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THE ROLE OF PAPER AND PROCESS TECHNOLOGIES FOR MECHANISMS AND IMAGE QUALITY IN DIGITAL ELECTROPHOTOGRAPHY

Hussain AL-Rubaiey

TEKNILLINEN KORKEAKOULU
TEKNISKA HÖGSKOLAN
HELSINKI UNIVERSITY OF TECHNOLOGY
TECHNISCHE UNIVERSITÄT HELSINKI
UNIVERSITE DE TECHNOLOGIE D'HELSINKI

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Doctoral Thesis

Hussain AL-Rubaiey

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Media Technology, Faculty of Information and Natural Sciences, for public examination and debate in Auditorium AS1 at Helsinki University of Technology (Espoo, Finland) on the 18th of December, 2009, at 12 noon.

Helsinki University of Technology
Faculty of Information and Natural Sciences
Department of Media Technology

Teknillinen korkeakoulu
Informaatio- ja luonnontieteiden tiedekunta
Mediatekniikan laitos

Tekniska högskolan
Fakulteten för informations- och naturvetenskaper
Institutionen för mediateknik

Distribution:

Helsinki University of Technology
Faculty of Information and Natural Sciences
Department of Media Technology
P. O. Box 5500
FIN-02015 TKK
Finland
Tel. + 358-9-470 22870
Fax + 358-9-470 25253
http://media.tkk.fi/

Available in PDF format at http://lib.tkk.fi/Diss/2009/isbn9789522482150/

ISBN 978-952-24-8214-3 (print)
ISBN 978-952-24-8215-0 (online)
ISSN 1797-7096 (print)
ISSN 1797-710X (online)

Monikko Oy/Multiprint
Espoo 2009

ABSTRACT OF DOCTORAL DISSERTATION	HELSINKI UNIVERSITY OF TECHNOLOGY P.O. BOX 1000, FI-02015 TKK http://www.tkk.fi

Author HUSSAIN AL-RUBAIEY

Name of the dissertation
THE ROLE OF PAPER AND PROCESS TECHNOLOGIES FOR MECHANISMS AND IMAGE QUALITY IN DIGITAL ELECTROPHOTOGRAPHY

Manuscript submitted 26.05.2009	Manuscript revised 12.10.2009

Date of the defence 18.12.2009

☐ Monograph	☒ Article dissertation (summary + original articles)

Faculty	Faculty of Information and Natural Sciences
Department	Department of Media Technology
Field of research	Media Technology
Opponent(s)	Professor ARVED HÜBLER
Supervisor	Professor PIRKKO OITTINEN
Instructor	

Abstract

Image quality and the mechanisms involved in digital dry toner electrophotography are influenced by the interactions between the printing machine, toner and paper in the last two steps where the paper is involved, i.e., in transferring the developed image toner to the paper, and in fusing the image to be fixed permanently on the paper surface. This study discusses the role of paper in these two steps in different technologies and its effect on the printing mechanisms and image quality. The control of optical, electrostatic and mass and heat transfer phenomena in the printing process are affected by the unevenness of the properties of paper due to its heterogeneous structure and its sensitivity to humidity conditions and printing process parameters. In this research, a set of experiments was conducted to understand the electrostatic behaviour of paper in toner transfer and thermal behaviour in toner fusing.

The results show that not only image quality is affected by the variability of paper properties, but also the mechanisms of toner transfer and fusing. Accordingly, the research suggests that the paper should be included as part of the printing mechanism, performance (printability and runnability), and image quality. Consequently, if there is a change in paper properties due to a change in ambient conditions or the use of another grade for a specific application, the process parameters can be adjusted to compensate for these changes in order to meet the requirements for image quality. It was found that the variability in image quality in terms of colours (the requirement for different toner layers), grey scale (halftone structure) and the location of the image in the xy-plane is affected when rendered through the electrophotographic process. The fast mechanical speed in printing machine direction drives the toner transfer and fusing mechanisms differently from the cross machine direction. As a result, a certain image element such as a line will have different quality in these two printing directions, or if the line is placed in the length or width direction of the page.

The conclusion was that the electrophotographic process should be designed to reduce or even to neglect the effect of paper when printing a high-quality colour image in a high-speed process. This can be achieved by eliminating the contact with paper from the image side in both transfer and fusing by adopting the technologies of toner jumping transfer and non-contact flash fusing. These technologies have special requirements for chemical and physical toner properties, such as modification for equal absorbance of the flash radiation by CMYK colours, a suitable melting viscosity and surface energy, and a small and narrow toner particle size and shape distribution to unify the charge-to-mass ratio of the toner, which is important for transfer quality and efficiency. To ensure high print quality for different applications, some of the transfer and fusing parameters need to be automatically adjusted according to substrate specific properties and levels of image coverage.

Keywords electrostatic transfer, thermal fusing, dry toner, paper, image

ISBN 978-952-24-8214-3 (printed)	ISSN 1797-7096 (printed)
ISBN 978-952-24-8215-0 (pdf)	ISSN 1797-710X (pdf)
Language English	Number of pages 67 p. + app. 66 p.

Publisher Department of Media Technology

Print distribution Department of Media Technology

☒ The dissertation can be read at http://lib.tkk.fi/Diss/2009/isbn9789522482150/

PREFACE

This study presents research work in the field of electrophotography. It has been carried out in the Department of Media Technology at the Helsinki University of Technology during the last 6 years.

I would like to express my sincere thanks and gratitude to my supervisor, Professor Pirkko Oittinen for her support, encouragement, guidance and advice throughout the work.

Financial support for the study is gratefully acknowledged. It has been provided by;

- Department of Media Technology at Helsinki University of Technology
- Graphic Arts Research Fund in Finland
- The National Technology Agency of Finland (TEKES)
- Research Foundation of Helsinki University of Technology
- International Doctoral Program in Pulp and Paper Science and Technology (PaPSaT).

Finally, I wish to express my thanks to my co-authors of the publications, the reviewers and the examiners of this work, my colleagues, friends, parents, wife and lovely children for their support and understanding.

LIST OF PUBLICATIONS

This dissertation is based on eight publications. They are listed below, and are referred to in the text by P1, P2, P3, P4, P5, P6, P7, and P8.

P1 Pirkko Oittinen, Hussain AL-Rubaiey, Katja Sipi and Katri Vikman, ***Research on Paper-Ink-Process Interactions in Electrophotographic and Ink Jet Printing***, (The Int. Conf. on Digital Production Printing and Industrial Applications, May 13-16, 2001, Antwerp, Belgium), In Proceeding DPP2001, (IS&T, Springfield, VA, 2001), pp. 327-330.

P2 Hussain AL-Rubaiey and Pirkko Oittinen, ***Transfer Current and Efficiency in Toner Transfer to Paper***, (The 17th Int. Conf. on Digital Printing Technology, Sep. 30-Oct. 5, 2001, Fort Lauderdale, Florida, USA), In Proceeding NIP 17 (IS&T, Springfield, VA, 2001), pp. 648-652.

P3 Hussain AL-Rubaiey, Timo Hartus and Pirkko Oittinen, ***The Influence of Flash Fusing Variables on Image Fixing Quality***, (Int. Congress of Imaging Science, May 13-17, 2002, Japan), In Proceeding ICIS'02, Tokyo, (2002), pp. 600-601.

P4 Hussain Al-Rubaiey and Pirkko Oittinen, ***The Future Potential of Digital Electrophotography***, (The Int. Conf. on Digital Production Printing and Industrial Applications, May 18-21, 2003 Barcelona, Spain), In Proceeding DPP2003, (IS&T, Springfield, VA, 2003), pp. 114-115.

P5 Hussain AL-Rubaiey, Nonkululeko Khanyeza, and Pirkko Oittinen, ***The Effect of Coating Colour on Toner Transfer in Digital Printing***, PulPaper 2004, June 1-3, 2004 Helsinki-Finland, In Proceeding of PulPaper 04, Coating, pp. 35-40.

P6 Hussain Al-Rubaiey, Pia Räsänen and Pirkko Oittinen, ***Detail Rendering in Digital Dry Toner Electrophotography***, The 31st International research conference of iarigai, 1-6 September 2004, Copenhagen, Denmark, Advances in Printing Science and Technology, IARIGAI Publication, Vol. 31, pp. 13-26 (2005).

P7 Hussain AL-Rubaiey and Pirkko Oittinen, ***Controlling Fusing Parameters by Optical Image Quality in Electrophotographic Printing***, The 32nd International research conference of iarigai, September 2005, Porvoo, Finland, Advances in Printing Science and Technology, IARIGAI Publication, Vol. 32, pp. 123-127 (2006).

P8 Hussain AL-Rubaiey and Pirkko Oittinen, ***Thermal Behavior of Paper in Contact Fusing Technology***, Journal of Imaging Science and Technology, Vol. 52, No. 3, (May/June- 2008), 1st page 030507 (10 pages).

THE AUTHOR'S CONTRIBUTIONS

In the above articles P1 - P8, the author contributed the following:

P2, P4, P7, P8	All experiments, literature reviews, analysis and writing of the manuscript.
P1	Part of the article, which is related to toner transfer and a portion of the toner fusing part.
P3, P5	A major part of the experiments, literature review, analysis and writing of the manuscript. The co-authors contributed to some of the paper measurements.
P6	Supervised the experiments, part of the literature review and analysis, and writing the manuscript.

The supervisor, Professor Pirkko Oittinen, has played a crucial role as the main co-author in all publications. Her involvement consisted of suggesting the idea for the research, design and set-up the experiments, following up the results and discussions, and helping in writing and correcting the manuscripts.

OBJECTIVES AND STRUCTURE OF THE STUDY

The general research goal of this study was to gain an understanding of the basic mechanisms of paper-toner-process interactions in digital dry toner electrophotography for the purpose of industrial development of related technologies to achieve better process efficiency and print quality. Specifically, the aim is to determine the influence of electrical interactions in toner transfer to paper with different transfer constructions and the main factors governing the toner transfer efficiency. Further, the goal was to determine the thermal, optical and mechanical interactions in fixing the toner on paper and their role in toner adhesion and formation of optical print quality.

In the transfer and fixing studies the printing system was conceptualised as consisting of three components which influence print quality separately and interactively. These components are the process, the toner and the paper.

The objectives of this work were:

- To establish the role of paper and the mechanisms of toner transfer and fusing in current technologies of digital dry toner electrophotograpy in a more detailed manner.
- To find the influence of paper and different process technologies on image quality.
- To determine the possibility of optimising and controlling the effective parameters of the process for higher efficiency and better print quality.

These objectives were pursued by using a variety of papers and toners, measuring their related properties, and by constructing and/or modifying special devices and instruments to measure, adjust, control and monitor the most important variables in both toner transfer and fusing processes in different technologies.

The research work was carried out according to the following procedure:

1. Reviewing the available technologies of electrophotography, and the current knowledge of the role of paper for the efficiency of the printing process and image quality.
2. Considering and selecting a set of available electrophotographic machines which are compatible with other installations for developing the experimental tools.
3. Constructing special devices and modifying existing ones to fulfil the experimental requirements.
4. Evaluating the performance and results in connection with measured image quality attributes.
5. Comparing the findings with other relevant studies.

The structure of the publications is highlighted in the following:

P1 *Research on Paper-Ink-Process Interactions in Electrophotographic and Ink Jet Printing.* This article introduced the general research and experimental approaches for toner transfer and fusing. Some pre-experimental results were included for evaluation purposes.

P2 *Transfer Current and Efficiency in Toner Transfer to Paper.* In the research presented in this publication, a special device to be attached to a suitable commercial laser printer was constructed. It is designed to adjust and control the transfer voltage as a main parameter in the toner transfer process. In addition, the device can measure and monitor the transfer current as a main output to indicate the surface charge density accumulated on the paper surface, and in turn the toner amount transferred to the paper as a result of electrostatic attraction. The validity of the toner transfer experiment was confirmed, and the effect of different paper grades on toner transfer efficiency was examined under different humidity conditions.

P3 *The Influence of Flash Fusing Variables on Image Fixing Quality.* A separate flash fusing unit was designed and constructed for this experiment. It was based on the hypothesis that white papers reflect almost all the near infrared radiation, but the black toner will absorb most of this energy to be fixed on the paper. In this unit, the flashing energy and the pulse width can be adjusted and controlled for a wide range of fusing energy. Several sets of experiments were included to characterise different toners and papers properties. A novel method was used to measure the surface energies of both toners and papers. In addition a controllable method to evaluate the different levels of toner adhesion was developed.

P4 *The Future Potential of Digital Electrophotography.* In this work, the limitations of sub-processes and sub-systems in electrophotography were examined, and the efficiency and quality of dry and liquid toner technologies were compared. Based on the limitations, a model was constructed for comparing dry toner applications with ink jet development. In addition, the possibility of developing hybrid applications and the hidden potential in electrophotography for use as a digital industrial tool for printing electronics were discussed.

P5 *The Effect of Coating Colour on Toner Transfer in Digital Printing.* This research consisted of an application of the experimental arrangements of toner transfer presented in P1 and P2. This paper deals with the effect of coating on the surface charge density of paper.

P6 *Detail Rendering in Digital Dry Toner Electrophotography*, The paper examines the differences of current technologies of eight desk top and industrial electrophotographic printers in terms of speed, resolution, toner transfer and fusing quality. A microdensitometer was used to study the detail rendering through calculations of dynamic range, contrast transfer function (CTF), signal-to-noise ratio (SNR), pixel size, edge noise and raggedness. Subjective evaluations were correlated to the objectives measurements. Microscopic and image analysing tools were also used in differentiating the performance of the printers. This paper has provided important information on the influence of different process technologies on the mechanisms and image quality.

P7 *Controlling Fusing Parameters by Optical Image Quality in Electrophotographic Printing.* The main variables in contact fusing technology are the pressure, temperature, nip width and the dwell time, which is determined by the speed and the nip width. In this paper, a modified fusing unit with variable nip width was used to provide variability in both pressure and dwell time. The effect of these parameters on image quality was tested using different papers. The rest of the fusing parameters were kept constant.

P8 *Thermal Behaviour of Paper in Contact Fusing Technology.* Another modified fusing unit was used to control and adjust the fusing speed and temperature. The pressure and nip width were kept constant. Accordingly, this article completed the study of all contact fusing parameters started in P7. The thermal behaviour of papers was evaluated at different humidity levels according to the recorded temperature and moisture, and image fixing quality measurements.

P3, P6, P7 and P8 seek to provide a better understanding of toner fusing and adhesion mechanisms, and the possibility of using online control of fusing parameters to achieve the desired image quality in different applications. Hybrid combination of contact and non-contact fusing will allow higher flexibility in a wide range of applications.

P1, P2, P5 and P6 were focused mainly on toner transfer to paper. These articles focus on understanding the mechanism of electrostatic toner transfer, and the effect of inter-related properties of papers on image quality in different temperatures and humidity conditions.

CONTENTS

1 INTRODUCTION

Printing and paper are always relevant to each other. This study is mainly focused on the role of paper in digital dry toner electrophotography. The mechanisms of electrophotographic printing are influenced by different printing machine technologies, and the way paper affects each of them in printing the final image. Simply put, this is the research area of this study. A lot of work and studies have been done in this field, including numerous studies focused on printing processes, papers and toners. Some studies examine them from the viewpoint of process optimisation, as a means to improve runnability or printability. The research on papers and toners has been done from different perspectives, for example, examining the role of raw materials in the printing process, or in fulfilling print quality requirements. The contribution of this study is to connect the three elements (process, paper and toner) in toner transfer and fusing to produce higher process efficiency and better print quality.

1.1 Electrophotography

In general, printing is a process for reproducing text, graphics and images, typically with ink on paper or any other substrate to transmit information in the form of print media as one tool of communication technology [1-4]. Based on the printing methods, printing technologies can be divided into two main categories [1,2]: First, the conventional or mechanical printing technologies using the impact of a master surface such as a plate carrying the image to reproduce the print media as in flexography, lithography (offset), and gravure. And second, the non-impact or electronic printing technologies which are characterised by digitising the reproduction (each print has a new image) without the master and its impact. Accordingly, these technologies are called direct, non-impact, or digital printing processes [1-3]. Examples of digital printing are electrophotography, ink-jet, thermal printing, magnetography etc. [3, 4]. Also, the traditional chemical method of producing photographs can be considered as a different third type of printing method.

The choice of printing method is mostly determined by the application. Factors, such as printed job size, general or customised information to be printed, and the cost per job are critical to the choice. Digital printing methods facilitate printing of variable information and are suited to short runs and fast turn around when cost is not a primary issue.

The electrophotographic printing process – the technology used in this research – creates a visible image using electrostatic latent images in the form of surface charge patterns on a photoconductive surface called photoconductor (PC). The visible image consists of fine particles called toner [3-6], which can be used as a dry powder or diluted with liquid. The electrophotographic process is also referred to as xerography, from the Greek words of (dry) and (writing). The process was discovered by Chester Carlson in the late 1930s and patented in October, 1942 [7-9]. The fist implementation of the process was an analogue copier. The black and white (B/W) laser printer was introduced in the 1970s, and multi-colour laser printing at the end of the 1980s [1]. Since then, the importance of process-toner-paper interaction has been realised, and the rapid development of toners and papers has been driven by increased demands for faster, better and wider applications.

At present, electrophotography has consolidated its position in the printing market as the preferred method of short-run digital printing in a variety of commercial applications and office environments [P6]. In terms of speed and quality, the production scale of electrophography has developed rapidly to reach the level of about 200 pages per minute (ppm) of (B/W) and exceeding 100 ppm of colour printing in addressable resolution of 600 dots per inch (dpi). This already corresponds to the performance of low-end offset printing presses. Figure 1.1 illustrates the position of digital methods in which electrophotography is included, compared to chemical and mechanical printing methods.

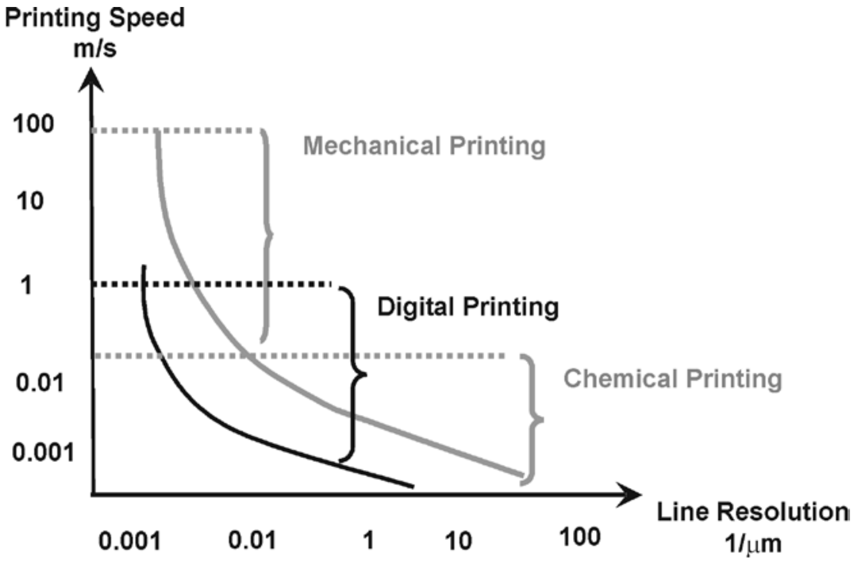

Fig. 1.1 Relative performance of digital printing.

The additional features of digital methods, such as customisation by including variable information and on-demand production of updated contents, have put digital technology in the core of nearly every business sector [P4].

The basic steps in the electrophotographic process are photoconductor charging, exposing the latent image to a light source (usually laser or a light emitting diode (LED)), toner charging, development of charged toner into the latent image on the photoconductor surface, transferring the developed image from photoconductor to paper, erasing the remaining charges and cleaning the residual toner, and finally fusing the image to be fixed and penetrated into the paper. These steps are identical with the six-step process originally proposed by Carlson [1, 5, 7, 10]. Figure 1.2 shows the steps of the electrophotographic printing process.

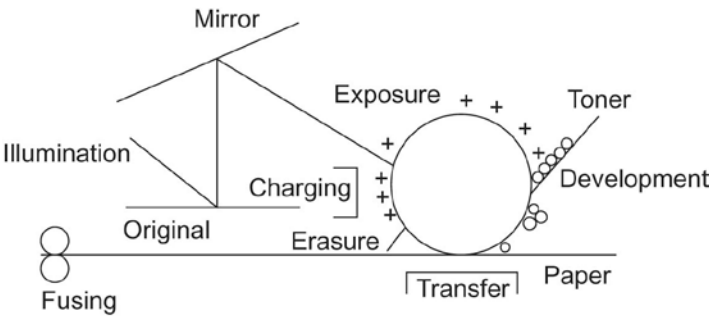

Fig. 1.2 Steps in analogue electrophotography [1].

There have been a lot of arguments to determine the number of process steps and the name of each one based on different viewpoints, such as the technology of the sub-system in each step, the functionality, the scientific principle, and even sometimes the names of persons or companies that have introduced certain developments in this technology. This attitude will continue to prevail because of the absence of standardising terminology in this field of relatively new technology [11]. For example, the author has suggested seven steps, naming toner charging as a separate step with different types of technologies, arguing that the process cannot be completed without this step [P4, P6]. Another study proposed five steps only, excluding the toner cleaning and charge erasure steps [11], claiming that they are not entirely part of the printing process. Considering them as pre- or post-printing requirements, this implies that printing could be done without cleaning even if the printing result is of poor quality. Some other studies include both steps of charging the PC and exposing the latent image in one step called imaging [2]. Therefore, one of the most important issues in designing electrophotographic machine is to determine the function of each sub-system in the process regardless of its name. Among different available sub-system technologies, the most suitable one should be chosen after careful evaluation. And when the technology of each sub-system has been chosen it should be optimised and integrated with the other sub-system process steps [5]. Figure 1.3, shows the functional diagram of the electrophotographic printing process.

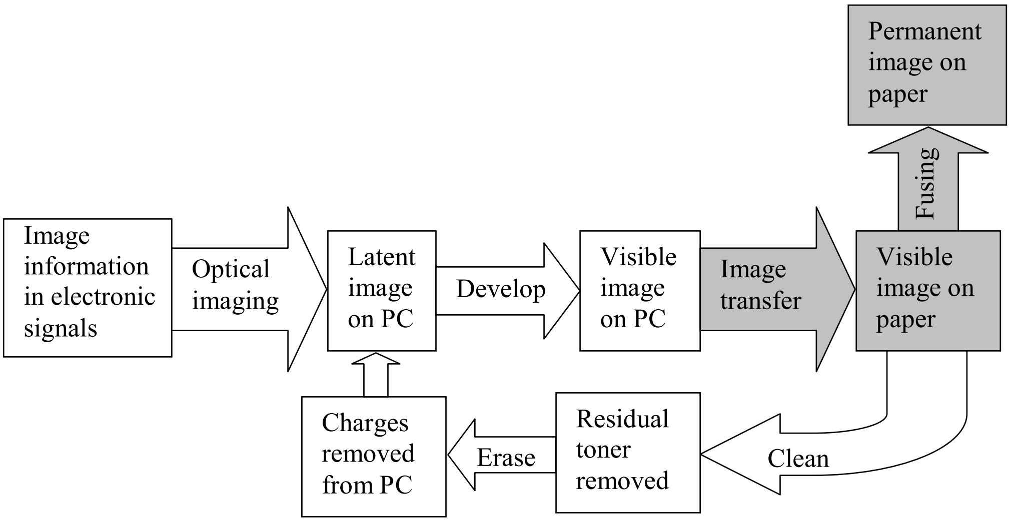

Fig. 1.3 Functional diagram of electrophotographic printing process [3].

In dry toner electrophotography, the paper is involved in the last two steps of the printing process: toner transfer, where the electrical properties of paper are important for transfer and holding the toner image, and fusing, where the image is fixed permanently on the paper [P2, P3, P8, 12]. These two steps are labelled by grey colour in Figure 1.3. This thesis is focused on the interactions between paper, toner and process parameters and technologies in the last two steps: toner transfer and fusing. From the viewpoint of paper, these interactions are characterised by the classic terms of runnability and printability [P1].

1.2 Toner transfer

Toner transfer to paper is a significant step in the electrophotographic printing process. In this step the toner, printer and paper meet each other for the first time during the printing process. The developed image on the photoconductor can be transferred to the paper by applying different principles, such as electrostatic forces, adhesive forces, thermal energy, mechanical forces or a combination of different energies [3, 4, P2]. Each principle can be implemented by using different technologies and configurations.

In principle, when the toner image is transferred to the paper by any means of mechanical contact, the image will be simultaneously transferred and partially fixed to the paper. This type of technology, on which Electron Beam Imaging (EBI) is based, is called transfixing or transfusing [13, 14], and it can be implemented with or without additional thermal energy. In transfusing technology a durable drum is used as a receptor instead of a sensitive PC. If thermal energy is involved, a silicone belt should preferably be used as an intermediate means in transferring the image from the receptor to the paper [15]. The thermal transfixing of the softened toner that has been applied directly from the hot receptor to paper, or indirectly through an intermediate hot silicone belt, is governed by the differences in surface tension (surface energy) between the receptor, belt, toner and paper [4, 16]. Pressure transfusing yields advantages of simplicity, reliability and high-speed performance, especially for black and white applications, but suffers from limitations relating to image permanence and print quality [13, 14].

1.2.1 Electrostatic toner transfer to paper

The electrostatic transfer method dominates in commercial colour laser and LED printers used in offices, and in a significant part of industrial presses meeting high print quality requirements. This method can be implemented by using different technologies such as a transfer roller, transfer belt, an intermediate transfer drum, transfer corona, and transfer drum (TD). Some of these technologies can be configured so that the toner is transferred to paper in two steps: first, the toner is transferred from the PC to an intermediate element such as a belt or drum, and second from the intermediate element to paper. Both toner transfer steps are achieved by electrostatic force, with or without pressure. If the transfer is done without pressure, it will be through a narrow gap of air, with the toner particles jumping over this gap because of the electrostatic attraction force [17-21]. This type of toner transfer is sometimes called "jumping transfer" referring to the absence of pressure. The air gap exists in all transfer technologies, even in those designed to avoid it. It is resulted from paper roughness, non-uniformity of toner particle shape and size, agglomeration of toner particles, and the differences in pile heights of the image. To avoid any contact with paper during the study of the electrostatic toner transfer mechanism, a printer technology based on jumping transfer was selected to be used in this research.

In all technologies using electrostatic toner transfer, the basic principle is to generate a sufficient electric field across the paper to attract and transfer the charged toner particles of the developed image from the PC to the paper. There are two ways of electric field generation for all electrostatic marking technologies. One is ion emission from a corona charger directly onto the paper or across a paper carrier element such as a belt. The other is to apply a DC voltage (direct current voltage) via the transfer drum or a transfer roller directly to the paper or across the carrier element [1, 5, 22-25]. Figure 1.4 shows these two electric field generation principles in different toner transfer configurations [1].

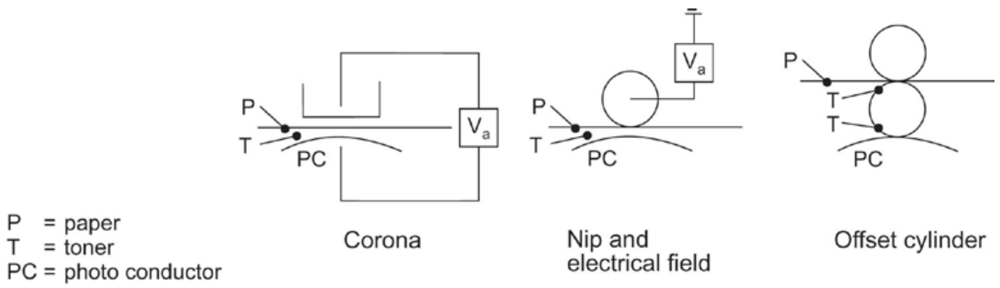

Fig. 1.4 Transfer of toner from photoconductor to paper [1].

For colour electrophotography, several toner transfer techniques are used according to the desired printing speed. At low speed, where the time required to print one colour page is the sum of the time to print each of the four colours, the four colours are accumulated either on the photoconductor, or on an intermediate element such as a transfer drum or belt, and then transferred simultaneously to paper [26-27]. In some technologies, the four colours can be applied by a single imaging unit four times, to be accumulated directly on paper, which is usually supported by a large transfer drum [31, 32]. This type of marking engine, called multi-pass transfer technology, was selected to be used in this research [32]. A schematic diagram of the process is shown in Figure 1.5.

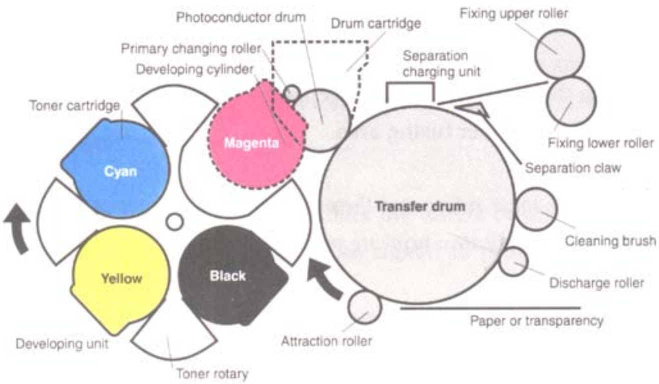

Fig. 1.5 Multi-pass transfer configuration [32].

For high-speed colour printing, the printer is constructed with four separate imaging units for each colour in a configuration called tandem or single-pass transfer [33]. The time to print one colour is equal to that of four colours. Figure 1.6 illustrates the performance of colour marking engine configurations in terms of speed and quality [1].

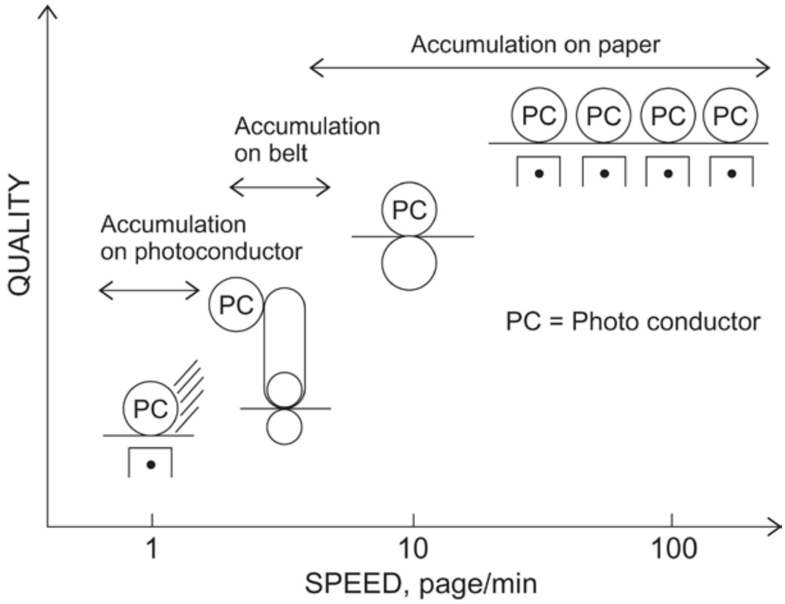

Fig. 1.6 Four-colour electrophotographic engines for different speed and quality [1].

1.2.2 Electrostatic toner transfer mechanism and efficiency

In the transfer step of the selected technology, the paper is clamped and attracted to the transfer drum-TD. As shown in Figure 1.7 (a), an electrical attraction occurs between the paper and the TD when a sufficient constant transfer voltage V is applied to the TD in a polarity to ensure an opposite charge on the paper surface to that of the toner charge. Part of the transfer voltage is consumed over the resistances of the TD layers, paper and the resistance of the contact regions between the layers of TD and the paper. The part applied to the paper is important for toner transfer and it must be high enough to cause effective polarisation of paper and to accumulate a sufficient charge density σ on the paper surface to allow an electric field E to be created between the paper and charged toner particles as shown in Figure 1.7 (c). The electrostatic force F_1 of this field -defined in Figure 1.7 (c)- will overcome several force components, mainly the adhesion of toner particles on the PC and transfer them to the paper according to Equation 1 [34, 35, P2]:

$$F_t=F_1-F_2 \qquad (1)$$

$$F_t = qE - [K_1(q/D)^2+K_2(DE)^2+F_a]$$

where F_t is the net transfer force acting on the toner, K_1 and K_2 are constants, q is toner charge, D is toner diameter, $(F_1=qE)$ is total transfer force due to electric field E, $(q/D)^2$ is toner adhesion forces on PC, $(DE)^2$ is dipole forces, and F_a is including all other adhesion and cohesion forces, other Van Der Waals, double layer, chemical, hydrophobic, capillary, coulomb, etc. [34, 35].

The charged toner particles transferred to paper are intended to neutralise the same amount of charges on the paper surface. The amount of charge moving per unit of time will create an electric current I, and if this movement covers the image area, it will be described as electric current density. [4, 5, 18, 35-37]

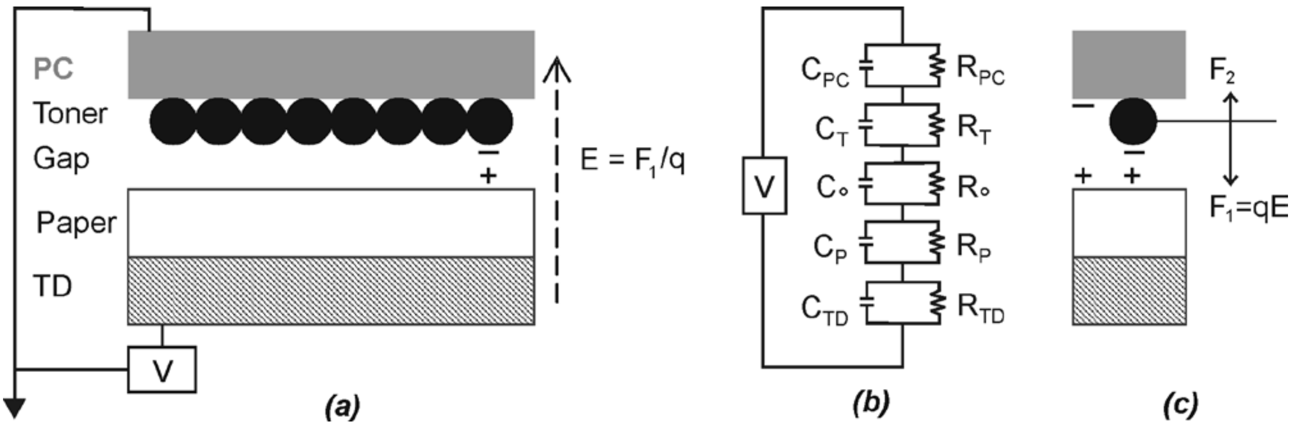

Fig. 1.7 One-dimensional schematic of transfer zone (a), equivalent RC-circuit (b), and forces act on toner particles (c).

Different assumptions have been made to derive a toner transfer model based on the configuration shown in Figure 1.7. One assumption [34] is that the transfer field is created from constant charge density Q, where the electric field E_i in different layers is independent of layer thickness d, as in Equation 2;

$$E_0 = Q/\varepsilon_0 \quad \text{(for the air gap)} \qquad (2)$$

$$E_{PC} = Q/\varepsilon_0\, \varepsilon_{PC} = E_0/\varepsilon_{PC} \quad \text{(for the photoconductor)}$$

$$E_P = Q/\varepsilon_0\, \varepsilon_P = E_0/\varepsilon_P \quad \text{(for the paper)}$$

$$E_{TD} = Q/\varepsilon_0\, \varepsilon_{TD} = E_0/\varepsilon_{TD} \quad \text{(for the transfer drum)}$$

$$E_T = Q/\varepsilon_0\, \varepsilon_T = E_0/\varepsilon_T \quad \text{(for the toner layer)}$$

ε_{PC}, ε_T, ε_P, and ε_{TD} are the relative dielectric constants of PC, toner layer, paper and TD, respectively. ε_0 is the permittivity of free space.

Another assumption [20, 21] is that the transfer field is created from the applied constant voltage V:

$$E = V / \Sigma D_i \qquad (3)$$

$D_i = d_i / \varepsilon_i$ *(dielectric thickness of all the layers)* (4)

Both assumptions neglect toner charge and assume the PC potential to be zero. The series connection of the equivalent parallel RC-circuits of each layer shown in Figure 1.7 (b) is a well known model [20-23, 34, 38] to analyse the transfer system and electrically characterise each layer (PC, toner, air gap, paper, and TD). Such a model has been used to characterise the performance of different materials in order to design the transfer element (roller, belt or drum) based on the time dependence of electric field and current [21, 22, 38]. This model has also been used to study the toner layer and paper considering them as homogeneous uniform materials in the electrostatic transfer zone. In reality, a toner layer consists of a huge number of toner particles of different shapes and sizes. This results in variations in electrical properties. This situation is further complicated by the non-uniform dielectric constant of paper: paper materials and their distribution across the sheet are non-uniform. Therefore, paper always creates a non-uniform electric field [39, 40, 41, 42]. This is a real problem since this model cannot express the local toner transfer variation, rather it consider the effect of the paper collectively as a uniform and homogeneous sheet. So, as a part of the configuration shown in Figure 1.7, this study has considered the paper layer only, to find out the role of different paper grades on toner transfer under different process settings and humidity conditions.

Whatever transfer configuration and assumption is used, the driving component in the toner transfer mechanism is the electric field across the toner layer. This component is determined by the net voltage which is the difference between the applied voltage *V*, and the voltage drop across the rest of the resistive layers [20, 21, 34-37]. To increase the net voltage and in turn the electric field of the toner layer for better transfer, the voltage drop across the rest of the layers should be reduced. One of these layers is the paper, and to reduce the voltage drop in paper, the electrical properties of paper, such as surface and volume resistivity, dielectric constant, permittivity, etc. should be controlled [3, 4, 20, 21, 37, 43]. Some variations in the electrical properties arise from the variations in the basic properties of the paper, and some others are due to the variations in the humidity conditions. Different moisture levels in paper will produce different sets of electrical properties, resulting in varying toner transfer performance.

This is a challenging problem in electrophography, and there have been many attempts to avoid or minimise the impact of the fluctuations of the electrical properties of paper in the toner transfer zone to ensure high and repeatable print quality. An old and powerful approach is to adjust the transfer voltage according to the ohmic resistivity of paper, in a closed loop control system which adjusts the required transfer voltage to each print job [32, 36-43] or even to every individual paper [44].

Another approach is to use a web or belt with high and constant value of electrical resistivity, as an element to carry the paper in the transfer step, which will stabilise the electrical properties of the complete transfer system. Another development is the intermediate drum with a flexible and high resistance surface between the PC and paper to ensure the two transfer steps with high image quality and long life of the PC [44]. But the approaches of introducing high resistance intermediate and carrier elements are usually associated with high energy consumption.

Toner transfer efficiency is determined as the ratio of the toner amount transferred to the paper to the toner amount developed on the PC. Also, it can be defined by the ratio of the optical image density transferred to the paper, to the optical density of the image developed on the PC [45, 46]. The optical density is not always a good indicator of the toner amount: it reaches a saturation level at a certain limit of the toner amount where a halftone image becomes solid. After this limit, any additional amount of toner will not influence the measured image density [P5]. The thickness of the image will only be increased. Accordingly, the transfer efficiency can be given as the ratio of the thickness of the image transferred to the paper to the thickness of the image developed on the PC [36, 43, 45, P2, P5]. The thickness of the image is in proportion to the number of toner layers and the layer thickness is the diameter of the toner particles. This assumption requires a uniform toner particle shape and size, and for further theoretical analysis, the toner layer in this continuous model has to be considered as a homogeneous slab, which can be split into two layers at any thickness point based on the transfer voltage applied to the transfer system [47, 48, P2]. In reality, some toner particles transfer earlier than others in such a model as an array of toner particles [49]. In this case the distances between toner particles in the air gap should be considered.

1.2.3 Factors affecting electrostatic toner transfer

The electrostatic toner transfer is the step where the toner and paper interact under the effect of the transfer step parameters. Thus, all the variations in paper and toner properties that are influenced by the electrostatic process parameters affect toner transfer. Printer manufacturers usually design the process parameters according to an ideal model in which the paper and toner are considered to be homogeneous, uniform and with stable properties. But in reality, they are not, and their properties are very sensitive to any change in ambient conditions [50, 51].

The variations in the bulk properties of paper arising from the materials, fibre orientation, filler content, thickness, density, grammage and roughness produce variations in the electrical properties defined by dielectric constant, dielectric loss, volume and surface resistivities, charging capacity, charging decay time, and dielectric breakdown strength. When applying the transfer voltage, these variations cause non-uniformity in surface charge density, which in turn leads to variations in the electric field and a net electrostatic transfer force acts on toner particles. In general, various paper properties are interrelated, and when a change is made to improve one property, some other property often deteriorates. In addition, values of most paper properties are relevant when referred to a certain level of moisture content. Therefore, any change in the relative humidity (RH%), the percentage of the moisture content (m.c.%) of the paper will be changed as well, and all the relevant properties will be changed. As a result, the surface charge on paper, the electric field, and the electrostatic transfer force will all have variations even within a single sheet of paper, leading at the end to non-uniform toner transfer to paper [1, 36, 50-54].

Toner variation is another factor influencing the electrostatic transfer step. Different toners are used in electrophotograpgy. They are classified according to toner charging mechanisms such as mono-component and two-component, or according to the manufacturing process such as chemical or mechanical grinding methods. Also, by choice of material properties magnetic, conductive or isolative toners are can be produced. Toners are composed mainly of thermoplastic polymer resin and small portions of functional additives such as charge control agent, colour pigments, dyes, and fine carbon black for black toner. The toner is characterised by particle shape and size, charge to mass ratio q/m, surface chemical and thermal properties [1-5, 54]. Toner properties are designed to be compatible with given electrophotographic process parameters [54-59]. The charge to mass ratio is very important in the toner transfer step. It is usually in the range of 0.1-10 µC/g [56]. The adhesion force of the toner to the PC is inversely proportional to the particle size. Therefore, toner size selection occurs during the transfer step. The toner size transferred to paper is larger than that remaining on the PC. The toner size classification in the transfer step sets the lower limit for the toner size employed in electrophotography, since the maximum transfer field is also limited by the air breakdown, which is about 35 V/µm [54, 60].

Paper properties, toner properties and transfer process parameters are all subject to variations in different ambient conditions, because the electrostatic process is quite sensitive to humidity and temperature. Thus, a highly automated system is required to compensate for the ambient effects by adjusting and controlling the desired process parameters [61-63]. The diagram in Figure 1.8 sums up the parameters influencing the toner-paper interaction in the process of electrostatic toner transfer.

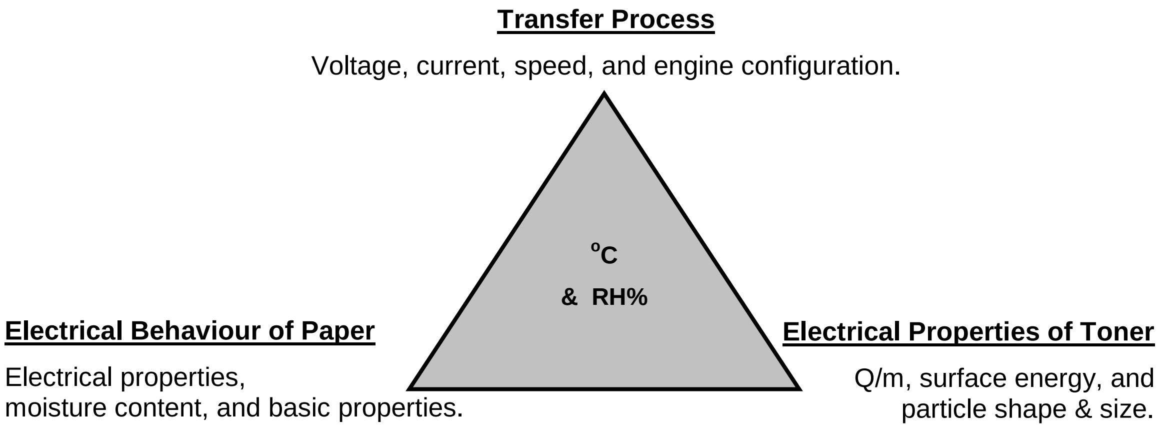

Fig. 1.8 Toner-paper-process interaction in electrostatic toner transfer.

1.3 Toner fusing

After the transfer step, the dry toner particles are slightly adhered to paper to facilitate transportation to the fusing unit for permanent fixing. As it is the final stage in electrophotography, the fusing process dominates the final physical and optical print quality. The energy applied in this step, should be compatible to the thermoplastic materials of the toner in order to allow softening, sintering, spreading and penetration into paper [60, 64-68] to take place prior to solidifying [60, 67, 68] as a fixed printed image. Figure 1.9 presents the phases of fusing. The fusing energy is usually in the form of pressure or heat, or a combination of both. Heat or thermal fusing is based on heat transfer that can be implemented by contact or non-contact fusing technologies. [2-5, 12, 64-68] Whatever the fusing method used, there are always three groups of parameters controlling the fusing mechanism and image quality: toner, paper and process parameters in given ambient conditions [P7, 69].

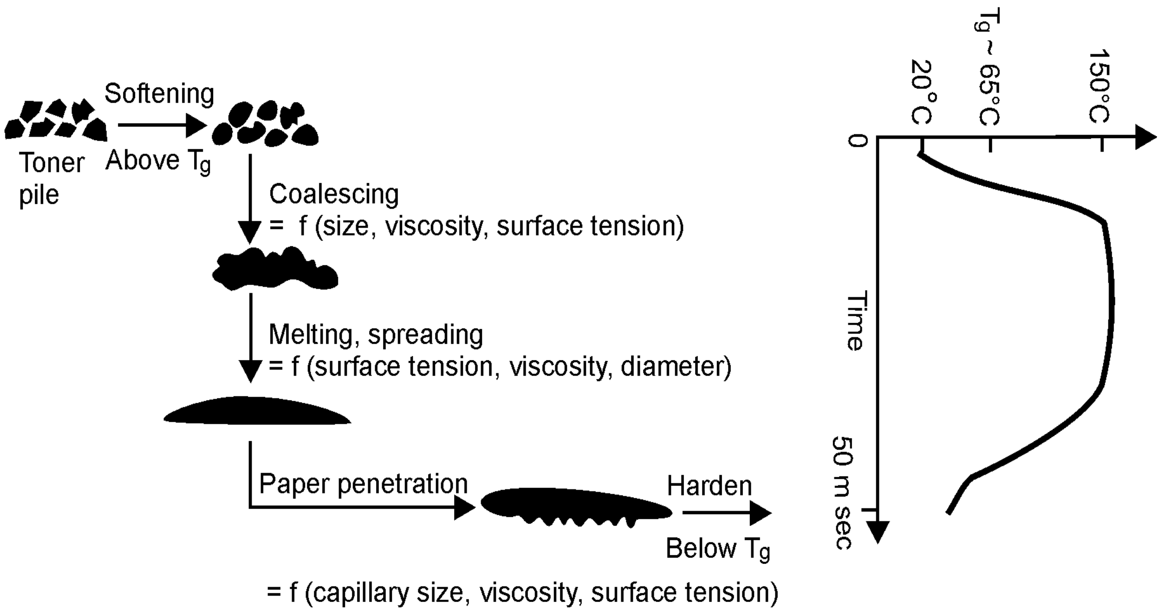

Fig. 1.9 Fusing mechanism of toner [60].

1.3.1 Heat contact fusing

In any contact fusing method, the fusing energy is applied as pressure, and as conductive heat transfer. Sometimes, pressure alone is applied by two steel rolls at room temperature, causing a high-gloss image and paper calendering [60]. The most common contact fusing technology employs both pressure and heat in a nip formed by a hot belt or roll from the image side and a hot or cold roll from the back side. To prevent the melted toner from sticking on the roll or belt, it is usually layered with a low-surface-energy polymer, and a release oil agent, such as silicon oil, is repeatedly applied on the surface of the fixing roll even in the cold nip [26, 32, 60, 64]. Figure 1.10 shows general configurations of both hot and cold nips.

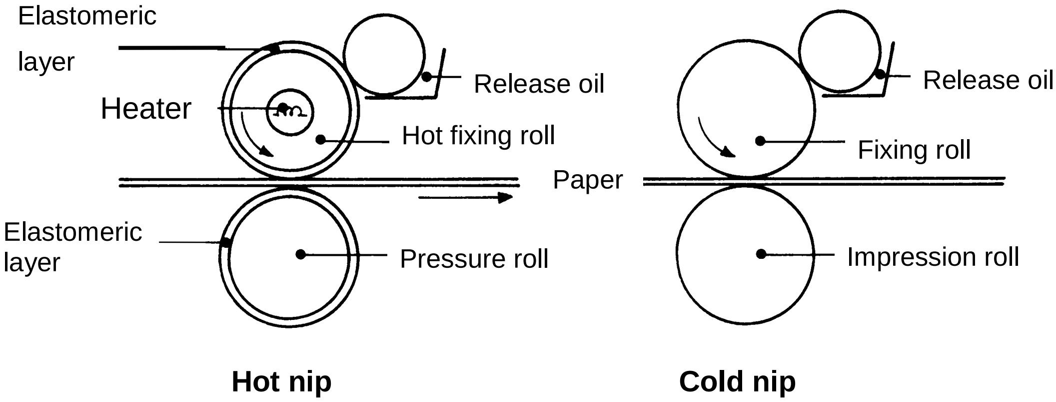

Fig. 1.10 Illustration of hot and cold nip fusing units [70].

In hot nip fusing the energy (heat and pressure) is transferred to the toner and paper. The energy is a function of dwell time determined by the process speed and nip width. The interactions of fusing process parameters with paper and toner properties influence image fixing quality. These parameters are shown in Figure 1.11.

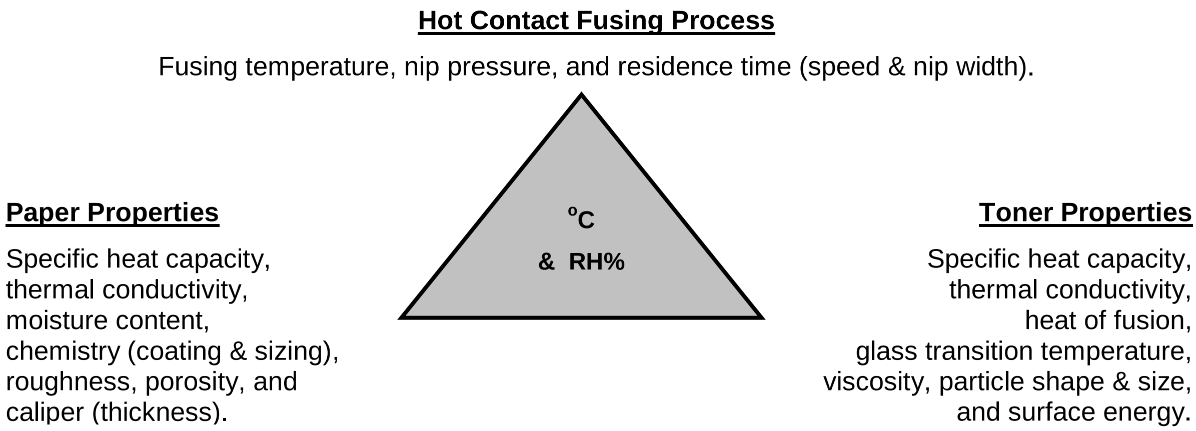

Fig. 1.11 Toner-paper-process interaction in hot contact fusing.

Image fixing quality is primarily controlled by the rheological characteristics of the toner [68, 69] that are designed according to the fusing process parameters. Therefore, toner properties are sometimes considered as part of process parameters. Paper properties also play an important role in governing the process of toner fusing and the quality of fixed image, especially in contact fusing. A significant amount of heating energy absorbed by the mass of paper, regardless of the image size and toner amount, needs to be fixed on this paper. If the grammage of paper is high, then at a given moisture content there is a larger amount of water, so it will absorb a higher amount of heat compared to low-grammage paper, leaving the rest to the toner, which may not be enough to complete all the fusing phases to produce acceptable fixing quality. In this argument the competition is between the amount and the thermal conductivities of the material compositions of paper and toner. In another words, which material is faster in picking up the heating energy available for the duration of the nip dwell time [P8]. Where is the limitation of the paper grade that allows the toner to get enough heat to reach melting point, and lowering the viscosity, while it is still under the nip to benefit from the pressure for better toner penetration, adhesion, and image strength. Coating colour is an additional component involved in the previous argument, and also causing the change in paper porosity structure and permeability to influence the toner spreading, penetration and adhesion [69, 71]. The surface sizing chemical of uncoated paper and the roughness of the paper are also known to improve the toner adhesion [69, 72, 73]. Therefore, the toner fusing mechanism in hot contact fusing should be discussed and analysed together with the thermal behaviour of paper in a defined fusing system and ambient atmosphere using a simple dynamic heat transfer model. This was the approach used in publication [P8].

Within the fusing range determined by cold-set and hot-set offset, toner, paper and fusing parameters interact differently depending on how far or near they are to the ends of the fusing limitations [P7]. The toner on the peaks of the paper roughness profile gets very glossy because of the direct effect of heat and pressure (nip calendering). If the paper is very rough, the toner in the valleys of the surface does not get into good contact with the fusing roll, so the area remains matte due to the effect of heat only. The calendering effect is proportional to the nip pressure and paper thickness, so reduced nip pressure results in reduced gloss and in optical density variations. The proportion of the reduced pressure energy should be compensated by increasing either the dwell time (or nip width) or heating energy to achieve the same level of physical fusing and to improve optical quality [3, 4, 74]. The nip width is proportional to the thickness and elastic modulus of the elastomer layer [74], so when the thickness of a softer layer is increased, the nip pressure is reduced and nip width is increased. By adjusting the fusing parameters and using a pre-determined variety of paper grades, different levels of image quality can be obtained due to different interactions and mechanisms of energy contribution to toner and paper [P6, P7].

1.3.2 Flash fusing

Flash fusing is one of the non-contact fusing methods available for toner image fixing. In this process, high uniform-intensity radiation energy supplied by a high-powered Xenon lamp with short pulse width is applied to soften the toner and to allow it to melt and flow into the paper, so it will be fixed permanently. The flash fusing process can be implemented alone as a main fusing unit or in combination with any other fusing technique, depending on the speed, the desired quality and application. At an early stage of implementation in 1978, it was combined with cold pressure fixing as a post-fusing method in high-speed black and white prints, to remove the gloss and improve the fixing quality [3-5, 76, 77]. Recently, it has been used alone to enable high-speed, high-quality digital colour printing of about 400 ppm [82] to compete with newspaper printing in the "on demand" printing market [82, 83].

The mechanism of Near-Infra-Red (NIR) flash fusing is designed to apply the fusing energy selectively to the toner only and without any contact with the toner and the paper. Theoretically, the black toner of about 2-2.5% carbon black [58] absorbs almost all the wavelengths, including the NIR radiation, whereas paper reflects this wavelength range. Other colour toners have negligible absorption of NIR, so suitable proportions of infrared absorbers and heat-sensitive materials have to be added to each colour to allow all the colour toners to perform similarly to that of black toner fusing. Colour darkness is a side effect due to optical non-transparency of NIR and heat additives [82, 84]. Since flashing and other non-contact fusing methods depend mostly on the toner's sensitivity to the fusing energy, and the availability of this energy, they can be used in a wide range of applications, regardless of the paper grade or other media [P3, 78-83].

If the fusing energy is high enough, either in the form of heat, pressure, or both, the toner fusing mechanism will follow the same phases as depicted in Figure 1.9: sintering, spreading and penetration. First, the toner particles become spherical prior to cohering to each other. Then the toner spreads and penetrates into paper as much as its weight and viscosity, and the smoothness of the paper surface allow spreading and penetration. In contact fusing the pressure helps the toner to flow while deforming it. In this phase the paper surface starts to interact with the pressure, generating a competing situation between toner spreading and penetration. The toner spreads more on a smooth surface, and penetrates deeper into a rough one [67-69, 85-87]. In flash fusing, there is no pressure to serve this role in the fusing mechanism, so the toner should be highly sophisticated and allow adequate fusing with the available flashing energy. As a result, a toner with a small and narrow particle size distribution and with a uniform spherical shape will require less energy for fusing [33, 78]. The chemical composition could also be changed to increase toner fluidity by adding a low-molecular material such as wax [33]. The paper could be pre-heated before the actual flash fusing to reflect as much radiation as possible [67, 69, 88], and to reach faster the thermal equilibrium at the toner-paper interface [67, 89]. The temperature of this thermal equilibrium is considered to be the fusing temperature [74]. More than one flashing lamp with an efficient reflection system can be used to increase the fusing efficiency and to overcome the shortage of time in high-speed printing [90].

The paper surface can be treated with polymer particles interacting with toner to increase the image adhesion. However, any attempt to customise the paper is ineffective compared to optimisation of the process parameters and toner properties. The suitability of a given paper grade for different printing processes and applications is dependent on the papermaking process, economic scale and the specific properties of the paper in question. The three groups of variables influencing flash fusing quality are shown in Figure 1.12.

The advantages of flash fusing as a non-contact method are due to the absence of pressure and image deformation. High image sharpness and very small dot gain lead to minimising the edge noise and high detail rendering of the image [P6, 91]. The flash fusing method supports high-speed printing of various paper grades with no jams and wrinkles. Finally, it is easy to maintain and operate with zero stand-by energy and heat-up time [82].

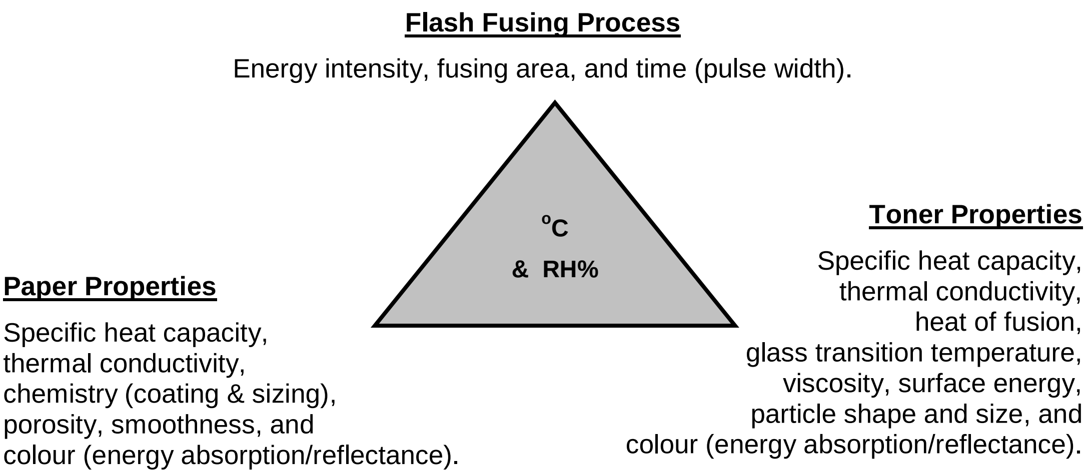

Fig. 1.12 Toner-paper-process interaction in flash fusing.

2 EXPERIMENTAL

Within the framework of this thesis, several experimental approaches were used to examine the role of paper and the interaction between toner, paper, and the parameters of the toner transfer and fusing processes. In all experiments, the relevant toner and paper properties were determined either by direct measurements, or provided by the projects' partners. In the transfer and fusing experiments, the process parameters were controlled, adjusted and monitored as input variables or output data. This was achieved by constructing and installing special devices for the pre-selected printers that would fulfil the experimental approaches. Also, some modifications were made in the printers used in the experiments in order to produce different input variables, especially in the fusing units. The details of these installations and modifications will be discussed with the experimental arrangement of each set of data. The results were evaluated through direct optical measurements of the printed images such as density and gloss and their variation, and indirectly where the toner adhesion rates were calculated. Microscopic tools were used to characterise the image sharpness, edge noise, dot size and print structure resulting from different input variables or technologies. Additional results were obtained through online acquisitions and monitoring of output data of toner transfer and fusing, such as the transfer current, temperature and moisture content. All the experiments of this research were carried out under controlled humidity and temperature conditions according to TAPPI standards. The test images were designed independently according to each experimental approach to predict and measure the change in outputs.

2.1 Toner and paper measurements

Toner and paper properties related to electrostatic transfer and thermal fusing were measured in conditions similar to those in the experimental processes. In addition to the physical and chemical properties of the toner, particle shape, size and their distributions are known to influence transfer efficiency and fusing quality. These properties are usually determined by microscopic imaging and provided by the toner manufacturers as a part of the data sheet and technical specifications. Two toners manufactured by two different processes were used: an irregular toner produced by the typical crashing or grinding method, and a spherical toner of uniform size and controlled properties, produced by the chemical method [93].

A description of the measurements of toner properties and the results can be found in the publications in which the relevant toner properties are part of the input experimental variables. Average particle size and the charge to mass ratio (q/m) were measured to characterise the electrostatic toner transfer. In the fusing experiments, the following toner properties were measured: glass transition temperature, melting energy, viscosity, surface energy, and the change of specific heat. Related to the flash fusing experiments [P3], the absorption/reflection of visible and near infrared (NIR) radiation of the four toner colours were determined as well.

Different coated and uncoated paper grades were used in the experiments. Some of them were specially made for the experiments provided by the partners of the projects [P2, P5, P8], and some others were commercial grades used in the experiments that did not require detailed knowledge about composition of the papers. Electrical properties, such as volume and surface resisitivies, charge decay time, and surface potential, were measured by the partners. These properties are affected by the moisture content of the paper; therefore the moisture content was monitored during the experiments in controlled humidity conditions. In flash fusing experiments, the absorption/reflection of the visible and NIR radiation was measured from both sides of two white paper grades: 80 g/m^2 uncoated and 100 g/m^2 coated.

2.2 Transfer experiments

In order to study the toner transfer mechanism and the electrical behaviour of paper in a dry electrophotographic process, several sets of experiments were designed [c.f. P1, P2, P5, P6] according to the diagram presented in Figure 1.8. The experiments are listed in Table 2.1.

Table 2.1 Toner transfer experimental design.

Method	Target
Special installation for monitoring, adjusting and controlling the transfer voltage	To test the toner transfer efficiency, and the role of paper and its properties in the transfer step
Special installation to measure and monitor the transfer current, online in a real-time process	Used as an online tool to characterise the transfer process, electric behaviour of paper and toner, and the effect of the environmental conditions
Measuring q/m of toners	To study the toner behaviour in an electric field
Measurement of basic and electrical properties of paper	To understand the inter-relation effect of paper in the toner transfer step
Nine sets of different toner transfer parameters and configurations (9 different printers)	To compare the detail rendering and image quality in publication [P6]
Microscopic imaging / image analyses tools	To illustrate and study the differences of the outputs and correlate them with the input variables
Image measurements	Such as image gloss and density to be used for evaluating the results
Basic laboratory instrumentations and measurements	To measure and/or control the humidity, moisture content, toner amount, and paper properties such as grammage, density, thickness etc.
Different paper grades were used as variables	
Different toners were also used as input variables	
Different test images to fit each experiment and allow relevant measurements and/or observation	

For experimental purposes, a four-color multi-pass laser printer with a transfer drum (TD) was selected. The configuration of the printer is shown in Figure 1.5. It was equipped with a device for adjusting the transfer voltage of each toner colour transfer in the range from zero to 2000 Volt. To monitor the transfer process, the printer was equipped with a system for measuring the transfer current. The installation allows the flow of current in the transfer zone to be recorded as the photoconductor revolves. The transfer current measurement is sensitive to any change in electrical properties of paper due to its moisture content at different humidity levels, or the use of different paper grades. It is also sensitive to changes in the colour and toner amount of the printed image.

Therefore, several experiments were carried out with a real printing process including the variables of transfer voltage, the image, the paper grade, and humidity level. The transfer current was monitored and measured for each case. The test image was designed to sense and measure the changes in the outputs, such as the transfer current and toner amount. The transferred toner amount was weighed for each print before the fusing step. Optical density was measured before and after fusing.

2.3 Fusing experiments

The fusing experiments were designed to study the influence of paper, toner and process parameters on the fusing mechanisms of contact and non-contact methods, and the resulting print quality. The experimental designs are listed in Table 2.2. In contact fusing, the variables of the fusing process were obtained by selection and modification of different contact fusing technologies. This was intended to cover the variation in fusing quality between cold- and heat-set offset in order to optimise the image fixing strength when using different paper grades [c.f. P7]. An additional purpose was to allow adjustment of the fusing parameters, i.e., pressure and nip width, speed and dwell time, and temperature [P7, P8]. Variations in paper properties, such as grammage, density, thickness and roughness, which have a clear influence on fusing quality, were chosen as the other set of input variables. The test image, colour and toner were also considered as a set of variables. The ambient conditions were kept constant in some experiments and varied in others to determine the influence of ambient effects on the toner fusing mechanism [P8].

In flash fusing experiments, different sets of fusing process parameters were generated and controlled by a flashing unit that was constructed in the Department of Media Technology for this experimental purpose. The variables are the pulse width and the intensity of energy supplied by the flashing lamp. These two parameters determine the effective fusing energy, and they are affected by many factors. More details about this unit will be presented in the section discussing toner fusing.

Table 2.2 Experimental design in fusing experiments.

Fusing method	Adjusted variables
Hot nip fuser	Dwell time, speed and temperature of both rollers
Hot (soft & hard) nip fusers	Pressure and roller hardness
Soft belt fuser	Used as a reference
Flash fusing	Fusing energy (pulse width and intensity)
Nine sets of different fusing parameters of 9 different printers	To compare the detail rendering in P6
In all the above methods	Different paper grades and toners were used as input variables
	Different test images used to fit each experiment and allow relevant measurements and/or observation

The paper properties influencing the fusing quality in flash fusing are mostly the surface properties, such as smoothness or roughness, surface chemistry, surface energy, coating materials, and the colour of the paper. Bulk properties are not important, in contrast to the case of contact fusing. Toner is playing a major role in the flash fusing process. Therefore, the four toner colours are designed specifically for this technology to absorb similar amounts of the near infrared (NIR) radiation and to transfer it as heat for melting and fixing at the same rate. Toner fusing should be accomplished in a very short time as determined by the pulse width designed to match the printing speed. Flash fusing toners should have functional properties to produce high-quality fixing without pressure. A chemical toner of spherical shape and small particle size was used. It should be different from typical irregular ground toners in terms of viscosity, melting energy, temperature of glass transition, surface energy, thermal conductivity, heat capacity, the polymer resin selected, carbon black concentration for the black toners, and the thermal and NIR additives for other colours. Some of these properties were measured for different toners to evaluate the flash fusing results [P3]. Optical image measurements and fixing rates were the main tools to investigate the results.

3 RESULTS AND DISCUSSION

3.1 Toner transfer

3.1.1 Monitoring the transfer voltage

Monitoring the transfer voltage in a real printing process was the first step to evaluate the experimental installation of transfer voltage adjustment, which is important to characterise the transfer mechanism of several marking technologies. It was found that the selected printer shown in Figure 1.5 can be operated in two transfer modes. These are shown in Figure 3.1.

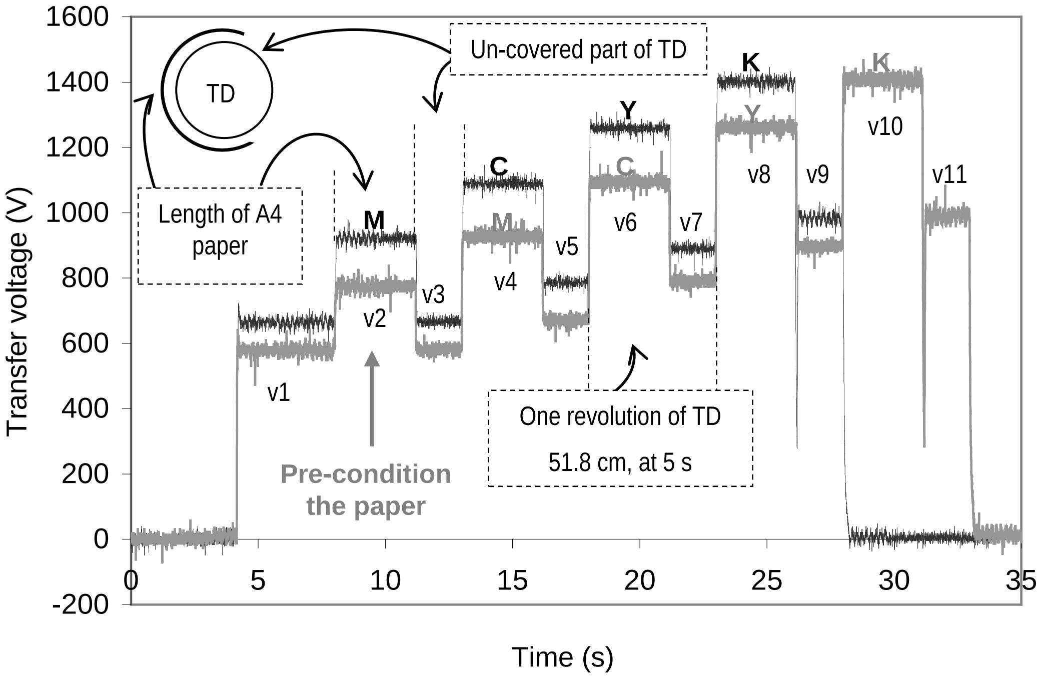

Fig. 3.1 Transfer voltage of one A4 page colour print in two quality modes; low (black) and high (grey).

The black colour data refer to the low-quality transfer mode were the transfer drum-TD rotates four times to register each colour at each revolution in a colour sequence of Magenta-M, Cyan-C, Yellow-Y and Black-K. In the high-quality transfer mode of grey colour data, the TD rotates five times. The extra revolution (*v2* + *v3*) takes place in the beginning to pre-condition the paper electrically by a voltage level of *v2*, prior to the same sequence of four-colour registrations in the remaining four revolutions. In both modes, the transfer process starts by applying *v1* for pre-conditioning the TD before the paper is involved. The single complete revolution of 51.8 cm, which is the circumference of the transfer drum, takes five seconds. The transfer voltage at each revolution consists of two levels. The first level is applied to the length of A4 paper (29.7 cm), which is the actual toner transfer voltage. This level denoted by *v2*, *v4*, *v6* and *v8*, respectively for each colour of M, C, Y and K in the 4- transfer mode, and by *v4*, *v6*, *v8* and *v10* in the 5- transfer mode. The second level of transfer voltage is applied to the remaining part of the TD circumference, which is not covered by paper (51.8 – 29.7 = 22.1 cm). This level is denoted by *v3*, *v5*, *v7* and *v9* to complete the revolutions of M, C, Y and K respectively in the 4-transfer mode, and *v5*, *v7*, *v9* and *v11* for the same sequence of MCYK in the 5-transfer mode. In Figure 3.1, the transfer voltage is increased after each revolution to overcome the resistance of the previous toner layer.

The transfer voltage of each colour is at the same level in both low- and high-quality modes. Clearly, the terms (low) and (high) quality are based on the pre-conditioning the paper at the fist of the five revolutions mode. This is the fist impression of the role of paper in toner transfer. At the pre-conditioning phase, no toner is transferred, but the paper will have enough time to be polarised and build up sufficient charge density to attract the toner at the next stage. In the absence of this pre-conditioning revolution, the paper and toner are facing one another in the transfer zone and at the same time the surface charge of the paper is building up. This means whenever some region gets enough charge, it will attract the toner selectively based on the charge to mass ratio, regardless of the location determined by *x*, *y* of the image.

Accordingly, toner attraction and transfer to paper is a function of the time required to build up a sufficient charge density on the paper surface. This attraction may not occur at the right time. It means that some toner particles are transferred early or late and left or right of the correct position. If the wrong position is a part of the image area, the effect is non-uniformity and unevenness of the image, such as mottling and graininess [94], and if it is just out of the image or near the edge of the image in the empty part of the paper, the effects are satellite formation, high edge noise and less image sharpness [91, 94, 95, 96, P6]. If the wrong positions are far from the image, the printed sheet will be dirty. The above phenomenon is associated with all transfer configurations. It occurs mostly in the pre- and post-transfer zone, where the electric field between certain points of paper and PC is high enough, but in the wrong position.

The introduction of the blade transfer technology has eliminated the effects of the pre- and post-transfer zone due to the narrow distribution of transfer voltage applied by the sharp edge of the blade under a high electro-resistive belt that transports the paper [94]. In high-quality mode the toner is expected to be transferred efficiently as a continuous layer. However, in the low-quality mode the toner particles are transferred in fragmented batches according to the weak and non-uniform surface charge density that develops faster on the paper surface compared to the extra charging time in the high-quality mode. The unevenness of toner and paper properties were considered when designing the two quality modes.

3.1.2 Adjusting and controlling the transfer voltage

Successful adjustment and control of the transfer voltage and measuring the transfer current corresponding to each adjusted value has been the core for building up many experiments in this study. Figure 3.2 shows three different adjustments of the transfer voltage. The dark grey data is the manufacturer transfer voltage setting representing the situation where the printer is operating in a normal low-quality printing mode of four revolutions. In this situation, the transfer voltage is applied to the TD at nine different levels, for full-colour prints. The installation of a controlling device helped to adjust those nine levels independently from zero to 2000 V. The light gray series in Figure 3.2 presents the adjustment of the nine levels of transfer voltage at a similar value of approximately 710 V. The black series represents the situation where level 4 (*v4*) was adjusted to be zero (in the figure it is not zero, because there is voltage applied by the current measurement device to complete the circuit). This voltage raised the current value by 10 μA, and all the rest were kept at 710 V. Level 4 is the voltage applied to transfer the cyan colour. A sample of a cyan image was printed under different input voltage levels to examine the efficiency of toner transfer.

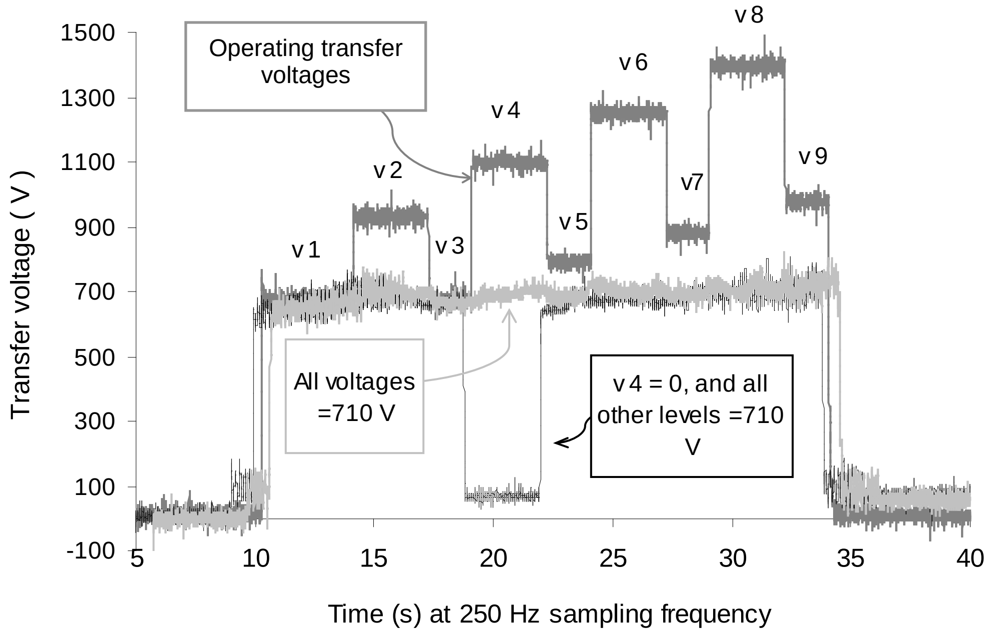

Fig. 3.2 Flexibility in adjustment of the transfer voltage.

3.1.3 Measurement and analysis of transfer current

The installation of current measurement allows capturing the current data between the photoconductor and the transfer drum when the transfer voltage is applied. Figure 3.3 presents the rough data of the transfer current collected during the printing process of one A4 page using the high-quality transfer of the 5-revolution mode.

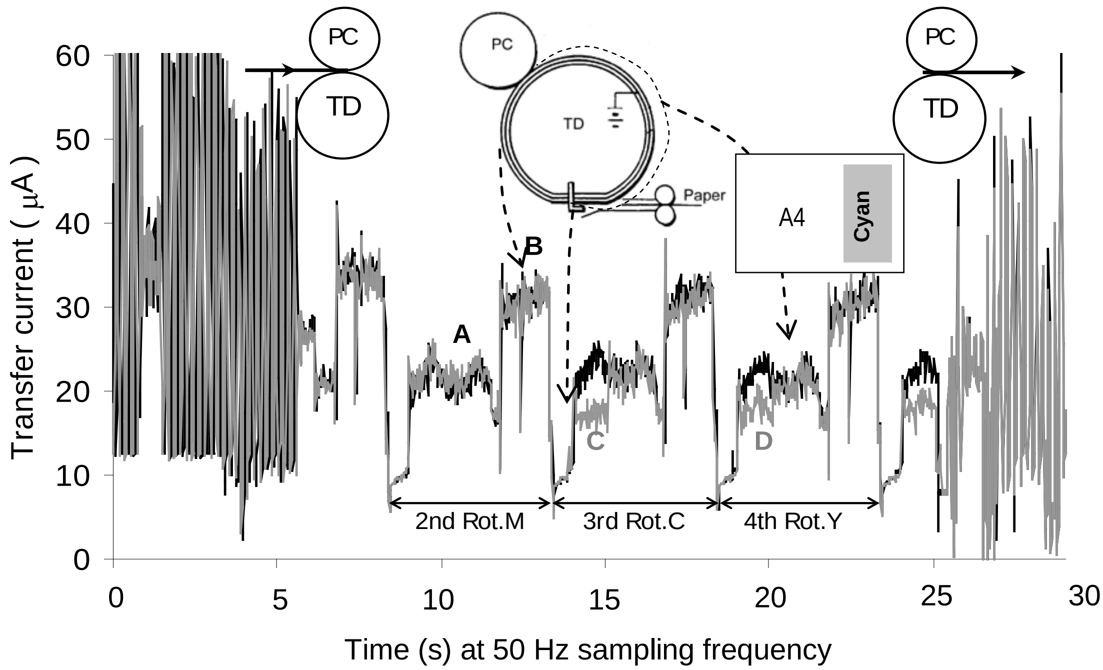

Fig. 3.3 Transfer current data of one A4 page in high quality mode.

The black colour data corresponding to the process of passing an unprinted A4 sheet five revolutions without transfer of toner or printing any image. The grey colour data is the transfer current where the cyan toner is transferred at the 3rd revolution (3rd rotation of the transfer drum) as a solid, full-coverage cyan rectangle image (10 cm, at the long side of A4 × 16 cm, at the short side of A4). Both trials were done under controlled temperature and humidity conditions, using the same paper grade and the same operating values of the optimum transfer voltage in high-quality mode, as shown previously in Figure 3.2.

The highly fluctuating current data during the first and last revolutions are due to the nature of the process where the paper is not completely attached to the transfer drum, and the design of the current measurement region. This is the transfer zone between the transfer drum and the photoconductor. At the 1st revolution, the current data starts to be recorded before the paper reaches the transfer zone, and at the last revolution (the 4th in the low-quality mode, and the 5th in the high-quality mode) the current data continues to be recorded, even though the paper has passed through the transfer zone and started to be released from the transfer drum, prior to entering the fusing unit. Also, at both ends, there are other voltages applied to the paper; the attraction voltage prior to the 1st revolution to help the paper to be attached to the transfer drum. At the last revolution the detached or pick-up voltage is applied to neutralise and remove the paper from the transfer drum [97-99]. The operation of the voltages overlaps the operations of the transfer voltages at the 1st and the last revolutions, respectively. Therefore, the electrostatic interactions at the two ends produce uncontrolled and fluctuating voltages, consequently resulting in fluctuating current data.

At the 2nd revolution, both the black and grey coded current data in Figure 3.3 show nearly the same behaviour, since the same paper completes this revolution without any toner transfer. As noted before, all the current data shifted up by 10 µA to allow the current measurement at zero value to be recorded (in other words to avoid the situation of an open electric circuit). A single revolution of the transfer drum is represented by two levels of transfer current data. The low-level values around 20 µA indicate the transfer current across the resistivities of paper (the length of the A4 page) and the transfer drum layers. In the figure, this level is denoted by A. The second level of the high values around 40 µA, which is labelled B, is the transfer current across the resistivities of the transfer drum layers only (the transfer drum is constructed of several electro-resistive layers) [54]. So, the difference between these two levels is due to the paper's resistivity. With this experimental arrangement, using the pre-determined input variables, the output transfer current data measures the differences between different paper grades. The inputs could be the grammage, coating colour, thickness and density, moisture content or any other paper property that is influenced by the bulk properties of the paper, such as its electrical properties.

The cyan toner transferred to paper is predicted by the grey current data at the 3rd revolution denoted by C, compared to the black current data where no toner is transferred. Clearly, the difference between these two levels consists of the toner transfer current or the current due to toner transfer. According to the transfer mechanism, the charged toner particles developed as an image on the photoconductor are attracted by the surface charge accumulated on the paper surface as a result of applying the transfer voltage. The charged toner particles move through the transfer field across the transfer zone to neutralise the surface charge density on the paper in the image area. The charge Q (in coulomb) movement in a time t (in seconds) is actually the current $I=dQ/dt$ (ampere), and this movement is through the xy-plane of the image to the same xy-plane on the paper. So, the charge movement is through an image area A; that is the definition of current density $J=I/A$ (ampere/meter^2) which is measured in this experiment [35-36, 54]. However, the phrase "transfer current per unit area" or just "transfer current" was used because the image area is the same on the PC and paper when comparing two trials, or two relevant parts of the current data collected from one trial. From the transfer current, image area, particle size and charge to mass ratio (Q/m) of the toner, and the weight of toner amount transferred to paper, the number of toner particles transferred to paper can be calculated, using the approximate assumption that the toner layer thickness of solid image is about 30 µm for an average toner particle size of 10 µm [5]. The result could also be compared and correlated to another measurement approach that enables simple numerical calculations from the microscopic image and dot and image sizes for assessing the reliability of the toner transfer current.

The 4th revolution is intended to transfer the yellow toner, if there is a yellow component in the image. In these two trials, there was no yellow; only the transfer of cyan toner colour recorded by the grey data, and the passing of an empty sheet (no toner image is transferred) recorded by the black data. So, during this revolution, there is no toner transfer in either print trial, but the resistance of the cyan toner layer transferred during the 3rd revolution is predicted by the current data at the 4th revolution, which is marked D, and this effect will continue to be seen at the non-fluctuating part of current data in the last revolution. This means that the current data responds sensitively to any change in the materials passing the current measurement zone between the photoconductor and the transfer drum, whether the change is in the paper or any sheet properties, in the toner materials or image colour and structure, or both in the image and the printed sheet. This part of the data was used to study the toner transfer to paper in different conditions, and to develop the experimental toner transfer model presented in the second publication [P2], which was found to be consistent with the theoretical model of toner transfer [45].

The experimental installations for controlling and measuring the transfer voltage and transfer current were used in many experimental approaches of this study. The experimental inputs can be any of the following five sets of variables. 1st: variability in the image, such as image size, halftone, colour, and image location in the paper. 2nd: variability in any of the bulk properties of the paper or any other dielectric sheet. 3rd: different toner types with the differences associated mainly with toner shape, size and charge to mass ratio (the chargeability of the toner). 4th: any of the previous set of inputs could be tested under a variety of humidity conditions. 5th: is the wide range of the transfer voltage at each colour revolution (0 to 2000 V) allowed to be adjusted as the main variable of the transfer process parameters. These alternatives produce a significant matrix of approaches to study the outputs in terms of transfer current, the toner amount, and image quality before and after fusing. The diagram in Figure 3.4 highlights the experimental approaches.

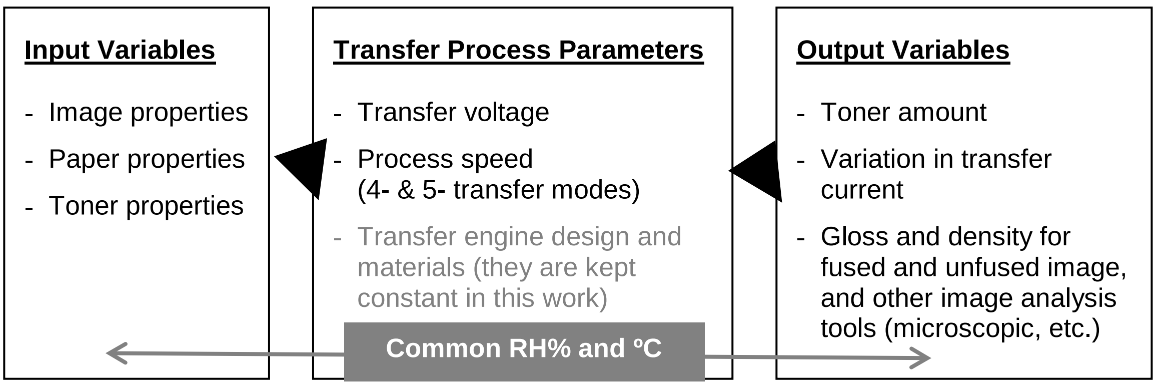

Fig. 3.4 Diagram of possible toner transfer experimental approaches.

3.1.4 Role of image properties in toner transfer step

In this experiment, the test image printed on an A4 sheet consisted of two parallel yellow strips of equal area but different halftone percentages; 25% grey-scale percentage and 100% solid image. The non-print area can be considered to be 0%. The high-quality transfer mode of five revolutions was selected with the designed operating value of transfer voltage relevant to each revolution. Figure 3.5

shows the current data of the toner transfer process at the 3rd and 4th revolutions of the transfer drum during printing of the test image shown in the lower right corner of the figure. At the 3rd revolution, where the cyan toner is transferred, the straight horizontal line represents the current data during the passage of the A4 sheet in the length direction, and there is no evidence of cyan toner transfer, because the image is designed to be yellow. So the current here results from the transfer voltage applied at this revolution and the resistivity of the empty A4 sheet.

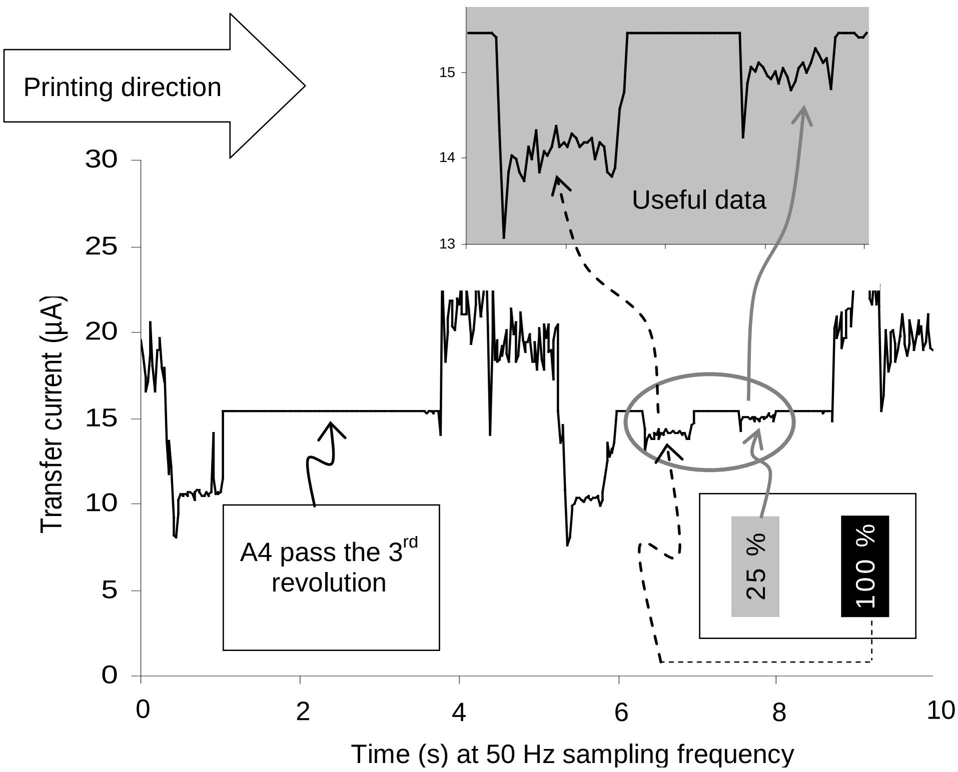

Fig. 3.5 Transfer current data of printing yellow image.

At the 4th revolution, where the yellow developed image is transferred from the photoconductor to paper, the changes in current data due to the transfer of yellow toner is clearly indicated to show the difference in toner amount transferred to a similar image area with a different halftone percentage (25% and solid). Magnifying and studying the current data of the printed image will provide a lot of information about the transfer process. This is true especially of the *x*-axis, which is the axis of the printing process direction. The current data is collected from the revolutions of the photoconductor as a function of time, at two levels of frequency; 10 and 50 Hz. So, the current in this experiment shows which colour is printed, the toner amount at each halftone, and partially, at the x-axis only, the type of image and image location on the A4 sheet. In this experiment, the transfer current was used to characterise the image.

3.1.5 Role of paper properties in toner transfer

When the paper reaches the transfer zone between the photoconductor and the transfer drum, the configuration is as presented in Figure 1.7, simply a “parallel-plate capacitor” filled by paper, toner layer, and an air gap. Some engines are designed to eliminate the air gap, but in practice the air gap cannot be avoided due to the variations in toner particle size, different toner colours (layers) and halftone structure of the image, and the thickness and unevenness of the surface profile of the paper. According to equations 2, 3 and 4 discussed earlier, the dielectric thicknesses of these layers (toner, air and paper) control the electric field to transfer the charged toner particles from PC to the TD. The dielectric thickness and other electrical properties of the paper are functions of its bulk properties, which are mostly dominated by the grammage and the thickness of paper.

The grammage is an important identification of any paper grade. Figure 3.6 shows the transfer current recorded for the 3rd and 4th revolutions to transfer a full-coverage A4-page yellow image to four different paper grammages of nearly the same density. At the 3rd revolution with no toner transferred, the higher grammage, the higher the transfer current obtained. This means in given transfer voltage and humidity conditions, that paper with a higher grammage creates a higher surface charge density, proportional to its polarisation effects [20, 100, P2, P5] and is therefore ready to pick up a greater amount of toner at the next 4th revolution.

For each paper, the differences between the current level at 3rd revolution denoted by A and the current level at the 4th revolution denoted by B is the current due to toner transfer. In Figure 3.7, they are plotted against the grammages to illustrate the relationship between toner transfer current and paper weight. Papers of the same grammage do not necessarily display the same transfer behaviour. The thickness or density, materials composition, surface treatment, and fibre type and orientation all have a strong effect on the electrical properties of paper. The relationship between the grammage and the transfer current presented in Figure 3.7 is influenced by the speed of the printing process, the paper grammage range used in electrophotography, and the applied transfer voltage that should not cause dielectric breakdown within the possible range of relative humidity of 20%-80%.

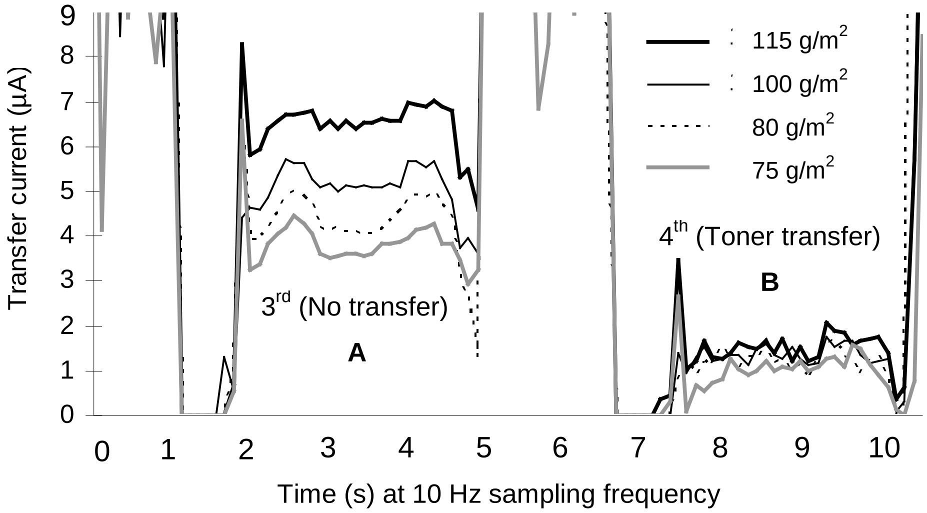

Fig. 3.6 Transfer current of printing four paper grades.

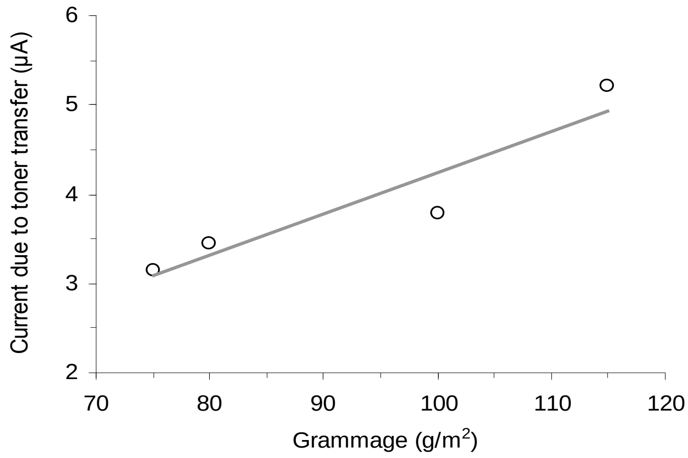

Fig. 3.7 Current due toner transfer to different paper weights.

3.1.6 Role of ambient conditions in toner transfer

The electrical properties of paper are related to its bulk also called basic properties. These relations are governed mostly by the moisture content (m.c.%) of the paper, which is quite sensitive to any change in ambient conditions; the relative humidity (RH%) and temperature. Toner and printing process parameters are also subject to ambient effects, but under strict control as part of the machine design, whereas the paper is the end user's choice. In these experiments, the transfer current was measured from papers in different humidity conditions. Some of the electrical properties of these papers were defined in the same conditions so as to study the influence of ambient conditions on electrostatic toner transfer. Table 3.1 shows the transfer current and the moisture content measured from two paper grades at four humidity levels. The data are illustrated in Figure 3.8.

Table 3.1 Moisture content (m.c.%) and transfer current at different RH% levels.

100 g/m² coated paper			80 g/m² uncoated paper		
RH%	m.c.%	Tr. Current (µA)	RH%	m.c.%	Tr. Current (µA)
76.30 %	11.43	2.645	72 %	9.88	1.939
60 %	9.18	5.530	60.20 %	8.58	5.544
50 %	8.02	6.220	52 %	7.59	6.038
45 %	7.42	6.260	44.50 %	6.97	6.383

Figure 3.8 presents the relationship between the transfer current and the moisture content. It shows how the moisture content of paper influences the transfer current during toner transfer. An increase in the RH% of ambient air results in an increase in the m.c.% of the paper, in turn decreasing the volume and surface resistivity of the paper. The sensitivity of the transfer current to moisture changes is remarkably high, but slightly better, or less fluctuating for 100 g/m² coated paper compared to the electrostatic performance of 80 g/m² uncoated paper within the experimental range of relative humidity. This is due to the higher resistivity of this grade, as shown in Figure 3.10. The coating colour thickness and its compressibility on both sides of the base paper have an effect on the grammage, density, pore structure, homogeneity and the surface profile, which all improve the resistivity of the paper. Figure 3.9 is a reproduction of the 80 g/m² uncoated grade data in Table 3.1.

It shows that the moisture content somewhere between 60% and 72% relative humidity causes the paper to lose its ability to establish enough surface charge density, which is essential for toner transfer. In all the figures where the transfer current appears, it demonstrates that the surface charge density determines the amount of toner transferred to paper.

At a higher humidity level, the moisture content of the paper is increased and the paper becomes more conductive. In this situation, both volume and surface resistivities of paper are decreased. This means that the paper will leak away part of the electric energy that is supplied by the transfer voltage. The remaining part may not be enough to produce the desired surface potential and to build up a sufficient surface charge density through the polarisation effects. Therefore, paper attracts less toner particles from the photoconductor. Figure 3.10 shows that the transfer current represents the surface charge density of paper. It is increased as the surface resistivity of the paper is increased in the direction of low relative humidity to reach a suitable electrostatic situation for toner transfer at a lower moisture content. The surface and volume resistivies are proportional to each other [101, 102], and both are sensitive to the ambient conditions [103, 104]. As a result, they are responsible for the electrostatic behaviour of paper. The higher the surface and volume resistivities, the lower the leakage current and the less conductive the paper is, which is better for fast establishing higher surface potential to accumulate higher surface charge density. In the transfer situation this is recorded as transfer current. This is clearly evident in Figure 3.11.

Figure 3.12 illustrates the relationship between the surface potential and the surface resistivity of many paper grades at two different humidity levels. According to the previous discussion, the lower humidity level of 20% provides a better situation for paper to reach a higher surface potential for toner transfer. This situation was accomplished by the low moisture content in all paper grades of this test, which in turn resulted in higher surface resistivities compared to the humidity conditioning of 50%.

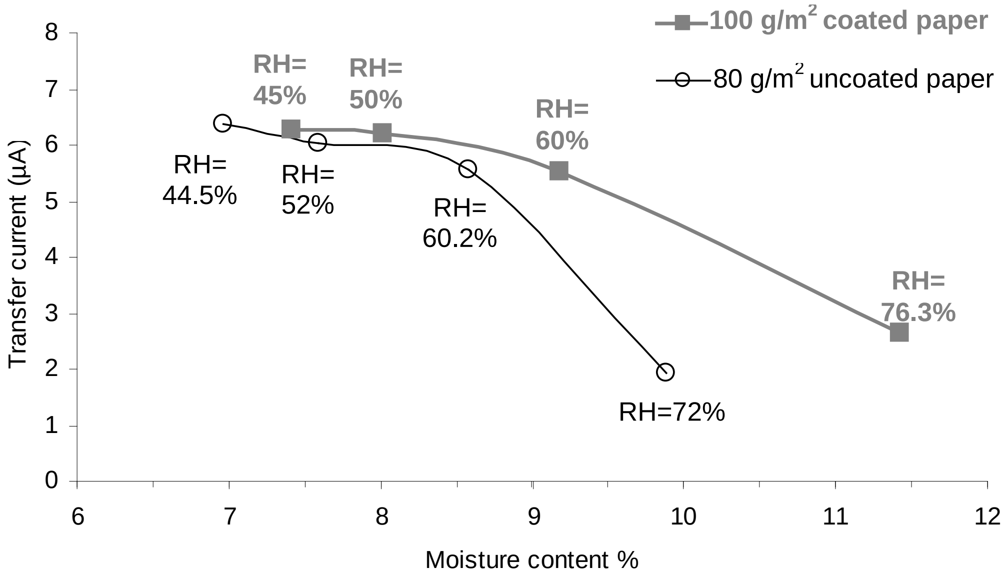

Fig. 3.8 Transfer current and m.c.% for two paper grades in different RH%.

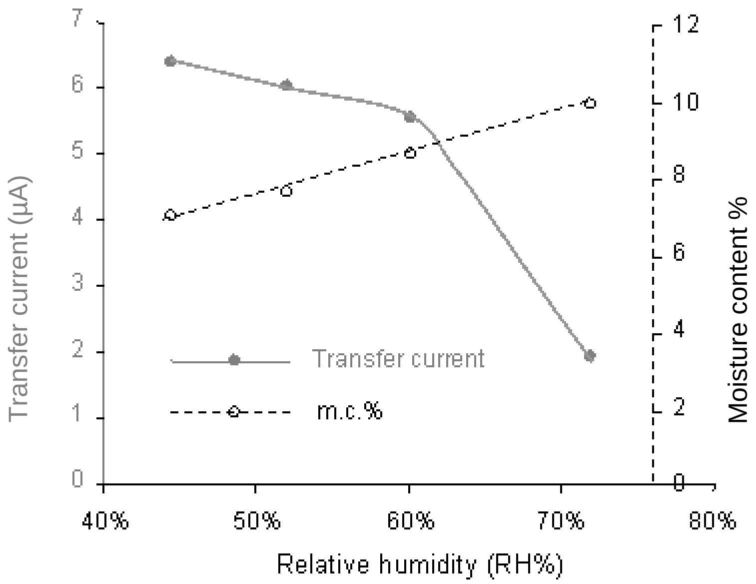

Fig. 3.9 The same data as in Figure 3.8 for 80 g/m² uncoated paper.

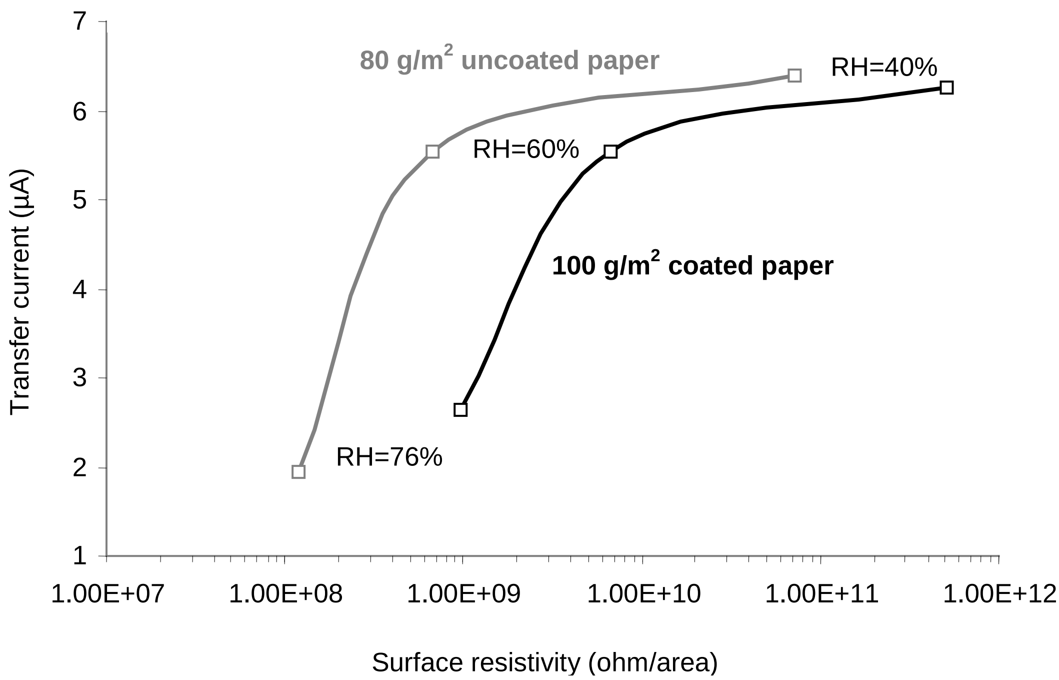

Fig. 3.10 Transfer current and surface resistivity at different RH% for two paper grades.

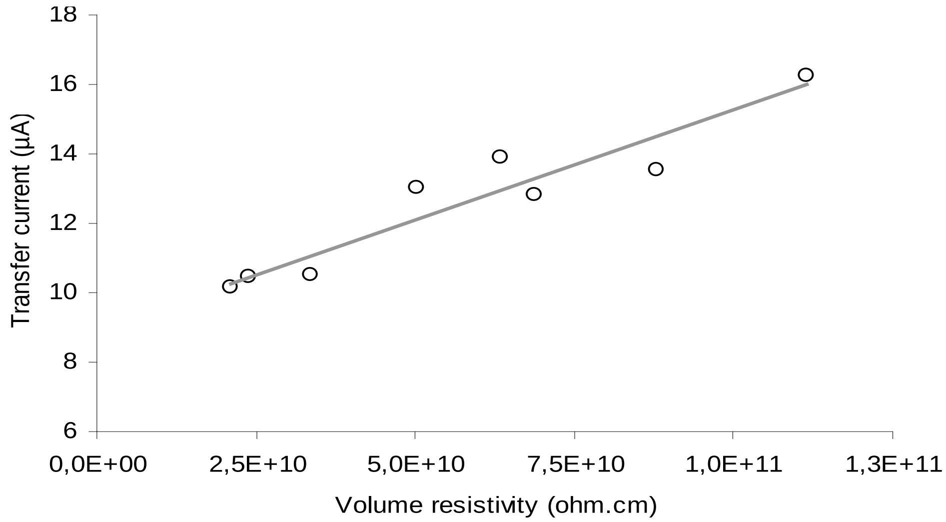

Fig. 3.11 Transfer current as a function of volume resistivity for eight paper grades.

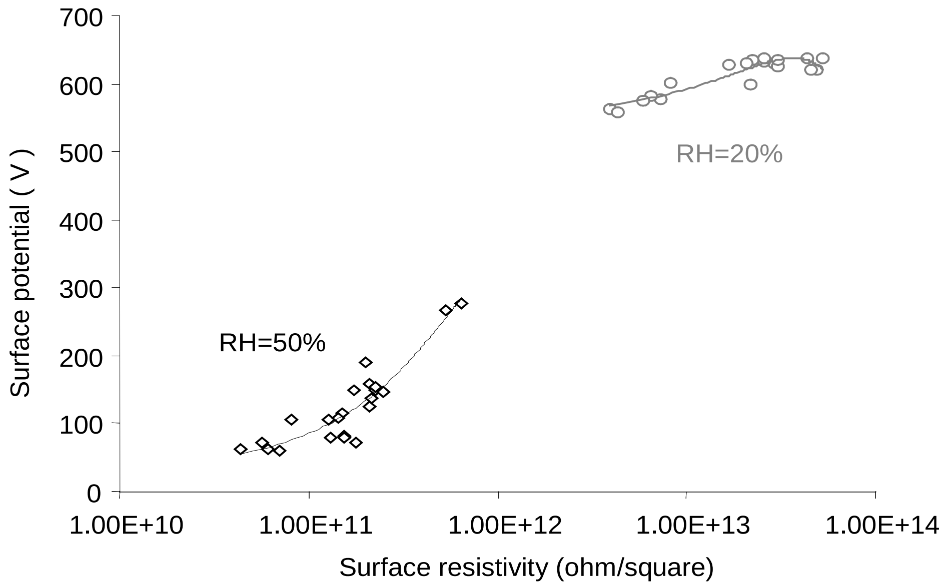

Fig. 3.12 Surface potential and resistivity of different paper grades at two RH% levels.

3.1.7 Toner transfer efficiency

Toner transfer efficiency was examined by means of the transfer current which is a new tool introduced in this study. The results were correlated to the conventional efficiency evaluation tools such as image density and toner amount, as well as to the theoretical model of toner transfer. Figure 3.13 shows the toner amount transferred to two paper grades as a function of transfer voltage, under the same ambient conditions. The test was repeated twice for 80 g/cm^2 uncoated paper to show that the measurement is highly reproducible. The toner amount transferred to 100 g/m^2 coated paper is more than the amount transferred to 80 g/m^2 uncoated paper. Previous results concerning the effect of paper properties in Section 3.1.5 showed that the higher-grammage paper reached a higher surface charge density, which in turn can transfer more toner. So, the paper grade has a considerable influence on the efficiency of toner transfer, due to its electrical properties such as volume and surface resistivity. It is also clear from Figure 3.13 that the experimental transfer curves are similar to the behaviour of the ideal transfer profile [45, 54, P2, P5].

Figure 3.14 shows that the current due to toner transfer and the amount of toner transferred to 80 g/cm^2 uncoated paper are directly related to each other and functions of the transfer voltage. The current curve also behaves similarly to the ideal transfer profile. It indicates the surface charge neutralised by the transferred toner particles. Therefore, the current curve also expresses the transfer efficiency. Figure 3.15 shows the optical image density measured before and after fusing the image, plotted as a function of the transfer voltage, presenting the transfer efficiency similarly to the current and toner amount curves in the Figures 3.13, 3 .14 and 3.15 . This conventional method provides additional support to the transfer current to be used as a tool for expressing the toner transfer efficiency and characterising different transfer situations.

Figures 3.13, 3.14 and 3.15 show that some toner is transferred to paper even if the transfer voltage is in the range between zero and 200 V , which is not enough to create any surface charge on the paper surface. This is due to minimal contact between the developed image and the paper surface (no air gap or a very small one), or the attraction voltage which is used to register the paper to the TD. The negative values of transfer current in the transfer voltage range (0-200 V) appear because the electric field created by the toner charges is higher than the fields created by transfer voltages in the range mentioned. The current will reach zero at the point where the summation of both fields equals zero (both electric fields have equal values in opposite directions). This point is somewhere around a transfer voltage of 200 V. Each point on the slope of these three figures presents the remaining force of toner adhesion to the PC, which is decreased gradually as the electrostatic force increases until a certain value relevant to the approximate transfer voltage of 600 V is reached.

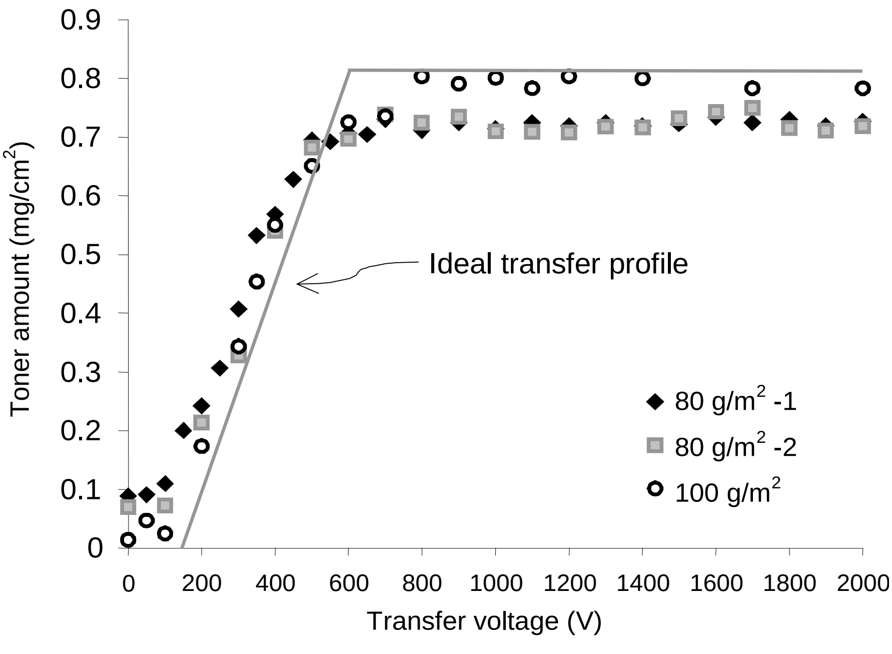

Fig. 3.13 Toner amount transferred to two different paper grades under different transfer voltages. The ideal transfer profile is also shown.

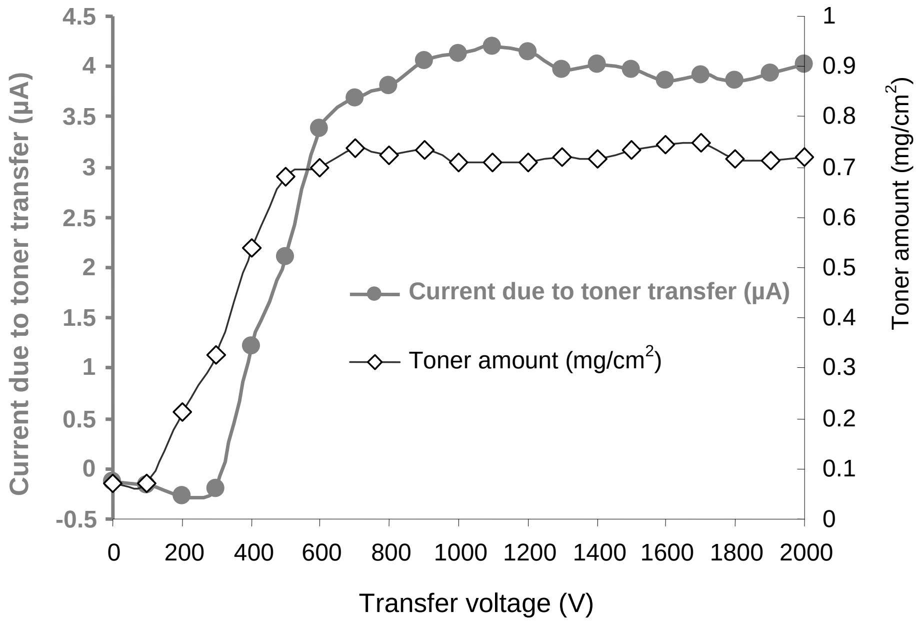

Fig. 3.14 Toner transfer efficiency presented as transfer current and toner amount as function of transfer voltage.

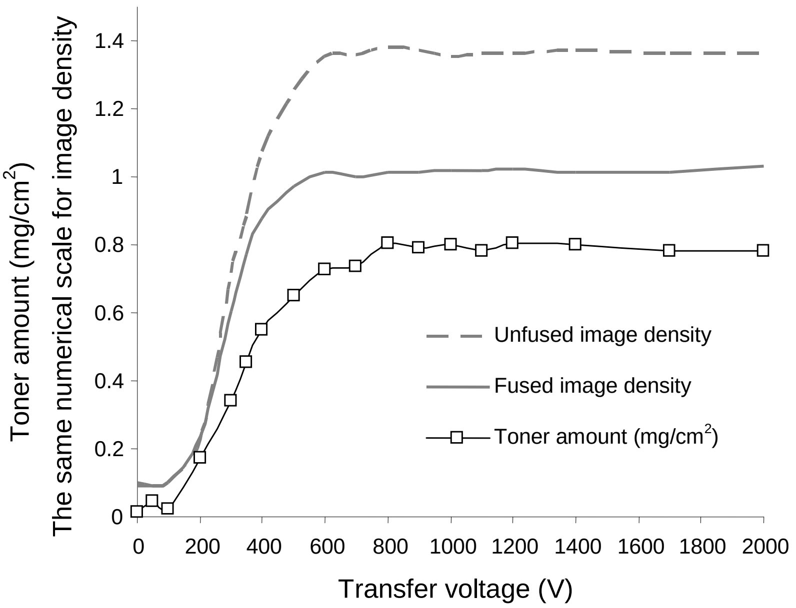

Fig. 3.15 Toner transfer efficiency presented by optical density before and after fusing, together with the toner amount as a function of transfer voltage.

3.2 Toner fusing

In the fusing step, the energy is applied as conductive heat transfer in a contact roller nip or as radiation from a flashing unit. The process variables of hot contact fusing are the fusing temperature, nip pressure and residence time (dwell time) that determine by the fusing speed and nip width. The process variables in flash fusing are the pulse width and the intensity of energy supplied for certain area of fusing window. In this work, these parameters were controlled and adjusted by four different contact fusing technologies sketched in Figure 3.17, and one flash fusing unit. They are described in the following (for a summary, see the diagram in Figure 3.19):

1st) Hot rollers. In this unit, both fixing and backing rollers are exactly the same in terms of materials and dimensions. They are heated with adjustable temperature from 20 to 230 ºC, and run with the selected speed between 30 and 720 mm/s. In terms of pages per minute, the speed range extends from 6 to 145 ppm. Due to the wide range, speed was used as a means to study the thermal behaviour of paper and the mechanisms of fusing. This unit was also capable of reaching the limit value of heat set offset, because it applies high pressure of about 43.5 kPa to form a nip of 5 mm, and supplies high heating energy for both the image and back side of paper. Figure 3.16 shows the configuration of this fusing unit, which was the main fusing unit used in the experiments of Publication 8 [P8].

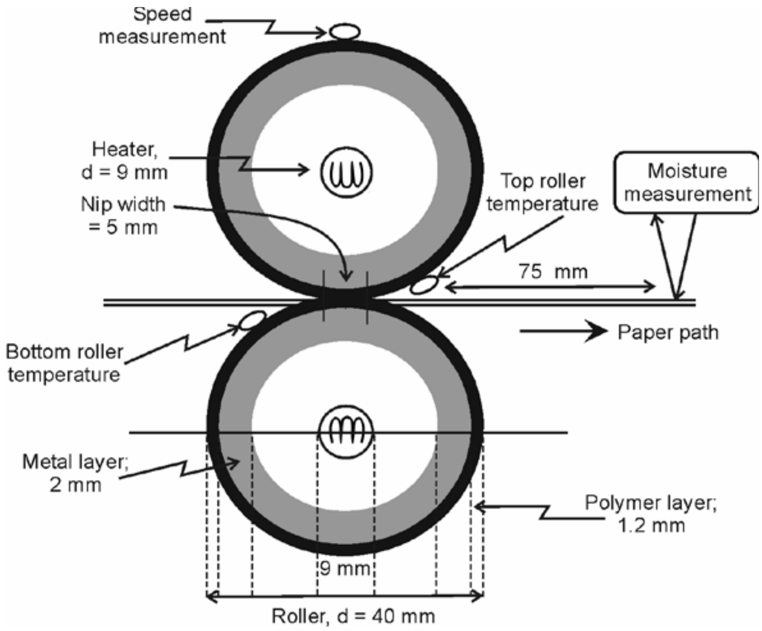

Fig. 3.16 The configuration of hot rollers (hot nip) fusing unit.

2nd) Hard nip. In this technology, only the fixing roller (at the image side) is heated to a temperature of 165ºC, and the contact width between fusing roller and back roller (nip width) is 4 mm, with a nip pressure of 45 kPa and dwell time of 40 ms.

3rd) Soft nip. The soft nip is modified from the previous one by replacing the elastomer coated layer of the back roller with a softer one of different elastic modulus. This is to obtain a softer nip with a pressure of 30 kPa. This modification produces a wider nip of 6 mm and longer dwell time of 60 ms. The speed and temperature are kept the same as in the hard nip. The new elastomer coating material of the back roller has different thermal conductivity compared to the original one, but this change will not affect the final temperature of fusing because this roller is not a heating roller but a pressure roller.

4th) Belt fusing. It is not easy to create a flat and wide nip between two rollers, so a belt fusing unit with a nip width of 10 mm was used for the other end of the fusing latitude close to that of cold offset. The unit consists of a belt of high thermal conductivity wound around two rollers: one far from the nip and the other forming the nip with a back heated roller with adjustable pressure. In this design, the heating energy is supplied through the backside of the substrate by the heated back roller and partially to the image side by the belt transferring the heat from the roller far from the nip. The idea is to reduce the heating energy supplied directly to the printed image so as to reach better quality.

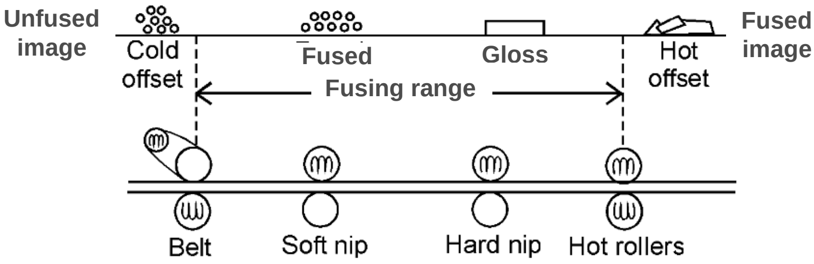

Fig. 3.17 Four Experimental contact fusing units.

5th) Flash fusing unit. The flash fusing unit was constructed for experimental purposes to adjust the fusing energy in a wide range. The output energy of this flashing unit is determined by many factors. Some of them are constant, such as the Xenon lamp specification, input voltage *V*, triggering, UV filtering, fusible area and optical reflecting system. Figure 3.18 shows the distribution of flashing energy resulting from the configuration of the optical system. Other factors are variables, such as the capacitance *C* and the inductance *L* in the electric system, used to control and adjust the output energy *E* and the pulse width $t_{1/3}$ from the equations 5 and 6:

$$E=\frac{1}{2}CV^2 \quad (5)$$

$$t_{1/3}=3(LC)^{1/2} \quad (6)$$

The time constant τ of the electric system is defined as:

$$\tau=3t_{1/3} \quad \text{or} \quad \tau=9(LC)^{1/2} \quad (7)$$

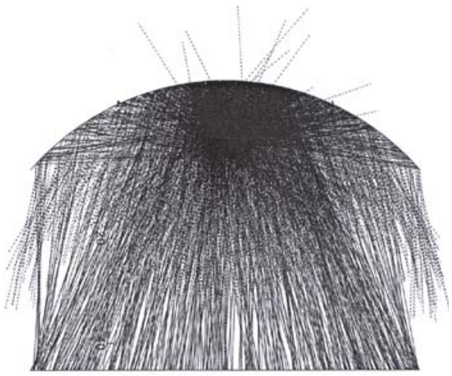

Fig. 3.18 Ray tracing of flashing energy in the experimental set-up.

In these technologies, the latitude of the fusing parameters is controlled according to the pre-study experimental fusing results, by heat and cold offset, and printed image quality. So, the range of process variables is flexible enough to allow the degree of image fusing to vary between the limits of cold and hot offset.

In addition to the process parameters, the image structure, toner, paper and the ambient environment are the factors which influence the print quality. With the help of the five experimental fusing machines, all these factors can be used as input variables to study the effect of single variables or combinations of many variables on image quality and fusing strength. Data obtained over a wide range of conditions supports an in-depth study of the thermal behaviour of paper and development of a model of fusing. The diagram in Figure 3.19 gives an idea of the experimental approaches used in this work. Publications 3, 7 and 8 cover these experiments. [P3, P4, P8]

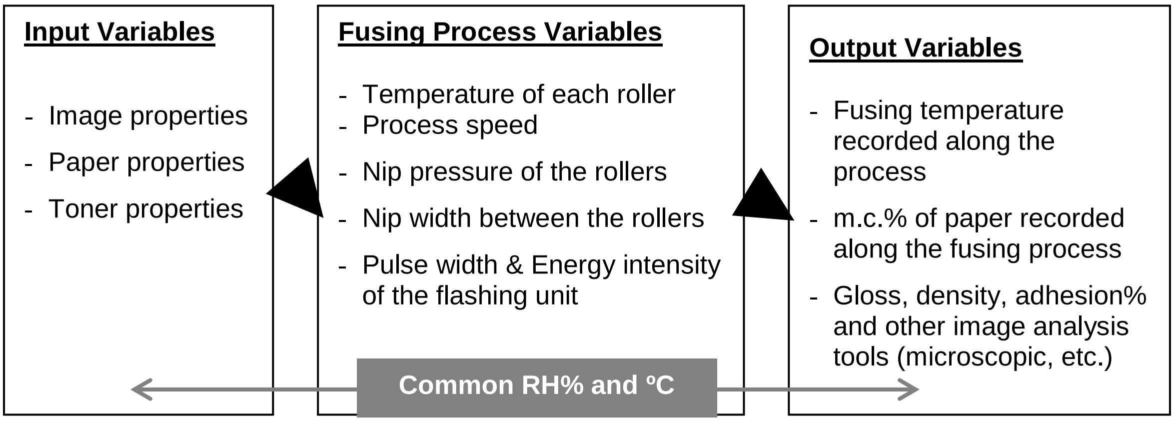

Fig. 3.19 Diagram of possible experimental approaches in contact fusing.

3.2.1 Role of fusing configurations

Preliminary experiments suggested that the gloss variation responds far more sensitively to adjustments of fusing variables than optical density. Consequently, it was of prime interest to use it as a criterion for examining the performance and roles of the fusing units for the quality of image fixing within the fusing range, and for determining the limitations of cold and hot offset. Flash fusing was included in this test because it is usually used to remove the unwanted gloss in some applications [13]. In addition, also its fusing mechanism is different because of the absence of pressure [P3]. Gloss variation was measured using an experimental gloss analyser at the 20º incident-reflectance angles for a minimum image area of 44 mm × 46 mm. The measurement was based on the concept of band-pass filtering of image. Three bands were used. The coefficient of variation in each range can be used as a measure for the strength of gloss variation. The scale of gloss variation, which was used in Figure 3.21 is a measure of the size of unevenness and it is obtained by dividing the coefficient of variation from the band >5 mm by the coefficient of variation from the band <1 mm [(>5 mm) / (<1 mm)]. The scale is lowest for fine-grained and highest for coarse-grained structures. A variety of papers with different grammages, uncoated and coated in different coating colour formulations, were used in this experiment. The test target was designed to meet the measurement requirements and to allow further examination of the results. The gloss and its variation were measured at acceptable levels of fixing strength and image adhesion and optical image density.

Based on tests with four different sets of fusing parameters, within acceptable results for the physical fusing window, each of the four fusing units was found to produce different density and gloss. In all cases ten replicate measurements were made from each of the five printed samples per one test point. According to the density measurements, different grey scale reproductions were produced from the same image at a certain grey scale %. In Figure 3.20, the higher level of densities obtained by hot rollers at each grey scale is due to heating energy being supplied from two opposite directions by both fixing and back rollers, which causes fast melting of toner and at the same time wide spreading under high pressure. As a result, image enhancement from a good level of coverage by high dot gain was obtained. From the black solid print, Figure 3.21 shows that the gloss variation of the image fused by the hot rollers is the highest. The gloss variation is an indication of print surface unevenness. The rougher the print surface, the higher the gloss variation. Reducing both energies, the heat and the pressure, and instead increasing the nip width as in belt fusing, less optical density is obtained in all grey scales, indicating less dot gain, which in turn means high accuracy (grey scale image reproduction), and less gloss variation from a smooth print surface. In belt fusing the optical image quality is improved.

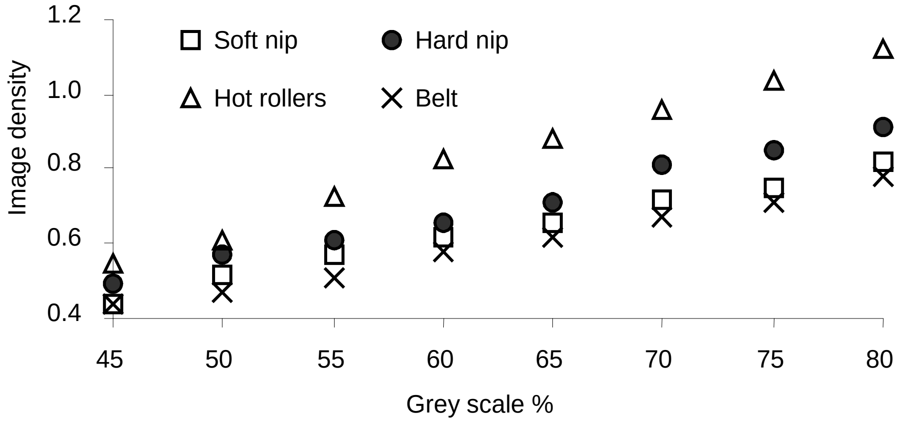

Fig. 3.20 Grey scale densities of black prints on 100 g/m² coated paper.

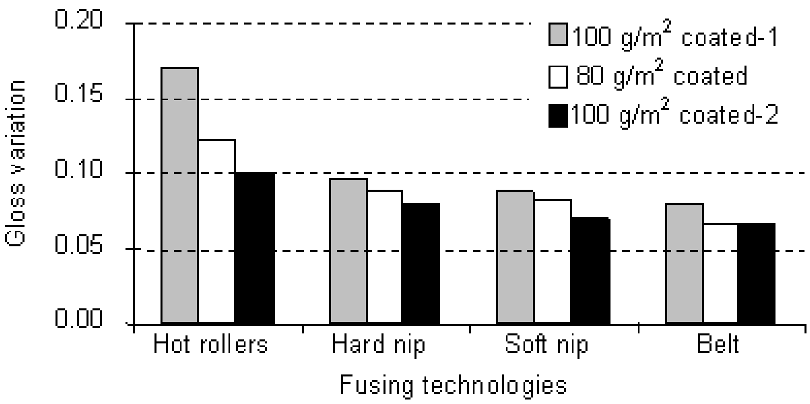

Fig. 3.21 Gloss variation of black solid print on three paper grades.

Between these two limits, the results of experiments with a hard nip and modified soft nip show the critical fusing factors influencing optical image quality. Table 3.2 shows that even the average gloss of solid green and black prints is higher with the soft nip, but still -- for both colours -- the gloss variations are lower at all the wavelength reflectance ranges. It is also clear from Figures 3.20 and 3.21 that the soft nip produces better optical image quality with less dot gain and lower gloss variation than that produced by hard nip. The only difference between these nips is the replacement of the coating material of the back roller by a softer elastomer. This modification has increased the nip width and dwell time, and reduced the pressure. It is to be expected that with the soft nip, there will be no major change in the fixing strength. From the following relationship [74]

$$K = f\,(Pt^2/MD,\ T/T_a) \qquad (8),$$

the fusing quality is a function of two dimensionless groups; (Pt^2/MD) and (T/T_a), where K is fusing quality, P is average nip pressure, t is dwell time, M is developed mass of toner per unit area on the substrate, D is average diameter of toner particle, T is fusing temperature in (Kelvin), and T_a is the ambient temperature in (Kelvin). Thus, the fixing quality is related directly to the nip pressure in one order of magnitude and to the dwell time in two orders of magnitude [74,P7]. The results show that the image quality obtained by belt fusing is better. Its energy consumption is also lower and lifetime longer.

Table 3.2 Gloss and its variation of solid prints on 80 g/m^2 paper.

Fusing unit/Sample	Gloss, %	<1 mm	1-5 mm	>5 mm	Scale
Hard nip/Green	9.4	60	17	6.5	0.11
Soft nip/Green	12	54	14	5.3	0.10
Hard nip/Black	2.8	47	14	5.7	0.12
Soft nip/Black	3.6	45	13	4.6	0.10

According to the results, an adjustable fusing system can be recommended for industrial electrophotographic machines to allow different applications meeting desired quality targets. Not all of the quality attributes are controlled and produced by the fusing step, but as it is the final stage in electrophotographic process, it has the final and definitely a crucial effect on the print quality achieved. Some of the fusing parameters examined in this study that have a clear influence on optical image quality could be adjusted within an acceptable fusing range. To ensure high performance, these parameters could be adjusted automatically according to the density and gloss variation measured from the first print as functions of different substrates and image coverage. The idea of this adjustment which will be discussed in detail later is simply done by a feedback control loop from the optical measurement system back to the fusing system.

3.2.2 Role of paper in flash fusing

In flash fusing, the colour of the paper is important. White papers reflect the wavelengths in the visible and near infra-red (NIR) range. (98%) Most of flashing energy is absorbed by black toner particles, in a mechanism similar to that of Black-Body absorption [105]. The NIR radiation spectra illustrated in Figure 3.22 were obtained by the diffuse reflectance measurement method. The figure presents the NIR radiation spectra of “normal white” coloured copy paper and, black and yellow toners. The reflectance spectrum of the paper is significantly higher than that of the black toner. The radiation energy is mostly absorbed by the black toner as the figure shows. Different white copy paper grades have nearly the same spectra of NIR radiation on both sides. This is also true for different irregular ground and spherical chemical black toners. The colour of any material is the dominating factor to determine the absorbed radiation in this range. Figure 3.22 also shows that a yellow toner reflects almost all the radiation in the wanted range. Magenta and cyan toners produce nearly identical NIR radiation spectra. These results indicate that the thermal effect of paper is neglected in flash fusing. However, the surface treatment and roughness of paper are important in toner adhesion and for the appearance of the image.

Density measurements in Figure 3.23 show the relation between unfused and flash fused images on two paper grades. The image enhancement is different on the two papers. It is higher on the smoother coated paper than on the rough uncoated paper. Image enhancement occurs (optical image density is improved) after fusing the halftone images in the range from 0.15 to 0.75 of unfused image densities. In this range, the toner particles tend to cohere to each other, creating a network across partially separated printed dots to cover the empty area in halftone images. Even though the dot gain after flash fusing is lower compared to that of contact hot roll-pressure fusing due to the absence of contact and deformation effects, it is still higher in the halftone part than the solid part of the image fused by flash fusing. This is obviously due to the easy spreading of the melted toner horizontally in a parallel direction to the smooth paper surface to cover part of the non-printed area in the halftone structure of the image. So the unfused toner area at the halftone structure of an image will consume high fusing energy for toner spreading and the area becomes larger after fusing. Because of the absence of pressure the spreading of melted toner is easier, wider and faster on a smooth surface, so the image is enhanced better on a smooth coated paper than on a rough uncoated one, where the peaks of the rough surface profile act as barriers to toner spreading [P3]. Under the roller pressure, the melted toner will penetrate into the rough surface of the porous structure of paper better than into a smooth coated surface.

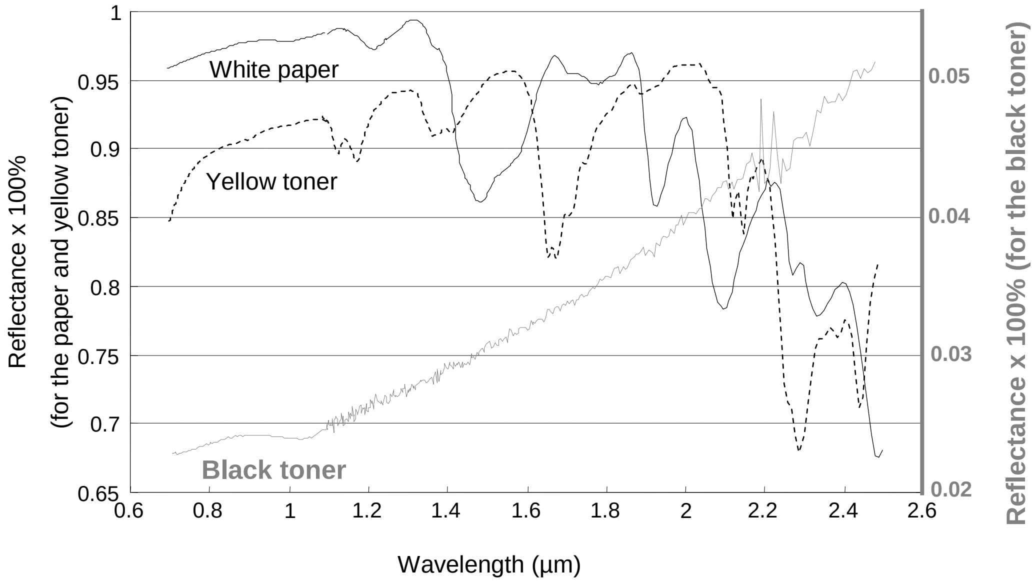

Fig. 3.22 NIR radiation spectrum of 100 g/m² paper, and black and yellow toners.

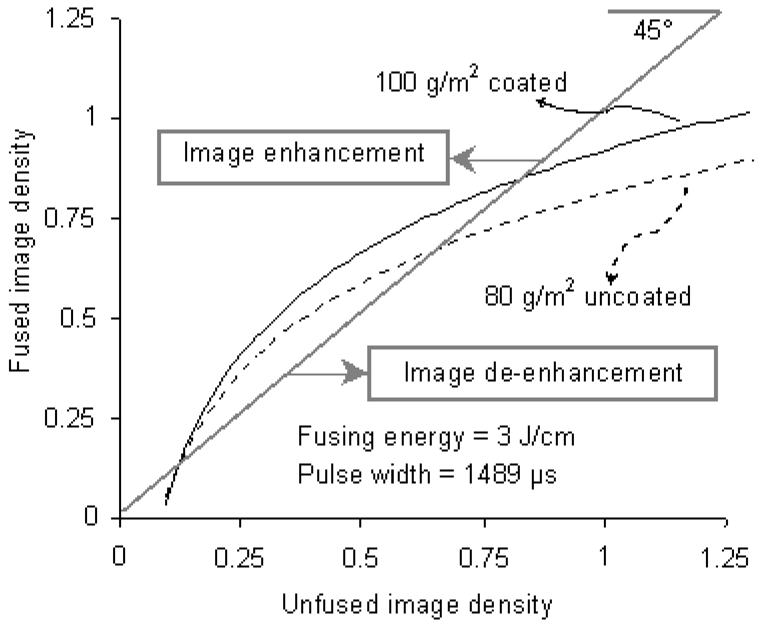

Fig. 3.23 Flash fused and unfused image densities for two paper grades.

Flash fusing in colour electrophotography is possible by adding the same proportion of NIR absorbing additives to the three colour toners. High heat sensitivity of NIR additives is required in flash fusing to ensure fast thermal transfer through toner layers to the substrate surface [83]. The achromatic nature of these additives will produce a high darkness level of the coloured image [84]. To avoid this, one solution would be to add as small a portion as possible and increase the flashing energy at the same time.

3.2.3 Role of paper in contact fusing

The role of paper in hot contact fusing was discussed in detail in publication 8 [8]. In summary, four uncoated paper grades were used in the experiments to study the behaviour of paper in hot contact fusing and the effect on image fixing quality. They are listed in Table 3.3 as A, B, C and D with their measured properties. The hot roller fusing system described in Figure 3.16 was adapted to this work to use its features for controlling and monitoring the speed and temperature of the fusing process.

Table 3.3 Measured properties of paper samples.

Paper sample	*Grammage (g/m^2)	Thickness (µm)	Density (kg/m^3)
A	160	168	959
B	85	102	812
C	80	103	766
D	70	65	1110

**Grammage given at ± 0.2 g/m^2*

The top and bottom rollers were both heated to 175ºC and kept at that temperature for some time to stabilise the system. Then it was run at the desired speed and the heating switched off, allowing the temperature of both of the rollers to drop freely. Recording the temperature data could be started at any point to cover the desired range of data. At any selected speed, when the heating was stopped and the average temperature of the rollers started dropping, a paper web with a length of 1782 mm (length of six A4 sheets) and a width of 210 mm was fed into the fusing unit at the moment (*t*) when the temperature of the rollers had dropped to 160ºC (called T_1). This temperature was always used as *y*-axis of the starting point (P_1) for feeding paper (T_1=160ºC). The temperature recorded when a paper web has passed the nip is denoted by T_2. During the course of the temperature drop, paper is heated by absorbing energy two-sidedly from the rollers. This means that the cooling rate of the fusing system is affected by the paper grade. The performance of the modified fusing system was found to be very repeatable. The experiments were made in a humidity- and temperature-controlled room. Figure 3.24 shows the cooling of the fusing system for two paper grades, compared to the reference of free cooling (where no paper was involved), at the same running speed of 30 mm/s.

Clearly, Figure 3.24 provides meaningful information for studying the thermal behaviour of different paper grades as related to its structure and other basic properties such as grammage, density, thickness etc. In this figure, the temperature of free cooling dropped by (-11.4ºC). The minus stands for cooling of the system rather than heating. Paper sample C of 80 g/m^2 caused the average temperature of the rollers to drop by (-20.4ºC). Paper sample A of 160 g/m^2 caused a temperature change of (-26.9ºC). The three cases of temperature changes occurred over a time period of about 60 s, which it took for the 1782 mm long web to pass the nip. It is important to note that the temperature data recorded include the energy transferred to the atmosphere in free cooling, and the energy used to heat the paper. When the paper web had exited the nip, the temperature of the rollers started to rise again. This means the paper conducted the heat from the polymer layer faster than the polymer conducted it from the metal layer, which is due to the lower thermal conductivity of the polymer layer compared to the metal core. This difference can cause a non-linear temperature gradient between the layers.

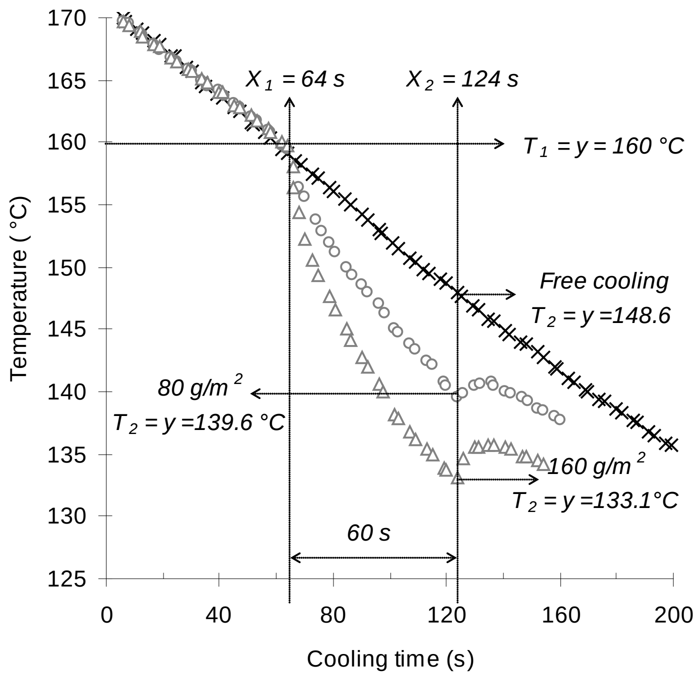

Fig. 3.24 Cooling of contact fusing with two paper grades (80 and 160 g/m^2), and free cooling (without paper) as reference.

To facilitate mathematical treatment, the real values of x_1 and y_1 were inserted in P_1 and the point P_1 (64s, 160ºC) as in Figure 3.24 moved to *x, y* (0, 0) the origin coordinates in Figure 3.25, and the rest of the points were moved accordingly. In both figures, the *x*-axis is the time scale denoted by *t* and *y*-axis is the temperature scale denoted by *T*. The area limited by the data points and the *x*-axis is a measure of the heat transmitted from the rollers. The best fit equation for the data points of free cooling is a straight line. The curves for cooling in the presence of paper are in the form of ($y = ax^2 + bx$).

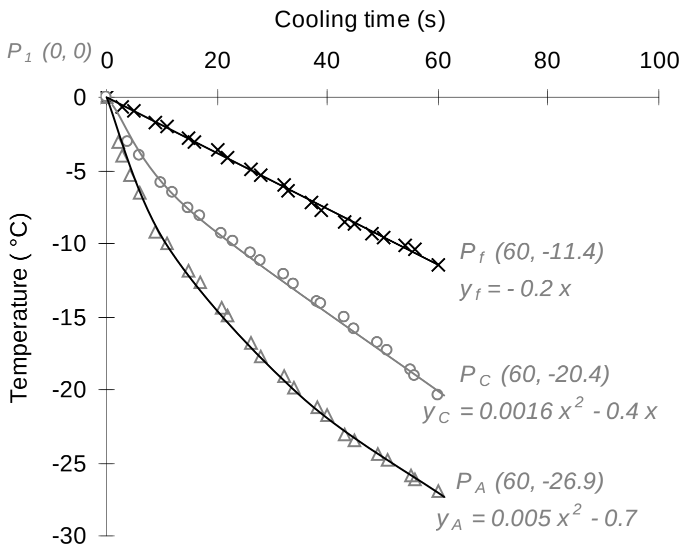

Fig. 3.25 The same curves of Figure 3.24 but in (0, 0) coordinates.

The thermal conductivity, *k* is the intensive property of a material that indicates its ability to conduct heat. It is defined as the quantity of heat *dQ* transmitted in a time interval *dt* (heat current *dQ/dt*) through a thickness *L*, in a direction normal to a surface of area *A*, due to a temperature difference *ΔT*, under steady state conditions and when the heat transfer is dependent only on the temperature gradient (*ΔT/L*). This definition is taken from the law of heat conduction, which is also known as Fourier's law [35,106,107]. Equation 9 gives expression to both; the thermal conductivity *k* measured in watts per meter-Kelvin ($W \cdot m^{-1} \cdot K^{-1}$), and the heat current *dQ/dt* measured in watts or (Js^{-1}):

$$k = \frac{Q}{t} \times \frac{L}{A \times \Delta T} \qquad \text{or} \qquad \frac{dQ}{dt} = \frac{kA}{L} \Delta T \qquad (9).$$

It is assumed that the heat transfer is governed by a heat current (*dQ/dt*) given by equation 9, which is mostly affected by temperature change ΔT. This assumption was suggested based on steady state heat flow (model) due to conduction in a uniform sheet [35] and supported [108, 109] for the similar experimental conditions, which are time dependent [107]. Therefore equation 9 solved for the time, and the following values are obtained;

The heat transfer at free cooling Q_{free}, expressed by the temperature change during 60s is;

$$Q_{free} = \int_0^{60} (-0.2t)dt \approx -360 \qquad (10).$$

The heat due to paper sample C during 60s is;

$$Q_C = \int_0^{60} (0.0016\, t^2 - 0.4t)dt \approx -600 \qquad (11).$$

The heat due to paper sample A during 60s is;

$$Q_A = \int_0^{60} (0.005\, t^2 - 0.7t)dt \approx -900 \qquad (12).$$

The negative values of the heat amounts refer to heat released by cooling of the fusing rollers, from which the average temperature is recorded. The heat is assumed to be conducted to paper, and from that standpoint the values are positive. The unit area in this calculation is temperature (ºC) per time (s), which was assumed to be proportional to the temperature gradient over time or heat current represented by Equation 9. The heat current is equal to the heat amount per time (*dQ/dt*), and the three cases of temperature changes have occurred at the similar time of 60s, which may allow considering the integration results as heat amount, which in this case is a function of temperature change. The heat due to paper C is 600 – 360 = 240 unit area, and the heat due to paper A is 900 – 360 = 540 unit area. It turns out that the ratio of heat calculated for samples A and C, is nearly equal to or close to the ratio of temperature changes of the same cases.

$$\frac{900}{600} = 1.5 \cong \frac{26.9}{20.4} = 1.32$$

This ratio remains approximately the same if it is correlated to the net temperature changes caused by papers;

$$\frac{900}{600} = 1.5 \cong \frac{(26.9 - 11.4)}{(20.4 - 11.4)} = 1.7$$

This suggests that temperature change alone can be used as a measure of the thermal behaviour of paper. This applies for instance to the influence of speed. Speed as a variable in the experiments provides a way to test the dynamic thermal behaviour of paper. Figure 3.26 shows paper C fed into the fusing system at five different speeds of 30, 50, 70, 90 and 110 mm/s. Free cooling data for each speed is available for calculation of conducted heat current in dynamic conditions, but the temperature differences may be enough to be counted and plotted against the speeds. The techniques used in producing Figure 3.26 were repeated for all the paper samples. The relationships between speeds and temperature changes are illustrated in Figure 3.28.

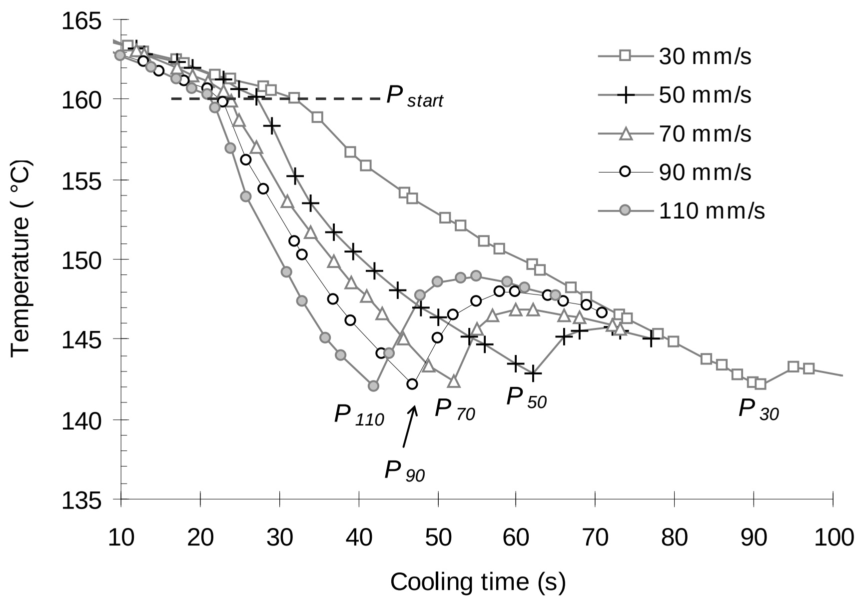

Fig. 3.26 Paper C fed to the fusing system run at five speeds.

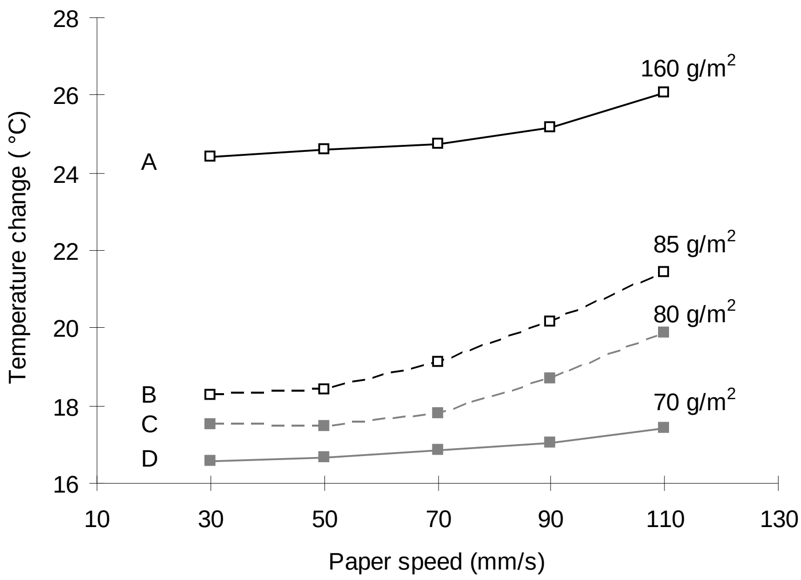

Fig. 3.27 Temperature changes of the rollers due to paper samples at five speeds.

Based on Figure 3.27, the temperature change increases as the process speed is increased for all the samples. This is made understandable by the fact that at the lowest speed of 30 mm/s the system radiates heat into the atmosphere for about 60s, while the paper web is running and absorbs the major part of the energy from the system. At the highest speed of 110 mm/s, the paper web takes about 16s to pass the fusing nip. In this shorter time, less heat is radiated from the system to the surrounding atmosphere, and instead the paper absorbs more energy as indicated by a greater temperature change. This is also an indication that the heat is conducted to the paper at a higher rate than the heat transferred to the atmosphere -- at least under these experimental conditions. Also, according to Figure 3.26, the temperature change as an indicator of the effective thermal conductivity of paper is strongly correlated with the grammage of all the samples. There are also some interrelated effects of density, thickness, moisture content and paper structure [52], but grammage, as a direct function of paper mass, is the property governing the thermal behaviour of paper. It is known that thermal conductivity is a weak function of paper density, but it also has a noticeable effect on the thermal diffusivity of paper, which is to some extent related to the filler content [110]. Therefore, based on the relatively small effect of paper density evident in Figure 3.27 for different speeds and samples, density clearly acts by reducing the slope of the curves so that a temperature change in a dense paper (such as samples A and D with the densities of 959 kg/m^3 and 1110 kg/m^3 respectively), is less affected by the running speed. This more stable thermal behaviour is beneficial in real applications allowing the paper to be used in a variety of electrophotographic machines running at different speeds.

3.2.4 Influence of coating on the thermal behaviour of paper

The coating colour is an important factor that influences the thermal behaviour of paper. Figure 3.28 demonstrates the temperature changes of a base paper coated with a single low weight coating colour, and a base paper with double coating layers and a silk surface finishing. The first coating colour has caused a drop in the slope of the temperature change curve, i.e., the slope is less than that of the base paper. This means that the paper behaves thermally in a more stable manner at different fusing speeds. The same result is evident in Figure 3.27 when the paper density increased. According to Figure 3.28, the second coating layer reproduced the results shown in Figure 3.27 when the levels of temperature change were increased at all the speeds due to the higher effective thermal conductivity gained by the mass of coating layers.

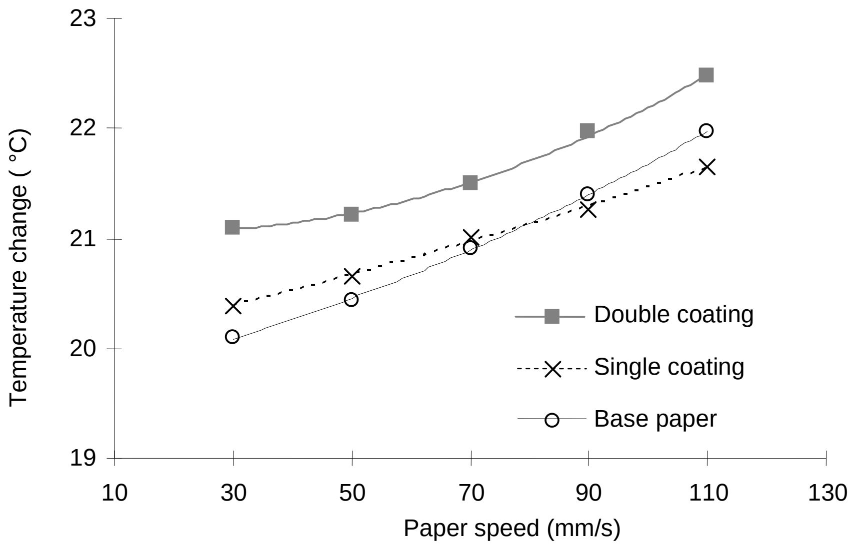

Fig. 3.28 Effect of coating on thermal behaviour of paper.

Regardless of the type of coating colour, coating is meant to improve the printability of paper by improving its uniformity of grammage, thickness and density, and surface smoothness [P5, P8]. The pressure of the experimental fusing unit was kept constant, but the compressibility of the paper was increased by the additional thickness of the coating layers. Because of the smooth surface obtained by coating and silk finishing, the effective contact area between the smooth paper surface and hot rolls is larger than with rougher [P5, 111], and good contact usually increases the thermal conductivity [112]. The coating method was also found to have an influence on the thermal properties of paper [64, 100,111].

It is difficult to establish a relationship between fusing quality of image and physical paper properties, because some correlation could be due to different surface energies produced by different paper chemistry, surface additives and coating colour formulation [72]. In this experiment, coated paper was merely tested to get a general idea of the effect of coating. Simply, it stabilises the thermal behaviour of paper, and increases the thermal conductivity.

3.2.5 Thermal effect of paper on image fixing quality

Table 3.4 provides some information about toner images printed on the four paper samples identified previously in Table 3.3, using black and cyan. A sheet carrying the un-fused toner image was fed as the 2nd sheet in the sequence of six A4 sheets forming the paper web. The hot roller fusing unit was run at the speed of 70 mm/s (about 14 ppm). The experiment was repeated for each of the samples A, B, C and D. Basic image quality factors such as density, gloss and adhesion strength were measured from both black and cyan regions as shown in Table 3.4.

Table 3.4 Measured image quality factors.

Paper sample	Grammage (g/m^2)	Gloss Black	Gloss Cyan	Adhesion % Black	Adhesion % Cyan
A	160	0.20	2.00	16.50	28.50
B	85	0.30	4.25	87.00	93.50
C	80	0.35	5.00	90.00	96.50
D	70	0.75	19.50	97.50	98.50

It is interesting to plot the observations of measured image quality attributes against the thermal behaviour and the basic properties of the paper samples. Figure 3.29 shows that the gloss values of both the black and cyan parts of the image decreased as the paper grammage increased. According to Figure 3.27, the temperature change and effective thermal conductivity of paper A are grater than those of papers B, C and D. Accordingly, the part of the energy conducted to the toner was less with paper A than with the other samples, and it was not enough to complete the fusing to the desired quality. This conclusion is supported by the adhesion% illustrated in Figure 3.30 as the image fixing rate%, measured as the ratio between image densities before and after a tape test. The fixing ratio indicates that also the temperature change was higher in paper A, though it did not reach the toner to be fused and penetrate into the paper, as in the case of paper C of 80 g/m^2.

Figure 3.31 shows the relationship between image gloss and adhesion, both as a function of paper grammage, Figures 3.29 and 3.30. The results of this figure explain that the extra thermal energy absorbed by the toner will contribute to the glossiness of the image after satisfactory image fixing quality. Even though toner properties were not examined in this experiment, the results show that the cyan toner has a higher thermal conductivity than the black toner. In all the samples, the heat transferred to the toner was picked up mostly by the cyan. This is one reason why the cyan image produced better gloss and adhesion strength compared to the black toner. In sample D, the temperature change with 70 g/m^2 paper left a lot of energy to produce a high-gloss cyan image. In this case, the fusing energy was sufficient to achieve thermal equilibrium between toner and paper through the toner-paper contact surface. Of course, the toner manufacturer prefers the black toner image to be less glossy since it is meant for text, whereas the other toner colours are designed for fine glossy images. The readability of black text should not be affected by the illumination and detection angles, which are sensitive to gloss.

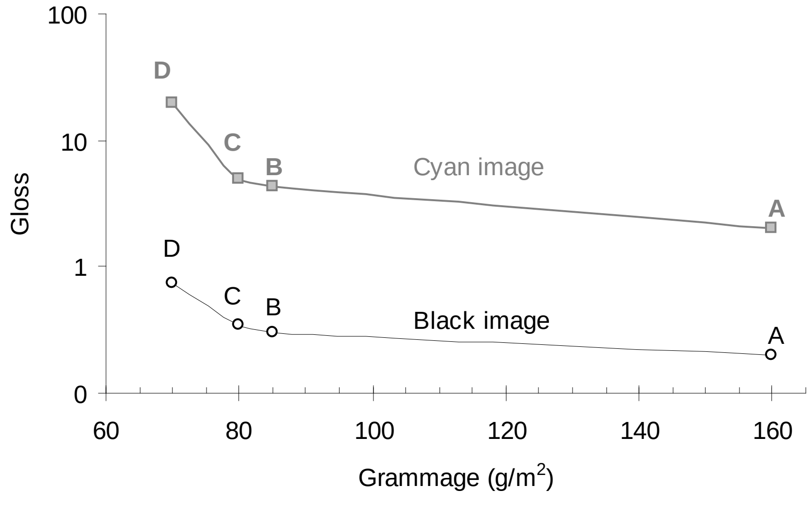

Fig. 3.29 Gloss of the images obtained on the paper samples.

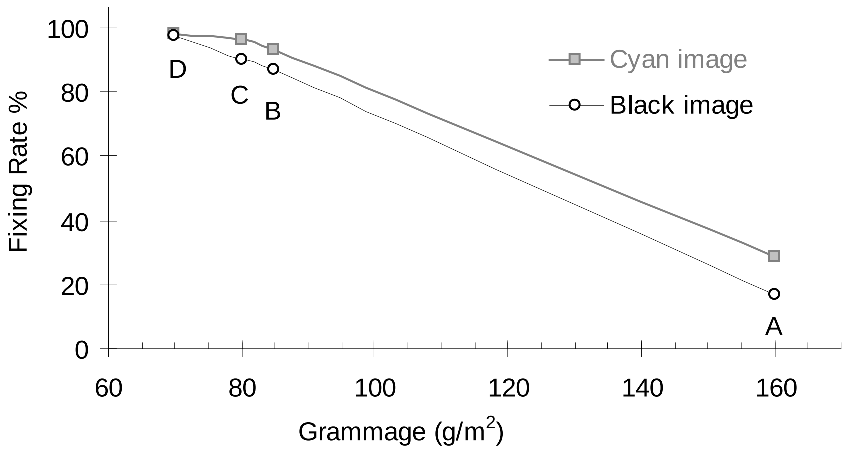

Fig. 3.30 Image fixing rate as a function of paper grammage.

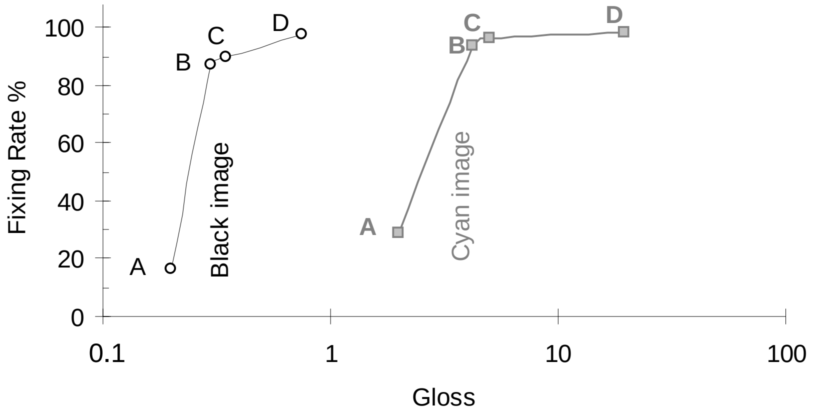

Fig. 3.31 The relationship between image gloss and fixing rate.

The effect of the paper grade on a flash fused image was discussed earlier in Section 3.2.2. As noted before, the flash fusing was found to be suitable for use, irrespective of the paper grade or any other media. The most important is the surface roughness and compatibility of the media with toner properties for image spreading and adhesion without the help of pressure.

3.2.6 Fusing mechanism

The results of the contact fusing study suggest that a simple phenomenological model can be drawn to depict the interactions between paper and toner in the fusing nip. Figure 3.32 shows a time-temperature plane sketch of the model.

Before the fusing nip, the toner and paper are all at room temperature of 23ºC. They enter the fusing nip at the same time to be treated by the same pressure and temperature for the duration of the nip dwell time. The heat required for the moisture content of paper to reach the boiling point is about 323 Jg^{-1}, which is calculated from Equation 13

$$Q=mc\Delta T \qquad (13),$$

where c= 4.2 J/gºC, m is the mass of the moisture, and ΔT=(100ºC -23ºC). The amount of moisture depends on the paper grade and relative humidity RH%. At this point, the toner has passed through the glass transition T_g region of about 60ºC [4] and sintering [66] of toner particles has started prior to coalescing [67]. The moisture needs about 2256 J g^{-1} of heat to reach the evaporation point at 100ºC, and by that time the toner is already softened and starts to melt in the so-called blocking region. After the evaporation point, the steam continues to consume about 2 J /gºC of heat as the temperature continues to rise to reach the flow region of the toner around [4] 125ºC with relatively high viscosity. It was found that the toner consumed about 20% of its fixing energy to reach the melting range where the viscosity is at its highest of about 130 Pas [113], and the rest 80% to cause the viscosity to drop from 130 to less than 5 Pas within a temperature change from softening point T_s (around 125ºC) to fixing temperature of about 185ºC, and at this range (from softening to fixing), the toner melting energy (Jg^{-1}) is an exponential function of temperature. However, in the flow region of toner, the viscosity starts to drop rapidly, causing the wetting and spreading of the toner on the paper surface which has already reached the same level of temperature. At low viscosity the melted toner flows to fill-in the irregularities [67] of the paper surface and promoted by the nip pressure, the toner then penetrates into the porous structure and the fibres [66] of the paper. The upper right corner of Figure 3.32 illustrates that at high fusing temperature, a wide range of toners are compatible with a wider range of papers for acceptable image fixing quality. Therefore, the designed roll fusing temperature in real applications always exceeds the highest possible toner flow point (125-130ºC) by at least 40 to 50ºC. Even such high temperatures do not cause heat-set off-set when the other parameters (pressure, speed and nip width) are optimised [P6].

Figure 3.32 illustrates that the heat consumption rates of toner, moisture and the solids content of paper are different at each phase of fusing. The range of thermal paper properties marked by the light grey region indicates the wide selection of paper grades which can be used in one given printer, compared to the dark grey region of the narrow thermal properties of toner. This is obvious, since the toner is the choice of the printer manufacturer, whereas the paper is the choice of the end user. The choice is made from a wide recommended range of papers. The toner is designed according to the printer's specifications and it is considered as an integral part of the printing process. Because of the nature of papermaking as a mass production concept and uncontrollable properties influencing the moisture content of paper in different humidity conditions, accurate customisation of paper for a certain set of printing process parameters is difficult [54]. Ultimately, the print application and desired quality are the main factors which influence the type of printing technology selected, limiting the freedom in choosing paper for printing.

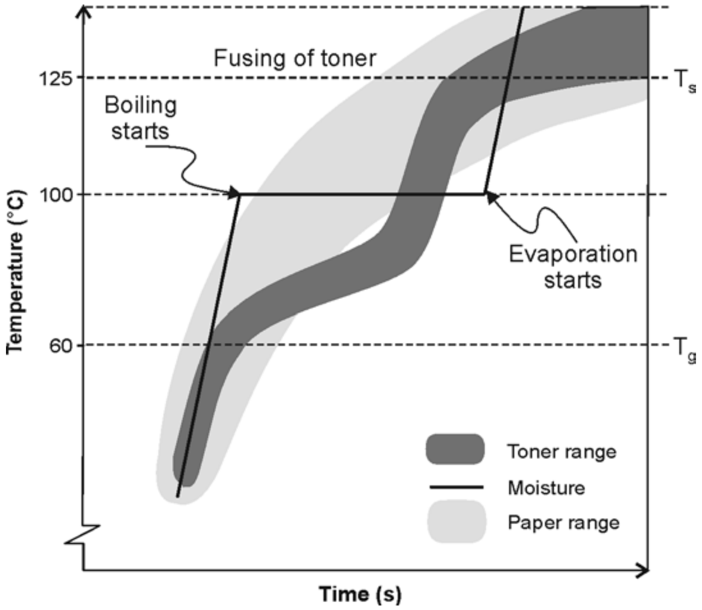

Fig. 3.32 Phenomenological model of fusing.

3.3 Combined effects of toner transfer and fusing processes

Detail rendering is one of the traditional measures used in evaluation of printed image quality. This tool was used to characterise the current level of detail reproduction in electrophotography, and to explore the role of different papers and technological choices in determining the appearance of printed images. It was also used to gain a better understanding of the relation between image quality and the specifications and features of each process step in different machines, especially in toner transfer and fusing steps where the paper is involved.

The test image was designed to contain the basic elements of any black and white image such as dots and lines in different frequencies, and image areas in a wide range of grey scale percentages. A microdensitometer was used to measure the optical density profiles of line bar patterns printed by eight different printers. A variety of paper grades were examined. The dynamic range, contrast transfer function (CTF), and signal-to-noise ratio (SNR) were calculated from the maximum average density of the printed area and minimum average density of the non-printed area [P6]. The smallest reproducible pixel size was also defined using the frequency at the half of the CTF curve. Microscopic image and software analysis tools were used to determine the edge noise, raggedness and sharpness of lines. [P6]

3.3.1 Printer performance

Eight dry toner electrophotographic machines of different specifications were used to study the performance of different transfer and fusing configurations. They are listed in Table 3.5. In Figure 3.33, microscopic images of dots printed on the same paper grade, by the different eight printers are depicted together with calculated values of edge noise of the dots. The frequencies of the printed lines are half of the nominal frequency and the dots are 25% halftones. The calculated values are a general indicator of the appearance of the printed microscopic images. Clearly the appearance varies a lot; each of the printers has a distinct fingerprint of its own. The subjectively determined impression of sharpness proved to be consistent with the appearance.

Table 3.5 Experimental printers, including specifications.

Pinter	IP1	IP2	IP3	IP4	IP5	DP1	DP2	DP3
dpi	800×400	800×400	600	600	600	600	600	600
Exposure	laser	laser	LED	LED	laser	laser	laser	laser
Toner size, type	8-9 µm, dual	8-9 µm, dual	5-6 µm, dual	6 µm, dual	6 µm, dual	8 µm, single	8 µm, single	8 µm, single
Transfer method	transfer blade	transfer blade	transfer belt	corona & belt	corona	transfer belt	transfer drum	corona
Fusing method	2 hot rollers	2 hot rollers	hot/press rollers	belt/roller nip	hot/press roller	fusing belt	2 hot rollers	1 hot roller
Fusing °C	175	180	140	160	198	170-185	162	200
Papers g/m^2	65-220	65-270	80-300	60-280	60-250	60-163	60-105	60-200
Colour-ppm	31 A4	50 A4	70 A4	60 A4		5 A4	3 A4	
B/W-ppm	same	same	same	same	135 A4	20 A4	12 A4	24 A4

IP *stands for Industrial Printer and* **DP** *for Desktop Printer.*

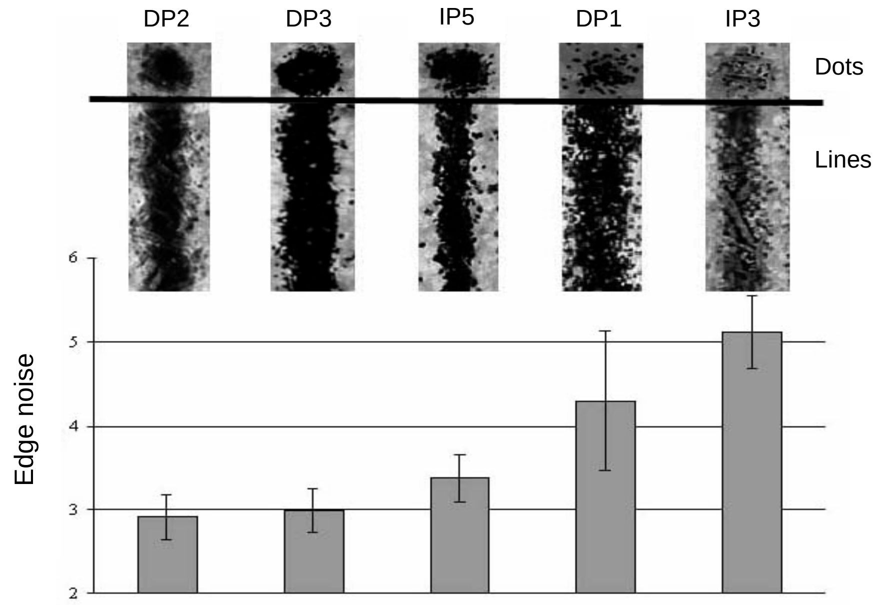

Fig. 3.33 Dots and lines produced by five different printers with their respective edge noise.

As Figure 3.34 shows, the quality deteriorates with increasing frequency. When measured as CTF at the highest frequency the resolving power of industrial printers was better than that of the desktop printers. The figure shows that the printer IP5 produced better quality than the rest. This is because it is designed as a black and white printer, where the process parameters are fewer and more easily controlled than in colour printers. The results of IP5 printer in Figures 3.33 and 3.34, and the smallest pixel size of 57 μm calculated from CTF curve of this printer [P6], support this conclusion. With the help of the specifications listed in Table 3.5, the second best print quality was produced by IP4, which represents a technology with fairly low fusing temperature applied by a soft and long fusing nip obtained by the use of a fusing belt. This is essential to improve the detail rendering. The transfer corona under the belt and the 6 μm toner particle size used in this machine are powerful factors in transferring the toner to paper efficiently. IP1 and IP2 printers have exactly the same engine, but IP2 is faster than IP1. To overcome the short dwell time in the fusing stage, the manufacturer has increased the fusing temperature of IP2 and the high fusing energy has caused more spreading of melt toner. Therefore the CTF curve produced by IP2 runs much lower than the CTF of IP1, especially at high frequencies. These same reasons apply for the performance of IP4 and IP3 in terms of raggedness, (as shown in Figure 7 of P6). It is also valid for the desktop printer DP1 compared to the other two similar range printers. The fusing temperature is higher in this printer, but the thermal energy is applied indirectly through the fusing belt. A high level of detail reproduction requires less fusing energy and efficient transfer of small toner size, so that less satellite particles arise. When they are melting with less energy, they will not spread much at the edge of the line. In the opposite case, raggedness increases and sharpness deteriorates. Other evaluation tools such as raggedness, dynamic range, sharpness percentage and signal to noise ratio, produced for all the experimental printers at a wide range of frequency, can be used to support these discussions. [P8]

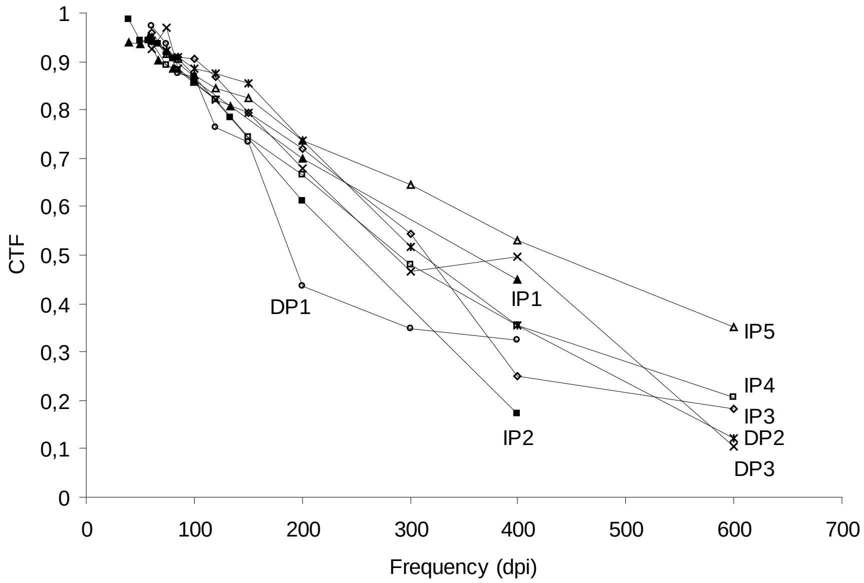

Fig. 3.34 CTF curves of the eight dry toner printers used in this approach.

3.3.2 Paper performance

Paper performance was judged by a simple test in which the contrast transfer functions (CTF) were measured from many samples printed by the same printer. A desktop printer coded DP2 was used. Six paper grades were examined. One was a commercial uncoated copy paper grade 80 g/m^2, which is commonly used in dry toner electrophotography. Another five coated paper grades had been made for research purposes. All of these five grades were made of the same base paper, coated by two different coating colour formulations coded C1 and C2. By using coating colour C1, two grades were produced: (100 g/m^2, C1) double layer coating, and (135 g/m^2, C1) triple layer coating. And by using coating colour C2, three grades were produced: (90 g/m^2, C2) single layer coating, (100 g/m^2, C2) double layer coating and (135 g/m^2, C2) triple layer coating.

Figure 3.35 shows the CTF curves for the printed samples on these six paper grades. The result provides a good basis for selecting the paper with the best CTF curve. It is clear that the best choice was the commercial uncoated grade 80 g/m^2. This result does not mean that this grade is absolutely better than the others, but its bulk, electrical and thermal properties as well as its surface treatment are in good agreement with the process parameters of the desk top printer DP2. Optimisation of the electrical properties with the thermal properties and surface energy is essential in designing the paper to be used in dry toner technology. Some coated paper can have efficient transfer through its electrical properties, and also suitable thermal conductivity [P8], but later the image quality may be destroyed in the fusing step because the paper surface may be incompatible with that of the melt toner at fusing temperature [P3]. A better solution is to design the required paper properties together with printing process parameters, but this is not a feasible approach because papermaking is a mass production process which is difficult to customise for a large number of different printers. Consequently, printing machine manufacturers may concentrate on further technological development in order to eliminate the effect of paper on print quality [44].

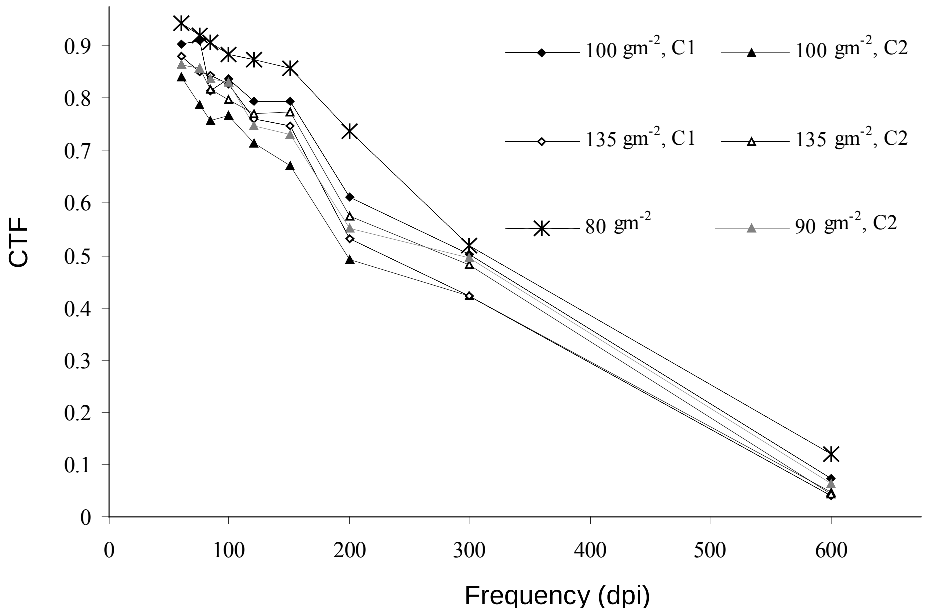

Fig. 3.35 Contrast transfer function (CTF) of different paper grades.

3.3.3 Control of print quality

A printed line in the direction of the axis of the photoconductor cylinder (in cross direction relative to the printing direction) requires less time to be exposed, developed, transferred and fused, than a line printed in the same direction as the printing process, which is printed in a mechanism determined by the circumference of the photoconductor and its number of rotations. The line printed in cross direction allows avoiding the variation of several parameters along the printing process. This appears to be true at least in the exposure and development steps, but definitely not in the transfer and fusing steps where other factors such as pre- and post-transfer, and the flow directions of melt toner under the hot deformation of the fusing nip influence the detail rendering in opposite direction more strongly than the speed. The difference in CTF of two perpendicular lines printed on 80 g/m^2 uncoated paper is shown in Figure 3.36.

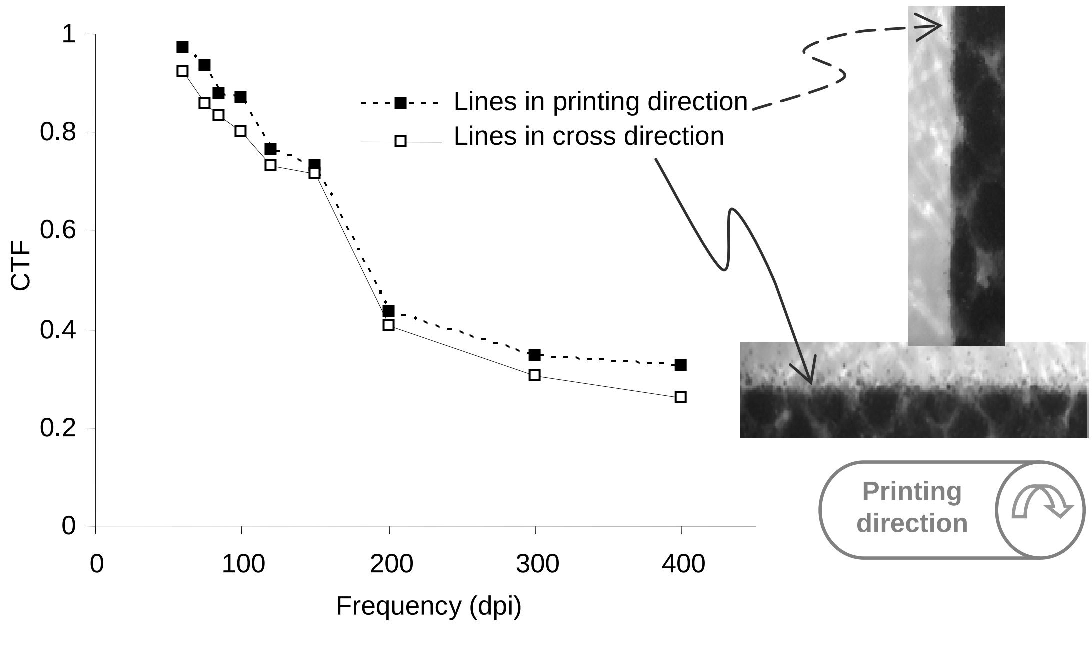

Fig. 3.36 CTF of two lines perpendicular to each other.

It is known that the image quality is a result of the interactions between toner, paper and processes parameters in the transfer and fusing steps, as illustrated in Figures 1.8 and 1.11. The lines shown in Figure 3.36, were printed at the same time, on the same paper, and by the same printer, using the same toner and the same transfer and fusing parameters. But still the lines' quality is different. Clearly, the print quality depends on the orientation of the lines relative to the fibre orientation of the paper and the direction of the printing process. Therefore, the image properties (colour, print lay-out, size and image content [114, 115] and location on paper) represent an additional group of variables that interact with the triangle groups of toner-paper-printer variables, to form a rectangle interaction group to produce the final image quality. Consequently, the diagrams in Figures 1.8 and 1.11 can be presented in a new way, as shown in Figure 3.37.

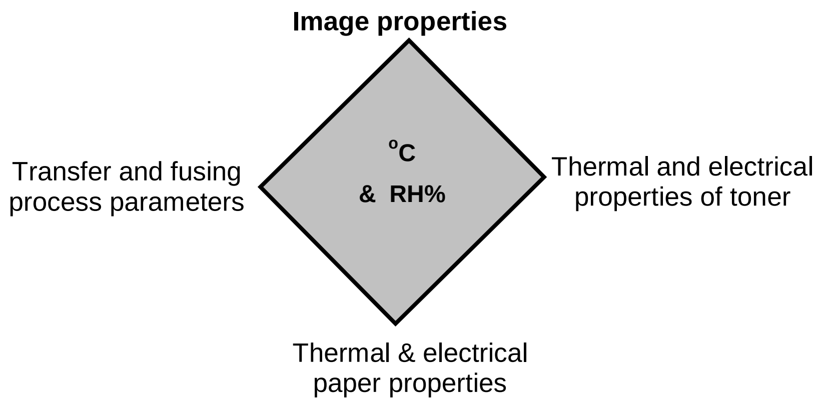

Fig. 3.37 Toner-paper-image-process interaction in transfer and fusing steps.

Most print quality criteria are subject to change in the final step of the electrophotographic printing process, where the image is fused to be fixed onto paper. Figure 3.38 shows the effect of fusing parameters on image quality.

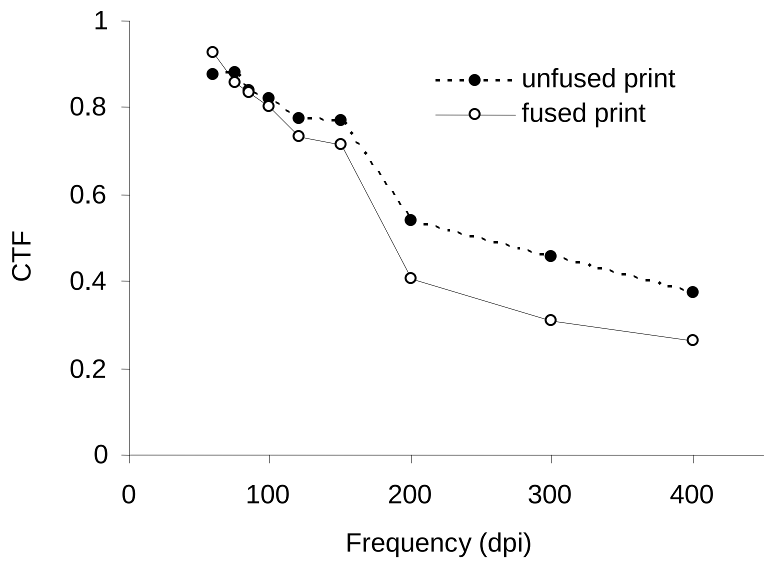

Fig. 3.38 CTF, before and after fusing.

From a process viewpoint, the final print quality is driven by the parameters of toner transfer and fusing steps. To ensure better performance, these parameters could be adjusted automatically according to the print application (paper used and toner coverage) and the ambient conditions. In the transfer step, the adjustment is possible based on the ohmic resistivity of paper calculated from the attraction roller's voltage, in a closed-loop control system which adjusts the required transfer voltage to each print job [32, 36,37,43] or to every individual paper [44]. In the fusing step, the parameters could be adjusted and controlled according to the density and gloss variation measured from the first print as functions of different substrates and image coverage. It is implemented by a simple feedback control loop from the optical measurement system, back to the fusing system [P7]. Figure 3.39 illustrates the parameters' adjustments of transfer and fusing steps.

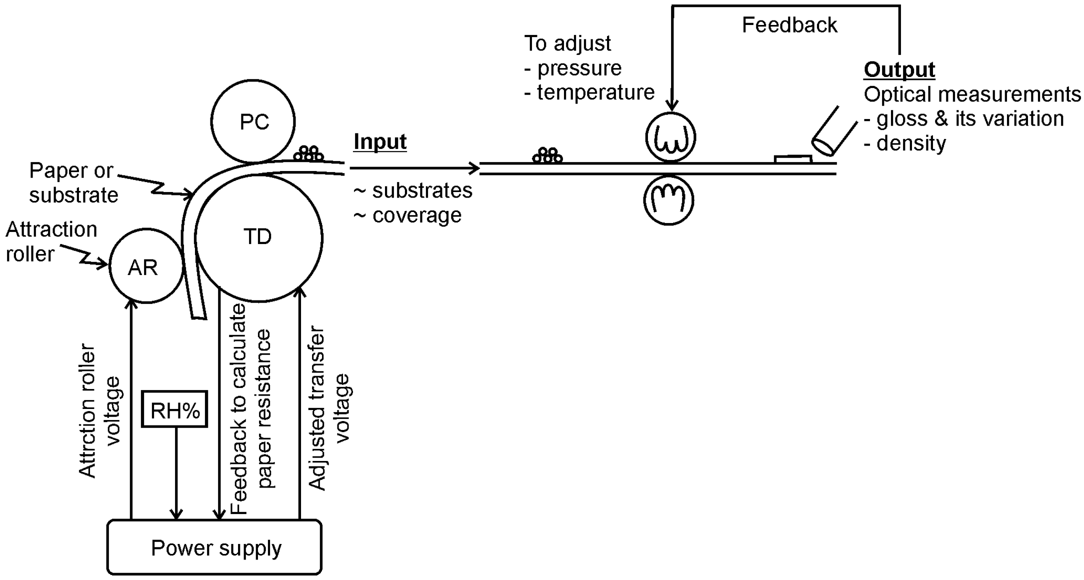

Fig. 3.39 Controlled transfer and fusing units.

If the transfer of toner to paper and image fusing are performed with an efficiency of 90%, the multiple efficiencies of the transfer and fusing steps will be 90% × 90% = 81%. Accordingly, in the seven steps of the electrophotographic process, the 90% efficiency of each step means that the final image quality is printed with a total efficiency of less than 50%. Reducing the number of steps as in the transfusing process, in which toner transfer and fusing of the image occur at the same time, will improve image quality [13, 116]. The same approach can be seen in the development of digital liquid toner technology, making the process leaner, faster and cleaner, and improving the image quality on wide variety of substrates [117]. This is achieved by reducing the number of process steps, and by optimising the parameters to ensure that the melting of the toner particles, drying of the hopping liquid and transfer of the image to the substrate are all done in one step with high efficiency. [117, P4]

4 CONCLUSIONS

The objective of this work was to provide an understanding of the role of paper in the mechanisms of toner transfer and fusing in current digital dry toner electrophotographic technologies. Both, theoretical models of toner transfer and fusing were experimentally validated. This was achieved by experimentation using a range of set-ups which allowed the process parameters in different technologies to be varied and measured, and the output to be measured. To achieve variation in electrical and thermal properties, some papers were specifically made for the experiments, some were commercial. Previous research on the mechanisms has largely focused on the interoperability of the process and the toner.

In electrostatic toner transfer to paper the main adjustable process parameter is the transfer voltage. The general finding was that the transfer current at different levels of transfer voltage characterises the transfer situation when using different marking technologies, such as a transfer roller, belt, intermediate drum or transfer drum. The adjusted transfer voltage and the transfer current measured as a function of time were both found to be useful experimental tools in determining the role and effect of the parameters involved in the interaction between the electrostatic transfer process, the toner and the paper in given ambient conditions.

The transfer current responds sensitively to any change in the materials, such as the bulk and electrical properties of the paper, and the charge-to-mass ratio of the toner, which is affected by the ambient conditions. The transfer current is also sensitive to image and process variables such as halftone, size and location of the image and transfer voltage, and relative humidity. For these reasons, the measured transfer current was used as tool to study the electrical behaviour of paper and all other variables involved in characterising the transfer situation in dry toner technology.

When the transfer voltage is adjusted to a given value and also measured together with the corresponding transfer current as a function of time, the resistance at any moment in the transfer zone can be calculated. Thus, the effect of each resistance layer between the transfer drum and the photoconductor, such as the paper's resistance, can be studied based on current measurement.

According to the findings of the toner transfer experiments, the transfer voltage creates a surface charge density on the paper, which determines the extent of transfer through the net current over the total resistance. When the surface charge is changed for some reason, such as a change in moisture content, the net flow of the transfer current will change in the opposite direction. So, under the electrostatic treatment in the transfer zone, the paper behaves as a conductor and as an insulator at the same time. The current component consumed by the insulating behaviour to polarise the paper is the most important in the transfer step. This insulating property can be influenced by the density of paper, the coating colour, the amount of calendering or any other bulk property that directly increases the resistivity of paper. Alternatively, the paper's resistivity will be lost if the moisture content is increased. In this situation, most of the electric transfer energy will leak away because of the increase in the conductivity of paper, instead of promoting the build-up of sufficient surface charge density.

The toner transfer efficiency was found to follow the ideal transfer profile when studied as a function of transfer voltage. The amount of toner transferred to paper is increased as the transfer voltage is increased to reach the ideal situation where no more toner remains to be transferred from the photoconductor. Thus, increasing the transfer voltage over that level will be a waste of energy. This saturation level was found to be influenced by the paper grade used and by the ambient conditions. The efficiency of toner transfer was determined as a function of transfer voltage in terms of the toner amount, the transfer current, and the optical image density before and after fusing. All values were found to be in good quantitative agreement with the theoretical, ideal, transfer profile.

After the toner has been transferred to the paper, the image is fused under two boundary conditions: First, the image structure should not lose any of its details when treated by the fusing unit. Second, the image should gain an improvement in its quality in terms of factors such as glossiness, uniformity, and adhesion. In accordance with these goals, the fusing mechanism was studied in both hot contact and flash fusing in order to determine the boundary limitations of fusing latitude, with due consideration of paper, toner and image properties.

In hot contact fusing most of the fusing energy is wasted in the transfer to paper, whereas the energy is meant to fuse the toner. According to the results, the higher the grammage of paper, the greater the heat energy conducted to the paper, and the less energy left for the toner to be fused. Therefore, lower-grammage papers produce better strength and optical fusing, as indicated by their adhesion percentages and gloss values. Higher density was found to stabilise the thermal behaviour of paper in fusing, regardless of printing speed. It was also found that if a sufficient amount of toner is present and the gloss has reached saturation level, extra thermal energy will contribute to image uniformity. However, the energy should be limited to avoid reaching the heat-set off-set level.

In flash fusing, the process variables are different, and being a non-contact method, it could be the perfect solution when integrated with non-contact (jumping) toner transfer to produce high perceived image quality. The fusing mechanism is different from that in contact fusing. The flashing energy is mostly reflected by the paper and absorbed by the toner at a rate governed by the colour of the toner. The fusing energy, generated by a balanced combination of pulse width and energy intensity, should be sufficient for heat transfer from the upper surface of the toner layer to the toner-paper interface to obtain a temperature equilibrium between toner and paper or any other substrate in order to allow complete image fixing. By optimising the paper surface, toner and the fusing process variables in relation to one another, the desired fusing quality can be achieved.

The optimal combination of print characteristics is application-specific. This is why it is important to understand the mechanisms and the combined effects of transfer and fusing on print characteristics. For instance, the lower noise of the edge line fused by the hot nip is due to the higher pressure that connects neighbouring toner particles at the edges. This is harmful for perceived quality and not good for photo printing, but it is necessary in order to achieve a slab of melted toner. This is essential in some functional applications such as those requiring electrical conductivity and lines which are a part of an electronic circuit.

It was also found that higher toner transfer performance may not be compatible with higher quality fusing performance, especially the factors related to the paper and image which are end-user choices. Therefore, optimisation is needed in both the transfer and fusing steps to fit a certain application. Moreover, the paper sometimes serves as a linking medium between the electrostatic and thermal phenomena in machines where the distance between the transfer step and fusing step is less than the length of the paper. In this case, a part of the paper is entering the fusing unit while another part is still subject to electrostatic toner transfer. Therefore, the basic properties of paper should have compatible electrical and thermal properties to comply with the simultaneous electrostatic transfer and thermal fusing treatments.

The study recommends an adjustable transfer and fusing system for industrial electrophotographic machines to support different applications in producing the desired image quality. This does not imply that all quality attributes are controlled by the transfer and fusing steps, but stems from the fact that paper is a relevant component in many printing applications, and both the paper and the application are end-user choices. Therefore, it must be possible to adjust the transfer voltage according to, at least, the paper grammage and the relative humidity. From these two parameters the printer should calculate the electrical resistance of the substrate from the attraction roller and RH% sensor immediately ahead of the transfer zone, and accordingly adjust the transfer voltage value. Some of the fusing parameters, such as temperature and pressure, have a clear influence on optical image quality. To ensure high performance, these parameters should be automatically adjustable according to the density and gloss measured from the print as functions of different substrates and image coverage.

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TKK DISSERTATIONS IN MEDIA TECHNOLOGY

ISBN 978-952-24-8214-3 (print)
ISBN 978-952-24-8215-0 (online)
ISSN 1797-7096 (print)
ISSN 1797-710X (online)