Wetting and levelling of toner during fusing of electrophotographic prints

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Abstract

This licentiate thesis comprises two studies dealing with the fusing step in electrophotographic printing. The first study addresses the development of a method for monitoring wetting/spreading of single toner particles in-situ on a heated substrate. The method employs imaging from above and thus makes it possible to use toner particles of realistic size (around 10 µm in this case). The results of this first study clearly show that high energy substrates not only exhibit far greater toner particle spreading, and work of adhesion generated by it, but also a strong dependence on the toner type. For the Xeikon toners used the cyan and black spread far more than the magenta, with yellow clearly the lowest. Conversely, low energy substrates exhibit limited spreading and lack of sensitivity to toner type. The results permitted the proposal of a simple generalised law to describe the spreading kinetics. This empirical relation was able to fit all experimental results with the bare minimum of input information from the equilibrium state. The method provides a readily visualisable and flexible means for more systematic design of toner-substrate interactions in electrophotography. A broad range of different toner particles can be rapidly screened in contact with model and real substrates, and the spreading then correlated to electrophotographic runnability, print quality and durability issues.

The second study is based on evaluation of print quality from trials on a Xeikon digital press with varying fusing conditions. The study illustrated the utility of white-light interferometric profilometry in quantifying the thickness and surface roughness spectrum of toner layers transferred and fused on two different paper substrates (coated and uncoated). These measurements generate increased insight into the mechanisms giving rise to toner print quality. Significant differences in surface roughness behaviour were observed between different toner colour combinations as a function of temperature settings and both paper type and fusing units (radiant and heated roll). The correlation between gloss and print surface roughness at micron length scales extends to longer length scales with increasing toner film thickness and on use of the heated roll glossing unit. These observations facilitate a more systematic approach to designing fusing units to avoid typical problems such as gloss variations in electrophotographic prints.
Sammanfattning


List of papers

Paper I

Spreading of individual toner particles studied using in-situ optical microscopy

Torbjörn Pettersson and Andrew Fogden, submitted to Journal of Colloid and Interface Science.

Torbjörn Pettersson’s contribution: all laboratory and all experimental work (except for the AFM measurements), most of the theoretical evaluations.

Paper II

Levelling during toner fusing: Effects on surface roughness and gloss of printed paper

Torbjörn Pettersson and Andrew Fogden, submitted to Journal of Imaging Science and Technology.

Torbjörn Pettersson’s contribution: all laboratory and all experimental work (except for the printing), most of the theoretical evaluations.

In the following these papers will be referred to as [I] and [II], respectively.

Not included in this thesis

In-situ spreading of individual toner particles and levelling of toner layers

# Table of contents

Abstract ................................................................. iii  
Sammanfattning ......................................................... iv  
List of papers ............................................................. v  
Table of contents ........................................................ vi

## 1 Introduction ....................................................... 1

1.1 Electrophotographic printing processes ......................... 1  
   1.1.1 Charging ..................................................... 3  
   1.1.2 Exposing .................................................... 3  
   1.1.3 Developing .................................................. 3  
   1.1.4 Transferring ............................................... 3  
   1.1.5 Fusing ...................................................... 4  
   1.1.6 Cleaning ................................................... 5  
   1.1.7 Commercial printing systems ......................... 5

1.2 Toner particles ..................................................... 5

1.3 Printing substrates ............................................... 7  
   1.3.1 Paper ....................................................... 7

1.4 Requirements on printed material ................................ 8

## 2 Methods and instruments ........................................ 9

2.1 Surface topography ............................................... 9  
   2.1.1 Optical profilometry .................................... 11  
   2.1.2 Atomic Force Microscopy (AFM) ......................... 12  
   2.1.3 Scanning Electron Microscopy (SEM) .................. 12  
   2.1.4 Gloss ...................................................... 13

2.2 Spreading and contact angles .................................... 14  
   2.2.1 Contact angle measurement of macroscopic drops ...... 14  
   2.2.2 Wetting and spreading of toner .......................... 15  
   2.2.3 Reology .................................................... 16  
   2.2.4 Surface free energy of solid surfaces ................. 17

## 3 Results and discussion .......................................... 19

3.1 Rheology of toner ................................................ 19

3.2 Surface free energy .............................................. 21

3.3 Toner modification ............................................... 21
3.4 Wetting of individual toner particles 22
3.5 Surface topography 26
3.6 Surface roughness and gloss 29
4 Conclusions and future work 34
5 Acknowledgement 36
6 References 37
1 Introduction

Advancement in fundamental knowledge of electrophotographic printing is required by paper manufacturers, printer manufacturers and suppliers of consumables, and the printing industry in order to further improve the printer runnability and print and product quality delivered to the final customer. As one specific example, improved knowledge of toner interactions with paper allows a more systematic approach to selection of the optimal method for screen ruling. Another example is the understanding of paper frictional properties necessary for optimal feeding and passage through the electrophotographic printer. Compared to long-existing techniques such as offset printing, the fundamental research within digital printing techniques is presently rather limited, and lags behind the rapid pace of product developments in printing systems.

The aim of this work is to investigate the physical and surface chemical mechanisms underlying the fusing of electrophotographic prints on paper, and in particular the wetting and spreading of toner particles or dots and levelling of toner films or full-tones. This involves both a laboratory study of the wetting of individual toner particles on model substrates during heating, and analysis of the topography of printed papers from a digital press. The combination of these two studies serves to increase the ability to interpret and predict electrophotographic print quality.

This project is included within the framework of S2P2 (Surface science for digital printing), a Swedish research programme that is financed by SSF (Stiftelse för Strategisk forskning).

1.1 Electrophotographic printing processes

The electrophotographic printing technique is used in photocopying machines, office printers and high volume commercial presses. The process can be used to print on a variety of substrates, including paper, plastic and fabrics. The “ink” is in the form of pigmented polymer particles, called toner, which are transferred to the printing substrate via electrostatic attraction. The process was invented by Chester Carlson, with his first patent on the technique from 1942 [1] and first patent on the electrophotograpical apparatus from 1944 [2].

The electrophotography process can be divided into 6 steps:
• Charging
• Exposing
• Developing
• Transferring
• Fusing
• Cleaning

These different steps will be explained briefly in the following six subsections; more detailed information is available in other reviews [3, 4]. All of these steps, shown in Figure 1.1, are arranged around a conductive photosensitive material, called a photoconductor, mounted on a drum or belt. This photoconductor is the central element in the process. Note that many process details vary between the different electrophotographic reproductive systems; the purpose of the explanation below is rather to illustrate the key underlying concepts.

Figure 1.1: Possible configuration of the 6 different steps around the photoconductor.
1.1.1 Charging
In this first step, the photoconductor is uniformly charged in the absence of light, most often using corona discharge. A corona discharge is a self-sustainable, non-disruptive electrical discharge that occurs when a sufficiently high voltage is applied between asymmetric electrodes such as a point or a fine wire and a plate or cylinder. Depending on the polarity of the corona either positive or negative ions are produced. In air, negative coronas mainly generate hydrated CO$_3$ ions and for a positive corona hydrated protons, (H$_2$O)$_n$H$^+$, predominate [5].

1.1.2 Exposing
The second step utilises the photosensitivity of the charged photoconductor to form an electrostatic latent image. The photoconductor areas representing non-image (and non-text) are exposed to light to discharge these areas. The light source can either be a LED (light emitting diode) array or a laser; the laser is controlled with mirrors. This results in a charge pattern on the photoconductor corresponding to the image or text.

1.1.3 Developing
In this third step the toner is transferred to the charged latent image and text areas on the photoconductor. Different types of developing units have been used (e.g. cascade, two-component magnetic brush, single-component)[3, 4], with the two-component type of magnetic brush being most common today. In such a magnetic brush developer the toner particles are mixed with larger-sized polymer-coated magnetic particles, called carriers. This mixing generates a tribocharging of the toner particles, which thus adhere to the carrier particles due to electrostatic attraction. The carrier particles are then transported using magnets to be in close proximity to the photoconductor, leading again by electrostatic attraction to transfer of the adhering toner particles to the oppositely-charged patterned areas. The emptied carrier particles are returned and the process continues. The magnetic brush developer is used mainly due to its ability to rapidly transport sufficient amounts of toner to the photoconductor [3].

1.1.4 Transferring
The fourth step involves transfer of the developed image from the photoconductor to the printing substrate, e.g. paper. This is achieved by
applying a charge on the backside of the paper (often using a corona device) exceeding the charge on the photoconductor, inducing the toner to move from the photoconductor to the printing substrate. This requires that charge be transported through the paper, which thus needs to have a sufficiently high electric permittivity.

1.1.5 Fusing

The transferred toner is then permanently fixed on the paper by fusing in the fifth step. This involves application of heat, e.g. radiantly with an infrared source, to induce toner flow, often together with applied pressure, e.g. in the nip between heated rolls. The fusing process is the central focus of this thesis, owing to the importance of surface chemistry. Interfacial sub-processes occurring after toner melting (see Figure 1.2) include particle sintering and coalescence, spreading on the paper, penetration into it, and levelling of the toner-air interface[6-9][I-II].

Figure 1.2: The different sub-processes proceeding during toner fusing: sintering / coalescence, spreading / wetting, penetration, and levelling.
1.1.6 Cleaning
In the sixth and final step the photoconductor is cleaned from untransferred toner, which can be performed for example with brushes or scraper blades. After cleaning the six-step process begins again.

1.1.7 Commercial printing systems
An enormous variety of electrophotographic printing systems exist, implementing different technical solutions for the six individual steps listed above and their integration. These systems are divided into copiers and printers, further segmented into high or low volume and multicolour or monochrome. Further, the substrate can be delivered as separate sheets or a continuous web. High volume multicolour digital presses are today produced by a number of vendors, including Xeikon, NexPress, HP Indigo, Xerox and Océ. These presses vary greatly in their design, from the overall arrangement of their different colour units down to the developing system used in each unit and the type of toner it transfers. While the majority use powder toner, some presses (notably HP Indigo) employ liquid toner, i.e. particles suspended in a carrier liquid. The latter allows the toner particles to be significantly smaller (1-2 µm) than those (around 8 µm) in powder form. The fusing systems used in these high volume multicolour digital presses are trending towards IR (radiant) units, especially for web-based presses, although heated nip units are still very common and predominate within the other printer and copier segments.

The printing trials in the present study were performed with a Xeikon DCP 320 D 4-colour press, which is web-based, employs powder toner and IR fusing followed by a heated nip glossing unit. However, the analysis techniques and many of the results are generally applicable to almost all electrophotographic systems.

1.2 Toner particles
Toner particles typically lie in the size interval from several µm to 10 µm, and are composite materials based on a matrix of polymer(s) within which the colourant (organic or inorganic pigment nanoparticles and/or dyes) are incorporated. A charge control agent (CCA) is also present in small amounts to stabilise the charging. Although the toner particle composition varies between manufacturers, the proportion of ingredients is usually as follows:
There are two main paths to toner manufacture, either mixing followed by grinding or emulsion polymerisation. The particles produced by the grinding process are irregular in shape while emulsion polymerisation produces spherical particles. Although the trend on the market today is towards spherical particles, the emulsion polymerisation route is protected by patents, so alternative strategies have been developed to transform the ground irregular particles to spheres. One such strategy involves heating the particles to their melting temperature, whilst airborne in a flow of hot air, thus allowing the surface tension to overcome viscous resistance and form the spherical shape of minimum surface area per volume.

The different toner manufacturing processes and electrophotographic printing systems place particular restrictions on the type of polymer base. The most often used type of polymer is polyester (which can be a mixture of different polymer resins), although polyacrylates are also common. The present study uses the four colours of the Xeikon Toner System V2, belonging to the class of ground polyester toners. Representative images of the irregular particles of this system are shown in Figure 1.3. More specific details are provided in [I].

Figure 1.3: Images of Xeikon black toner particles, at two magnifications.
1.3 Printing substrates

Although the predominant substrate used in electrophotography is paper, this printing technique is also used on polymeric materials and fabrics [10]. The process places a number of fundamental requirements on the substrate. It must possess sufficient electrical permittivity to enable transfer of the toner, sufficient heat stability at the high temperatures often used in fusing, and give sufficient toner adhesion throughout these processes and in end-use. Other substrate properties affecting the printer runnability include friction and mechanical strength properties, dictating the handling and passage of the substrate through the process, and thermal conductivity, dictating the heating demands during fusing and cooling rate after printing.

1.3.1 Paper

Paper is a complex composite material, based on wood pulp fibres and including a range of chemical additives to improve the runnability of the paper machine and tailor the final paper properties. Depending on the types and amounts of pulp raw materials and additives, and the manufacturing and finishing sub-processes employed, a spectrum of different paper and board grades is produced. Options for paper machine surface treatment, if required, span from surface sizing (based on starch) to coating of one or more pigmented layers for superior optical properties and a more uniform basis for printing. Calendering is performed for almost all paper grades to reduce the final surface roughness. The paper surface can be further modified in post-production converting processes, e.g. by extrusion polymer coating and lamination for packaging applications.

Paper grades used in electrophotography are primarily uncoated and coated wood-free filled fine papers, with properties intended to meet the general requirements listed above (or rather a compromise between requirements for all conceivable printing techniques, conventional and digital). To provide the necessary electrical permittivity, electrolytes are incorporated into the paper and coating layers if present. The required heat stability and conductivity of coated papers influences the choice of coating binders (latexes) and pigments (typically calcium carbonate and clay) to avoid possible electrophotographic pitfalls such as hot and cold offset and blocking. The attainment of adequate toner adhesion is intimately related to this choice of coating pigment and binder, whereas for uncoated papers the hydrophobising agents (e.g. ASA, AKD) used in the internal and surface sizing to increase water resistance for aqueous-based printing techniques strongly influence the toner adhesion. These same components
also dictate the adhesion and friction between paper, itself, and all other electrophotographic elements.

Given this multitude of often-conflicting requirements on the paper for printer runnability and print quality, specific to each electrophotographic printing system, papers are divided into those multipurpose grades and products designed to function adequately on almost all printers and presses, and more specialised products targeting a particular system. The present study uses one glossy coated paper (Galilei Art Gloss, 150 g/m²) and one uncoated paper (Galilei Opal, 160 g/m²), from Metsä Serla (now M-real). At the time the printing trial was performed, both products were recommended by Xeikon for use on their presses.

1.4 Requirements on printed material

Why do we print? The purpose of printing covers a number of needs, either personal or commercial:

- I want to read information.
- I want to store information.
- I want to share information with others.
- I want to illustrate something.

Each of these needs is then coupled to issues of image quality and permanence, relative to the particular conditions and environments of end-use. Although most of these requirements on the printed material are judged subjectively, a range of objective technical methods exist to provide guidelines and aid quantification of printability and print quality. The quality of printed colours (full-tones and half-tones) can be decomposed and analysed using a spectrophotometer, while the spreading of points, sharpness of printed edges and lines, and quality of text can be quantified by microscopy and image analysis. Permanence and resistance properties are judged by the deterioration in these optical measures as a function of the applied conditions. In particular, a number of different tests of toner adhesion exist, such as rubbing and scratching, creasing and tape peeling, and IGT picking.

One optical measure of importance to all printing techniques is the gloss of printed full-tones and half-tones (see Section 2.1.4). The attainment of a desirably high, yet laterally uniform, print gloss has been a challenge for electrophotography, stemming from its fundamental “relief” principle of building relatively thick assemblies of solid particles on the substrate. The effect of toner fusing parameters on the residual roughness and gloss of the print surface is the subject of [II].
2 Methods and instruments

As this study focuses on the surface chemistry of electrophotographic fusing, the instrumental focus is directed at characterisation of surface topography and wettability using well-defined techniques. These techniques allow a deeper interpretation of the results from standard methods of the paper and printing industry. As two examples, detailed mapping of print topography explains the origins of gloss and its variations, while studies of toner particle spreading and surface energetics serve as important input to understanding industrial adhesion test results.

2.1 Surface topography

Surface topography can be measured with different types of instruments that can be divided into three groups: optical, stylus or averaging instruments. The averaging type, and in particular air leakage, instruments are commonly used within the paper industry. Two specific examples are the Bendtsen and PPS instruments, which measure the flow of air passing through the gap between the sample and a pre-defined metal surface, then interpreted as a surface roughness [11-14].

The optical and stylus instruments give as their output topographical data as a function of position, either a height map of \( z = f(x,y) \) or a line profile \( z = f(x) \). From this topographical data statistical parameters of surface roughness can be calculated, to enable comparison between samples. Prior to calculation of such parameters the underlying form may need to be removed. Commonly a least-squares plane or line is removed from the raw data. If the sample is nominally planar, this subtraction is performed to set the zero level and flatten the data if the sample is tilted. The topographical data can then be filtered with different types of signal processing; average filters or Fast Fourier Transform (FFT) filters are often used. The Fourier transform decomposes the surface roughness into its amplitudes at each wavelength or frequency, from which a chosen part of the spectrum can be filtered (low pass, high pass, or band) to return the topography or surface roughness corresponding to only the accepted wavelengths. This allows, for example, separation of small-scale (random noise) variations, intermediate-scale waviness, and large-scale form.

After removal of the underlying form and filtration if necessary, the statistical surface roughness parameters can be calculated. There are a huge number of such parameters, of which the most common are arithmetic mean, \( Ra \), or root mean square (r.m.s), \( Rq \). The capital \( R \) is the ISO standard for line measurements (i.e. one-dimensional) on specific
lengths. For image measurements (two-dimensional) a similar subscript nomenclature is used, but without a standard choice of capital letter (an ISO standard is under preparation by ISO Technical Committee 213). Thus both $Pa$ and $Pq$ or $Sa$ and $Sq$, are used today, with the latter adopted in this study [15]. The r.m.s. roughness of a 2-D area $(x, y)$ determined from a $m \times n$ matrix of height values is then:

$$Sq = \sqrt{\frac{1}{mn} \sum_{x=1}^{m} \sum_{y=1}^{n} z(x,y)^2}$$

(2.1)

It is important to bear in mind that roughness values are statistical parameters and hence dependent on the number of points sampled. Thus, a fair comparison of surface roughness values requires that the measurements were performed over areas of the same size, with the same lateral resolution, and the same number of points retained in the calculation. Figure 2.1 illustrates this issue by plotting the different interpretations of surface roughness of a model periodic bumpy surface depending on the chosen sample size and lateral resolution.

**Figure 2.1:** Surface roughness versus size of sample and lateral resolution ($d_{xy}$), for the following calculated surface with $B=10$:

$$f(x,y) = \left| \sin \frac{\pi x}{B} \right| + \left| \sin \frac{\pi y}{B} \right|$$
2.1.1 Optical profilometry
In this study surface topography was mainly measured using a reflecting interference microscope using filtered white light, New View 5010, Zygo Ltd (USA), with a 20X lens. The measurement principle is based on dividing the light into two parts, one of which is reflected at the sample surface while the other is reflected at an internal flat reference surface. The reflected parts are then combined in the interference lens to give an image of the sample as an interference pattern of lighter and darker fringes (see Figure 2.2). The instrument ramps the lens in the height direction using a piezoelectric transducer (PZT, pifoc) and at the same time captures the corresponding images with a CCD-camera. This generates a 3D-matrix of interference information that is analysed in the Fourier domain to extract information regarding the sample surface, thus generating a height map of the sample [16]. All of the above functions are controlled by the instrument and its software, MetroPro 7.1.3. Different types of parameter describing the surface can then be calculated by the software, e.g. the r.m.s. surface roughness parameter $S_q$. The program also performs various kinds of signal processing of the height map, such as removal of the least-squares fitted plane, FFT spectral analysis etc, before and after calculating the roughness parameters.

Figure 2.2: The Zygo New View 5010 instrument, showing a) a schematic of its measurement principle, and b) the interference pattern of a cylindrical sample.
In this study the Zygo profilometer is used to quantify the surface topography of paper, printed paper and melted toner particles on model surfaces. From the topographical data the software is employed to evaluate the thickness of printed toner films on paper and their surface roughness contributions from different wavelength bands (FFT-analyses). Surface profiles from the individual melted toner particles on model substrates are also extracted to accurately evaluate their shape.

2.1.2 Atomic Force Microscopy (AFM)

Atomic force microscopy is a useful complement to the Zygo profilometer for imaging fine-scale topographical features at lateral resolutions below the limit of the latter (i.e. less than approximately 1 µm). The AFM used in this study was a Digital Instrument Nano Scope IIIa multimode, operated in tapping mode. In this mode a cantilever with a sharp tip is oscillated and scanned over the region of interest. The position of the tip is monitored with a laser beam as the sample is moved in the x, y, and z directions with a PZT. This enables the attainment of resolutions below 1 nm. In addition to the height image, tapping mode also provides the phase image, containing information on local material properties, such as hardness and viscoelasticity. This second image thus facilitates identification of the distribution of hard and soft material (e.g. inorganic and organic) on an otherwise flat surface.

In this study AFM was used to image melted toner particles on model substrates, in particular to probe the distribution of material and measure the contact angle very close to the three-phase line.

2.1.3 Scanning Electron Microscopy (SEM)

Scanning electron microscopy is a useful complement to the above-mentioned two instruments. Although it is not capable of providing quantitative height information, SEM gives images of surface features of local slopes too steep to allow their imaging with either the optical profilometer or AFM. One such example is the edges of microparticles.

In this study a ESEM, FEI/Philips XL 30 TMP, in SEM mode was used to image toner particles after gold coating. Examples are given in Figure 1.3 and 3.3.
2.1.4 Gloss

The gloss of a sample is influenced by the texture or roughness of its surface and the refractive index of the sample, as well as the instrument parameters of angle and wavelength of the incident light. Paper and print gloss are important measures by which both unprinted and printed papers are differentiated and valued. This applies to both the average value of gloss over the surface, with high gloss often associated with luxury products, and its lateral variations, which are unwanted as they disturb the observer’s impression. For a given illumination, gloss is most strongly dictated by the short-scale surface roughness. Locally varying surface roughness is found to be a major contribution to the gloss variations on unprinted and printed paper [17].

A number of ways to describe and predict gloss dependence have been proposed by the paper and printing industry. Chinmayanadam [18] showed that specular reflection could be approximated as the following function of surface roughness, $\sigma$, angle of incident light, $\theta$, and its wavelength, $\lambda$:

\[
\frac{I}{I_0} = f(n, \theta) \exp \left( \frac{4\pi \sigma \cos \theta}{\lambda} \right)^2
\]  

(2.2)

Here $f(n, \theta)$ is the Fresnel coefficient of specular reflection, also depending on the sample refractive index, $n$:

\[
f(n, \theta) = \frac{1}{2} \left[ \frac{\cos \theta - \sqrt{n(\theta)^2 - \sin^2 \theta}}{\cos \theta + \sqrt{n(\theta)^2 - \sin^2 \theta}} \right]^2 + \left[ \frac{n(\theta)^2 \cos \theta - \sqrt{n(\theta)^2 - \sin^2 \theta}}{n(\theta)^2 \cos \theta + \sqrt{n(\theta)^2 - \sin^2 \theta}} \right]^2
\]  

(2.3)

Lee [19] used the above relation to correlate gloss and surface roughness of paper. Oittinen [20] discussed the same relation for both paper gloss and print gloss and proposed a modification to the expression with an extra factor accounting for the size distribution in combination with surface roughness.

In this study gloss was measured using a Zehntner ZGM1022 gloss meter and the Tappi standard [21] was used as a guideline for the gloss measurements. According to this standard, the light from a tungsten lamp is reflected on the sample at $\theta = 75^\circ$ angle from its normal, and the gloss in percentage units is obtained from the measured reflected light intensity $I$ as

\[
gloss \text{ unit} = \frac{I}{I_0} \cdot 100
\]  

(2.4)
Here $I_0$ is the intensity of light reflected from a smooth black glass standard substrate having refractive index $n_i = 1.540$. In the present study the reported value is the mean of 3 different measurements. The gloss of unprinted and printed papers is measured and compared to the surface roughness determined by Zygo profilometry.

### 2.2 Spreading and contact angles

As mentioned above, the study of the surface chemical mechanisms of electrophotographic fusing requires input both from characterisation of the substrate topography (both below and above the toner layer) and the toner spreading processes connecting the initial and final states. The challenge is both to devise experimental techniques to directly measure toner particle spreading, and also to characterise the substrate surface energy and toner surface tension and rheology in order to explain and predict the spreading behaviour.

Central to these endeavours is the concept of the contact angle of a liquid drop (e.g. melted toner particle) spreading on a substrate (e.g. paper) in air. The angle formed at a liquid front in equilibrium is called the static contact angle, and is determined by the balance of the three interfacial energies according to the Young equation (or generalisations to include the effect of surface roughness). Prior to reaching equilibrium, the angle is referred to as the dynamic contact angle, driven spontaneously by the interfacial energies acting at the three-phase line and opposed by the viscous resistance to flow. Other forces can also contribute, e.g. gravitational in the case of a large drop or external pressure for forced motion.

Gravitation is only significant in the case of large drops, with their shape then determined by the local balance of the hydrostatic pressure and the Laplace pressure [22]. For drops of the size of single toner particles gravity is negligible and the liquid-air interface at equilibrium will be a spherical cap, i.e. with uniform curvature everywhere. During spreading, the drop shape will also be a spherical cap, provided the rate of contact angle change is rate determining. If on the other hand the flow rate of the bulk liquid determines the overall rate then a cap with foot will be formed [23].

### 2.2.1 Contact angle measurement of macroscopic drops

The contact angles of drops in the µl range (i.e. mm diameter range) and above can be measured with a goniometer, showing the side view of the
spreading drop. The Fibro-DAT instrument used in the present study is an automatic goniometer using a CCD-camera connected to a computer and software to calculate the contact angle, base diameter and remaining volume of a spreading drop after its application with a pipette to the substrate. In particular, this instrument was employed to calculate the contact angles of test liquids (water, ethylene glycol and methylene iodide) on different solid samples in order to establish the latters’ surface energies, according to the standard procedure described in Section 2.2.4.

2.2.2 Wetting and spreading of toner

The method described has previously been applied to macroscopic (i.e. µl volume) particles of coalesced toner or toner resin spreading on a heated plate [6, 19]. This represents a large step away from the reality of individual toner particles of approximately 10 µm diameter (0.5 pl volume). A method to monitor the spreading of individual toner particles during heating was developed and used in [I], and is briefly summarised below.

Figure 2.3: Schematic of the measurement principle for toner wetting on a heated plate.
For drops of this size, the side profile dynamics are experimentally almost impossible to resolve, necessitating a limitation to information obtained in top view. This information suffices to determine the drop contact angle provided the drop spreads as a spherical cap of known initial volume and retains this volume during spreading (i.e. no evaporation or penetration occurs). If these assumptions hold true, the contact angle of the spreading drop is uniquely determined by the ratio of the particle covering area to its initial covering area, $A/A_0$, as expressed in equations 2.5 a and b. From these the contact angle corresponding to a measured dimensionless covering area can easily be solved numerically.

\[
\frac{A}{A_0}(\theta \leq \frac{\pi}{2}) = \left(\frac{4 \sin^3 \theta}{2 - 3\cos \theta + \cos^3 \theta}\right)^{\frac{2}{3}} \quad (2.5 \text{ a})
\]

\[
\frac{A}{A_0}(\theta \geq \frac{\pi}{2}) = \left(\frac{4}{2 - 3\cos \theta + \cos^3 \theta}\right)^{\frac{2}{3}} \quad (2.5 \text{ b})
\]

The experimental set-up for monitoring the toner particle spreading on a substrate during the course of heating is illustrated in Figure 2.3. Two different substrates were used, namely a high-energy clean glass and a low-energy hydrophobised glass. Heating of the plate was performed from ambient temperature at rate of 20°C/min. to 70°C, then held for 3 min., followed by continued heating at 10°C/min. to 125°C, held for 10 min. A Nikon Optiphot 100S with a 50X lens was used as reflection optical microscope, onto which a CCD-camera (Sony XC-75) was mounted. Its images were captured with a frame grabber (IMAQ-1411, National Instruments) connected to a computer with National Instruments software Lab View including IMAQ vision 5.1. A self-built Lab View program was used to measure the area ratio during the heating and spreading of the toner particle and calculate the corresponding contact angle evolution.

### 2.2.3 Reology

The concept of shear viscosity was introduced by Newton’s postulate [24], in which the shear stress $\sigma$ (force per unit area) acting on a plane due to fluid motion parallel to this plane was related to the perpendicular gradient of this in-plane velocity, or shear rate $\dot{\gamma}$, through the relation:

\[
\sigma = \eta \dot{\gamma} \quad (2.6)
\]
Here \( \eta \) is the shear viscosity, and is constant for liquids with Newtonian behaviour. For non-Newtonian liquids \( \eta \) is a function of shear rate, i.e. decreasing for shear thinning fluids and increasing for shear thickening (or dilatant) fluids. Moreover, the apparent viscosity can also depend on shear history, e.g. higher on increasing shear rate than for decreasing shear. This hysteresis is referred to as thixotropy for shear thinning fluids.

Many models exist for fitting the rheogram of apparent viscosity versus shear rate for non-Newtonian fluids. Many shear thinning liquids can be well fitted to the Bingham approximation:

\[
\sigma = \sigma_y + \eta_p \dot{\gamma}
\]  

(2.7)

In this simplest generalisation of Newtonian behaviour the linear relation in equation 2.6 is offset by a constant, \( \sigma_y \), referred to as the yield stress, representing the shear stress required to induce a non-zero shear rate. Having induced flow, the rate of subsequent increase of stress with shear rate is referred to as the plastic viscosity, \( \eta_p \).

In this study viscosities of bulk molten toner of the four process colours have been measured at different temperatures using a Physica USD200 rheometer with cone-plate set-up in controlled shear stress mode. In each case the shear rate was increased from 0.01 to 10 Hz and reversed back down to 0.01 Hz, with 7 measurements distributed on a logarithmic scale for both increasing and decreasing shear rates. The results are presented in Section 3.1 and [I].

2.2.4 Surface free energy of solid surfaces

The measurement of surface free energy of solids cannot be performed as directly as for liquids, for which a multitude of well-established surface tension techniques exist. The most common of the indirect techniques to determine solid surface free energy involves measurement of the contact angles of various test liquids (with known characteristics) on the solid substrate of interest. The measurement of contact angles of these liquid drops can be simply performed using for example the technique described in Section 2.2.1. The challenge then passes to the calculation of the solid surface free energy based on the liquid surface tensions and measured contact angles, for which different theories have been discussed in the literature for over half a century [25].

This study has employed the method described by van Oss et al.[26–28] The method employs three different pure liquids with known total surface tension and polarity values, from which the corresponding total surface...
energy and polarity of the solid substrate are derived. For three test liquids it is thus possible to determine the dispersive (or non-polar) component, as well as the acid and base contributions giving the polar component, of the solid substrate. The assumptions underlying this model have been criticised in the literature by various authors [29-32], however this procedure has proven to be very useful in relative comparison of substrates. Specifically, in this study the surface tensions and their constituent components for the four toner solids are determined using this procedure by melting and resolidifying the toner as flat cast films, upon which the test liquid spreading is performed. The results are presented in Section 3.2 and [1].
3 Results and discussion

In the following the key results from [I] and [II] are summarised and combined. In [I], outlined in Sections 3.1-3.4, the properties of the toner particles and their spreading on solid substrates are systematically analysed. For these purposes well-defined model substrates were used, in particular high-energy and low-energy glass, to examine the role of surface chemistry without the complications of real paper topography and pore structure. In [II], summarised in Sections 3.5-3.6, the focus switches from laboratory experiments to pilot printing trials, from model substrates to real paper products, and from the shape of individual toner particles to the topography of their layers and multilayers.

3.1 Rheology of toner

The toner particles used in this study (Xeikon toner system V2) have a glass transition temperature around 70°C, typical for most toner systems. Due to instrument limitations the toner viscosity was only determined in the temperature range from 100°C to 130°C. Lower temperatures correspond to shear stresses above the measurable range, whereas the upper temperature is the maximum allowed for the instrument. Figure 3.1 shows rheograms of cyan toner at high (130°C) and low (110°C) temperature. At both temperatures the toner is shear thinning, but with higher temperature giving dramatically lower viscosities and shear stresses, as expected. Note also the thixotropic nature of the molten toner, yielding considerably higher viscosity for increasing shear rate.

The shear rate of interest when studying spontaneous drop spreading and film levelling due to surface tension is in the range 0.01–0.1 Hz. For this reason the low shear rate range of these rheograms has been used in fitting the Bingham approximation in equation 2.7.

Figure 3.2 shows the Bingham approximation for the cyan toner at these two temperatures in Figure 3.1, based on shear rates in the range 0.01-0.3 Hz and taking the average from increasing and decreasing measurements. The linear approximation is shown to be accurate, yielding the plastic viscosity and yield stress as the gradient and intercept, respectively. The plastic viscosity for cyan toner at 130°C and 110°C is 349 and 1644 Pa s, respectively, with corresponding yield stresses of 5.2 and 16.7 Pa. For all four process colours the plastic viscosity and yield stress decrease with temperature, with black giving highest values and cyan lowest. The values for the intermediate colours, yellow and magenta, are quite similar.
**Figure 3.1:** Rheogram for cyan toner at 130°C (left hand side) and at 110°C (right hand side), in both cases displaying viscosity and shear stress as a function of shear rate. Unfilled and filled symbols refer to increasing and decreasing shear rates, respectively.

**Figure 3.2:** Bingham approximation (solid line) for cyan toner at 130°C and 110°C. Unfilled and filled symbols refer to increasing and decreasing shear rates, respectively.
### 3.2 Surface free energy

Table 3.1 lists the calculated values for the 3 components of the surface free energy for each of the four toner colours, i.e. cyan (C), magenta (M), yellow (Y) and black (K), obtained using the procedure outlined in Section 2.2.4. For all colours, the dispersive (van der Waals) component is clearly dominant, as expected for these polymer materials, with the significantly smaller acid-base component mostly influenced by its base part. The total surface energy, as well as its non-polar (dispersive) and polar (acid-base) components, all decrease from black to cyan to magenta to yellow. By way of comparison, the surface free energy of a black toner measured with inverse gas chromatography gave 41 mJ/m² for the dispersive part [33]. Table 3.1 also lists the corresponding surface energy components for the low-energy substrate (hydrophobically modified glass) on which the spreading experiments in Section 3.4 are performed. For the high energy substrate (clean glass) the contact angles of the test liquids were too low for measurements to be possible.

#### Table 3.1: Surface free energy components for the four different toners and the substrate.

<table>
<thead>
<tr>
<th>Surface energy</th>
<th>Total</th>
<th>Dispersive</th>
<th>Acid/Base</th>
<th>Base</th>
<th>Acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mJ/m²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>34.8</td>
<td>33.3</td>
<td>1.5</td>
<td>5.9</td>
<td>0.092</td>
</tr>
<tr>
<td>M</td>
<td>33.4</td>
<td>32.2</td>
<td>1.2</td>
<td>4.0</td>
<td>0.093</td>
</tr>
<tr>
<td>Y</td>
<td>31.7</td>
<td>31.2</td>
<td>0.51</td>
<td>2.9</td>
<td>0.023</td>
</tr>
<tr>
<td>K</td>
<td>37.6</td>
<td>35.8</td>
<td>1.7</td>
<td>8.8</td>
<td>0.087</td>
</tr>
<tr>
<td>Hydrophobised glass</td>
<td>23.7</td>
<td>22.9</td>
<td>0.82</td>
<td>2.9</td>
<td>0.057</td>
</tr>
</tbody>
</table>

### 3.3 Toner modification

The measurement principle outlined in Section 2.2.2 for in-situ monitoring of individual toner particle wetting requires that the toner particle volume be known a priori. The most elegant approach is to first transform the originally irregularly shaped toner particles to spheres, thus providing the simplest possible initial state from which spreading then proceeds. The transformation was performed by heating the toner particles in a liquid, thus allowing the interfacial tension to overcome viscous resistance. This process is the wet-state analogue of the air-borne spherical transformation process mentioned in Section 1.2. Figure 3.3 displays the transformation in toner particle shape from irregular (in Figure 1.3) to almost perfectly spherical. Higher resolution micrographs show that the fine structure of the surface, namely from embedded charge control and pigment particles, is
relatively unchanged, although somewhat smoother, after the transformation.

Figure 3.3: SEM images at different magnifications for transformed black toner particles.

3.4 Wetting of individual toner particles

The foregoing results from measurement of molten toner rheology and surface tension (the latter is assumed not to differ substantially from the solid-state surface free energy values) thus provide the basis for interpreting the results of the particle spreading experiments on the two heated substrates.

The spreading results for single particles of the four toners on the hydrophobised and clean glass are provided in Figure 3.4. On the hydrophobic substrate, the temperature and time evolution of contact angle is quantitatively identical for the four different colours, all of which display the same onset of softening and spreading at 70°C, followed by the linear regime terminating at a plateau value of approx. 85° with no further decrease for temperatures above 100°C. This angle corresponds to a covering ratio $A/A_0$ of around 1.7. On the high-energy substrate, the spreading is far more substantial and significant differences between the four colours emerge. Again all colours begin spreading at this same temperature common to all 4 base polymers, and follow approximately a common slope of decreasing contact angle with time and temperature up to just below 100°C. However, the cyan and black particles then continue to spread to reach a contact angle of approx. 15 at 120°C. The yellow particles display a plateau above 100°C, similar to the behaviour on the low-energy surface, although now with a much lower contact angle. The magenta particle behaviour is somewhat intermediate to these two extremes. Note that these lower contact angles on the hydrophilic substrate correspond to substantially larger spreading ratios, with equilibrium values
ranging from 3.9 for yellow and 4.7 for magenta to approx. 7.5 for black and cyan.

These results clearly point to the importance and sensitivity of substrate surface chemistry. In particular, the black particles, expected from their high surface tension and high viscosity to exhibit least spreading, are either identical to the other colours or spread most, depending on the specific interactions with the substrate. The surface energy penalties for the low-energy substrate in contact with air and with toner are almost equally matched, irrespective of toner type, as the toner-substrate interactions are dominated by the non-polar component, approximately equal for the four colours. The energy cost of the toner interface with the high-energy substrate varies greatly between the toner colours. The black toner is most compatible with the cleaned glass, giving the lowest toner-substrate cost and thus more than compensating for the high cost of its interface to air. This is reflected in its highest value of work of adhesion. At the opposite extreme, the yellow toner has much lower compatibility with the clean glass, so despite the benefit of low toner-air energy cost, the spreading is least. This sensitivity to toner type is due to the predominance of polar interactions between the clean glass and toner, and in particular the relatively strongly varying base component of the toner surface energy, giving high (for black) and low (for yellow) affinity to the acidic glass surface.

Note that these conclusions regarding contact angles are based on the assumption in equation 2.5 that the interface is a spherical cap. To verify this, topographical images over melted toner particles in their final state

![Figure 3.4: Contact angle vs. temperature for spherical toner particles on cleaned glass (left hand side) and on hydrophobised glass (right hand side).](image)
were measured using both interferometric profilometry (Figure 3.5) and AFM (Figure 3.6). Line profiles over the former gave very good correlation to the spherical cap geometry [I]. Further, from the AFM height map corresponding to Figure 3.6 the contact angle at this fine scale was found to agree almost exactly with that obtained from the analysis of optical micrographs in Figure 3.4 and from the Zygo instrument in Figure 3.5.

**Figure 3.5:** Topographical image over an originally spherical black toner particle in its final state melted on cleaned glass (colour bar is height in µm).

**Figure 3.6:** AFM phase image over the edge of an originally spherical black toner particle in its final state melted on clean glass.
The measured single particle spreading rates from Figure 3.4 were compared to predictions from theories [6, 34] using the measured equilibrium contact angle ($\theta_e$), surface tension and viscosity for the toners as input parameters. In particular, van Oene’s equation for rate of area ratio ($A/A_0$) increase as a function of dynamic contact angle, $\theta$, fails to correctly rank the spreading rates of the 4 toners. Instead [I] proposed a general empirical relation that both fits the measured data for all toner-substrate combinations and only depends on input of equilibrium contact angle and surface tension (see Figure 3.7).

![Figure 3.7: Spreading rates versus contact angle difference, showing experimental mean value points and their calculated fitting curve, for both cleaned glass (filled symbols) and hydrophobised glass (unfilled symbols).](image)

![Figure 3.8: Optical microscope images of an unmodified irregular black toner particle on clean glass, at left: before heating, middle: its transformation to spherical shape on heating above the softening point, and at right: its final spread state after heating to the maximum temperature. Scale bar = 10 µm.](image)
All of the above-mentioned spreading experiments were performed on thermally pre-treated particles in order to utilise their well-defined spherical geometry in extracting the contact angle. However, other measurements in this study have been carried out on unmodified toner particles. An example of such an experiment, for an unmodified black particle on clean glass, is given in Figure 3.8. Around the glass transition temperature, approximately 70°C, the irregular particle first contracts to a sphere or spherical cap, analogous to the pre-treatment stage, and at higher temperatures spreads in this same spherical cap form. Accordingly, the covering area first decreases to a minimum, and then increases strongly at these higher temperatures. Profilometric measurements on this final state give a contact angle very close to that measured for the modified particle, thus confirming that the pre-treatment affects the form but not the surface chemistry.

3.5 Surface topography

In [II] the glossy coated paper and uncoated paper were printed using a Xeikon DCP 320 D press with solid print (full-tone) fields of 100% cyan (C), magenta (M), yellow (Y), and black (K), 200% blue (CM) and red (MY), 300% black (CMY), and 400% black (CMYK). This press has two types of fusing units, one radiant source (infrared, IR) followed by two pairs of heated rolls. The fusing conditions were varied from no fusing to only radiant fusing, at a number of increasing temperature settings, to radiant followed by heated roll fusing (again at a series of increasing temperatures). The details of these settings are provided in [II].

After transfer of toner to these two paper substrates, the toner layer thickness and surface roughness were determined to provide the initial conditions for the following analysis of the fused prints. Figure 3.9 shows examples of the boundary between unprinted and printed areas on the coated paper, in this unfused state. Note that significant differences exist between the coverage of the single (100%) colours at their standard density settings, which directly translate to differences in their effective layer thicknesses (since particle size is approximately equal for all 4 colours). This effective thickness increases from Y to C to M to K on both coated and uncoated papers. For the 200, 300 and 400% layers the thicknesses increase to approximately two, three and four times the average value (15 µm) for the 100% layers, as expected. All thicknesses decrease on fusing, with the thicker layers exhibiting a stronger decrease. As an example, on
Figure 3.9: Topographical images (175 x 130 µm) over the edge between printed (to the left of each image) and unprinted (to the right) coated paper, for the 4 colours: top left, yellow; top right, 100% black (K); bottom left, blue (CM); bottom right, 400% black (CMYK). The colour bar units are µm.

Radiant fusing of 100% and 400% black on coated paper, the thicknesses decrease exponentially with temperature from their unfused values at 70°C (polymer softening temperature) to 8 and 22 µm, respectively, at 145°C.

Figure 3.10 provides profilometry images of toner printed areas subject to varying degrees of fusing, and analysed with different bandpass filtrations, in order to illustrate the trends in corresponding surface roughness values discussed in Section 3.6. The example is for 100% black (K) on coated paper, fused radiantly at the two extremes and midpoint of the temperature range examined, i.e. 105, 125 and 145°C. The top row displays the unfiltered image, while the middle and bottom rows show the corresponding images for relatively low and high wavelength bands, 10-20 and 40-200 µm, respectively. The colour range corresponds to the height scales shown (in µm), and the black textures (present on all images irrespective of wavelength) are regions in which the local slope is too steep (above 29.5°) for the profilometer to measure, typically occurring near the boundary between toner and paper. Observe from the unfiltered images that the toner particles have a strong tendency to build a network of linear chains of partly coalesced particles on the substrate (the blue background), which subsequently broadens, merges and flattens to give the texture at the highest fusing temperature. This behaviour is analogous to that observed
by Sipi et al[7, 8] using optical microscopy, namely that the uncovered white specks are small, evenly distributed and have sharp edges at low IR fusing temperatures, and become fewer, but larger and with softer edges at higher temperatures. From the shorter-wavelength band (middle row in Figure 3.10) it is apparent that the finer features on the single-particle level progressively disappear on increasing fusing temperature, as would be expected from this coalescence and merging. On the other hand, the larger-wavelength band images (lowest row) show that this transformation of fine to coarse structures on merging actually leads to an increased roughness on these length scales, even though the overall height variations diminish. These trends, applying to all toner colours, will be quantified in the surface roughness analysis.

![Figure 3.10: Representative topographical height maps over areas 311 × 233 µm, for 100% black (K) on coated paper, fused radiantly at the three temperatures 105°C (left column), 125°C (middle) and 145°C (right). The upper row shows the unfiltered images, whereas the middle and lower rows correspond to their bandpass filtrations in the wavelength intervals 10-20 µm and 40-200 µm. The colour bar units are µm.](image)
3.6 Surface roughness and gloss

Figure 3.11 plots the surface roughness contributions from three wavelength bands, corresponding to relatively short, intermediate and long length scales, for radiant fusing of all 8 toner combinations at increasing temperatures on coated and uncoated paper. For wavelengths below 20 \( \mu m \), roughness decreases with temperature due to smoothening of individual toner particle profiles and their merging with neighbours to eradicate the gaps in-between. However, yellow displays the opposite trend in the 10-20 \( \mu m \) band on coated paper, owing to its low surface coverage, hindering merging. At the higher band, 20-40 \( \mu m \), on coated paper the roughness of C, M and K first increases with temperature, then decreases, reflecting the continued particle and cluster merging that creates features at this length scale and which then merge further at the higher temperatures and begin contributing to the even higher band. At this highest band of 40-200 \( \mu m \), on both coated and uncoated paper, all colours increase their roughness with temperature due to contributions from merging at the smaller length scales, which more than outweigh the general tendency to flattening (with no nip pressure applied). For toner radiant fusing on the uncoated paper the roughness values are typically lower, owing to the melted particles’ ability to partially sink into inter-fibre voids. Accordingly, the roughness increase with temperature occurs only in this highest band (40-200 \( \mu m \)).

The question then arises as to the consequences of these surface roughness values for the print gloss of these samples. The standard formula in equation 2.2 predicts that the logarithm of gloss decreases linearly with the square of the short-scale r.m.s. surface roughness. This theory is tested by comparing measurements of print gloss with the surface roughness bands, examples of which are shown in Figure 3.12. Each graph includes results on both coated (filled symbols) and uncoated (open), and both IR fusing alone and followed by heated nip (at all temperature settings tested). For all colours (excepting yellow) and substrate-fusing types this log-square relation between gloss and \( S_q \) is approximately linear with negative slope, as expected, provided the roughness from wavelengths below 20 \( \mu m \) is used. This is especially clear for the print types fused only radiantly, over which a wide range of roughness and gloss values is obtained at the different temperatures. In this case the magnitude of the slope is generally greater for the uncoated paper prints, meaning that the same reduction in surface roughness (squared) gives a greater reward in gloss. This implies that some of the surface roughness due to toner particles in uncoated paper inter-fibre crevices is detected by the profilometer but not in the 75° gloss measurement.
Figure 3.11: Surface roughness of toner films of the 8 colour combinations on coated paper (left side) and uncoated (right side), divided into 3 wavelength bands indicated in μm, plotted as a function of radiant fusing temperature.
Figure 3.12: Logarithm of print gloss of 200% CM toner films (left side) and 100% yellow (right side) vs $Sq^2$ for three different wavelength bands indicated (in µm).
For curing with IR followed by heated roll the trends in Figure 3.12 are slightly less clear, owing to the narrow range of low roughness and high gloss obtained, due to the high radiant temperatures used plus the added effect of the rolls. However it appears that the slopes in these cases are also high, at roughly the level of those for purely IR fusing on uncoated paper. The extra glossing benefit of the heated rolls is the direct result of toner particle flattening, on the micro-scale, as well as increasing orientation over more macro-scales to increase the number of areas contributing to the same 75° reflection.

For the wavelength band 20-40 µm, the correlation between gloss and surface roughness persists for all colours (excepting yellow) and for all substrate-fusing types excluding purely IR fusing on coated paper. The latter gives poor correlation for the colours in Figure 3.11 for which this band does not give decreasing roughness with increasing IR temperature. In particular, the low fusing temperatures give low roughness values since the particles have not merged sufficiently to give sizes contributing to this band, however the gloss is still very low, as apparent from the particles’ contribution to lower wavelength roughness. The low physical coverage of yellow results in weaker gloss-roughness correlations and different results for the different fusing types, since melting-induced merging is limited and only the nip pressure is capable of flattening the isolated particles.

Figure 3.13 summarises the correlation between the printed paper gloss and surface roughness in all 5 bands. The maximum length scales over which the correlation persists clearly increase with degree of toner coverage or layer thickness, i.e. from Y to C to M and K to the 200-400% print layers. This correlation length also tends to increase from coated to uncoated paper, and from radiant fusing alone to its combination with the heated rolls.
Figure 3.13: Coefficient of determination, $R^2$, of the least-squares fits of the gloss-roughness log-square plots to straight lines, for all 8 colour combinations, averaged over both coated paper and uncoated paper and both fusing combinations. The coefficient varies from +1, indicating fit to a negatively sloping line, to –1, indicating fit to a positively sloping line.
4 Conclusions and future work

Paper I in this thesis describes a newly developed and relatively simple instrument to image and quantify in-situ the spreading of individual particles of toner, or indeed of any thermoplastic material, on a heated substrate. Unlike other related instruments, based on imaging the profile, this method uses only imaging from above, thus making it possible to consider particles of realistic size (around 10 $\mu$m in this case) and so avoid the complication of introducing irrelevant interactions (e.g. gravity) and altering the size-dependent kinetics of the other interactions.

The results of this study clearly show that high energy substrates not only exhibit far greater toner particle spreading, and work of adhesion, but also a strong dependence on the toner type. For these Xeikon toners the cyan and black spread far more than the magenta, with yellow clearly the lowest. Conversely, low energy substrates exhibit limiting spreading and lack of sensitivity to toner type. The results permitted the proposal of a simple generalised law to describe the spreading kinetics, able to fit all experimental results with the bare minimum of input information from the equilibrium state.

Although the method was mainly applied to spherically-transformed particles, the results obtained here provide a foundation for interpreting spreading of irregularly-shaped particles (and indeed require no extension for the spherical “chemical” toner becoming more common in recent years). Similarly, the use of smooth and inert model substrates of well-defined surface chemistry in this study paves the way for interpreting behaviour on real electrophotographic media. The method provides a readily visualisable and flexible means for more systematic design of toner-substrate interactions in electrophotography. A broad range of different toner particles can be relatively rapidly screened in contact with model and real substrates, and the spreading then correlated to electrophotographic runnability, print quality and durability issues.

Paper II in this thesis illustrated the utility of the white-light interferometric profilometer in quantifying the thickness and surface roughness spectral decomposition of toner layers transferred and fused on paper substrates, thus giving increased insight into the mechanisms giving rise to toner print quality. As expected, significant differences in surface roughness behaviour were observed between the eight different toner colour combinations, as a function of both substrate type (coated and uncoated paper) and fusing units (radiant and heated roll) and their temperature settings. As a result, the extent to which the correlation between print surface roughness and gloss at micron length scales extends
to longer length scales is also dependent on these parameters. This cut-off length increases with toner film thickness and on use of the heated roll glossing unit. These observations facilitate more systematic approach to designing fusing units to avoid typical problems such as gloss variations in electrophotographic prints.
5 Acknowledgement

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