VARIABILITY REDUCTION IN STENCIL PRINTING OF SOLDER PASTE FOR SURFACE MOUNT TECHNOLOGY

MUSTAFFA BIN HAJI IBRAHIM

A thesis submitted in fulfillment of the requirements for the award of the degree
of Master of Engineering (Mechanical)

Institut Teknologi Tun Hussein Onn
Universiti Teknologi Malaysia

November, 1998

DEDICATION

Untuk ibu dan isteri tersayang,
Hajah Halimah Bte. Mohammed dan Widiawati @ Wahidah Bte Saia'an,
pengorbanan mu hanya Allah saja yang dapat membalasnya.

ACKNOWLEDGEMENT

The writer would like to convey his sincere appreciation to his supervisor, Tn. Hj. Khalid B. Hasnan for his consistent encouragement, advice and invaluable guidance throughout the course of this research project. A special thanks to the Sapura Electronics Industries Sdn Bhd. and Promosol Asia Pacific Sdn. Bhd. for their permission and co-operation given throughout the research activities in the factory and lab environment. Also my appreciation to the officers from Sirim Berhad for their contribution. Finally I would also thank those who have contribute directly or indirectly to the success of this project.

ABSTRACT

Competition in stencil printing to produce excellence in the finished product is intense. Faults in the printing process are a major source of board failure. Studies have shown that over 63% of defects identified after reflow originated from the solder paste printing (A. Lotfi ,1998) . However, understanding these failures are a challenging problem as the printing process has a large number of non linearly dependent variables such as factors relating to paste (formulation, viscosity), the environment (temperature, humidity) and machine parameter (alignment, pressure and speed of squeegee, blade hardness etc). The process engineer is challenged to widen the process window so that future modifications to the process, such as the addition of a new component, can be achieved with little, if any, change in materials or process parameters. This thesis reports the effect of temperature and humidity variation from the manufacturing environment on the solder paste consistency and optimization of the essential parameters of squeegee pressure, squeegee speed, separation speed and print gap. The outcome of variation in temperature and humidity to the solder paste viscosity were analyzed and tests were done to determine the characteristic of the solder paste. The tests results indicate that the temperature and humidity has an impact on the solder paste printability, thus some attempts must be taken to control these variables. For parameter optimization, the analysis was carried out using statistical optimization. The main aim was to combine these parameters with three main pitch categories to produce the acceptable print formation. The results showed that, the ideal print result requires optimum statistical combinations of four parameters essentially related to a particular pitch. It is also shown that there is a diversity and contrasts of the combination of the parameters for each category of pitch. Detailed explanations as to the phenomenon are outlined in the thesis.

Abstrak

Persaingan dalam mencetak pekatan pateri ke arah menghasilkan produk yang bermutu telah menjadi semakin sengit. Kerosakan yang disebabkan oleh proses mencetak adalah punca utama kepada kegagalan papan litar. Kajian yang lalu menunjukkan bahawa lebih 63% kerosakan yang dikesan datang nya dari proses mencetak pekatan pateri. Walau bagaimanapun, memahami kerosakan ini adalah masalah yang mencabar kerana proses ini dipengaruhi oleh banyak faktor yang tidak bertindak secara terus dan saling bertindak antara satu sama lain. Faktor-faktor yang berkaitan dengan pekatan pateri (formula, kelikatan), keadaan sekeliling (suhu, kelembapan udara) dan teknologi mesin pencetak (tekanan 'squeegee', kelajuan 'squeegee', kekerasan bahan 'squeegee'), dan lain-lain faktor. Jurutera proses dicabar untuk memper luaskan lagi tingkap proses pembuatan agar pada masa hadapan, modifikasi terhadap tingkap proses pembuatan seperti penambahan komponen baru, boleh dilakukan dengan sedikit, jika perlu, perubahan bahan atau perubahan proses pembuatan. Tesis ini melaporkan kesan variasi suhu dan kelembapan udara sekeliling kilang pembuatan dan proses mengoptimumkan parameter-parameter asas seperti tekanan 'squeegee', kelajuan 'squeegee', kelajuan pembebasan 'squeegee' dan kelegaan pencetakan. Kesan dari variasi suhu dan kelembapan udara terhadap kelikatan pekatan pateri telah dianalisis dan ujian-ujian dijalankan untuk menentukan ciri-ciri pakatan pateri. Bagi mengoptimumkan parameter-parameter, analisis dijalankan dengan kaedah statistik. Tujuan nya adalah untuk menggabungkan parameter-parameter ini dengan tiga kategori pic untuk menghasilkan cetakan yang unggul. Keputusan nya menunjukkan bahawa terdapat percanggahan dan kelainan dalam kombinasi parameter-parameter untuk setiap kategori pic. Penjelasan yang lebih jelas terhadap fenomena ini diterangkan dengan lebih lanjut di dalam tesis ini.

CONTENT

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW AND PROBLEM DESCRIPTION

Manufacturing electronic boards requires an extensive knowledge of the processes involved. The main processes are paste application, component placement and reflow. Each process has many machine and material parameters that affect the final product. All of these parameters are important, but only a limited number are considered 'critical'. The process window for each process in an SMT manufacturing line decreases in size as the pitch of the component decreases. Smaller operating windows have forced manufacturers to study processes in order to ensure that operating windows are maintained during full-scale production. Each process has a number of parameters that critically affect the product as it passes through that process.

The printing of solder paste is the foundation of the SMT assembly process. Maintaining a consistent print is the key to avoiding solder joint defects that result in lower than optimal yields, increased rework costs, and customer dissatisfaction due to increased levels of field failures. Preventing these defects by controlling the printing process provides significant cost advantages by eliminating rework, improving product yield, and reducing the number of field failures caused by marginal solder joints that pass in-circuit and functional testing. By controlling the process to a relatively stringent tolerance, additional margin can be introduced in the assembly process at the first stop. The result is a more robust process that can tolerate additional variation in the fine-pitch lead coplanarity, PCB variations, and slight component misplacement.

1.2 PREVIOUS STUDIES

Stencil printing evolves from screen printing, a process originally developed from the textile industry. Screen printing was embraced by the electronics industry for printing thick film inks, adhesives and solder pastes. Two approaches have been adopted in the modeling of printing in Thick Film technology. The first is based exclusively on the rheological behavior of ink, whilst the second considers the forces generated during the screen printing processes.

1. Trease and Dietz (1972) showed a hypothetical relationship of viscosity as a function of time during screen printing and the corresponding shear stress rates associated with major printing steps.

2. Miller (1974) investigated the effect of rheology of polymer solutions on their screening performance.

3. Evans and Beddow (1987) carried out morphological characterizations of solder paste particles and studied the rheological behavior of solder paste.

Most of these studies relate to thick film ink, and the data on solder paste printing performance is still meager, so efforts in obtaining the data are warranted. The viscosity of solder paste is much higher than that of inks. In ink printing, it is the pressure difference above and below the screen that causes ejection of ink during the snapping off the screen, whereas in solder paste printing it is the adhesion of the paste to the pad that is the dominant effect.

More recent attempts at modeling the paste printing process are based on investigating the various printing forces.

1. Hwang (1989) identified several forces that contribute to the paste transfer during printing.

2. Riemer (1988a, 1988b, and 1989) has investigated the hydrodynamics of screen printing of ink and derived the relationship between hydraulic pressure and some printing parameters based on adhesion theory.

3. Huner (1987, 1988) evaluated Riemer's model and proposed an upper bound alternative based on the blade coation analogy.

Both models, however do not address the problem associated with the rheological behavior of solder paste during printing, particularly the relatively coarser size of particles used in solder paste and the paste's vehicle and flux system.

A cooperative study was undertaken by a team of engineers from six companies in the United State (Dodly, 1985): Austin American Technology, IBM, Delco, MCC, Motorola and TI ; to determine the limits of fine pitch solder paste printing capability. Their investigation involved varying the stencil aperture size, squeegee blade hardness, squeegee speed, snap off distance, solder pastes and squeegee angle of attack in order to find the best printing conditions. As this study was undertaken commercially only very brief details of the results were reported in the literature, and commercial confidentiality prevented the release of the component pitch sizes tested.

Recently more studies have been carried out on improving the solder paste printing.

1. Li et al (1995) presented a statistical – neural network modeling to optimize the fine pitch stencil process. The aim of the study was to determine the optimum setting of the design parameters that would result in minimum solder paste variation for 20 mil, 25 mil and 50 mil component pitch.

2. Clouthier (1995) studied the performance of three stencils. The three stencils used in this study are :

- Chemically etched
- Laser cut
- Electroformed

3. Myklak and Coleman (1995) also studied the performance of a laser cut and a chemically etched stencil in which the apertures were electropolished on hybrid stencil.

Currently there are many universities, companies and research centers that have contributed to a broad understanding of the stencil printing process. However, the information and knowledge gathered is not shared publicly due to the confidentiality policy of the company or institute.

1.3 RESEARCH METHODOLOGY

The solder paste deposition process is effected by an abundant number of interactive variables including the solder paste (formulation and viscosity), the manufacturing environment (temperature, humidity), the stencil (type, aperture sizes), the squeegee (material), and the printer setup (squeegee alignment, pressure, speed, etc.). The goal of this study is to understand the interaction of some of these variables to the manufacturing environment, identify the significant process variables, and assess the current process capability. The Taguchi design of experiment (DOE) methodology will be presented (Appendix B). The information gained from the experimental analysis will be used to determine the capability of the stencil printing process. The work accomplished can be divided into two main parts:

- The Manufacturing Environment Effect on Solder Paste.

  To determine whether solder paste viscosity is a variable with respect to temperature and humidity. As temperature and humidity has an impact on viscosity so it does effects the printing process.

- Machine programmable parameter setting optimization

To investigate the effect of equipment variables (squeegee speed and pressure, print gap, squeegee separation speed) and determination of the process window for defect free printing.

1.4 STRUCTURE OF THE THESIS

There are six chapters in this thesis. Chapter two introduces surface mount technology assembly and its benefits. It also gives further background on the stencil printing process. The final section of this chapter examines the need for further research on solder paste printing.

Chapter three describes on the control of the printing process parameters. These parameters are related to the printer, the solder paste, the squeegee system and the environmental influence.

Chapter four reviews the experiments and tests done to investigate the influence of temperature and humidity to the solder paste viscosity and its printability settings. Chapter five presents the investigation done to determine the optimum settings of the design parameters (squeegee speed and pressure, print gap [snap off distance] and squeegee separation speed) that would result in minimum solder paste height variation for the board with 12 mil, 16 mil and 20 mil pitch pad patterns.

Chapter six presents the conclusion of the research. It reviews the results of the experiments and summarizes the contribution of this research work. It also identifies the potential areas for further work.

1.5 THE INDUSTRIAL COLLABORATORS

Three industrial partners were involved in the project reported in this thesis. These industrial partners are:

- SAPURA Electronics Industries Sdn Bhd
- PROMOSOL Asia Pacific Sdn. Bhd.
- DEK Printing Machines Ltd.

1.6 UNITS

The units used in industry for specifying stencil apertures is the mil, which is equivalent to one thousandth of an inch or conversion S.I units can be achieved using:

1 mil = 25.4 micron
1 mil = 0.001 inch
1 mil = 0.025 mm

CHAPTER 2

SURFACE MOUNT TECHNOLOGY

2.1 INTRODUCTION

Constant innovation in packaging technology to improve the product has been the history of the electronics industry and has resulted in a continual reduction in the size of various electrical components. This dynamic nature has gone from large vacuum tubes, to transistors, to initial integrated circuits (IC's) with six components, to the currently produced IC's with over a million components. This transition from vacuum tubes to megabit memories has taken place in approximately 50 years, less than the average lifetime of men.

Even as the active elements of electronics were shrinking, the method of packaging them has also been changing in form. This has gone from wire interconnections, to printed circuit boards (PWB) with components soldered in plated through holes, and now to the technologies discussed in this report - Surface Mount Technology (SMT) and Fine Pitch Technology (FPT). These transitions have taken place in even less time, approximately 30 years by some references.

2.2 What is Surface Mounting?

In conventional board assembly technology the component leads are inserted into holes through the PC board and connected to the solder pads by wave soldering on the reverse side (through-hole assembly). In hybrid circuits (thick and thin film circuits) " chips", i.e. leadless components, are reflowed onto the ceramic or glass substrate in addition to the components already integrated on the substrate. Surface mounting evolved from these two techniques (Figure 2.2). In through-hole technology the components are placed on one PCB side (component side) and soldered on the other (solder side) (Figure 2.2, top), whereas in surface mount technology the components can be assembled on both sides of the board (Figure 2.2, bottom). The components are attached to the PCB by solder paste or non-conductive glue and then soldered.

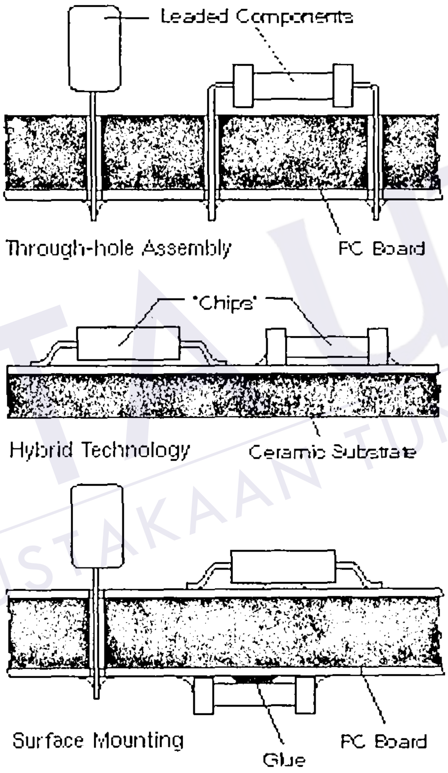

Figure 2.2: Through-hole Assembly -- Hybrid Technology -- Surface Mounting

So briefly, surface mount technology is the technique of attaching components only to the surface of the board. No holes are used in the process, only the board pads are soldered.

2.3 SMT Processes

There are five major subjects that make up the SMT electronics assembly process: (1) the PCB loading, (2) the Solder paste printing (3) component placement. (4) soldering, and (5) inspection and rework (Figure 2.3.1).

Figure 2.3.1: Basic SMT Processes.

Figure 2.3.1 shows the basic processes used in SMT electronics assembly. The assembly process begins with the PCB and preparing it for assembly. Next. solder paste is applied with a stencil in a solder printing process. The PCB then moves to the component placement machines. In many situations, a high-speed "chipshooter" will place small (passive) components; a fine-pitch machine will place components with great precision and accuracy (Figure 2.3.2).

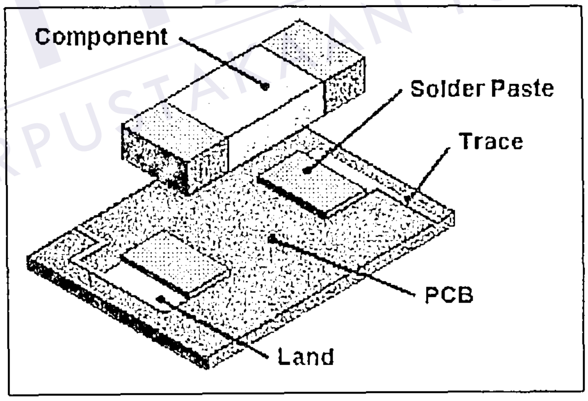

Figure 2.3.2: Main components of a typical SMT electronic assembly.

The entire board is then sent through a reflow oven. The reflow oven gradually heats the PCB until the solder flows and forms the solder joints. Finally, the board is inspected and tested. Soldering problems such as shorts and bridges are corrected at a rework station, if necessary, with specialized equipment.

2.4 Solder Paste Application Background

There are a variety of techniques for applying solder paste and adhesives to the substrate. They include screen and stencil printing, deposition by syringe and mass pin transfer. The dominant method in SMT assembly is stencil printing. Stencil printing emerged from screen printing, which was embraced by the electronics industries for printing thick film, inks, adhesives and solder pastes. The latter, characterized by larger particles and high viscosity, prompted the use of metal masks (stencil).

Stencil printing is a process that uses a stencil to create the pattern of lands on the substrate. The stencil printing process is usually the first step for SMT electronics assemblies. Since the substrate and the quality of the solder paste application will determine the overall quality of the assembly, it is also the most critical process. Solder paste printing is a process depending on many interacting variable (Hwang, 1989), (Table 2.4). Special attention to detail is required to prevent defective solder "prints" from perpetuating.

Solder paste is relatively easy to clean in the event of a poor print. However, any defects must be detected before entering the reflow oven when the solder fuses to the lands. The printing process begins with the stencil machine where the board is located and clamped. Then, the stencil is placed over the substrate. The machine must align the substrate with the stencil with great precision. A blade called a squeegee wipes the solder paste across the stencil. As the squeegee pushes the paste across the stencil, it presses the stencil against the substrate and forces the solder paste through the holes onto the substrate (Figure 2.4).

Table 2.4: Variables Affecting Solder Paste Printing (Hwang, 1989)

• Solder Paste Viscosity
• Solder Paste Particle Size
• Solder Paste Particle Shape
• Solder Paste Vehicle Rheology
• Solder Paste Metal Composition
• Solder Paste Percent Metal Content
• Flux Type And Activity
• Thixothropic Index
• Stepped Or Uniform Thickness Stencil
• Aperture Size
• Aperture Shape
• Aperture Arrangement
• Aperture Aspect Ratio
• Sidewalls Surface Finish : Electropolished Or Not
• Stencil Etching : One Side Or Both Sides
• Snap-Off Distance
• Squeegee Pressure
• Squeegee Speed
• Squeegee Angle
• Squeegee Blade Cross Section
• Squeegee Hardness
• Squeegee Material (E.G. Metal Vs Polyureth)
• Solvent Evaporation Or Absorption When Exposed To Air
• Stencil / Board Registration
• Stencil Material
• Stencil Cleaning Frequency
• Stencil Thickness
• Registration Repeatability
• Unidirectional Or Dual Directional Printing

REFERENCES

1. A. Lotfi and M. Howarth, "An Intelligent Closed-Loop Control of Solder Paste Stencil Printing Stage of Surface Mount Technology". The Nottingham Trent University, Nottingham, UK, August 1998.

2. Clouthier, R, "Appraising Stencils for Fine Pitch Printing", Surface Mount Technology, March, pp 60,62-64, 1995.

3. Dodly, G, " A Co-operative Screen Printing Project Report ", Microelectronic Packaging Technology, Material and Processes, Proceeding of the 2nd ASM International Electronic Materials and Processing Congress, Philadelphia, PA, USA, pp 281-293, April , 1985.

4. Ekere, N.N, Lo E.K, and Ismail,I, " Factors for controlling solder paste stencil printing quality ", Proc 8th Int. Conf. Computer-Aided Production Engineering Conference, Edinburgh, pp 105-110, August ,1992.

5. Ekere, N.N, Lo, E.K, Mannan, S.H, and I Ismail, " The future of solder paste printing for SMT reflow soldering", Soldering and Surface Mount Technology Journal, No 13, February, pp 22-25, 1993.

6. Ekere, N.N, Ismail, I, Lo.E.K and Mannan, S.H, " Experimental study of stencil-substrate separation speed in solder paste printing for reflow soldering", Journal of Electronics Manufacturing, Vol 3, No1, April , pp 25-29, 1993.

7. Ekere, N.N. Ismail.I. Mannan,S.H. Lo.E.K. " Experimental Study of the Printing of Solder Paste using metal Blade Squeegee system". Proceeding of 30th International MATADOR Conference, August,1993.

8. Ekere, N. N, Mannan , S . H, Lo, E.K, Ismail, I, " Application of ink screening models to solder paste printing in SMT assembly", Journal of Electronics Manufacturing, Vol 3, pp 113-120, 1993.

9. Ekere, N.N, Mannan, S.H, Ismail,I, Lo,E.K, " Squeegee Deformation Study in the Stencil Printing of Solder pastes" IEEE Transactions on Components, Hybrids and Manufacturing Technology, Vol17, No3, pp 470-476.September, 1993.

10. Ekere, N.N, Mannan, S.H, Lo,E.K, Ismail,I, " Predicting Scooping and Skipping in Solder Paste Printing for Reflow Soldering of SMT Devices", Soldering and Surface Mount Technology Journal, Vol 15, pp 14-17, October, 1993.

11. Ekere, N.N, Mannan,S.H, Lo, E.K, Ismail, I, " Process Modelling Maps for solder paste printing", Proc. of NEPCON Southeast Conference, Orlando, Florida, USA, October, 1993.

12. Ekere, N.N, Mannan, S.H, Lo, E.K, Ismail,I, " Squeegee deformation study in the stencil printing of solder pastes" IEEE Transactions on Component, Hybrids and Manufacturing Technology, Vol 17, No3, pp 470-476, September,1994.

13. Ekere, N.N, Mannan,S.H, Ismail, I, Currie, M.A, " Effect of Stencil Aperture Wall Finish and Shape on Solder Paste Printing in SMT", Proceeding of the 10th National Conference on Manufacturing research, Loughborough UK, September, pp 612-617, 1994.

14. Ekere, N.N, Mannan, S.H, Ismail,I, Currie, M. A. "Computer Stimulation of solder Paste Flow Part I: Dense suspension Theory" Journal of Electronic Manufacturing, Volume 4, Number 3, September, pp 149-154, 1994.

15. Ekere, N.N, Mannan, S.H, Ismail,I, Currie, M. A, "Computer Stimulation of solder Paste Flow Part II: Flow Processes", Journal of Electronic Manufacturing, Volume 4, Number 3, September, pp 149-154, 1994.

16. Ekere, N.N, Currie, M.A, Mannan, S.H, Ismail, I, " Solder paste characteristics and their effect on fine pitch printing", Fourth International Conference As Factory 2000, Advanced Factory Automation, University of York, U.K, October, pp 552-558, 1994.

17. Ekere, N.N, Currie, M.A, Mannan, S.H, Ismail, I, " Tensile strength of a Dense suspension : Solder paste", Submitted to the Journal of Material Science, Volume 4, December, 1994.

18. Evan, J. W and Beddow, J . K, " Characterisation of Particle Morphology and Rheology Behaviour of Solder Paste ", IEEE Trans Vol. CHMT-10, No 2, June, pp 224-231, 1987.

19. Frederickson, D, Michael, "Gage R&R and Utility Evaluation of Solder Paste Measurements Using Impedance Spectroscopy, American Competitiveness Institute, Electronics Manufacturing Productivity Facility, 1997.

20. Hobby, Alan, "Process solutions for printing solder paste down to 0.3mm pitch, DEK Printing Machines Ltd, Albany Road, Granby Industrial Estate, Weymouth, UK, 1997.

21. Hobby, Alan, "Fine pitch solder paste printing, The basic ", Dek Printing machines Ltd, Albany Road, Granby Industrial Estate, Weymouth Dorset DT4 9TH, England, 1997.

22. Hobby, Alan, "Auditing the printing process ", Manager, Applications Engineering, DEK printing Machines Ltd, January, 1997.

23. Huner, B, "Comment on : The Function and Performance of the Stainless Steel Screen during the Print Ink Transfer process", International Journal of Hybrid Microelectronics, Vol 10, No. 4, pp 6-13, 1987.

24. Huner, B, "A Simplified Analysis of Blade Coating with Application to the Theory of Screeb Printing", International Journal of Hybrid Microelectronics, Vol 12, No. 2, pp 88-90, 1988.

25. Hwang, J. S, "Solder Paste in Electronic Packaging", Van Nostrand Reinhold, New York, 1989.

26. Hwang, J. S, "Modern solder Paste for Competitive Electronics Manufacturing", McGraw Hill, 1996.

27. Ismarani, I, " Stencil printing of solder paste for reflow soldering of surface mount technology assembly ", PhD thesis, Department of Aeronautical, Mechanical and manufacturing Engineering, University of Salford, UK, 1995.

28. Li, Y, Mahajan, R.L, Nikmanesh, N, " Fine Pitch Stencil Printing Process Modelling and Optimization ", Advance in Electronics packaging, EEP-Vol. 10-1, ASME, March, pp 119-127, 1995.

29. Marks T, Gary and Sergent E, Jerry, AMTX Incorporated 5450 Campus Drive, Canandaigua, NY 14425, 1992.

30. Mearig, Joel, "Surface Mount manufacturing process Control", Process Research Engineer, Electronics Manufacturing Productivity Facility, 714 North Senate Avenue, Indianapolis, IN 46202-3112.

31. Mearig, Joel, "Stencil Printing Fine-Pitch", Process Research Engineer, Electronics Manufacturing Productivity Facility, 714 North Senate Avenue, Indianapolis, 1998.

32. Miller, L. F, " Screenability and Rheology ", Solid State Technology, October, pp 54-60, 1974.

33. Myklak, P.P, Coleman, W.E, " The hybrids stencil : A laser cut / Chem-etch stencil to optimize fine pitch stencil printing ", National Electronics Packaging & Product Proceeding of the Technical Program, Vol 2, pp 1116-1128, 1995.

34. Morris, R. John, Wojcik, Thaddeus, "Stencil Printing of Solder Paste for Fine-Pitch Surface Mount Assembly", IEEE Transactions on Components, Hybrid, And Manufacturing technology, Vol. 14, No. 3, September 1991.

35. Peace, Glen Stuart, :Taguchi Methods, A Hands On Approach", Addison-Wesley Publishing, 1993.

36. Ranjit K. Roy, "A Primer on the Taguchi Method" , Society of manufacturing Engineers, Dearborn, Michigan, USA, 1990.

37. Riemer, D.E, " Analytical Engineering Model of the Screen printing Process : Part 1 ", Solid State Technology, August, pp 107-111, 1988.

38. Riemer, D.E, " Analytical Engineering Model of the Screen printing Process : Part 2 ", Solid State Technology, September, pp 85-90, 1988.

39. Riemer, D.E, " The Function and performance of the Stainless Steel Screen during the Screen Print Ink Transfer process ", International Journal for Hybrid Microelectronics, Vol 10, No. 2, pp 1-8, 1987.

40. Sammy G. Shinna, Dennis Gagne, Mike Quaglia, "Method for Paste Selection and Process Optimization for Fine Pitch SMT", University of Massachusetts Lowell Manufacturing Laboratory, 1995.

41. Scheiner, David, " Solder Materials ", Kester Solder Div. Litton Industries, 515 E. Touhy Ave.,Des Plaines, Ill. 60018 - 2675 ; (847) 297-1600, 1998.

42. Trease R.E and Dietz R.L. "Rheology of Pastes in Thick Film Printing ". Solid State Technology, January, pp 39-43, 1972.

43. Y. Li, R.L. Mahajan, "Fine pitch stencil printing process modelling and optimization ", Center for Advanced Manufacture & Packaging Of Microwave. Optical and Digital Electronics, Department of Mechanical Engineering. University of Colorado. Boulder. TR95-08,1995.