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THICK FILM TECHNOLOGY

FOR

MICROELECTRONICS

by

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Abstract

The maturing of modern electronics design and the forces of economics have led to the inevitable growth and prominence of thick film hybrid microelectronics. Screen printed thick film circuits have many advantages from the viewpoint of design flexibility, cost of electronics designs, shorter and simpler fabrication cycles, and capital equipment requirements. Many variables affect the screen printing process. The setting of screen printer is a manual operation. Thus the quality of screen printed thick film strongly depends on the operator and the process variables. Understanding these variables using statistical process control techniques would help to improve the quality of the thick film circuits. Analysis of the setup process would help to reduce the setup time of the machine. Setup analysis and variables analysis would help to improve the quality of the product and increase the productivity of the operation. There are some benefits associated with automation. However, the automation benefits should be evaluated against the manufacturing and business strategies.

Chapter 1
Introduction

Microelectronic engineering and technology has made very considerable advances over the past decade and a half. This has had a major impact on the electronic industry. Film technology has an important supporting role to play for the success of microelectronics. Film technology is the generic name given to an electrical interconnection technique based on "*thick film*" or "*thin film*" methods. When either of these are combined with active add-on components the result is called a "hybrid" circuit. The labels "thick" and "thin" detail the method by which the conductive , resistive or insulating films are deposited onto the substrate and also the film thickness. Thin film (thickness commonly less than 0.08 mil [39]) involves the use of an evaporation or sputtering process performed in vacuum while thick film technology uses screen printing and subsequent processing of paste materials [59]. A typical circuit is shown in Figure 1-1.

The thick film process has a critical role in almost every aspects of the interconnection of silicon devices. The term *thick film* is a generic description for that field of microelectronics in which specially formulated pastes are applied and fired onto ceramic substrate in a definite pattern and sequence to produce a set of individual components, such as resistors, and capacitors, or a complete functional circuit. The common process for printing thick films is based on ancient Chinese silk-screen process, generally referred to as screen printing process. The screen printing process is unique in its ability to place thick deposits of ink precisely while maintaining extremely good volume control and line definition. The high temperature firing matures the thick film elements and bonds them integrally to the ceramic substrate.

Typically, the thickness of a thick film element would be 0.5 to 1 mil or

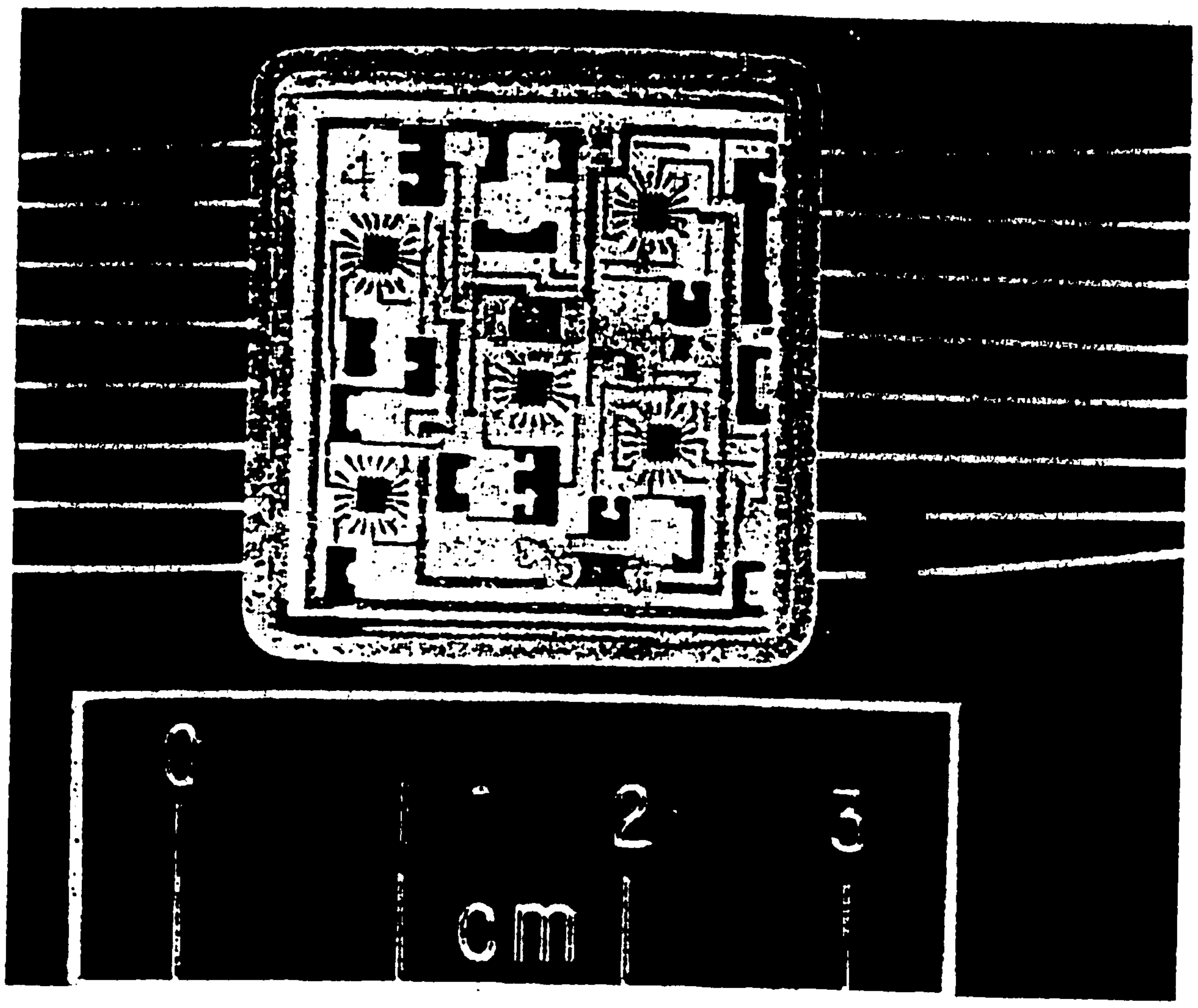


Figure 1-1: A Typical Thick Film Circuit

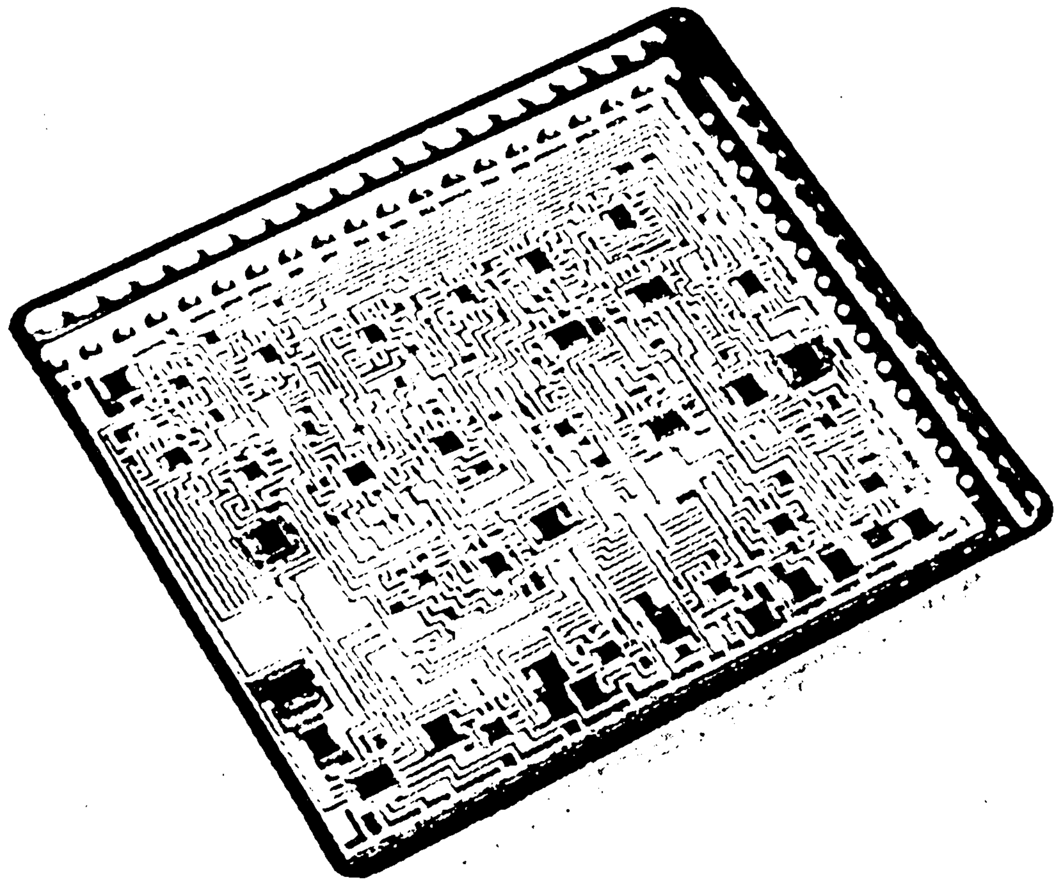


Figure 1-2: A Multilayered Hybrid Circuit

more. This distinguishes it from thin film, where film thickness is generally in the neighbourhood of 0.0004 - 0.04 mil [46]. (Figure 1-4) The growing volume of hybrid circuits, membrane switches and solder mask-covered printed circuit boards(PCBs) rely heavily on the screen printing process.

1.1 Historical Perspective [59, 61, 48]

Thick film technology, which will be described in much greater detail in subsequent chapters, has either a very long history or a shorter history than any of the other interconnection techniques depending on where one wishes to define the beginning.

The origins of thick film date back to some 3000 years (compare this with solid state electronics which has had a life so far of only 30 years) and was developed from the method of '*silk screen*' printing used by the Chinese. The very fine silk threads comprising the mesh were ideal for depositing multilayered colored patterns onto fabrics. Surprisingly, even today a large amount of screen printing is carried out in the field of graphic art and decoration. Metallizing of ceramic materials probably began somewhere in 19th century; however the earliest work which has greatest relevance to thick film today was done by Pulfrich, in the 1930s [66, 67]. In this work, vacuum tight seals were fabricated by coating ceramic with a finely distributed iron and molybdenum powder and then firing the samples at high temperature in a controlled atmosphere. The thick film technique as it is currently used for electronic circuitry was developed from work in the mid-1950s when the transistor was beginning to be applied more widely. After the WW II, conductor pastes consisting of silver powder, glass powder and petroleum jelly were being fired onto ceramic materials [59].

However, it was probably not until the early to mid-1960's that the idea of making the circuit in such a manner using a ceramic substrate began to take

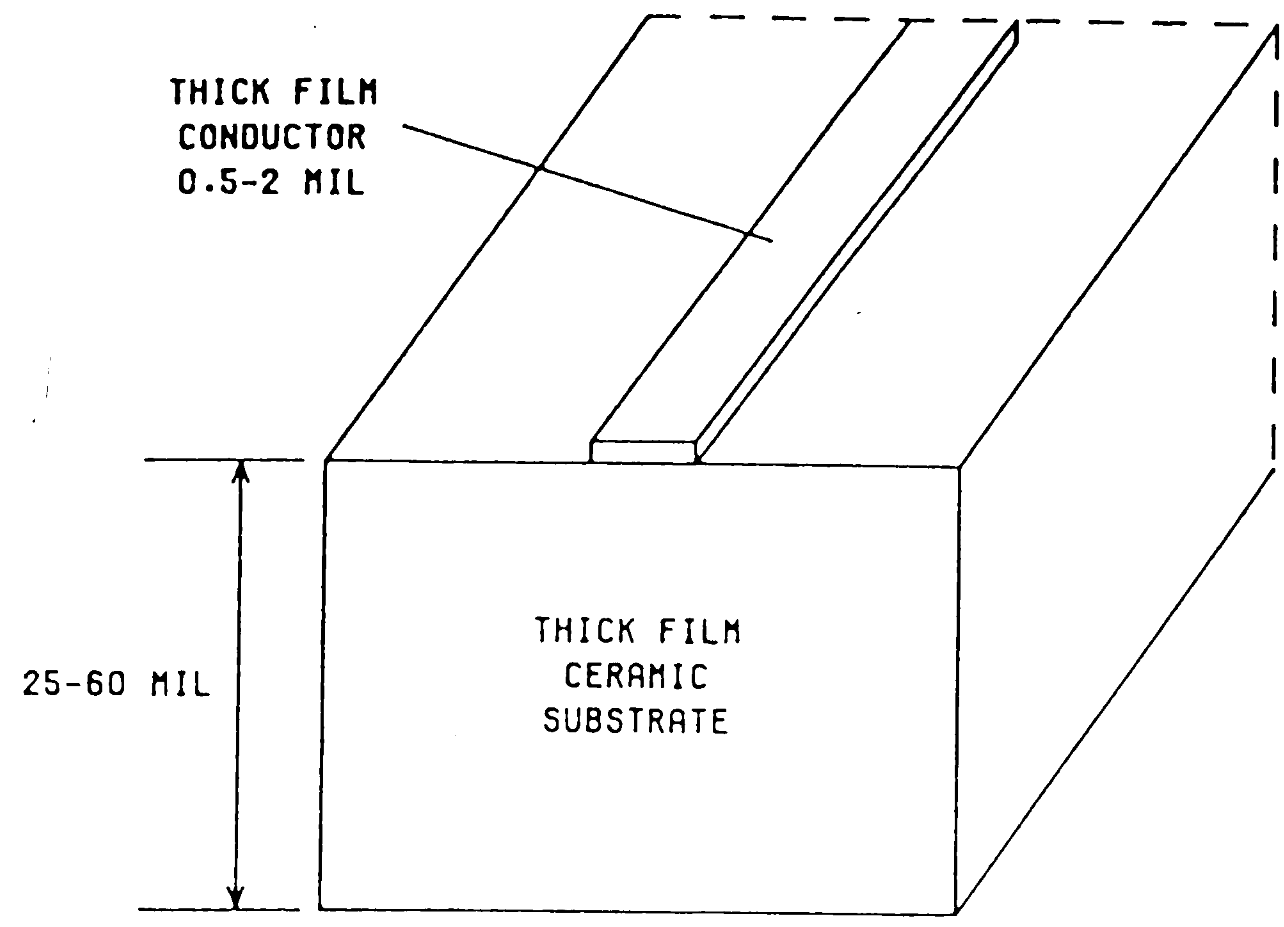


Figure 1-3: Thick Film Dimension

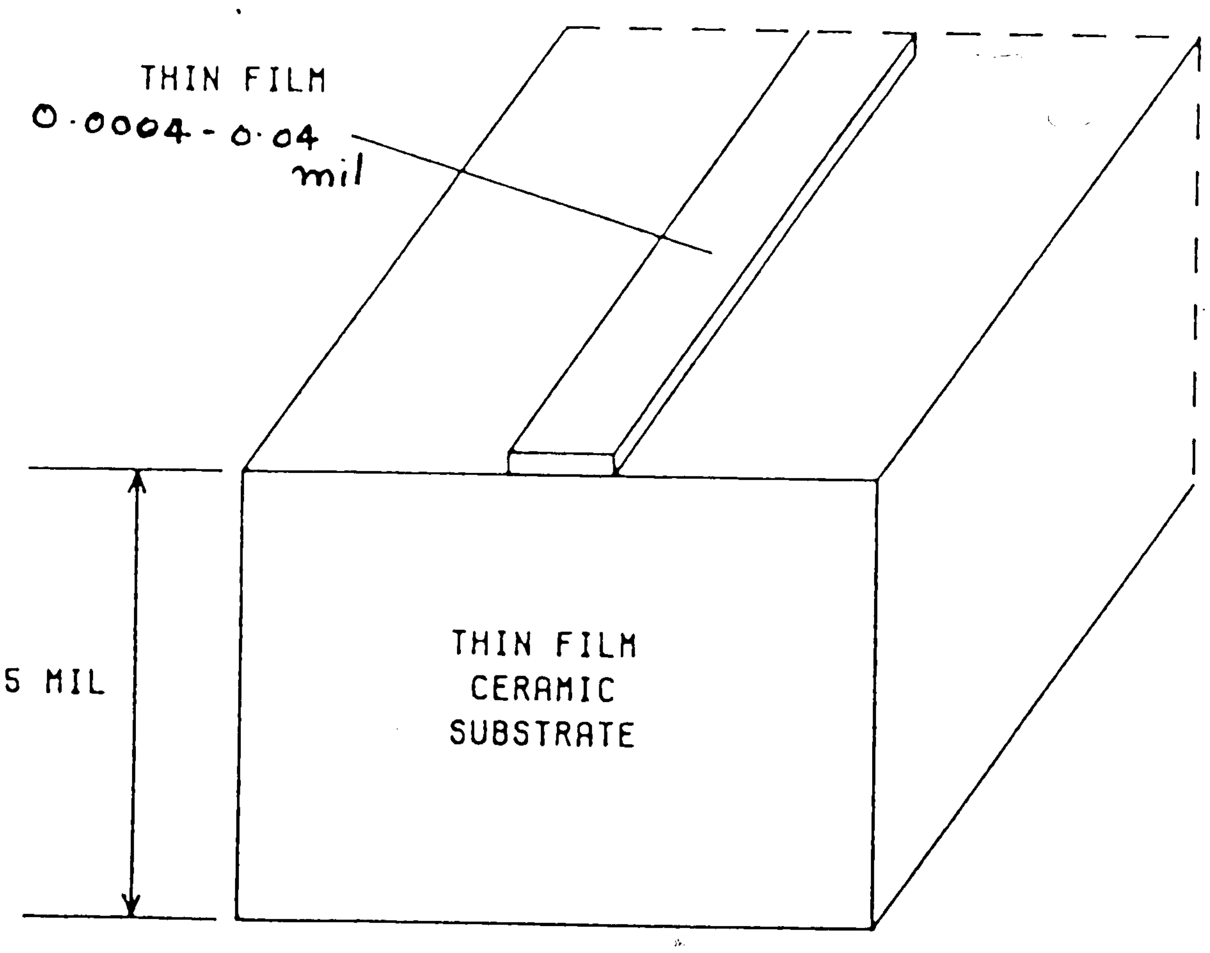


Figure 1-4: Thin Film Dimension

on real significance. IBM lead the general acceptance of thick film processing by designing it into their 360 range of computers [59]. Although Centralab had been using the technique for some while [61]. IBM output was, and still is, enormous running into hundreds of millions of units per annum and the development of automatic handling methods and improvements in the materials became essential. As result of purchases from subcontractors the technology spread to other industries.

IBM, with a large scale customer base, adopting the technology helped other developments to follow. It was soon found that good quality gold conductors could be manufactured and unlike the thin film process there was no wastage through etching. Laser trimming, which is a high speed operation, both for resistor value and circuit function tended to eliminate the need for manually adjustable resistors. The gradual availability of insulating thick film materials meant that first of all simple crossover and subsequently full multilayer assembly were readily manufacturable -- an important advantage over thin film techniques. A typical multilayered thick film circuit is shown in Figure 1-2. The range and performance of thick film resistors gradually improved and the processing gradually became more routine. Typical temperature coefficients are now $\pm$ 50 ppm/°C [59]. Resistors are routinely trimmed to $\pm$1 % tolerance [59].

Historically the major motivation for the thick film process was resistor networks for use in transmission line termination and load resistors combined with very small scale integrated circuits. The ruggedness and relative ease of automation of the technique permitted high volume production. The networks were assembled together with the packaged active devices on a printed wiring board. Gradually the space and reliability advantages of using unencapsulated integrated circuits, either as multidevice assemblies or combined with resistors and capacitors came to be appreciated. The acceptance of thick film techniques into consumer and industrial applications was rather slow. This was due to the high cost of handling the unencapsulated devices. Additionally semiconductor manufacturers often charged more for the unpackaged device than a packaged one [59]. In many early thick film industrial circuits, conventional wire ended components were attached through holes into the substrate - simply because that was the way components were attached to printed wiring boards and it was known to be reliable. Gradually the advantages of automatic placement of the components on the surface were appreciated. Also at the same time active components became available that were specifically packaged for the so-called surface mounting method. The credit for a large range of components in the new package style must go to Phillips Corporation for their pioneering work [59].

Simultaneously with the emergence of the low cost surface mounting devices, three market forces were becoming apparent.

1. The relative cost of the electronic devices was falling rapidly compared to the costs associated with the cabinets, connectors, etc. and there was a need to reduce the size of the electronic assemblies.
2. The electronic assemblies were becoming more complex. There was need to break down circuit functions into less complex subassemblies.
3. Conventional semiconductor packaging techniques were not adequate for high pin count integrated circuits. It was found that pinless surface mounting packages were more suitable for the higher number of connections.

For all these reasons it can be seen that the thick film process has a role to play in almost every aspect of the interconnection of silicon devices. The products range from simple but high performance compact resistor networks, through reasonably complex, yet complete functional entities, industrial grade products, to very complex, miniaturized high reliability circuits. Although the disciplines involved in each of these product areas are different, many of the materials and processes are the same. In the past thick film technology has been used exclusively for networks and to obtain miniaturization by interconnecting a number of unencapsulated small scale integrated circuits. Some specific applications, for example analog to digital convertor and heart pacemakers, used the ability to combine active devices with high performance resistors (and good quality capacitors, if required) to obtain a complete functional entity inside one package. The introduction of miniature packaged active devices enabled hybrid assemblies to be price-competitive with printed wiring techniques. It also became economically feasible to use the printed wiring board to interconnect a number of reasonably complex sub-assemblies. As a result of this the printed wiring board becomes denser, and usually, smaller for a given circuit functionality.

The future of interconnection technique is currently the subject of much discussion. For low to medium pin count integrated circuits, current methods are adequate. However, in future high pin count gate and cell array integrated circuits are going to be implemented and the current methods are impractical for such devices. There is therefore much room for innovation in thick film technology. The flexibility of the thick film process would appear to be invaluable to the evolution of new interconnection ideas.

1.2 Literature Review

The foregoing has described the history of the thick film technology with some introduction about integrated circuits and microelectronics. The traditional information on thick film technology, i.e., basic principles, materials, design and manufacture/fabrication is well documented in various books, [22, 83, 46, 35, 82] and articles [62, 70, 14, 12, 27, 5, 50, 11, 49]. As the thick film technology gained popularity, the automatic screen printers were introduced. The selection criteria and performance are subject of Heimsch, Jacobs [40, 72, 45, 85, 51, 4]. Printing fine line geometry has always been a concern in the screen printing process. Some novel techniques are discussed in references

[77, 74, 31, 63].

There have been many advances in ink/pastes and new applications are being developed using these new thick film materials [23]. The substrates are also undergoing some changes [86]. There have been experiments using non-ceramic substrate and polymer based inks/pastes [15, 6, 32, 75]. Hoffman and Vest studied thick film materials from the material science perspective [41, 88]. The type of screen has always been a concern during the printing process, various aspects of screen are discussed in references [52, 53, 80, 26, 71, 73, 42, 28, 1, 30, 24].

A major problem is the setup procedure for a screen printer is in the area of thick film technology. Some techniques and recommendation are found scattered in the literature [74, 59, 65]. The quality of thick film is strongly dependent on the many process, printer and material variables [16, 10]. There has been some attempt to study the effects and interactions of some critical variables on the quality of the film thickness and resistor values [60]. This attempt uses *Design of Experiment* approach to study the effects and interactions [18].

In recent years, there have been attempts to study the effects of inks/pastes using more mathematical approach [38]. A similar approach has also been tried to study the screen printing process using the principles of hydrodynamics of inks and analysis of various forces applied due to squeegee design and mesh [68, 69].

Solar cell applications and superconductivity films (by screen printing process) are a relatively new area where thick film technology has been under study [37, 43, 13, 21].

Since the technology of hybrid microcircuit is dynamic, it becomes important to have various sources to keep the field current. The more common and useful resources are:

Technology Periodicals

1. Solid State Technology
2. Semiconductor International
3. Hybrid Circuit Technology
4. The International Journal for Hybrid Microelectronics
5. Electronics Test
6. Printed Circuit Fabrication
7. Circuits Manufacturing
8. Test & Measurement World
9. Hybrid Circuits, UK
10. Screen Imaging Technology for Electronics (SITE)

Technical Proceedings

1. International Microelectronics Symposium, (ISHM)
   Annual since 1967
2. Electronics Components Conference, (IEEE)
   Annual since 1950
3. International Microelectronics Conference, (ISHM)
   Alternate years (even) since 1980
4. European Hybrid Microelectronics Conference, (ISHM Europe)
   Alternative years (odd) since 1977

This thesis is organized as follows. Chapter 1 introduces the subject of thick film technology with relevant historical perspective and literature survey. Some sources for further readings are also included in this chapter. Chapter 2 covers thick film materials, namely, the substrate and the inks/pastes with some insight to future trends in materials. Thick film inks/pastes are discussed in detail in Chapter 3, which covers the rheological characteristics and type of inks. Chapter 4 discusses the screen printing process, beginning with layout and art work, screen selection and preparation, followed by the printing process and drying and firing process. Problems associated with screen printing are the topic of discussion in Chapter 5. Chapter 6 discusses setup and statistical process control (SPC). Two common SPC techniques, the use of control charts and design of experiments, are also discussed in this chapter. Chapter 7 is the actual case study which explores the concept discussed in Chapter 6. The results and conclusions of this study are discussed in in Chapter 7. Some thoughts about automation of this technology are briefly covered in Chapter 8. Finally conclusion is discussed in Chapter 9.

Chapter 2
Thick Film Materials

Since the fabrication of thick film circuits is designed around the materials used, it is appropriate at this point to discuss the properties of thick film materials prior to describing the processing steps. The basic materials involved in the thick film process are:

- The Substrate
- Thick Film Inks/Pastes

2.1 The Substrate

From the users point of view, the substrate provides a passive mechanical platform for the circuit elements. The substrate must perform three essential functions in a thick film circuits: [74]

1. Heat dissipation
2. Mechanical support
3. Electrical isolation

In addition, the substrate may have to withstand temperatures as high as 1000 °C, must not react chemically with external parts or solvents, and should be inexpensive. These criteria limit the available materials to refractory ceramics, such as alumina and beryllia.

The vast majority of thick film circuits are fabricated on alumina substrates (Figure 2-1), which are made of a mixture of finely ground Al_2O_3, MgO, and SiO_2 mixed with an organic binder and sintered at a high temperature. Typical percentages of these compounds in two commercially available substrates are represented in Table 2-1 [74].

Beryllia (BeO) substrates (99.5 % BeO) are used in small proportion if

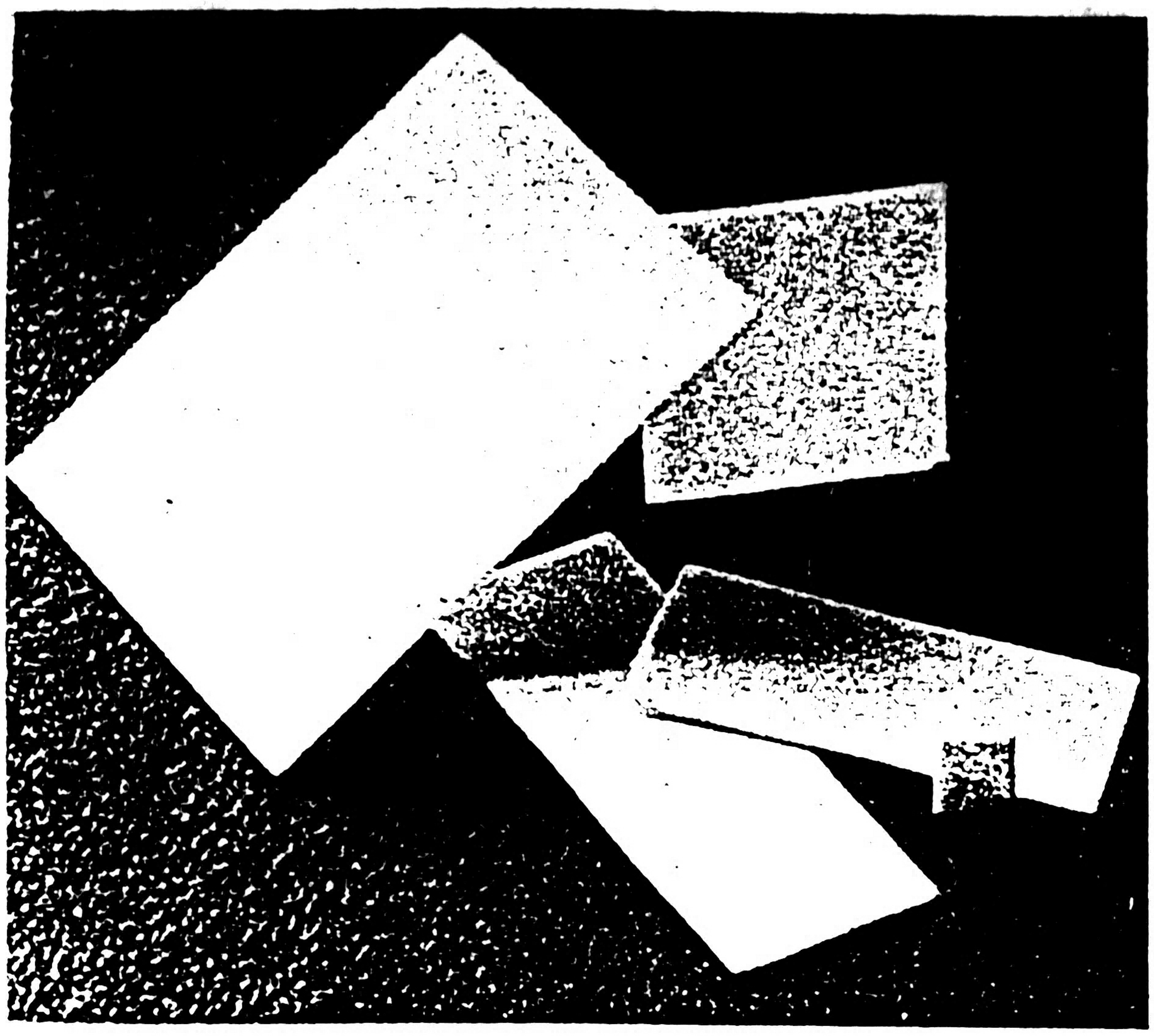
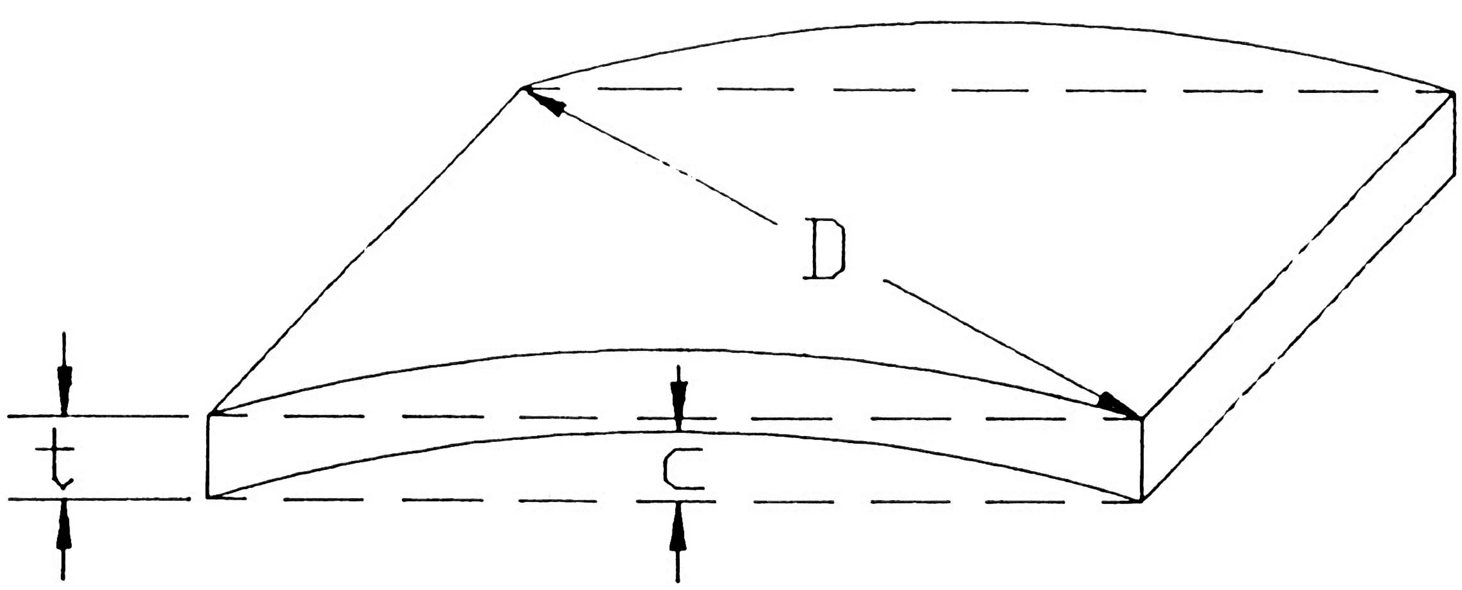


Figure 2-1: Alumina Substrate



c = gross camber
D = diagonal
$\frac{c}{D}$ = Normalized camber

Figure 2-2: Camber

	96% Alumina	99% Alumina
Al_2O_3	95.0 %	98.9 %
MgO	0.8 %	0.06 %
SiO_2	4.2 %	1.04 %

Table 2-1: Composition of Commercial Substrates

exceptional thermal properties are required [82]. BeO dust is extremely toxic, so great care is required in handling this material. BeO substrates have lower flexural strength and are considerably more expensive than 96% Alumina (Al_2O_3) substrates. Both have good electrical characteristics (i.e., high resistivity, low dielectric constant, and high breakdown strength).

For all substrates, certain surface and dimensional tolerances must be maintained to ensure good printing quality. Specifications will vary, but a typical set might include the following: [82]

1. Surface finish variation (peak-to-valley height variation) not to exceed 0.6 µm.
2. Camber, (variation in flatness per cm of edge length, Figure (2-2)) not to exceed 0.004 cm/cm.
3. Random voids (pits in surface) in surface not to exceed 25 µm in diameter.
4. Length and width dimensions ± 1 %.
5. Thickness dimension ± 10 %.

It is important to realize that a certain degree of surface roughness is necessary to achieve sufficient adhesion between the ink and the substrate.

Substrates may be purchased in all shapes and sizes and with pre-punched holes if desired. For faster production, larger, pre-scribed, substrates are available on which several circuits may be fabricated and, after processing, they are broken along the scribe lines. Tighter dimensional tolerances may also be obtained by using the pre-scribed substrates [74].

Consistent results in fabricating thick film hybrid circuits require very clean substrates. Problems with the adhesion of conductive films, pinholes in dielectric insulating films, and resistor drift can be directly traced to foreign material on the substrate during printing and firing. There are many techniques for cleaning substrates. One such technique for cleaning which gives excellent results is described as follows [74]:

1. Ultrasonically clean in detergent for 5 minutes to remove any gross dirt and loose particles.
2. Flood rinse with running water for 15 minutes to remove detergent film.
3. Ultrasonically clean for 5 minutes in isopropyl alcohol to remove any residual detergent and gross organic material.
4. Allow substrates to travel through moving belt furnace at firing temperatures to remove any residual organic material and bake out surface moisture.

After this step, the substrates should be handled only with tweezers or finger cots and should be stored in a clean (microelectronic clean room specification) environment until use. Before any screening step, the substrate should be blown clean with filtered compressed air or with "canned" compressed air.

The main substrate problems encountered by users are concerned with dimensional tolerances; size, flatness, and surface smoothness. The difficulties of maintaining accurate dimensions and flatness result directly from the enormous shrinkage which occurs when the green ceramic is sintered at high temperature by the substrate manufacturer [59]. The advent of CO_2 laser scribing has resulted in more accurate lengths and widths of substrates. Processing of flat ceramic substrates has greatly improved over the last fifteen years and substrates with camber of less than 0.001 " per inch are obtained without recourse to surface grinding [59]. Surface finish has also been improved and is now more than adequate for thick film processes.

The use of vitreous enamelled steel substrates (porcelain enamelled steel) has recently attracted lots of attention [59]. These substrates are low carbon steel sheets coated with glass. Because glasses begin to soften at temperatures above 600 °C, special low firing temperature thick film pastes have been developed for use with steel substrates. The principal advantages of steel substrates are mechanical robustness, availability in large sizes at low cost compared with ceramic and high thermal conductivity compared with PCBs. However, at the present stage of development, the electrical characteristics of thick film elements fired on enamelled steel are inferior to those obtainable with conventional thick film pastes used with alumina [59].

2.2 Thick Films Inks

The ink is the heart of the thick film system: The mechanical and electrical properties of the fired inks determine whether or not the circuit will be operable. (The terms "*inks*" and "*pastes*" are used interchangeably throughout the industry and in this thesis.) Thick film inks have varied compositions of glass particles, metal and/or metal oxide particles, and organic solvents with viscosity control agents. Thick film inks are available for a wide variety of passive functions. The types of ink available are: conductor, resistor, dielectric for capacitors and crossover, glass for encapsulation and solder dams, thermistor, and solder [82]. There are four main constituents of a thick film ink [74].

1. Active material particles

2. Binding ingredient
3. Organic binder
4. Volatile solvent

The active material consists of very fine particles (around 5 microns in diameter). This determines the electrical characteristics of the fired film. Inks with metal particles are conductive in nature, inks with metal oxide particles are generally resistive in nature, and inks with dielectric particles are capacitive in nature. Inks with no active particles are also dielectric in nature since the glass is insulating. The dielectric constant of the pure glass is somewhat lower than inks with dielectric particles added and are used where a low degree of coupling is desired, such as in cross-over.

The binding ingredient is usually consists of fine particles of low melting point glass, such as lead borosilicate glass. The purpose of the glass is twofold; to hold the active particles in contact and to promote adhesion to the substrate by reacting with the the substrate during the firing process. The glass has a lower melting point than the active particles and, during firing, wets the active particles, suspending them in contact with each other. Also during firing, both chemical and physical changes take place between the glass and the substrate, adhering the fired film pattern to the substrate. A second type of binder material is a metal oxide, such as copper oxide, used in lieu of the glass. The metal oxide forms a totally chemical bond between the active material and the substrate and is used in the so-called "*fritless*" inks.

The purpose of the organic binder is to hold the active and glass particles in suspension prior to firing and provide the proper fluid properties for screen printing. Thick film inks must have a high rest viscosity in order not to flow through the screen prior to the squeegee pass and to retain the pattern on the substrate after the squeegee pass. The viscosity must decrease during the squeegee pass in order to allow the ink to flow through the screen onto the substrate.

The purpose of the volatile thinner is to reduce the yield point. As more thinner is added, the yield point decreases.

Types of inks along with some ink characteristics are discussed in Chapter 3.

2.3 Future Trends

Future developments in thick film inks/pastes and substrates can be expected to reflect economic pressure for cost reduction and the need to meet new technical requirements. These pressures are generated by the trends in microelectronics towards ever higher packaging densities and switching speeds.

The obvious scope for cost reduction in inks/pastes is in the replacement of precious metals by cheaper, base metal alternatives. Nitrogen-firing copper conductors and matching dielectric seems to improve and is likely to find a place in future multilayer circuitry, particularly for large digital systems [87]. Glazed steel or similar dielectric coated metal substrates with improved characteristics are likely to be used where large boards are required. The thick film inks/pastes applied to metallic substrates with high thermal conductivity may give rise to new generations of dense, high speed circuitry.

A further development, not strictly based on conventional ceramic thick film technology, the use of screen printed polymer materials doped with silver (for conductors) or carbon (for resistor). Such technology may have large quantities for consumer equipment in the future. The low cost of the inks/pastes plus the ability to employ inexpensive substrate materials is very attractive in non-demanding applications [79].

Chapter 3
Thick Film Inks

Screen printing is a "*through-printing*" process. The inks/pastes used in screen printing are deposited on substrates by being forced through a screen mesh. The effectiveness of this printing method is largely determined by the 'flowing' or rheological characteristics of these substances, collectively referred to as inks. This chapter examines how rheology effects the printing process and what processing parameters and measurement techniques are available for control. Also different types of inks and their properties are discussed briefly in this chapter.

3.1 Rheology of Inks

Thick film inks must have a high rest viscosity in order not to flow through the screen, prior to the squeegee pass and retain the pattern on the substrate after the squeegee pass. The viscosity must decrease during the squeegee pass in order to allow the ink to flow through the screen onto to the substrate. In the printing process as squeegee blade passes over the screen, the ink is rapidly sheared, the viscosity falls and the ink passes easily through the fine mesh of the screen onto the substrate. Shearing action then stops and the viscosity of the ink regains its initial higher value and flow almost ceases. Thus the ink does not flow out on the substrate and the shape of the printed pattern is retained. The inks showing this behaviour are classified as ***thixotropic*** and the characteristic curve for thixotropic inks is shown in Figure 3-1.

Referring to Figure 3-1, no flow takes place until the force has reached a certain minimum value called the 'yield point'. As the force is further increased, the flow rate is increased and the ink readily flows through the screen. As the

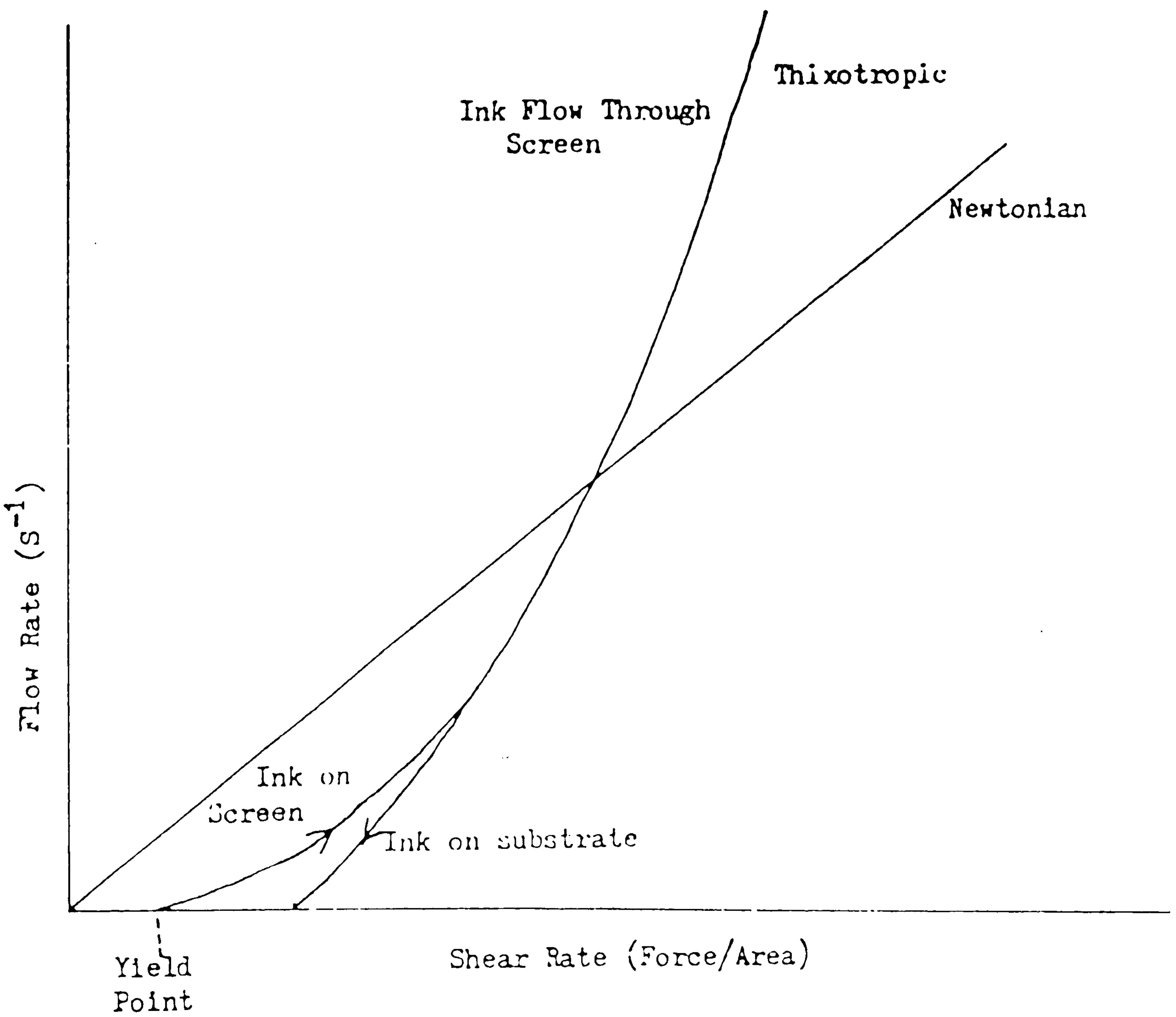


Figure 3-1: Flow Rate vs Shear Rate

force is decreased, a hysteresis is noted in the Figure 3-1, indicating a sharper decrease in flow rate. This assists the printing process to retain the proper dimension on the substrate. Trease and Dietz made some viscosity measurements at various shear rates. (Figure 3-2) [84].

The importance of the rheological characteristics of inks are not immediately apparent to the processor. Inks are selected and purchased on the basis of their cured, physical properties, such as color, flexibility, conductivity, resistance to chemicals and host of other performance considerations. The

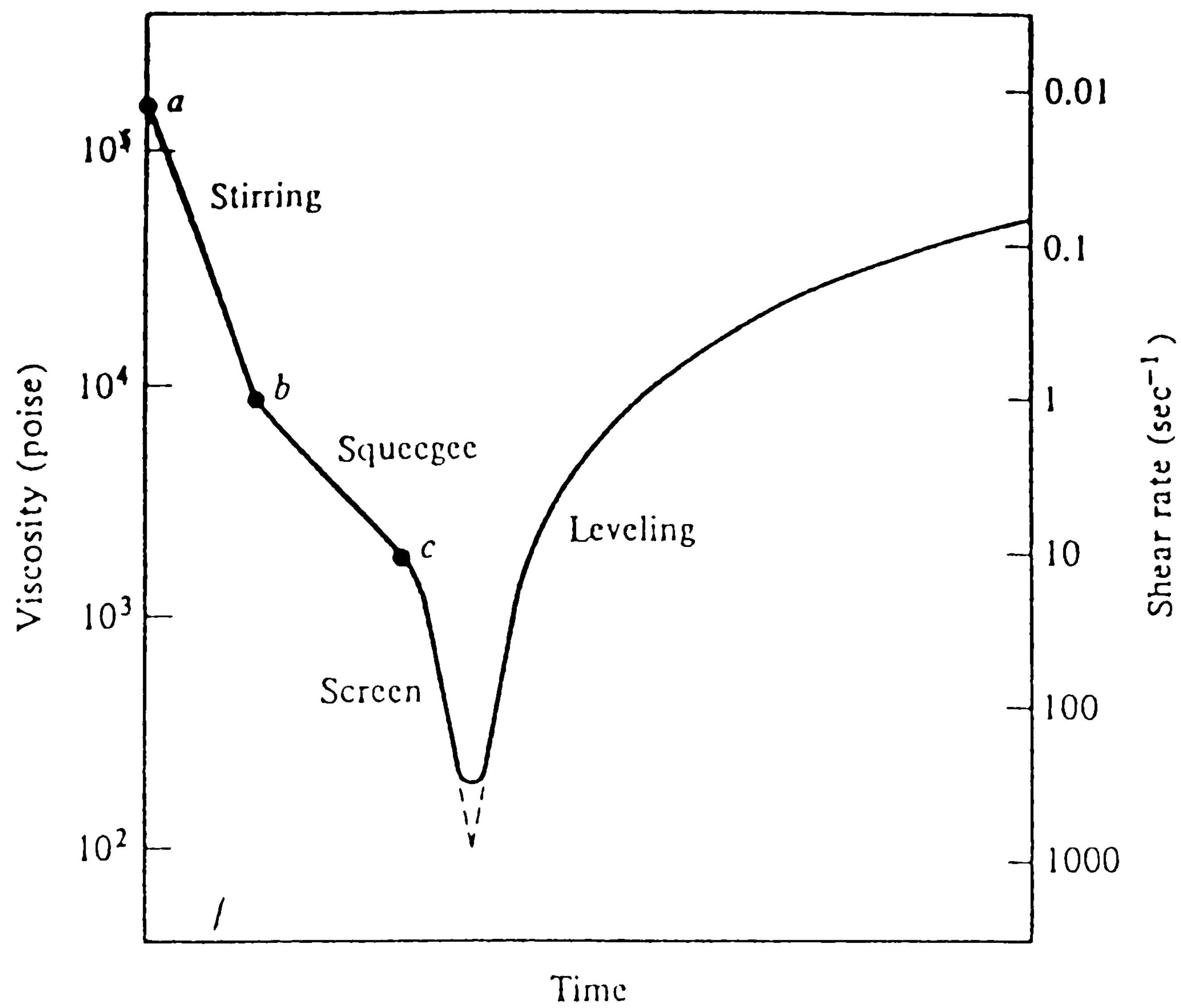


Figure 3-2: Viscosity Changes during Screen Printing

printability of ink is seldom considered in relation to screen fabric parameters, squeegee speed, and image definition.

There are three main reasons why ink rheological properties are not considered: [23]

1. The science of rheology is highly theoretical and difficult to comprehend without a significant mathematical background.
2. Practical rheology, lags a quarter of a century behind the scientific theories.
3. Most inks are manufactured in ready-to-print form.

Ink rheology affects many aspects of screen printing, from considerations of productivity (production speed, quantity and quality) to the selection of screen fabrics and squeegees. Making rheology part of the processing parameters offers the opportunity to standardize production. While there are costs associated with both options, in the long term, standardization offers consistent quality at lower production cost.

Viscosity and the production process mutually affect each other: [23]

Viscosity affects production by:

- setting limits of the squeegee speed ranges
- setting limits of screen mesh ranges
- influencing in the ink deposition role of the screen

Production parameters may change viscosity through:

- lack of temperature control
- solvent modification
- storage

Selecting a slower than necessary speed for a given ink can result in slow and inefficient production. While printing at too high speeds will reduce the quality and yield of the product. Selecting the improper screen fabric for a job will produce uneven ink deposits and loss of quality and detail. Also, planned or accidental changes in viscosity during production will make standard operating procedure impossible and turn an otherwise efficient production method into an inefficient guessing game.

The screen fabric and the squeegee are to a certain extent the controlling parameters in viscous flow: the screen fabric determines the rate of shear; the angle of squeegee determines the shear stress within an ink. The rate of shear can be calculated from the mesh parameters and squeegee speed, since all these are known production data. By recording the setup parameters on squeegee speed and fabrics for a given ink, the effects of other squeegee speed and fabrics may be calculated. The shear stress within an ink can not be predicted from the production parameters, however change in the squeegee angles predicts the relative changes in shear stress, determined by the tangent of the angle [23].

The viscosity of an ink may be affected through temperature variations, the addition or evaporation of solvent, and length of storage time. By understanding rheology and the dynamic properties of inks, a number of unnecessary variables can be eliminated from production.

3.2 Types of Inks

All thick film inks used in hybrid microelectronics consist of a permanent inorganic content and a temporary organic vehicle. The inorganic material remains as a film after the firing process while the organic content is removed during the drying and subsequently during firing in the furnace. A typical firing profile is shown in the Figure 3-3 [59]. The inorganic content, largely metal and metal oxides, is present as a finely divided powder while the organic content is in the form of a viscous solution and the two are blended into a paint like consistency. The inorganic content varies considerably according to the type of inks, while the organic vehicles are basically similar for all inks. There are a number of special types of thick film inks available but the most important classes are conductors, resistors, and dielectrics, and these are discussed in the following sections.

3.2.1 Conductors

The primary requirements of thick film conductors are high electrical conductivity and strong adhesion to the substrate. The cost is another significant and often dominant factor. The many secondary characteristics include: [59]

- solderability
- suitability for bonding (ultrasonic, thermocompression, and eutectic)

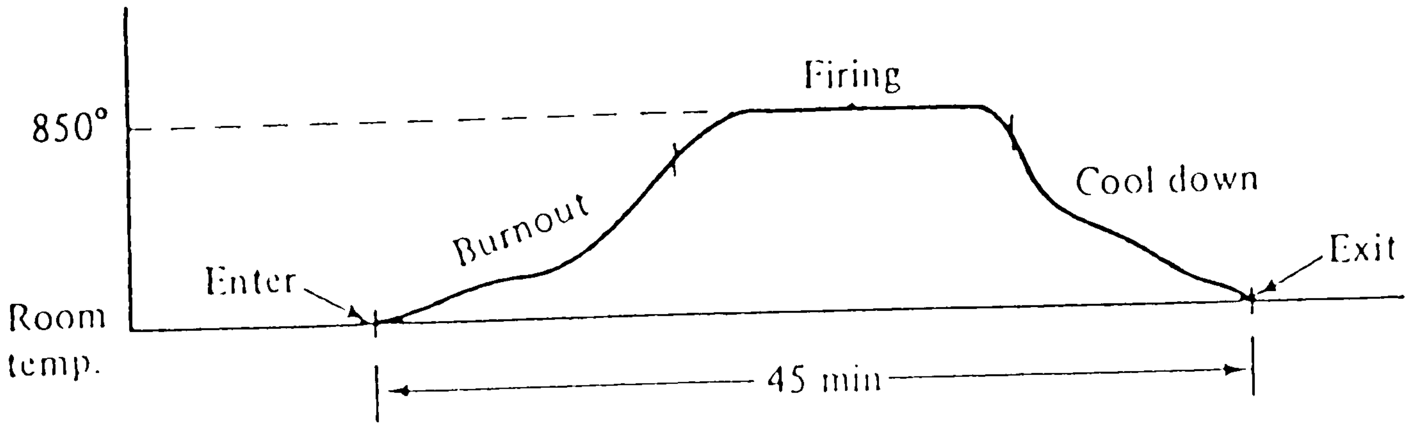


Figure 3-3: Typical thick film firing profile

- printing capability
- compatibility with other thick film inks and substrates
- processing conditions
- ageing characteristics

High conductivity is achieved by selecting a metal or alloy with a high intrinsic bulk conductivity and by maximizing densification during firing. Adhesion is achieved either by adding a small amount of glass in the ink (so called 'fritted' conductors) or else by the inclusion of certain metal oxides which react chemically with the metal and underlying ceramic (these are known as reactively bonded conductors) [56, 78]. The inclusion of these additives impairs the conductivity. In the case of fritted conductors, the structure of the metal at the interface should be porous so that the glass adheres with the conductor to the substrate. This also reduces conductivity. Thus in general it is not possible to maximize adhesion and conductivity simultaneously and a compromise has to be made. In a similar way there are trade-offs to be made in secondary characteristics and consequently a very large number of formulations, each offering advantages for certain applications have become commercially available.

Conductors may be conveniently classified according to metal or alloy

content. The salient feature of the main types are given in Table 3-1 [59].

3.2.2 Resistors

Resistive systems are perhaps the most complex of the thick film inks. The main technical challenge in producing a thick film resistor series is that of obtaining a wide range of resistance value with a low temperature coefficient of resistance (TRC), coupled with stability over long periods of time at elevated temperatures or on electrical load. This is achieved by arranging a conducting phase dispersed in a non-conducting phase (usually glass) in the fired film.

The choice of materials for the conducting phase is very restricted. Metals have very low resistivities and generally large positive temperature coefficients. Semiconductors have higher resistivities but generally large negative TCRs. Also, the conducting phase has to be chemically stable when exposed to the furnace atmosphere at high temperature and when in contact with molten glass. Ruthenium dioxide and related mixed oxides such as bismuth ruthenate are unique compounds they combine moderate electrical conductivity with a near-zero temperature coefficients of resistance [59]. These oxides are also stable in air at typical thick film firing temperature (about 800 °C). They are therefore the basis of the conducting phase in most successful thick film resistor systems used today, sometimes in combination with precious metals [3, 20]. A range of resistance value is obtained basically by varying the concentration of conducting oxides in the glass. The changes in conductivity results as the conductor to glass ratio is varied.

In order to obtain a very wide range of resistance value (up to 6 or 7 orders of magnitude) with low TCR (typically 200ppm/°C or less) the geometric distribution of the conducting phase in the glass matrix has to be non-random and carefully controlled [59].

Metal or Alloy	Principal Features
Silver	Very low cost. Highest conductivity, silver ion migration and tarnishing problems, seldom used in microelectronics. Migration occurs through glass as well as between conductors.
Palladium Silver	Low cost. Palladium inhibits migration but lowers conductivity.
Platinum Silver	Low cost. Smaller quantity of platinum replaces palladium in the binary alloy.
Gold	Very expensive. Highly conductive and chemically inert. Reliable bond to gold wire. High solubility in common solder makes soldering difficult.
Palladium Gold	Compared with gold the solubility in solder is reduced but conductivity impaired.
Platinum Gold	Very expensive. Reliable solderable alterative to gold but not so conductive.
Copper	Fairly low cost. Highly conductive. Has to be fired in neutral or reducing atmospheres to achieve excellent soderability.
Nickel	Very low cost. Can be fired in air but not solderable from the furnace.

Table 3-1: Conductor Inks and their Properties

The parameters that should be considered when selecting resistor materials are: [82]

1. Screenability (quality of the print and the degree of difficulty in obtaining good prints)
2. Passivation requirements (i.e., will the resistors need a protective coating?)
3. Firing requirements (e.g., reducing or oxidizing atmosphere, temperature profile)
4. Reproducibility
5. Stability (long-term changes in TCR, VCR, noise, and resistance)
6. Temperature coefficient of resistance (TCR)
7. Voltage coefficient of resistance (VCR)
8. Power density capacity
9. Cost
10. Trimability (ruthenium oxide materials are not easily trimmed by lasers)

The materials used are expensive and the manufacturing procedures are complex. Hence precious metal resistor inks are expensive. Some attempts have been made to introduce base metal resistor systems but most of these have to be fired in a neutral or reducing atmosphere and have rather inferior characteristics [54, 32].

3.2.3 Dielectrics

Dielectric films are used in hybrid circuits to provide insulation between successive layers of conductor, as capacitor dielectrics, and as a final protective coating. The properties and composition vary accordingly.

For multilayer hybrids and as an insulation the dielectric should have a low permittivity to minimize capacitive coupling between layers, and for use in high frequency circuits with low dielectric loss [59]. The most important factor of modern multilayer dielectrics, is that these materials can be re-fired several times without further flow so that fine details are not lost. This is generally achieved by the use of glass-ceramics which are present in the ink initially as glassy particles. They readily soften and sinter on heating, but then crystallize on cooling and cannot be soften by reheating to the same temperatures [19]. An alternative technique is to select the dielectric having a glass mixed with crystals of either alumina or silica which dissolve in the glass thus raising the softening temperature of the composite [55]. The glasses are typically based on lead boro-alumino-silicate systems and contain numerous minor additives to achieve the desired adhesion, flow, hermeticity etc. properties.

Capacitor dielectrics should have electric strength, a high permittivity and low loss. These three properties are not readily achieved in a single material. Low loss dielectrics of high electric strength and low permittivities are available for low value of capacitors. High permittivity materials on other hand have high losses and may have relatively poor breakdown strength. Many high permittivity dielectrics consists of ferroelectric crystals bound together with a small amount of glass. In order to maximize the permittivity, the glass content must be kept to a minimum and this tends to result in a somewhat porous structure. The effect of the air voids is highly significant and reduces the measured permittivity considerably and gives rise to poor electrical strength. Better results can be obtained with special glass ceramic materials which yield a ferroelectric phase when they devitrify [17, 9].

Overglazes consist simply of glasses which have reasonably low softening point (to avoid a final high temperature firing), good chemical durability, and a coefficient of expansion which reasonably matches that of the substrate.

It is important in the formulation of thick film dielectric inks to avoid the use of any material that might be mobile in the dielectric, particularly when under the influence of electric fields.

Chapter 4
Thick Film Processes

4.1 Screen Printing

The object of screen printing is to deposit a film of ink of predictable dimensions on a ceramic substrate. Screen printing is still somewhat an art when compared with other processes in that skill and judgement plays a large part in achieving good results. Screen printing determines the accuracy of the printed pattern and subsequently the accuracy of such geometry-dependent devices as resistors. Many problems with finished circuits can be traced to the screen printing process.

There are two basic methods of screen printing,

- off-contact printing
- contact printing

In off-contact printing, the most widely-used method, only one portion of the screen, the portion directly under the squeegee, is in contact with the substrate during the printing process. In contact printing, the entire screen is in contact with the substrate during the complete pass of the squeegee.

Before any circuit can be produced the electronic design based on the circuit diagram has to be translated into a physical layout.

4.2 Layout and Art Work [83, 59, 8]

The starting point in the design of thick film hybrid circuits is the layout, which the designer develops from a schematic of the circuit. The layout is usually drawn at a scale of either ten to one or twenty to one. The most commonly used material for making the artwork masters is rubylith or stabilene, a clear mylar sheet covered with a red film. The areas of red plastic are removed to define the pattern [83].

The object of the design layout is to produce a set of artworks from which the substrate can be fabricated. The routing of interconnects, dielectric areas for crossover and resistor dimensions must be detailed taking into account value, tolerance, stability, power dissipation and terminating of conductor material.

Drawings of the layout are produced at this stage for all subsequent fabrication, assembly and testing operations. Computer Aided Design (CAD) can be used to speed up the design process and produce all manufacturing documentation.

A cut and peel rubylith artwork is produced either manually or using machine for each layer of the circuit, sealed typically to five times final size in order to obtain sufficient accuracy for registration between each layer. Photographic reduction is used to produce the master artwork of high contrast film. Master artwork could be either of glass or of Mylar, depending on the tolerances and permanency required. Mylar tends to change dimensionally with time, whereas a glass master exhibits excellent dimensional control over a long period of time. The master artwork should be stored flat to prevent scratching, under controlled humidity and temperature conditions [59].

An alternative method for producing artworks directly, the photoplotter, is now used more frequently. The photoplotter can accept dimension information from the CAD system and translate this information into the movement of an X-Y table. Patterns defined on a mask are projected as appropriate onto high contrast film mounted on the X-Y table. Hence the master artwork can be produced automatically by *writing* the necessary shapes directly onto film.

Computer aided design (CAD) tools for hybrid circuits have improved greatly over the last few years. Using CAD effectively for hybrid circuit design requires a hybrid-specific CAD system that supports the wide range of geometric shapes and interconnect schemes typical of hybrid designs. Such system could eliminate days from design cycle and also provide a data base of parameters for use in laser-assisted hybrid production. Figure 4-1 summarizes the potential time savings. Figure 4-2 supports the time savings with a flow chart comparison of thick film hybrid generation without CAD, with CAD, and with direct laser screen generation [8].

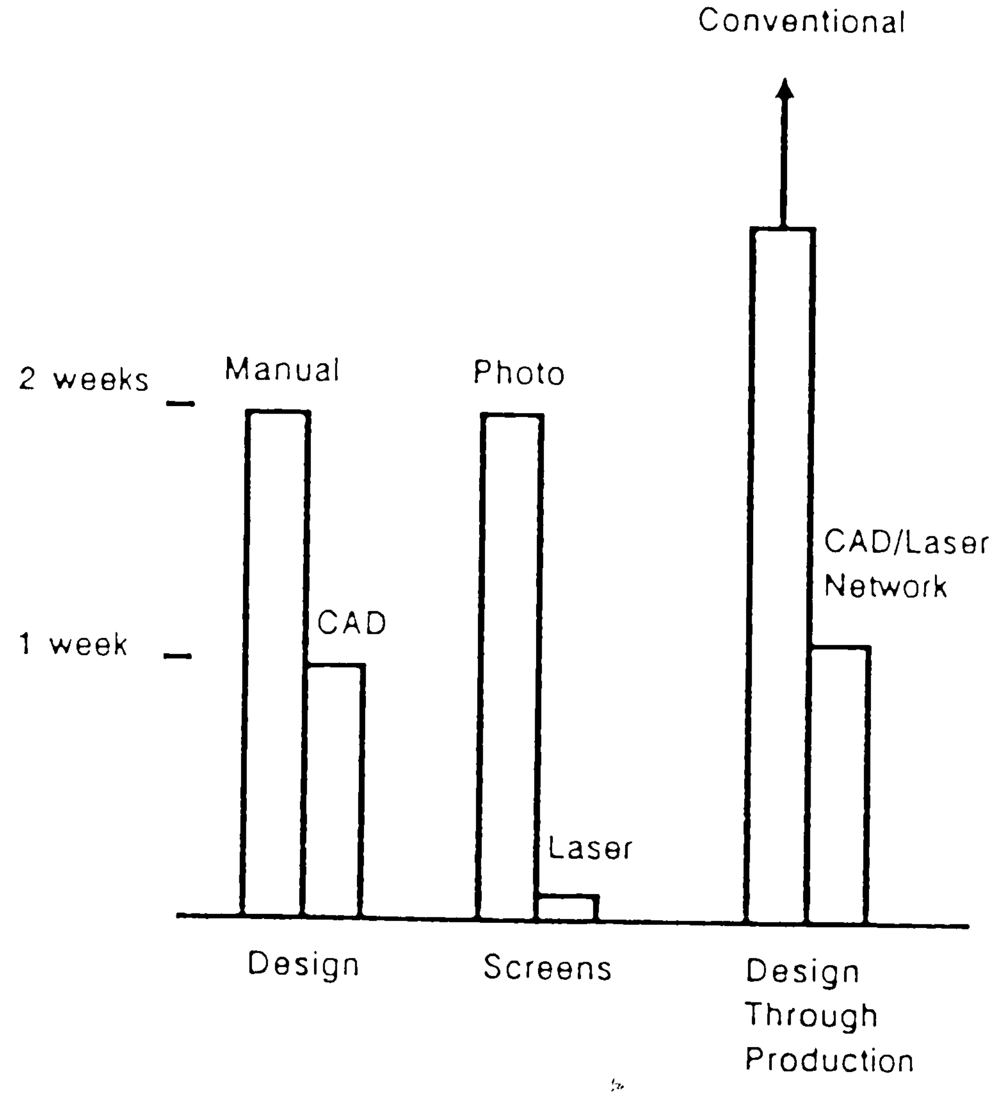


Figure 4-1: Typical time spent for creating 2x2 inch hybrid

Thick film substrates are fabricated by a screen printing process but before printing can be undertaken a screen defining each pattern must be produced.

Thick Film Hybrid Generation Flow Chart Comparison

Without CAD	With CAD	With Direct LaserScreen Generation
• Hand drawn schematic	• Schematic drawn on CAD workstation	• Schematic drawn on CAD workstation
• Artwork layout at 10X magnification	• CAD-assisted hybrid design layout and output to photo-plotter as S&R pattern if desired	• CAD-assisted hybrid design layout and output to laser screen exposure system, as S&R pattern if desired
• Photoreduction to 1X to to create master mask • Step and repeat for multi-up substrates	• Photoreduction to 1X to create master mask	• Laser exposure of thick film screen
• Develop and etch chrome mask	• Develop and etch chrome mask	• Screen printing each layer of hybrid
• Contact UV exposure of thick film screen emulsion	• Contact UV exposure of thick film screen emulsion	
• Screen printing each layer of hybrid circuit	• Screen printing each layer of hybrid circuit	
Subnotes:		
Without CAD Total time approx. 1 week minimum, depending on circuit complexity.	*With CAD* Considerable time saved by using CAD. Simpler data storage and easier to make modifications.	*With Direct Laser Screen Generation* Same as with CAD, but total time is only minutes longer than it takes to lay out the circuit. Trim and scribe parameters are already entered.

Figure 4-2: Thick film Hybrid generation flow chart comparison

4.3 Screens [83, 74, 24, 25, 80, 73, 1, 71]

Screen is a term primarily to a completer printing screen, including frame, fabric, and stencil [1]. In practice, the importance of the screen to high-quality, high-precision printing is not always self-evident, but designing and planning for thick film screen printing starts with the understanding of the interrelationships between the screen components and their effects.

The frame is one of the components of the complete screen. The size of the frame is based upon the dimension of the pattern, the screen printer, and the substrate. The function of the frame is to support the fabric and to prevent any distortion that might result in loss of tension and registration. Frames suitable for thick film applications are typically cast iron with top and bottom surfaces machine-ground to attain flatness and parallelism of $\pm$ 0.002 in. [40]. The frames are drilled and tapped for attachment to the screen printing machine. (Figure 4-3)

4.3.1 Screen Selection

There are four types of screens available: [83]

1. Direct-emulsion screen
2. Indirect-emulsion screens
3. Suspended metal masks
4. Solid metal etched masks

The most widely used are the direct-emulsion screens. The screen material (referred as fabric) most often used in thick film printing applications is stainless steel. Although other fabrics are available, including polyester, metallized polyester, and sometimes nylon, stainless steel is usually selected for its superior chemical and abrasion resistance, tensile strength, dimensional stability, and favorable relationship between the wire size and the correspond-

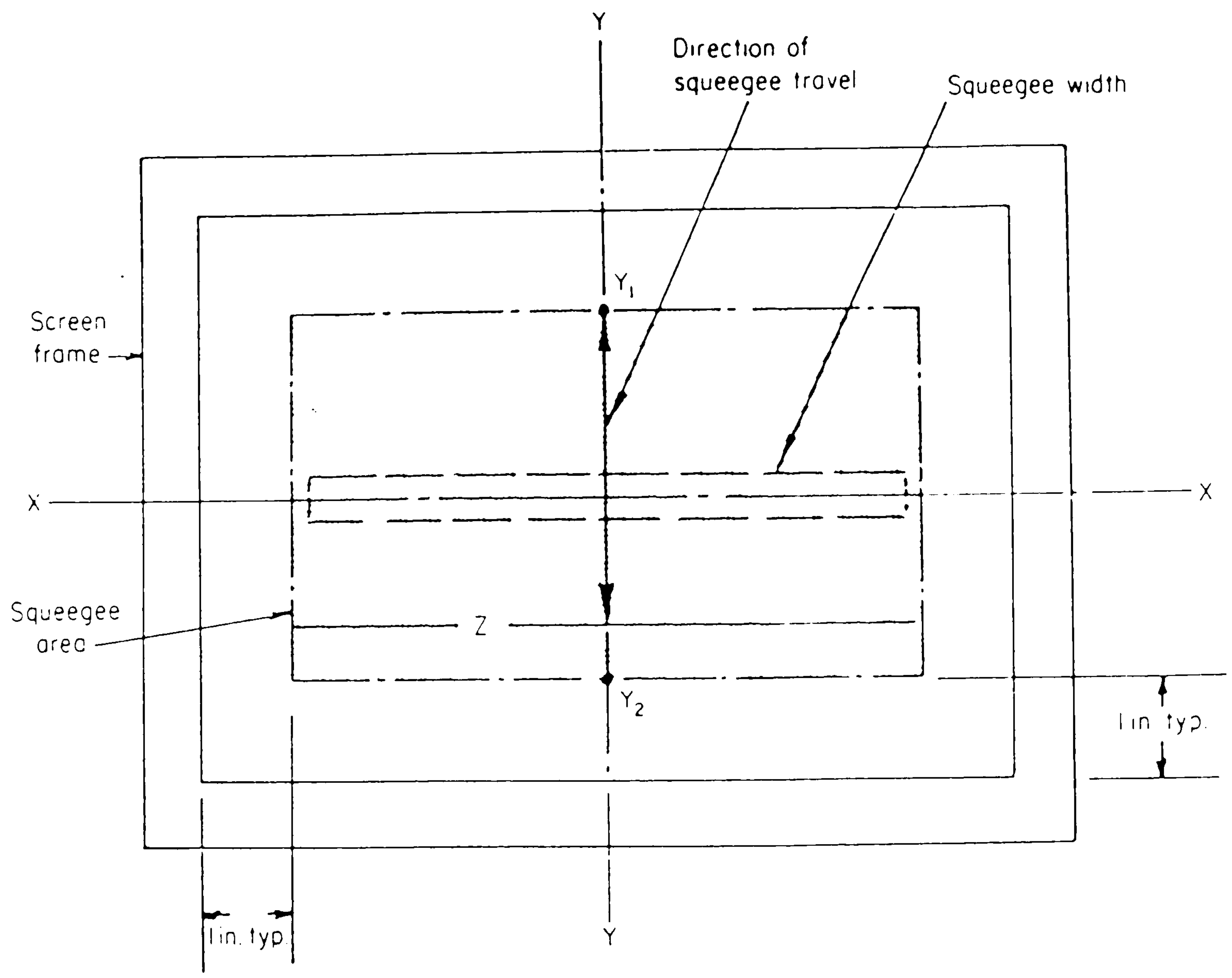


Figure 4-3: Reference Axes for Screen

ing mesh openings [40].

The screen fabric is the primary control for determining the thickness of the ink deposited on a substrate. It also plays an important role in ink flow and printable image resolution. The physical dimensions of the screen fabric, such as mesh count, mesh opening, thread diameter, and fabric thickness, are important in calculation of some screen printing parameters. Ink-film thickness (or wet film thickness) and image resolutions are the two most important production parameters which can be predicted if the fabric dimensions are known. Other fabric-related production parameters that may significantly affect the printing are viscosity, ink-particle size, and strength of fabric itself [25].

The screen is fabricated by stretching a fine stainless steel mesh fabric over a cast aluminum frame and either epoxying or clamping the mesh to the frame. The screen parameters of most interest are: [74]

- Mesh angle
- Frame size
- Fabric mesh size
- Screen tension

When the fabric is stretched, it is usually oriented so that the wires are parallel to the frame, the angle of attachment is said be to 90°. Alternative angles, such as 45°, 30°, or 22.5° may be selected in order to eliminate interference of the strands with the printed image. Mounting the fabric at an angle other than 90° will also lengthen the screen life by reducing the amount of stress caused by the squeegee during the print stroke, as the stress will then be distributed among more wire strands [40].

Fabric mesh size is measured by the number of wires/unit length. Mesh counts vary from 80 wires/in. to 400 wires/in. in discrete steps. The most common sizes are 200 mesh used for conductors, resistors, and dielectrics. In general, the finer the mesh (more wires per unit length), the thinner the print and more precise the line definition For example: For very narrow prints of 3 to 5 mils, it is necessary to use a 400 mesh (157.5 wires/cm) fabric, and also mesh angle should be 45 ° [74].

The selection of a particular mesh size for a particular application is based upon the following consideration: [40]

1. Fine resolution in pattern
2. Maximum particle size in the ink to be screened
3. Ink viscosity
4. Desired print thickness

Screen tension is extremely important in maintaining consistency in the screen printing process. The most common method of measuring the tension is to measure the deflection which is a standard weight produces on a screen. A 1 lb. weight will typically cause a 50 mil deflection in a 200 mesh screen and a 65 mil deflection in a 325 mesh screen when stretched over 5x5 in. frame [74].

4.3.2 Screen Preparation

Cosistent off-contact screen printing requires a screen with an even coat of emulsion with no pinholes and a pattern with a sharply defined edges. Further, mesh within the pattern must be free of particles which can cause gaps in the printed film.

Screen preparation consists of the following basic steps. The flow chart is shown in Figure 4-4.

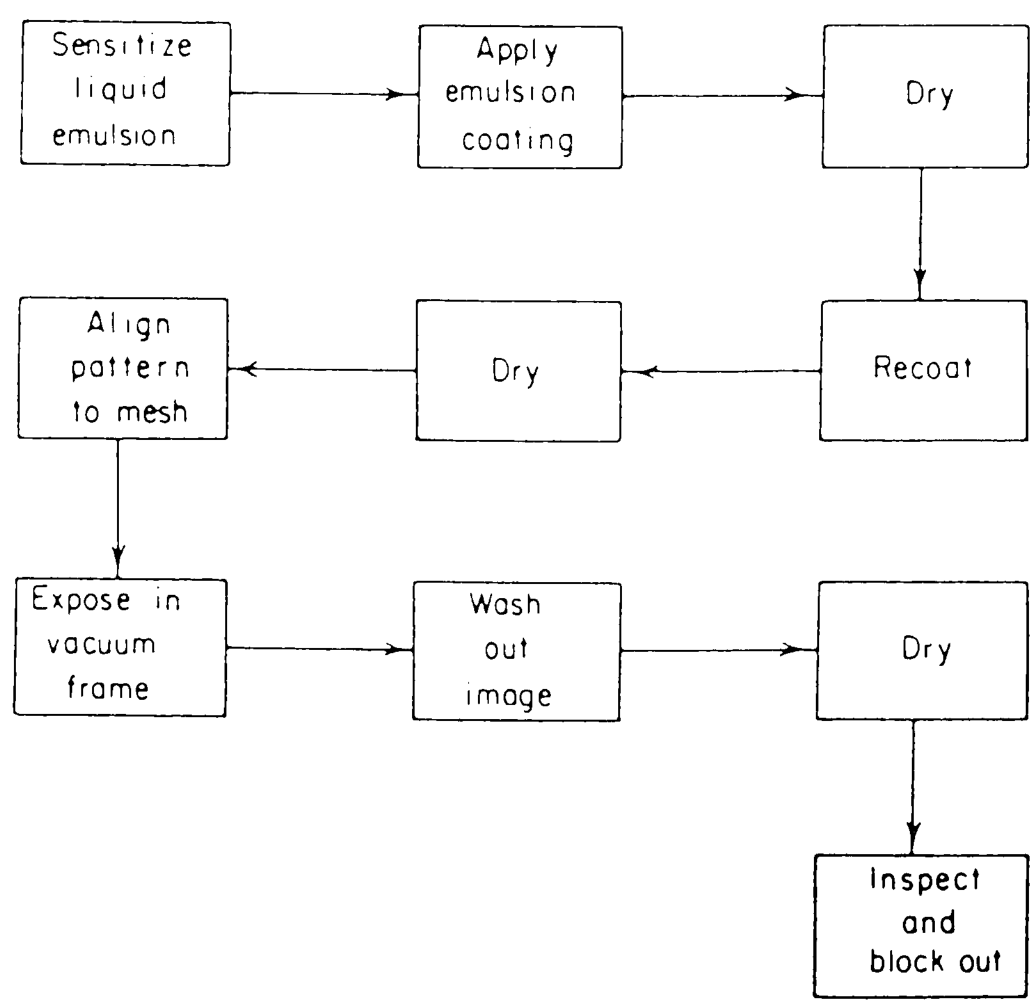


Figure 4-4: Flow Chart for Screen Making Process

1. tensioning and stretching the fabric to the frame
2. cleaning the fabric
3. coating
4. applying the stencil
5. exposing
6. developing and washing out
7. drying
8. touching up, and
9. tapping the screen

The screen must be cleaned thoroughly before applying the photosensitive emulsion. This may be accomplished by washing with a mild detergent, rinsing thoroughly with water, and rinsing with isopropyl alcohol. After washing, the screen is blown dry with clean air or dry nitrogen and baked at 100 °C for 15 minutes.

The photosensitive emulsion may be applied by two methods: by using a liquid emulsion poured directly on the screen (the *direct* process) or by using a film which is sensitized after being placed on the screen (the *direct-indirect* process).

When using the liquid emulsion, scotch tape is placed around the bottom of the screen, just inside the frame to achieve a consistent thickness of film. A small amount of emulsion is poured on the bottom of screen. Using a flat piece of metal, emulsion is spread over the bottom of the screen until scotch tape barrier is evenly filled. The excess emulsion may be allowed to drip onto next screen to be coated. The emulsion is then dried as per manufacturer's instruction and the tape is removed. Thicker emulsion may be formed by repeating the process.

It is very important to achieve a uniform, reproducible thickness of emulsion on the screen, as this affect the thickness of the printed pattern. The advantage of the film technique is that the thickness is constant and eliminates operator's skill factor.

Stencil, (a photographic film with desired circuit artwork developed on it [80]), then is placed on the dried emulsion. The alignment of screen fabric and stencil is important to place stencil in the center of the frame.

The screen then is exposed to ultraviolet light for the predetermined time. The unexposed photosensitive emulsion may be washed away with a fine spray of water. The washed screen then is dried by placing in the drying cabinet which may have a filtered air circulating system with or without applied heat.

The blockout liquid is used to cover the mistakes, pinholes, and other defects, if any, in exposed and developed screen. The final sealing of the screen fabric where it joins the frame is done as a final step before inspection. The completed screen then is inspected and is ready for use.

The essence of screen preparation is presented pictorially in Figure 4-5

4.4 The Screen Printing Process

The screen printing procedures used in the fabrication of thick film hybrid circuits are very similar to the techniques used in the graphic are industry. In the ideal screen printing process, the object is to completely fill the pattern on the screen with ink during the squeegee pass and to leave all the ink on the substrate in the exact pattern as on the screen after the squeegee passes. A printed pattern formed in this manner has a uniform, predictable thickness. (Figure 4-6) Figure 4-7 illustrates the flow chart of the screen printing process.

The quick, accurate positioning of the substrate on the printer is very essential. This is often accomplished with three-pin alignment. The alignment pins, usually made of hardened steel, should have good wear characteristics, and have a completely flat surface to insure that the screen and the substrate are kept parallel during the printing process. In three-pin alignment, one pin is

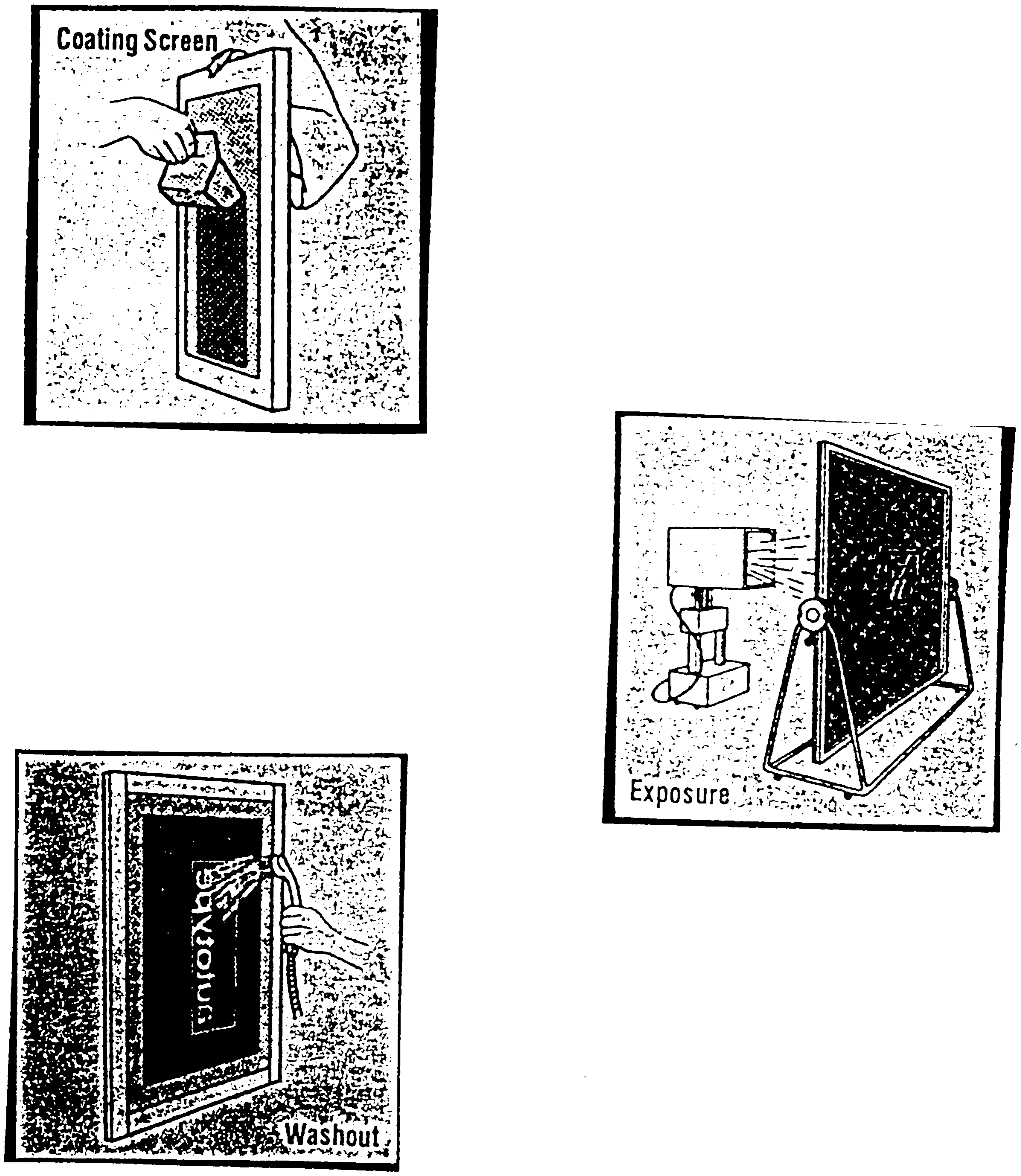


Figure 4-5: Screen making process

centered on the short dimension of the substrate if there is one, and other two pins are located at one-quarter and three-quarter of the length on a perpendicular side. The substrate is usually held in place by vacuum hold-down. (Figure 4-8) When a large volume is required, it becomes necessary to load the screen printer automatically from magazines. The printer can be unloaded ei-

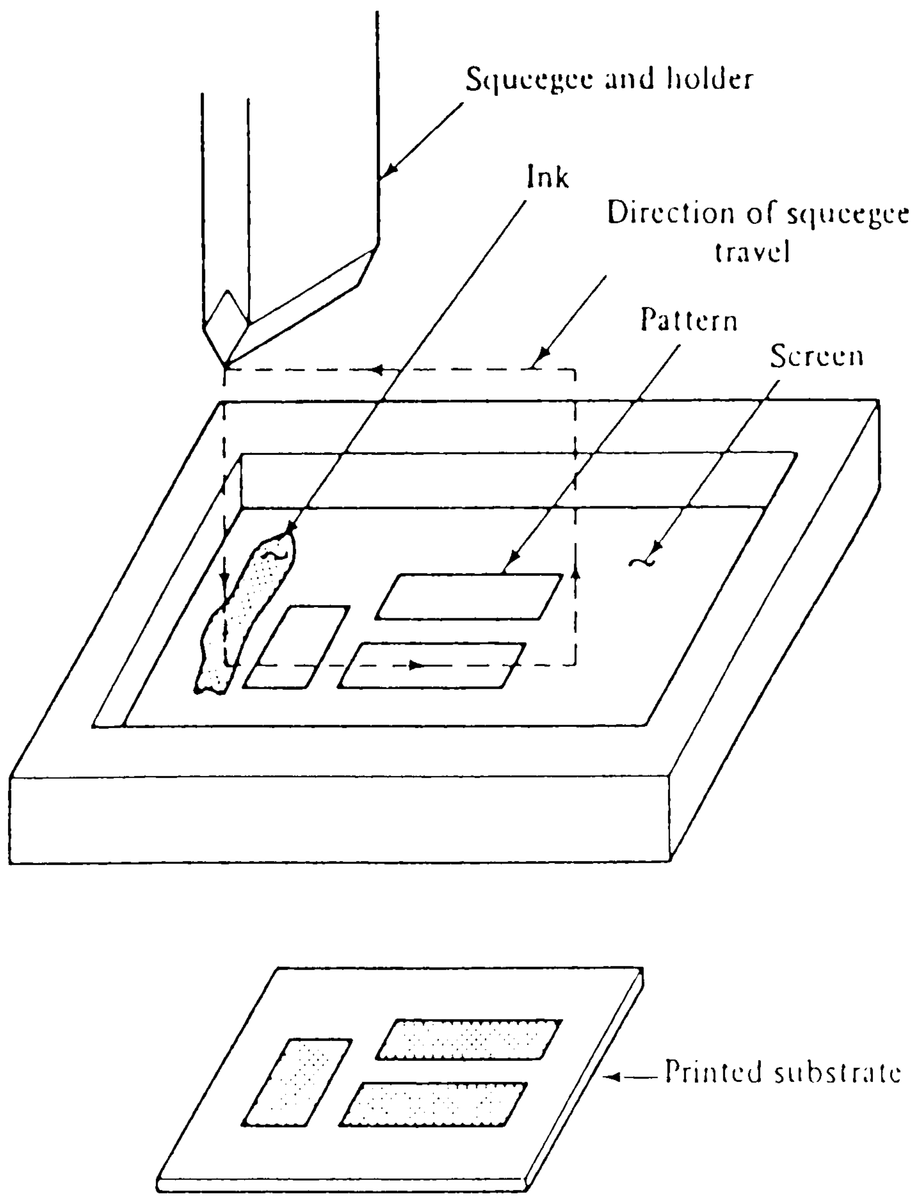


Figure 4-6: Screen Printing Process

ther into a magazine or directly onto a conveyor belt which goes to the drying system.

When the substrate is held in place, sweeping of squeegee forces the ink through the pattern in the screen, and image is printed on the substrate. (Figure 4-9) As the squeegee moves over the pattern in emulsion, ink is forced to fill the openings in the screen. The ink is transferred to the substrate by one of the two methods. The methods of transferring inks are: [74]

1. If contact printing is being used, either the substrate mounting

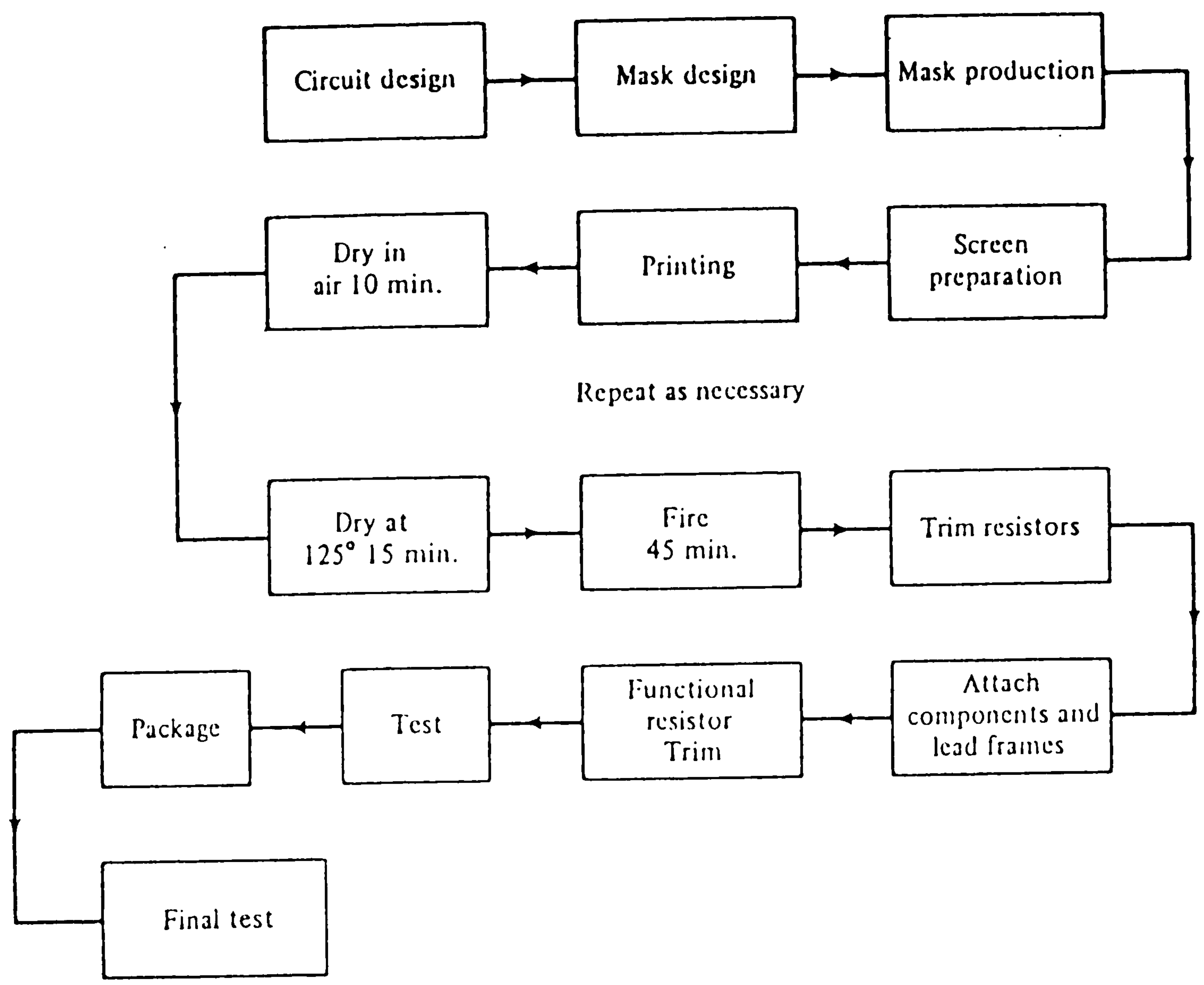


Figure 4-7: Flow Chart for Screen Printing Process

platform is suddenly dropped or the screen is suddenly raised, (operation referred to as *snap-off*). The shear force of moving the screen mesh easily separates the ink particles, leaving the ink pattern on the substrate.

2. If off-contact printing is used, the screen is mounted on a certain distance away from the substrate, called the *snap-off distance*. As the squeegee passes the screen pattern, the screen is stretched until it comes in contact with the substrate and ink is forced through the openings in the mesh. After the squeegee passes, the tension in the screen causes it to *snap-back*, leaving the ink on the substrate. This process described in Figure 4-10.

The choice of squeegee design and material is critical. The material must be compatible with the resins and solvents used and not to be subject to swell, excessive wear and distortion. The most common materials that meet these re-

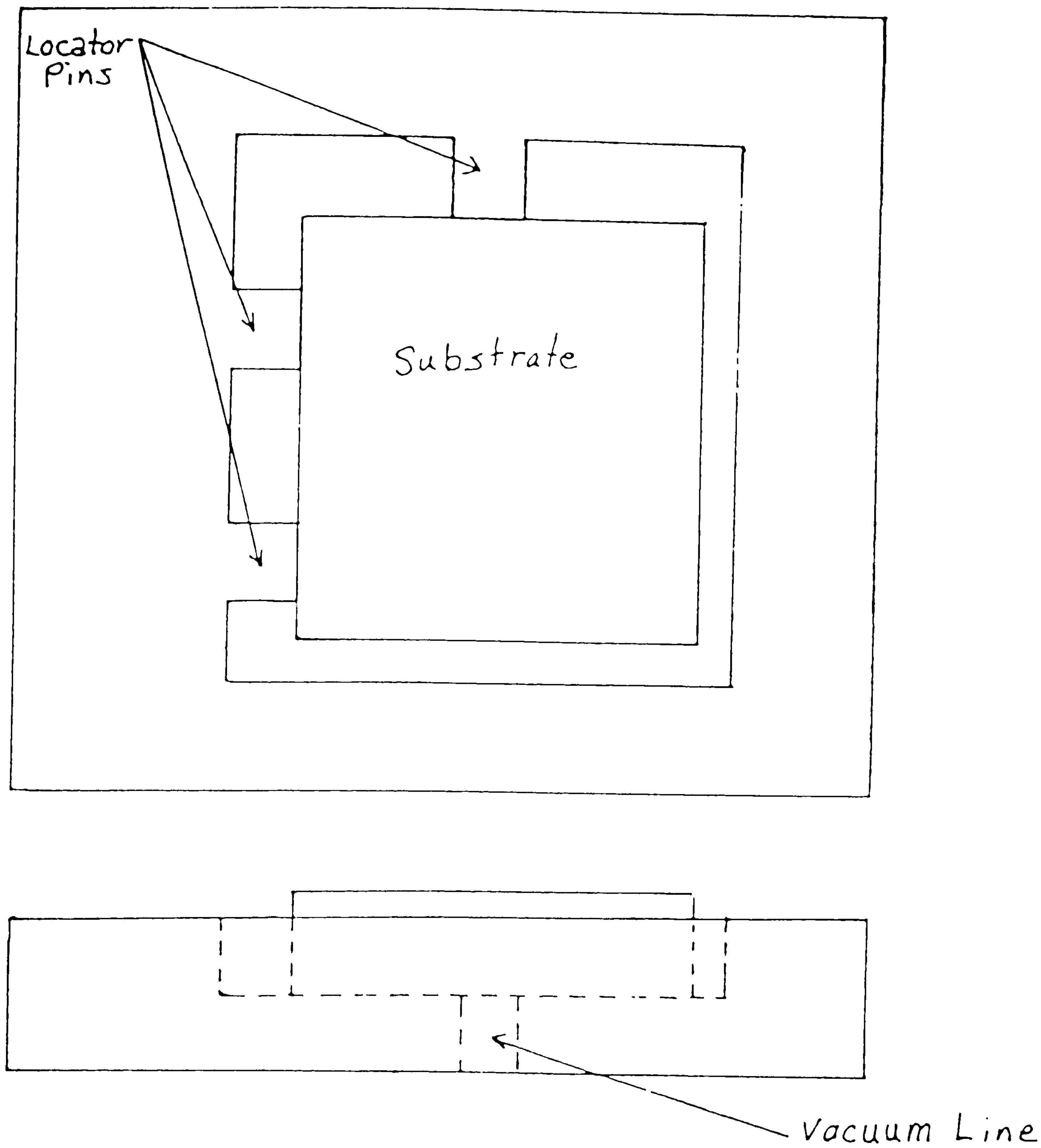


Figure 4-8: Three pin arrangement

quirements are neoprene, polyurethane, and Viton, later two presently appear to be the most commonly used materials. The hardness of the material is usually between 50 to 90 durometer. The choice is rather subjective; a more pliable squeegee will be allowed to conform to the irregular printing surface more readily while the harder material, 80 to 90 durometer, should be used to main-

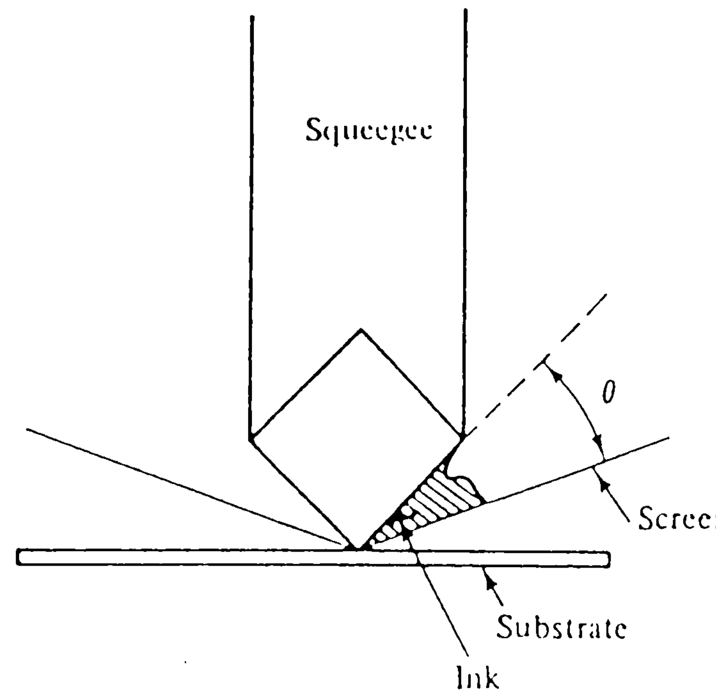


Figure 4-9: Ink being Printed

tain a constant attack angle, cut off the ink sharply, clean the screen surface, and provide longer life [39].

The shape of the squeegee also depends on attack angle considered. The main purpose of the squeegee is to present an even, sharp edge to the screen, the angle generally being 45 ° to 60°. This pushes a roll of ink ahead of the squeegee, creating a pressure which forces the material through the screen mesh. The sharp edge of the squeegee deflects the screen ahead of it and allow for a sharp breakaway and more printing accuracy in off-contact printing [39]. (Figure 4-11)

Pressure is applied to the squeegee by dead weight, spring loading, or pneumatic cylinders. The most common method is pneumatic cylinder. The pressure applied to the squeegee affects both the definition and uniformity of the print achieved. The exact pressure for the best results depends on the ink vis-

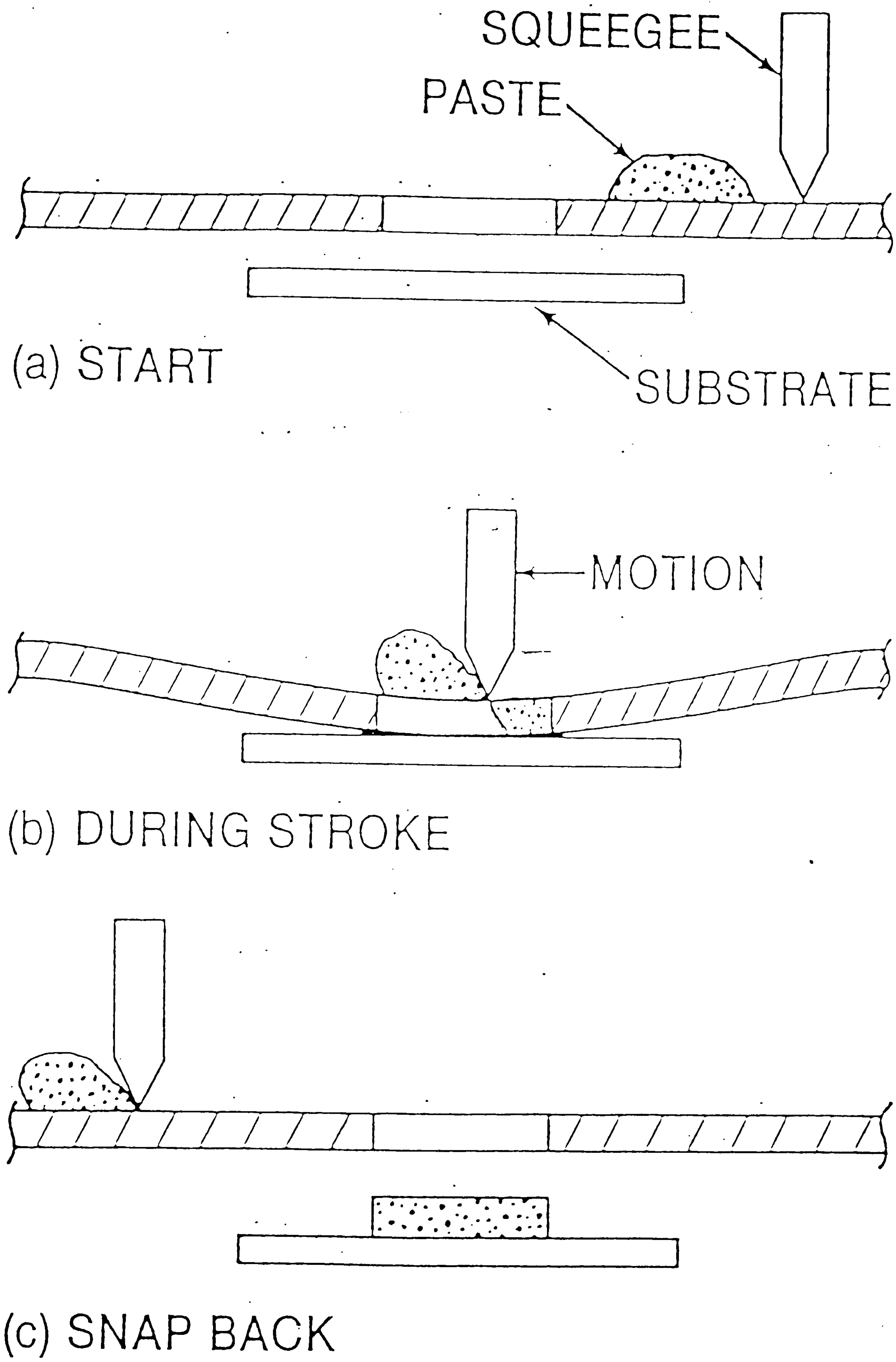


Figure 4-10: Off-Contact printing

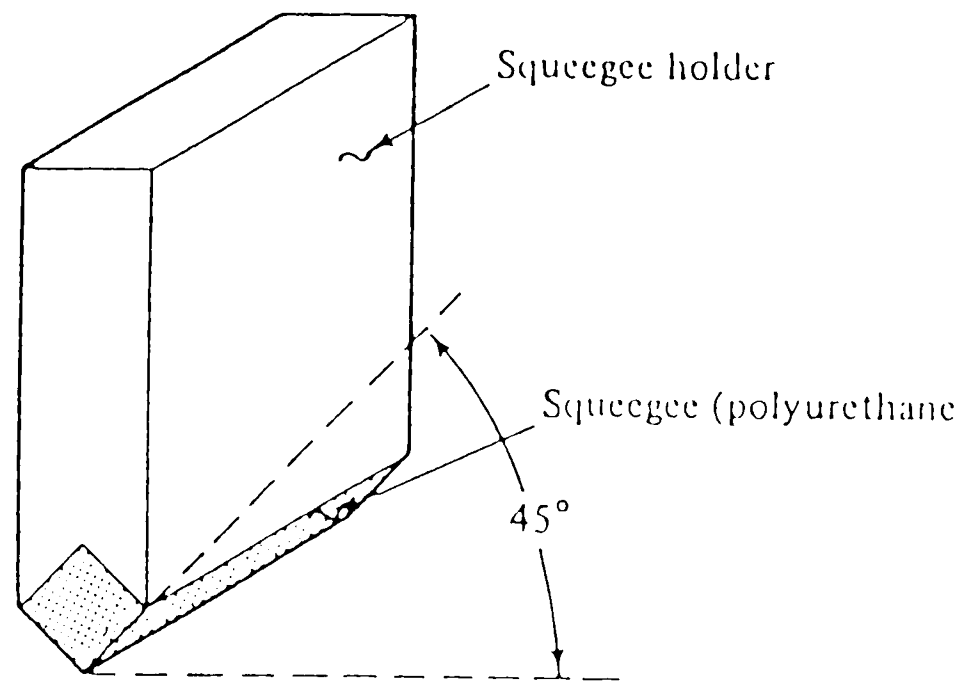


Figure 4-11: Squeegee Configuration

cosity, the screen tension, and the snap-off distance. The range of pressure is 1 lb per linear inch of squeegee and should be determined. Too much pressure would substantially reduce the life of squeegee. In order to prevent overtravel of the squeegee, a mechanical stop is also provided in most printers [39].

Squeegee travel is as important as squeegee pressure. Slower speed generally require higher pressure. Many methods are used to move squeegee across the screen, air cylinders being the most common. The primary objective is smooth, uniform travel as uniformity is required within a lot and in print thickness. Single-direction printing requires some method of returning the ink. This is generally accomplished by means of a flood blade which spread the ink for the next printing operation [39].

In practice, screen printing often deviates from the ideal process described earlier. This deviation usually manifests itself itself in three ways: [74]

1. *The screen pattern does not completely fill with the ink, leaving either gaps in the printed pattern or a pattern is somewhat thinner than desired.*
2. *The ink pattern is not completely transferred to the substrate after snap-back, leaving ink in the screen mesh and resulting in an uneven pattern.*
3. *The printed pattern is somewhat distorted. The dimensions of the pattern may not conform to those of the emulsion pattern on the screen, the thickness of the printed pattern may not be uniform, or the edges may be ragged or scalloped.*

There are many variables which affect the printed printed pattern. These can be divided into five basic categories: [74]

1. The rheological properties of the ink.
2. The setting on the screen printer.
3. The geometry of the pattern in the emulsion on the screen.
4. The size of the screen mesh.
5. The substrate

Rheological Properties of the Ink/Paste

The viscosity of the ink determines to a large extent the quality of the printed pattern. Generally speaking, for a given printer setup, ink with low yield point will result in thinner printed pattern. Thinners may be used to change the yield point of the ink without changing the shape of the viscosity curve. The appropriate thinner is recommended by the manufacturer. One point to note that a little thinner goes a long way. Once thinner has been added to the ink, it is very difficult to get it back to its original consistency. Therefore, if the printed films are thicker than desired, it is better to make adjustments to the screen printer controls to obtain thinner pattern before attempting to thin the ink.

Screen Printer Adjustments

The setting of the screen printer which most affect the pattern quality are: [74]

1. Snap-off distance and parallelism between the screen and the substrate,
2. Screen tension, (Figure 4-12)
3. Squeegee speed,
4. Squeegee pressure and angle of attack of squeegee blade.

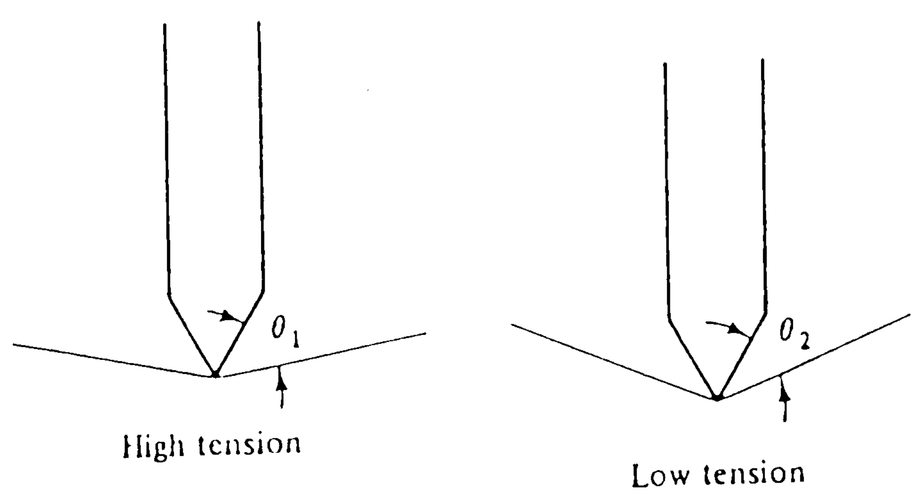


Figure 4-12: Comparison of High and Low Screen Tension

Snap-off (a preset distance between the screen and the substrate to be printed) is probably the most critical adjustment on the screen printer. If the snap-off distance is too small, ink will remain in the screen mesh after printing due to insufficient tension and the printed pattern will be too thin and will also tend to have gaps. If the distance is too great, it will require excessive squeegee pressure to deflect the screen, the print will be too thick, and screen life will be shortened. The screen must also be absolutely parallel to the substrate to insure uniformity of printing from one side of the substrate to the other.

Squeegee speed represents a fine control by the operator over print thickness. In general, increasing squeegee speed will decrease print thickness. If the speed is too fast, gaps will occur in the printed film [74].

Squeegee pressure is usually increased or decreased by lowering or raising the squeegee mount, respectively, and allowing the deformation of the squeegee material to provide the pressure. Increasing squeegee pressure will increase the print thickness and will compensate for ink with a high yield point. However, increased pressure will force ink between the screen and substrate resulting in a print with scalloped edges and loss of line definition. As a further consequence of excessive pressure, severe coining of the screen may occur at the substrate edge as the squeegee passes [74]. (Figure 4-13)

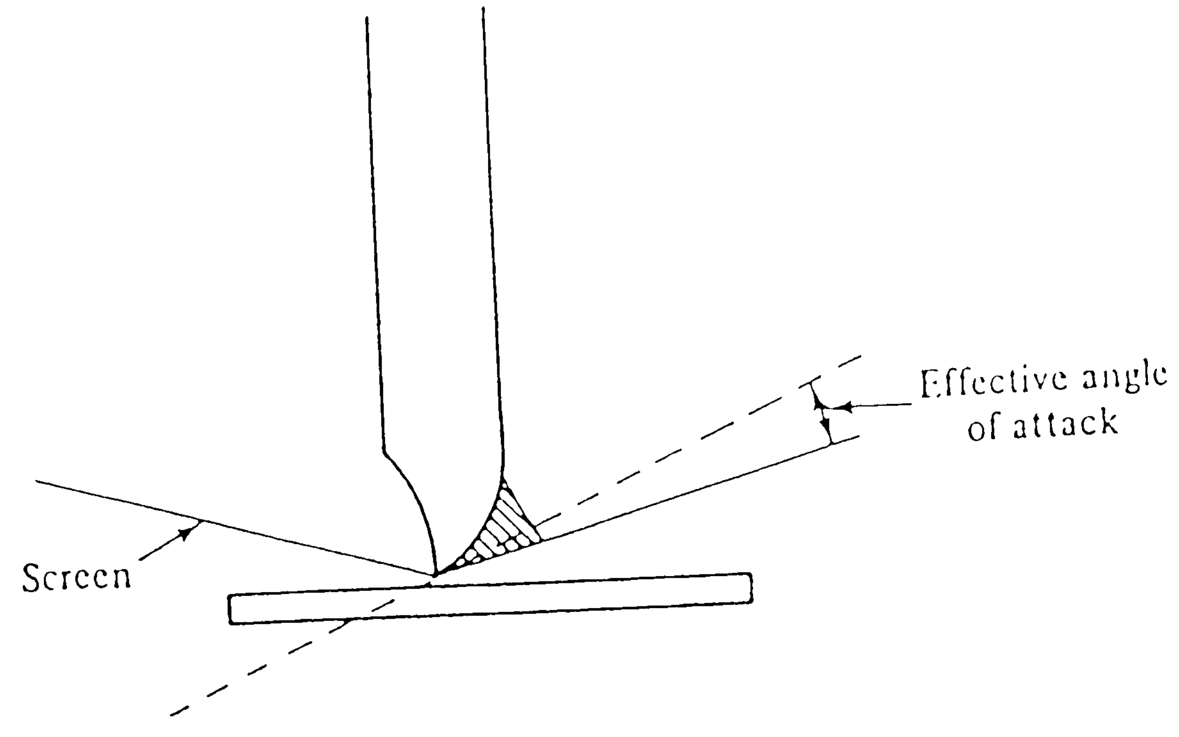


Figure 4-13: Squeegee Tip Deflection

To a certain extent, the effect of increased squeegee pressure may be duplicated by increasing the *angle of attack* of the squeegee blade. The increased angle increases pressure on the ink without increasing pressure on the screen, and will result in thicker print. A worn squeegee blade will give similar results to decreasing the angle of attack [74]. (Figure 4-14)

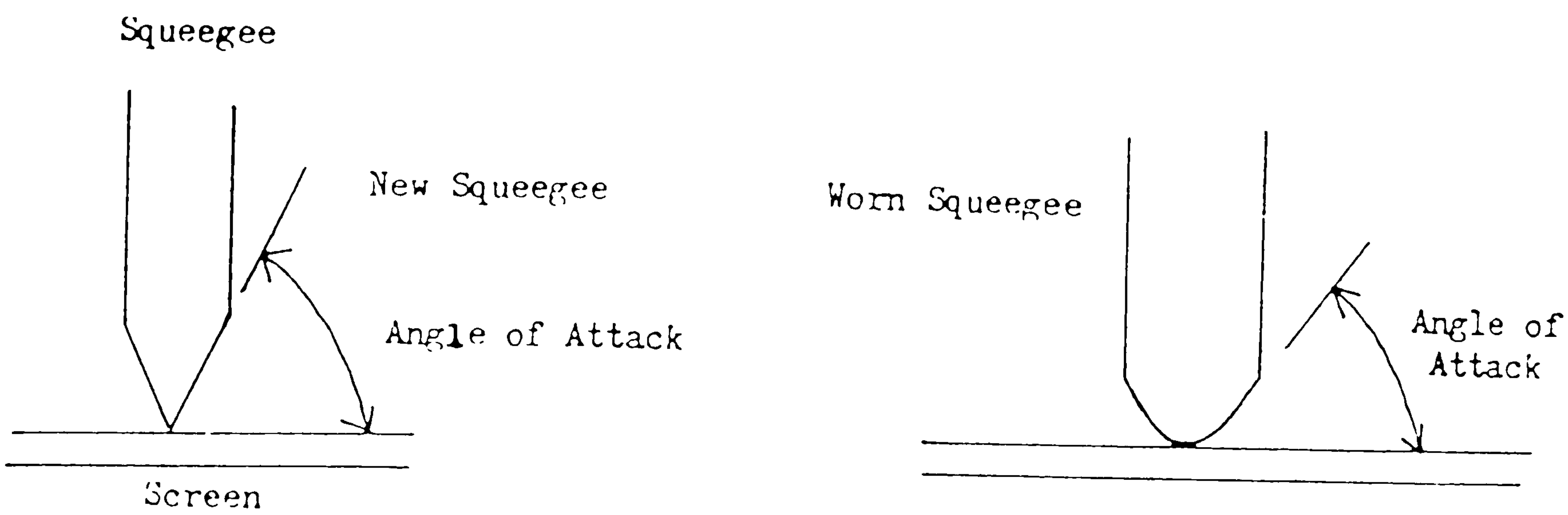


Figure 4-14: Decreased Angle of Attack

To produce very consistent results, the following screen printer setup procedure is suggested [74].

1. *With the screen out of the printer, the squeegee installed, and a substrate in the substrate mounting platform, lower the squeegee until it touches the substrate.*
2. *Level the squeegee to the substrate by the appropriate method. Squeegee level may be checked by placing a thin piece of paper between the squeegee and the substrate and checking uniformity of pressure.*
3. *Lower the squeegee three mils below the level of the substrate. This insures that the printer will make a reasonable print the first time and only minor adjustments will be required.*
4. *Install the screen, level it and adjust the snap-off distance.*
5. *Adjust the squeegee speed as fast as possible consistent with good printing.*

Adjustment in the thickness of the print may then be made by minor changes in the pressure and/or speed.

Pattern Geometry

The dimensions and orientation of the pattern in the emulsion both affect the dimensions and the printed pattern, as well as the thickness. The thickness of emulsion is not as significant, although it does affect the thickness to a certain extent [74].

The screen printing of thick films is basically an extrusion process in that ink is trapped in the screen and emulsion and extruded onto the screen by the squeegee. Up to a point, a thicker emulsion will, therefore, produce a thicker print. The ink trapped in the mesh is the more important factor, than the thickness of the photoemulsion.

The initial alignment of the pattern on the photosensitive emulsion to the mesh is necessary to obtain sharp lines on the printed film. Prior to exposure, the line edges on the emulsion film are aligned with the wires on the screen under a magnifying glass. (Figure 4-15)

Screen Mesh Size

A screen with a small mesh size (fewer wires/length) uses larger wire and has a larger opening than a screen with a large mesh size. Further, the ratio of open mesh area to total screen area is somewhat larger for a screen with a small mesh size and more ink may be trapped in the mesh openings. Therefore, a screen with a small mesh size will produce a thicker print than one with a larger mesh size.

The Substrate

The major property of the substrate which affects the screen printing

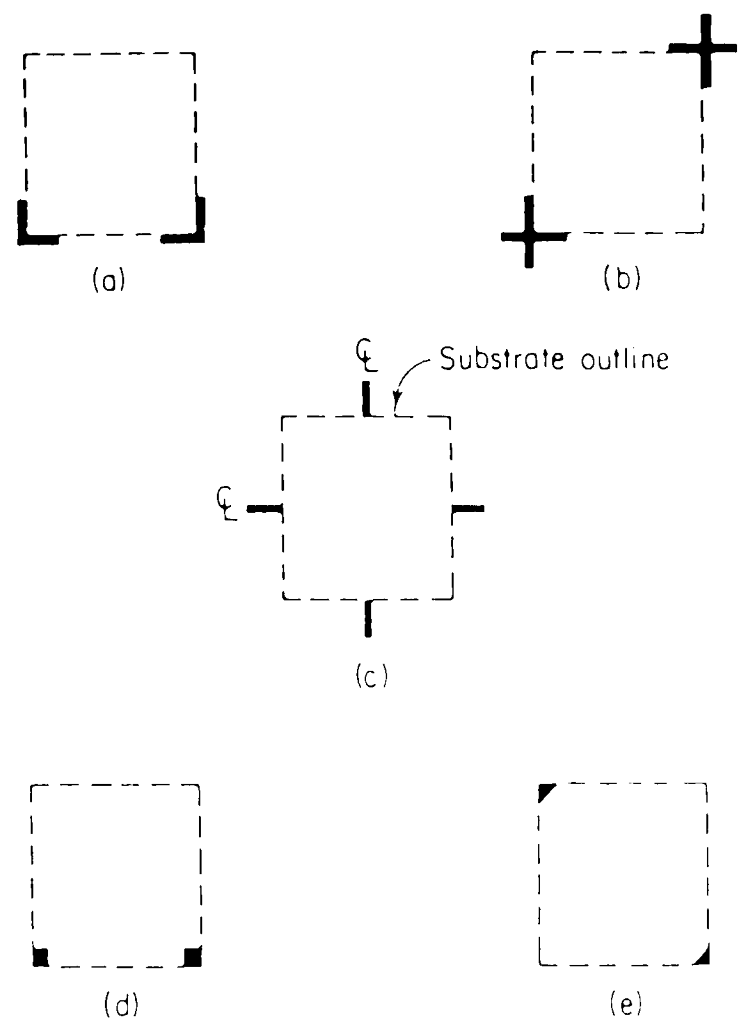


Figure 4-15: Substrate Registration Marks for Positioning

process is camber. Even a very slight camber can result in uneven printing across the substrate. A floating squeegee head can compensate for some problems caused by camber [74].

The most common screen printing process is ***off-contact screen printing***. There are two types of off-contact systems available on screen printing equipment: fixed off-contact and automatic peel (Figure 4-16). Fixed off-contact (or snap-off) distance means that the distance between the screen and the substrate can be adjusted to any value, but once set, it remains fixed at that value during the printing. In addition, a properly set-up screen with a fixed off-contact will always be parallel with the substrate. The automatic peel, on the other hand, involves a mechanism that lifts the screen away from the substrate during printing, thereby continuously changing the angle between them. The initial setting of the automatic peel mechanism determines the rate of screen/substrate separation and it has nothing to do with parallelism, which in most cases can not exist [25].

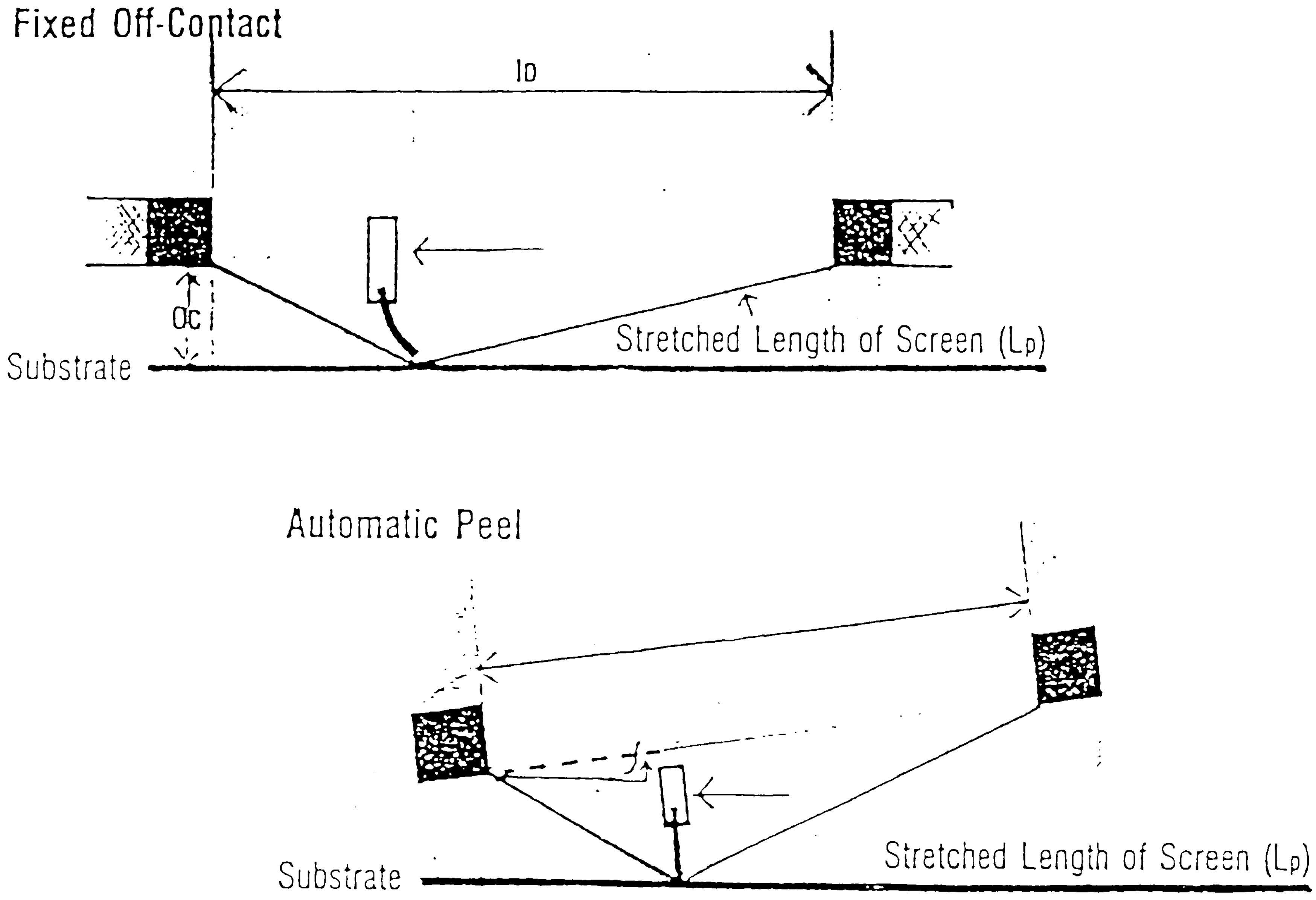


Figure 4-16: Off-contact and Effects

The advantage of automatic peel is that it creates a high separating force between the screen and substrate, often necessary when printing large areas and large reverse images (e.g. soldermask). The disadvantage of automatic peel, and the reason for its absence on small precision presses, is that it causes significantly more screen distortion than the fixed off-contact systems [25].

4.5 Drying and Firing Process

After the ink has been deposited onto the ceramic substrate, the ink is allowed to *settle*. As a result of printing through a mesh screen, the deposited film has the mesh pattern around the periphery of the printed line. If the printed substrate is allowed to stand, the wet film would settle and result in a more uniform film with the edged deformities removed. The settling time varies from ink to ink -- usually between five to fifteen minutes.

After the film has been allowed to settle, it must be dried; this is usually done at from 100 to 150° C. This process is carried out on hot plates, in ovens, or under infrared lamps, all of which have yielded excellent results. The typical cross-section of the belt furnace is illustrated in Figure 4-17. The drying process removes the volatile components in the ink without removing the binders. The drying time again dependent on the ink -- usually between five and fifteen minutes.

Infrared drying has drawn attention in last few years. Using a wavelength longer than three microns is most suitable for allowing the energy to penetrate and assuring uniform drying of the film. With the other drying techniques, the initial surface drying causes a crust to form which may entrap some of the vehicle and cause subsequent blistering during the firing process and voids in the fired films. When the film has been dried properly, it is sufficiently porous during the subsequent firing for the binder to escape without disrupting the film. After the films are dried, they can be handled, additional printing operations can been carried out without affecting the dried film either mechanically or electrically [83].

Dried substrates can be fired in number of ways, most common being small box kiln or a continuous belt furnace. It has been found latter achieves the best results. The furnace should be capable of achieving temperatures of 1100°

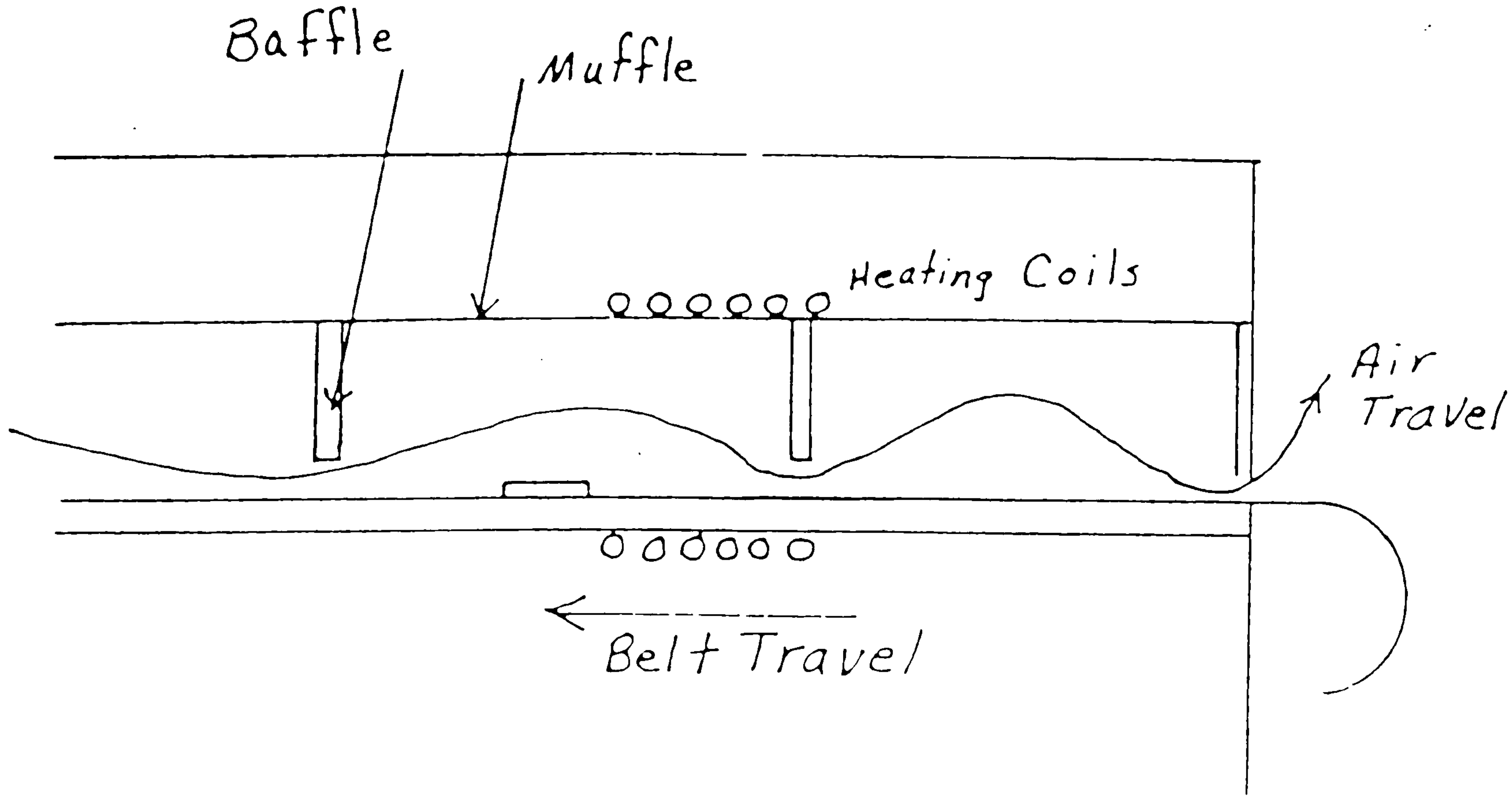


Figure 4-17: Cross-Section of Belt Furnace

C. Since the heating elements and the surrounding tiles can emit materials that can contaminate the thick film substrate, muffle is used to insure clean firing conditions. The best muffle material is fused quartz, which transmits the heat well and does not exhibit thermal lag, as ceramics do. The film can be kept clean by flushing dry air through it by means of a slight incline on the furnace or by using forced air [83].

The temperature in the furnace is monitored by thermocouples placed along the length of the furnace and adjusted by silicon-controlled rectifier proportional controller. A well-designed furnace can maintain the same temperature profile regardless of load conditions; for resistor firing, a temperature tolerance of $\pm 1^{\circ}$ or $\pm 2^{\circ}$ C should be maintained [82]. Higher tolerances are acceptable for firing conductor materials where resultant properties are not as sensitive to firing conditions.

Figure 4-18 is a furnace profile (temperature vs time or distance along the furnace) for a thick film resistor material obtained by attaching a thermocouple directly to the belt and allowing it to travel through the furnace in the same manner as a printed substrate. There are three distinct regions in the profile: burnout, firing, and cool-down regions. The burnout section of the furnace is usually partially separated from the firing section by a baffle. This section should be atmospherically isolated from the firing section so that gases released during burnout do not contaminate the final product.

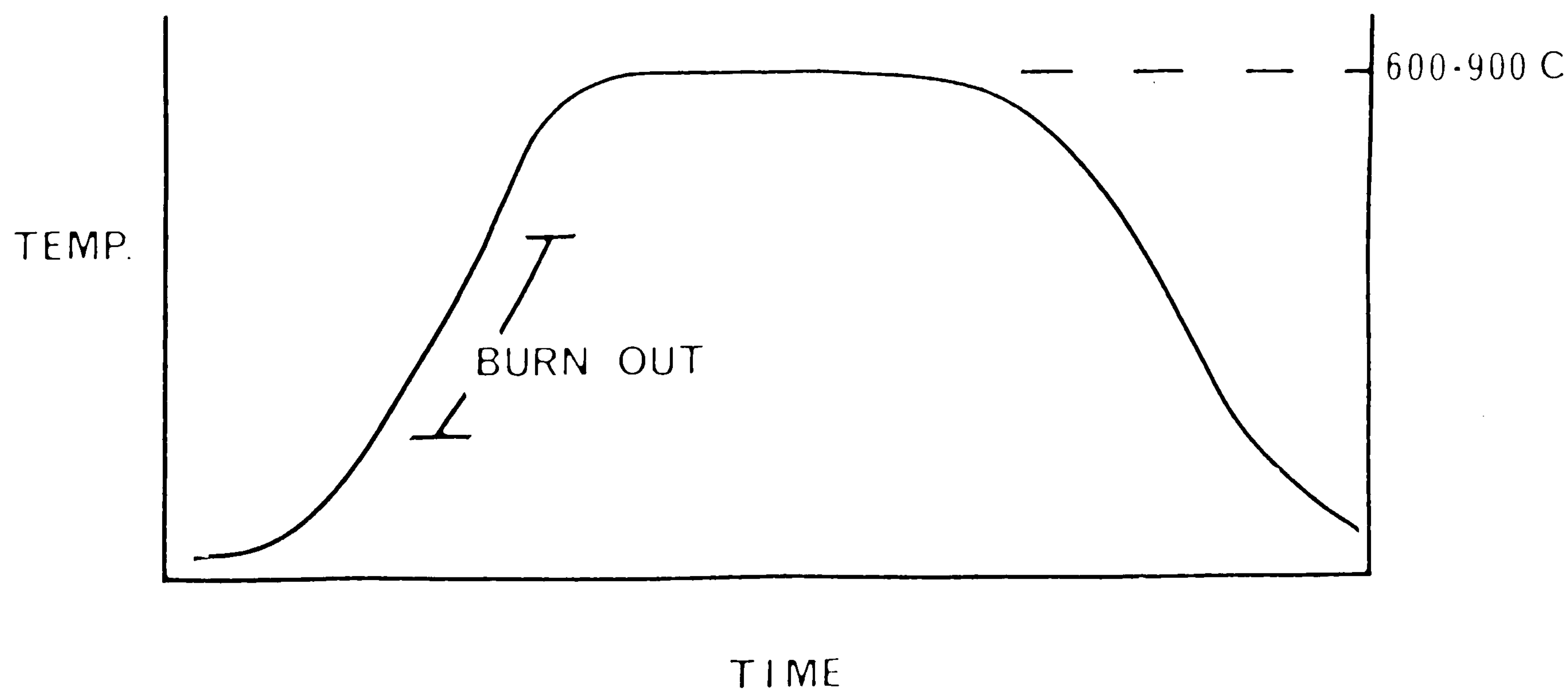


Figure 4-18: Furnace Profile for Resistor Ink

The number of regions in the furnace is dependent on the material to be fired in the furnace. For firing conductor materials, two controller-monitored regions are adequate; but for firing resistor and insulator films requirements are different. The conveyor belt must be chosen carefully, depending on the operating temperature required. The most commonly used belt materials are

Inconel, Nichrome V, and stainless steel [83]. The belt drive mechanism should be controlled and positively maintained. Once the firing profile is set, a reproducible profile must be maintained. The best way to determine the profile is to use three thermocouple probes and measure three points across the belt and a multiple recorder. There is no universal profile. The ink supplier may help in setting up the correct profile for a particular ink.

In firing thick film materials, cofiring of two layers can result in higher outputs of the furnace. It is important to set a firing schedule in which each succeeding firing step is carried out at lower temperature, thus minimizing the interactions between layers which may cause shorting problems. The desired firing profile varies from material to material. In glazes, it is necessary to completely burn off organics before glass melts. There are also limits to allowable cooling rates to eliminate cracking of the film. The airflow direction is from the exit end of the furnace to the entrance, thereby insuring that the organic decomposition products quickly leave the furnace and do not penetrate the hot zone. Too low airflow will not move the organics quickly enough; and too high airflow will result in turbulence in the furnace and an unstable profile [83].

Refiring the substrate a number of times can result in a spread in the electrical properties of the already deposited films as well as low yields. Whenever possible, the last step in any firing schedule should be to fire the resistors in order to minimize the change in resistance caused by refiring.

After thick film resistors have been fired, resistors are trimmed to desired tolerance using an air-abrasive (sand blasting in miniature) or laser techniques. This is known as passive trimming and involves removing portions of the resistor while continuously monitoring its value. The resistor will increase in value until desired resistance is obtained. Trimming to a tolerance of 1 % is readily achieved [59]. Air abrasive trimming is slow and can cause damage to resistors other than the one being trimmed. The pulsed Yttrium-Aluminum-Garnet (YAG) laser is now the favored approach for trimming. It is more suited to fast programmable automatic trimming as the laser beam can be steered sequentially without operator intervention [59].

Active trimming is performed on assembled and tested substrates. In this case the resistor is not trimmed to a specific ohmic value. Instead the circuit is powered up and a circuit parameter such as gain, phase or frequency is monitored while resistor is being trimmed. In this way circuit parameters can be defined very accurately despite the use of other low tolerance components. The technique is useful for active filters, oscillators, precision amplifiers, digital to analog and analog to digital and similar circuits [59].

To complete the circuit prior to test, add-on components are assembled onto the substrate using epoxy die-attach or solder connect or a combination of both. Gold or aluminum wire bonding is used to connect not encapsulated semiconductors onto the substrate. Packaging is normally semi-hermetic (e.g. plastic, potting epoxy etc.) or fully hermetic (e.g. metal welded can, solid sidewall package or glass sealed ceramic package). Final test and burn-in concludes the fabrication process [59].

4.6 Quality Control of the Screen Printing Process

Quality control measures generally fall into two categories: [74]

- visual inspection for print quality
- dimensional measurement of the prints.

A microscope with a backlighting capability is a very useful tool. Uneven prints are readily visible when backlighting is used. Each circuit should be inspected for print quality and alignment.

The thickness should be checked after drying in the oven (referred to as

the *dried thickness*) on all four sides of the print to insure the print uniformity. The thickness may be measured by a position indicator which measures the gross thickness, or by a fine stylus connected to a piezoelectrical crystal which gives an electrical signal proportional to the thickness. This method gives much better resolution. The dried prints may not be fired immediately. They may be stored for sometime in a dust-free environment for period of time. Manufacturer's recommendation should be followed.

Cleaniness of the laboratory is a very important feature of adequate quality control. The laboratory should be kept as dust-free as possible. Lint-free towels should be used for clean-up. All surfaces exposed to ink should be cleaned immediately after use with isopropyl alcohol, or toluene. The squeegee should be removed from the holder and cleaned to avoid contamination of subsequent printing. Chlorinated solvents must be avoided as they adversely affect thick film resistors during the firing process. White suit (specified by the electronics standards) should be preferred as a working dress code.

Chapter 5
Screen Printing Problem Areas

Thick film multilayer technology has acquired an extensive data base of scientific research. However, the material available about pragmatic approaches to the basic, day-to-day problems encountered in the screen printing of multilayer hybrids is scant. These problems are the same ones found in any applications of screen printing, the only major differences being tight tolerance levels required for acceptability in electronics industry.

Screen printing problems can usually be prevented with a three-fold effort:

- better documentation,
- re-evaluation of specifications and tolerances, and
- proper inspection criteria.

5.1 Circuit Design and Artwork

Parameters for hybrid circuit design have yet to be standardized. Successful implementation of a circuit design depends upon communication between the manufacturing and design engineers to prevent design-related problems that only show after a job is in production.

Problems encountered in a circuit design and artwork [16]

- Incorrect component spacing
- Insufficient overlap of interconnects
- Inaccurate line-width orientation and geometry
- Layer-to-layer misregistration
- Omission of reference points
- Original artwork size too small

- **Poor resolution**

Resolution of the image can be improved if the original artwork is produced in an oversized format and reduced to its working size. Artwork photographed from CAD/CAE input (which has greater dimensional accuracy than hand-made art) may have acceptable resolution at a 1:1 size. The ideal art master is a glass plate that includes reference data for size, alignment, and the environment conditions at the time of its production.

5.2 Photography

Problems encountered in photographic reduction [16]

- Errors in reduction
- Errors in registration
- Poor resolution of artwork
- Scratches, fingerprints and smear

Poor photographic reduction, duplication, reversal, and step-and-repeat would degrade the resolution and alter the dimensions of an image. Improper exposure, poor equipment, and incorrect processing would also affect resolution. The out of alignment camera would result in distorted image. The major cause of dimensional changes in the photographic image is the instability of polyester films. Glass plates could eliminate this problem, as they have a negligible thermal coefficient expansion and are inert to changes in humidity.

5.3 Screen Fabrication

Problems encountered in screen fabrication [16]

- Incorrect frame/fabric specifications
- Incorrect mesh orientation and tension
- Insufficient cleaning of fabric
- Incorrect emulsion type and thickness
- Improper storage of presensitized screens
- Lack of traceability
- Improper calibration of exposure system
- Improper setup of vacuum frame
- Harsh image wash-out and drying conditions
- Inaccurate image position and orientation
- Absence of registration references (targets or fiducials)

Proper inspection of screens would prevent, if not solve, some printing problems.

1. *Frame Size:* the inside dimension of the frame should be 1.5 to 3 times larger than the circuit or substrate.
2. *Fabric Adhesive:* thorough, periodic inspections for complete fabric-to-frame bonding should be made.
3. *Fabric:* fabric should be examined to verify:
   a. Mesh type and count
   b. Wire diameter
   c. Even Stretch and weave
   d. Overall mesh thickness

Screen tension should be tested by the fixed-weight deflection method (Figure 5-1) or by an electronic tension meter that displays N/cm. The evenness and thickness of the emulsion would influence image quality and the consistency of ink deposit. Careful inspection after coating would reveal problems, such as lint, air bubbles, or pinholes, that often go unattended. After drying and inspecting each emulsion layer, the overall thickness of mesh and emulsion should be checked for a close tolerance (about 0.1 mil). Some simple precautions would improve the processability and storage-life of presensitized screens: [16]

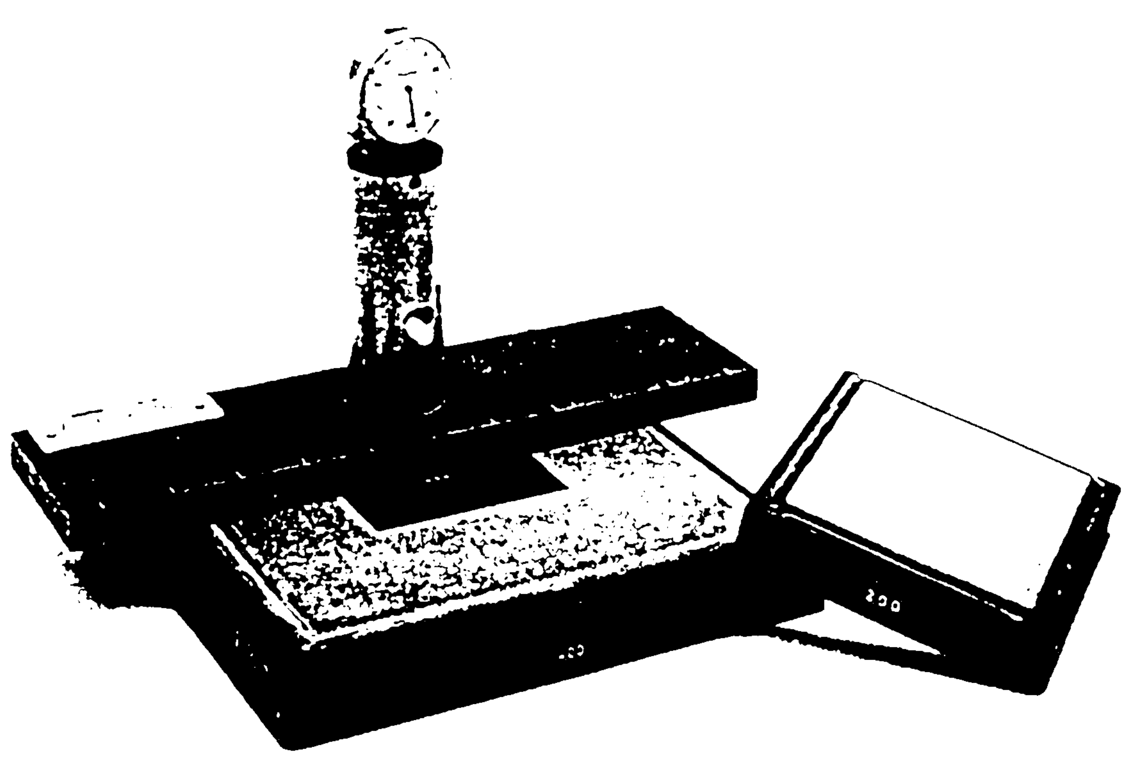


Figure 5-1: Screen-Tension Gage

1. Protect emulsion surface with polyester film, cellophane or waxed paper. Do not use paper or cardboard products, as they generate dust.

2. Package screens for shipment in a manner that prevents damage from heat, light, moisture, or physical damage. Do not use sealed black bag though they keep dirt out but breathe to let in moisture and initiates the hardening of the emulsion. Poly/foil bags are recommended for this purpose. Storage longer than six month is not recommended.

3. Standard positives should be used to calibrate an exposure system providing a guide to over-/underexposure using reference line width and emulsion thickness. Periodic readings taken with radiometer could be used to monitor the consistency of the lamp's output.

4. Use a clean water supply under low pressure for image wash-out.

Water temperature should be held at 105 °F, and the subsequent drying temperature at 120 °F.

5.4 Substrate and Ink/Pastes Selection

Problems encountered in substrate and inks/pastes selection [16]

- Insufficient ink testing and calibration
- Discrepancies between rheology and printing setup
- Incorrect mixing
- Unknown particle size and/or solvent
- Ink contamination

The following substrates parameters are generally recommended [16].

1. Linear tolerance: $\pm$1 % minimum, $\pm$0.05 % ideal
2. Thickness: $\pm$10 % minimum, ideal
3. Flatness: 1/3 of thickness maximum, 1/4 of thickness ideal

Inks/Pastes should be specific for the following: [16]

1. Firing range (850 °C standard)
2. Conductivity, resistivity, and insulation resistance
3. Line resolution
4. Fired thickness
5. Viscosity
6. Pull strength and adhesion
7. Solderability

The above mentioned substrates and inks recommendations would help to overcome the some of the material selection problems.

5.5 Printer Setup and Operation

This is the probably least understood problem associated with the screen printing process. Various techniques and solutions are recommended for different situations. However, what works once, does not necessarily work next time for the similar problem. The solutions to these problems strongly depend on the operator;s experience, knowledge and willingness. Setup in general is a major concern for today's manufacturing operations. Setup procedures for a screen printing press should be accomplished in a minimum of time and should achieve maximum consistency.

There are some problems which have simple solutions [10].

1. *The screen image position is beyond the adjustment range.* Pre-align the image to the screen within a known tolerance.
2. *Squeegee, screen, and image are not center-aligned to one another.* Use a squeegee and floodbar with floating central axis.
3. *No fiducial marks from previous printing are retained on substrate.* Retain a substrate `master` to repeat setups from batch to batch.
4. *Problems caused by printing press's register mechanism.* Always print in the same direction, and pull into the registration stops. Use electro-mechanical instead of pneumatic devices.
5. *Printing press is not level.* Keep printer leveled and use nested tooling, flat screens, and a floating squeegee.

Problems encountered in Printer Setup and Operation [10]

- **Setup**
    - Positioning time and accuracy
    - Inaccurate tooling
    - Equipment not level
    - Excessive squeegee pressure and speed
    - Registration offset error
    - Loss or omission of parametric records

- **Excessive setup time**
- **Wasted print during setup.**

- **Operation**
  - Tooling, screen, or squeegee wear
  - Frequent screen cleaning
  - Loss of solvent
  - Ink contamination by oil, ceramic dust, or lint
  - Print registration
  - Poor image resolution
  - Thickness and leveling problem
  - Opens or shorts
  - Substrate and/or screen damage
  - Parameter changes during batch run
- **Clean-up/Tear-down**
  - Failure to log parameters
  - Incompatible ink and solvent
  - Emulsion wear from cleaning
  - Ink trapped in squeegee blade
  - Screen, squeegee, and flood-bar removal

Wear in the printer's tooling is lessened through the use of large titanium carbide stops, which provide an increase in wear resistance. The usable life of screens can be extended by using larger screens; nominal off contact, squeegee pressure and speed; substrate nesting; and automatic screen washing. Nominal squeegee settings, harder durometers, finer fabrics, and adequate emulsion coating on the inside of the screen minimize wear of the squeegee. Also, the solvents used should not soften or degrade the squeegee.

Care of the screen during the printing operation is important if consistent results and minimal downtime are to be maintained. The following precautions should be taken to protect the screen and maintain image quality: [10]

1. Balance ink viscosity to mesh count.
2. Install dust covers on screen printers.
3. Verify proper exposure and thickness of emulsion.
4. Use a fabric with a higher percent open area.
5. Use lint-free wipes and fast-drying solvents.
6. Clean all substrates before printing.
7. Slow the squeegee speed to match the shear rate of the ink.
8. Always print away from operator to facilitate view of wiping action.

Using dust covers on screen printers not only limits solvent evaporation, but also cuts down on the amount of airborne contaminants introduced to the working ink. Used inks/pastes should not be returned to the original container. Most dust and dirt comes from clothing, substrates, and other environmental influences. Clean room with controlled environment and white clean suits should be the initial requirement for the printing operation. Oils come from equipment lubrication and compressed air supplies. Thus all bearings should be grease-packed and sealed, and only electro-mechanical mechanisms should be used in clean-room environment.

Accurate layer-to-layer and layer-to-substrate registration can only occur during printing if it exists at all levels of artwork and screen production. The recommended total registration accuracy is $\pm$0.25 microns (0.001 inch). If resolution needs improvement, finer fabric should be used [10].

5.6 Drying and Firing

Problems encountered during drying and firing [10]

- Excessive setup time and lack of repeatability
- Loading/unloading damage
- Quality Control(QC) response time
- Incorrect or variable control parameters
- Dust accumulation during settling
- Skinning and blistering
- Power/floor consumption
- Transfer of dirt from belts to substrate
- Air draft in room affecting furnace
- Excessive work-in-process(WIP)
- Finished tolerance of resistors
- Atmosphere contaminated by solvents, dust, oil vapors

As in screen printing operation, the key to successful drying and firing is documentation. Incorrect firing of a multilayer hybrid could damage its structural integrity. Preheat and cool down periods should be strictly observed to prevent undue thermal stress. The electrical characteristics of resistive elements could be affected significantly if firing conditions are altered. A system for monitoring the furnace should be in place and maintained for repeatability of process from batch to batch.

5.7 Print Quality

So far we talked about the problems associated with screen printer and related process variables. There are some problems observed in the quality of print. Some common print defects are illustrated in Figure 5-2. The causes of these problems may be the printer or the related process variables or some combinations of these two. The more notable quality problems are: [74]

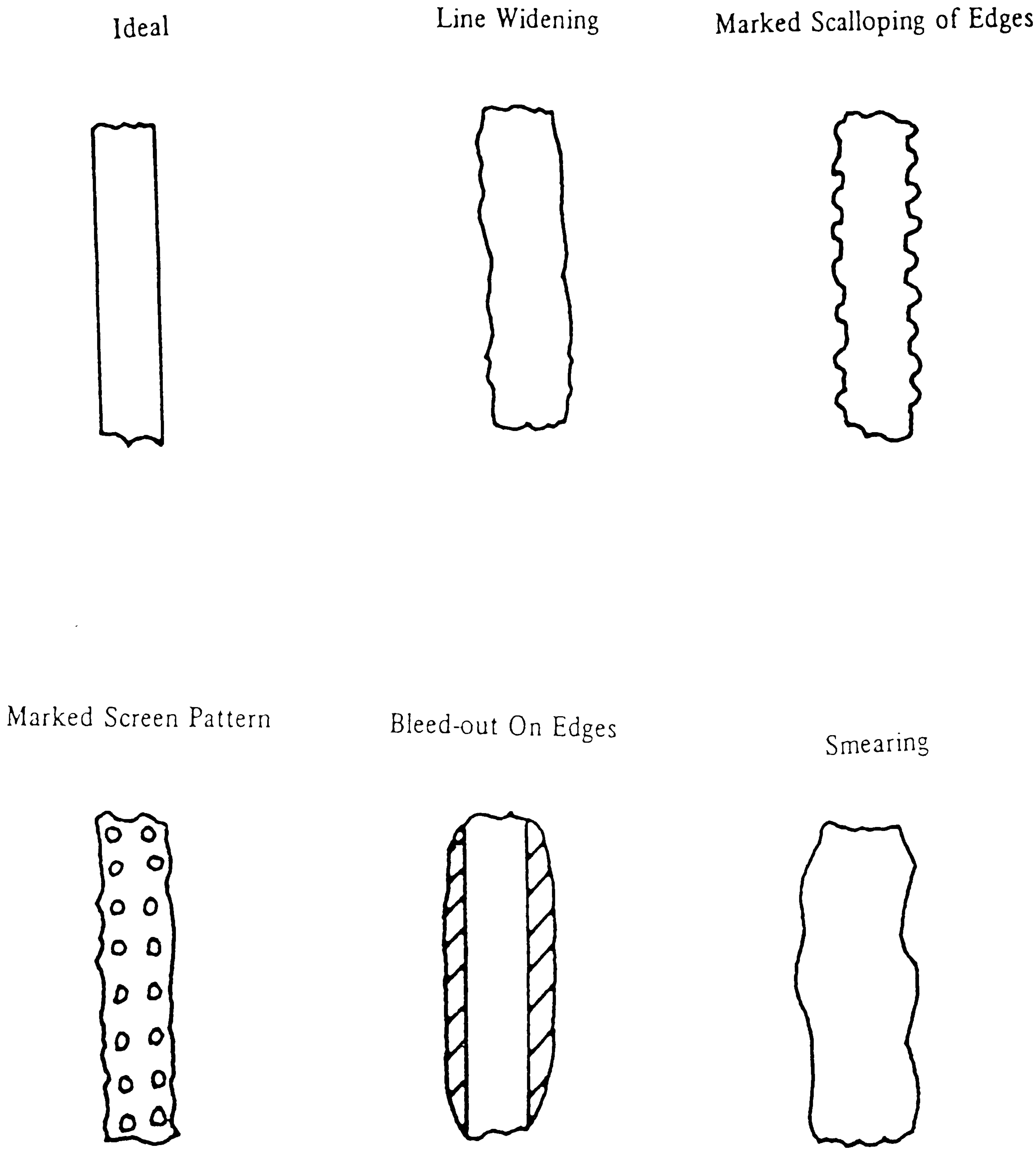


Figure 5-2: Common Defects in Screen Printing

1. **Improper or uneven thickness of print**
2. **Poor line definition**
3. **Partial or uneven prints**
4. **Poor alignment of prints**
5. **Smearing of prints**

(1) ***Improper or Uneven Thickness of Print***

PROBABLE CAUSES

1. Improper screen tension
2. Improper screen to substrate spacing
3. Excessive squeegee pressure
4. Improper squeegee speed
5. Improper rheological properties of inks/pastes

Assuming that the screen tension and viscosity of the ink have been checked prior to printing, the first step in correcting the film thickness should be to adjust the squeegee speed in the proper direction. If this is insufficient, adjust the squeegee pressure accordingly. If this, produces prints with scalloped edges, the snap-off distance (screen to substrate spacing) may have to be adjusted.

(2) ***Poor Line Definition***

PROBABLE CAUSES

1. **Improper rheological properties of the inks**
2. **Excessive squeegee pressure**
3. **Excessive substrate camber**
4. **Improper screen mesh**
5. **Improper alignment of pattern with mesh**

An ink which has a low yield point may spread after the printing process, resulting in a print with larger dimensions and thinner than desired. The solvent in the ink may have evaporated to a certain degree due to jar being open or by placing lightly over the top of a hot oven. The ink should be carefully monitored by removing and stirring every few minutes.

Excessive squeegee pressure may cause ink to be squeezed out of the pattern between the screen and substrate, resulting in prints with scalloped edges. Reducing the pressure to alleviate the problem may have to be compensated for by increasing squeegee speed.

Excessive substrate camber may act much the same as squeegee pressure. If precise line definition is a necessity, as for fine line printing, careful substrate selection is essential. Printing with a screen with small mesh size (fewer wires/length) can also cause scalloped edge due to the large openings in the screen.

(3) ***Partial or Uneven Prints***

PROBABLE CAUSES

1. Ink with high yield point
2. Insufficient squeegee pressure
3. Insufficient snap-off distance
4. Improper screen tension

The first step should be to adjust the squeegee pressure slightly, adjusting the speed if necessary to maintain print thickness. If this doesn't work, adjust the yield point by adding solvent. The screen tension should be checked prior to printing. Snap-off distance should be changed only as a last resort.

(4) ***Poor Alignment of Print***

PROBABLE CAUSES

1. Improper alignment of substrate mounting platform
2. Excessive camber
3. Substrate improperly positioned

The substrate mounting platform must have **X**, **Y**, and rotational controls to properly position the substrate under the screen. The alignment is especially critical if more than one layer is required. Visual inspection would align the substrate roughly, but final alignment usually requires thorough inspection.

Excessive camber may cause the vacuum to release during the printing operation and the substrate may shift.

The positioning of the substrate is a critical operation in the printing operation. The substrate holder is usually recessed and generally has three points against which the substrate is placed. A care should be taken that substrate fits snugly against all three points.

(5) ***Smearing of Prints***

PROBABLE CAUSES

1. Improper screen tension
2. Improper snap-off distance
3. Excessive squeegee pressure
4. Excessive camber

Improper screen tension and snap-off distance could cause the screen to "peel" away from the print instead of "snapping" away, resulting in a smeared print. Excessive squeegee pressure causes ink to spread out between the screen and substrate.

Excessive camber can act much the same way as excessive squeegee pressure. A further possible consequence of excessive camber is the release of the vacuumhold, causing the substrate to shift during the printing operation and thus smearing the print in process.

In many cases, smearing of the print would necessitate cleaning the bottom of the screen. This should be done with a dry, lint-free towel. Solvents should be avoided, as it may affect the rheological properties of the ink on the screen.

In summary, the screen printing problems described in this chapter are by no means all that a manufacturer would encounter, but they are common ones. In general, the greatest problems for the screen printing process are registration, quality, and repeatability, both from piece to piece and batch to batch. Careful and well-planned testing of process variables coupled with systematic documentation could help to improve yields and reduce cycle time.

Chapter 6
Setup, Quality and Productivity

Production activities may best be understood as networks of processes and operations. A ***process*** is a continuous flow by which raw materials are converted into finished goods. An ***operation***, by contrast, is any action performed by man, machine, or equipment on raw materials, intermediate, or finished products. Each phase of the process has a corresponding operation. Each of these operations, further has four subcategories: [76]

- Setup
- Essential
- Auxiliary
- Marginal Allowance

Setup has a major significance on the productivity and quality of the finished product. Thus it must be studied in greater detail.

6.1 Setup

In the past, setup improvements were achieved through skill and large-lot production. The concept of economic lot size was introduced to counterbalance the effect of increasing inventories. There is an important blind spot in the concept of economic lot size: THE ASSUMPTION THAT DRASTIC REDUCTIONS IN THE SETUP TIME ARE IMPOSSIBLE. Setup reduction is an essential move to lower order quantities, shorten lead times, and reduce inventory.

Setup procedures are usually thought of as infinitely varied, depending on the type of operation and type of equipment being used. Yet when these procedures are analysed from a different viewpoint, it can be seen that all setup operations comprise a sequence of steps. In traditional setup changes the distribution of time is often that shown in Figure 6-1 [76].

Operation	Proportion of Time
Preparation, after-process adjustment, and checking raw materials.	30 %
Mounting and removing parts and tools.	5 %
Centering, dimensioning and setting of other conditions.	15 %
Trial runs and adjustments	50 %

Table 6-1: Steps in the Setup Process

Let us examine each of these step in greater detail:

Preparation, after-process adjustment, and checking raw materials

This step ensures that all parts and tools are where they should be and that they are functioning properly. Time for after-process activities is also included in this step.

Mounting and remove parts and tools

This includes the removal of parts and tools after completion of processing and the attachment of the parts and tools for the next batch.

Centering, dimensioning, and setting of other conditions

This step refers to all of the measurements and calibrations that must be made in order to perform a production operation effectively.

Trial runs and adjustments

This step includes adjustments are made after a test piece is run. The greater the accuracy of the measurements and calibrations in the preceding step, the easier these adjustments would be. The frequency and length of test runs and adjustment procedures strongly depend on the skill of the operator. The major problem in a setup operation is adjusting the equipment correctly. The large portion of the time associated with trial runs could be attributed to the adjustment problems.

There are two types of setup, *internal setup* -- one that can be performed only when machine is is stopped; and *external setup* -- one that can be conducted while machine is in operation. The key to success is to analyze the setup problem and improve it as best as possible. There are four conceptual stages of setup improvements: [76]

- PRELIMINARY STAGE: Distinguishing Internal and External Setup
- STAGE 1: Separating Internal and External Setup
- STAGE 2: Converting Internal Setup to External Setup
- STAGE 3: Streamlining all Aspects of the Setup Operation

The conceptual stages involved in setup improvements are shown Figure 6-1.

(1) Distinguishing Internal and External Setup

In traditional setup operations, internal and external setup are confused; what could be done externally is done as internal setup, and equipments therefore remain idle for extended periods. In order to achieve the goal of this preliminary stage, one must study actual shop floor conditions in great detail. Some suggested method are: [76]

1. A continuous production analysis performed with a stopwatch is probably the best approach, but is time consuming and requires a great skill.

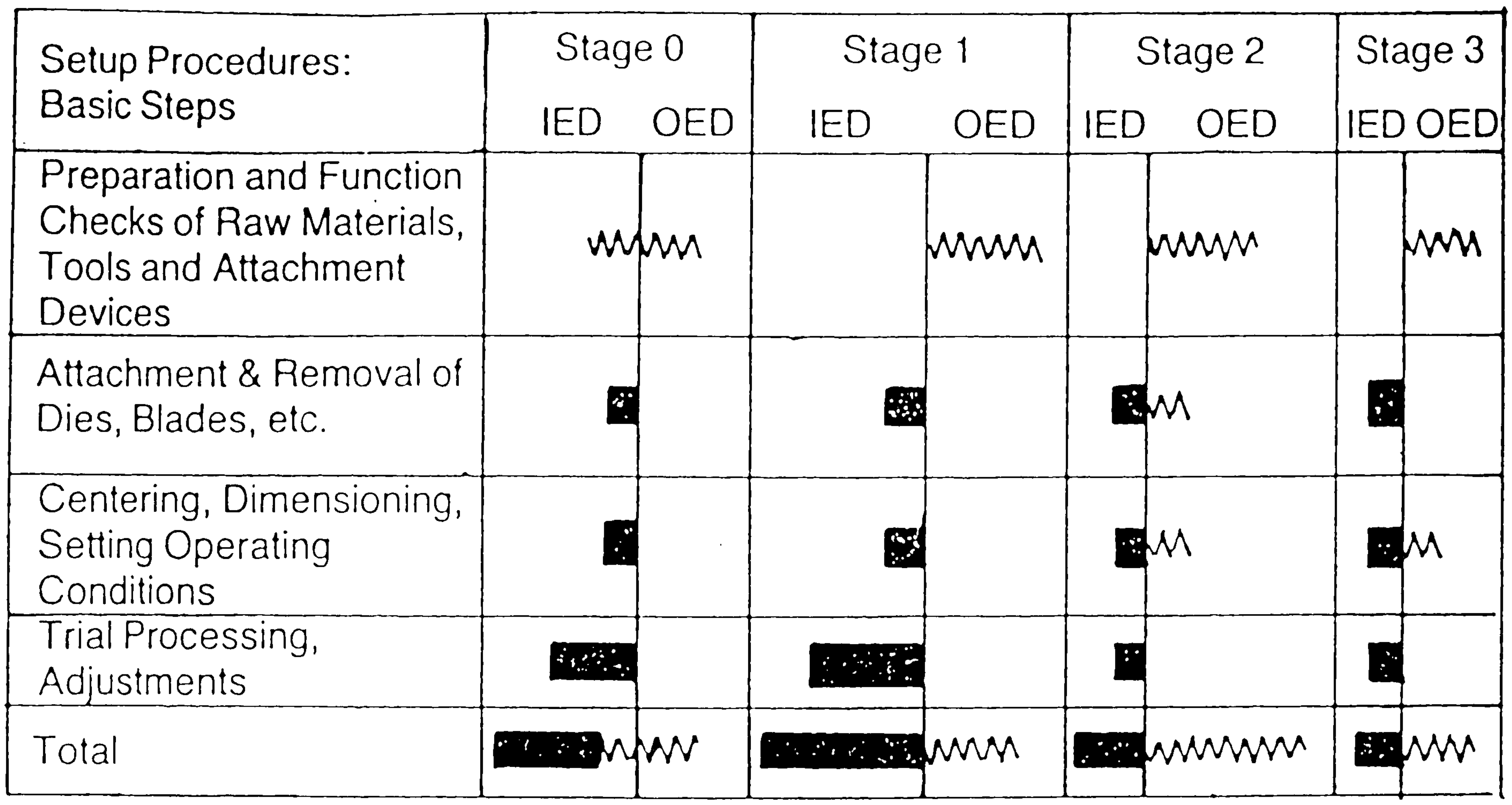


Figure 6-1: Conceptual Stages for Setup Improvement

2. Work sampling study; requiring many repetitions.
3. Interviewing workers gives the idea of the prevailing conditions on the shop floor.
4. Videotaping the entire setup operation is another good option. This is extremely effective if the tape is shown to the workers immediately after setup has been completed. Giving workers the opportunity to air their views often gives useful insights.

(2) Separating Internal and External Setup

Every scientific effort should be made to treat as much of the setup as possible as external setup. This could reduce internal setup time as much as by 30-50 % [76]. Some techniques are recommended to ensure that certain setup operations are performed as external setup. They are: [76]

1. ***Use a Checklist***: Make a checklist of all the parts and steps re-

quired in an operation. On the basis of this list double-check that everything is in order.

2. ***Perform Function Checks*: This helps to determine whether all equipments and tools are operating properly.**

3. ***Improve Location and Transportation of the Required Parts*: Parts should be stored at a pre-determined location and should be accessible to the operator when necessary.**

(3) Converting Internal Setup to External Setup

The first step in converting setup operations is to prepare operating conditions beforehand. The function standardization could help the process of conversion. This stage involves two important ideas: [76]

1. Re-examine operations to see whether any steps are incorrectly assumed to be internal.
2. Finding ways to convert these steps to external setup.

It is extremely important to adopt new perspectives that are not bound by old habits.

(4) Streamlining all Aspects of the Setup Operation

Concentrate the efforts to streamline each internal and external setup operations. Prepare the detailed analysis of each elemental operations. Actually Stage 2 and 3 may be done simultaneously.

Though reducing setup times may not reduce the total setup cost, the benefits derived would be visible in form of improved product quality and increased productivity. One of the key to successful implementation of setup improvements is understanding of all the independent variables pertinent to the operation that affect the quality characteristics of a finished product. The one of the approach is Statistical Process Control, commonly referred as SPC.

6.2 Statistical Process Control

Statistical Process Control(SPC), or as it is sometimes called, Statistical Quality Control(SQC), is not new. SPC has been used as a productivity improvement tool for some decades. It allows the reduction of the process data into forms that detect and correct problems *before* they can cause production deficiencies and thus result in waste, scrap, and rework [34].

SPC is a technique that is used to monitor, control, evaluate, and analyze a manufacturing process. The operating characteristics of the process determine the quality. To control and improve quality , it necessary to control and improve the process.

Technically, SPC techniques are mathematical models of a process that can take into account the variations inherent in most aspects of a process. These variations are due to many causes, few of which can be predicted with any certainty. Using appropriate technique, for the available data, the decision maker can draw conclusions about the stability of the process. The target of the SPC program is to first achieve stable, predictable process performance. Only after the process is in control quality improvements are feasible.

SPC techniques measure the results against realistic, meaningful measures of past performance, not against someone's idea of what performance should be. The technical tool of statistics is used to separate the features about the process that are important from those that are less important. There are a number of statistical tools that have been developed for use on SPC. The two widely used techniques are:

- Control Charts
- Design of Experiments

6.2.1 Control Charts [36]

A control chart is a technique for plotting the measured values of certain characteristics of the process output over time to determine if the process remains in statistical control. Control charts are most appropriately applied to monitor the critical processes in high- and mid-volume production plants. The general form of the control chart is illustrated in Figure 6-2

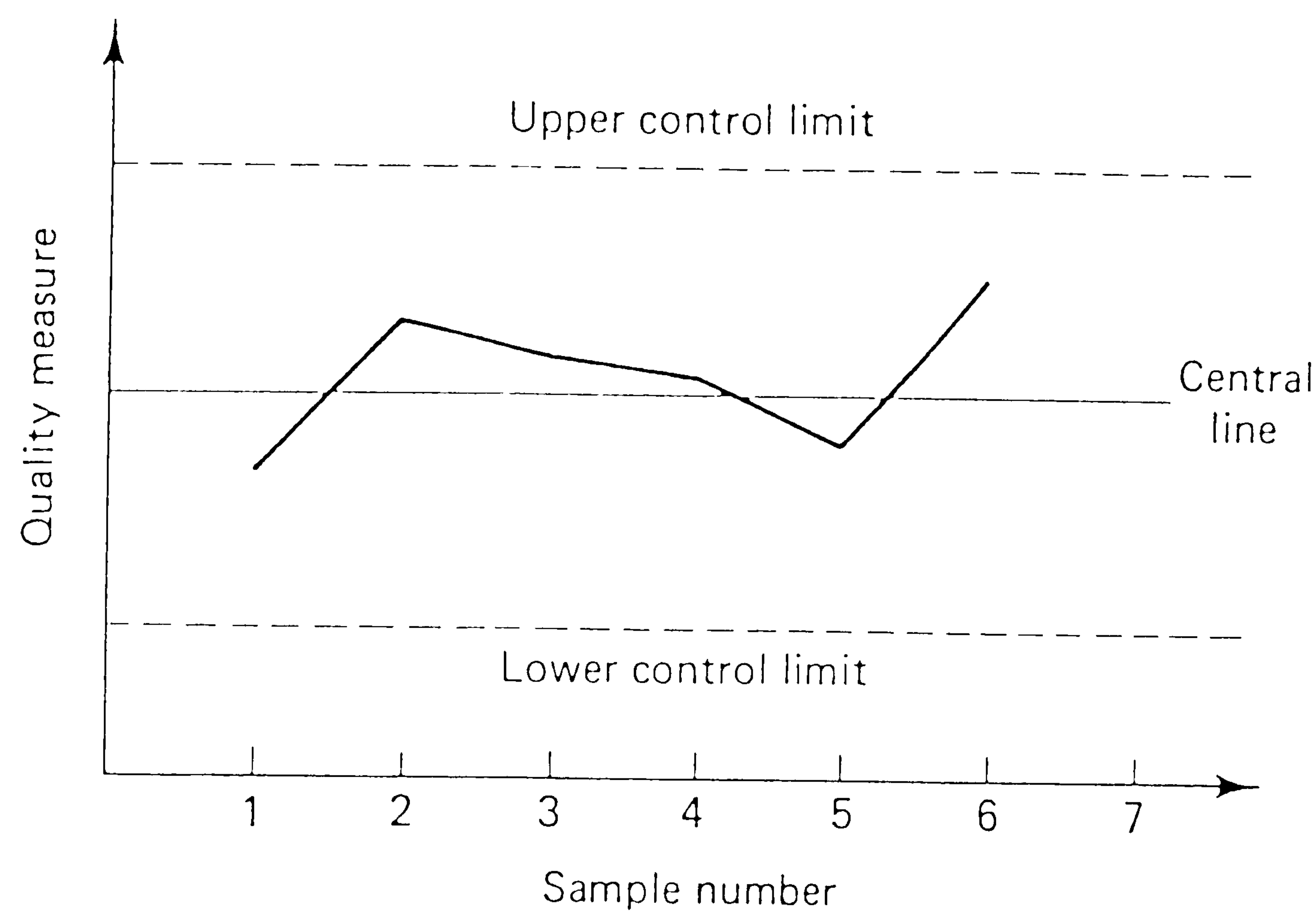


Figure 6-2: General Form of a Control Chart

The chart consists of three horizontal lines (lines that are constant over time): a central line, an upper control limit (UCL), and a lower control limit (LCL). The central line corresponds to the mean of the process output. It represents the expected nominal value of the output. The upper and lower control limits indicate extreme statistical values of the process. If any measured values of the output are plotted outside these limits, it is an indication that the process is no longer in statistical control; and that an investigation should be undertaken to determine the reason for the out-of-control condition. The condition is illustrated in Figure 6-3

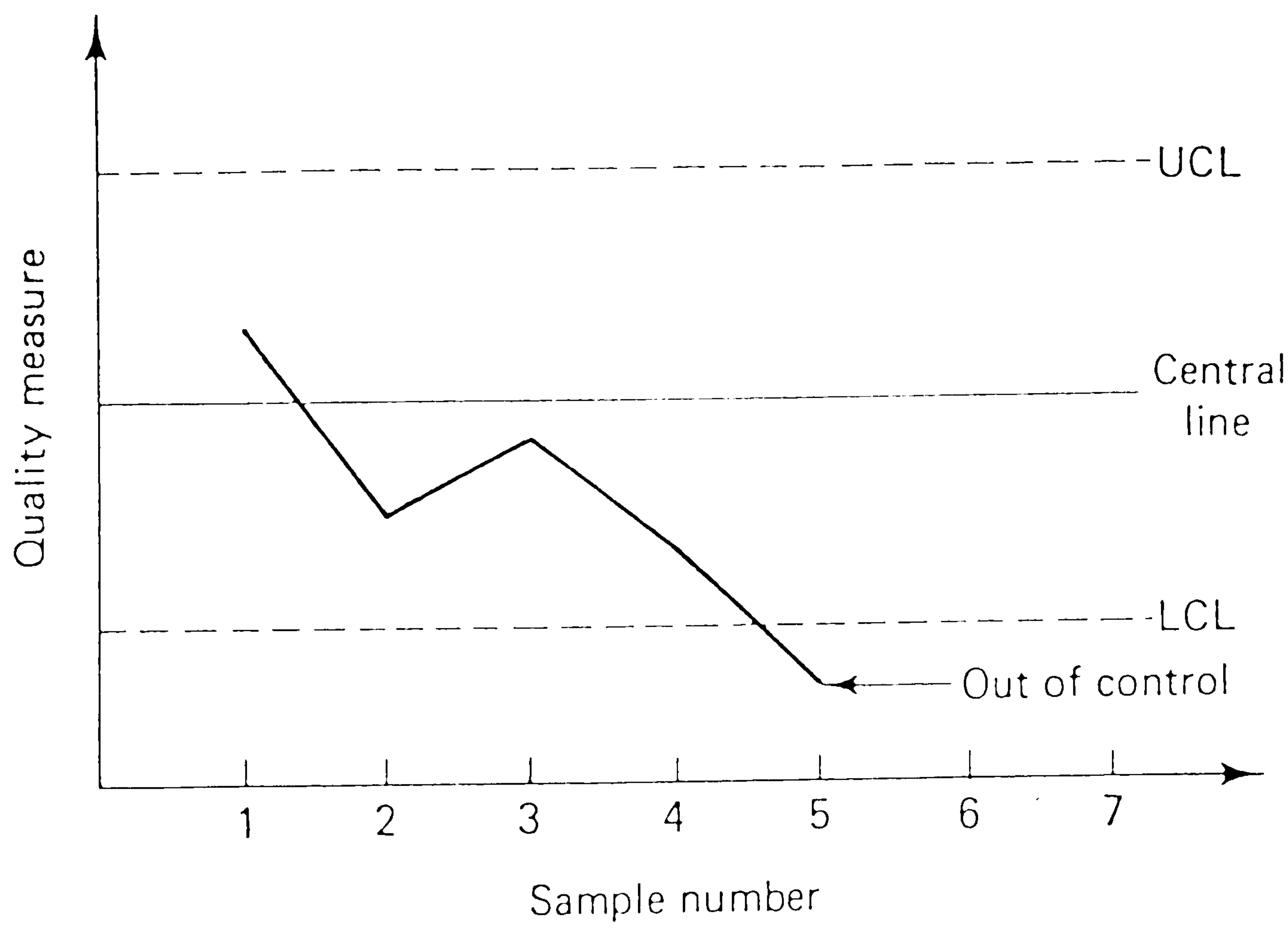


Figure 6-3: Out-of-control condition

The natural tolerance limits ($\pm$3 standard deviation) are usually used to define the upper and lower control limits in control charts. There are several types of control charts used in the industry for SPC. They all have the same general form shown in 6-2. The types include: [36]

- *X chart* This control chart is used to plot the average measured value of a certain quality characteristic for each of a series of samples taken from the production process. It indicates how the process mean is varying over time.
- *R chart* In this control chart, the range of each sample is plotted. The R chart monitors the variability of the process and indicates whether the variability changes over time.
- *p chart* This chart is used to plot the percentage (*p* for percent) of defectives in the sample. If the percent defectives suddenly increases beyond the UCL, the process is out of statistical control.

• <u>*c chart*</u> Here the number or count (*c* for count) of defects in sample are plotted as a function of time.

The X chart and R chart require that the quality characteristic of interest be measured during the inspection process. The *p* chart and *c* chart simply require a determination of whether each part is defective or how many defects there are in the sample.

6.2.2 Design of Experiments

Design of experiments are the most effective strategies available for determining relationships among multiple variables. Design of experiments strategies are rapidly becoming recognized by industry as an invaluable resource. The application of design of experiments methods early in the product and process development cycle plays a role in reducing development lead time, engineering changes, and product and process development costs.

An experimental design represents a plan for deliberately changing input variables in order to evaluate their effects on the output variables. Input variables are also known as factors, predictors, control variables, or independent variables; output variables are often referred as responses, properties, or dependent variables. A variety of design of experiments strategies are available to obtain different kinds of information within the number of experimental runs possible [57].

The systematic approach to design of experiments can be used to: [58]

1. meet objectives cost effectively,
2. decrease development time,
3. optimize process capability and first-pass yields,
4. minimize effects of variations in manufacturing conditions,
5. achieve the best process for consistent product quality.

Most experimental design strategies consist of three basic steps: [57]

- **Screening Design**
- **Interaction Design**
- **Optimization Design**

SCREENING DESIGN

Screening designs are usually used to identify the few critical factors from a list of many potential important ones. Each factor typically is investigated at only two levels, low and high. As few as (k + 4) experimental runs are required to evaluate k factors.

Screening designs usually involve 6 to 30 factors. They are used to estimate effects of individual factors, rank their influence on each response measured, and improve efficiency of next stage by eliminating unimportant factors.

INTERACTION DESIGNS

These designs are used to estimate individual and interaction effects among various factors. Interaction designs require more experimentations than screening designs for the same number of factors. They are suitable for factors having two or more levels and produce reliable estimates of experimental uncertainty.

Interactions identify key process and control variables, identify ways to compensate for, or minimize, effects of difficult-to-control factors, and increase understanding of the system behavior. 3 to 8 factors are most common, and require a minimum of 2^k runs for k factors.

OPTIMIZATION DESIGNS

Optimization designs develop empirical relationships between a response and all of the factors influencing it. Each quantitative factor is tested at three or more levels so that individual, interaction, and curvature effects can be estimated, as well as experimental error.

It certainly requires more experiments than previous steps for the same number of factors. It typically involves 2 to 6 factors. They are used to predict response value throughout the experimental region, or to estimate values of input variables that achieve the desirable response value.

Figure 6-4 shows the evolution process of design of experiments.

The factorial design concept is a powerful design of experiment strategy. In many practical situations, however, the factorial design would require a large number of runs. In situations where the number of variables is large, fractional factorial designs can be used very effectively. This fractional factorial is a very useful concept. It allows a large number of factors to be investigated easily, using designs having a very small number of runs.

Several principles are essential for good experimental strategy, regardless the method used: [57]

- Diagnose the environment and match a design of experiments objective.
- Use balanced statistical designs to study multiple factors simultaneously.
- Measure all relevant properties at each experimental run.
- Use a sequence of experiments, each only large enough to assure clear results.
- Be bold by exploring each factors over a wide range, and by including many candidate factors at the screening stage.
- Randomize and block data collection to avoid misleading results owing to bias factors.

Evolution of the Experimental Environment

Design Category:	Screening	Interaction	Optimization
Factors Explored	6 to 30	3 to 8	2 to 6
Effects Estimated:	Individual	Individual, Interaction	Individual, Interaction, Curvature
Result:	Identify Important Factors	Understand System Behavior	High Quality Prediction, Optimization

Figure 6-4: Evolution of the Experimental Environment

- Estimate experimental errors as a built-in part of the design.
- Avoid mistakes in carrying out the experiment.
- Plan for statistical analysis of the data.

As throughout the discussion of setup and statistical process control, the major impact of these techniques is quality improvement and increased productivity. This is well explained in Figure 6-5

The next chapter describes the concept of setup and statistical process

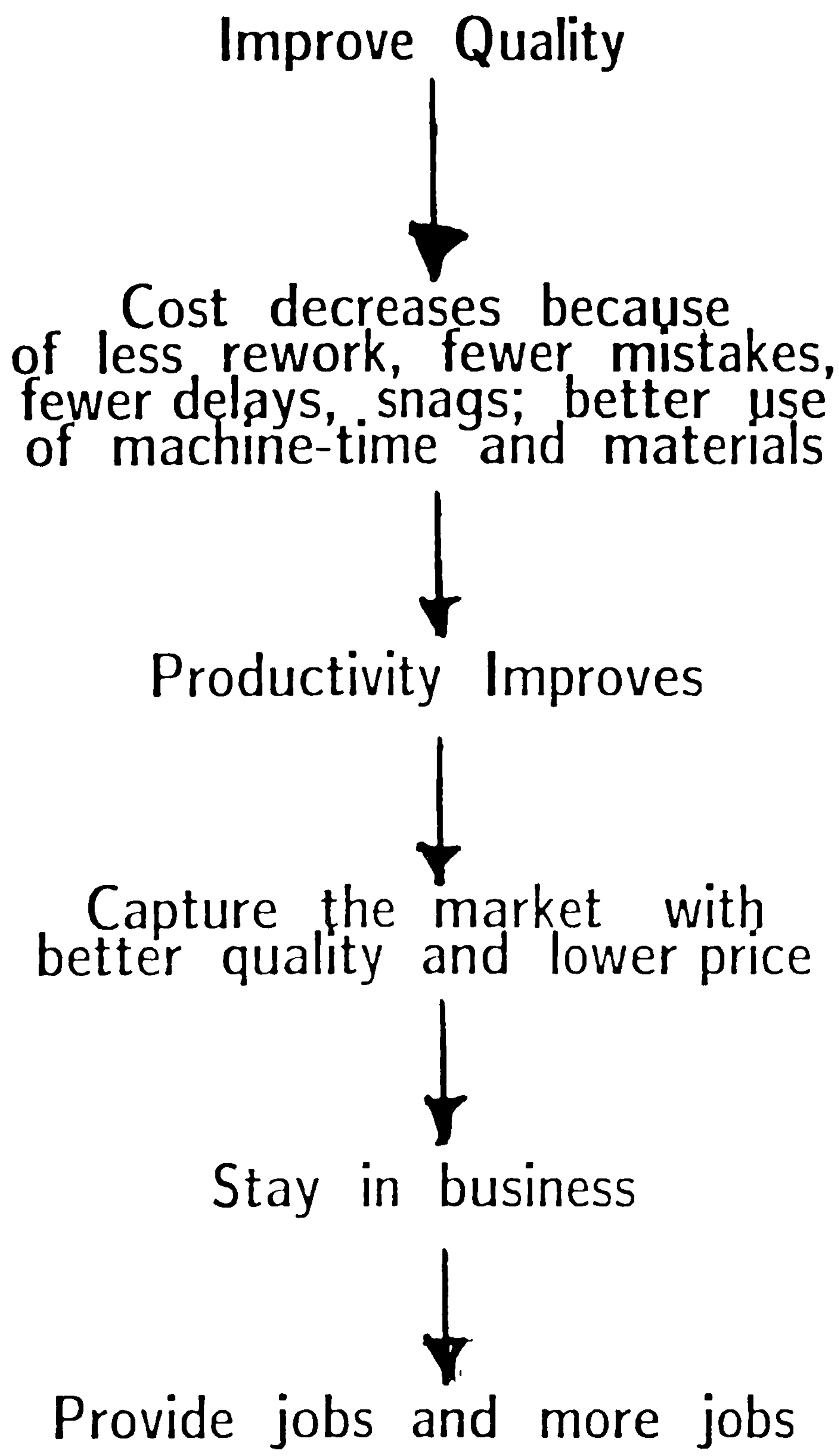


Figure 6-5: Deming's Chain Reaction

control, especially the design of experiments as applied for the analysis of a major electronic circuit manufacturing company.

Chapter 7
Case Study

7.1 Introduction

The thick film printing process starts in the print room. The quality of the product generated by the print room impacts the quality of the thick film process and the final product. To date, the printing process never has attained adequate process control status. The printing process is more of an *art* than a *science*. Typical printing concerns are:

1. Printer setup is often difficult and time consuming, resulting in lost production.
2. The process is not stable; a good setup changes for no apparent reason resulting in frequent adjustments to the printers, lost production, and possible out-of-spec product.
3. What work last time does not work this time, thus the operators use the "trial-and-error" approach and rely on personal experience to get the job done.

The case study involved the study of setup related problems with the screen printing machines, primarily used for thick film printing. The problem statement was long setup times with high variability and complexity. The goal of the study was to reduce the setup time. A permanent solution to the above problem was thought to be complete understanding of all the independent variables pertinent to screen printing that affect setup procedure and the quality characteristics of the product. The study focussed on two main areas:

- Setup Analysis
- Design of Experiments

The setup was studied based on approach described by Shiego Shingo [76]. The approach is discussed in detail in Setup Analysis. The goal of design of experiments to study the few critical factors that were considered to be important from the quality stand point. The set operation was observed and recommended setup procedure manual was studied in detail for setup analysis.

7.2 Setup Analysis

The setup time was estimated about 40-45 minutes which represented about 30 % loss of utilization of machine per cycle. (Of 3 1/4 hour of cycle time, only 2 1/2 hour was actual production cycle, remaining 3/4 hour was lost in setup). The setup process was observed for resistor as well as conductor printing. During the observation, some setup activities were categorized as external setup, internal setup and adjustments. Internal setup consisted of activities that were done when machine is not in operation, i.e., it involved machine downtime. External setup were those setup activities which could be done prior to the completion of the previous run and involved no machine downtime. Adjustments were setup related activities that merely involved the tweaking of one or more parameters to get the desired quality characteristics. The Table 7-1 summarizes the setup procedure.

As seen from the table that all setup activities involve machine downtime. It can also be seen that activity 3, 7, and 8 could be done while the machine is still in operation. According to shop personnel setup times average 30 minutes but could go as high as 90 to 120 minutes. Further, it was observed during the setup analysis that most of the time was spent on the activities 9-12 in case of conductor and cross-over layers, and on the activities 13-14 in the case of resistor layers. The adjustment procedures which were aimed at achieving the specified circuit tolerance with respect to the substrate edges and film thickness, consumed most of the time. These are non-documented procedures, very strongly dependent on the operator's prior experience with similar problems.

There were many external variables affecting the screen printing

Description	Extl	Intl	Adj
(1) Remove previous screen from machine.		x	
(2) Apply solvent and wipe ink off screen. Return screen to shelf.		x	
(3) Retrieve next screen from the shelf and setup instruction for the new print.		x	
(4) Mount new screen on machine.		x	
(5) Locate a standard sample of the new substrate pattern using the three pins.		x	
(6) Check/adjust approximate X-Y alignment by lowering printhead/screen on to the standard substrate.		x	
(7) Fetch specified ink bottle from the lab.		x	
(8) Apply specified ink over the new screen.		x	
(9) Run first piece and check X-Y alignment of wet film.		x	
(10) If X-Y adjustments is not within the tolerance, adjust X, Y, axis knobs. Wipe the standard test substrate clean and repeat earlier step.			x
(11) If X-Y alignment is okay, check for angular alignment.		x	
(12) If angular alignment is not okay, adjust the angular dial and repeat earlier step.			x
(13) If angular alignment is okay, check the wet film thickness.		x	
(14) If wet film thickness is not within the tolerance, adjust snap-off distance			x
adjust squeegee pressure			x
check the squeegee hardness			x
check ink viscosity			x
check for loose mechanism in the printhead			x

Table 7-1: Setup Analysis

process. The analysis of independent variables was done Sridharan [60]. It was reported that the problem of achieving and maintaining the circuit alignment was due to poor machine capability. However, the extreme difficulties in achieving and maintaining the correct thick film thicknesses were due to a very large number of variables, mostly external variables.

A permanent solution to the setup problem requires a thorough understanding of all independent variables pertinent to screen printing, especially to thick film thickness. Design of experiment was one of the alternative to study the effects of various variables.

7.3 Variable Analysis

The value and effectiveness of SPC techniques in improving productivity and quality in various manufacturing industries is well documented [2, 29, 64, 44, 47]. Use of SPC in hybrid manufacturing should be very valuable and effective in improving productivity and quality.

The critical variables affecting the screen printing process are discussed in detail in earlier chapters. Here only those variables that particularly affected the product quality based on the tolerance limits are considered.

Conductor/Termination Layer:

Alignment of all circuit lines with respect to the edge of the substrate is a very critical requirement for this layer. The following variables affect this characteristic:

1. Tension level in the screen mesh
2. Alignment of the exposed area on the screen with respect to the edge of the screen
3. Positioning and angularity of the printhead along the X and Y axis and Z axis respectively

4. **Rigidity of the mechanical structure of the screen printing machine**

Resistor Layer:

The location and orientation of the individual resistors with respect to the terminations in the conductor layer as well as the thickness of the wet film, dry film, and fired film are quality characteristics of the resistor layers. The location and orientation of the individual resistors is not much of a problem as the tolerance band is fairly broad, (2 mil compared to 1 mil for conductor/termination layer). The thickness of the resistor layer is the most critical quality characteristic for the resistor layers. The variables having impact on this characteristic are:

1. Ink/pastes: Not very well understood.
   - Viscosity of ink/paste --- currently varies from
   - Age of ink/paste in the bottle --- viscosity changes
   - Length of time on screen --- as solvent evaporates, viscosity increases
2. Screen: continuously changes during the process.
   - Screen tension
   - Emulsion thickness --- the squeegee abrasion wears the emulsion
   - Size and weave pattern of the screen
   - Impurities on the screen
3. Screen Printing Machine: process capability study should be done. Some problems may be caused by the poor design.
   - **Squeegee speed and the direction of the stroke**
   - **Snap-off distance**
   - **Squeegee pressure, hardness grade and color**
   - **Rigidity of the mechanical structure of the machine**

- **X, Y, and θ location on the printhead**
- **Dimension accuracy of the locator pins**

4. Operator probably the most important variable

    - Experience
    - Motivation
    - Awareness of cost of quality

5. Circuit Design: geometry effects

    - Resistor shape and size
    - Circuit pattern in underlying layers

6. Firing Conditions

    - Furnace air supply: adequacy and air supply
    - Furnace profile: temperature distribution and conveyor speed
    - Exhaust rate of burnout gases from firing environment

7. Measurement of Film Thickness: procedure and equipment

    - Accuracy
    - Repeatability

8. Laser Trimming

    - Quality of trimmer probes
    - Programmed maximum trim length

With so many variables affecting the thickness of wet, dry, and fired films, controlling the process involves tweaking of some controllable parameters to compensate for some uncontrollable variables. As seen from the earlier discussion, there are too many process variables interacting with one another. The behavior of the individual variables and their interactions are not well understood. As a result, no guidance or systematic approach is available to operator in form of past data, tables, or charts to get to the right controls. Setup analysis indicated that the tweaking or adjustment during the setup of operation, sometimes did not yield the desired quality. The operator sometimes had to go through a trial-and-error sequence using almost every possible adjustments on the machine to obtain the desired product quality. Further, what works once does not seem to work always. This explains the duration and stochastic nature of the setup times.

7.4 Design of Experiments

Based on a discussion with laboratory, SPC and operators in the print room, the following controllable variables were identified as "*most critical*" with relation to printer setup, film thickness and fired resistance. The variables are:

1. Thickness measurement instrument
2. Screen tension (or screen deflection)
3. Screen emulsion thickness
4. Snap-off distance
5. Ink viscosity
6. Squeegee pressure
7. Squeegee hardness

In the initial proposal, two three three level experimental designs, with three and four factors respectively, were proposed. Upon further study, it was found that the results from two separate three levels experimental designs may indicate some quadratic interactions and it would be difficult to interpret physical significance of those interactions. Also results from both separate experiments may present difficulty to establish a significant correlation. New proposal was to design experiments based on the design of experiments strategy. This involved experiments at two levels for all factors, followed by optimization, where empirical relationship between response and critical factors would be determined. In optimization stage, the critical factors were to be tested at three levels so that individual, interaction, and curvature effects could be estimated along with the experimental error.

After detail discussion for new approach, it was felt that thickness measurement equipment should not be considered as a critical factor and be dropped from consideration. Instead process capability of equipment should be performed to establish the repeatability and accuracy of the measurement. So final six factors were:

1. Screen Tension (or deflection)
2. Screen Emulsion Thickness
3. Snap-off Distance
4. Ink Viscosity
5. Squeegee Pressure
6. Squeegee Hardness (or durometer)

The response measured would be:

1. Wet film thickness (an approximate measurement)
2. Dry film thickness
3. Fired film thickness
4. Cross-sectional area (for fired film)
5. Resistance value

The benefits derived from such experimental design would be:

- determination of significance of variables
- ranking of the variables
- determination of the interactions of variables
- development of a problem solving approach

7.4.1 Design

Fractional factorial design was appropriate for the given case. One fourth replication of 2^6 factorial experimental design was agreed. This design would require $2^{6-2} = 2^4 = 16$ experiment runs, with major setup change involved only with 8-10 experiment runs. After setup is complete, five substrates would be run as a trial to achieve the appropriate tolerance. Eight substrates would be printed without any interference. Then measurements would be taken. All the pertinent information about the run would be recorded. ***NOTE***: Due the complexity of the setup involved, the randomization would not be considered. The results may show some bias. Future study must consider the randomization effects.

Consider the 2^{6-2} fractional design. Let six factor be A, B, C, D, E, and F. Selecting fourth order interactions as generating relations. Let generating relations (I) be

$$I = ABCE \text{ and } I = ACDF$$

The generalized interactions of the generators is BDEF, and thus the complete defining relation for this design is

$$I = ABCE = ACDF = BDEF$$

In this design each effect has three aliases. These are illustrated in Table 7-2

An approach to construct the design is to first write the combinations for a full $2^{6-2} = 2^4$ design in A, B, C, and D. Then remaining two factors are added by defining;

$$I.E = E.ABCE$$

$$\text{i.e., } E = ABC$$

and

EFFECTS	ALIAS		
A	BCE	CDF	ABDEF
B	ACE	DEF	ABCDF
C	ABE	ADF	BCDEF
D	ACF	BEF	ABCDE
E	ABC	BDF	ACDEF
F	ACD	BDE	ABCEF
AB	CE	BCF	ADEF
AC	BE	DF	ABCDEF
AD	CF	BCDE	ABEF
AE	BC	CDEF	ABDF
AF	CD	BCEF	ABDE
BD	EF	ACDE	ABCF
BF	DE	ABCD	ACEF
ABF	CEF	BCD	ADE
CDE	ABD	AEF	CBF

Table 7-2: Aliases

$$I.F = F.ACDF$$

$$\text{i.e., } F = ACD$$

The high (+) and low (-) factor levels are chosen to cover the extreme limits of the variables, so that the results could be interpolated within the range. The construction of the 2^{6-2} design with generators I = ABCE = ACDF is presented in Table 7-3.

The factors were chosen at two levels, high and low. Table 7-4 is listing of the factor levels for the experimental design.

A	B	C	D	E = ABC	F = ACD
−	−	−	−	−	−
+	−	−	−	+	+
−	+	−	−	+	−
+	+	−	−	−	+
−	−	+	−	+	+
+	−	+	−	−	−
−	+	+	−	−	+
+	+	+	−	+	−
−	−	−	+	−	+
+	−	−	+	+	−
−	+	−	+	+	+
+	+	−	+	−	−
−	−	+	+	+	−
+	−	+	+	−	+
−	+	+	+	−	−
+	+	+	+	+	+

Table 7-3: 2^{6-2} Design

7.4.2 Analysis

The Yates Algorithm would be used for analysis. Table 7-5 illustrates ANOVA analysis of the data.

This analysis would enable to rank the factors and indicate the influence on the product quality. Once this is established, optimization design, three level analysis with most critical factors, could be developed. This would eventually lead to model the printing process and predict precisely the effect of critical variables on the setup time and quality of the final product.

Experimental Design - Factors and Levels					
Factors	Symbols	Levels			
		Low		High	
Screen Tension	A	37- 45	lbs.	47- 60	lbs.
Squeegee Speed	B	6	in./sec.	12	in./sec
Squeegee Durometer	C	60	durometer	80	durometer
Ink Viscosity	D	140	Pa.- sec.	190	Pa.- sec.
Emulsion Thickness	E	0.1 - 0.2	mil	0.3 - 0.4	mil
Snap-Off Distance	F	10	mil	30	mil

Table 7-4: Factors and Levels

7.5 Recommendation

The setup analysis resulted in few procedural modification.

1. Supervisors' instruction, traveler and SPC charts for next run should be made available while previous run is still in progress.
2. Ink, screen, and squeegee should be stored at the same place.
3. Supervisors' instructions, SPC chart, ink, screen, and squeegee should in the form of a complete package which operator could pick up while the previous run is still in progress. This saves considerable amount of operator's time looking for individual things at various places.
4. Tap method for establishing the snap-off should be eliminated as it is least accurate and relies strongly on operator's experience. More accurate method like feeler gauge should be explored.
5. In case of zero method for snap off, the calibration should be periodically checked.

	Degree of Freedom
Main Effects: A,B,...,F	1 each for 6
First Order Interactions:	
AC (or BE or DF),	
AB (or CE), AD (or CF),	
AE (or BC), AF (or CD),	
BD (or EF), BF (or DE)	1 each for 7
Second Order Interactions:	
ABF, CDE	1 each for 2
Error	115
Total	127

Table 7-5: One-Fourth Replication of 2^6 Factorial Design

6. Screen checking should be done while production is still in progress.
7. Front of the screen should be clearly marked with an appropriate identifier so that operator could find the front the screen easily.
8. All inks (conductor, dielectric, backplan, resistor, etc.) should be stored in one area. There should be a log-book to keep the record of who has which ink, so in case same ink is required by another operator, he/she would know immediately who has the ink.
9. Explore the possibility of commercial automatic screen washer.
10. Cleaning the screen should be done after starting the next run.
11. Systematic record keeping should be encouraged. This would indicate any trends if any present.

These procedural modifications resulted in better organizing the print room and resulted in some improvement in the productivity.

7.6 Future Work

The success of these recommendations depends strongly on a continual effort to reduce the setup time. After the analysis, the next step is to a design three level experiment and develop an analytical model to relate the quality of the product to the process variables. Also further refinement of setup analysis should be carried out; efforts should be made to video tape the setup operations and study them with the operator to get the feedback to improve the setup. The printer supplier should be involved in this study. The possibility of innovative design modification should be kept open.

Chapter 8
Automation: A Hybrid Industry Perspective

8.1 Introduction

An overview of the automation available in the late 70s, would describe the effort as islands of process automation with all product movement and other processing done manually. Subsequently, the enhancement of the manufacturing process has been directed more toward increasing the rate of certain processes rather than automating and integrating the total system. Manufacturing in electronics involves multiple transformations of materials before the final products are realized. It is essential that this activity is viewed holistically and managed as a system. A successfully integrated manufacturing system will exhibit a seamless organizational continuum from design, through the manufacturing processes, out to the marketplace and the generation of ultimate customer satisfaction [33]. With today's equipment in microelectronics it is possible to have higher throughput rates, but, there still has not been a transition from the semi-automatic state to a fully automated integrated one [85].

Automation can provide many benefits including improved quality and lower costs. However, there should be a method for applying automation to manufacturing. The most appropriate method for developing a successful automation plan for manufacturing business is to first develop a *Manufacturing Strategy* which complements the business strategy. Once these have been defined, then an automation strategy can be developed and pursued [85].

8.2 Business Strategy

If the manufacturing is a key strategic resource for a business, it is essential to define the business objectives and to communicate them. Manufacturing related objectives are: [85]

1. Cost
2. Delivery Response Time
3. Product Customization
4. Design Innovation
5. Quality

For some businesses, success in the market is determined by product cost, and the lowest cost producer is most successful. In other markets, delivery response time is the key determinant of success. The ability to customize product could provide the leading edge. Today, quality and reliability are essential for most businesses, if they are to remain competitive. It is important that management have thought in detail and articulated the role of each of these elements in the business strategy. With this information, it is then possible to develop a manufacturing strategy which is consistent with the strategic goals of the business [81].

8.3 Manufacturing Strategy

This is one of the important areas of management decision related to factory automation. It is also one of the least understood, and as result, is often neglected in planning for automation. In many businesses, top management focuses on marketing and financial issues of business, while manufacturing is ignored. As a result, manufacturing is left to pursue a strategy completely independent of, and possibly inconsistent with the real needs of the business [81].

In the long run, if manufacturing is to support the strategic needs of a

business, management must define the business strategy first. Having defined and communicated the business strategy, the next step is to develop a relevant manufacturing strategy. The key strategic manufacturing factors are: [85]

1. Market
2. Volume
3. Technology
4. Quality
5. Reliability
6. Cost
7. Product Mix
8. Response Time
9. Flexibility
10. Infrastructure
11. Human Resources

The relative importance of these factors is strongly dependent upon the nature of the business. Understanding the inter-relationships of these factors is essential before undertaking the next step, i.e., development of automation strategy.

8.4 Automation Strategy

Once the business and manufacturing strategies have been established, then it is possible to develop an automation strategy which would complement them. Figure 8-1 shows a three axes system which has a key area of automation as each axis. These three axes are *process, information* and *materials*. Each of the axes could be developed independently, the total system requires that all axes be developed [7].

The **X** axis indicates the steps of automation for the manufacturing ***process***. Automation increases as we go up the **X** axis. Progression from com-

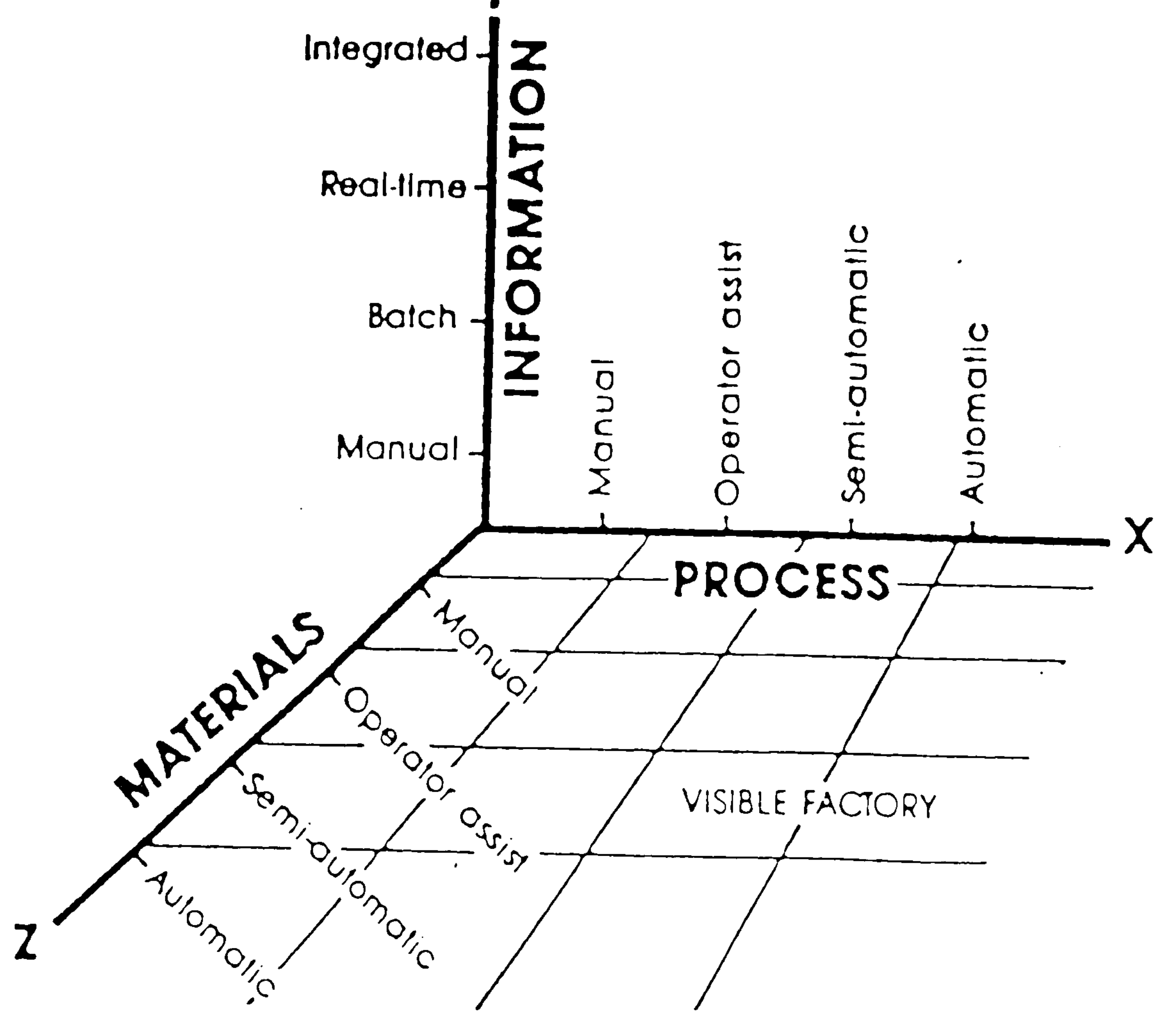


Figure 8-1: Three Axes System

pletely manual stages of operator/computer interaction to total automation (machine doing all the work). The **Z** axis represents the automation of the ***material*** handling systems and becomes more automated as **Z** increases. "Manual" refers to total human performance of the specific function while "automatic" implying complete mechanization of material handling and storage functions. The **Y** axis is the ***control*** or ***information*** axis. Beginning with clip boards and scrap of papers for control, the automation would result in a totally integrated system [7].

The **X** and **Z** axes are the foundations of the automated factory. These are also visible elements of automation. Without the **Y** axis, there would not be the ability to monitor and control the visible factory. Figure 8-2 reflects three axes inter-relationships [7].

Summary [85]

Process Mechanization	Materials Management	Management Systems	ASSESSMENT
(X Axis)	(Y Axis)	(Z Axis)	
Strong	Weak	Strong	Undesirable
Strong	Strong	Weak	Manageable
Strong	Strong	Strong	Most Effective

Figure 8-2: Three Axes Inter-Relationships

In order to successfully apply automation, there are three steps which must be taken:

1. establish the business, manufacturing, and automation strategies,
2. track and apply the existing technological developments, and
3. develop a [plan to implement the automation strategy in a manner that minimizes the disruption of the business.

Automation requires that each business should consider what it wants to do and develop a strategy accordingly. The most successful programs must involve all levels of management and preferably outside experts. The requirement of quality would demand the increase role of automation.

8.5 Automated Hybrid Printing

Making the move from a semi-automatic screen printing environment to a fully automated one is a big step. Fully-automated equipment is more expensive and more complex than the semi-automatic equipment, necessitating highly skilled personnel for operation and maintenance. However, the payoffs in increased production of quality product and scrap reduction could be worth the expense.

An automated screen printing has been around for over two decades [72, 51, 4]. Automatic equipment is optimized for high-volume hybrid production of the same type of circuitry. Whereas the semi-automatic equipment automates the printing process but still requires the human intervention for substrate loading and unloading, print registration, machine initiation, and quality control. It is also relatively affordable, easy to refixture and easy to operate and maintain. An automated screen printer reduces machine variability within the production lots, since the same equipment can handle an entire order. It reduces operator variation in registration, increasing print-to-print matches and reduces the scrap by reducing the amount of substrate handling. Automated screen printers are no more complicated to setup and maintain than semi-automatic equipment [45].

One set of selection criteria for automatic screen printer could be: [45]

- Speed or throughput
- Repeatability
- Setup Time
- Variable Substrate Sizes
- Design Quality & Simplicity
- Space Requirements
- Track Record and Support of Vendor

Chapter 9
Conclusions

With constant advances in multilayer hybrids, packaging techniques, and diagnostics abilities it is becoming feasible to put many integrated circuits down on a single board. Two film technologies are encountered in the hybrid area: thick film and thin film. The foregoing chapters discussed the thick film technology in detail. The term thick film is derived from the fact that the fired films are fairly thick, typically 10 to 50 μm (approximately 0.5 to 2 mil) in thickness. Thick film is a generic description for the field of microelectronics in which specially formulated inks are applied and fired onto a ceramic or insulating substrate in a definite pattern and sequence to produce a set of passive components. Conductors, resistors, dielectrics for capacitors and crossover, and solder sites can be fabricated with thick film technology. The most common process for obtaining thick films is the screen printing process. A high temperature firing sinters or oxidizes the metallic elements to develop the required component characteristics.

The screen printing process is the most difficult operation for the successful production of thick film circuits. As many as 20 to 30 variables have been identified, many of which are difficult to control. The following major variables should be understood and controlled to achieve a high-yielding printing process.

1. Rheological properties of inks
2. Screen tension and type
3. Emulsion thickness
4. Squeegee hardness and pressure
5. Squeegee speed
6. Snap-off distance
7. Circuit design

8. Overall cleanliness of the process

The basic functions of the screen printer are to provide a mechanism for mounting the screen, a method for holding the substrate, some method for aligning the circuit with respect to the substrate, and a mechanism to adjust the snap-off distance. As discussed in previous chapters, the setup of the printer is a major obstacle to high utilization and increased throughput. Sometimes more than 30 % of the cycle time is lost in setting up the printer to obtain quality product consistently. The setup analysis method suggested by Shigeo Shingo is an appropriate method for studying a printing operation. The importance of such analysis is illustrated in set of recommendations for the case study.

The number of variables involved in the screen printing leads to a need for variable analysis. A test matrix using *Design of Experiments* is required where the effects of each variable and interactions among variables can be estimated. Statistical process control is a very essential tool for the success of all these analyses. A process capability study should employ SPC to validate the success of implementing changes. Finally the most important, and commonly neglected fact is that ***better documentation and the designing of manufacturable tolerances would alleviate most of the problems associated with any process.***

The wave of "*advanced*" technologies and "*the Factory of the Future*" concepts has led to a rapid automation trend. The issue of automation must be evaluated carefully. The automation strategy of the company must reflect the business and manufacturing strategy. Additionally, the development of the manufacturing strategy must be consistent with the business strategy of the company. Management should be integrated covering all the phases of operations, whether it is design, or quality, or automation or developing manufacturing strategy.

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Working on a project for Ford Motor Company, Electronic Division, involving setup time reduction of thick film printing machines.
Designing statistical experiments to study the effect of key variables on the quality of film thickness.
Application of Single-Minute-Exchange-Die (SMED) approach to setup time reduction.
Worked on a computer program to blend batches of unacceptable mixtures to satisfy the desired characteristics.

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Supervised processing of Oxalic Acid from Rice Husk at agricultural chemicals manufacturing unit.
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