15 Screen Printing

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OUTLINE

15.1 Fundamentals of Screen Printing

Screen printing is a stencil process where the printing involves closed nonimage areas and open-image areas. In screen printing, ink is forced through a screen by resilient squeegee (Figure 15.1). Also, we can say that the screen printing consists of the screen, the frame covered with the screen fabric, and the stencil containing the printed information. The stencil/plate is most commonly made from a light-sensitive emulsion, photographically imaged, so the printing areas are washed away, while the nonimage areas are made permanent. The stencil is processed on a fine fabric, which holds the parts of the design in place. The screen is a fine fabric made of natural silk, plastic, or metal fibers/threads. Ink is transferred through the open mesh that is not covered with the stencil. The screen printing plate is, therefore, a combination of screen and stencil (Kipphan, 2001).

The stencil on the fabric defines the actual print image. The stencil is on the side of the screen opposite to the side on which the squeegee (blade) works, to avoid damage and wear of the stencil (Kipphan, 2001). Combination of stencil, screen, and printed image in screen printing is shown in Figure 15.2.

Also, an important parameter in platemaking is frame. Today, screen frames are usually made of aluminum, although we can find in some companies wood and steel frames. When a screen printing frame is selected, its characteristics to be considered include the frame size, durability, stability, cost, and stretching method (Ingram, 1999).

A squeegee is a tool used to push the ink through the stencil produced on the screen. They are usually made from rubber or polymer and have a wooden or plastic handle in the case of manual printing. A squeegee should be an inch or two shorter than the width of the screen (Novaković & Kašiković, 2013).

The basic elements of screen printing are shown in Figure 15.3.

In practice, three methods are used for screen printing (Figure 15.4):

- *The flat-to-flat method (flatbed)*: the printing plate and the printing substrate are both

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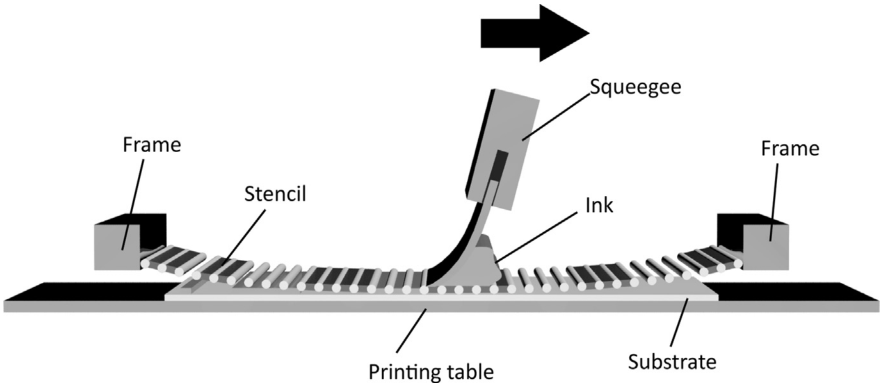

Figure 15.1 Screen printing process.
Novaković and Kašiković (2013).

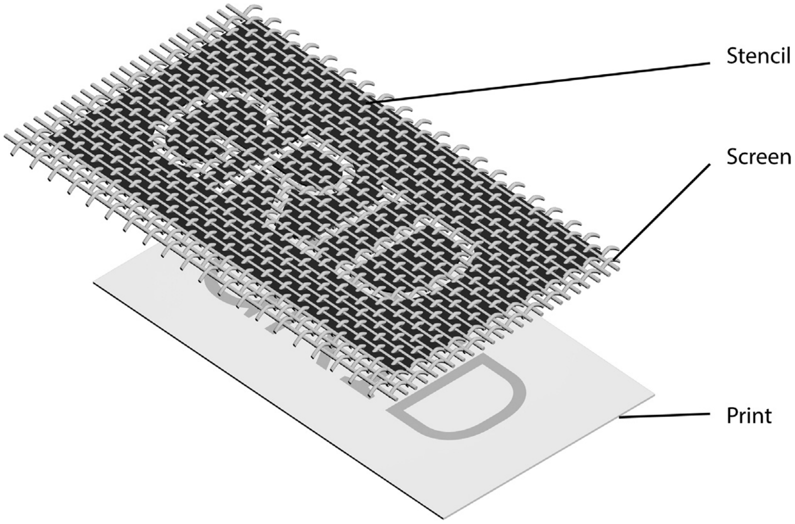

Figure 15.2 Stencil, screen, and print in screen printing process.
Novaković and Kašiković (2013).

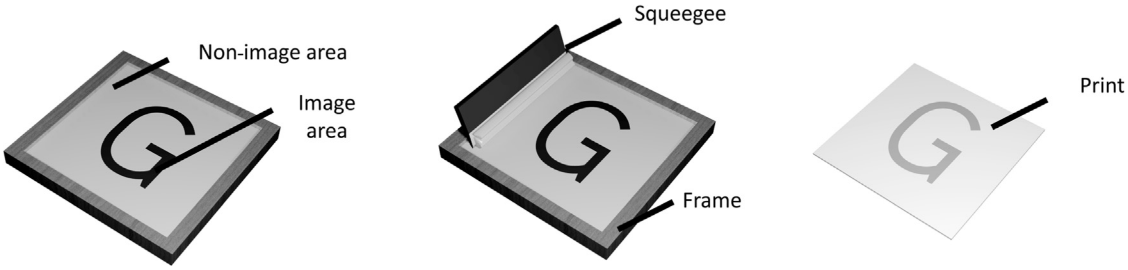

Figure 15.3 The basic elements of screen printing.
Novaković and Kašiković (2013).

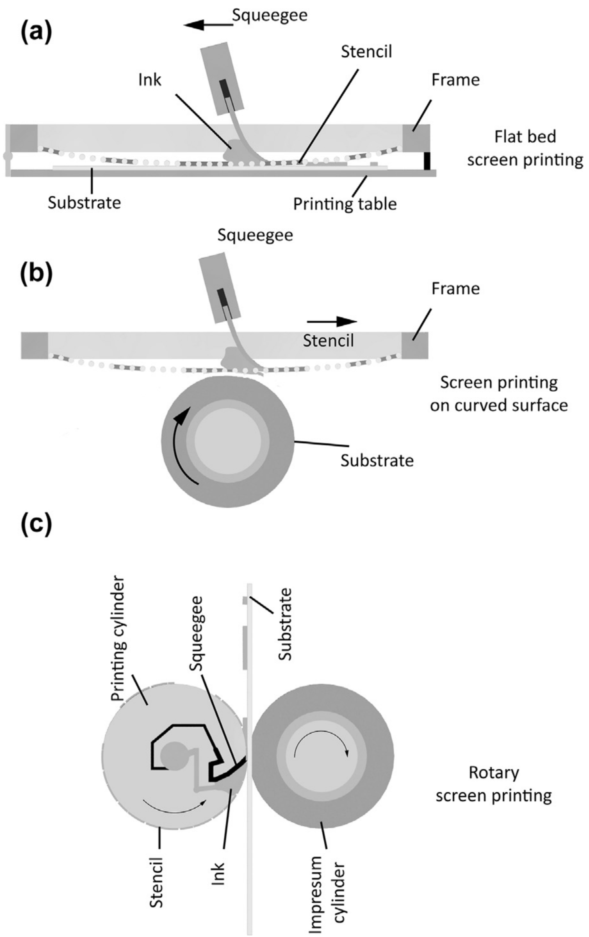

Figure 15.4 Screen printing technologies: (a) The flat-to-flat method (flatbed). (b) Screen printing on a curved surface. (c) Round-to-round method (rotary printing).
Novaković and Kašiković (2013).

flat; the ink is transferred through the mesh apertures and onto the printing substrate by the movements of a squeegee (Kipphan, 2001).

- *Screen printing on a curved surface*: the printing plate is flat, printing onto the printing substrate in a rotating cylinder.
- *Round-to-round method (rotary printing)*: the printing screen is cylindrical; the printing plate, printing substrate, and pressure cylinder all move synchronously; ink is transferred from inside through the cylindrical printing plate and onto the substrate (Kipphan, 2001).

15.2 Stencil/Plate Making

The screen stencil plays a very important role in screen printing. The selection of the right stencil, which should always be reproduced in the same quality, is an important prerequisite for good printing results. When selecting a stencil, stencil must be optimally suited to the print job. Relevant factors include the choice of screen mesh, the selection of photo emulsion and coating technique, the exposure, and the structuring of the printing process (Baro et al., 2008).

15.2.1 Screen Printing Mesh

A wide range of materials can be stretched over the frame to make the screen. Materials like cotton, silk, nylon, mono- and multifilament polyester, or metal are commonly used today (Novaković & Kašiković, 2013). Fabric count is one of the most important parameters that influences printing quality. It corresponds to the number of threads/cm. Fabrics can be obtained in levels of fineness from 10 to 200 threads/cm, although the most frequently used fabrics are in the range of 40–120 threads/cm. Fabrics with higher threads/cm provide a better print quality (Novaković, Pavlović, & Kašiković, 2011).

In addition, the fabric quality is also determined by the thread thickness used. It is indicated in a maximum of four thicknesses that range from "light" to "heavy." The fabric count determines the mesh width, and consequently the open screen area in threads/cm, and the thread thickness in micrometers. This measurement and the stencil's thickness influence the thickness of the ink film transferred (Kipphan, 2001).

Failure to optimally coordinate fabric fineness, screen resolution, and the desired ink film thickness (projecting stencil) may also result in moiré-type defects. The fabric chosen for fabric printing should be as strong as possible to avoid splitting when stretched, dimensionally stable, and unaffected by moisture or humidity. The material should be inert and impervious to the chemicals to be used in contact with it.

Multifilament and monofilament are two basic categories of fabrics commonly used in screen printing. Multiple strands twisted together to form a single thread produce multifilament fabrics. The multifilament threads are woven together, and they form the screen mesh. Fabrics of this type used for screen printing applications are either silk or polyester (Ingram, 1999).

The strongest natural fibers are silk fibers. However, silk filaments could vary in width causing irregular mesh apertures and can distort the printed image. Silk is suitable for the printing process where fine details, as well as good registration, are not required. Silk has been replaced by the multifilament polyester, mainly because of difficulty in cleaning. These difficulties are consequence of the rough surface structure of the silk that causes ink particles to be lodged in the twisted strands (Ingram, 1999).

Multifilament polyester has more uniform mesh apertures and does not expand as much as silk during the printing process. Another important factor in replacing silk by polyester is that the polyester is not affected by cleaning and reclaiming chemicals. Even so, the multifilament polyester is far from a perfect solution as its fibers tend to flatten more at thread intersections than monofilament fibers, causing the mesh apertures to show in prints as sawtoothed image edges (Ingram, 1999).

When comparing monofilament and multifilament fabrics, multifilament fabrics have a rougher surface structure, and they are also thicker. Such fabrics are ideal to print large posters, textiles, and textured or contoured surfaces, in all cases where heavy ink deposits are required (Ingram, 1999).

Smooth surface structure is characteristic of monofilament fabrics that produces uniform mesh apertures. Monofilament fabrics are polyester, nylon, metal wire, and metalized polyester.

Nylon (monofilament) has construction characteristics similar to monofilament polyester with the exception of stability. It is a very elastic fiber. Nylon is the right choice for printing irregularly shaped or contoured surfaces. However, elasticity is an undesirable characteristic wherever critical registration is a necessity. When nylon fibers are used, the main factors that influence on multicolor registration are temperature and humidity (Ingram, 1999).

Wire mesh, also called wire cloth, is commonly used with abrasive inks, or ceramics printing for extreme sharpness, when thick ink film deposits are required, and for circuit boards printing. Wire mesh is extremely stable, and they can be reused many times (Ingram, 1999).

Metalized mesh is a relatively new type of fabric. It is a composition of monofilament synthetic fiber (nylon or polyester), coated by an extremely thin layer of metal. In this combination, metallized nylon or polyester mesh has the advantages of both wire and monofilament synthetics. Cleaning the screen with metal coating is easier than cleaning synthetic fiber mesh. Metalized mesh has excellent dimensional stability and can be used for long runs where close tolerance and exact register are a necessity (Ingram, 1999).

Selection of screen fabric is very important decision. Some of the rules that may help printers choose their choice are given below:

1. The open mesh area is the area between threads, and it allows for the passage of ink. That means, in case greater amount of ink is required, printer must use the larger percentage of open mesh area.
2. The average pigment size is in a correlation with mesh opening. Mesh opening must be at least three times larger, or the screen will clog during printing.
3. Mesh count varies according to the thread diameter. Smaller thread diameter produces finer mesh.
4. Thickness of the ink in the screen printing can be determined by the thread diameter.
5. For reproduction of finer details in the design, a finer mesh is required.

The correct screen tension is an important factor in achieving good print quality. There must neither be disruptive distortion of the image as a result of the shear force applied by the squeegee during the printing process nor must the screen tension reach the yield point of the material, otherwise the screen would be damaged. Particular attention must be paid to this aspect with multicolor printing or when printing in the technical field—for example, in printed circuit board production, where high demands have to be made on the precision of the impressions. Screen tension depends on the material, the fabric count, the fabric quality, and the yield point they determine. The screen loading may be 0–25 N/cm. The tension that has been applied diminishes depending on the nature of the screen fabric, the stress during printing, and the passage of time. It is, therefore, possible, in the case of synthetic fabrics, for example, for the tension to fall by 50% after just two days, depending on the type of adhesion technology employed. Also, the flexible frame leads to uneven tension, which may lead to distortions in the image (Kipphan, 2001) (Figure 15.5).

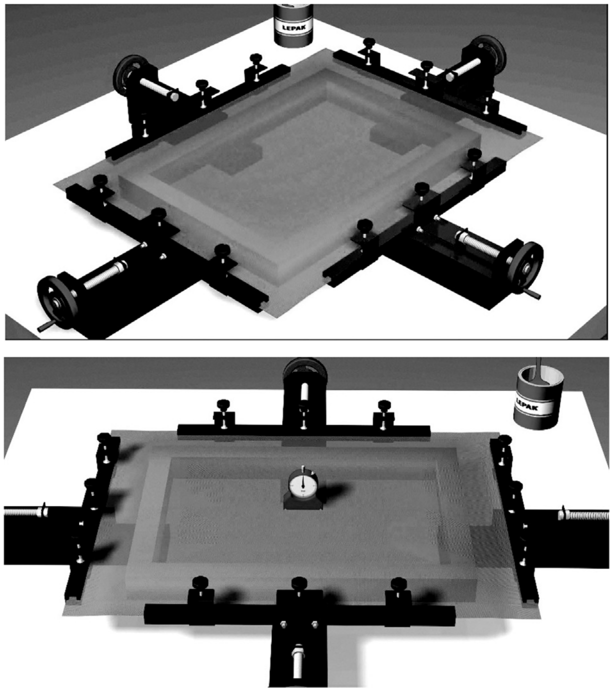

Figure 15.5 Screen tension process and tension measuring.
Novaković and Kašiković (2013).

15.2.2 Screen Printing Frame

The main purpose of screen printing frame is to ensure constant mesh tension during stencil production as well as during the printing process. In order to ensure constant tension screen printing, frame must have a certain rigidity as the mesh that will be stretched over the frame creates considerable tension. Printing frame is exposed to various chemical substances used in the stencil production, printing, and cleaning processes, some of which are aggressive (Novaković & Kašiković, 2013).

15.2.2.1 Screen Printing Frame Materials

Screen printing frames are usually produced from wood studs or metal tubing. Each material has its own advantages and disadvantages.

15.2.2.1.1 Wooden Screen Printing Frames

Wooden frames are commonly used for screen printing forms because of their low price, light weight, and ease of manufacturing. However, they also have many drawbacks: they are not very stable, thus usually used for single color, relatively small format of print jobs, not larger than 50 cm on either side (Novaković et al., 2011).

In order to ensure stability, pieces of wood making the frame must be glued, nailed, or bolted together. Usual corner joints used are end-lap joint, rabbet joint, miter joint, butt joint, and finger joint, shown in Figure 15.6. It is important to note that adhesives must be resistant to water and solvents. If nails or bolts are used, they must be rust-resistant. Steel brackets can be used to additionally reinforce corners for higher stability.

To ensure water, chemicals, and UV light protection, all of which can cause wooden frame to warp, the frames need to be protected by a coat of polyurethane varnish or shellac. Using wooden frames for multi-color screen printing should be avoided, because they do not guarantee good enough color registration.

15.2.2.1.2 Metal Screen Printing Frames

Steel and aluminum are two metal materials usually used for screen printing frames. Metal frames are almost exclusively used in professional screen printing. Metal frames have much better stability than wooden ones, this is very important for print formats larger than 50 cm in length on any side and multi-color printing, which demands precise color registration. In order to make the screen printing frame metal tubing is joined by welding (Novaković et al., 2011).

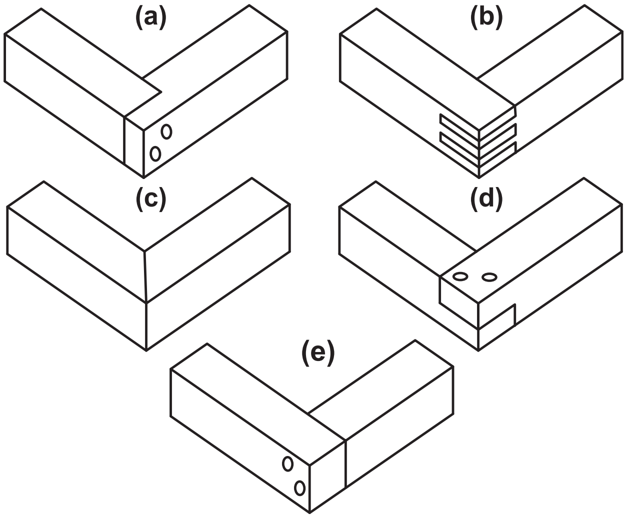

Figure 15.6 (a) Rabbet joint, (b) finger joint, (c) miter joint, (d) end-lap joint, and (e) butt joint.

Shape and size of metal tubing for screen printing frame depends on the size of the frame, material, and the intended use. Thus, there are open hole tubing for small frames, X shape tubing for large formats and high precision (electronics) printing, concave side tubing for textile materials, etc. Cross-sections of some tubing used for metal frame production are shown in Figure 15.7.

Both materials, steel and aluminum, have specific advantages and disadvantages. Steel frames offer high rigidity, stability, and durability, resistance to temperature changes (low thermal expansion), lower price than aluminum frames, and easier to weld. Steel has two times smaller coefficient of linear expansion (12×10^{-6} compared to that of aluminum 24×10^{-6}) which means that change in temperature of 20 °C causes dimension change 0.24 mm/m for steel, compared to 0.48 mm/m for aluminum. This can cause registration problems. On the other hand, the weight of the steel frames is a considerable factor, especially in the case of large format frames. Density of steel is 7850 kg/m^3, while for aluminum it is 2650 kg/m^3 which makes aluminum three times lighter, but its mechanical properties do not fall three times behind steel. Dimensional stability of aluminum frames can be improved by thicker tubing walls. Thicker walls mean higher weight, but even with thicker walls aluminum frames are nearly half the weight of steel frames. Having this in mind, aluminum frames are usually preferred for large formats, except in cases where high accuracy of color registration is required (Novaković & Kašiković, 2013).

Steel is prone to corrosion (electrochemical oxidation), while aluminum frames are more resistant to corrosion, but they are not resistant to acidic and basic chemicals, which degreasing agents often are, and must be properly protected if such chemicals are used in the process.

Alongside wooden and metal frames, the market offers a wide variety of innovative frame constructions that can stretch the mesh directly or be adjusted.

15.2.3 Screen Printing Squeegee

It could be said that squeegee is one of the most important screen printing components. The squeegee is a rubber or plastic blade fixed to the handle for manual printing or to a clamp in mechanized screen printing. For larger runs typically over the 200 prints, squeegee blades are composed of synthetic materials, such as polyvinyl and polyurethane, rather than rubber, as rubber tends to lose the edge more quickly. Squeegee blade is used to force ink into the mesh and through the printing areas of the stencil, thus applying it to the substrate. Squeegee controls the spread of ink across the screen; it pushes the screen on to the substrate adapting the screen to the surface of the substrate. It also removes the excess ink from the mesh. Thickness of the printed ink film can be controlled by the amount of pressure applied to the squeegee (Novaković & Kašiković, 2013).

15.2.3.1 Squeegee Types

Certain squeegee shapes are recommended depending on the intended use. Squeegees can be

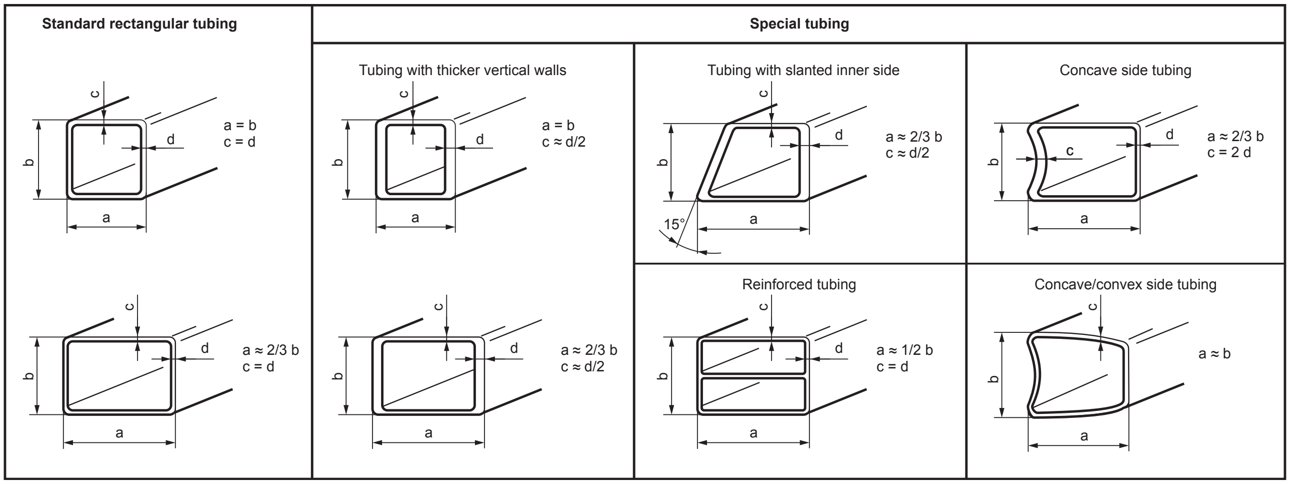

Figure 15.7 Tubing used in metal screen printing frame production.

sorted according to their edge shape as shown in Figure 15.8:

- square edge for printing flat objects,
- square with rounded corners for large deposits of ink,
- single-sided bevel edge for printing on glass,
- double-sided bevel edge or knife edge for direct printing on rounded surfaces,
- rounded and double bevel for printing textile.

Squeegee blades can also be categorized by their hardness, roughly as (Novaković & Kašiković, 2013):

- extra soft (45−50 Shore A) and soft (50−60 Shore A) for low-resolution images and large ink deposit usually textile and rough surface printing;
- medium hard (60−70 Shore A) are most often used as they provide good resolution with possibility of variations in ink deposits;
- hard (70−80 Shore A) and extra hard up to 95 Shore A are used for flat surfaces such as glass and offer high-resolution prints.

Hardness of the squeegee stated above is measured by a durometer gauge based on standards established by American Standard Testing materials (ASTM).

Squeegees are produced as single, double, or triple durometer squeegee. Single durometer squeegee piece of polyurethane material or rubber is designed to balance the squeegee's resistance to all the different inks while maintaining a high resistance to abrasion, with usual hardness of 60−80 Shore A. Double durometer squeegee is a combination of a hard shaft, 85−90 Shore A, and a softer side pressure of 50−80 Shore A. This allows for utilization of the soft blade side to conform to surface irregularities but still keep the upper harder portion of the blade from bending over. The triple durometer squeegee is a "sandwich" type with two softer outside layers and the harder durometer in the middle. Squeegees can also be internally reinforced with fiber glass. Concepts of single, double, and triple durometer and reinforced squeegees are shown in Figure 15.9.

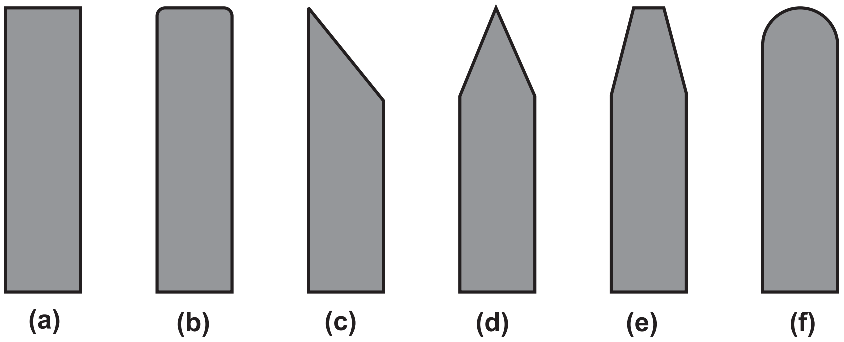

Figure 15.8 Squeegee shapes: (a) square edge, (b) square with rounded edge, (c) single-sided bevel edge, (d) double-sided bevel edge (knife edge) (e) blunt, and (f) round.

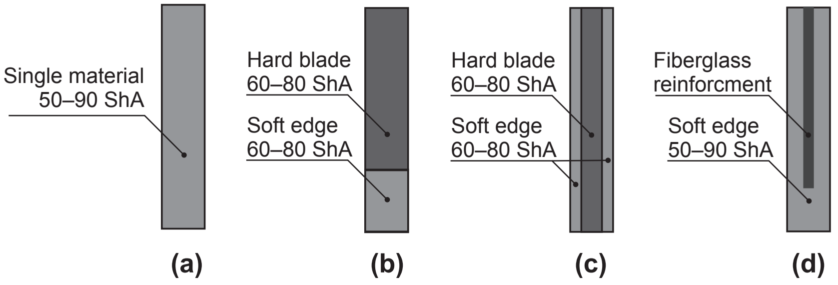

Figure 15.9 Squeegee construction: (a) single durometer, (b) double durometer, (c) triple durometer, and (d) reinforced squeegees.

15.2.4 Screen Printing Emulsion

After the stretching process, fabrics must be properly prepared to receive the stencil. In this process, the printer must know the print job and the properties of the photo emulsion, such as solids content and viscosity. High solids content permits a lower surface roughness value. A high-viscosity coating is suitable for coarse mesh. In general, the following applies (Baro et al., 2008):

- Conventional UV inks should use solvent-resistant photo emulsion.
- Water-based UV inks should use water-resistant or water- and solvent-resistant photo emulsion.

Photo emulsions for halftones and fine lines should have a very good resolution and high solids content; however, they must still ensure proper exposure. The stencil must have a low profile and good screen structure compensation (Baro et al., 2008).

The emulsion is simply a light-sensitive material. It reacts or changes when exposed to light. The parts that do not receive light stay soft.

In the direct method, emulsion is applied to both sides of the screen, first onto the print side and then onto the squeegees side. The best quality direct emulsion stencils require multiple coatings, applied with horizontal drying between coatings. The emulsion is often a mixture of poly(vinyl acetate) and poly(vinyl alcohol), and a dye is added to make the stencil readily visible on the screen.

In the direct—indirect method, a sheet of polyester film is coated on one side with an emulsion, often with a mixture of poly(vinyl alcohol) and poly(vinyl acetate), which is not light-sensitive. The screen is placed on top of the film, coated side up. Then a sensitized emulsion (the same as is used in the direct method) is squeegeed over the top of the screen. This emulsion sensitizes the coated film underneath and also binds it to the screen.

In the indirect method, the wet gelatin film is placed, emulsion side up, in contact with the print side of the screen.

15.3 Imaging, Hand-Cut Stencils, Photostencils, Computer to Screen Systems

Among the frame and the screen printing mesh, the stencil represents the third part of the image carrier in screen printing process. As mentioned earlier, during the printing process the ink is pushed through a fine fabric mesh, where the stencil can be identified as a carrier of the printed information, since it covers the nonprinting areas on the mesh.

There are many factors that influence the final print quality, but considering stencils there are two significant parameters: surface roughness (Rz value) of the stencil on the printing side and its profile or thickness (Figure 15.10) (SaatiPrint, 2001).

With lower surface roughness (from 4 up to 10 μm is desirable), the stencil can stop the ink spreading around the image area, and the printed image will have good edge definition and shape quality. Higher Rz values cause unwanted spreading of the ink, resulting in raggedness on the edge of printed details and fine lines (Figure 15.11), but too low Rz values will also decrease the printed image quality, due to the ink splattering caused by vacuum effect between the stencil and the substrate (SaatiPrint, 2001).

The stencil profile or thickness, along with the chosen screen mesh, defines the amount of ink that is printed, namely the ink deposit. Some applications require thick ink layer on the substrates, therefore a thick stencil is needed, but in other applications the minimized stencil thickness would be beneficial (Ingram, 1999; SaatiPrint, 2001).

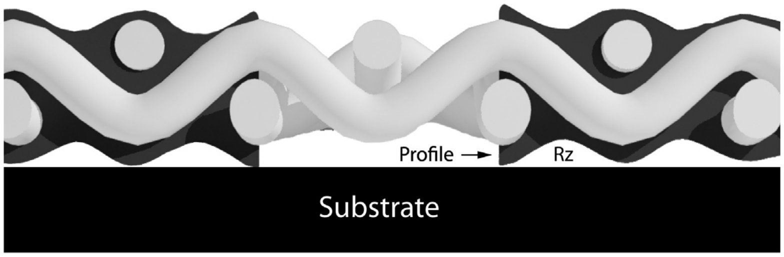

Figure 15.10 Stencil profile and surface roughness.

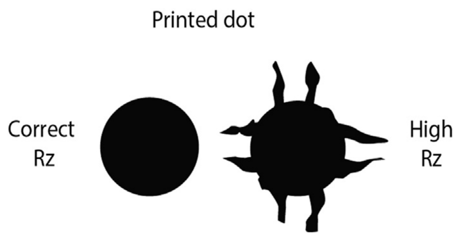

Figure 15.11 Results of different Rz values.

The stencil production techniques can be divided into two major groups. Indirect stencil preparing, where the separately formed stencils are adhered to the fabric screen, and direct stencil preparing, where the image carrier is prepared directly on the screen itself (mostly by exposing and developing a photosensitive emulsion). In addition, there is a direct–indirect stencil preparing process, too, where the stencil material provided on the base film is first transferred to the screen and then exposed and developed like the direct stencil, but this type of stencil is used only for extremely high precision applications. A further categorization can be made based on whether the stencils are created mechanically, photographically, or electronically (Ingram, 1999; Kipphan, 2001; SaatiPrint, 2001). According to these preparation techniques, several stencil creating methods are known today, and they are discussed in Sections 15.3.1–15.3.3.

15.3.1 Hand-Cut Stencils

Hand-cut stencils were initially prepared by hand, but today they can also be prepared on cutting plotter using appropriate CAD programs. Hand-cut stencils (or just cut stencils) are mechanically prepared using a sharp knife to create different shapes of printing elements. The early hand-cut stencils were made from paper (and adhered to the underside of the screen) but today, most hand-cut stencils are made of lacquer or water-soluble films. These films consist of two layers: the backing or support layer, made of transparent paper, vinyl or polyester, and the emulsion layer. The indirect producing technique is the same for both types of films: the stencil is prepared by cutting the emulsion from the backing layer and then adhered to the screen with water (for water-soluble film) or lacquer (for lacquer film). The adhering liquid softens the emulsion layer, which becomes gel-like allowing the mesh to be pushed into it (Ingram, 1999). The application process of a water-based film stencil is illustrated in Figure 15.12.

15.3.2 Photostencils

Photostencils are made from different light-sensitive emulsions that harden when exposed to ultraviolet light. Photostencils have been the most commonly used stencil type for screen printing since the mid-1950s. In order to form the printing and nonprinting areas on the screen by selective UV radiation, a positive have to be used. On the positive, the image/printing areas are opaque, absorbing the UV light, but the nonprinting areas are transparent allowing the light to shine through and harden the emulsion (Figure 15.13(a)). After exposing, in the developing process, the non-hardened (soft and soluble) areas are washed out with water or other fluid (developer) forming the open, that is, printing areas on the stencil, and the hardened parts of photostencil emulsion form the nonprinting areas (Figure 15.13(a)) (SaatiPrint, 2001).

The positive can be produced photographically resulting in the positive film and mechanically, giving a knife-cut masking film as a result. It should be free from specks, stains, or pinholes, and the printing areas should have sharp edges. The stencil preparing technique can be direct, indirect, and direct–indirect (Kipphan, 2001). The commercially available photostencils can be divided into four main categories, listed below and illustrated in Figure 15.14 (SaatiPrint, 2001).

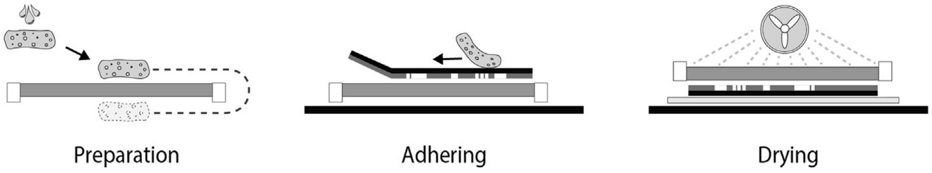

Figure 15.12 Water-based film stencil application process.

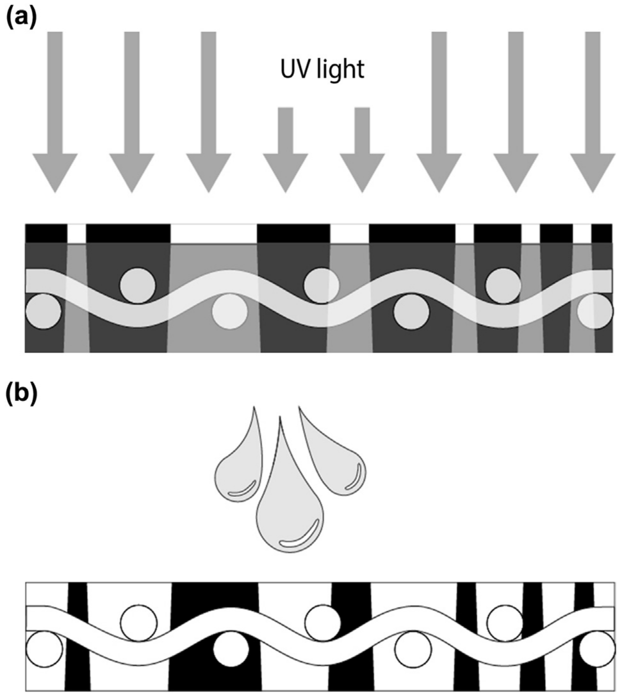

Figure 15.13 Exposing (a) and developing (b) the photosensitive emulsion on the screen.

Indirect photostencils or transfer films are very similar to hand-cut stencils in structure and application procedure. They consist of a clear plastic backing or support sheet and a dry photosensitive emulsion layer. After the exposure and development process, the prepared film is applied to the bottom of the screen mesh with emulsion side up. The gel-like emulsion is then blotted through the mesh and left to dry thoroughly before the backing sheet is being removed. This type of photostencil allows the highest print resolution and shape definition, mostly due to the direct contact between the stencil and printing substrate (it is placed to the underside of the screen) and drying technique (the backing sheet prevents any shrinking of stencil emulsion during drying). Along these positive qualities, short print run, poor durability, and applicability only on fine mesh can be mentioned as disadvantages (Ingram, 1999; SaatiPrint, 2001).

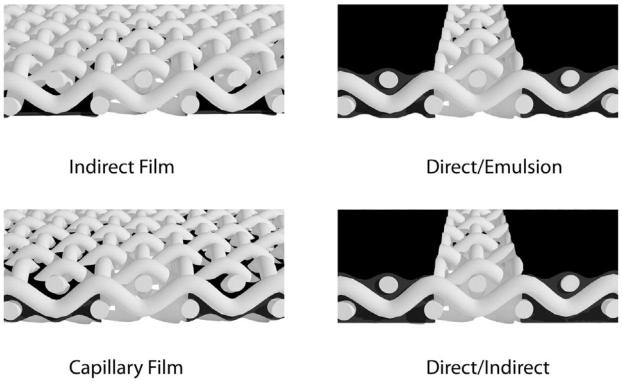

Figure 15.14 Categories of commercially available photostencils.

Direct photostencils, also known as direct emulsions, are made from liquid photographic emulsion applied directly to the screen mesh surface without any support/backing film. The photosensitive emulsion has to be coated onto the screen mesh and dried thoroughly before the exposing process. During the exposing procedure, the positive film has to be in direct contact with the applied emulsion layer. In the developing process, the unexposed areas are washed out from the screen and then the screen with the finished stencil is left to dry. Since this kind of photostencil does not have any backing film, undesirable stencil contraction will occur while drying. The high liquid content (approximately 50%) of direct emulsions just more emphasizes the emulsion shrinkage and allows seeing trough the mesh structure on the finished stencil. To eliminate the stencil shrinking and achieve a thicker and evener emulsion layer, the emulsion can be repeatedly coated on both sides of the screen (stencil and squeegee) with the necessary intermediate drying. The emulsion penetration into the mesh and its direct processing on the screen allow for the formation of stronger and more durable stencils compared to the indirect technique. These types of stencils are very durable, appropriate for long-run printing, and suitable for all frame sizes and formats. Thread thickness and mesh count for good printing quality, although the print results highly depend on the emulsion type and method of stencil processing (Ingram, 1999; SaatiPrint, 2001).

Capillary film is one of the direct–indirect phostecil types. It consists of a precision-coated film of pre-sensitized liquid photopolymer emulsion applied to a polyester backing/supporting film. Adhering the stencil to the screen is done through capillary action between the liquid emulsion and wet screen mesh which are in contact in the pre-coating process. Once the applied emulsion is dry, the polyester backing film can be peeled and the photo-processing can be done similar to the direct emulsion stencil system. There are several advantages of the capillary film: very good print resolution and edge definition, predictable stencil thickness, easy application, and very low surface roughness (Rz value), but they are more expensive than direct emulsion photostencils (Ingram, 1999; SaatiPrint, 2001).

Direct—indirect stencil preparing technique combines the advantages of direct emulsion and indirect stencil system. It uses a backing film coated with unsensitized emulsion layer which is laminated on the stencil/printing side of the screen mesh. From the squeegee side of the screen mesh, a liquid emulsion with a photosensitizing agent is applied which passes through the screen to adhere the backing film. When the mixture of emulsion and sensitizer is dry, the backing film can be removed and the emulsion is left on the screen mesh. The exposing and developing procedure is similar as outlined previously. Uniform emulsion thickness throughout the stencil, high durability, and high precision of printing are the primary advantages of this technique, however, the higher material expenses (unsensitized film and liquid emulsion are required), the complicated stencil lamination process, and the screen/frame size limitation are the drawbacks of this stencil type (Ingram, 1999; SaatiPrint, 2001).

15.3.3 "Computer to Screen" Systems

"Computer to screen" (CtS) terminology covers the digital stencil production system, where the printing and nonprinting areas on the screen mesh are defined directly using a computer. The stencils produced by CtS systems are durable and have high printing image resolution. There is no positive film in the stencil preparing process, therefore less exposure time is needed (no glass in between the light source and the emulsion-coated screen), and the potential image distortion caused by vacuum blanket is eliminated just like the stencil undercutting (so there is no loss in definition) (Baro et al., 2008; Kipphan, 2001).

The four primary technologies of CtS imaging systems can be divided into two main groups. Ink-jet and thermal-ribbon systems fall into the group of conventional emulsion exposure systems, whereas the digital light processing (DLP) and laser systems form the direct exposure system group.

Inkjet systems, based on the conventional piezo drop on demand printing technique, create a positive image directly to the screen, previously coated with a photosensitive emulsion. The printed image replaces the film in the conventional exposure and developing process. Two types of ink can be used for printing a positive image: conventional water-based opaque ink and solid opaque thermal wax. The UV light cures the emulsion beneath the noncovered areas and the used water-based ink or thermal wax is removed in the following development process together with the uncured emulsion. The speed of the stencil-making process is mainly determined by the selected imaging resolution and number of nozzles in the print head. CtS systems with conventional water-based ink could provide durable stencils in resolution of up to 1440 dpi, whereas those with opaque thermal wax (where the melted water-soluble wax is injected onto the screen and solidifies) deliver halftone stencils with great details and sharpness at resolutions up to 1300 dpi. Considering the economical aspect of different ink-jet stencil preparing techniques, the water-based ink system are more cost-effective in comparison with the thermal wax system, since the replacement costs of thermal print head are more significant than the conventional one (Novaković & Kašiković, 2013).

In the thermal CtS systems the positive image on the emulsion-coated screen is formed by thermal transfer technology. The water-soluble opaque ink from the ribbon to the emulsion-coated screen is transferred by heat and contact (pressure) in resolutions of up to 1200 dpi. The imaging process is then followed by standard exposing and developing process of the emulsion. High cost of used ribbon, the need for a clean printing environment, and a perfectly uniform emulsion coating layer are the most relevant disadvantages of this system.

DLP system is one of the direct exposure systems. With directly exposing the emulsion-coated screen using UV light, this system has no need for positive film, ink, or chemicals for stencil-making. The exposed screen is usually developed with water, and after drying it is ready for printing. The stencil imaging process is carried out by digital optical semiconductor chip, a rectangular array of up to two million hinge-mounted micro-mirrors. These mirrors can be easily repositioned in order to reflect UV light from the conventional metal-halide lamp to the screen, where the nonprinting areas are exposed and cured negatively. The negative exposure requires additional screen filler or a longer processing time to expose the emulsion fully from edge to edge on the screen. Furthermore, the emulsion layer has to be consistent, with no variations in thickness, but the variations in distance between the light sources and the screen have to be kept as low as possible also in order to produce precisely imaged and fully harden emulsion for stencil. High imaging resolution, no film or masking material consumption, and versatile emulsion application are the positive features of this system (Baro et al., 2008).

Laser imaging systems represent the latest technology in CtS applications, where one or more finely tuned lasers are employed to expose the emulsion-coated screen. The solid-state diode lasers (in violet—blue wavelength domain) can produce stencils at resolutions from 850 dpi up to 2400 dpi, but usually for small-format screens. The system has stringent requirements regarding the applied photosensitive emulsion (Baro et al., 2008).

15.4 Printing Process

Process of screen printing is based on the principle of squeezing the ink trough open areas of the mesh that have not been hardened and allow ink through. As the ink is squeezed by a squeegee from the inside of the mesh, it exits through the open mesh on to the substrate. All of the screen printing machines are constructed to follow this basic principle. Two basic construction types are flatbed and rotary system—the main difference between them being the shape of the frame, or rather the shape of the screen. According to the level of automation, the equipment varies from manual substrate feeding and squeegee operation, to a fully automatic press and mechanical handling of the substrate. Equipment can be classified as manual (hand-operated), semiautomatic, and automatic. Further classification of the equipment can be done according to the number of colors it can print in one cycle, design, intended product, size, and so on.

15.4.1 Flatbed Screen Printing

Flatbed screen printing presses are used for printing on flat substrates, cylindrical, or spherical surfaces. Size of the flatbed presses vary from common A4 format up to extreme 8 m_2. Large presses are usually automatized. Flatbed presses are produced in many variations, all of them optimized for specific use, such as printing T-shirts, textiles, wallpaper, electronic circuits, etc. All of these are printed against a flat table or a flat vacuum table where the squeegee moves while the screen and the substrate are stationary. For the cylindrical or spherical substrates cylinder press is used. During the printing cycle on cylindrical press, the impression cylinder (or substrate) and the screen carriage both move, while the squeegee is stationary. This type of press can print sheets, but then impression cylinder must have the grippers. Automatic cylinder presses can print up to 6000 impressions per hour. Its principle is shown in Figure 15.4(a) and (b).

Manual screen printing tables are used mainly in smaller organizations or for test runs before they are printed on automatic screen printing equipment. The frame is clamped on the hinges, allowing the operator to lift the screen in order to replace the substrate. Often counterweights are added in order to make the operation easier. Vacuum tables can be added to keep the substrate from moving and make precise multicolor prints possible.

Multicolor prints are possible by stacking multiple printing stations in line or circular arrangement. In this arrangement, the substrate moves from one printing unit to the next, while in circular arrangement substrate is stationary and the frame carriage is moving bringing different ink colors to the substrate. These movements of the substrate or the frame are achieved manually. Figure 15.15(b) shows the manual flatbed multicolor rotary screen printing machine, not to be confused with rotary screen printing principle (Novaković & Kašiković, 2013).

Semiautomatic flatbed equipment uses the same principle as manual ones. Operation of the squeegee and frame lifting is mechanized, mostly using pneumatics. Feeding is usually manual, but it can be mechanized according to the specific needs; in the same manner, the delivery can be automatized of left manual. The main difference of the manual process is a metal blade attached to the back of the squeegee that floods the screen with ink after an impression stroke as the squeegee returns to the starting position (Novaković & Kašiković, 2013). Semiautomatic flatbed presses offer consistent quality because of mechanized, thus constant, squeegee pressure and angle. Semiautomatic single color screen printing machine is shown in Figure 15.15(b).

Automatic flatbed presses are used in highly productive environments. In contrast to previous two types, all of the operations in such presses are mechanized, requiring minimal human involvement. The substrate is automatically fed and registered. Speed is the main advantage of the automatized presses, as smaller format presses can achieve up to 2000 impressions per hour. Speed is considerably reduced if the bigger formats are printed (Novaković & Kašiković, 2013).

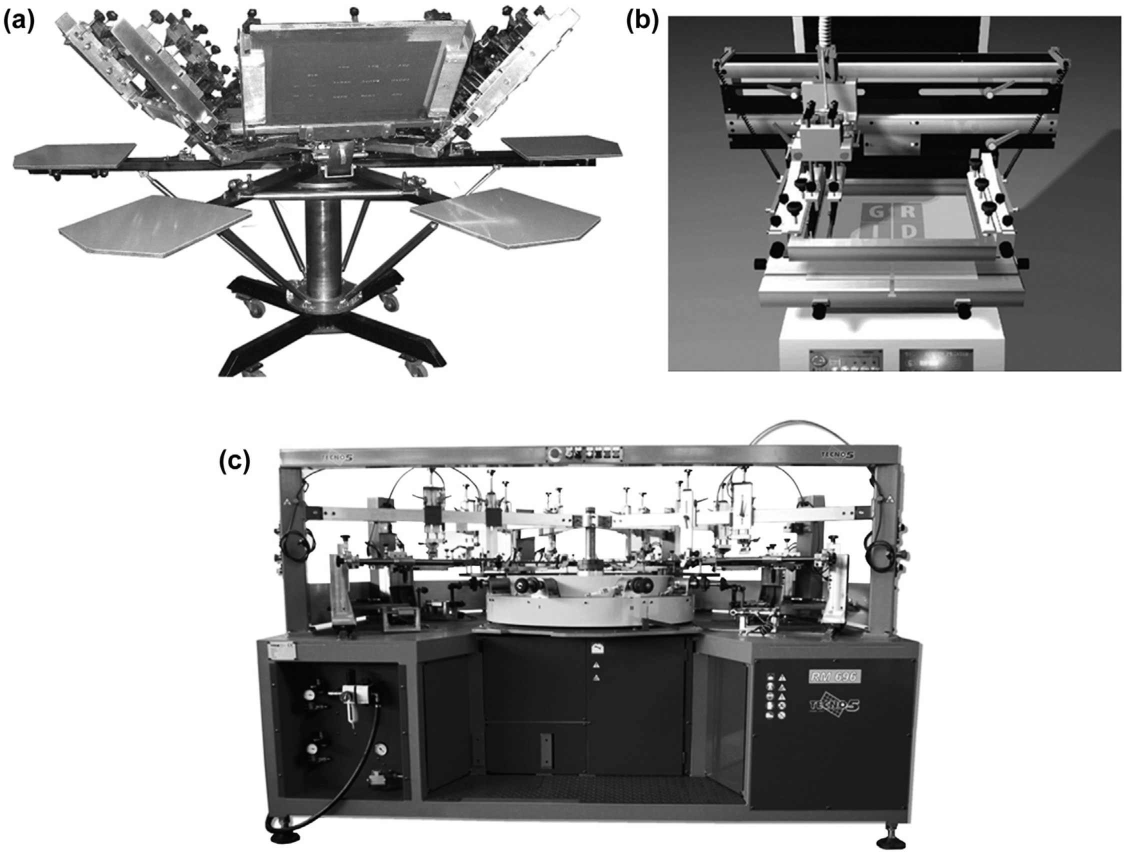

Figure 15.15 Flatbed screen printing: (a) manual multicolor rotary machine, (b) semiautomatic single color machine, and (c) automatic multicolor inline machine.
Novaković and Kašiković (2013).

Both semiautomatic and automatic systems use the same principle for multicolor printing; only difference is that movements are automatized, usually by pneumatic and electronic components. Automatic multicolor inline machine is shown in Figure 15.15(c).

15.4.2 Rotary Screen Printing

Rotary screen printing is a technique derived from flatbed screen printing. It offers the advantage of printing at higher speed (up to 120 m/min, depending on the substrate) and much lower manufacturing costs than flatbed screen printing. Flatbed screen printing is limited in length up to 30 m, while rotary construction can print up to 3000 m long continuous web. Rotary screen can have up to 100 cm circumference and width up to 4 m, thus making large patterns possible. Wall papers, textiles, and other rolled up materials can be printed with constant quality using this technique (Novaković & Kašiković, 2013). Its principle is shown in Figure 15.15(c).

Basically, rotating cylindrical screen envelopes the squeegee-like blade which presses ink on to a continuous roll of substrate, while the ink is continuously pumped inside. The rotary printing screen itself is a very fine nickel mesh, usually made as hexagonal structure. In-line configuration is usually used. Modern systems can integrate over 10 printing stations, each printing different color. Considering the high speed and the amount of ink transferred to the substrate, dryers must be used after printing each color. Hot air or UV dyers are used depending on the type of ink.

15.4.2.1 Drying Equipment

Drying process is crucial for ensuring high-quality, long-lasting product. Screen printing is characterized by a thick layer of ink transferred to the substrate. This is one of the most valued features, but it causes considerable difficulties as the printed substrates cannot be stacked or rolled on each other immediately after printing. In order to achieve speed, the prints must be dried after printing. The substrate and ink composition and characteristics are the determining factors for choosing adequate drying technique. The most commonly used dryers are drying racks, wicket, jet, infrared, and ultraviolet dryers.

Wood or metal drying racks are commonly used for air-drying where air is able to circulate between the sheets. Optionally racks can be inserted into an oven that dries the printed sheets faster. Wicket dryers are composed of a series of metal wire racks mounted on a conveyor belt. The wire racks carry the printed substrate as it moves through the enclosed chambers with heated air circulation. Jet dryers are usually conveyor belts that carry the printed substrate through a hot air tunnel. Optional cooling sections can be added. Similarly, infrared drying units use a conveyor but the method of drying in this case is heat radiation. Ultraviolet curing units dry the substrate by curing process (toughening or hardening of a polymer material by cross-linking of polymer chains) with conveyors used to transport the printed substrate. Ultraviolet curing units are compact and efficient (Novaković et al., 2011).

15.4.3 Polymer Substrates and Inks

One of the biggest advantages of screen printing is that it can be used on almost any substrates, including paper, paperboard, polymer materials, textiles, wood, metal, ceramics, glass, and leather. In addition, the screen printing process enables ink application not just to flat surfaces but to irregular ones too, as long as the thick ink adheres properly to the printed substrate and the screen can adapt to the substrate's shape consistently without distortion (Baro et al., 2008; Kipphan, 2001).

Polymer substrates can be made from diverse types of plastic materials. Polypropylene, polyethylene, poly(vinyl chloride), polyester, polystyrene, and a lot more polymers are available in today's industry practice in a wide range of shapes. Different type of containers, tubes, and other package items, toys, sports equipment, signs, credit and identity cards, RFID tags, solar cells, and panels for appliances, sensors, and other printed electronic components are all made from polymer materials and they all are printed mostly by screen printing (Ingram, 1999; Kipphan, 2001; Komi, 2015).

The wide variety of polymer substrates also requires different types of inks. Printing inks must be selected accordingly to the type and surface characteristics (surface roughness and surface tension) of printing substrates. In order to fulfill the intended function of printed goods with high printing quality and desired ink layer thickness, the mesh fabric and the stencil material, its profile, and surface roughness (Rz value) have to be adapted to the used ink, and therefore to the printed substrate, too. Additionally, a sharp edge of printed image requires inks with higher viscosity in screen printing than in other printing techniques (Ingram, 1999; SaatiPrint, 2001).

Screen printing inks can be categorized by the drying process in the following groups: evaporative (water-based and solvent-based), oxidizing, catalytic, and UV inks. Solvent-based inks are very common in polymer screen printing applications, but there are some other inks that are dried by a slower process of oxidation and polymerization, too. Inks that use UV energy for drying (curing) by polymerization are mostly used on high-capacity and continuous web printing machines, since the drying process is very quick and it is completely under control, and thus the screen will be open for sure during the printing process, and the ink will be cured only on the substrate. In plastic bottles and containers, self-adhesive labels are regularly printed with UV inks (Baro et al., 2008; Eldred, 2001; Ingram, 1999).

15.5 Screen Printing Industry

Screen printing is one of the oldest printing techniques. Although there have been numerous technological improvements, till date, the basic principle of ink transferring has not changed significantly. Simplicity in application made this printing technique a very attractive choice for ink and technical coating deposition, hence screen printing is recognized today not just as fine art printing technique, but as a manufacturing process. Its application to decoration varies from large-scale billboards to small format decals, from household products to textile patterning, and from high runs package printing to single-item display production. As a manufacturing process, screen printing can provide cost-effective solution for printed electronics, capacitors, membrane switches, solar cells, biomedical sensors, etc. (Ingram, 1999; Kipphan, 2001).

Screen printing allows for the application of thick ink or coating layers (5−25 μm) on a wide range of substrates which is one of the major advantages compared to other printing techniques. These thick ink layers can be felt not just seen; therefore, besides the 3D visual effects, screen printing could be used for creating a 3D object or Braille alphabet. The flexible printing form, made from screen mesh and stencil, allows for printing on three-dimensional objects not just flat substrates, since it can wound around any irregular shaped object. This ability of the mesh that it could conform even to the very specific surface characteristics of printed substrates opens far more application possibilities than any other direct printing technique. The wide ink range covers not just typical graphic arts applications, but special value-adding printing or electronic component or sensor manufacturing as well (Baro et al., 2008; Ingram, 1999; Komi, 2015).

The versatile application of screen printing does not allow a simple market share analysis and makes a trend prognosis far more complex than the other printing techniques. For example, according to Moldvay (2012), in terms of market share for commercial graphic products (magazines, books, posters, etc.) screen printing held approximately 9% among other techniques in 2012 in the USA. On the other hand, in the field of printed electronics, screen printing is the major technology (Komi, 2015; Market and Markets, 2014).

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