10360-11, is being researched so as to provide further guidelines and procedures that will provide accurate CT measurements. Different calibrated specimens are considered for this standard to accurately measure length errors (Borges De Oliveira, et al., 2015) so as to be able to compensate. More guidelines and standards are expected in the following years.

According to the guidelines each CT application can provide dimensional measurements when the metrological procedures are followed. In this project, the R&D applications provided dimensional measurements while the production application of welding investigations can provide measurements of the volume of the pores. This chapter examines the metrological applications of CT in the manufacturing phases. The majority of the materials of the received parts from the industrial partners were composites (CFRPs) and metal (titanium and aluminium alloys). The CT examination of metallic parts creates beam hardening and noise from scattered radiation that affect any metrological applications. This chapter demonstrates the reduction of beam hardening and scattered radiation by utilising an innovative combination of physical filtration.

7.1 Scattering in CT

X-rays transfer energy through photons without transferring matter from one point to another and they can interact with matter in three fundamental ways, the photoelectric effect, the Compton effect and coherent scattering (Hsieh, 2009; Als-Nielsen & McMorrow, 2011). The Compton effect describes incoherent x-ray scattering which is caused by x-ray photons that strike and remove electrons from the orbit of the atom. The x-ray photon gets deflected or scattered with partial loss of its energy and results in the production of a positive ion, a recoil electron and a scattered photon. The scattered photon maintains sufficient energy and may be deflected at any angle between 0° to 180° but it generally deviates slightly from the original path of the photon due to momentum. The result of the scattered radiation is random and its intensity distribution is low background signal that reduces the contrast and signal to noise ratio (Hsieh, 2009; Kalender, 2011).

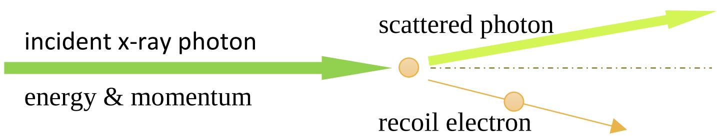

Figure 32: Illustration of Incoherent Scattering based on A Hsieh (2009) diagram

Scattered radiation causes streaks, inhomogeneities, cupping artefacts and loss of contrast in CT and influences negatively dimensional measurements due to blurred edges and shadowing which reduce the effectiveness of the threshold selection. These issues can also lead to incorrect readings and to obscure cracks and voids (Schorner, et al., 2011).

7.2 Filtration of X-rays

The x-ray emission spectrum, an example of which is demonstrated in Figure 33, includes rays with a range of energies with many low energy x-rays, which are easily absorbed by matter and cause CT artefacts such as beam hardening and noise. Pre-filtration of x-rays is a common remedy aiming to reduce the radiation dose and improve the x-ray beam quality. Traditional filtration is placed before the scanned object and reduces beam hardening artefacts and noise (Hsieh, 2009). Post – filtration can also be used after the scanned object to remove low energy scattered radiation before reaching the detector.

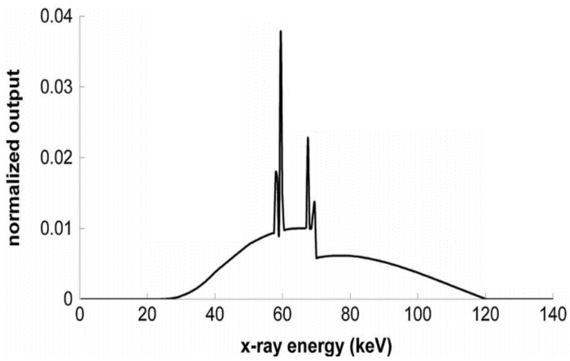

Figure 33: X-ray emission Spectrum (Hsieh, 2009)

7.3 Method and findings

The examination of the effect of different combinations of filtrations on the scattered radiation and beam hardening was achieved by placing lines in each volume and inspecting the grey values of the material or background at the position of each point on the line. Three different lines were examined from different angles; line (a) passes diagonally through the sample and through five holes, line (b) passes horizontally from the middle of the specimen and through five holes and line (c) passes horizontally at lower set of holes through three holes, as shown in Figure 34. The grey values of each point of the lines are demonstrated in the graphs that show their variations through material and background; material is represented by higher grey values while background has lower values. The ideal values of background are close to zero with minimum variations while the opposite conditions demonstrate scattered radiation. The influence of scattered radiation on CT measurements was examined by investigating threshold dependent and independent measurements for the different combinations of filtering.

The results of the investigation of the effect of different combinations of physical filtration on scatter radiation are shown in Figure 34 and demonstrate in all three lines beam hardening and scattering when no filter is used, with greater grey values in the edges of the part showing beam hardening and greater variations of grey values in the rest of the line. Pre-filtration of the radiation improves both issues. The combination of pre and post filtration eliminates beam hardening and reduces scattered radiation with different combinations achieving different grey values and variances between material and background. The results indicate that beam hardening can be eliminated with the right amount of post-filtering without any pre-filtering. However, the best results of reducing scattering can be achieved by combining pre and post filtering.

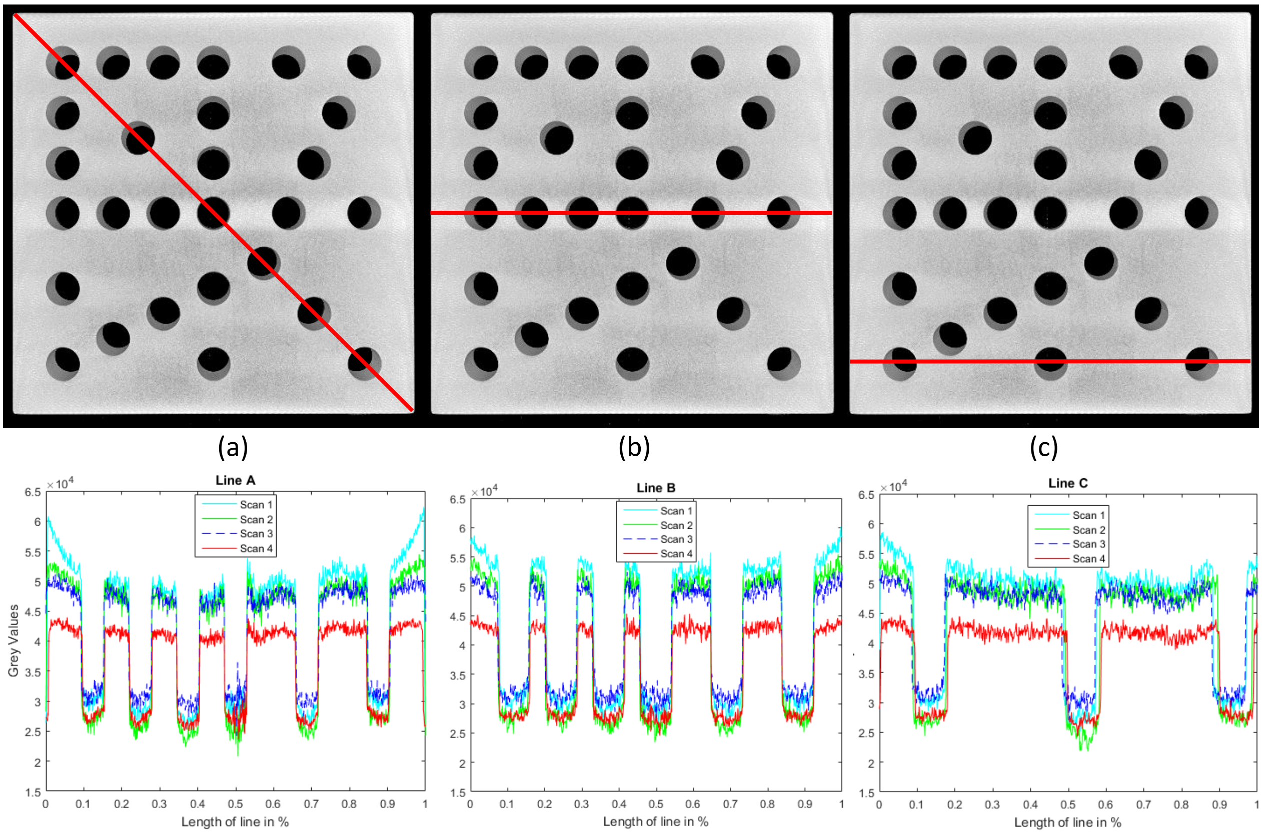

Figure 34: Example of the achieved results

The fluctuations of the grey values of the matter in Figure 34 indicate beam hardening. In order to confirm the reduction of beam hardening when using different filtrations, the grey values range was calculated for background and matter, the results being provided in Table 3. The results demonstrate that the thickest pre filtration reduces the range as well as all of the combinations of pre and post filtrations except when minimum pre and post filtrations were used. The fluctuations of the grey values of the background indicate noise and scatter radiation and the results of this examination indicate a significant reduction of the grey values range when filtration is utilised.

Scan	**Gr. Values Range**	
	Background	Material
R0S0	21982	13531
R1S0	15709	16366
R2S0	11273	13092
R3S0	8844	9770
R1S1	11424	11280
R1S4	9485	9817
R2S1	9552	9552
R2S3	8489	6237
R3S1	8961	8909
R3S2	9662	8311
R0S4	8510	7125

Table 3: Calculated range of grey values in background and matter

The distribution of backgrounds were examined and demonstrate skewed and long distributions with high variations of grey values of background which indicate noise and scatter radiation when no or little filtration is used. The use of thicker pre filtration leads to smaller skewed distributions which indicate the reduction of noise and scatter radiation. The combined distributions of backgrounds and materials indicate best results achieved when both pre and post filtration is used.

Dimensional measurements of threshold dependent and independent distances were evaluated by using inspection software and by using least squared method and three diameters were used to identify and demonstrate the influence of filtration to the measurements error calculated by the optical CMM measurements. The cylinders were also used to measure three centre-to-centre distances and the results of the measurement error are presented in Figure 35. Physical filtration of radiation reduces the measurement error significantly for threshold dependent distances such as diameters with the best results achieved with combinations of pre and post filtration. The results of threshold independent measurements demonstrate a greater measurement error for scans with no filtration and radiation pre-filtration only while the measurement error is reduced by utilising a combination of pre and post filtration or post-filtration of radiation.

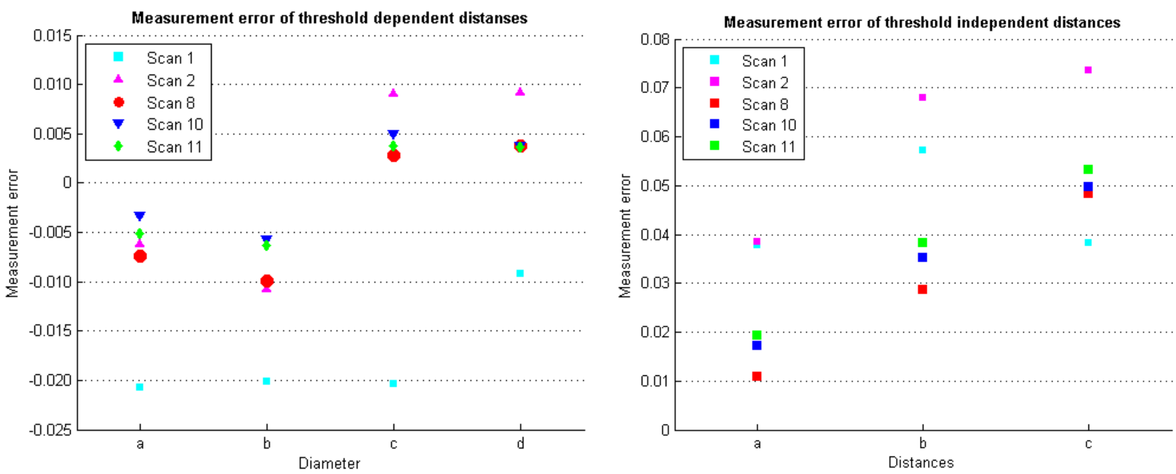

Figure 35: Threshold dependent and independent measurements indicating improvements achieved when utilising radiation filtrations.

The limitations of CT influence the measurement uncertainty that is required to be identified in every measurement. The factors that influence the uncertainty of the measurements include the nature of polychromatic x-rays and x-ray spot size, the geometric alignment of the CT system, the reconstruction algorithms used to create the volume and environmental influences such as temperature. Scatter radiation increases noise in the scan and as a result the threshold selection that separates the material from the background and consequently affects the dimensional measurements.

The results of this study demonstrate that the combination of pre and post filtration of radiation provide fewer variations between grey values of the same matter, indicating reduction of scattering and beam hardening. The range of grey values within material is dramatically reduced with the utilisation of filtration that demonstrates significant reduction of beam hardening. The distributions of grey values of background and material are also reduced with filtration which demonstrates the reduction of noise. The combination of pre and post filtrations also reduces the difference of grey values between matter and background and as a result the contrast is affected and similar grey values are difficult to be manually distinct and analysed. However, automatic selection of threshold of grey values uses the mean of grey values distribution to separate background and material and it is not affected by the individual grey values. The reduction of variation of grey values and automatic selection of threshold can provide the required results and reduction of measurement uncertainty in single material scans but manual selection of grey values would be required in multi-material scans. A precise threshold selection of grey values leads to accurate results for both threshold dependent and independent measurements.

The measurement error of threshold dependent measurements is dramatically improved with any filtration because of the reduction of beam hardening while the best results are achieved with a combination of pre and post filtration of radiation. The results of measurement error of threshold independent measurements demonstrate similar results with the threshold dependent measurements with best results achieved with a combination of pre and post filtration and similar results achieved with post filtration of radiation. Finally, the results demonstrate the potential improvement of scatter reduction with the combination of pre and post filtration of radiation, although further examinations and observations are required in order to achieve the optimum selection of different filters for different materials and sizes of specimens.

Consequently, this case study suggests a novel method of filtration that can lead to improved measurements of metallic parts. The exact combination of filtration for each scan will require investigation and the operators need to have further training in order to identify the optimum selections. The results demonstrate that the combination of pre and post filtration reduces the measurement error that can lead to automatic metrological inspections in production lines.

7.4 Summary

This chapter examines the application of CT in metrological investigations in aerospace industry and demonstrates an innovative method of radiation filtration that reduces beam hardening and scattering. The results demonstrate the reduction of measurement error when applying this method and the improvement of CT measurements. This case study establishes the suitability of CT while it highlights the necessity of identifying optimum scanning settings. It also demonstrates the application of CT in the quality inspection phase of NPD of aerospace industry. This innovative method can lead to the continuous application of CT for investigations of materials with high atomic number and density such as titanium alloys. Metallic Additive Manufacturing (AM) components with inaccessible inner structures that require thorough examinations can be examined by utilising this method non-destructively cost effectively.

8. CT applications in failure investigations

According to Henry Petroski, a professional engineer specialised in failure analysis, the knowledge to go beyond the state-of-the-art is acquired by past mistakes, even though most engineers prefer to learn from success (Petroski, 1985). Professionals from different disciplines are inclined to emphasise successful projects and underestimate lessons learned from failures. Engineering failures can contribute to engineering knowledge used in design, construction, manufacturing, operating engineered facilities and products and assist in improving the designing practices and development of standards (Petroski, 1985; Petroski, 1994). In order to capture this knowledge, the professionals need to effectively communicate their failures or engineering accidents. This knowledge then can be used in the designing process with the lessons learned assisting in the reduction of uncertainties and leading to improvements when combined with mathematical theory to predict the behaviour of engineering systems. The designing process of mass produced products often includes a trial-and-error phase with destructive and non-destructive tests on components and assemblies (Carper, 2000).

According to the Technical Council on Forensic Engineering of the American Society of Civil Engineering, '*a failure is an unacceptable difference between expected and observed performance'*. In cases of failures the end result is often the only known and evidences need to be gathered to 'reverse engineer' the cause and occurrence of the failure (Carper, 2000; Noon, 2001). According to Randall K. Noon, '*forensic engineering is the application of engineering principles and methodologies to answer questions of fact. These questions of fact are usually associated with accidents, crimes, catastrophic events, degradation of property, and various types of failures'* (Noon, 2001).

The concepts of failure analysis and forensic engineering are closely linked since they both examine failures. The difference between the two is highlighted etymologically with the word 'forensics' that is based on the Latin 'forensic', meaning the forum and implies discussion or the administration of justice. Forensic engineering examinations do not necessarily lead to legal proceedings but they are generally used for studying problems which may be decided in a legal forum (Kardon, 2012). On the other hand, failure analysis investigates specific parts, components or assemblies in order to determine the reasons behind a failure. These investigations are private and they are concerned with the product's design when there is no fraud or criminal activity (Noon, 2001).

In an investigation, the forensic engineer or failure analyst examines the physical evidence, verifiable facts and utilises scientific principles, knowledge, skills and methodologies in order to interpret the facts and reasons of the failure. The thorough understanding of the failure and the magnitude and extent of the failure are required. This is achieved by assessing the failed product or area where the failure occurred and by understanding its condition prior to the event and then assessing its condition after the event in order to hypothesise the reasons that may have led to the failure. During the investigation, the information gathered influences the original hypothesis which is modified according to the evidence which is considered to ensure that the hypothesis answers the questions of how and why the failure occurred. The hypothesis can then be tested to ensure the sequence of events. Engineering knowledge and skill are required in this phase in order to answer these questions and provide a complete scenario of the sequence of events that have led to the failure (Petty, 2013; Noon, 2001).

According to the scientific method, evidences should be obtained by several observations and accumulation of facts that support one explanation, which establish a general rule or conclusion. The scientific method identifies the common evidences that demonstrate a principle or proposition by close observations and experimentation. The scientific method is easier when followed in laboratories where variables are controlled and changed so as to determine their effect. In the event of failures or accidents the variables cannot be controlled and therefore it is difficult to determine the variables at the moment of the failure. In the case of forensic examinations, it is infeasible to examine the effect of each variable separately and therefore it is generally accepted that all of the observation can lead only to the reconstruction of one hypothesis with consistent results. The conclusions should be based on scientific laws and knowledge (Noon, 2001).

The combination of facts, evidences, engineering knowledge and scientific principles can lead to the analysis that will provide conclusions explaining the failures. A failure or accident is not usually due to a single cause or event and therefore information about the different events and causes need to be gathered and included in the analysis. The conclusions should be based on all the facts and analysis and should not be affected by the different hypotheses considered during the collection of information related to the failure or accident. The investigation is only complete when a hypothesis accounts for all the verified observations and complies with scientific principles, knowledge and methodologies. In the case of inconclusive analysis results, additional information is required to either confirm or eliminate the different hypotheses and lead to a thorough explanation of the events (Noon, 2001).

This case study examines the application of CT in forensic examinations and failure analysis by utilising all available techniques to examine and provide answers of defective components and parts that were unable to be examined with other NDTs. Each investigation is considered individually while their combination demonstrates the application of CT in failure analysis. Due to the examination of the entire volume instead of portions of the problematic part, CT can identify defects that can lead to catastrophic failures.

8.1 Computed tomography and engineering forensic investigations

Each investigation is unique and requires different sets of knowledge, skills and methods to be followed. Destructive testing is often essential in order to demonstrate the causes and effects of the failure while non-destructive methods may not provide the required information. The objective of any failure analysis is to identify the reasons of the failure while the purpose of the analysis depends on the nature of the failure and the different required levels of analysis depend on the required procedures that need to be followed after the failure. In industry there are four different levels of failure investigations, condition report, failure analysis, root cause analysis and expert analysis (Jose, 2014).

Mechanical components are designed to be in operation for specific periods before they need to be maintained or replaced due to the growth of defects or materials' discontinuities. The service life of parts may be reduced by inadequate maintenance or operational misuse. Mechanical failure modes can be separated to instantaneous and time dependent failures. Instantaneous failures occur due to overloads causing ductile or brittle fractures which affect the microscopic structure of the material by creating either micro-voids or cleavages. Time dependent failures include fatigue, corrosion, creep and wear (Jose, 2014).

NDTs utilised in failure analysis include eddy current, magnetic particles, acoustic emission, ultrasonic, radiographic and liquid penetrant testing. Further destructive analysis may be required and it includes damage resistance tests such as Charpy impact tests and correlation with toughness, tensile testing, true strain-true stress curves, spectrometry analysis and hardness mapping, testing of fatigue life, global spark interferomentry chemical analysis and microprobe chemical analysis (Jose, 2014).

CT can provide good representation of voids/porosity, cracks and surface irregularities when capable scanners are utilised with optimum settings. The method of analysis depends on the requirements of the investigation. The different methods of analysis can be separated into two categories, image analysis and volumetric analysis. In image analysis, the 3D model is separated again into 2D images that demonstrate the volume in slices while the volumetric analysis separates the volumes in different 3D regions for visualisation and volumetric fractionation. The image analysis can be used for metrological applications since distances are better measured on a plane.

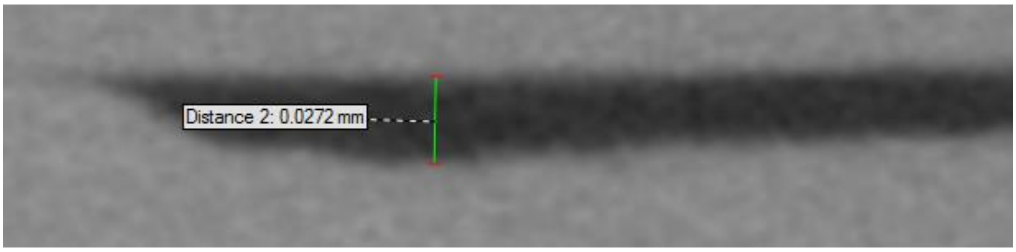

Figure 36: Example of a measurement for a failure analysis with uncertainty ±6.8µm at confidence level of 95%.

The method of image processing initiates with the alignment of the 3D model to a relevant 2D plane before exporting the 2D image stack. Then the images are analysed by identifying geometrical shapes such as lines or circles. Distances are measured in regards of pixels that are then transformed to metric measurements by using a known distance or the corresponding size of the pixels. This method can provide with automatic measurements of outer geometries and identify and measure defects.

In the volumetric analysis, the model is separated in regions according to the grey values of the pixels that demonstrate different materials and background/air and as a result achieving the demonstration of porosity and cracks, inner structures and joints non-destructively. The regions can then be used for identification of ratios such as porosity analysis or material ratios in composites. The different regions can also be illustrated in 3D to demonstrate structures. Volumetric analysis can also provide qualitative results such as videos or image stacks that demonstrate material differences and defects.

CT is the most precise non-destructive method that can demonstrate 3D representations of inner structures and materials' combinations that can result in characterisation of failures. The most common CT analysis method in failure investigations is volumetric analysis, which provides the investigations with 3D representations of inner structures that can be lost with destructive examination methods. These representations can demonstrate faults, material deficiencies and the manufacturing processes that produced the examined object such as welding methods and can assist in the creation of a strategy for destructive examinations.

8.2 Industrial applications

X-ray CT is not widely used in failure analysis and forensic examinations but its successful industrial applications provide the possibility of utilising it in failure investigations. This case study has examined a series of defaulted aerospace components from different companies and their supplier, so as to demonstrate the potential application of CT in failure analysis and engineering forensic examinations. The cases cover the examination of the different manufacturing processes, the exact position of defects and the CT assistance in the categorisation of the failures. This information is used to alter the designs, material selection and the preparation of destructive tests so as to avoid the destruction of defects. The results provided by CT scanning have been evaluated with destructive methods so as to ensure their credibility.

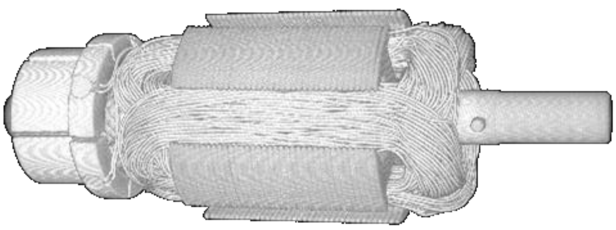

Figure 37: Component of a motor

Volumetric analysis was applied in all failure examinations while the method chosen and applied in each case was selected according to the examined parts and the requirements of the investigation. The CT settings for each part were different, according to the materials scanned, the size of the part and the chosen magnification during the scanning. In some cases the areas of interest have been analysed further by reducing or manually removing the noise and CT systematic errors, such as beam hardening.

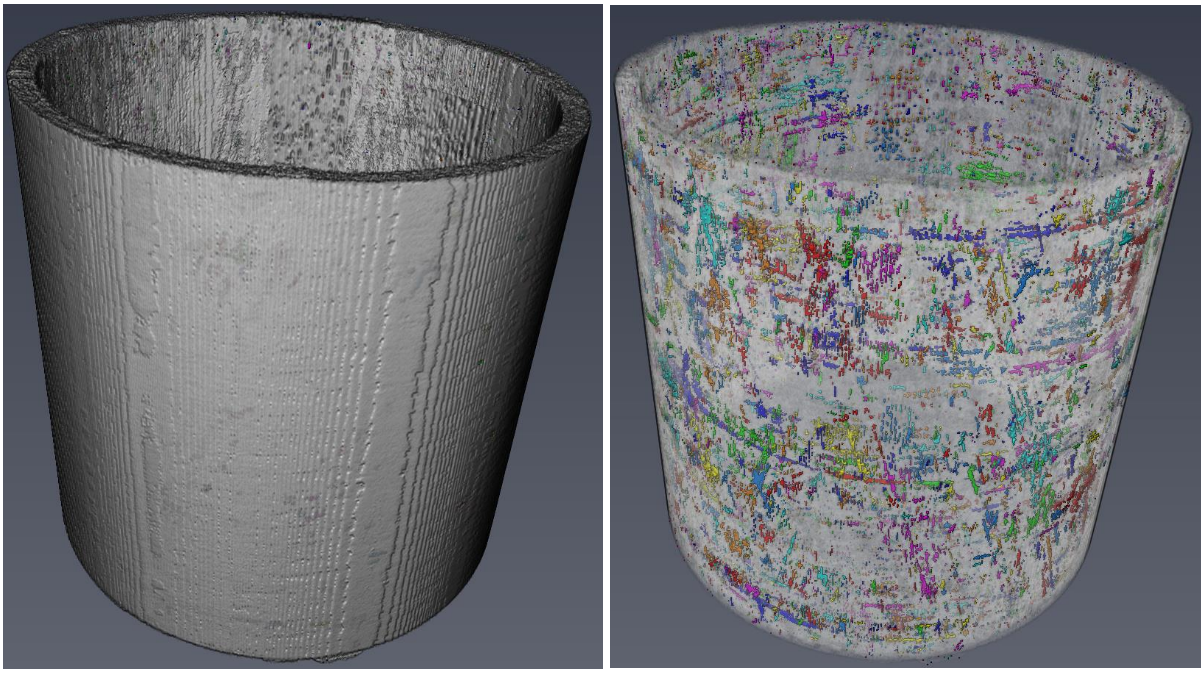

Figure 38: 3D Representation of CFRP and its porosity

This investigation has covered cases where the separation of the volume in sections according to the grey values of the voxels/material, demonstrates the area of interest, manufacturing processes and defects. Other examinations have demonstrated the identification of inner structure that assist in the preparation of destructive tests, such as tensile test, in order to identify material properties by providing the required cutting position. CT scanning has also been used to measure defects and alter the design and manufacturing procedures of parts.

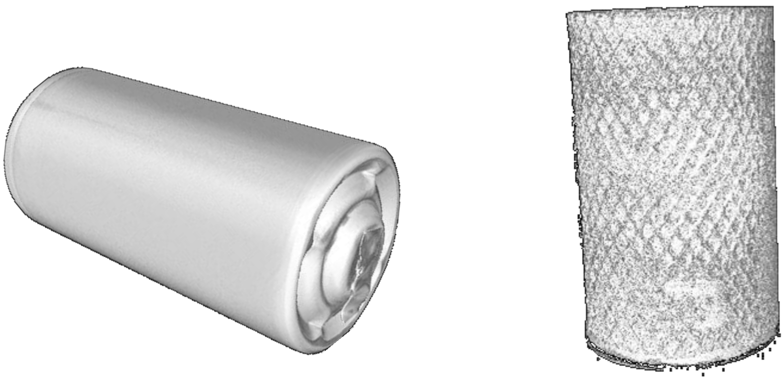

Figure 39: 3D representation of outer surface of a battery and its inner structure

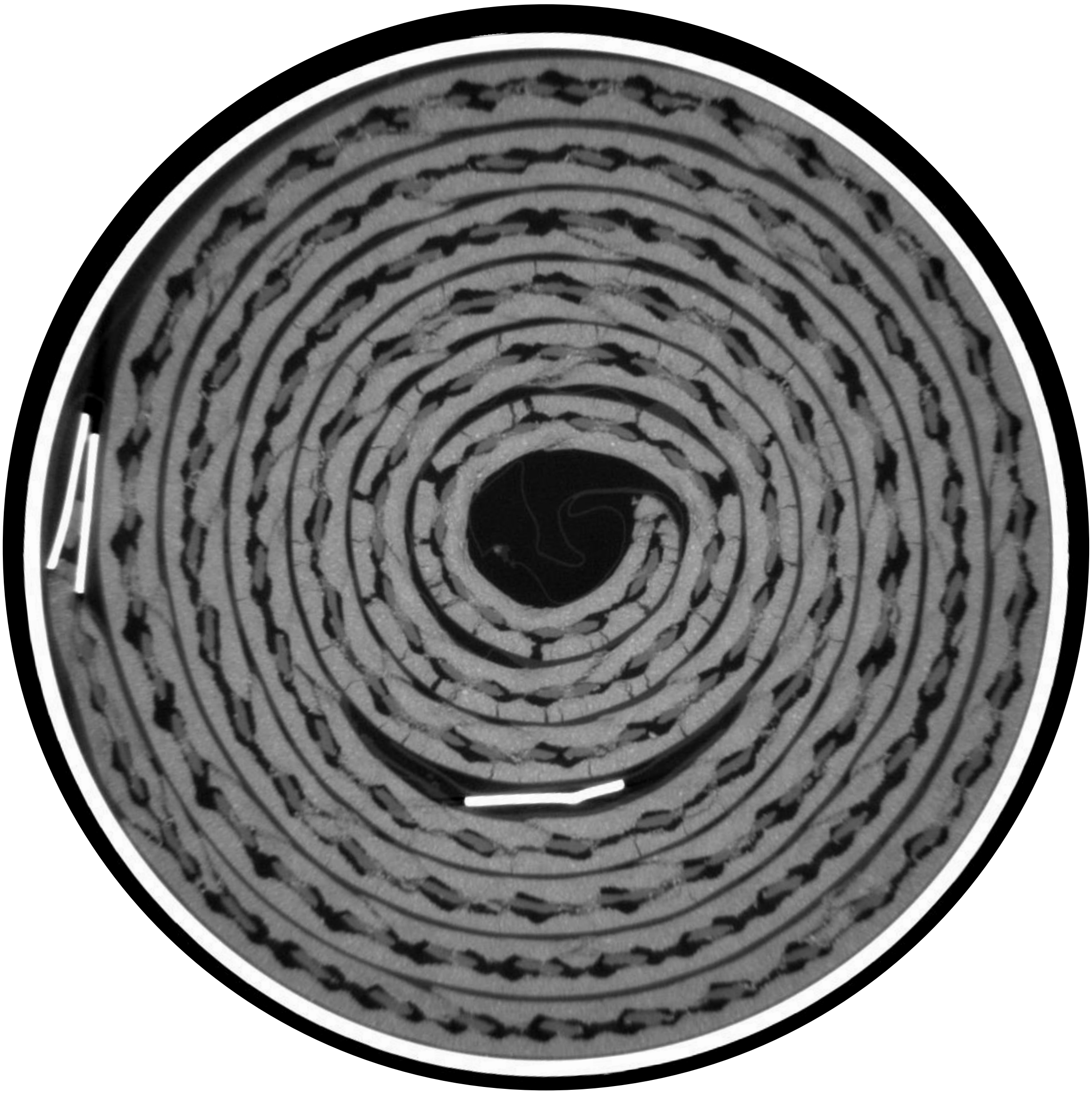

Figure 40: 2D representation of inner structure of the core of a battery

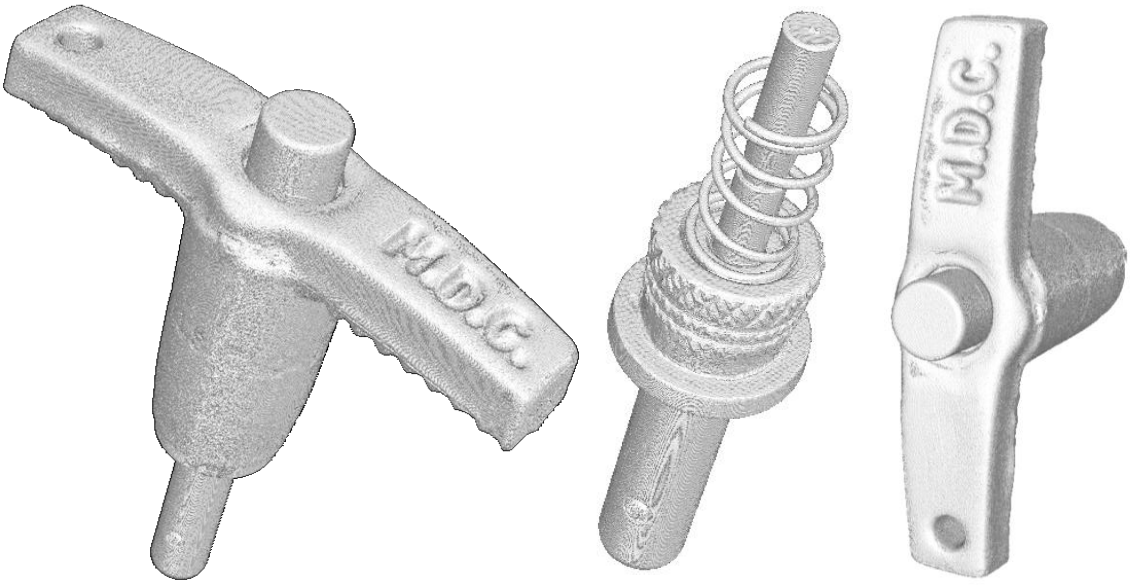

Figure 41: 3D representation of parts (the images are not scaled)

The results of all these investigations demonstrate the application of CT in forensic engineering and failure analysis as a non-destructive test. The information gathered from CT would be unobtainable with any other non-destructive method while destructive methods always endanger the destruction of defective areas. In order to achieve best possible results, each part has to be considered separately with the CT settings chosen according to the materials and the required resolution while the analysis method depends on the nature of the failure.

8.3 Summary

This chapter considers the application of CT for failure analysis and forensic engineering examinations. The examination of failures leads to better understanding of high quality requirements in the aerospace industry and prevention methods. The lessons learned from the failure investigations are fed back in the designing phase of NPD to avoid future failures. This application is required in the disposal and as part of the development phases of the NPD for improved concept creation. In this study, it was demonstrated that CT can provide volumetric information of defects that can assist in the investigation of circumstances identification. The improve designs assist in the growth of the company by ensuring the competence and competiveness of current and future products while minimising the costs of replacing parts, warranties and compensations. An investment in future products can ensure the future of the company.

9. Discussion

One of the famous quotes of Albert Einstein is "*imagination is more important than knowledge*" and imagination leads to innovation. There are numerous definitions of innovation from scholars, entrepreneurs and business leaders that comprise ideas, practices and experience to achieve a positive outcome. According to Levitt Theodore, 'Creativity is thinking up new things. Innovation is doing new things'. It could be concluded from the plethora of different definitions of innovation that the concept of innovation cannot be well defined and there are some researchers who request further classification (Massa & Testa, 2008). Indeed, it can be considered that the concept of innovation is elusive due to its nature. Most definitions describe it as a process of development and production of an invention or service that has commercial success (Garcia & Calantone, 2002). After all, according to Duncan, 'Innovation is the ability to convert ideas into invoices'. According to Dyer, et al. (2009), innovators have excellent skills in associating, questioning, observing, experimenting and networking that allows them to identify opportunities and create solutions (Dyer, et al., 2009). A summarised definition for the purposes of this discussion is: Innovation is the application of available knowledge, methods, technologies and products to create new goods, services or methods that add value and create profit.

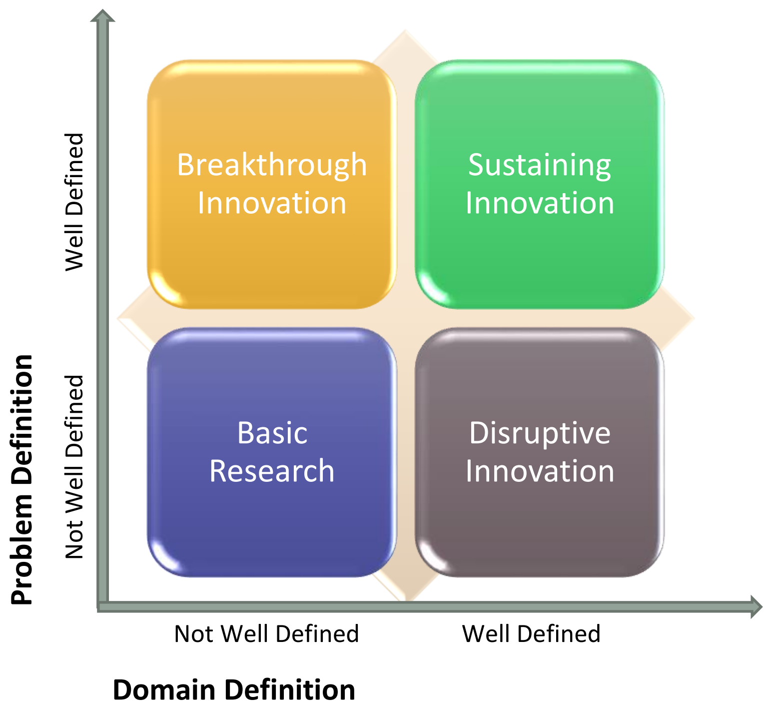

Figure 42: Innovation Management Matrix (Satell, 2013)

The main objective of the EngD program is to innovatively apply knowledge to the global engineering business. This section summarises the outcomes of the literature review and case studies and demonstrates the innovation of the applications. It critically discusses the research, its strengths and weaknesses and suggests potential future directions. As a result, it highlights the innovative application of knowledge and novel methods in aerospace industry.

9.1 Research question and objectives

The research question of this project is: *How can CT be applicable in aerospace industry*? This well-established medical technology gains industrial interest in the last decade. However, due to its reasonably recent industrial applications and its limitations, its growth in the industrial sector is delayed. The aim of this project is to identify the industrial requirements and potential applications and develop the required methods that will allow the technology to be applied and progress further. In order to achieve this, four research objectives were selected by considering the business requirements and current applications of NDTs and CT.

- *Identification of capabilities and limitations of CT technology*
- *Identification of NPD phases where CT can be applied in aerospace industry*
- *Development of novel methods to provide CT inspections and measurements while minimising human error in aerospace industry*
- *Development of improved scanning methods and standard operating procedures for the aerospace industry*

These objectives consider the capabilities and limitations of the technology that was primarily developed up to now for medical applications. New methods are examined to overcome the limitations and assist its further development.

9.2 Innovation

The research question and objectives were selected based on the business requirements that were established with a series of interviews with stakeholders from aerospace industry who have experience with NDTs. One of the objectives is the identification of capabilities and limitations of CT technology that was achieved by a thorough literature review. **Academic innovation** is established through research by critically examining the literature so as to provide answers on how CT can be used in this industrial sector and examining for the first time the requirements of aerospace industry through interviews. The identification of business requirements and the capabilities of CT provide an understanding of the potential applications of CT.

CT can be used in:	
	Research and Development
	Material characterisation
	Quality inspections
	Metrological Applications
	Failure investigations

Figure 43: List of potential applications of CT in aerospace industry

The objective of the identification of NPD phases where CT can be applied in aerospace industry is achieved through case studies. In order to answer the research question, the project proceeds by examining the application of CT in the areas identified in the business requirements. The examination was achieved in a series of case studies that also demonstrate the suitability of the technology in the different stages of NPD. **Academic innovation** is demonstrated by identifying the NPD stages where CT is applicable, which can lead to further CT related projects and case studies in this and other industrial sectors. For example, this project demonstrated the application of CT in the concept creation phase and R&D while one of the business requirements is the examination of complicated AM parts. The NPD stages highlight the area of interest and the business requirements guide the specific interests.

The third objective of 'developing novel methods to provide CT inspections and measurements while minimising human error in aerospace industry' is achieved in Submissions 3, 4, 5, 6 and 8 where new methods combining CT scanning settings, filtration and image processing are presented. The methods are developed so as to allow the utilisation of this technology in aerospace industry as a NDT and metrological tool. **Industrial innovation** for this objective is established by creating new methods that can reduce inspection times, scrapped costs and improving new products.

Submissions 3, 4 and 5 demonstrate new methods that combine image processing with CT scanning to improve the quality of the inspections, reduce human error and examination times. As a result, these methods reduce errors that can lead to significant legal and maintenance costs. Submission 6 demonstrates the application of this technology in the classification of defects that are usually identified by radiography. The volumetric analysis provided by CT scanning, demonstrates the overestimation of defects by other methods which consequently leads to the approval of parts. Due to this, the 30 - 35% of welded parts per year that are usually scrapped for an organisation such as the sponsoring company will require re-examination with CT scanning so as to be classified. Based on results of the weld examinations during this project, only the 2% of these parts will be scrapped after CT scanning. This reduces the time of further classification attempts with other NDT methods, the cost of scrapping which can reach £125,000 and rework times that is required after three different classification attempts and consequently reduces costs significantly. Submission 8 demonstrates the application of this technology in the identification of defects in failed components by volumetric analysis. This step is at the end of NPD process but the information received from CT should be passed to the concept creation and the beginning of the process so as to prevent the same failures in the future. In this case, the innovation is in the new concepts and improved designs which prevent business stagnation and allow growth.

The final objective of this project is '<u>the development of improved scanning methods and standard operating procedures for aerospace industry</u>'. This objective was achieved by performing a series of commercially sensitive scans for the sponsoring company which demonstrate the vast materials selection applied in this industrial sector. Based on the requirements of these scans and the systematic errors of CT such as beam hardening and scattering related to high density materials, Submission 7 investigates an improved scanning method that is suggested as a standard operating procedure when high density materials are examined. The method suggest the utilisation of combined pre and post filtration of the radiation so as to improve metrological results and reduce beam hardening and scattering. The **industrial innovation** of this objective is in the future benefits that the methods and procedures will provide. These methods deliver excellent investigations that can be used in all the NPD phases as explained previously and allow the company to develop advance product designs, new better manufacturing procedures, reduce costs and increase productivity by reducing human error. The advancements achieved through this objective can ensure the competitiveness of the company for years to come.

Figure 44: Advantages of the application of CT in aerospace industry

In order to achieve the optimum results, novel methods were developed combining CT and image processing in Submissions 3, 4 and 5, two of which are published in the International Journal of Advance Manufacturing Technology. A new radiation filtering technique is discussed in Submission 7 that assists in the reduction of common reconstruction errors of CT. Submissions 6 and 8 demonstrate the application of CT in production, minimise human error and provide information that were previously unreachable. These applications demonstrate industrial innovation by providing novel methods to improve quality levels, minimise error, characterise defects, and identify optimum machining methods and techniques. The results demonstrate the application of CT throughout the NPD phases and highlight the capabilities of the technology. The methods discussed can be utilised to improve quality level, reduce re-machining expenses and increase productivity, therefore, increasing value and profit to the companies.

9.3 Limitations of research

Limitations exist in every research and it is important to identify them to reduce the bias of the results. The business requirements were identified by interviewing participants from five companies and that reduces the possibilities of examining the requirements of the sponsoring company. However, the collaboration with this company may have affected the perspective of possibilities and limitations. Smaller companies in the aerospace supply chain do not have the capital to invest in such an expensive new technology.

CT is still a developing technology and even though VDI/VDE provides guidance for metrological applications there is no official standard that can ensure the quality of the results. Aerospace industry has often inspections from a series of quality ensuring organisations and needs to demonstrate that the standards are followed. The new ISO 10360-11 standard on the application of CT in metrology is currently researched and it will be available in the following years. However, the lack of an international standard can be ruinous for the application of this technology in production.

Case studies examine a specific situation at a specific time and place and therefore they may be misleading. This project has been based on a series of case studies which were chosen based on the business requirements at that specific time. The requirements may change and the necessity of this technology may pass. However, the potential applications throughout the NPD demonstrate that even if a specific need is overcome, a similar application can be achieved.

The limitations of this research are not so significant as to alter the results of this project since main aerospace companies can assist their suppliers with their investigations and CT standards are expected in the following years. The results of the case studies demonstrate the potential of applications and not necessarily the exact application. Consequently, the research discussed in this report is considered valid and the further application of CT in aerospace industry is promising.

9.4 Future work

The applications of CT examined in this project are a sample of the potentials of this technology. CT is still a developing technology with new systems entering the market every year. Systems, currently under development, include metrological CT scanners, Real Time Tomography (RTT) that can examine large parts in seconds (Figure 45), and more powerful scanners that can reach 750keV voltage with constant spot size of 5μm. The new developments in this field will allow more applications and they will require the selection of specific machine for specific applications. Due to these developments in this technology, further research will be required to identify the limitations of the new machines as well as to ensure the quality of the results and measurements. Furthermore, additional research is required to identify and calculate measurement uncertainties, develop methods to overcome the technology's limitations and investigate further areas, machining techniques and procedures.

Figure 45: The Rapiscan RTT110 baggage scanner

10. Conclusions

During this project, a review of the literature, an investigation of the business requirements and six case studies have taken place in order to provide an answer to the research question: '*How can CT be applicable in aerospace industry?'* by undertaking the following research objectives:

- *Identification of NPD phases where CT can be applied in aerospace industry*
- *Identification of capabilities and limitations of CT technology*
- *Development of novel methods to provide CT inspections and measurements while minimising human error in aerospace industry*
- *Development of improved scanning methods and standard operating procedures for aerospace industry*

The common NPD process of aerospace industry has been identified through the sponsoring company and a series of case studies have been carried out to identify where this technology can be utilised while considering the business requirements that were identified by a series of interviews. The summary of the results of these case studies have been presented in this innovation report demonstrating the capabilities and limitations of this technology while demonstrating the novel methods created to overcome the limitations and providing standard operating procedures.

The first three case studies have examined the application of CT in R&D by identifying optimum machining processes and settings for CFRPs as a result of creating novel methods of inspection that combined CT scanning, volumetric analysis and image processing. The application of this technology in manufacturing has been demonstrated through the investigation of welds that compared conventional, digital radiography and CT. The results of this investigation have highlighted that CT is applicable in production even with its limitation of long inspections by providing categorisation of parts that are unable to be categorised with other NDTs. The application of CT can reduce the re-machining time and the number of scrapped parts due to lack of classification.

The majority of received components from aerospace industry during this project were metallic which are usually challenging to be examined because of systematic errors such as beam hardening and noise due to scattered radiation. The fifth case study has investigated a new method of reducing beam hardening and scattered radiation by utilising a combination of pre and post filtration of the radiation. The results demonstrate the effectiveness of this novel method that reduces the measurement error and assist in metrological investigations. Consequently, metrological investigations in aerospace can utilise this method in CT examinations. Lastly, the sixth case study has investigated the application of

CT in engineering forensic examinations and failure analysis with numerous examples of defaulted parts from the aerospace industry. The results of this investigation demonstrate the application of CT in the supporting during operation phase and disposal phase of NDP which can lead back to the concept development and R&D.

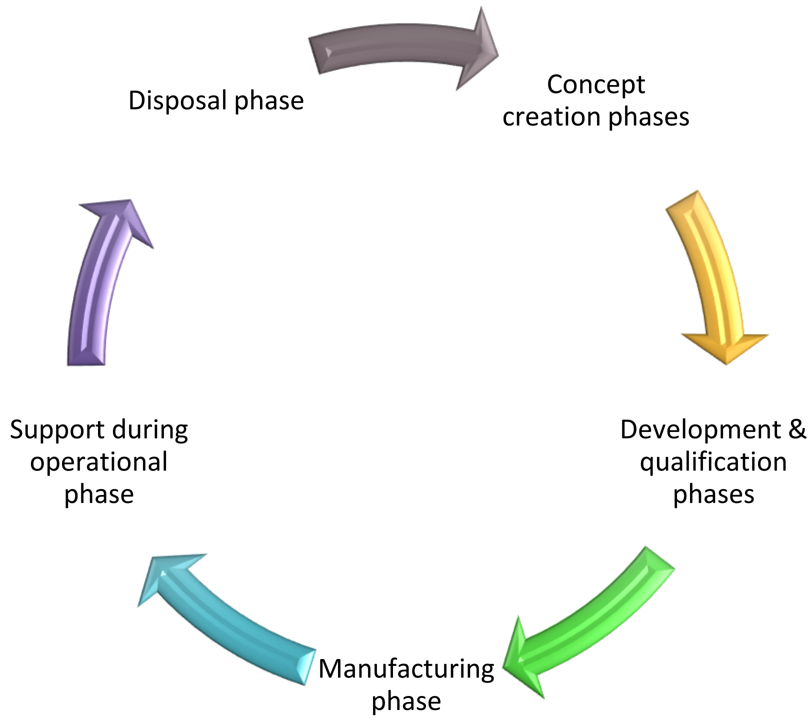

Figure 46: NPD process in aerospace industry

Based on the results of these investigations, CT can be utilised in aerospace industry in concept creation, development and qualification phases through R&D investigation, manufacturing phases by supporting the production and providing characterisations of parts that cannot be categorised with other NDT methods, and by providing measurements. It can also be utilised in support during operational and disposal phases by examining and studying failed components and assemblies in order to improve design, material selection and machining processes so that they can be used for longer and that leads back to concept creation and R&D. The presented case studies demonstrate the application of CT in aerospace industry by utilising innovative methods that have never been combined together to provide examinations and measurements.

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