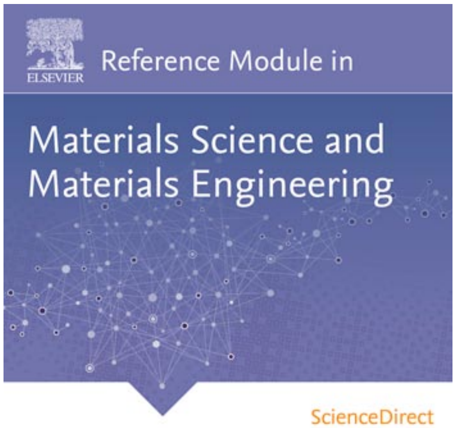

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Paper and Print Technology☆

RW Lovelace, Trekbrook Papers, Tring, UK
K Thom, Curtis Fine Papers, Guardbridge, UK
AA Abdullahi, University of Malaya, Kuala Lumpur, Malaysia, and Federal University of Technology, Minna, Niger State, Nigeria

1 Introduction

Printing technology has evolved through the years into a very sophisticated and highly engineered process, with ever-increasing machine speeds, finer image quality, and increased flexibility. Paper has followed the developments within the print industry to ensure that it remains a suitable substrate, capable of withstanding the rigors of modern printing processes.

Great advancements have been made at the end of the twentieth century in both prepress and printing processes, particularly in the exploitation of digital technology, with the introduction of direct-to-plate and direct-to-press imaging as well as the sophisticated work flow management systems and image setting functions. It is, however, the area of true digital printing that has seen rapid development in terms of both technological advancement and implementation. Much of the benefit of this new technology is within the short-run or personalized (variable data) printing. Along with this evolution of printing technology, paper has also developed to keep pace with the ever-increasing demands of quality and performance that the new technology places on the substrate. With the increase in activity within the digital print area it is essential that the very different demands placed on paper are accommodated and it is essential that the paper industry monitors and develops its products to ensure they perform well. To achieve this, it is important to understand both the papermaking process and the print process and how the substrate and press interface during printing.

Three types of printing process will be considered: off-set lithography, laser/led (electrophotographic), and inkjet (thermal and piezo drop on demand) as these processes dominate the traditional and digital graphical printing market. Uncoated wood-free paper will be examined as a printing substrate and compared with conventional pigment-coated offset paper.

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2 Paper Technology

In terms of performance, paper must provide a suitable imaging surface (printability) and also be able to be transported through the imaging device at an acceptable speed (runnability). As printing speeds increase, the need for accurately controlled and consistent quality is imperative. Much of this is achieved by the on-line quality measuring and control systems that exist on modern papermaking machines. The vast majority of graphical papers are made on the standard Fourdrinier paper machines and use wood as the basic raw material.

The key molecule within the wood that forms the paper product is cellulose. Cellulose is a carbohydrate (a polysaccharide), constructed from repeating glucose units – $(C_6H_{10}O_5)_n$ – where n is the number of repeating glucose units or degree of polymerization, typically around the 600–1500 level for the materials used in papermaking. Much of the graphical paper sold worldwide is derived from wood, but this is not the only source of cellulose. Bast fibers such as flax, hemp, and jute; grasses such as straw, bamboo, bagasse, and maize; leaf fibers such as esparto, manila, and sisal; and seed hairs, mainly cotton, are all sources of cellulose which can be used as raw materials in papermaking. These differing sources of raw materials produce fibers with differing physical characteristics which in turn affect the physical characteristics of the final paper. This is due to the variation in fiber construction and length. In terms of tons produced, wood is by far the biggest source of cellulose fiber. Wood itself produces a variety of fiber types depending on the type of tree and also from which region of the world the tree is grown. Trees belong to the Spermatophyta group of plants (seed-producing plants) and can be broadly categorized into:

- Hardwoods – Angiosperms, broad leaf trees and deciduous such as Birch, Red Maple and Aspen.
- Softwoods – Gymnosperms, needle leaves, cone-bearing and evergreen such as Scots Pine, Norway Spruce and Douglas Fir.

There are many different types of paper made from wood but a broad classification can split such paper into two groups, wood-containing and wood-free. It may seem somewhat paradoxical to describe a paper being made from wood as a wood-free but in papermaking terms, a wood-containing grade (sometimes referred to as a mechanical paper or ground wood paper) is one where much of the woody material ends up in the final paper product, whereas a wood-free grade (often called a chemical paper) has much of the resinous impurities chemically removed. The cellulose fibers form the structure of the wood within the tree and these fibers are cemented together by resins (lignin). Lignin is a very complex polymer and forms the middle lamella (the outer layer of the fiber) which in turn cements all the fibers together. Lignin is also found within the fiber. Much of this lignin will find its way into mechanical or wood-containing paper while wood-free grades have this lignin extracted prior to papermaking. The choice of wood-containing or wood-free will be determined by end application and commercial restrictions. Newsprint is a perfect example of wood-containing paper – it has no need to be durable, has only limited print quality requirements, and needs to be a low-cost product. On the other hand, papers used for birth certificates, for example, require a quality print application, need to be stored for many years and are less critical in terms of market price – such papers are made wood-free (or certainly free from mechanical pulp).

Prior to paper making, the wood material must be converted into a material suitable for papermaking. This is the pulping process and can be carried out in two ways, either mechanically or chemically.

2.1 Mechanical Pulping Methods

Mechanical methods grind the wood into a pulp form and the friction of grinding generates heat which softens the lignin to allow the fibers to separate. The majority of wood that goes into the process ends up in the pulp. This means that most of the original lignin remains in the pulp to produce what is termed a mechanical wood pulp and could typically have a yield of around 95% (i.e., very little is lost in the mechanical process). Pulps of this form are of a lower grade and are commonly used for newsprint and other lower-grade papers. Due to the presence of lignin, such mechanical papers are unstable to light (yellowing of newsprint is an example). This is because lignin itself is unstable to light due to the production of phenoxy radicals (produced by the daylight) being oxidized to yellow quinone chromophores which discolor the sheet.

2.2 Chemical Pulping Methods

Chemical methods cook and bleach the pulp to chemically remove (dissolve) the lignin, leaving a much purer, whiter, and more stable pulp. Chemical pulps are more expensive as the yield is less (with the lignin impurities being removed) combined with the chemical and energy costs involved in the chemical processes. A typical fully bleached Kraft (sulfate) pulp yield is around 50%. Papers made from fully bleached chemical wood pulps are termed ‘wood-free’ – this does not mean that there is no wood fiber, it means it is free from mechanical pulp.

There are also hybrid processes between chemical and mechanical methods such as Neutral Sulfite Semi-chemical (NSSC), Chemi–Thermo Mechanical Pulp (CTMP), Refiner Mechanical Pulp (RMP), and Thermo–Mechanical Pulp (TMP). Some specialized pulps are further treated with sodium hydroxide to produce very pure pulps (used, e.g., in the production of Rayon) – these are termed ‘dissolving pulps.’ Also, paper itself can be used as a raw material (to produce recycled paper). There are a number of interpretations of what constitutes a recycled paper. A fairly straightforward scheme is to classify the waste paper into four categories using, the A B C D system:

- A – Wood-free internal mill waste. This is paper produced within the mill but not saleable which would otherwise go to a landfill site. An example of this is paper produced during a grade change (say when changing from 80 to 90 g m^{-2} paper or changing from a white to a cream shade; the paper machine still produces paper during the change, which becomes waste).
- B – Bought-in wood-free unprinted waste. This is paper bought by the mill which has previously been sold and used but is still unprinted. Examples of this would be edge trim from envelope manufacture.
- C – Bought-in de-inked wood-free printed waste (post-consumer waste). This is waste paper that has gone through its final and intended end use and has been reclaimed. Examples of this would be reclaimed printed waste. This is often de-inked if used for higher grade recycled papers (inked waste results in a dirtier sheet).
- D – Bought-in mechanical printed/unprinted waste. This is reclaimed lower-grade printed or unprinted material, repulped and made back into paper.

The National Association of Paper Merchants (NAPM) define a recycled paper as one that contains at least 75% of recycled fiber excluding mill waste (i.e., can include B, C, or D-type waste fiber).

If the paper mill is an integrated one (a mill that has a pulp and papermill combined) then it can take the pulp straight in from the pulping plant in wet form. This has benefits over nonintegrated mills which have to take in pulp in lap form, which use bales of dried pulp, normally in 250 kg bales.

For a nonintegrated mill, the first step in the papermaking process is to re-wet the pulp and disperse the fibers in water. This is usually called slushing or pulping. The correct blend of fiber types, such as hardwoods and softwoods, are selected to obtain the appropriate paper characteristics and these pulps are then slushed in water. A standard pulper will take a batch of pulp and redisperse this in water, using a mechanical action to separate the fibers. This wet stock is processed by mechanical mixing to break up the lap pulp to form dispersion to around 6% consistency – although this can be higher for specialized processes. This wet stock is then processed through a refining system which will result in the cellulose fibers being cut (reduced in length) and fibrillated by breaking open the outer surface of the fiber. Refining is a key step in the papermaking process as it has a fundamental effect on the physical properties of the final product. Once treated, the wet stock is further diluted with water and blended with mineral pigments (precipitated and ground calcium carbonates. clays, zeolites, and other specialty materials). Dyes, process aids, and sizing chemicals (to impart a degree of water repellency to the paper) are also added to the wet stock flow. The stock is then pumped toward the paper machine into the flow box which allows the stock (now at around 1% consistency) to flow out of a gap (the slice) onto a moving wire on the paper machine itself. This wire, which historically was made of phosphor bronze but is now made from a synthetic material, acts as a filter to allow the water to drain out of the stock, leaving behind a mesh of fibers which bond together. It is the way that the stock lays down on the wire and how it is dried that is the key to successful papermaking. The stock is further dried by wet pressing and evaporation by contact with hot drying cylinders, and is then smoothed by pressure through calender rolls to produce the paper product. This can be further processed by applying mineral pigments (such as clay or chalk) onto one or both surfaces of the paper to produce coated paper. Paper that does not receive such an application is termed an uncoated paper. The paper is reeled up into jumbo machine reels which can be many tons in weight, then slit down to webs for supply to web-fed presses or sheeted to a specific size for sheet-fed presses.

2.3 Physical Properties of Paper

There are many physical properties of paper that have to be controlled to ensure that the final product has the appropriate esthetic characteristics and degree of printability and runnability. These key paper properties are as follows.

2.3.1 Substance

This is basically the physical weight of the paper per unit area. This is quoted as the weight in grams of a 1 m^2 sheet (g m^{-2} or gsm). In the USA, this is often quoted slightly differently and is expressed as the weight in pounds of a ream (of 500 sheets) of a specified sheet size. This can be calculated back to g m^{-2}. Substance has a profound effect on virtually all other paper properties as it basically defines how much fiber is present within the sheet.

2.3.2 Thickness

Usually quoted in microns (μm) or in thousands of an inch (thou), it is, simply, the thickness of a single sheet. Thickness is also known as caliper.

2.3.3 Smoothness

Smoothness is basically a numerical measurement of the surface roughness of the paper and can be calculated in many different ways. A common method is an air leak method as used by the Bendtsen apparatus. Bendtsen measurements are roughness measurements, i.e., smoother sheets have lower Bendtsen values, and are expressed in ml min^{-1}.

2.3.4 Porosity

This is a measure of the air permeability of the paper. There are various ways of measuring this fading property, a common one being the Bendtsen apparatus (same basic unit as for Bendtsen roughness testing but with a different measuring head). Bendtsen porosity is expressed in ml min^{-1}, the higher the value, the more open the internal structure of the paper. Porosity is not a direct measurement of pore void volume but does give an indication of the level of air voids within the paper.

2.3.5 Cobb

Cobb is a measure of the water repellency of paper, which is termed the degree of sizing. Blotting papers or waterleaf papers are unsized and will quickly absorb water. Graphical papers, being sized, are more resistant to water penetration.

2.3.6 Strength

Paper has many strength properties which have differing significance depending on the end application of the paper. Examples of which are,

- Tensile – Paper for web presses or base paper for reel-fed coating.
- Tear – Base paper for gummed stamps.
- Fold – Map papers, particularly concertina-folded types.
- Stiffness – Cheque papers going through automated reading systems.
- Surface strength – Offset litho printing.

Of these, surface strength is a key property for offset lithography as, during the transfer of ink from the blanket cylinder to the paper, there is quite a substantial pulling force to the surface of the paper and insufficient surface strength can result in fiber picking (or linting) which can adversely affect the printed image quality. To achieve the surface strength, the cellulose fibers must be of a sufficient strength, well bonded together, and also be sealed down on the surface, usually achieved by a coating of starch (size) on the surface. Starch is applied on a Fourdrinier paper machine at the size press.

Surface strength is less critical for laser printing as there is no real force applied to the surface during imaging. As for inkjet printing, surface strength is virtually irrelevant during the actual imaging process as it is a true noncontact printing technique. Most of the paper strength properties are heavily influenced by the substance (i.e., weight) but the type of fiber (softwood, hardwood, etc.), the way the fiber is processed (inter-fiber bonding), and the percentage of nonbonding materials in the paper (mainly mineral pigments) can also have an effect.

2.3.7 Opacity

Opacity is the measure of the degree of show-through from one side of a paper to another, i.e., the degree of visibility of printed material on one side of the paper when viewed from the reverse.

2.3.8 Electrical conductivity

This is basically the ability of the paper to conduct (or resist) the flow of electricity. With offset lithography, there is very little influence over the imaging process, but static electrification can influence the feeding and delivery of the paper. If the paper is prone to static electrification then the paper can cause feeding problems into the press and poor jogging in the delivery section once printed. ('Jogging' is the process of aligning the edges of a pile of paper, usually by vibration.) Laser printing is much more influenced by the electrical properties of the paper as the toner image is attracted onto the surface of the paper by a static charge. If the paper has too high a conductivity, then the charge buildup within the paper may be insufficient to transfer a satisfactory amount of toner onto the surface. With the reverse situation, too high resistivity will allow good toner transfer but the paper may be reluctant to give up that charge and the static buildup can cause poor delivery of the paper in the delivery trays. The electrical properties of the paper are influenced by the chemical constituents of the paper and also by the moisture content. Increasing moisture content will increase conductivity.

2.3.9 Paper coating

Conventional coated paper, usually coated with a clay or chalk pigment held together by a pigment binder, is often unsuitable for inkjet printing as the pigment layer is too absorbent for the water-based ink and can result in significant lateral spread. Specially formulated coating systems have been developed to capture and hold the inkjet ink in place near the paper surface. These are often based on silica.

2.3.10 Recycled paper

Throughout the paper industry, there has been a need to recycle fiber and this has been done for many years as a matter of course on a commercial basis. Paper made within the mill that fails to meet specification (termed 'broke') is a valuable source of fiber and is re-used wherever possible as this makes sound commercial sense. Over recent years, the market place has generated interest in recycling paper and has produced a variety of recycled grades, from those made only with mill broke, to those made with preconsumer waste and postconsumer waste. Recycled papers can be of a high standard, provided that the source of recycled fiber is of a similarly high standard. Areas of concern with use of high percentages of recycled fiber for premium grades would be batch consistency, cleanliness, and brightness. Obviously, variations in quality of recycled fiber can induce variations in the final product – it depends on market perception as to what is acceptable in terms of product performance against the environmental credentials of the paper. These environmental credentials are much more than the quantity of recycled fiber that has been used. The environmental impact goes through the whole supply chain from forest management systems; pulp and paper mill emission controls; energy conservation; and social responsibility for employees, customers, and local inhabitants. It also covers manufacturing waste management and packaging waste. Paper is a natural product, made from sustainable natural fiber and is easily recyclable and biodegradable. Its flexibility in format and type makes it an ideal substrate for virtually all printing applications.

2.3.11 Permanence

The biodegradability of paper has an adverse effect on its long-term storage. Old books of historic value can, if stored in adverse conditions, be susceptible to disintegration principally by acidic degradation of the cellulose fiber. An acidic environment in combination with acid-made papers severely reduces the degree of permanence of a paper. Modern sizing chemistry and alkaline fillers, in combination with purer cellulose wood pulps, have greatly increased the longevity of paper. Permanent and archival papers are easily sourced and the paper can be stored without detriment for hundreds of years. The standard ISO 9706 details the requirements for the appropriate manufacturing, raw materials, and conditions for papers that require a degree of permanence for long-term storage. The requirements for a long-life paper are freedom from the presence of lignin, use of a neutral or alkaline pH during papermaking, and the inclusion of an alkaline pigment (typically calcium carbonate) to act as a pH buffer.

3 Print Technology

Digital printing is becoming increasingly popular in the printing industry because of its ability to produce short-run jobs; it is also user-friendly and economical. Toner-based digital printing, like laser jet printing, is one of the major digital printing technologies today (Ataeefard, 2014). Though, Offset lithography, laser, and inkjet are very different in their approach to imaging. They all apply a colorant to the print substrate in a controlled manner but depends on the way the image is formed and the nature of the colorant in each case which is radically different. Therefore, the concepts of these printing technologies shall be discuss under the following subsection.

3.1 Offset Lithography

Offset lithography uses oil-based pigmented inks which go through a series of ink film splitting processes to eventually lay down ink in the correct areas on to the surface of the paper. A typical offset press has three cylinders: plate, blanket, and impression cylinders as shown in **Figure 1**.

A series of damping rollers lay down a fine film of water on the printing plate, the surface of which is broken down into hydrophobic (image) and hydrophilic (nonimage) areas. The formed water film is laid down in the hydrophilic nonimage areas. The inking rollers then lay down a film of oil-based ink over the plate – this ink is rejected by the wet areas but is taken up by the

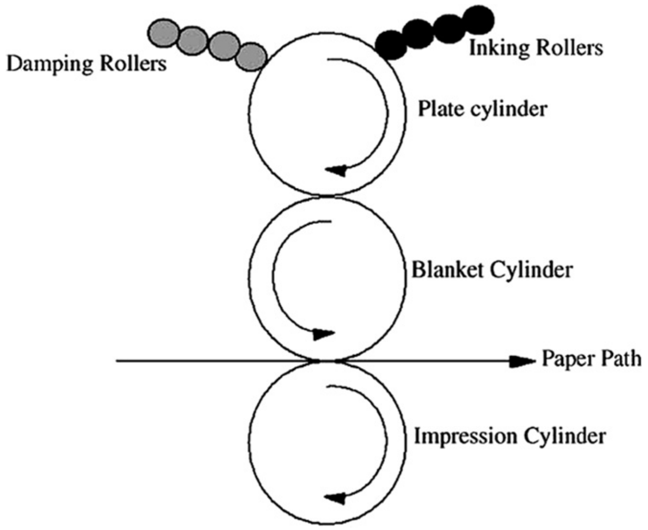

Figure 1 Basic layout of an offset litho printing unit.

hydrophobic image areas. This results in the printing plate having an inked image formed. The inked image is transferred from the plate cylinder onto the blanket cylinder which is composed of a rubber type material. The ink film splits between plate and blanket cylinders. As the press rotates, the ink film splits once again as it contacts the paper that is pressed onto the blanket cylinder by a nip formed by the impression cylinder. For each revolution of the press, one image is transferred onto the paper (either in sheet or web form). For multicolor printing, this process is repeated in separate units for all the colors required. A typical full color image will require four subtractive primary colors – cyan, yellow, magenta, and black. These are termed the process colors, characterized by the letters CYMK where black is referred to as the 'key' color.

An important point to note is that the ink film splits and does not transfer totally. At each revolution, the inked image is refreshed to keep the color density constant. However, as the image on the plate determines what is to be printed every copy will be identical in terms of image detail. There is a rapid development in the area of 'digital litho presses.' However, these presses use digital information to create the litho plate rather than a true digital (variable) printing technique. There are presses that use digital imaged plates which are imaged on the press by taking digital data directly, that is, it eliminates the need for intermediate photographic films. This speeds up the process and is well suited for shorter runs; however, as with standard lithography, once the plate is created only copies of this plate can be made and they cannot incorporate variable data printing as part of the litho process.

3.2 Laser Printing

Laser printing is fundamentally different to offset lithography. There are no plate or blanket cylinders, and indeed there is no fixed image to copy from. Laser is a true digital process as the image is created for the first time from digital data within the print engine.

The image generation goes through a number of stages as shown in **Figure 2**:

1. Corona discharge charges up the organic photoconductor (OPC) drum to build up a static charge on the drum surface.
2. The laser beam scans and pulses across the OPC drum (controlled by the digital data coming from the computer) to selectively discharge areas to form a latent image of charged and noncharged areas on the drum surface. Where the drum is illuminated by the laser, the charge decays.
3. The developer unit applies toner to the OPC drum which electrostatically adheres to the areas corresponding to the image areas.
4. This visible image is then transferred onto the paper by a transfer charge which pulls the toner electrostatically onto the paper surface.
5. The paper and toner are then fused by heat and pressure.
6. The OPC drum is illuminated to decay all charges on the drum surface.
7. The drum is then cleaned of any residual toner.

The whole cycle repeats. It is important to note that for each sheet being printed, the whole image has to be created from scratch each time. This slows the process (in comparison to offset lithography) but increases flexibility – as the image is created each time it can be altered each time – that is, the image can be varied sheet to sheet. There is no wet ink film splitting, and image transfer

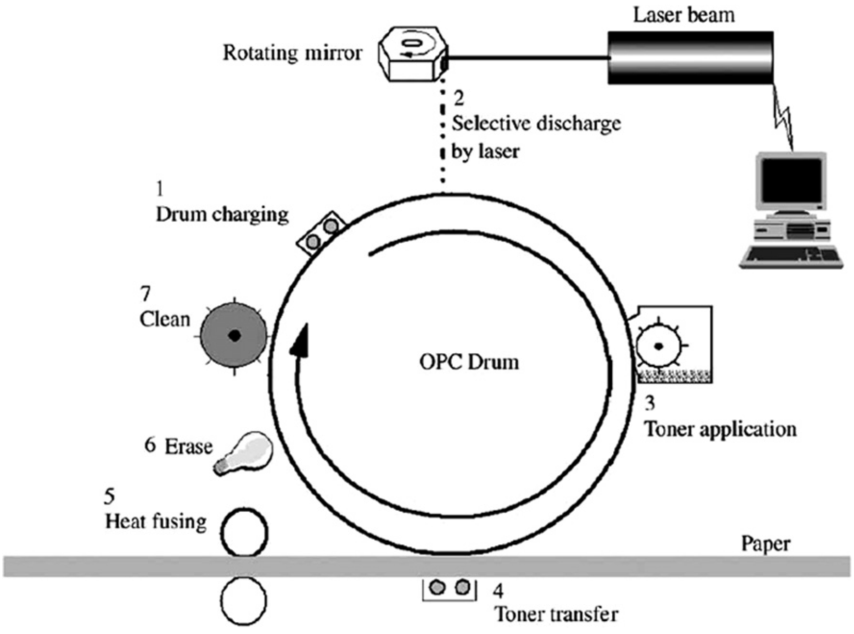

Figure 2 The stages of the laser printing process.

from OPC drum to paper is by electrostatic attraction. As with lithography, a color laser image is formed by applying the four process colors. This can be either with a single-drum system, where the four color toners are applied in turn, or with a four-drum system which has separate drums for each color.

3.3 Inkjet Printing

Inkjet printing is another true digital printing process but is very different from laser. Inkjet basically sprays very fine droplets of ink onto the printing substrate to build up the image dot by dot. There are two basic inkjet systems, the continuous and the drop on demand system. Most inkjet printers will use the drop on demand system, where ink is only ejected from the ink cartridge when it is required. High speed, continuous inkjet systems continually pump ink out of the nozzles but electrostatically deflect it on to the paper when an image is to be printed. The drop on demand system ejects droplets of ink from the ink nozzles either by thermal or mechanical pulse effect. The thermal inkjet head (see **Figure 3**) has a heating element close to the ink reservoir (**Figure 3(1)**). When a drop is to be printed, the heating element heats up (**Figure 3(2)**) to form tiny gas bubbles in the ink. These bubbles rapidly expand (**Figure 3(3)**) to apply a pressure pulse within the ink to force out a droplet (**Figure 3(4)**). The heating element cools (**Figure 3(5)**) and more ink replaces that lost from the ejected drop as the ink head goes back to its ready state (**Figure 3(6)**).

3.4 Others Printing Techniques

Researchers investigates to improve the efficiency of both paper and printing technology, especially on effect of paper properties on color reproduction of digital printing (Ataeefard 2014; Badalov *et al.*, 2015). In the near future, it is expected that the traditional flat or rotary screen printing and roller printing techniques were superseded by digital printing technologies, which have found an increasing number of applications in printing textile (Eckman, 2004; Soleimani-Gorgani *et al.*, 2015). Some inkjet printers will use a different approach to eject ink and are based around a piezoelectric crystal. Basically, the piezoelectric crystal is pulsed with a voltage that causes the crystal to alter its shape and so applies a mechanical pressure pulse within the ink to eject a droplet. Once ejected from the ink nozzle (either by thermal or piezoelectrical process), the ink hits the paper surface and is absorbed. Inkjet is a true noncontacting process. The ink movement once on the substrate will be influenced by the physical and chemical composition of the substrate.

The longevity of the printed image has also to be considered. This has never been too much of an issue with offset litho inks as these are based on pigmented materials which penetrate into the paper (or coating) substrate. The litho ink is inherently light-fast and has a good degree of abrasive resistance. Inkjet ink, on the other hand, can have a problem with fading after prolonged exposure to light. The early inkjet printers and most home or office inkjet printers use dyes as the colorant. While the dyes penetrates well into the body of the paper and does not suffer from abrasion problems, they can be susceptible to fading by light. To overcome this fading problem for the higher end machines (giclee printers), but also for the home and office market, pigmented ink formulations have been developed. These can increase the level of light fastness but often have a more limited color gamut (the range of colors that can be created from the colors available within the inkjet print head). Pigmented ink formulations have to overcome ink clogging – the very fine nozzles within the inkjet head can be blocked with the pigment particle suspensions (not an issue with the dye formulations which have the colorant dissolved in a water-based carrier). Development in inkjet pigment formulations and nozzle constructions have allowed the use of pigments in high-resolution inkjet printers.

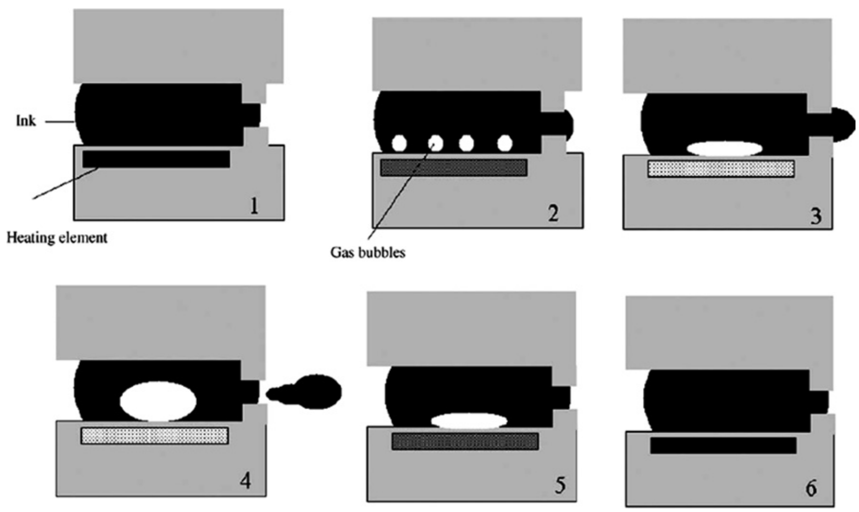

Figure 3 Thermal inkjet process.

Laser printers have the reverse problem: the toners are based on pigments and so are very light-fast but as they sit on the surface of the paper, they can be prone to abrasion and cracking. Improvements can be made to increase the chemical bond between the toner particles and the paper surface by special surface chemical coatings. This helps avoid some of the issues with toner removal, particularly in the area of fraudulent attack, but still may leave issues with abrasion, particularly with documents that are frequently handled and folded.

4 Conclusions

Each of the print processes mentioned has advantages and disadvantages. Litho benefits from high speed and is, therefore, more economical for longer runs but each copy has to be identical to the previous one. Laser has speed benefits over inkjet and is capable of variable data but suffers from the need to heat fuse and imaging with a dry toner which can be susceptible to rubbing. Inkjet is the slowest of the three but can produce lightfast and physically resistant images and has much potential for development.

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