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Printing

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Introduction

Printing has been called the single most significant technical development of human history. Prior to the invention of printing, virtually all communication was verbal. It was difficult to communicate to a large number of people. Printing provided the ability to record ideas in a manner that can be passed through generations. Paper is still the most utilized substrate for printing.

As early as 35 000 BC, people were drawing messages on cave walls. Pictographs were used to represent real objects. Pictographs evolved to ideographs, which were developed by the Phoenicians. By 900 BC, the Phoenicians had also assigned sounds to the symbols.

The Greeks adopted and expanded the Phonetic system. The Romans borrowed 13 Greek letters, revised eight, and added two more in order to write in Latin. Three additional letters were added later for a total of 26, as we know the Roman alphabet today.

Printing Processes

All printing processes produce lines and/or dots to form an image. Printing has made possible the production of multiple copies of graphic images. There are five types of processes, which can be used for graphic reproduction. They are all used to print on paper as well as other substrates. These processes are:

1. Relief printing
2. Intaglio printing
3. Screen printing
4. Lithographic printing
5. Nonimpact printing

Relief Printing

Relief printing was the basis for the original printing press, as invented by Johann Gutenberg. This is based on raised letter type (**Figure 1**). Gutenberg's characters were molded out of lead, a metal, which was used until only recently. This process came to be known as Letterpress and was the basis for all newspaper printing until only recently.

The letterpress process is still used today for die cutting, numbering, perforation, scoring, hot-foil stamping, and embossing. Letterpress inks are relatively high in viscosity to assure its even distribution as it passes through the multiple rolls (**Figure 2**) of the inking system. To distribute the ink better, some or all of the rolls oscillate.

Letterpress has evolved into flexography (flexo), which uses a flexible plate, which contains a raised image area of a cured photopolymer. The plate is wrapped around a cylinder and is used to put ink on the substrate. A typical flexo print station is illustrated in **Figure 3**.

Flexo is the fastest-growing conventional printing process, especially in packaging, such as corrugated containers and flexible films. It has also made significant advances in publication printing, particularly newspapers. Because the quality of flexo printing has improved so much, it is now used extensively for process color printing, as well as spot color, on a wide variety of substrates. It is used extensively for printing tags and labels, many in full process color.

Flexography was originally called 'aniline' printing because of the aniline dye inks originally used in the process. These were made from coal tar and were banned from food packaging by the Food and Drug

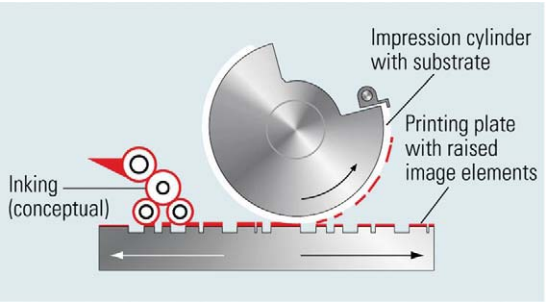


Figure 1 Illustration of raised image as used in relief printing. Source: © H. Kipphan, *Handbook of Print Media*, Springer 2001.

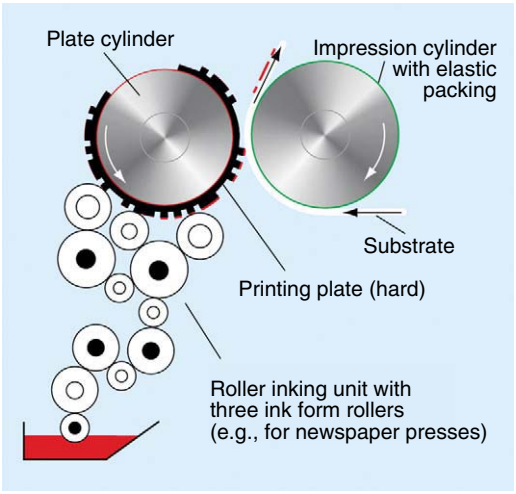


Figure 2 Illustration of multiple rollers used for letterpress printing. Source: © H. Kipphan, *Handbook of Print Media*, Springer 2001.

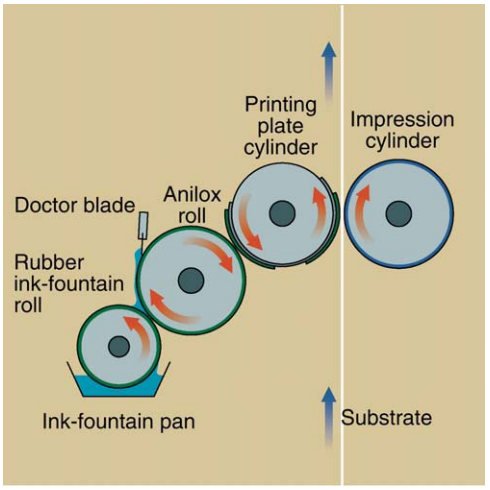


Figure 3 Typical arrangement of rollers for flexographic printing. Courtesy of the Flexographic Technical Association.

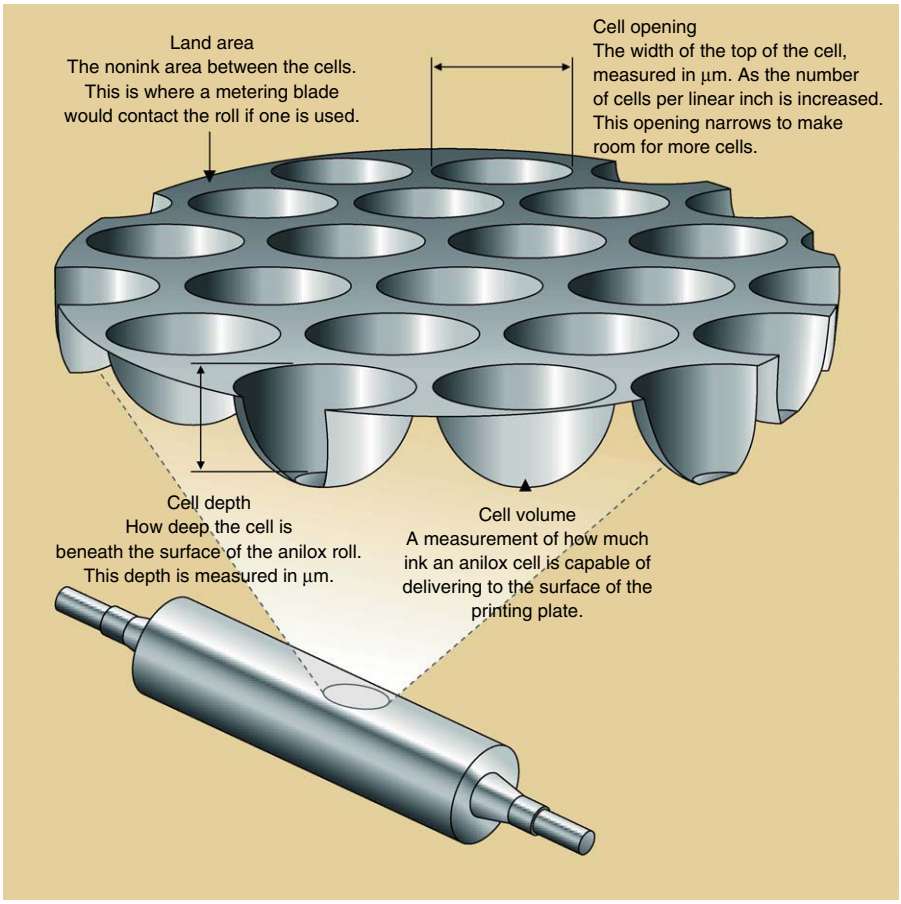


Figure 4 Cells in anilox roll. Courtesy of the Flexographic Technical Association.

Administration because of their toxicity. Other coloring agents were developed that were safer, but the name aniline printing persisted. Because the name carried bad connotations, the name was changed to flexography in 1951.

Flexo plates are flexible and imaged in relief, a natural outgrowth of letterpress printing. The origin of these plates was in rubber stamps, which were formed in Bakelite molds that had been pressed with lead type. Thus, the original plates for aniline printing were made of molded rubber.

The first aniline press was built in 1890 by Bibby, Baron and Sons in Liverpool, UK. It used water-based dye inks, which were not chemically bleed-proof. In 1905 C.A. Holweg built an aniline press as a tail-end unit on a bag machine and patented it in 1908. The ink metering on these presses was crude until 1938, when the anilox roll was introduced. This employed a mechanically engraved copper-coated roll with controlled cell sizes (**Figure 4**). The idea grew out of gravure printers laying down coating from a uniform cell-engraved roll. The anilox uses this process to coat the raised surfaces on the plate.

Anilox rolls are coated with chrome to prevent corrosion and wear. The original aniline inks gave way to ones based on polyamide resins. These stable, fast-drying inks enabled web speeds to increase from 45–230 m min^{-1}.

The 1980 Clean Air Act led to more extensive use of water-based inks in flexo. Water-based inks are now used extensively for printing on paper-based substrates. The quality is now approaching that of lithography and is even impinging on gravure.

Intaglio Printing

Intaglio (engraved or cut in) printing is the reverse of relief printing. As used in commercial printing, it is called gravure or rotogravure. The process utilizes an engraved image consisting of a series of recessed cells, which hold a liquid ink. The ink is transferred to the substrate from these cells with an image based on the cell pattern. A gravure press generally employs a rotating metal cylinder consisting of these cells, and hence the roto in rotogravure. A typical gravure print station is illustrated in **Figure 5**.

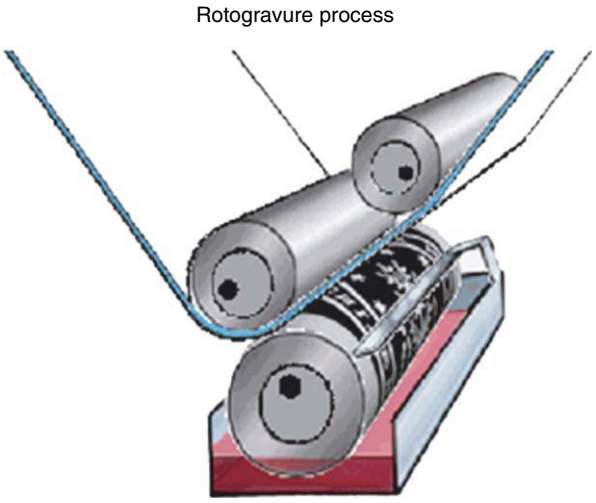


Figure 5 A rotogravure printing unit.

Rotogravure printing has a significant advantage relative to other printing processes for medium to long runs. Gravure can produce very-high-quality multicolor printing on a variety of substrates. Its success results from the simplicity of the process. Having fewer variables to control ensures consistent print quality throughout a run. Each print unit has four basic components: an engraved cylinder, the ink fountain, the doctor blade, and the impression roller.

The origins of gravure printing were with the creative artists of the Italian Renaissance in the 1300s. Fine engravings and etchings were cut by hand into soft copper.

Considerable force or pressure is needed to press the entire surface of paper against an image carrier evenly. Early presses were made entirely of wood. Thus, it was possible to print only small images without cracking. The first metal intaglio plate was used for printing in Germany in 1446, about the same time as Gutenberg. Unfortunately, the intaglio process was not compatible with Gutenberg's letterpress, so it was not adopted by early printers. The first metal printing press was built in 1550. This allowed larger sheets, but was still difficult to operate.

The modern gravure printing press resulted from the invention of photography and the adoption of rotary printing from cylinders. Auguste Godchaux received a patent for a reel-fed rotary gravure perfector press in 1860. This press was still in use in 1940! The process was refined by the German Karl Klic (Klietsch) and Samuel Fawcett. They did not have patents on their process, so they tried to keep the process secret. They sold prints from their press as 'heliogravure' prints, even though they were really rotogravure, as we know it today. Their process remained a trade secret, until an employee emigrated to the USA and made it public.

The process continued to improve and gravure presses were used to print Jell-O cartons, starting in 1938. Engraving continued to improve with electromechanical engravers being introduced in 1968, with digital controls added in 1983.

Screen Printing

This process transfers an image by allowing ink to pass through openings in a stencil that has been applied to a screen mesh. The process is often called silk screen printing, because silk was originally used to make the screens. Silk is not used industrially any more. Screen printing is commonly used to print on textiles.

Screen printing has two characteristics that make it distinctive from other forms of printing.

1. Versatility – screen printing can be adapted to print on almost any shape or object. It has been called 'the print-anything' process.
2. Variable ink thickness – screen printing can vary the ink film deposit from 25 to 130 μm.

This is the widest range of ink deposit of all the forms of printing.

The origins of screen printing are unknown. Evidence dates the process back to the Orient with links to China and to ancient Egypt. They used a simple open-stencil process. The stencil was pressed against the substrate surface. To hold the stencil in place, they brushed or painted the natural pigmented color on to the object.

Using this simple open-stencil process the Japanese devised a way to hold small stencil areas in place. A long piece of hair or silk thread was used to 'glue' an open spot on the stencil. This stencil process was also used to adorn fine silk fabric. Hence, the term 'silk screen' came into use.

In the 1830s silk was woven into a mesh and used for sifting purposes in the flour-milling industry. It was not until about 1870 that silk was used for 'silk screen' printing in Germany, France, and England. In 1907, John Pilsworth, an American, started using the screen method to make banners and short-run signs.

The basic concept of screen printing is based on a stencil. A stencil must be open or permeable in the image area and impermeable in the nonimage area. It is well suited for low-cost production of high-quality, short-run printed materials. It is versatile, capable of printing on nearly any surface, texture, or shape. The process is limited only by the size of the screen frame. Very high ink densities can be obtained.

Lithography

This process is based on a process discovered by Alois Senfelder in 1789. It literally means 'stone writing,' because it was originally based on images created on limestone plates. The plates are neither raised nor recessed and the process is often referred to as planographic.

Lithographic printing is based on wettability of different areas of the plate. The image area is oil (ink)-wet and the nonimage area is water-wet. The process makes use of the nonmixing of the oily ink and water (actually aqueous fountain solution). Lithography is the most chemical of the printing processes and Senfelder preferred the designation 'chemical printing.'

Because the transfer was made directly to the substrate, it was necessary to generate a mirror image on the plate. This was changed by the invention of the offset press, attributed to Ira Rubel in 1904. In this process, a set of three rotating cylinders is used and the image is first transferred from the plate (on a plate cylinder) to a rubber blanket (on a blanket cylinder) from which it transfers (offsets) to the substrate. A schematic of the cylinder arrangement of an offset press is shown in **Figure 6**.

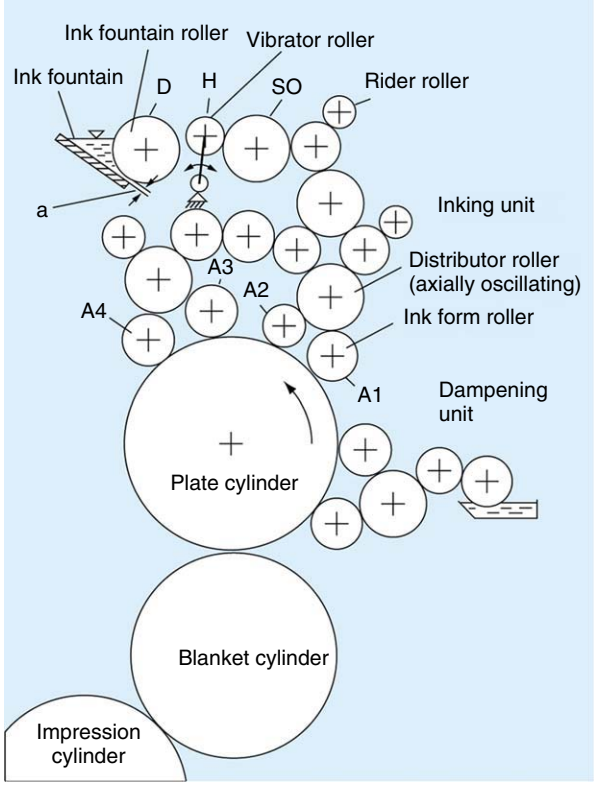


Figure 6 Complicated roller arrangement of an offset lithographic press.

On this we see the master, or plate, cylinder, the blanket cylinder, and the impression cylinder. The substrate passes between the blanket cylinder and the impression cylinder. The other rollers are part of the inking and dampening systems.

The advent of the offset press did not change the basic printing process; the image area needs to be oleophilic (oil-liking) or hydrophobic (water-hating), while the nonimage area must be hydrophilic (water-liking) or oleophobic (oil-hating).

Originally, when stone lithography was employed, letterpress was good for text, but poor for images, while lithography was good for images but poor for text. Books were often printed by a combination of the methods.

Stone lithography was primarily a picture-printing process. This changed and the printing industry was revolutionized by the advent of photography. It created demand for a totally new kind of printed picture. It became possible to combine pictures, including photographs, with text, on a single printing plate.

The relationship between lithography and photography was very strong from the beginning. Joseph Nicephore Niepce, a pioneer in photography, experimented with lithography. Lithography was the first printing process to make its whole plate, graphics and text together, photographically and photomechanically.

Nonimpact Printing

All of the conventional printing processes are impact methods. The plate and/or image carrier comes in direct contact with the substrate. Nonimpact printing refers to series of computer-driven devices that have evolved in a revolutionary fashion over the past 15–20 years. The developments in these devices have followed the dramatic improvement price and performance in desktop computers and the rapid reduction in cost of microelectronic devices. Because of the association with digital computers, nonimpact printing is often referred to as digital printing. These printing devices include laser printers, ink-jet printers, dye sublimation printers, thermal transfer printers, and others.

Because all these devices print directly from digital files, it is just as easy to print a single copy as many. This has made possible on-demand and variable data printing. Some concepts of on-demand ('I want it now') printing can be applied to conventional printing, but they are most appropriate for digital printing. A more rigorous difference between nonimpact printing devices and conventional presses is that nonimpact devices do not have 'permanent

image carriers' (e.g., plates). On-demand printing provides many opportunities for printers and publishers to expand their capabilities.

On-demand printing is defined as short-notice, quick turnaround of short, economical print runs. When used efficiently, this can result in lower inventory costs, less risk of obsolescence, lower production costs, and reduced distribution costs.

This definition is not satisfied by traditional printing, where 31% of output is discarded before obsolescence. This includes 11% of all publications, 41% of promotional literature, and 35% of other material. Approximately one-third of magazines displayed on a newsstand are discarded.

Digital printing is defined as any printing completed via digital files. This includes all types of devices, from desktop printers to wide-format printers and digital 'presses.' These generally employ nonimpact printing processes as opposed to conventional impact printing. Digital printing also includes some of the devices used to make plates for conventional printing.

Variable printing is printing capable of incorporating data from a database to generate a short- to medium-length run of different but related pages. A traditional press may perform on-demand printing, but not variable printing.

Shorter runs comprise an increasing share of the total printing market. Short runs are usually defined as less than 5000 copies. Fifty-six percent of commercial, book, and office printing is between 500 and 5000 copies.

Digital color printing is the fastest-growing sector of printing, because of its suitability for short-run and variable printing. Unlike conventional printing devices, digital printers are falling in price and improving in performance.

Digital color printing currently supports the following:

1. Just-in-time production – printed items often have an unpredictable demand. With shorter runs, a purchaser can buy smaller lots more frequently.
2. Individual or variable output – it is just as easy to print every copy differently as the same. An advertiser can tailor a communication to different readers.
3. In-house production – simple color document production can be accomplished through in-house reprographics, as devices get cheaper and better.
4. Distributed information – reference items such as encyclopedias, manuals, and catalogs are now distributed more efficiently in electronic forms. High-quality digital printers at business locations allow use of the distribute-and-print model, rather than the traditional print-and-distribute model that has been in use since Gutenberg.
5. Visualization and prototyping – it is easy to produce single copies or short runs to test and approve visual concepts. The customer can view a printed copy on a local printer or soft-proof it on a monitor.
6. Compilation and offprints – if journal or magazine articles are stored in a digital database, then individual articles (or even bound custom collections) can be printed and distributed (or distributed and printed) easily.
7. Short-run printing – reports, manuals, posters, and specialty books can be produced with on-demand digital printing.

All digital printing systems have three basic components:

1. raster image processor (RIP) – converts image into device-specific bitmap.
2. A buffer to store rasterized data for printing.
3. A marking engine, which forms the image on the substrate.

Some of the marking engines are reviewed here.

Laser (or electrophotographic) printers use the same imaging method as office copiers. Indeed, modern color copiers have a direct computer and/or network interface, so they can be printed using the appropriate printer driver. A color copier is really a color laser printer with a built-in scanner. These devices can be versatile and may sustain high throughputs. The printing process is also known as xerography (literally, 'dry' writing) and has formed the basis for the success of the Xerox Company.

Electrophotographic printing also includes high-speed digital presses from Xeikon (now Punch) and Indigo (now Hewlett Packard). The Xeikon uses fixed light-emitting diodes (LEDs) instead of lasers, while the Indigo uses liquid toners. The process is illustrated in **Figure 7**, where a charged photoconducting drum is selectively discharged by the laser or LED. The drum is toned by charged pigment particles and the image is transferred and fused to the substrate with heat and pressure.

Inkjet printers use tiny nozzles to spray ink precisely on to the substrate. There are two broad classes of inkjet printers: continuous and drop-on-demand.

For continuous ink-jet printing, a thin stream of liquid is ejected from a container through a tiny orifice and is broken up into a steady stream of uniform droplets when subjected to a high-frequency vibration. After being electrically charged, the drops

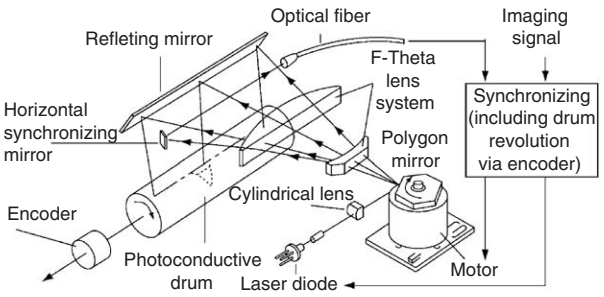


Figure 7 Mechanism of a laser or electrophotographic printer.

can be placed by an electrostatic deflector. Undeflected drops are recirculated. The Scitex 3600 digital press can print at 305 m min^{-1} in monochrome.

For drop-on-demand ink-jet printing, ink droplets are expelled from tiny orifices and directed immediately to the substrate. Most commonly, these devices use heat to vaporize a small amount of water-based ink in a chamber to form a gas bubble (bubble-jet). An illustration of the bubble jet process is shown in **Figure 8**.

The piezo drop-on-demand printer uses pressure pulses instead of heat to expel ink drops. The pressure pulses are generated by precisely charging a piezoelectric crystal. These are offered for desktop applications by Epson. An illustration of the piezo drop-on-demand process is shown in **Figure 9**.

Drop-on-demand inkjets are available in multiple formats, from letter size to 1.83 m-wide web. The wide-format versions can be used to proof imposition.

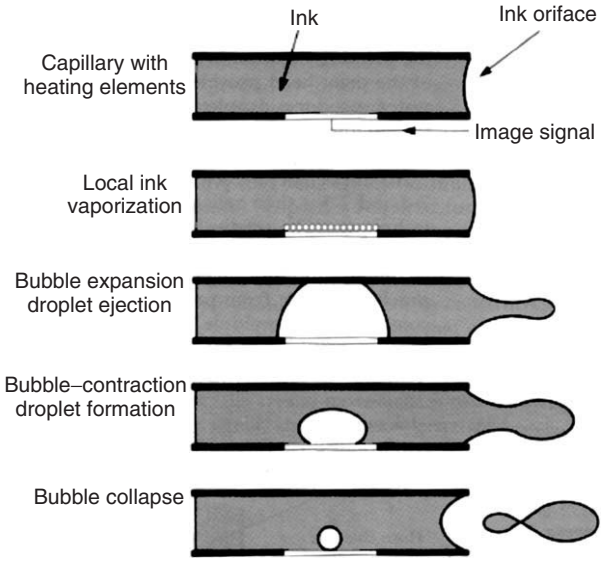


Figure 8 Illustration of thermal ink jet process.

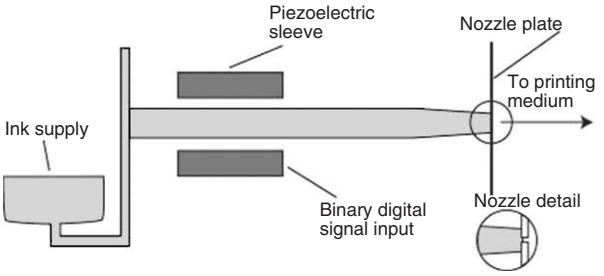


Figure 9 Illustration of piezo ink jet process.

The Printing Industry

Depending on the measure, the printing industry is between the fourth and seventh largest manufacturing industry in the world. Printing companies range from very large Fortune 500 organizations to small corner print shops. Because of the large number of small print shops and the large number of printing plants owned by the large companies, there are more printing manufacturing sites than for any other industry.

Types of Printers

Because of the diversity of the customer base, there are many different types of printing establishments. These are:

1. Commercial: commercial printers can vary greatly in size and can take on a wide variety of printing jobs. Their jobs can range from business cards to glossy color brochures.
2. Trade shops: trade shops provide services to the printing trade. They perform printing and finishing functions for printers who do not have all of the equipment for the job.
3. Special-purpose: special-purpose printing involves a limited type of job such as labels or forms.
4. Quick printing: quick printing includes copy centers such as Kinko's. These shops now employ direct digital printing devices as well as photocopying equipment. Many of these also still have small offset presses for larger numbers of copies.
5. In-plant: in-plant printing consists of any company which has its own print shop on site that performs printing functions for the organization.
6. Publishing: publishing involves printing of books, magazines, and newspapers. These usually employ very-high-speed web-fed printing presses.
7. Packaging: package printing involves printing on boxes, cans, and plastic films and foils.

There are also several related industries that provide services and materials to the printing industry. Related industries consist of ink companies and paper companies, along with film and plate material suppliers. Also included are the press and peripheral manufacturers.

Printing Inks

Printing inks are complicated mixtures of chemical compounds. The composition of printing inks varies by the printing process, by whether printing is sheet-fed or web-fed, and by the target substrate. The composition varies by the solvent base, be it oil or water. It varies by drying mechanism and by whether the drying is by primarily chemical, e.g., oxidation polymerization, ultraviolet cure, or physical processes, e.g., evaporation, absorption.

Inks are divided into liquid and paste inks. Gravure, flexo, inkjet, electrographic, and some electrophotographic inks (or toners) are liquid inks. Lithographic, screen, and letterpress inks are paste inks. The distinction between liquid and paste inks can be an arbitrary one, since it is based on apparent viscosity.

A printing ink consists of vehicle and pigment. Vehicle is all in the ink except the pigment. 'Varnish' is often used interchangeably with vehicle, but actually vehicle consists of varnish plus performance additives and solvent/diluent. As suggested by the name, the vehicle transports the pigment to the substrate. Varnishes must be chosen to wet the pigment. It they don't, suspension is virtually impossible and the ink will not have the desired rheological (flow) properties.

Pigments

Most pigments are used for all of the printing processes. Pigments are classified as carbon black, organic, white inorganic, and colored inorganic.

Carbon black is the major ingredient in black inks. Chemically it is mostly carbon, with small amounts of mineral matter and some volatile materials of the form C_xO_y. The typical particle size is 20–30 nm (10^{-9} m), the smallest of the pigments. Note that these may be truly nanoparticles. The smallest particles might be individual 'bucky balls' (single polymer molecules of carbon, possibly with other atoms encapsulated or bonded, e.g., C_{60}).

The C_xO_y improves the flow properties and serves as a natural wetting and dispersing agent. The amount of carbon varies between 90 and 99%, depending on the method of manufacture.

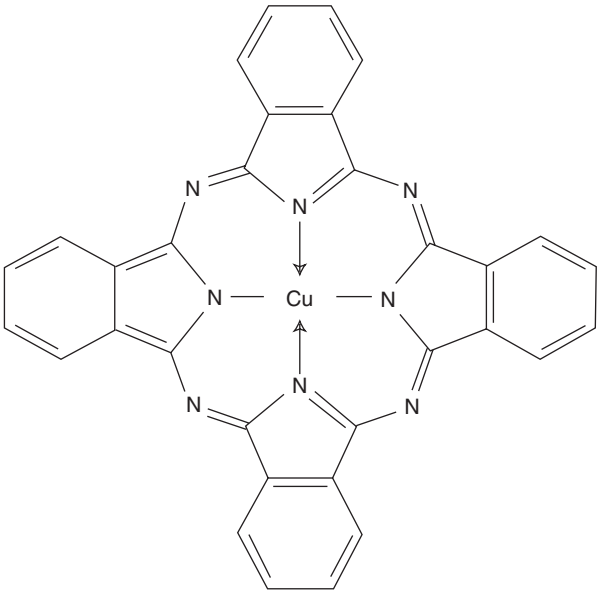
Organic pigments are used for process (photographic) color printing because they form transparent films. Most of these are derivatives of the aromatic hydrocarbons, benzene, naphthalene, or anthracene. The pigment molecules generally contain chromophoric groups such as $=C=NH$, $-CH=N-$, and $-N=N-$. The electrons in the double bonds selectively absorb some visible wavelengths and change energy levels. The color results from the wavelengths not absorbed. This is the subtractive color theory of colored objects.

The electrons in the chromophores are generally coupled to those in the conjugated aromatic rings. Dyes are soluble in the vehicle, while pigments are generally suspended in the vehicle. Pigments are preferred to prevent bleeding and fading. Dyes can be converted to pigments by reacting with phosphomolybdic and/or phosphotungstic acid.

Azo pigments, which have the $-N=N-$ group, include diarylide yellow, lithol rubine, red lake C, toluidine red, Hansa yellow, DNA orange, and napthol red. Phthalocyanine pigments are restricted to the blue and green regions of the spectrum. The phthalocyanine structure is given in **Figure 10**. Other pigments include pigment yellow 13, quinacridone magenta pigment, and pigment red 57, which are given in **Figures 11–13**.

White inorganic pigments include titanium dioxide (TiO_2), calcium carbonate ($CaCO_3$), and clay. (There are no white organic pigments.) The clay used is a hexagonal plate-like form of aluminosilicate called kaolin. It has low opacity and is used as an extender for letterpress and screen inks. Barium sulfate and fumed silica are also sometimes used as extenders in inks. These white pigments are all also used to whiten paper.

Colored inorganic pigments are mostly the iron blues, which are based on ferric ferrocyanide. These are formed by oxidizing ferrous ferrocyanide with a strong oxidizing agent such as sodium dichromate or sodium chlorate. Different shades of blue are



Pigment Blue 15

Figure 10 Structure of phthalocyanine (pigment blue 15).

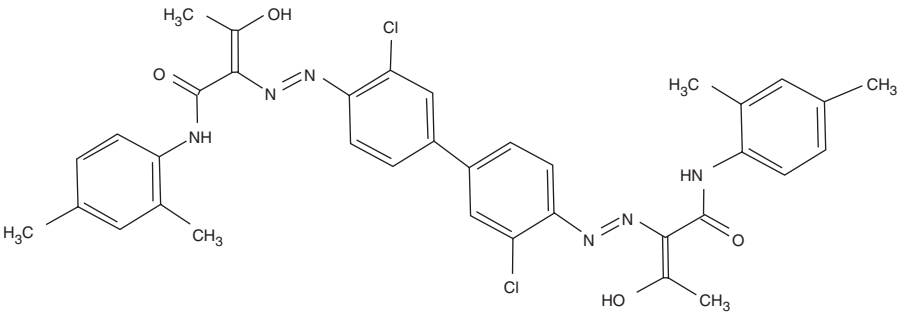


Figure 11 Structure of pigment yellow 13.

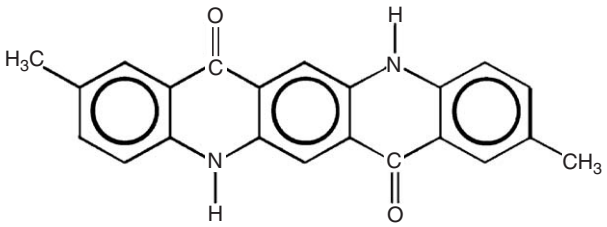


Figure 12 Structure of quinacridone magenta pigment.

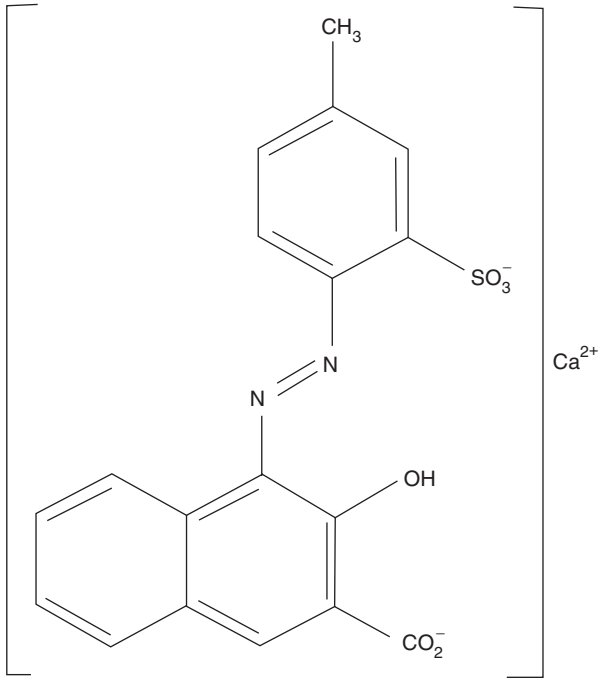


Figure 13 Structure of pigment red 57.

obtained by varying the pH, temperature, and time of heating during oxidation. These were used by printers for all printing inks through the mid nineteenth century, before the discovery of synthetic organic dyes.

See also: **Papermaking**: Paper Grades; The History of Paper and Papermaking; World Paper Industry Overview.

Further Reading

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Packaging Grades

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Introduction

Nasiri Khosrau of Persia (now Iran) recorded the first use of paper as a packaging material in 1035 AD when he observed vendors in Cairo (Egypt) wrapping vegetables, spices, and dry goods in paper. Today, paper continues to be an important material used to