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CUKUROVA UNIVERSTY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

M.Sc. THESIS

Murat ÇAKIRCA

ALTERNATIVE PROPOSALS FOR AUTOMATING REWORK OF ADVANCED SURFACE MOUNT COMPONENTS

DEPARTMENT OF MECHANICAL ENGINEERING

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ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

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YÜKSEK LİSANS TEZİ

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ABSTRACT

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ALTERNATIVE PROPOSALS FOR AUTOMATING REWORK OF ADVANCED SURFACE MOUNT COMPONENTS

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DEPARTMENT OF MECHANICAL ENGINEERING
INSTITUTE OF NATURAL AND APPLIED SCIENCES
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Owing to the inevitably increasing complexity in the printed circuit board assemblies (PCBAs), continuing improvements in current state of art technology remain elusive to achieve 100 percent manufacturing yields. Hence, rework and repair of complex, high value PCBAs is inevitable process during their service life. Additionally, due to the complicated natural structure of advanced surface mount components (SMCs) coupled with the novel technological requirements, there is a significantly growing need for a fully automated robotic rework system that can carry out the whole rework process of the advanced SMCs on the basis of a batch size of one. Thus, this study substantially aims to investigate and find out viable alternative proposals for fully automated, robotic rework of advanced type SMCs by effectively scrutinizing existing manual rework procedures, methods, tools and currently available technology on automation including industrial robots, sensory devices, inspection and control equipments etc.

Development of such an automated robotic rework cell system was found to be technically and economically possible.

Keywords: Automated PCBA Rework, Advanced SMCs, Robotic Rework, Automated Advanced SMCs Rework.

ÖZ

YÜKSEK LİSANS TEZİ

YÜZEYE YAPIŞIK İLERİ DÜZEY ELEKTRONİK DEVRE ELEMANLARININ TAMİRİNİ OTOMATİK OLARAK YAPABİLEN UZMAN ROBOTİK TAMİR SİSTEMİ GELİŞTİRMEK İÇİN ALTERNATİF ÇÖZÜMLER

Murat ÇAKIRCA

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
MAKİNA MÜHENDİSLİĞİ ANABİLİMDALI

Danışman : Prof. Dr. Necdet GEREN

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: Yrd. Doç. Dr. Murat AKSOY

Günümüz teknolojilerindeki ilerlemelere rağmen, baskılı devre kartlarına elektronik devre elemanlarının montajındaki giderek artan zorluklar %100 hatasız üretimi imkansız kılmaktadır. Bu nedenle, karmaşık ve pahalı olan devre kartlarının tamiri kaçınılmaz bir işlem olmuştur. Ayrıca, hem ileri düzey elektronik devre elemanlarının doğal karmaşık yapıda oluşları hem de yeni teknolojik gereksinmelerden dolayı tek bir elektronik ürünün hedeflendiği grup üretimi esasına göre ileri düzey elektronik devre elemanlarının bütün tamir işlemini gerçekleştirebilen tamamıyla otomatikleştirilmiş, robotik tamir sistemine önemli derecede giderek artan bir ihtiyaç vardır. Bu çalışmada, yüzeye yapışık ileri düzey elektronik devre elemanlarının tamirini tamamıyla otomatik olarak yapabilen bir uzman robotik tamir sistemi geliştirebilmek için çeşitli alternatif çözüm yollarının ve önerilerinin mevcut tamir işlemleri, kullanılan teknikler, araçlar ve otomasyon için gerekli endüstriyel robotlar, algılayıcılar, denetim ve kontrol ekipmanları vb. konular detaylı olarak araştırılıp incelenerek ortaya çıkarılması hedeflenmiştir.

Böyle bir otomatikleştirilmiş, robotik tamir sistemi geliştirilmesinin teknik ve ekonomik açıdan mümkün olduğu görüldü.

Anahtar Kelimeler: Otomatik Baskılı Devre Kartı Tamiri, İleri Düzey Elektronik Devre Elemanları, Robotik Tamir, Otomatik İleri Düzey Elektronik Devre Elemanları Tamiri.

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1. INTRODUCTION

On the eve of the new millennium, printed circuit boards (PCBs) are used in the widespread application areas from handheld consumer electronic products to sophisticated electronic tools of military and space industry. Substantially, for such a wide application range, variety of different electronic devises is employed in printed circuit board assemblies (PCBAs), which make the PCBAs inevitably more complicated processes.

1.1. Overview of Printed Circuit Board Technology

The printed circuit or wiring board is a substrate on which electronic components are mounted for electrical interconnection and mechanical support. The interconnection is provided by patterned metal tracks either on the surface or on the inner layers of the printed circuit board. Based on the raw materials used for manufacture, PCBs can be either organic or ceramic boards. The PCBs are identified using several criteria. One of the criterions is the method of manufacturing; single sided, double sided, and multilayer boards (Blackwell, 2000-(3); Mahajan, 2001; Cluff and Pecht, 2001). Another is the type of substrate utilized; rigid boards, flexible and rigid-flex boards, metal-core boards, and injection molded boards (see Figure 1.1 and 1.2) (Blackwell, 2000-(3).

Keeping the above descriptions in mind, the circuit boards can be mainly classified according to their manufacturing methods. Single sided boards have circuits on one side of the board. Double sided boards have circuits on both sides of the boards, but no inner layers (Blackwell, 2000-(3); Cluff and Pecht, 2001). The growing pin count of ICs has increased the routing requirements, which led to multilayer boards. Multilayer boards typically consist of several layers of circuits in which the top and the bottom layers essentially planned for component mounting, and the interconnecting tracks are buried in the inner layers of construction, with plated through holes (PTHs) connecting the various layers (Blackwell, 2000-(3); Mahajan, 2001). In multilayer boards, the PTHs can be buried (providing interconnection between inner layers), semiburied (providing interconnection from one of the two outer layers to one of the internal layers), or through vias (providing interconnection between the outer two layers), see Figure 1.3, (Blackwell, 2000-(3).

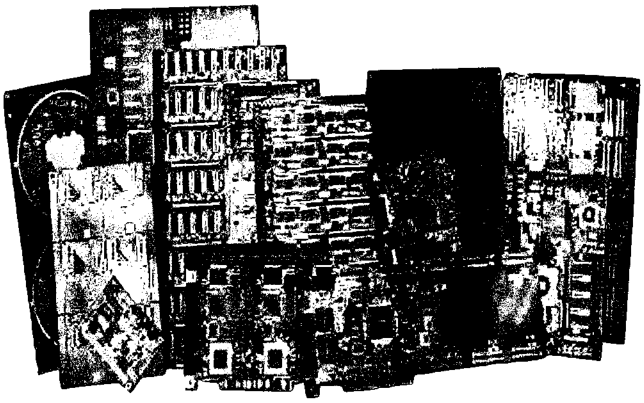
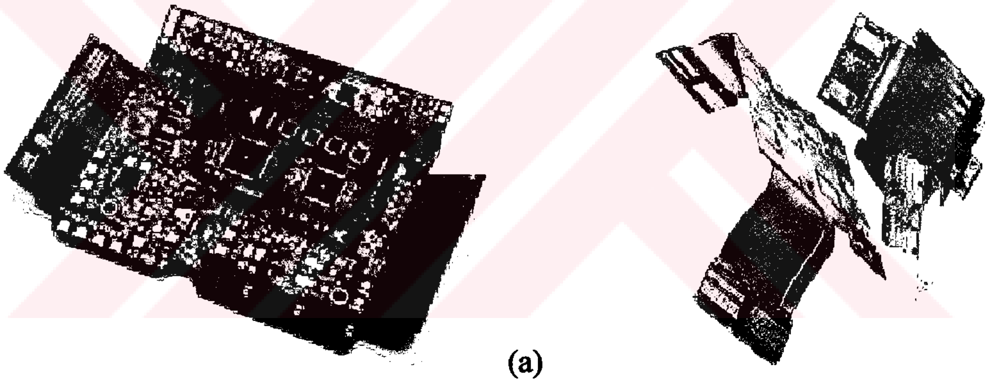


Figure 1.1. Typical Rigid Boards (http://www.welsa.com, 2003)



(a) (b)

Flexible Rigid-flexible

Figure 1.2. Flexible Boards (Liu, 2001)

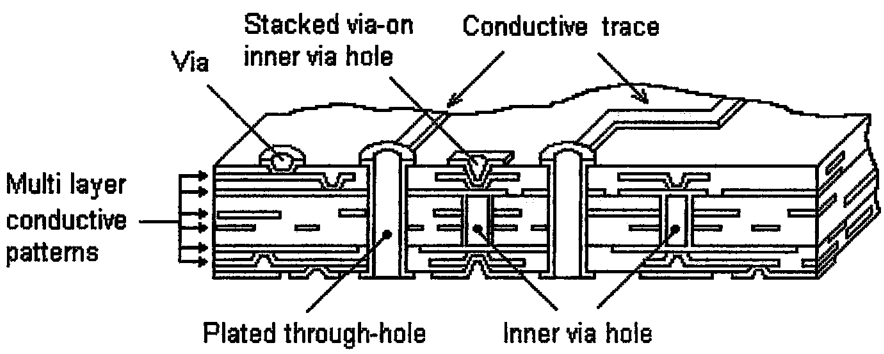


Figure 1.3. Schematic of Typical Multilayer Board

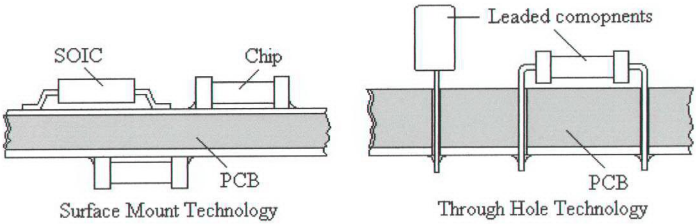
Many types of base materials are available, and the most commonly used is (fire resisted) FR-4 epoxy glass (Blackwell, 2000-(3); Mahajan, 2001; Cluff and Pecht, 2001). Table 1.1 shows some key parameters and the relative costs of common base materials employed in the manufacture of the PCBs.

Table 1.1. Comparison of Common Printed Circuit Board Materials (Cluff and Pecht, 2001)

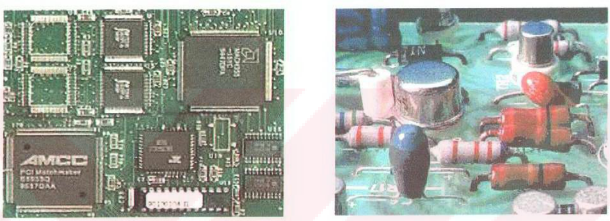
Substrate Material	Glass Transition Temp. (°C)	In-Plane CTE (ppm/K)	Relative Cost (FR-4 = 1)
FR-4 epoxy-glass	125–135	14–16	1
Polyfunctional FR-4	140–150	14–16	1.1–1.5
Multifunctional FR-4	150–170	14–16	1.1–1.5
Polyimide-glass	210–220	12–14	2–3
BT epoxy	180–190	13–17	1.1–1.5
Cyanate ester-glass	240–250	11–15	4–5
PPO epoxy	175–185	12–13	2–3
PTFE-glass	327 melting	70–120	15
Alumina	N/A	6.8	8–12

1.2. Mounting Technologies in Electronics Assembly

Conventional Through Hole Technology (THT) to assemble traditional electronic components reached its limits in terms of improvements in cost, weight, volume and reliability (Coombs, 1988; Prasad, 1989). Surface Mount Technology (SMT) permits production of more reliable assemblies with better performance at increased density, decreased weight, volume and cost (Bergman, 1999; Lee, 2002). With THT, electronic components are inserted through holes in the PCBs (Prasad, 1989). On the contrary, SMT is used to mount the electronic components on the surface of PCBs without holes for leads (Blackwell, 2000-(1); Khandelwal and Shenai, 2000). Figure 1.4 simply depicts the difference of these technologies.



(a) Schematic View of Technologies (http://www.electrocomponents.com, 2003)



(I) Surface Mount Technology (II) Through Hole Technology

(b) Real Photographs of Technologies (http://www.workmanship.nasa.gov, 2003)

Figure 1.4. Comparison of Surface Mount and Through Hole Technology

Surface mounting solves many of the shortcomings of the THT. The primary advantage of surface mounting is improved performance and savings in space at the PCB and system levels. This savings in space can reduce PCB costs by as much as 60 percent, while improving performance at the same time (Bogatin, 1997). The conspicuous advantages of implementing SMT can be summarized as follows (Bogatin, 1997; Bergman, 1999; Blackwell, 2000-(1);

- Reduction in PCB size, weight, and number of layers in PCB
- Increased circuit density and improved electrical performance
- Reduction in trace lengths on the PCB, with correspondingly shorter signal transit times and potentially higher-speed operation
- Higher SMT product quality and reliability with reduced handling costs
- Ease of SMT component assembly automation, rework and repair (because of the complexity and density of some assemblies proper design and process

control are essential if the reduction of processing costs, rework and repair are to be achieved)

- Reduction in board assembly cost through automation

Due to the outstanding features of SMT, it has replaced the THT increasingly in every application areas of electronics (Bogatin, 1997). Figure 1.5 shows the transition of technology from through hole to surface mount.

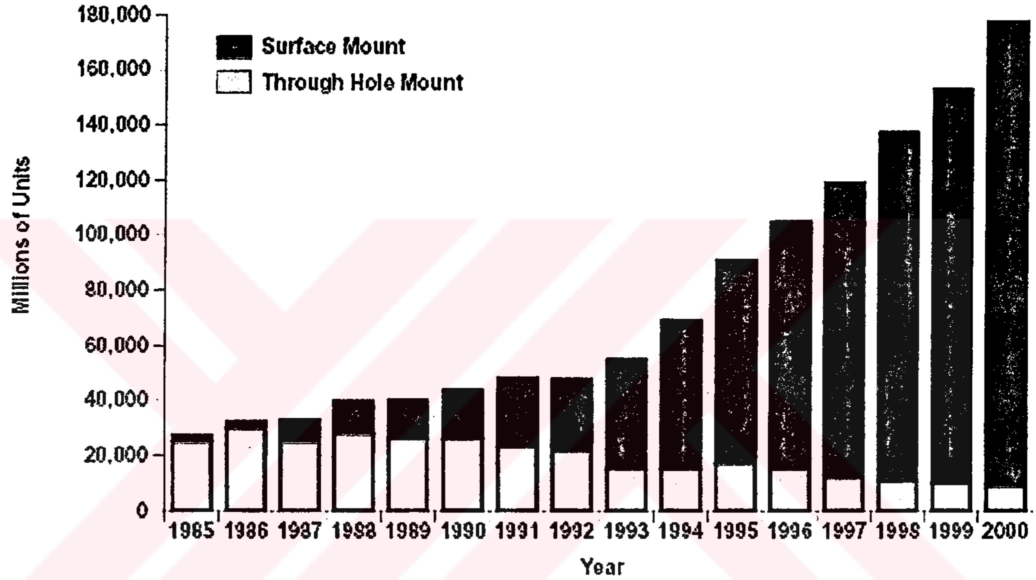


Figure 1.5. Transition from Through Hole to Surface Mount (Bogatin, 1997)

However, SMT is not without limitations. Presently, due to continuous miniaturization in electronics, SMT technology has some difficulties as far as component assembly, inspection, repair and rework are concerned. Fortunately, with the continuous effort of committees of Institute for Interconnecting and Packaging Electronic Circuits (IPC), Electronic Industries Association (EIA) and the like, essential process parameters and standards have been addressing (Bergman, 1999).

Obviously, most of the current products, such as digital watches, laptop computers, mobile phones etc., would not be possible without the size and cost advantages of SMT (Blackwell, 2000-(1). Various end use applications for electronic products have been categorized into three general groups. These are (Bergman, 1999; Blackwell, 2000-(2):

1. General Electronic Products: Includes consumer products, some computer and computer peripherals, and hardware suitable for applications where the major requirement is function of the completed assembly.

2. Dedicated Service Electronic Products: Includes communications equipment, sophisticated business machines and instruments and military products where high performance and extended life are required, and for which uninterrupted service is desired but not critical.

3. High Performance Electronic Products: Includes equipment of commercial and military products where continued performance or performance-on-demand is critical under varying conditions.

1.3. Surface Mount Components

Surface mount components (SMCs) are available for almost any type of application, such as capacitors, resistors, transistors, diodes, inductors, integrated circuits (ICs), and connectors (Lee, 2002).

IC components have been developed over time to meet the requirements of faster, smaller, lighter, and lower cost electronics systems. The history of IC package development has been the continuous battle to miniaturize (Khandelwal and Shenai, 2000). Surface mount ICs come in a wide variety of packages, from 8-pin small outline packages to ≥1000 connection packages in a variety of sizes and lead configurations (Blackwell, 2000-(1). While the IC possibilities become overwhelming, the most common commercial component packaging formats currently include plastic leaded chip carriers (PLCCs), small outline packages (SOPs), quad flat packs (QFPs), Ball grid arrays (BGAs), and other newer technologies (Blackwell, 2000-(1); Lee, 2002).

Despite many types of SMCs, as illustrated in Figure 1.6 there are only four major lead types with numerous variations of each.

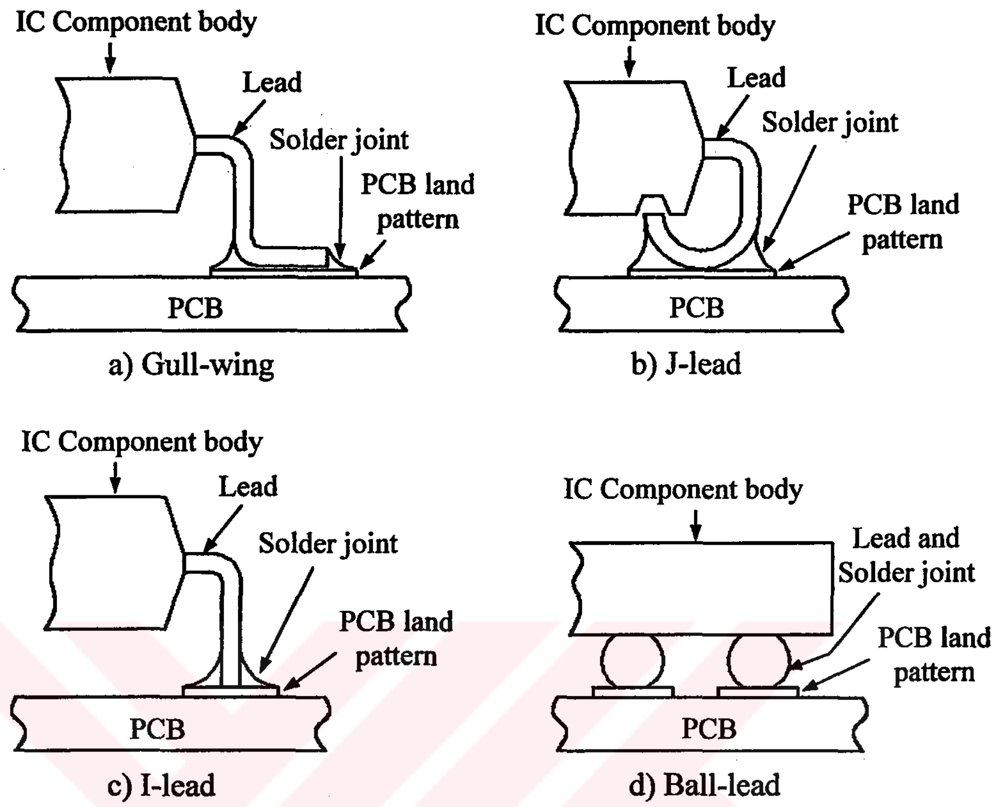


Figure 1.6. Lead Configurations of SMCs

However, in spite of the variations in SMT component types, a comprehensive classification of IC components can be made based on the package construction including; Ceramic, Plastic, and Metal packages (http://www.intel.com, 2003; http://www.philips.com, 2003). Figure 1.7 shows the classification of the packages.

Plastic packages are very popular in commercial applications because of their low cost and small size compared to ceramic packages (Cluff and Pecht, 2001). Ceramic and metal packages have been used predominantly for military and space applications because of their perceived reliability advantage over plastic packages. Metal packages are typically used for small integrated circuits with a low lead count and in applications that require electromagnetic shielding (Cluff and Pecht, 2001). Ceramic and metal packages are hermetically sealed which means that all external chemical species (especially moisture) are permanently prevented from entering into them (Cluff and Pecht, 2001; Khandelwal and Shenai, 2000). Currently, plastic and ceramic type packages are widely used in electronics.

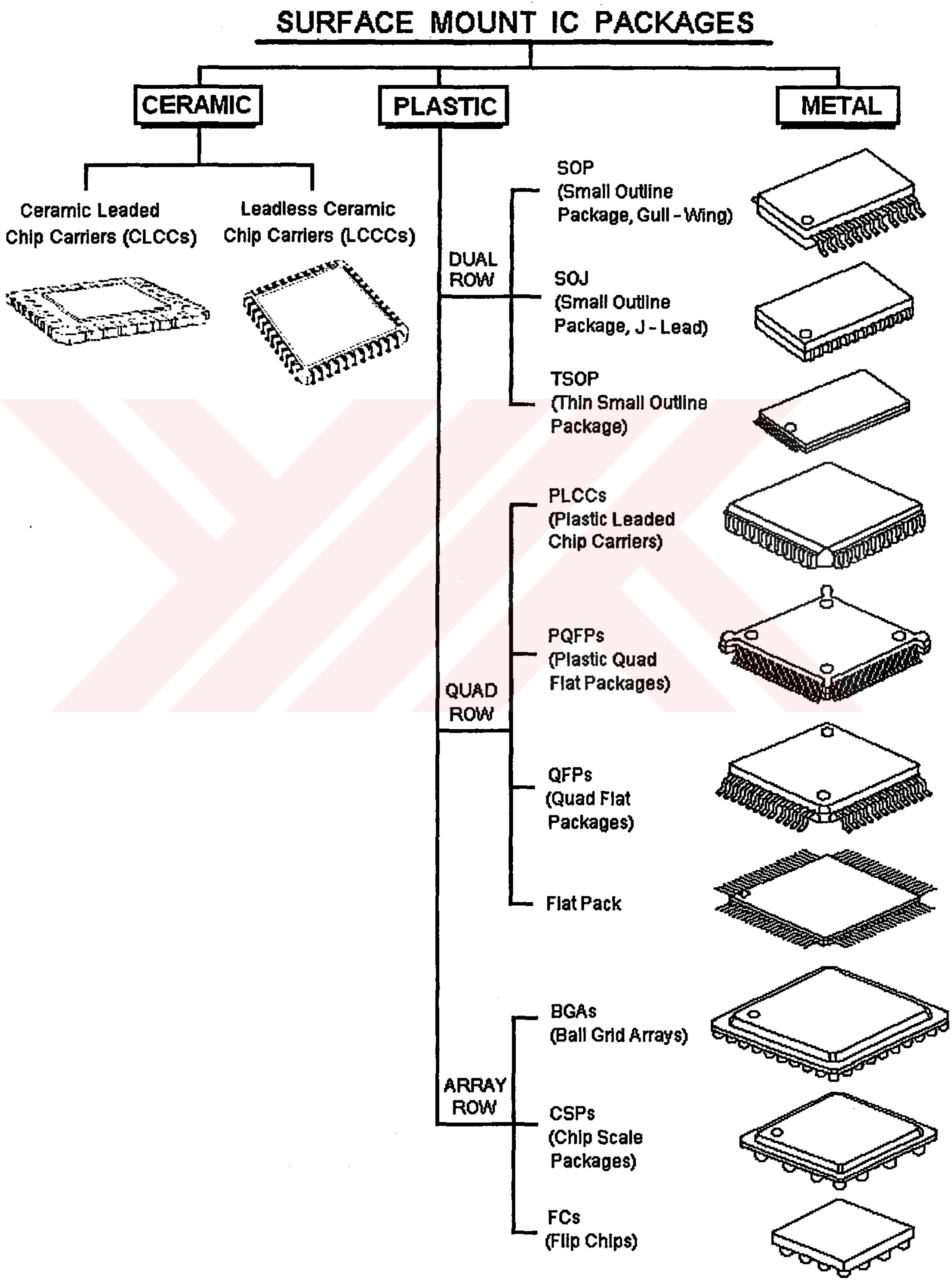


Figure 1.7. Classifications of the Surface Mount IC Packages

The array row of the plastic packages consists of the Ball Grid Arrays (BGAs), Chip Scale Packages (CSPs) and Flip Chips (FCs) (see Figure 1.7). These packages are area array types and are also called advanced type SMCs. They have followed the path of surface mount technology providing faster, lighter, smaller and less expensive electronics. Since these advanced type IC components are the scope of this study, only a general overview of those is given below.

1.3.1. Ball Grid Arrays (BGAs)

In SMT, integrating more and more functions into the same silicon die forces the surface mount packages progressively evolved toward higher densities and finer pitches (below 0.5 mm pitch sizes) (Bergman, 1999; Bird, 1999; Virpi et al., 2000; Mahajan, 2001; Cluff and Pecht, 2001). However, at reduced pitches, the peripherally leaded fine-pitch packages with their fragile leads susceptible to serious handling damages such as lead coplanarity and lead bending (Bird, 1999; Mahajan, 2001). Furthermore, the fine pitch problems with paste printing, placement and cleaning makes the process window tighter. When it became clear that peripherally leaded packaging had reached its practical limits, area array packaging came to forefront of package technology and new packages called BGAs have been emerged and drastically become very popular (Prasad, 1999; Mahajan, 2001; Lee, 2002).

The BGA is an area array package which uses solder bump interconnections instead of leads (Prasad, 1999; Mahajan, 2001). Solder balls are located underside of the package in a full array or perimeter array forms. They usually compose of 63% tin and 37% lead or high temperature 10% tin and 90% lead compositions (Cluff and Pecht, 2001). As shown in Figure 1.8, among the variety of different package configurations, BGAs can be classified into three main categories including, Plastic Ball Grid Arrays (PBGAs), Ceramic Ball Grid Arrays (CBGAs), Tape Ball Grid Arrays (TBGAs) (Tazi and Bergman, 1999; Prasad, 2001-(1); Chen et al., 2002). CBGAs and PBGAs are the common types of BGAs used in electronics (Mahajan, 2001).

Basically, family of BGA packages could be divided into to two groups of pitches. The first group is regular which are 1.50, 1.27, and 1.00 mm. The second group is the fine pitch, which has the following pitches 0.80, 0.75, 0.65, 0.50, 0.40 and 0.30 mm. The present usage shows that the 1.27 mm as being the most popular followed by the 0.80, 1.00, 0.75, and 0.50 mm (Bergman, 1999).

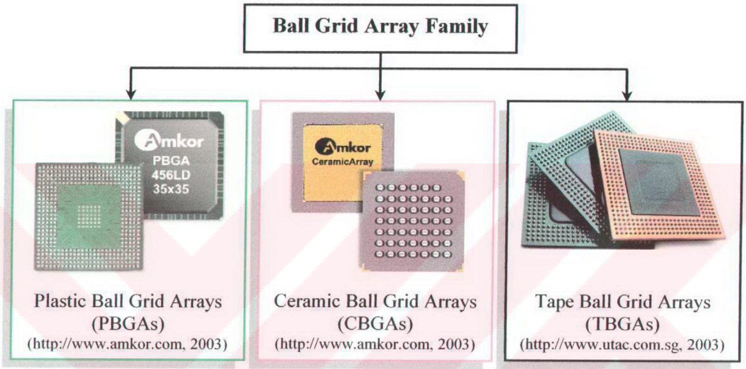


Figure 1.8. Ball Grid Array Types

Applications requiring improved portability, form-factor/size and high-performance such as microprocessors/controllers, application specific integrated circuits (ASICs), memories (SRAM, DRAM, Flash), digital signal processing devices (DSPs), programmable logic devices (PLDs), graphics and PC chip sets and other similar products benefit from BGA technology attributes (http://www.amkor.com, 2003).

1.3.2. Chip Scale Packages (CSPs)

It was stated that while emergence of BGA satisfies the need for high I/O density, it slows the drive toward finer pitch. However, with increasing demand toward further miniaturization, the packaging technology of BGA also reduces over time and consequently results in CSPs (Lee, 2002). CSPs are multi-I/O packages that are no larger than 1.2 times (20%) the area of the bare IC chip (Cluff and Pecht, 2001; Nguty et al., 2000-(1); Naugler, 2002). They are miniaturized and enhanced versions of the BGAs and their names like miniBGA and μBGA indicate this (see Figure 1.9). Unlike BGAs at typically 1.27 mm pitch, CSPs utilize lower pitches, e.g. currently 0.8 mm to 0.4 mm and provide higher packaging density than BGAs (Bergman, 1999; Bird, 1999; Ghaffarian, 2000).

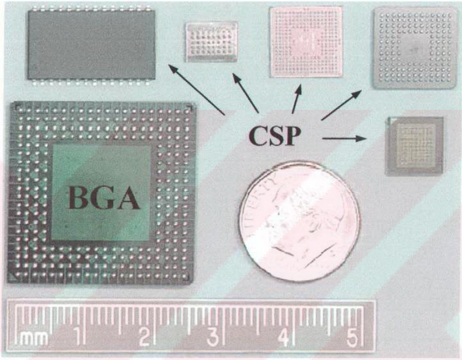


Figure 1.9. Miniaturization Trend from BGA to CSP (Ghaffarian, 2003)

To combine the advantages of both packaged chip and bare chip in one solution, a variety of CSPs have been developed such as leadless packages similar to LCC structure, leaded packages similar to a gull-wing package and array packages similar to BGAs (see Figure 1.10) (Bogatin, 1997; Khandelwal and Shenai, 2000).

Recently, it was reported that there are more than 150 different styles of CSP and some of the common names for CSPs are Fine Pitch BGA (FBGA), micro BGA (μBGA), and Small Outline No Lead (SON) (Bird, 1999). Among the variety of CSPs the most popular one is the μBGA (see Figure 1.11).

End use applications for CSP technology include personal digital assistants (PDAs), camcorders, notebooks/subnotebooks, mobile phones, memories (SRAM, DRAM, flash), low-pin count low-power ASICs, microprocessors and other wireless and consumer products (http://www.amkor.com, 2003).

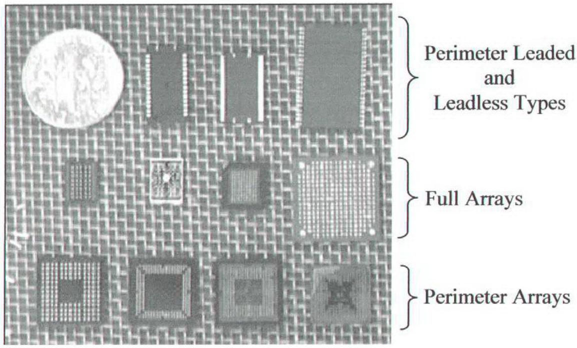


Figure 1.10. Examples of CSP Devices (Chen et al. 1999)

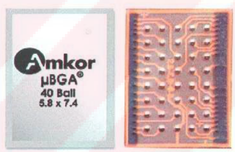


Figure 1.11. µBGA (http://www.amkor.com, 2003)

1.3.3. Flip Chips (FCs)

During the inevitable evolution of IC packaging towards the miniaturization, the aim is to increase the packaging density, improve the performance while still maintaining or even improving the reliability. At the same time, product costs should remain at a sufficiently low level with high assembly yields and throughput. These somewhat contradictory requirements are difficult to fulfill with conventional SMD technology. Thus, new design solutions, as well as advanced packaging and substrate technologies are needed to meet the challenge. FCs are one of the solutions meeting these requirements (Boustedt and Vardaman, 1997; Savolainen, 1998; Beelen-Hendrikx and Verguld, 1998).

FC technology is a "face-down" attachment of the active side of the silicon chip onto the substrate. In terms of packaging efficiency, this technology reaches the ultimate goal of reducing component size (see Figure 1.12) (Wang and Wong, 2000; Blackwell, 2000-(4); Lee, 2002).

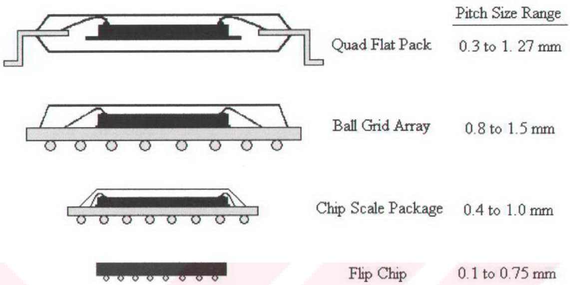


Figure 1.12. Shrinking Size of Packaging

FC technology can be used either inside a package, called Flip Chip in Package (FCIP) or directly on board, called Flip Chip on Board (FCOB) or Direct Chip Attach (DCA). FCIP technique has been used in many BGAs and CSPs, especially those with high I/O count, high performance components (see Figure 1.13) (Wang and Wong, 2000).

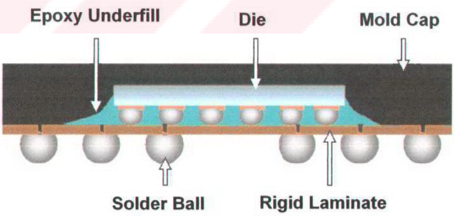


Figure 1.13. Cross Sectional View of a Typical Flip Chip in Package Application (http://www.amkor.com, 2003)

Application areas of FC technology include automotive industry, computers, smart cards, telecommunication equipments, liquid crystal displays (LCDs) and watch modules, etc (Zhong, 2000).

1.4. Type of Electronics Assembly Processes

The electronic component assembly types can be mainly divided in two groups (Bergman, 1999; Blackwell, 2000-(1);

- Type 1: Components (SMT and/or THT) mounted on only one side of the board
- Type 2: Components (SMT and/or THT) on both sides of the board or interconnecting structure

In addition to that, these types are further subdivided by the types of components mounted on the board (Bergman, 1999; Blackwell, 2000-(1) and some of these assembly types are illustrated in Figure 1.14.

- Class A: Through hole components mounting only
- Class B: Surface mounted components only
- Class C: A mixture of simple through-hole and surface mount components
- Class X: Through hole and/or complex surface mount components, including fine pitch and BGAs
- Class Y: Through hole and/or complex surface mount components, including ultra fine pitch and CSPs
- Class Z: Through hole and/or complex surface mount components, including ultra fine pitch, chip on board (COB), flip chip, and tape automated bonding

Currently mixed assembly types are used in electronics industry (hybrid assembly technology). All the assembly types require different process sequences and equipments. The process flows of assemblies are shown in Figure 1.15.

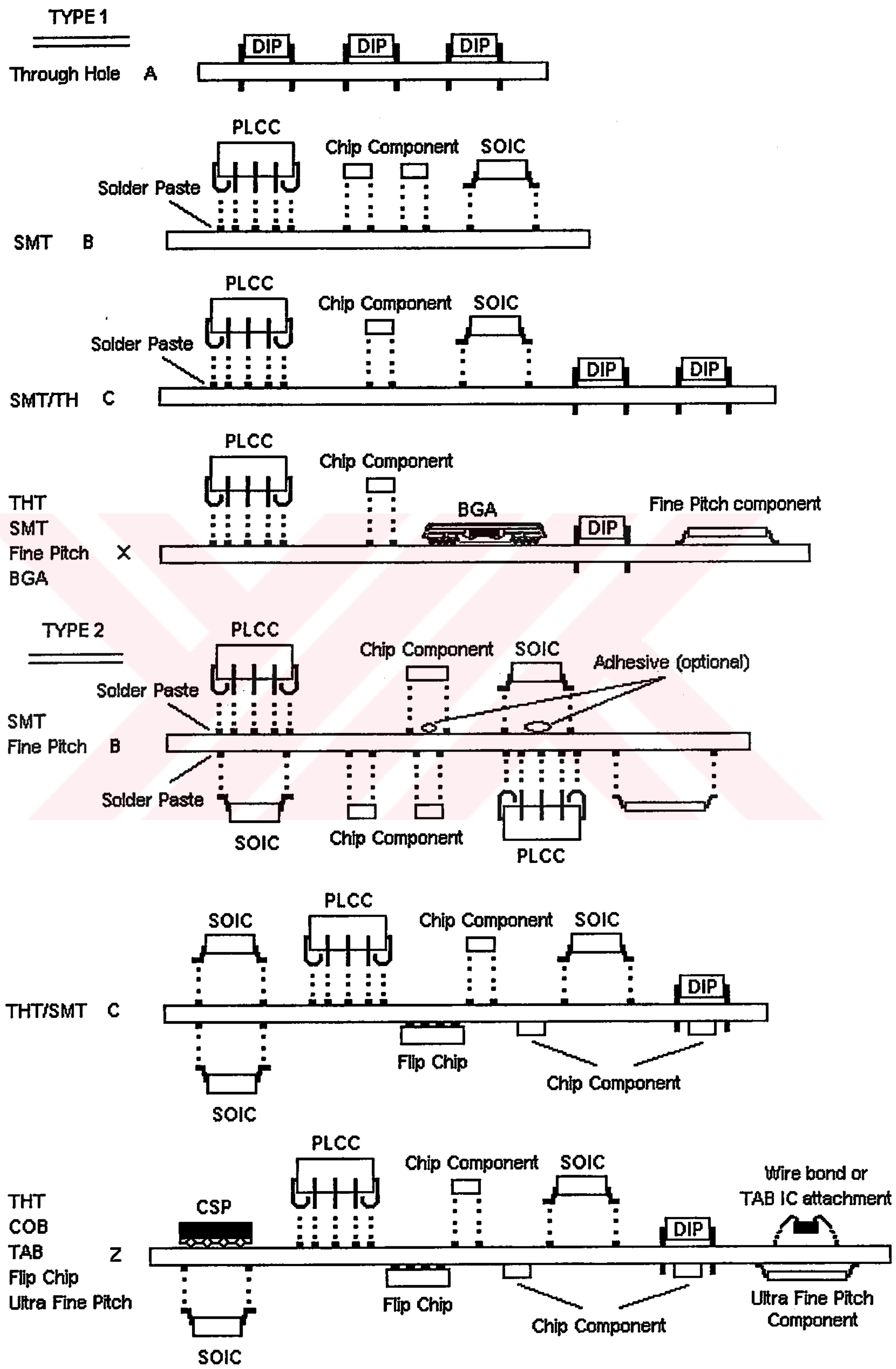
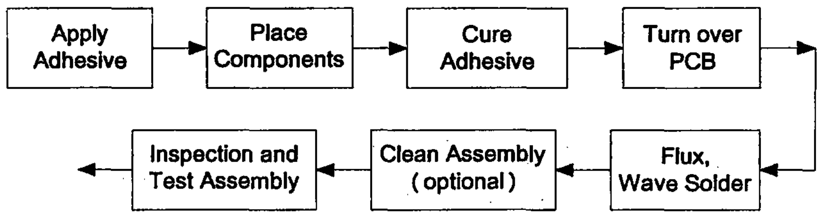
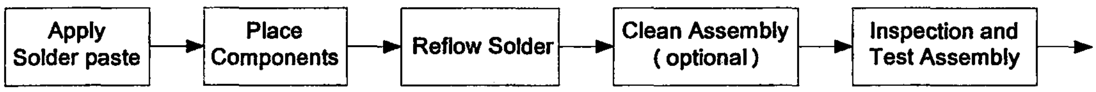


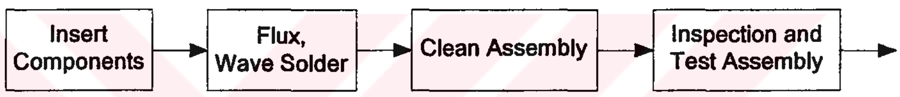
Figure 1.14. Electronic Assembly Types (Bergman, 1999)



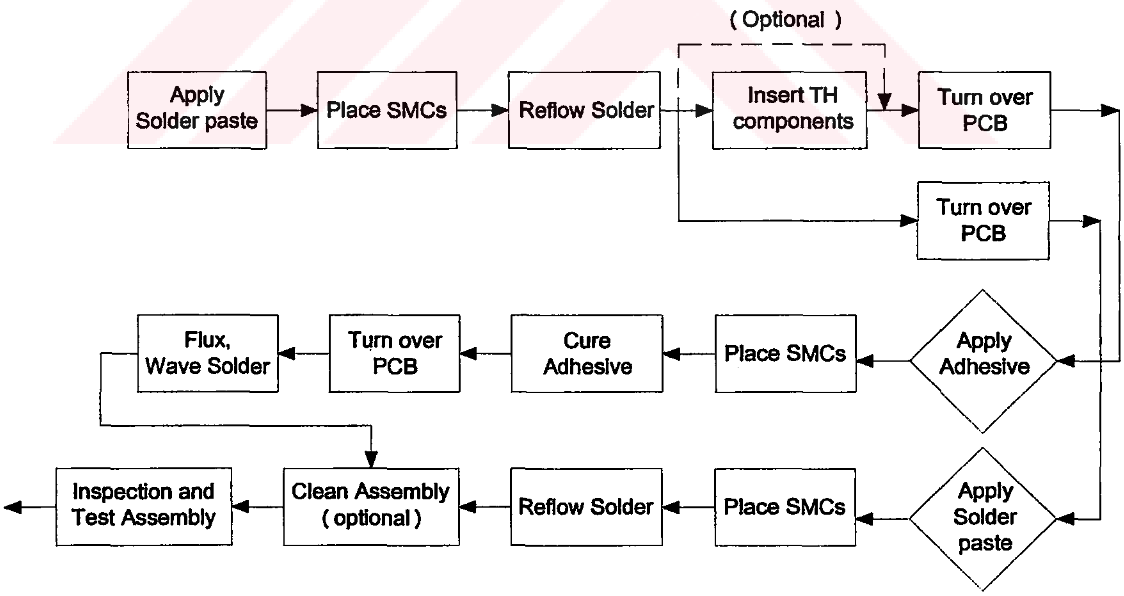
(a) SMDs Single Sided, Wave Soldering



(b) SMDs Single Sided, Reflow Soldering



(c) Typical Through Hole Assembly



(d) Double Sided Complex Assembly Processes

Figure 1.15. Possible Assembly Procedures of Electronic Devices

1.5. Evaluation of IC Packaging Trends

Today, new technologies have created a tremendous miniaturization impact on the electronics. While the trend in requirements of electronic packaging is toward higher I/O, greater performance and functionality, higher density and also lighter weight, area array packaging technology have evolved as a viable solution to the requirement of the industry, as such the use of BGAs, CSPs, and FCs is expected to increase (Lau and Alto, 1997; Hill, 1997; Nguty et al., 2000-(2); Chan et al., 2001; Yunus et al., 2003).

Figure 1.16 illustrates the size and weight reduction of IC packages over time and the trend towards the area array packages. Since the application areas of area array components range from simple handheld consumer electronic products to high-tech electronics equipments used in the military and space industry, they play an important role in electronics manufacturing environments.

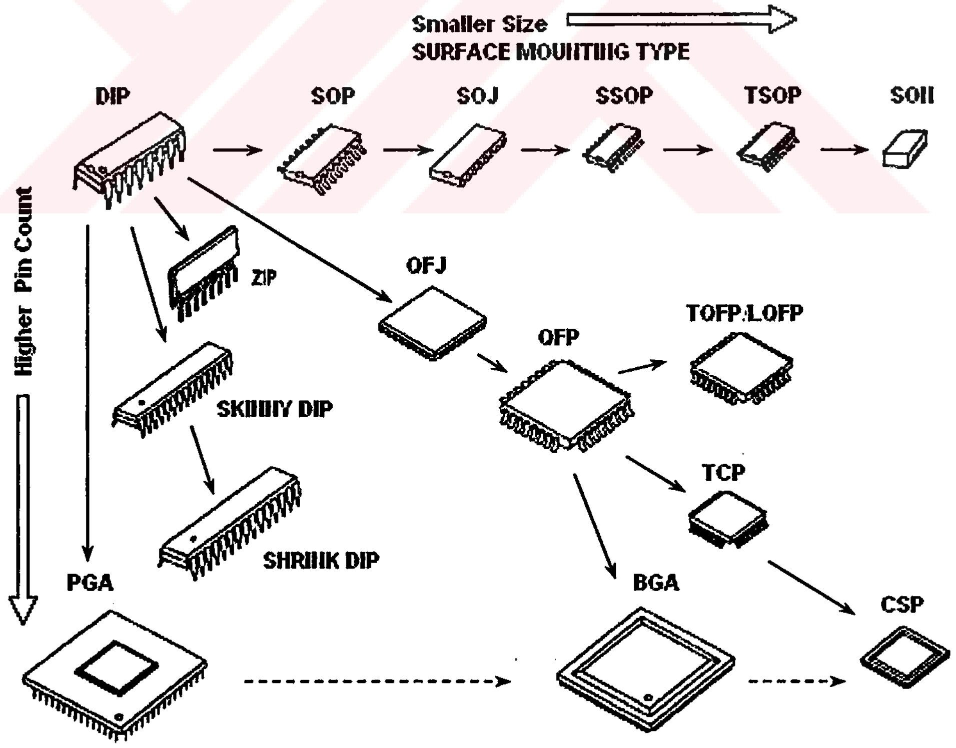


Figure 1.16. Packaging Trends (Khandelwal and Shenai, 2000)

1.6. The Rework

By means of the technological improvements, sophisticated systems and equipments have been developed and utilized in the PCBA technology to respond the progressively increasing demand of consumers for smaller and weightier electronic products.

On the other hand, the exponential miniaturization in the PCBAs associated with the use of SMT components have revealed inevitable defects which cannot be totally eliminated despite all improvements made in PCBA techniques, advanced control methodologies, and sophisticated inspection-test systems (Geren and Lo, 1998). This means that complex, high value PCBAs may require repair and rework during their service life (Stennett and Whalley, 1999).

As a consequence of above, inherently, rework has become a major part of the PCBA technology not only because of the financial cost concerned in scrapping faulty PCBAs and the limited availability of increasingly complex, high value PCBs (Geren, 2001) but also disposed PCBs can be a problem when the heavy metals in most boards are classified as hazardous waste (Geren, 1997-(2); Fidan et al., 1999).

The rework is a kind of remanufacturing process of the PCBAs in electronics and general steps of the SMCs rework are as follows (Nguty et al., 2000-(1, 2); Horsley et al., 2002; Rupprecht, 2002; Wood, 2003);

- Removal of defective component
- Site cleaning
- Application of solder paste or flux
- Replacement of new component
- Reflow soldering

In the rework process; the defective component must be heated to solder reflow temperatures to dismantle it without causing any damages to the board itself, the adjacent components or the solder joints of the adjacent components. Afterwards the remnants should be cleaned from the PCB site. This process is followed by the application of fresh solder or flux to the PCB site, enabling the attachment of the new component accurately. Finally, after the replacement, the new component is reflowed to form the solder joint interconnections between the PCB and component.

1.7. Scope of Study

Conventionally, rework of standard SMCs such as PLCCs, SOICs, and QFPs is carried out manually by skilled operators using manual or semi-automated equipments (Geren, 2001). However, manual rework is labor-intensive, time consuming, and extremely difficult to accomplish, even with the assistance of special equipments, because of miniaturized components and complexity of high density boards (Geren, 1998). Accordingly, it is not uncommon to achieve unsatisfied results with respect to quality and effectiveness of the rework process.

As for advanced SMCs (BGAs, CSPs, FCs), the rework process turns out to be more strenuous that makes the manual rework impractical to perform. Moreover, the essential training and skill required to rework these kinds of defective components have significantly increased to an extent where manual replacement and solder dispensing are nearly impossible steps of rework (Geren, 1997-(2); Huerta, 2002). Hence, manual rework of advanced SMCs can no longer be counted on to provide acceptable results (Naugler, 2002).

Currently, since the ability of reworking BGA, CSP and FC components is the inevitable problem that the manufacturers of PCBAs have to be faced, varieties of semi-automated rework systems have become available on markets. However, except removal and replacement processes they are not capable of performing the whole rework process automatically. Because of this deficiency, the quality and efficiency of rework is affected by heat application, placement accuracy, handling of components, solder dispensing and accessibility to the defective component. Consequently, it is obvious that not only increased complexity, cost and lead count of SMCs coupled with the continuous package size shrinkage and reduction of pitches, but also reduction of clearance areas available around the components (increased density of assembly) and increased utilization of BGAs, CSPs and FCs, have made rework of PCBAs troublesome enough to consider the full automation for all steps of rework (Geren, 1997-(2); Russell, 2000). Presently, because of the insufficiencies of manual and semi-automated rework equipments and the restrictions mentioned above there is an increasing demand for a fully automated robotic system in the rework of these types of SMCs to achieve consistent, flawless and reliable results.

According to literature survey, there have been some attempts with the number of published reports on developing the automated rework cell so that the level of skill required by the operator would be minimized or the operator involvement would be eliminated completely. The first system has been developed in the University of Salford, England, based on the iris-focused IR reflow soldering method by Geren et al. (1992). It is a fully automated robotic rework cell capable of reworking both surface mount and through hole technology components based on the batch size of one. Secondly, two of those attempts have been done in Rensselaer Polytechnic Institute, in USA, by Merrick et al. (1994) and Fidan et al. (1996). It is a laser based remanufacturing cell system that have been designed and developed for fully automated rework of fine pitch SMCs.

On the other hand, these automated rework cell systems are capable of reworking either standard or fine pith SMCs. None of them capable of reworking advanced SMCs. Therefore this study substantially aims to investigate and find out viable alternative proposals for automating the rework of advanced type SMCs. To do this effectively the existing manual rework procedures, methods, tools and available technology on automation including industrial robots, sensory devices, inspection and control equipments etc. are scrutinized in details so that alternative solutions are to be found out. Finally, the possible alternatives are compared between each other to examine their adaptability to the automated rework system to reach optimum alternative solutions for the fully automated robotic rework system for advanced type SMCs.

2. PREVIOUS STUDIES

2.1. Necessity of Rework in Electronics Manufacturing

Because of the continuing trends toward the miniaturization, structure of both PCBs and SMCs has become more complicated with the decrease in feature size and increase in the scale of integration. In addition to that, inherently value of these types of complex, high density PCBs and miniaturized components is higher compared to their older versions.

On the other hand, owing to the inevitably increasing complexity in the electronics assembly environment continuing improvements in process technology, sophisticated systems and equipments remains elusive to achieve 100 percent manufacturing yields as companies use these improvements to enable the construction of ever more complex assemblies (Stennett and Whalley, 1998, 1999; Geren, 2001; Naugler, 2002). As an inevitable result; rework and repair of complex, high value PCBAs seems to remain necessary process during their service life since the cost of each components and PCB itself may be hundreds of dollars (Geren and Lo, 1998). It should be emphasized that the number of defective PCBAs ranges from 10% to 35% in the electronics manufacturing environment (Geren, 2001). Moreover, it was stated that with the increase in component density accommodated by the gradual decrease in pitch sizes, the defect rates are predicted to increase, especially for surface mount boards (Geren, 2001; Nguty et al., 2001).

2.2. Manual Rework Procedures of Area Array Components

The rework process refers to the general technical difficulties of removing and replacing defective components on a PCB. When the aim is to automate the rework process, first of all, the way which the manual rework procedure currently performed in the electronics environment should be accurately identified. In doing so, it provides the knowledge of existing manual rework procedures and methods as well as the tools used during rework, and related rework considerations and problems.

In general, the manual electronic component rework procedure for SMCs has the following steps (Geren and Redford, 1996; Geren and Lo, 1998);

Preparation of defective PCBA

- Clean dust and contamination from the PCBA
- Identify defective component(s), and remove all obstructions if exist.

Removal of defective component

- Apply flux to target area (only with a flux compatible with that used in the soldering process).
- Preheat the assembly or local target area below to the reflow temperature.
- Desolder the defective component by heating to the reflow temperature with a suitable heater.
- Remove the defective component by a tweezers or a vacuum suction tool.

Site clean up and preparation

- Clean the pads from residual solders by using a braid or a vacuum desoldering iron, etc.
- Clean flux from the board with a solvent cleaner.
- Pre-tin and flux or dispense solder cream to the pads.

Replacement of new component

- Place the new component onto the PCB by a tweezers or a suction tool.
- Preheat the assembly or local target area.
- Resolder the new component applying heat to reflow the solder paste.

Cleaning and inspection

- Clean PCB site from all traces of flux.
- Inspect assembly and replace the items that have been removed for clear access.

As a result, basically manual rework procedure can be summarized as follows; preparation of faulty PCBA, defective component removal, site redressing, new component placement, reflow soldering, cleaning and inspection. On the other hand, while the procedure mentioned above could be valid for all SMCs, there are some differences when the advanced SMCs; BGAs, CSPs, and FCs are considered. Due to the nature of the area array components, they have introduced some difficulties not encountered with conventional SMCs (Philpott et al., 1999; Nguty et al., 2000-(2). Since they have no visible solder joints, rework process is potentially troublesome and lack of individual solder joint reworkability further complicates the rework process (Bell and Kampfert, 2002; Rupprecht, 2002; Horsley et al., 2002; Wood, 2002, 2003; Ghaffarian, 2003). This means that in order to perform rework process, instead of individual repair of component lead(s) there is no way to successfully rework area array components without complete removing and replacing the defective one (Philpott et al., 1999; Bell and Kampfert, 2002; Nguty et al., 2000-(2); Rupprecht, 2002).

In addition, some of the traditional tools of the trade, such as the soldering iron, cannot be used during the operation by the rework technicians (Rupprecht, 2002). Moreover, each component requires inherently different rework considerations which have significant importance and may condition the implementation of the entire rework. Accordingly, the manual rework processes for each type of area array components are introduced in subsequent sections respectively.

2.2.1. Manual Rework Procedure of BGAs

While traditionally SMT rework is accomplished with very coarse methods such as hand placement and soldering iron reflow, such approaches do not work for BGAs (INTEL, 2000 Packaging Data Book, http://www.intel.com, 2003). As shown in Figure 2.1, manual rework process of BGAs has the following steps;

Preparation of defective PCBA

- Prior the rework, defective PCBA should be free from moisture (prebake the assembly at 125°C for at least 12 hours)

Removal of defective component

- Preheat the entire assembly or defective component area to the temperatures around 100~125°C with a suitable hot air/gas or IR bottom heater.

- Desolder the defective BGA by heating to the reflow temperature (210~220°C) with a handheld hot air/gas or IR rework tools.
- Remove the defective BGA by a tweezers or vacuum pick-up tool.

Site clean up and preparation

- Clean the pads from residual solders by using temperature controlled desoldering tools such as blade tip soldering iron with a solder wick (desoldering braid) or a vacuum desoldering iron.
- Clean the rework area with a brush and proper solvent cleaner, preferable one prescribed by the solder manufacturer.
- Apply solder paste or flux with a suitable method.

Replacement of new component

- Place the new BGA onto the PCB by a suction tip with a split-prism optic.
- Preheat the assembly or local target area.
- Resolder the new component applying heat to reflow the solder paste.

Cleaning and inspection

- Clean all residues from the PCB site. However, if no clean solder paste or flux is used, cleaning is not necessary.

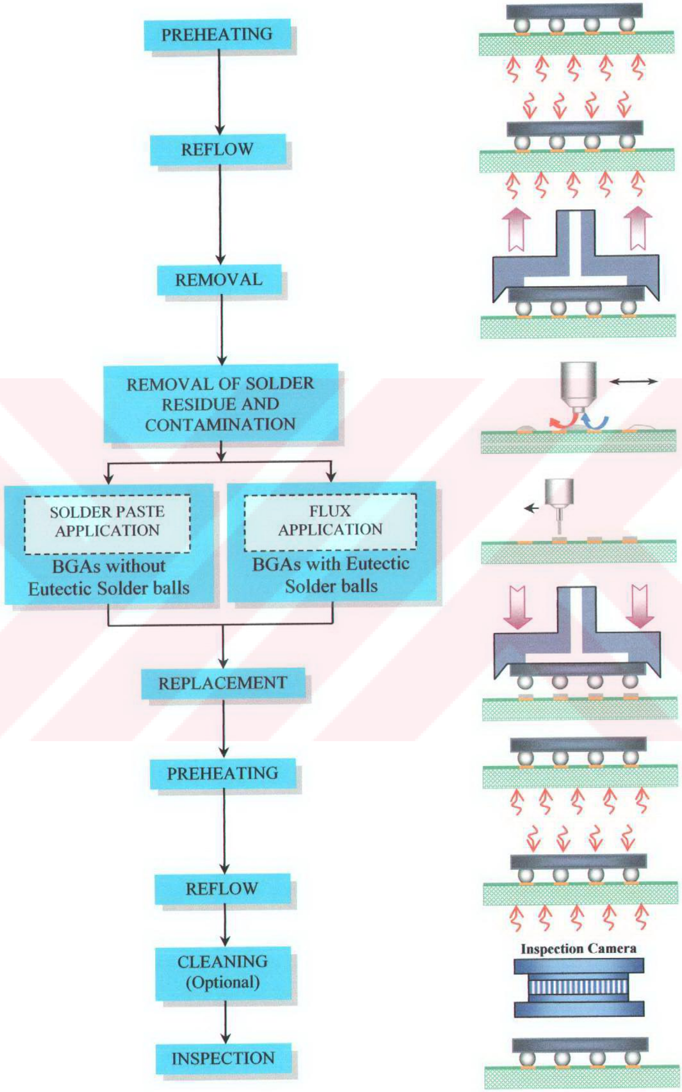


Figure 2.1. Rework Process of BGAs

2.2.2. Manual Rework Procedure of CSPs

Today, vast majority of CSP components are in area array formats and both having either eutectic or high melt solder balls versions are available on markets. The CSPs are miniaturized and enhanced versions of the BGAs (Primavera, 1999-(1); Ghaffarian, 2000), so inherently there are quite similarities between rework processes of CSPs and BGAs (Wood, 1998; Bergman, 1999; Primavera, 2003). As shown in Figure 2.2, typical CSP component rework process as follows;

Preparation of defective PCBA

- Prior the rework, defective PCBA should be free from moisture (prebake the assembly at 125°C for 4~12 hours)

Removal of defective component

- Preheat the entire assembly or defective component area to the temperatures around 100~125°C with a suitable hot air/gas or IR bottom heater.
- Desolder the defective CSP by heating to the reflow temperature (210~220°C) with a handheld hot air/gas or IR rework tools.
- Remove the defective CSP by a tweezers or vacuum pick-up tool.

Site clean up and preparation

- Clean the pads from residual solders by using temperature controlled desoldering tools such as blade tip soldering iron with a solder wick (desoldering braid) or a vacuum desoldering iron.
- Clean the rework area with a brush and proper solvent cleaner, preferable one prescribed by the solder manufacturer then apply solder paste or flux with a suitable method.

Replacement of new component

- Place the new CSP onto the PCB by a suction tip with a split-prism optic.
- Preheat the assembly or local target area.
- Resolder the new component applying heat to reflow the solder paste.

Cleaning and inspection

- Clean all residues from the PCB site. However, if no clean solder paste or flux is used, cleaning is not necessary.

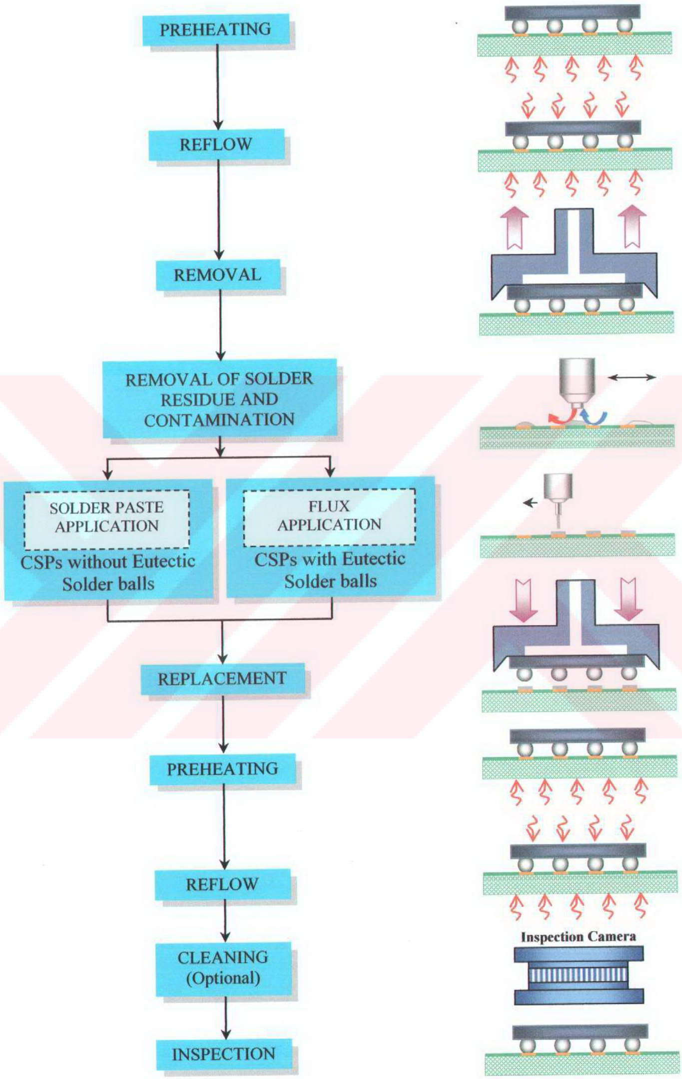


Figure 2.2. Rework Process of CSPs

2.2.3. Manual Rework Procedure of FCs

Flip chips (FCs) offer the smallest IC "package", because it allows placing bare die directly onto the board (Savolainen, 1998; Beelen-Hendrikx and Verguld, 1998). Flip chip packaging technology is not new; however, with the advent of new technologies, such as underfilling technology that uses a polymeric material to fill the gap between IC device and PCB, and encapsulates the solder joint interconnects, it is receiving renewed interest by product and component designers over the past several years (Bird, 1999). As depicted in Figure 2.3, the rework process of the FCs has the following procedures:

Preparation of defective PCBA

- Prior the rework, defective PCBA should be free from moisture (prebake the assembly at 125°C for 4~12 hours)

Removal of defective component

- Preheat the entire assembly or defective component area to the temperatures around 100~125°C with a suitable hot air/gas or IR bottom heater.
- Then underfilled defective FC is heated to the reflow temperature (210~220°C) to melt solder joints and break down the underfill with a handheld hot air/gas or IR rework tools.
- Remove the defective FC by a tweezers with a slight twisting action.

Site clean up and preparation

- Clean the pads from residual underfill and solder with a combination of a gentle mechanical brushing and solvent application.
- Afterwards apply flux with a suitable method.

Replacement of new component

- Place the new FC onto the PCB by a suction tip with a split-prism optic.
- Preheat the assembly or local target area.
- Resolder the new component.

Cleaning and inspection

- Clean all residues from the PCB site. However, if no clean solder paste or flux is used, cleaning is not necessary.

Underfill application and curing

- Once new FC placed, underfill is dispensed along the edge(s) of the component. While dispensing underfill by capillary flow technique, in order to accurately dispense underfill in a possibly short time PCBA is held at 90°C.
- After the completion of dispensing, finally PCBA is held around 150°C~160°C temperatures until complete underfill curing is achieved.

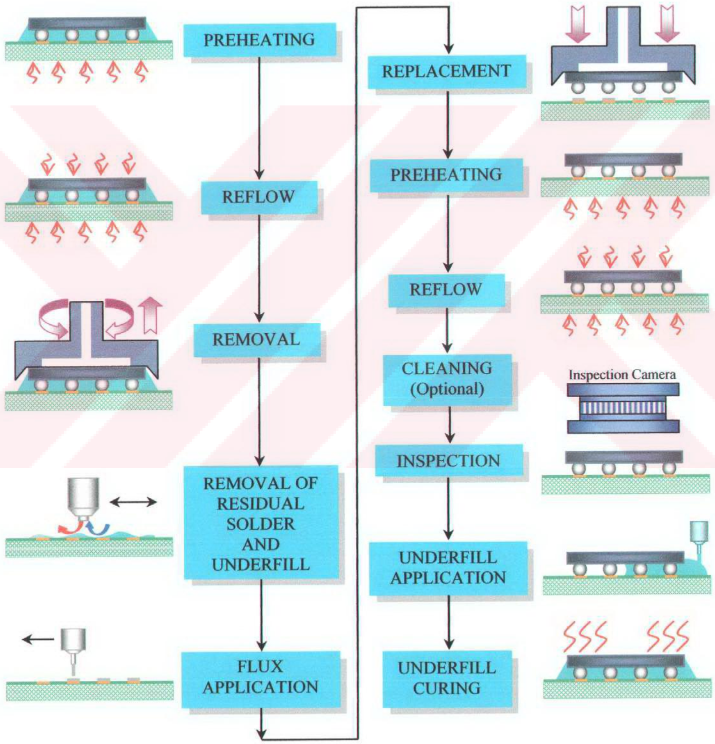


Figure 2.3. Rework Process of FCs

2.3. Detailed Studies on Rework Considerations of Area Array Components

2.3.1. Thermal Processing Specifications

2.3.1.1. Overview of Reflow Thermal Profile

In surface mount assembly, a key step in producing finished assemblies is the reflow soldering process which consists of remelting solder material previously applied onto a PCB pad sites (Blackwell, 2000-(1); Cluff and Pecht, 2001). Solder paste manufacturers supply a recommended reflow thermal profile for use with their specific solder paste. These "generic" profiles offer a convenient starting place for setting up a reflow profile (Scheiner, 2003). An example of a generic thermal profile is shown in Figure 2.4. The reflow soldering process has mainly four stages; preheat, soak, reflow and cooling (Blackwell, 2000-(1); Cluff and Pecht, 2001).

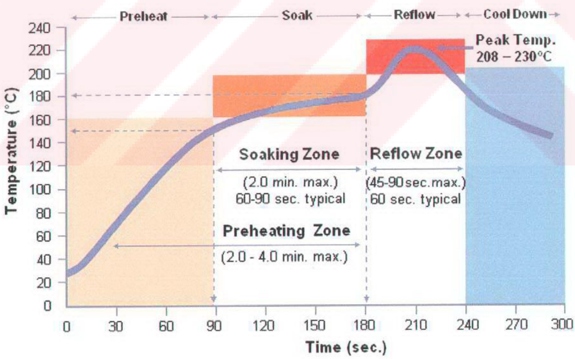


Figure 2.4. Recommended Generic Reflow Profile for Eutectic Sn/Pb Solder Alloy (http://www.kester.com, 2003)

- ***Preheat Zone (Rapid Heating Stage):*** The purpose of this stage is to quickly bring the assembly from room temperature up to a temperature where solder paste can become chemically active (http://www.kester.com, 2003). This means while the assembly is heating gradually, solvent evaporation from the deposited solder paste commences (Rowland, 1999; Cluff and Pecht, 2001; Scheiner, 2003).

- ***Soak Zone (Temperature Equalization Zone):*** The purpose of this stage is to bring the temperature of the assembly up to a uniform temperature so that there is a very small differential between the hottest and coldest soldering locations on the assembly (i.e. minimizing temperature gradients) (http://www.kester.com, 2003). Furthermore, in this stage the temperature of the assembly is raised slowly to the solder melting point. At this temperature, the flux in the solder paste becomes more active and removes oxides and contaminants from the surfaces of the metals to be joined and evaporates (Blackwell, 2000-(1); Cluff and Pecht, 2001).
- ***Reflow Zone (Rapid Heating):*** The purpose of this stage is to rapidly heat the assembly just above the melting (liquidus) temperature of the solder (http://www.kester.com, 2003). When the solder melts, it replaces the liquid flux formed in the previous step and subsequently complete wetting of solder onto conductor pads occurs (Blackwell, 2000-(1); Cluff and Pecht, 2001).
- ***Cooling Zone (Solder Solidification):*** The purpose of this stage is to cool the assembly down quickly to solidify the solder. To do this, the temperature of the assembly is dropped below the solder liquidus point, forming acceptable (shiny and appropriate volume) solder joints (Blackwell, 2000-(1); Cluff and Pecht, 2001).

2.3.1.2. Preheating

In present, high I/Os of area array components require multilayer or high density interconnection PCB designs to support the wiring needs for closely spaced components. Similar to standard printed boards the high density interconnecting (HDI) structures have additional surface layers that incorporate very fine holes called microvias. These added layers become part of the multilayer structure and provide the additional needed high density conductor routing and interconnection capability

(Bergman, 1999; Cluff and Pecht, 2001). In a similar manner, so as to meet the high pin count demand, area array components are generally constructed from high-density microcircuit substrates accommodated internal vias or plated through-holes. These packaging substrates are substantially similar to PCBs and consist of different multilayer laminate materials of varying coefficient of thermal expansion (CTE) (Bergman, 1999; Primavera, 1999-(1).

As a consequence, not only the substrate of area array components but also their assembled PCBs are constructed from different materials of varying CTE. Significant differences between properties within a package (from layer to layer or between the carrier and the die) can cause extensive internal stresses (Geren, 1997-(2); Primavera, 1999-(1). Typically, once a component is mounted to a PCB, the solder joint is naturally induced strains generated by the expansion of the package and PCB in the thermal excursions. Because the multilayer boards do not expand identically in the x, y, and z directions as temperature increases. Plated-through holes will constrain z-axis expansion in their immediate board areas, whereas nonthrough-hole areas will expand further in the z-axis, particularly as the temperature approaches and exceeds glass transition temperatures (Tg). This unequal expansion can cause delamination of layers and plating fracture (Blackwell, 2000-(1, 3). However, in area array SMCs, the solder balls alone must provide CTE mismatch compliance (Ghaffarian, 1999; Primavera, 1999-(2). It is generally well known that preheating of PCBAs is crucial in the rework of electronics devices. Due to the localized heat application during rework process destructive differential stresses may occur both within the component body and PCB. This is especially critical on high density multilayer circuit boards (Blackwell, 2000-(1); Geren, 2001; Alander et al, 2002).

Not only does the preheating prevents warping and thermal stress to the board, but also brings the assembly up to a temperature that expedite component removal and contribute to reduce reflow time (Blackwell, 2000-(1); McCall, 2000; Prasad, 2001-(1); Naugler, 2002; Primavera, 2003). In addition to these, preheating also provides to achieve more uniform heating profiles and to minimize adjacent components disturbance. Of course preheating is important for all SMCs, however, in area array component rework, it becomes critical because to melt all the hidden solder balls simultaneously it is imperative to provide additional thermal energy underneath the package (Prasad, 2001-(1); Wood, 2002). Accordingly, as a rule of thumb, the optimum area array rework process is to necessarily apply 75% of the total heat from bottom side and just 25% of the heat from top side (http://www.pdr-smt.com, 2004).

The preheating temperature is a function of PCB and component material, as well as type of the solder and flux material. In order to maintain the integrity of the PCB structure, the maximum preheat temperature should be kept below the glass transition temperature of the PCB material (Blackwell, 2000-(1). For the most common epoxy-glass PCB materials their glass transition temperatures range from 125°C to 180°C (Cluff and Pecht, 2001).

Typically a suggested preheating temperature for tin/lead solder alloys is about 100°C~150°C (Ward, 1999; Wood, 1999; Cluff and Pecht, 2001). Moreover, it was stated that any part of the PCBA over 160°C~170°C is close to the solder melting temperature of 183°C and risks damaging the solder joint integrity of adjacent components on the board (Ward, 1999; Geren, 2001).

In addition, the ramp rate of the preheating needs to be in a reasonable range. During preheat, too rapid temperature rise causes the solder paste splatter and solder balls, resulting solder bridging. Moreover, thermal shock or cracking of sensitive components and PCBs, especially ceramic based, is possible (Gray, 1999; Blackwell, 2000-(1); Geren, 2001). Accordingly, during the preheat of the assembly from the room temperature to 100°C~150°C, the preheating rate which is one of the critical process parameters should be limited and determined carefully (Hwang, 1998). Consequently, the preheating ramp rate around 2°C/s has been accepted as an industry norm to avoid any damages during reflow (Ward, 1999; Blackwell, 2000-(1); Cluff and Pecht, 2001). In addition to that according to Geren (1997-(2), it was stated that the rate of the preheating temperature increase is ideally limited to 2°C/s for plastic SMCs and 1°C/s for ceramics.

2.3.1.3. Reflow Heating

Owing to the nature of area array components, they are heat-sensitive and individual solder joint rework is intrinsically prevented, both of which dramatically complicate the rework process and increase essential overall process control methodology (Rupprecht, 2002; Wood, 2002, 2003). Therefore, for area array packages within the basic rework steps there are additional concerns related to establish an adequate thermal profile and its more precise controlling. Thermal energy should be directed through the component body to the solder joints without heating adjacent components. During the entire rework process keeping the applied heating temperatures greater than the solder's melting point within the sufficient time without over heating the PCBA has the remarkable merits.

A reliable rework process begins with the component removal that uses a reflow profile and associated process parameters that provide for effective and efficient component removal while simultaneously minimizing any adverse effects like component delamination, overheating of adjacent components, and board warpage (Primavera, 2003). Moreover in component removal step sufficiently high reflow temperatures should be maintained because insufficient heating does not completely melt the solder and this will lead to degradation in the quality and reliability of PCB. For instance, during component removal some parts of the board materials (copper traces, solder masks etc.) may be lifted off and damaged (Cluff and Pecht, 2001; Geren, 2001; Naugler, 2002).

Besides the above, replacement of the new component requires more precise thermal profile, especially to avoid jeopardize the valuable new component. Moreover, also peak temperature of the solder joint during reflow should be greater than the melting point of the solder within the suitable dwell time for adequate fluxing action and solder flow to obtain good solder joint formation. Too little time or too low peak temperature results improperly formed faulty solder joints like poorly wetted or cold joint, etc. (Hill, 1997; Primavera, 1999-(1); Cluff and Pecht, 2001; Naugler, 2002). On the contrary, too much time or excessive reflow peak temperature will damage the new component, PCB or even surrounding components as well (Cluff and Pecht, 2001; Prasad, 2001-(1). Further, during the reflow soldering excessive heating and long dwell time promotes intermetallic growth in the solder joint and results brittle interconnections which remarkably decrease the solder joint fatigue life (Hill, 1997; Primavera, 1999-(1); Cluff and Pecht, 2001; Naugler, 2002).

As with reworking all SMT components, subjecting temperature sensitive components to temperatures above 230°C may result in die cracking, adhesive degradation, or delamination. Common circuit board materials such as FR-4 are potentially subjected to degradation, excessive warpage and delamination because the organic portion of the laminate has limited ability to withstand elevated temperatures for extended period of time. Likewise, many of the solder masks currently employed have limited resistance to the elevated temperatures that will be experienced at reflow and may result failures such as discoloration and blistering (Andrew, 1996; Primavera, 1999-(2).

As a general approach, the solder paste must be elevated to a reflow peak temperature that is 20°C to 50°C greater than its melting point (Su et al., 1997; Ward, 1999; Primavera, 1999-(1). It is commonly recommended that for eutectic tin/lead solder, the reflow peak temperature of the solder joints is in the range of 205°C to 235°C (Blackwell, 2000-(1); Prasad, 2001-(1); Scheiner, 2003). Additionally, most of the SMCs are designed to withstand temperatures of up to 240°C~250°C, so the maximum reflow heating temperature should not exceed these temperature range during rework (Yang et al., 2001; Beckett et al., 2002; Wölflick and Feldmann, 2002; Rupprecht, 2002; Huerta, 2002). However, it is strongly recommended by the IC component manufacturers that the maximum reflow peak temperature of the component body should be kept around 220°C, since higher temperatures increase the risk of die cracking, adhesive degradation, and internal package delamination (http://www.intel.com, 2003; http://www.amkor.com, 2003; http://www.ibm.com, 2003; http://www.amd.com/us-en/, 2003; http://motorola.com, 2003). Besides the above, since the effects of heating a solder joint to the temperatures below the melting point may substantially affect the reliability of the solder joint, as a good rule of thumb, no adjacent component temperature should be above 150°C at any time in the rework process (Russell, 1999; Primavera, 1999-(1).

Further, to avoid submitting sensitive components to a thermal shock, board warping and excessively drying the solder paste, the heating rate must be precisely controlled and increased gradually throughout the rework process. Therefore it is imperative that area array components must be heated gradually and maximum rise of the temperature of the component body and interconnects should be below 3°C/s during reflow heating (Tazi and Bergman, 1999; Russell, 2000; Wood, 2002).

Additionally, before increase the PCBA temperature to the reflow soldering level, bring the assembly to the uniform temperature condition while activating the flux is necessarily taken into account. But at this stage unnecessarily excessive temperature and/or time gives undesirable results such as rapid evaporation of the flux which entrapped within the component solder balls causing voids (especially if the flux is of the no-clean type) (Andrew, 1996; Casey, 1999). Further, cold solder joints, solder balling, poor wetting, and solder splattering, as well as oxidation of solder, circuit pads, and component solder balls are the consequences of the unoptimized heating and process duration at this assembly temperature equalization stage (soak zone) (Blackwell, 2000-(1); Scheiner, 2003). Accordingly, as stated by Scheiner (2003), at this soaking stage the board temperature could be ramped up at a rate in the range of 0.3°C/s to 0.8°C/s, resulting in a soak time of approximately 40 to 100 seconds.

It is important to maintain thermal uniformity across the PCB and within a component being reworked. High thermal gradients (>25°C) can be damaging at excessive temperatures resulting thermal shock leading to board and component package warpage, component cracking and also results cold solder joints (Russell, 1999; Primavera, 1999-(1); Prasad, 2001-(1); Nguyen, 2003). In general, for area array devices, a good rule of thumb is to maintain a temperature gradient of 10°C or less so as to prevent warpage of the package and to ensure all joints reflow properly (Primavera, 1999-(1); McCall, 2000; Wood, 2003).

The temperature gradient between the solder balls at the center of the package, and the top surface side of the package should be 5°C or less than the solder balls on the corners (Nguyen, 2003). Further, efficient solder paste drying is important when processing large BGAs with small pitches (Koch, 1998).

The cooling rate of the solder joint after reflow is important because the faster the cooling rate the smaller the grain size of the solder, and therefore this means enhanced fatigue resistance of solder (Su et al., 1997; Prasad, 2001-(1). However, too rapid cooling should be avoided because rapidly cooling down not only creates an undesired temperature gradient between the component body and solder balls which may lead to package warpage but also cause excessive board warpage (http://www.ibm.com, 2003; http://www.intel.com, 2003). As a consequence of above, based on the main IC component manufacturers' recommendations, typical cooling rate should be lower than 6°C/s (http://www.amd.com/us-en/, 2003; http://www.national.com, 2003; http://www.ibm.com, 2003; http://www.intel.com, 2003; http://www.philips.com, 2003).

As a result, the amount of heat required in desoldering and resoldering, temperature ramp up rate, and dwell time are vital and should be strictly controlled to achieve successful component removal and replacement result without causing any damages to the component or PCB (Hill, 1997; Cluff and Pecht, 2001; Geren, 2001). Specific temperatures and dwell time at temperatures are not only function of the type of component and PCB but also function of the solder and flux material (Dody, 1999; Wood, 1999).

All things considered, while series of interactions and reactions take place during the reflow soldering process, it has inherent complexity. Hwang (1998) and Gupta et al. (2002) stated that major characteristic parameters of a reflow profile that most affect soldering performance include; the maximum peak temperature experienced, time over solder liquidous temperature, total time reaching peak temperature, and temperature increasing/decreasing rate.

2.3.2. Component Removal and Placement

In the defective component removal step it is emphasized that removal should be done with as small a force applied to the component as possible to avoid applying excessive pressure to the component because this may bring about solder joint collapse and adherence to the board surface, complicating the PCB site cleaning process (Russell, 1999; Dalrymple and Milkovich, 2000; Wood, 2002; Naugler, 2002; Primavera, 2003). With respect to placement, Primavera (2003) concluded that applying slight pressure during placement did not cause any solder bridging when the larger components (>0.8 mm BGA) are the case. On the other hand, placement force should be fine tuned so as not to deflect the board or damage the tiny CSPs or FCs (Russell, 1999; Primavera, 2003).

Due to the intrinsic complexity of area array components manual pick and place with only eye-ball alignment is not generally recommended because it is difficult to achieve consistent placement accuracy. Depending on the component type, proper placement can be done either by using alignment marks on the board (component body alignment) or by aligning bottom of the component to the individual pad site (component ball alignment) (Saint-Martin et al., 1996; Koch, 1998; Willis, 1998; Lewis, 2003). The latter needs using an up-down vision facility.

An equally important piece in the placement problem is the table/board holder. Board support should be as uniform as possible, since even a slight tilt or bend in a particular side results in solder bridging or balling (Primavera, 2003). The board must be held secure in a fixture or board holding table but allowed to expand during the process (Russell, 1999). Moreover, it should be stable, durable, adjustable, spring-loaded, and able to hold various board shapes and sizes. Additionally, if PCBs are thin, proper underside support to ensure planarity is required (McCall, 2000).

It is generally well known that area array components have excellent self centering capability during the reflow which significantly facilitate the complexity of replacement process. This means, a misaligned component up to 50% off the pad can align itself during reflow by means of the surface tension of solder balls which pulls the component onto the pad (Savolainen, 1998; Primavera, 1999-(1); McCall, 2000; Nikeschina and Emmen, 2002; Wölflick and Feldmann, 2002). This contributes reducing placement problems during surface mounting (see Figure 2.5). The placement accuracy should be determined based on the smallest solder ball diameter of the component being reworked (McCall, 2000). While component I/Os and PCB assembly density increase, the placement precision tolerance is shrinking (Dalrymple and Milkovich, 2000; Dreel and Chen, 2003).

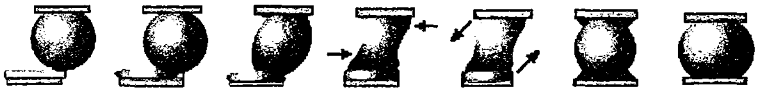


Figure 2.5. Solder Joint Self Alignment at Reflow Soldering
(http://www.intel.com, 2003)

The self alignment properties of area array components can be further improved by increasing surface tension. To do this, theoretically proper adjustments of reflow temperature, solder deposition quantity, solder alloy, oxide level of reflow atmosphere, and circuit board pad geometry are to be considered (Bell and Kampfert, 2002). However, it was stated that this linear offset tolerance seems to gradually diminish with decreasing pitch size for BGAs and CSPs. Contrarily, it was also reported that FCs exhibit self alignment at up to 60% misplacement, in spite of the reducing pitch size. This conflicting result may stem from the fairly light weight of FCs (Lee, 2002). Component misplacement tolerance is aggravated by both linear and rotational offset limitations. As mentioned before it is generally postulated that a 50% of linear misplacement in X-Y axes is acceptable for area array component family. As for rotational offset tolerance limit, it is defined such that 50% of the component upper solder balls are always in the pad site, resulting approximately 1° rotational offset value for BGAs and 2° for CSPs and FCs. This is because the relative shift of solder balls near to the centroid is far less than those balls near perimeter, providing more balls-to-pad contact area, thus a greater associated self-centering force (Lee, 2002).

2.3.3. Site Cleaning

PCB reworked sites should be made as uniform as possible prior to reattachment of the new component. In its simplest form, site cleaning comprises applying a source of heat to the PCB and removing the residual solder by some means. The aim is to effectively remove the residual solder without adversely affecting PCB quality (McCall, 2000; Nguty et al., 2000-(1); Naugler, 2002). Currently, two methods are commonly used for the removal of residual solder. Either a vacuum desoldering tool or a soldering iron with a solder wick is used (Wood, 1998; Tazi and Bergman, 1999; Naugler, 2002; Primavera, 2003). These are manual site cleaning methods and are handheld tools as such process results highly depend on the operator level of skill. Nowadays automated site cleaning tools, known as site scavengers, become more prevalent and remarkably facilitates achieving high quality cleaning results. Basically, the scavenging tool consists of two concentric tubes and hot gas is used to liquefy the residual solder, and vacuum sucks the molten solder into a filter or reservoir (Naugler, 2002; Primavera, 2003).

The site redressing process is critical since it poses significant risk to the integrity of the board. Damage to the board usually takes the form of lifted pads, lifted traces, and more commonly damaged solder mask (Wood, 1999; McCall, 2000; Naugler, 2002; Primavera, 2003). With many area array packages, the space between pads is densely populated with traces and vias. PCBs featuring microvias are generally not good candidates for conductive desoldering techniques. When the desoldering tip is moved across the land pattern, the vias can fill with solder, which is not easy to clean; attempts to do so usually result in via, soldermask or PCB damage (McCall, 2000). The smallest defect in the solder mask may result in bridging and shorts (Naugler, 2002; Primavera, 2003). Additionally, appropriate flux application is prerequisite for the site cleaning and the bottom side heating (85°C~100°C) is also recommended during the residual solder removal process. Applied flux expedites the cleaning and bottom side heating decreases top and bottom temperature gradients, reduce the thermal shock to the board, further eliminating any accidental pulling of fragile pads (Wood, 1998; Primavera, 2003).

If the component removed contains high temperature solder balls, not all of them will remain on the package after removal. Some high temperature solder balls will adhere to the package while others will remain on the board. As a result, cleaning of the residual consists of removal of high melt solder balls and solder residue, respectively (Wood, 1998; Willis, 1998; Prasad, 2001-(1).

Once all residual solder has been removed from the lands, they should be cleaned with an approved solvent, preferably one prescribed by the solder manufacturer (Tazi and Bergman, 1999; Ward, 1999; Blackwell, 2000-(1).

2.3.4. Solder Paste/Flux Application

After the PCB site cleaning, new solder paste or flux is applied to the pad site. Solder paste replenishment can be performed in various methods; screen or stencil printing and dispensing solder paste dots to individual pads (Blackwell, 2000-(1); McCall, 2000). Solder paste application is the most difficult surface mount process to control (Pan et al., 1999; Ward, 1999; Durairaj et al., 2001).

Dispensing and printing are the common methods used to apply solder paste in the electronics manufacturing industry. Printing has evolved as the preferred method for solder paste application. Dispensing offers flexibility and printing offers a faster cycle time. Further, dispensing can be done on flat and irregular surfaces while printing requires a flat surface. Dispensing can be accomplished with equipment that ranges from simple hand held units to fully automatic dispensing systems (Ward, 1999). Stencil printing of solder paste is the most commonly used method in the electronics assembly environment (Gray, 1999; Primavera, 1999-(1); Pan et al., 1999; Blackwell, 2000-(1); Durairaj et al., 2001; Nikeschina and Emmen, 2002). The solder paste deposit must have both adequate thickness and volume to compensate flatness defects due to the board warpage and/or poor component coplanarity (Saint-Martin et al., 1996; Bird, 1999).

As the current miniaturization trend continues, area array type packages are now being increasingly designed into products. The application of solder paste with the stencil printing in order to assemble these devices depositing precise volumes of solder paste onto the PCB from pad to pad is becoming increasingly difficult particularly for fine and ultra fine pitch components (Hill, 1997; He et al., 1998; Wood, 1999; Primavera, 1999-(1); Pan et al., 1999; Caswell and Partridge, 2001; Durairaj et al., 2001). As indicated by the fact that industry reports over 60% of the surface mount assembly defects are originated from the solder paste stencil printing process, thus the stencilling is a critical step in the SMT assembly (He et al., 1998; Pan et al., 1999; Nguty et al., 2001). Therefore, there are lots of studies in the literatures investigating the factors affecting stencil printing results to find out optimum process parameters (Lau and Yeung, 1997; He et al., 1998; Nguty et al., 1998, Pan et al., 1999; Gopalakrishnan and Srihari, 1999; Kennedy, 2000; Rajkumar et al., 2000; Durairaj et al., 2001). It was reported that there are more than 45 variables that influence the final quality output of the stencil printing process (Pan et al., 1999). As a consequence, from the view point of reliability the stencil printing process itself is highly complicated and with the miniaturized area array components this process turns out to be much more complex and it is even impossible to achieve acceptable printing results with the reasonable process yields.

The present usage shows that the pitch size range of 0.5 mm to 0.8 mm is highly common in area array components (Wood, 1998; Bergman, 1999). Solder paste reprinting is not practical at 0.5 mm pitch, requiring tacky flux to be used instead of solder paste (Primavera, 1999-(2); Kennedy, 2000; Caswell and Partridge, 2001). It was stated that, for 0.5 mm pitch CSPs, it is not uncommon to achieve a print efficiency of less than 50-60% (Primavera, 1999-(1). Based on the experimental studies of Kennedy (2000), the same results were also obtained. According to experienced printing results, 1.27 mm pitch BGAs offered a printing efficiency ranging from 70% to 85% while with CSPs having pitch size of 0.5 mm, 0.75 mm, 0.8 mm offered printing efficiency of only 25% to 55%. Furthermore, Nikeschina and Emmen (2002) stated that, stencil printing method has not worked well for components with pitches smaller than 0.3 mm. For these components, application of tacky flux is a better alternative. It can be implemented simply dipping the component bumps in the predetermined amount of flux. With this method components with bump pitches down to 0.1 mm can be handled. Since the solder paste stencil printing of area array components was proven to be less reliable and more likely to provide insufficient solder it is strongly recommended to inspect the printing results regularly to minimize printing related defects and to achieve high throughput as well (Hill, 1997; Koch, 1998; Wood, 1998; Kennedy 2000; Blackwell, 2000-(2).

While solder paste application is often part of the original assembly process, due to the impracticality of solder paste application process mentioned above, soldering of array packages with tacky fluxes and liquid fluxes is becoming more prevalent (Ward, 1999; Wood, 1999; Berger, 2003). Moreover, in general not every manufacturer of area array components approves the application of solder paste during the rework or assembly process. Certain manufacturers recommend only the application of a gel-based, high viscosity flux (Wood, 1998, 1999; Ward, 1999). Higher viscosity is recommended to provide adherence between the component and circuit board during the rework/assembly process.

As a matter of fact, there is no need to additional solder paste application for an area array component which consists of eutectic solder balls. This is due to the fact that the eutectic solder balls are in molten form during reflow contributing to the solder joint formation and also they have proven to be sufficient to provide reliable solder joints. As such only flux can be applied for component attachment (Anderson and Primavera, 1997; Koch, 1998; Primavera, 1999-(1); Caswell and Partridge, 2001; Naugler, 2002).

Fluxing can be achieved by dipping the component into a flux film deposit, dispensing, spraying, and brush methods (Ward, 1999; Primavera, 1999-(1); Lee, 2002). Dip fluxing and spray fluxing are the most commonly used methods (Lee, 2002). In order to minimize the flux residue left on the PCB following reflow, it must be precise in terms of exactly where flux is applied and how much put down, and no flux can be deposited beyond the intended target area (Primavera, 1999-(2); Naugler, 2002; Berger, 2003).

Flux dipping is a well-proven and controlled method of applying flux (Primavera, 1999-(1); Naugler, 2002). On the other hand, spray fluxing (topside fluxing) is gaining in applications dealing with the packaging of semiconductor devices such as BGAs, FCs and other advanced components since spray fluxers are being used to apply very controlled amounts of flux, especially when no clean fluxes are used. In present, most commonly no clean tacky fluxes are often used in these applications (Ward, 1999; Wood, 1999; Berger, 2003). Besides performing their normal functions, they keep the device that is positioned over the fluxed area in place during subsequent processing and eliminate post-solder cleaning (Bergman, 1999; Wood, 1999; Naugler, 2002; Nikeschina and Emmen, 2002; Berger, 2003).

It is known that somewhat misaligned components (<50% from pad center) will automatically self align during reflow for the area array components with "flux"

(Chan et al., 2001). As Nikeschina and Emmen (2002) pointed out, flux-only implementation of component replacement does not significantly decrease the self alignment feature of the area array component. In this study most components with eutectic solder balls replaced with the flux aligned themselves successfully. Furthermore, Chan et al. (2001) also demonstrated that misalignment of larger than 50% from pad center, the assembled components were still able to self align. As a result, it has been shown that with the flux-only replacement process consistent and acceptable results can be achieved.

On the contrary, when high reliability requirement is a main issue as in the case of the military or space industries, solder paste must be applied whatever the solder ball material and the pitch size is. Similarly, for the components populated with non-eutectic solder balls application of additional solder paste is essential because desired amount of solder for the reliable joint is only provided by the added solder paste (Anderson and Primavera, 1997; Bergman, 1999; McCall, 2000; Prasad, 2001-(1). Further, if the area array component has an elastomer layer between the silicon die and the PCB material for CTE differences it is emphasized to use solder paste in component placement process (Wood, 1999; McCall, 2000).

All things considered, substantially following are summary of the factors affecting the selection of solder paste or flux application in the component placement;

a. Component type specifications

- *Material composition of the solder ball;* If component has eutectic solder balls, there is no need to use additional solder paste while non-eutectic solder ball composition necessitates using.
- *Pitch size;* The difficulties in solder paste application coupled with the unreliable and insufficient printing results dictates to use flux for fine pitch components.
- *The component structure;* If the component include elastomer layer, solder paste should be used.

b. Cost and Reliability specifications

- *PCB cost;* The value of the PCB also determines the selection of material. With the high value multilayer PCB, assemblies of electronics are performed with the solder paste application to maintain long service life. In sum, higher the PCB value, higher the necessity of the solder paste.

- *Product type;* Reliability requirements depend upon the medium that the electronic product works. Inherently, different electronic devices have varying reliability level according to their application areas, such as a personal pager or an engine control PCB in a plane must compensate totally different reliability constrains. They are exposed different thermal loading. As a result, the increased the reliability constrains, higher the necessity of the solder paste.
- *Standoff height;* In some cases, higher standoff height should be maintained to increase the component reliability or to facilitate the post reflow cleaning process. Implementation of component attachment with only flux results in a slightly lower standoff height from the PCB which somewhat decrease the thermal cycle reliability of the component. Therefore, if there is a specification exists for the joint standoff height for function or cleaning, additionally solder paste should be applied.

2.3.5. Prebaking

Moisture sensitive SMCs and PCBs must be dried by a prebake prior to any thermal processes. Hence, it is strongly recommended that PCBA should be baked at 125°C for 24 hours (Koch, 1998; Primavera, 1999-(1), 2003; Blackwell, 2000-(1). Doing this effectively removes any residual moisture from the assembly; preventing moisture induced component delamination and cracking (popcorning phenomenon) as well as PCB delamination during the removal or replacement process (Andrew, 1996; Koch, 1998; Blackwell, 2000-(1); Yang et al., 2001; Primavera, 2003). In addition to that, instead of baking for 24 hours, it is also recommended that to avoid moisture effects at least 12 hours PCBA baking should be done (Andrew, 1996; Hill, 1997; Nguyen, 2003).

However there are some considerations that should be kept in mind. Firstly, high prebaking temperatures should be avoided because it will result in the growth of intermetallic layer at the interfaces of tin-lead plated copper lead frame of the component. Additionally, oxidation rates of tin-lead plating materials increase at elevated temperatures, resulting in decreased solderability (Blackwell, 2000-(1). It is recommended that to avoid oxide contamination during baking, inert gasses like nitrogen or argon should be used (Casey, 1999). As a consequence, baking must be limited to only the required time and temperature.

2.3.6. Reflow Atmosphere

It should be emphasized that, reflowing area array packages in nitrogen atmosphere is recommended and has a significant positive affect on component alignment capability and solder joint integrity, reliability, and quality (Hill, 1997; Wu et al., 1998; Casey, 1999; Bell and Kampfert, 2002). Moreover, it was revealed that nitrogen atmosphere provide smaller temperature differential across the rework site. In addition, the residual solder would be more uniform with a nitrogen atmosphere which facilitates the site cleaning (Primavera, 2003).

Nitrogen atmosphere is strongly recommended if no clean fluxes are to be used. Because they are not as active as other fluxes therefore have poor ability to reduce the oxides formed on the solder paste and board surface metallizations (Hill, 1997; Ward, 1999; Blackwell, 2000-(1).

Contrarily, different levels of oxygen in the nitrogen reflow atmosphere produced profound effects on the formation of voids in the solder joints, i.e. the less oxygen that the solder joint was exposed to, the lower the level of voiding in the joint. The oxygen level should be reduced to less than 200 ppm. However, oxygen concentrations lower than 100 ppm were deemed to have less effect and increased the process costs substantially (Casey, 1999).

Consequently, nitrogen atmosphere has positive impact on reflow soldering process with respect to solderability, extent of solder balling, solder paste residue, solder joint appearance, board discoloration (temperature tolerance), reflow process window, and overall yield and quality (Klein, 1994; Hwang, 1998).

2.3.7. Inspection

Because the solder joints are hidden beneath the area array component body, effectively direct inspection of solder joints is impossible with the conventional methods and therefore improved inspection techniques such as real-time transmission x-ray or acoustic microscopy are needed (Savolainen, 1998; Philpott et al., 1999; Prasad, 1999; Bird, 1999; Nguty et al., 2000-(1); Horsley et al., 2002).

2.3.8. Common and Specific Component Considerations of Area Array Components

Knowing the type of component and its pros and cons will aid tremendously in assembly and rework process development. Each area array component type has distinct material features, characteristics and properties.

The PBGAs consist of an array of eutectic (63Sn/37Pb) solder balls that reflow completely at 183°C or of eutectic-like (62Sn/36Pb/2Ag) solder balls that reflow at 179°C (Cluff and Pecht, 2001; Prasad, 2001-(1); Lee, 2002). Figure 2.6 shows cross sectional view of a typical PBGA package structure and Table 2.1 gives qualifications of PBGAs commonly in use.

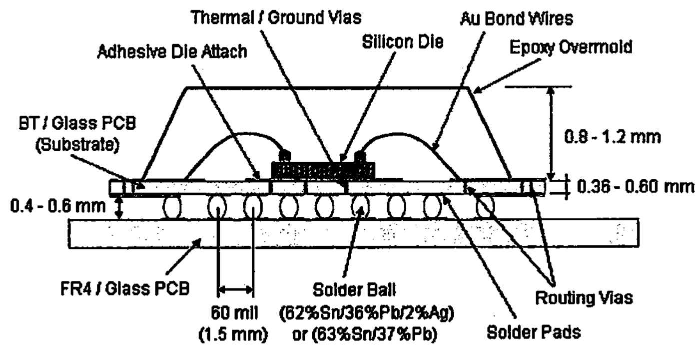


Figure 2.6. Cross Sectional View of a Typical PBGA (Mahajan, 2001)

Table 2.1. General PBGAs Specifications

I/O Count Range	Body Size (mm)	Pitch Size (mm)
16 to over 900	7 x 7 to 50 x 50	1.0 - 1.27 - 1.5

The PBGA is such a low thermal mass and moisture sensitive component, so needs careful control of reflow temperature increasing rate (Andrew, 1996; Dody, 1999). Generally, there is a significant rework process consideration when reflow soldering the plastic SMCs. The major cause of IC component failure mechanism such as internal delamination of the plastic from the die and/or lead frame, internal cracking or external package cracking (popcorning), wire bonds lifting, die surface cracking is component saturation with moisture and subsequent exposure to high temperature during the reflow soldering (McCluskey et al. 1997; Huang et al. 1998; Blackwell, 2000-(1); Yang et al., 2001; Chien et al., 2003).

The CBGAs and TBGAs are generally populated with an array of 90Pb/10Sn solder balls that melt at 302°C (Cluff and Pecht, 2001; Prasad, 2001-(1); Lee, 2002). However, according to IC component manufacturers' product data sheets and catalogues, in present eutectic solder balled CBGAs and TBGAs have been developed and become commercially available in the markets (http://www.amkor.com, 2003). Figure 2.7 and Figure 2.8 schematically shows internal view of a typical CBGA and TBGA component.

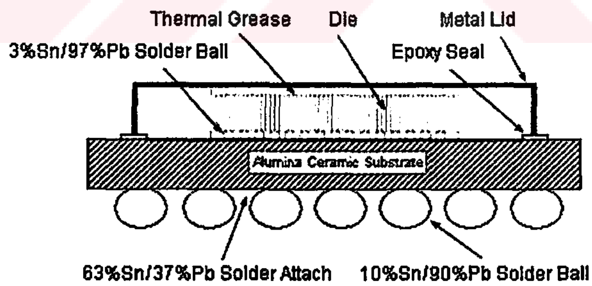


Figure 2.7. Cross Sectional View of a Typical CBGA (Mahajan, 2001)

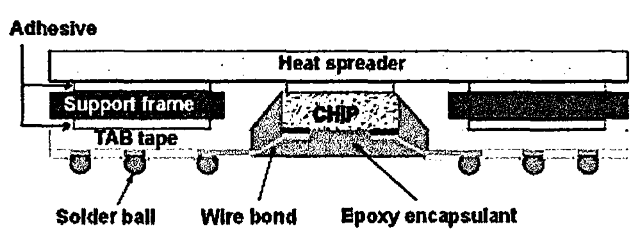


Figure 2.8. Cross sectional view of a Typical TBGA (Virpi et al., 2000)

The high temperature solder balls of CBGAs are attached to the die and PCB with eutectic solders (Prasad, 2001-(1); Lee, 2002) whereas in TBGAs they are welded into the package by partially melting (Frank and Richard, 1994; Prasad, 2001-(1). General specifications of CBGAs and TBGAs are given in Table 2.2.

Table 2.2. General CBGAs and TBGAs Specifications

Component Type	**CBGA**	**TBGA**
I/O Count Range	121 to over 900	256 to over 900
Body Size (mm)	10 x 10 to 35 x 35	27 x 27 to 45 x 45
Pitch Size (mm)	1.0 - 1.27 - 1.5	0.8 - 1.0 - 1.27

Unlike the PBGAs, CBGAs and TBGAs can be heavy thermal mass and therefore this result tight restriction on the reflow thermal profile (Saint-Martin et al., 1996). TBGAs are thermally sensitive components and like PBGAs they may be also moisture sensitive, so prone to moisture induced defects during rework whereas CBGAs are hermetically sealed and do not pose the moisture-related problems (Saint-Martin et al., 1996; Khandelwal and Shenai, 2000; Cluff and Pecht, 2001; Prasad, 2001-(1). As a difference from the PBGAs and TBGAs, the CBGAs have the problem of thermal mismatch with epoxy based PCBs, due to the difference in thermal coefficient of expansion, so solder joint fatigue is the primary failure mode of the CBGA assemblies (Saint-Martin et al., 1996; Bird, 1999; Cluff and Pecht, 2001).

An excessive reflow temperature risk to melt high temperature solder balls of CBGA and TBGA, and this allows the dissolution of lead from the solder balls to the eutectic solder which increases the melting point of solder and also makes the component removal much more difficult (Prasad, 2001-(1).

PBGAs and TBGAs are susceptible to warping and have tendency to bend during reflow, thus resulting in no connections on the outer rows of the component due to the insufficient physical contact between the component leads/balls and solder paste (Saint-Martin et al., 1996). However, Saint-Martin et al. (1996) and Hill (1997) stated that with PBGAs this problem is not sever, since the component solder balls participate in the solder joint formation and collapsed during reflow.

Typically for CBGAs, since the high-melt solder balls are eutectically soldered to both the component body and the PCB besides the residual solders, some of the component's solder balls remain on the PCB site after component removal. After CBGA component removal, cleaning of the remnants from the PCB site includes two steps; removal of high-melt solder balls and lead-rich solder residue respectively (Willis, 1998; Prasad, 2001-(1).

In addition to that, after the CBGA and TBGA removal remaining solder residue composition varies due to the lead dissolution from the high-melt balls as such require higher melting temperatures for cleaning action (Prasad, 2001-(1). Additionally, it should be aware that during the site redressing, high temperature of cleaning process can create excessive growth and oxidation of intermetallics, which results in non-solderable surfaces. The temperature during cleaning process should be limited by the maximum temperature that the PCB material can withstand. For FR-4 material, the accepted maximum allowable temperature is 245°C (http://www.ibm.com, 2003).

There are two complementary technologies for the miniaturization of electronic devices, CSPs and FCs (Boustedt and Vardaman, 1997; Beelen-Hendrikx and Verguld, 1998; Crane et al., 1999). CSPs are the next generation of component after BGAs (Nguty et al., 2000-(1); Cluff and Pecht, 2001; Naugler, 2002). FCs offer the smallest IC package, since bare die is directly attached to the substrate, on component, module or mother board level (see Figure 2.9) (Savolainen, 1998; Crane et al., 1999; Vincent and Wong, 1999).

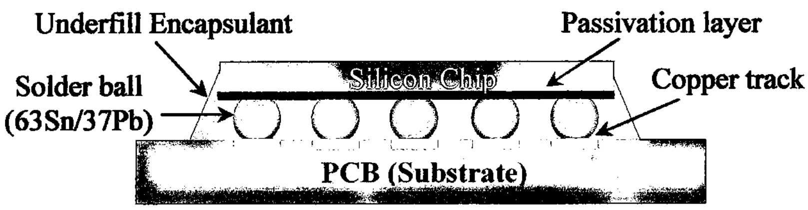


Figure 2.9. Cross Sectional View of a Typical Flip Chip Assembly

CSPs were designed in order to bridge the gap between BGAs and FCs, and are considered to be the best package type to meet the needs of the electronics industry for the years to come (Nguty et al., 2000-(1).

Based on package structure, CSPs are often categorized into four major groups (Boustedt and Vardaman, 1997; Wang and Wong, 2000). These include custom lead frame, flex circuit interposer, rigid substrate interposer and wafer-level assembly, as shown in Figure 2.10. Based on the component manufacturers' data sheets, common specifications of current CSPs and FCs are given in Table 2.3.

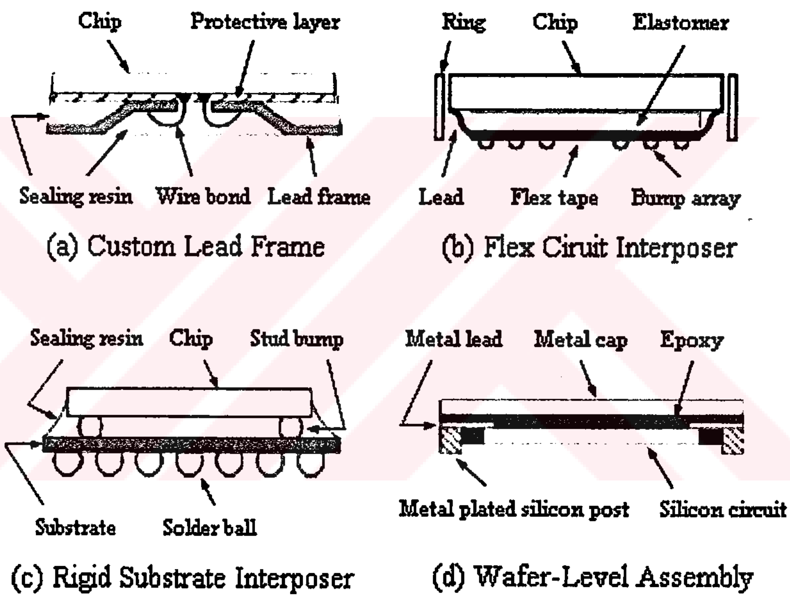


Figure 2.10. Main CSP Package Types (http://www.techsearchinc.com, 2003)

Table 2.3. General CSPs and FCs Specifications

Component Type	CSP	FC
I/O Count Range	8 to over 200	21 to over 1200
Body Size (mm)	4 x 4 to 22 x 22	3.81 x 3.81 to 12.7x12.7
Pitch Size	0.4 to 1.0 mm	100 to 750 µm

CSPs provide higher packaging density than BGAs but not quite the density that is possible with FCs. However, the CSP assembly process is not as complex as the FC process either (Bird, 1999). Since most of the CSPs are miniaturized and enhanced versions of the BGAs, as their names like miniBGA and μBGA indicate, the critical parameters that affect BGAs should be the same as for CSPs (Primavera, 1999-(2).

Substantially the method of rework for CSPs is very similar to the rework procedure for BGAs except for tighter tolerances. Due to their relatively smaller size new challenges are presented in the rework and repair of CSPs especially in the solder paste or flux deposition process (Wood, 1998; Bergman, 1999; Primavera, 2003). Similarly, FC assembly requires more attention on placement and alignment due to tighter pad pitch. In addition, FCs need underfill for reliability enhancement, adding process steps and costs (Savolainen, 1998).

In fact, the rework process of FCs is similar to the rework process of BGAs and CSPs. The main difference is being the presence of the underfill between the component and PCB, which adds a new set of issues that need to be addressed in terms of component removal and site redressing (Wong et al., 1999; Wang and Wong, 2000; Gowda et al., 2002). The underfill adds the difficulty of FC rework. Once the underfill is cured, excessive methods are needed to remove the component. Some force must be applied in addition to heat to remove the component (Savolainen, 1998, Wang et al., 2000). Removal of the residual underfill material may be problematic issue; however, it was pointed out that a combination of a gentle mechanical brushing process and solvent application would clean the site (Crane et al., 1999; Wang et al., 2001-(1).

Because CSPs are small and lightweight; component skewing, misalignment and open solder joints will be problematic issues in the convection heating based reflow soldering (Dalrymple and Milkovich, 2000; Naugler, 2002; Primavera, 2003).

Accurate heat control and uniform heating across the component are critical factors that affect the final rework results, especially in the case of low mass CSPs and FCs (Naugler, 2002). Hence, throughout the rework particular attention should be given to the heating rate for CSPs and FCs to prevent warpage of the component and to ensure all joints reflow properly (Primavera, 1999-(1). Reflow soldering should ideally take place in an encapsulated, inert gas-purged environment, where temperature gradients do not exceed ±5°C across the working area (Wood, 1998).

2.4. Underfilling Technology in the PCBAs

Today, new technologies have created a tremendous miniaturization impact on the electronics. While the trend in requirements of electronic packaging is toward higher I/O, greater performance and functionality, higher density and also lighter weight; area array packaging technology have evolved as a viable solution to the requirement of the industry, as such the use of BGAs, CSPs, and FCs is expected to increase (Lau and Alto, 1997; Bird, 1999; Chan et al, 2001; Yunus et al., 2003).

While these area array packages provide significant advantages, they must compensate some reliability requirements in terms of consumer expectations and operational conditions. In other words, due to having widespread application areas of these packages from handheld personal communication products to automotive industry they must meet different and unforeseen reliability requirements.

For SMCs, solder joint possesses both electrical and mechanical functions and has been the weakest link in assembly reliability. As a result, damage to solder can readily affect the functional integrity of the entire electronics system (Ghaffarian, 1999; Primavera, 1999-(1); Adamson, 2001).

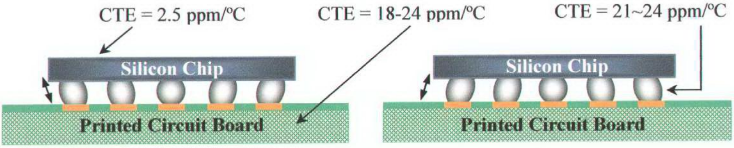
In fact, both BGAs and CSPs have high solder bump height that provides acceptable solder fatigue during thermal cycling. However, many of these packages face serious reliability problems. High power devices that require massive heatsinks could lead to cyclic creep phenomena as a result of the static load applied by these heat spreaders. In addition, the strain is generated on the solder joints during regular operational temperature cycling, as well as during dynamic loading induced by mechanical vibration, impact shock and bending, causes in further reliability detractors for BGAs and CSPs (Doba, 2000; Wang and Wong, 2000; Wang et al., 2001-(2); Gowda et al., 2002). Furthermore, fine pitch BGAs and CSPs have difficulty meeting mechanical shock and substrate flexing tests for portable electronics applications (Peng et al., 2001).

As for FCs, due to the rapid advances of IC fabrication technology and the accelerated growing of the market demand for faster, smaller, lighter and less expensive products, FC technology on an organic substrate has been developed and practiced over the last decade, as an ultimate solution for this trend (Shi and Wong, 1999-(2); Wang et al., 2000; Zhang et al., 2001; Moon et al., 2003). As a result, conversion from low expansion inorganic to high CTE organic PCB presents the well-known thermal mismatch problem between IC component and organic substrate (Wang et al., 2001-(1); Lau and Chang, 2002; Kuerbis et al., 2003). During thermal excursions the problem with CTE mismatch between the silicon IC chip (CTE = 2.5 ppm/°C), low-cost, high CTE organic substrate (CTE = 18-24 ppm/°C) and solder interconnects (eutectic alloy CTE = 21~24 ppm/°C) becomes critical (Liu et al., 2001), particularly with the large IC components and fine pitch, low profile solder joints (Gilleo et al., 1999; Wang and Wong, 1999-(1); Schneider, 2001). Due to the CTE mismatch, temperature cycle excursions experienced by the components generates tremendous thermo-mechanical stress at the solder joint interconnects, which subsequently results in early failure of the components (Wang and Wong, 2001; Wang et al., 2001-(2); Miao et al., 2001; Liu et al., 2001).

On the other hand, the problems mentioned above, of course, happen in peripherally-leaded packages, but most have plenty of compliance resulting from the use of flexible leads or greater standoff heights. The problem for area array components is further compounded by the fact that most of this strain is concentrated in just a few of the joints (Gilleo et al., 1999).

As depicted in Figure 2.11, the thermal mismatch strain (shear stress) is highest at the solder joints furthest from the neutral point or center of the component, resulting in very high plastic deformation in these regions (Gilleo et al., 1999; Wang and Wong, 2000; Babiarz et al., 2001; Schneider, 2001).

All in all, underfilling is the key process that can over come whole problems mentioned above because when the underfill is applied it acts as an adhesive which reinforce the physical and mechanical properties of the solder joints by compensating stresses occur during thermal cycling and/or dynamic loading conditions (Wong et al., 1999; Wang et al., 2001-(1); Wang and Wong, 2001).



a) Cooling b) Heating

Figure 2.11. Thermal Cycling Effect on the Solder Joints

Substantially, underfill is a polymeric material that fills the gap between IC component and PCB, and encapsulates the solder joint interconnects (Wang et al., 2000; Tu et al., 2001; Kuerbis et al., 2003).

The underfill is a key material that enhances the thermal-mechanical strength of the area array component solder joints (Wang and Wong, 2001; Liu et al., 2001; Gowda et al., 2002; Stoyanov et al., 2002). Substantially, unlike the FCs, improvement of the thermal reliability is not the goal of underfill with BGAs and CSPs; the goal is to improve the resistance to mechanical shocks and vibrations, by uniformly distributing the induced stress (Chan et al, 2001; Tu et al., 2001; Adamson et al., 2002). As Blackwell 2000-(4) pointed out, the use of underfill with various solder alloy compositions have revealed an increased fatigue life resistance by at least a factor of ten. Besides, the underfill material provides not only drastic improvement on solder joint fatigue life but also provides improved level of environmental protection (Hsu et al., 2000; Liu et al., 2001; Gowda et al., 2002).

Due to these overwhelming features, underfilling technology has been gaining acceptance in the PCBAs especially to improve the mechanical reliability of area array packages (Wong et al., 1999; Wang et al., 2000; Peng et al., 2001). Unfortunately, underfilling adds process step to the assembly process and potentially limits reworkability of packages (Gilleo et al., 1999; Wong et al., 1999; Peng et al., 2001; Lau and Chang, 2002), due to the fact that current underfills are epoxy-based materials that are not reworkable after curing (Wang and Wong, 1999-(1); Wang et al., 2000). This is not only an obstacle in Flip Chip On Board (FCOB) and the high performance Multi Chip Module (MCM) technology developments but also in the widespread use of underfills for the PCBAs (Wong et al., 1999; Wang et al., 2000).

Since the inability to replace one defective component makes the whole board useless, reworkability of underfill is very important characteristic in electronics manufacturing (Wong et al., 1999; Wang and Wong, 2000; Wang et al., 2001-(1). Furthermore, the ability of rework a faulty component is generally desirable in market while many electronic devices are integrated onto an expensive multi layer PCBs in current (Crane et al., 1999; Wang and Wong, 2000; Doba, 2000; Wang et al., 2001-(1). Basically, the reworkable underfill has to be twofold to be successful. First the component has to be released from the board and second the residual underfill has to be removed from board easily (Crane et al., 1999; Wong et al., 1999).

Reworkable underfill is not only the key material to address the non-reworkability of the FCs, but it can also be used to improve the board level reliability of BGAs and CSPs without losing their good reworkability feature (Doba, 2000; Wang et al., 2001-(2). As a result, during the past several years many researches have been done to try making underfill material reworkable (Crane et al., 1999; Tong et al., 1999; Wong et al., 1999; Wang et al., 2001-(1), and today commercially well established reworkable underfill materials have become available from such companies as Loctite, Emerson & Cuming, Kester, etc.

2.4.1. Underfill Dispensing Techniques

Currently, underfill dispensing is implemented substantially in two ways with respect to board level assembly (Wang et al., 2001-(1); Liu et al., 2001; Miao et al., 2001; Lu et al., 2002): conventional capillary flow underfilling and novel no flow underfilling.

2.4.1.1. Conventional Capillary Flow Underfilling

The most common method of dispensing underfill into the gap between component and substrate is by capillary flow of the underfill. The underfill is normally dispensed along one or two edges of a heated package and permitted to fill the gap by capillary action (Wong et al., 1999; Vincent and Wong, 1999). As depicted in Figure 2.12, this conventional method takes place as follows; initially solder paste or flux is applied onto the pads, then component is aligned and placed onto the PCB, followed by the solder joints reflow and cleaning processes. Afterward underfill is dispensed by capillary flow technique and finally underfill is cured (Firmstone et al., 1999; Hsu et al., 2000; Liu et al., 2001; Schneider, 2001; Previti and Ongley, 2002; Stoyanov et al., 2002).

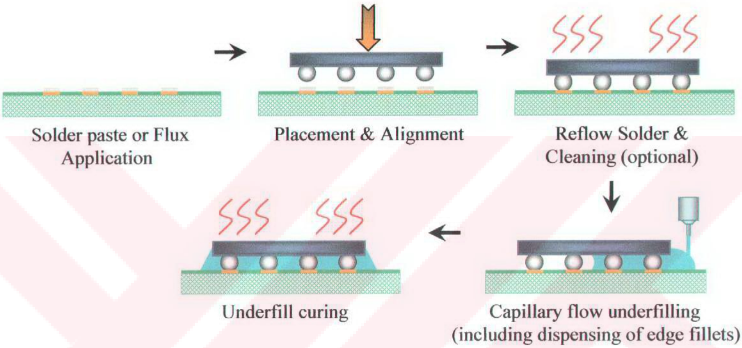


Figure 2.12. Conventional Capillary Flow Underfilling

A key factor in successful void free capillary flow underfilling is the pattern used to apply the underfill. Because the material flow rate is greater when it migrates from bump to bump than in any other area, air could be trapped if an inappropriate dispense pattern is used. The dispense pattern must be optimized for the specific application. Many different dispense patterns can be used to achieve void-free underfilling in the required time. As depicted in Figure 2.13, traditionally underfill dispensing process involves dispensing the underfill in a "L" or "I" pass using single or multiple passes and following with a "seal pass" (Adamson, 2001; Babiarz et al., 2001; Adamson et al., 2002; Miquel, 2002).

According to underfill material suppliers, the recommended typical dispense patterns for small components (0.25") are single side or single corner only without the need for a secondary dispense (the longer side of the component should be preferred to minimize flow time) (http://www.aimsolder.com, 2003;

http://www.cooksonsemi.com, 2003; http://www.loctite.com, 2003). The pattern length generally varies from 50% to 125% of the component edge length. The greater lengths minimize the dispense fillet but increase the probability of trapped air at the far edge of the component (http://www.cooksonsemi.com, 2003).

With respect to large components, it is also recommended that an L pattern along both sides of the component is typically required and may also require a second and third pass to ensure complete and void free underfill flow, depending upon the size of the component. On asymmetrical components, it is recommended to start the dispense pattern at the point furthest from the component center, which will help to ensure a void free fill underneath the component. In addition, a final perimeter bead/fillet may be dispensed to ensure uniform stress distribution at the component edges (http://www.loctite.com, 2003; http://www.emersoncuming.com, 2003; http://www.cooksonsemi.com, 2003; http://www.aimsolder.com, 2003).

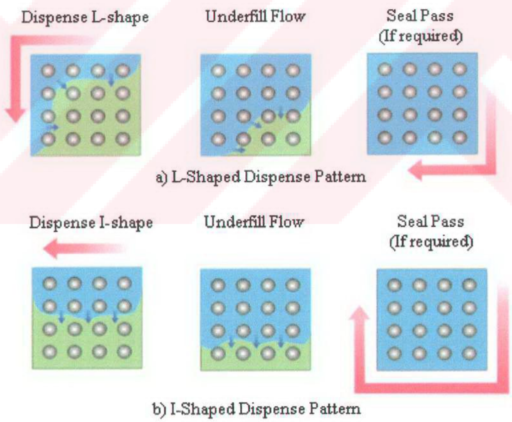


Figure 2.13. Conventional Capillary Flow Underfilling Dispense Patterns

The initial fillet acts essentially as a reservoir that feeds the capillary flow-out process beneath the component. After the first pass of underfill has begun flowing under the component, additional underfill material is dispensed to the fillet(s) along the edge(s) that feed the continuous flow out (Adamson, 2001; Lewis et al., 2003-(1). The time between passes in a multiple-pass dispensing process depends on the flow of the material. In addition, once the underfill fluid is dispensed and completely flows under the component, it is normal practice to perform a final seal pass around the perimeter of the component (Firmstone et al., 1999; Adamson, 2001; Huang, 2002; Lewis et al., 2003-(1). It is important that, however, to prevent voiding, the seal pass may not be applied until the fluid has completely flowed under the component (Lewis, 2003). The seal pass ensures an even distribution of mechanical stresses around the component, and provides additional protection against the moisture from the environment (Firmstone et al., 1999; Lewis et al., 2003-(1). Furthermore, it prevents air from being trapped beneath the component (Huang, 2002; Lewis et al., 2003-(1). It is most critical on parts that have a large difference in the CTE between the component and substrate or on parts that experience large temperature changes (Lewis et al., 2003-(1).

It is also essential that sufficient amount of underfill should be dispensed not only to completely fill under the component but also to provide a fillet that covers greater than 50% of the edges of the component (http://www.cooksonsemi.com, 2003). Currently, there are many commercially well established, contemporary underfills in markets which have low viscosity and excellent wetting characteristics and provide "self filleting action" along the opposite edge of the component that is sufficiently reliable and aesthetically pleasing to negate the need for further dispensing (http://www.cooksonsemi.com, 2003; http://www.emersoncuming.com, 2003; http://www.loctite.com, 2003). If self filleting character is not acceptable or if very symmetric filets are desired, then the initial pattern is complemented with a second pattern, or seal pass designed to give the required fillet. Therefore, after gap filling is complete, the I-shaped dispense will be followed with a U-shape or an initial L-shape will be followed with another L-shape to dispense underfill along the remaining component edges (see Figure 2.13) (http://www.cooksonsemi.com, 2003; http://www.loctite.com, 2003).

In conventional capillary flow method, application and curing of the underfill are carried out after the reflow soldering. These are extra processes that become an obstacle to achieving high throughput and low cost production, compared to standard surface mount assembly procedures (Smith et al., 2000; Wang and Wong, 2000; Wang et al., 2001-(1); Zhang et al., 2001; Lu et al., 2002).

2.4.1.2. Novel No Flow Underfilling

The increase in component size, I/O counts, decrease of bump pitch and standoff height will eventually reveal more problems and prevents the capillary flow underfilling method i.e. the capillary force may not be sufficient to draw the underfill through the gap, resulting incomplete underfilling (Chan et al., 2001; Liu et al., 2001; Miao et al., 2001; Tu et al., 2001; Wang et al., 2001-(1); Previti and Ongley, 2002).

Therefore, a new method of dispensing underfill called "no flow" process has been invented (Wong et al., 1998-(1); Wang and Wong, 1999-(2); Shi and Wong, 1999-(1); Wang et al., 2001-(1) to cope with such limitations. As shown in Figure 2.14, the process entails initially solder paste application (if necessary), followed by dispensing a controlled volume of no flow underfill onto the PCB. Afterward component is placed onto the PCB, compressing the no flow underfill to flow outward to the edges of the component. Finally, it is then possible to execute the solder bump reflow and underfill curing simultaneously, with the underfill fluxing effect (Firmstone et al., 1999; Baldwin et al., 2000; Hsu et al., 2000; Liu et al., 2001; Previti and Ongley, 2002; Stoyanov et al., 2002).

The aim of the no flow underfilling method is to reduce the process time and cost and to enhance the production efficiency (Zhong, 2000; Smith et al., 2000; Baldwin et al., 2000; Wang and Wong, 2000). With the no flow underfilling method, beside the elimination and combination of some of the earlier capillary flow processing steps, an additional reduction in cycle time is also stem from not having to wait for the underfill material to flow and cure, and also not having to preheat the assembly prior to dispensing (Babiarz et al., 2000).

Additionally, since the no flow underfills combine the underfill and fluxing capabilities into one product, solder paste or flux application is not necessary with no flow underfills (Liu et al., 2001).

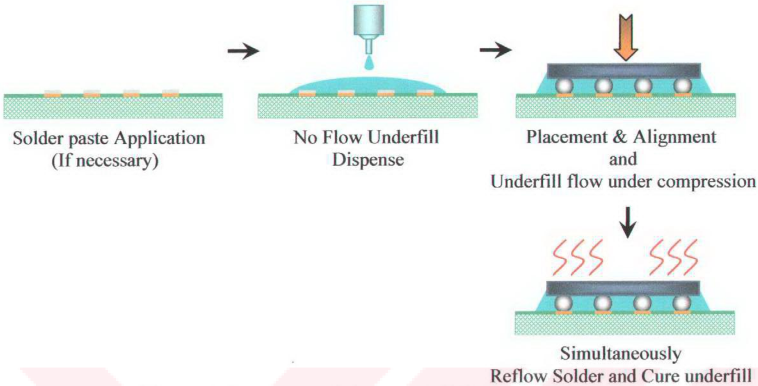


Figure 2.14. Novel No Flow Underfilling Process Steps

Wang and Wong (2000) stated that a successful no flow underfill material by itself should exhibit the essential characteristics at each reflow temperature zone. In the preheating zone, the no flow underfill should drastically drop its viscosity at the initial stage and then maintain the low viscosity so that the underfill can wet the all contact surfaces and the component easily compress down by its own gravity to contact the solder bumps and copper pads each other. In the soaking zone, the material should provide fluxing capability to remove the metal oxide at the surface of solder bumps and copper pads. In the reflow zone, the material should keep flowable until the completion of solder reflow and then either quickly and fully or can be separately fully cure at the temperature below solder melting point. In the cooling down zone, the cured material should have reasonable CTE value, modulus, toughness value, and adhesion strength so that the cured material and any other components of the assembly will not crack and delamination.

The key to success of no flow underfilling technology lies in the availability of successful no flow underfill materials (Shi and Wong, 1999-(1); Zhong, 2000; Zhang et al., 2001). Therefore, comprehensive studies have been done by researches and special no flow underfill materials have been successfully developed and demonstrated (Wong et al., 1998-(1); Firmstone et al., 1999; Wang and Wong, 1999-(2); Shi and Wong, 1999-(2); Zhang et al., 2001).

Underfill material costs are potentially lower for no flow underfilling process because fillers are not used (Baldwin et al., 2000). Presence of fillers in no flow underfill interferes with the solder joint formation. On the other hand, because of having no filler no flow underfills have higher CTE compared to capillary flow underfill class (Miao et al., 2001; Zhang and Wong, 2002-(1); Previti and Ongley, 2002; Lu et al., 2002). This may lead to lower solder joint reliability, especially in the case of large components (Zhang and Wong, 2002-(1), and thus create a technical barrier in applying the no flow underfill technology (Wang and Wong, 2000; Lu et al., 2001; Moon et al., 2003). Currently, the main technical challenge lies in how to reduce CTE mismatch (Miao et al., 2001). Furthermore, it is necessary to reduce the no flow underfill CTE, so as to apply actually to BGAs and CSPs (Tu et al., 2001). Therefore, researchers have been working to optimize the properties of no flow underfill materials and presently appropriate no flow underfills are developed and demonstrated successfully (Wong et al., 1998-(1); Shi and Wong, 1999-(1); Previti and Ongley, 2002).

When working with no flow underfill materials, the goal is to place the underfill in a pattern that will flow to fill the gap evenly in all directions. The additional complexity having the underfill flow in the gap and around the bumps without creating voids during component placement remains a challenge (Babiarz et al., 2000). According to no flow underfill manufacturer's data sheets, it is recommended to dispense the no flow underfill in a single dot/glop pattern over the center of component attachment site at room temperature to avoid air entrapment and shorten the dispensing time. The component can then be placed into the no flow underfill material utilizing compression flow so that the underfill encapsulant spread evenly underneath the component (http://www.emersoncuming.com, 2003; http://www.kester.com, 2003). It was stated that, the dispensed no flow underfill should have the shape like a glop or dome with its highest point in the middle (Debarros and Katze, 2000; Kuerbis et al., 2003; Kondos and Borgesen, 2004).

Viscosity of the no flow underfill inherently tends to produce a dome shaped deposit on the substrate as dispensed (Kondos and Borgesen, 2003).

It was reported that, both the amount of underfill material dispensed and the patterns are very critical. Too much underfill will cause the component to float and form incomplete solder joints or none at all. But, too little underfill will cause voids under the component and incomplete filleting. The underfill must be symmetrically dispensed or the component will tend to skew or move off center (Gilleo et al., 1999). As a result, the requirement from the dispense step is the formation of a single glob of material, of the appropriate volume and shape, which will allow the fluxing of all the bumps during reflow and form proper fillets afterwards, with the minimum number and size of voids (Kuerbis et al., 2003; Kondos and Borgesen, 2004).

2.4.1.3. Comparison of Underfilling Techniques

If conventional capillary flow underfilling and no flow underfilling are compared, following are mainly revealed;

- Since capillary flow underfilling is performed after the component reflow soldering, capillary flow underfilling needs separate solder paste/flux application and cleaning steps, separate solder joint reflow, underfill dispensing and flow, and also off-line underfill curing procedures (Liu et al., 2001). As such, the capillary underfilling process is tedious, expensive, and not transparent to the SMT facilities (Wong et al., 1998-(1); Shi and Wong, 1999-(2); Smith et al., 2000; Wang et al., 2001-(1); Zhang et al., 2001).
- In the no flow underfilling technique; underfill is dispensed before solder joint reflow, eliminates processing steps of solder paste/flux application, cleaning, underfill flow, and secondary thermal curing of underfill, and combines the solder joint reflow and underfill cure into a single step (Liu et al., 2001). Thus enables high throughput, reduces process complexity and capital equipments requirements, as well as increasing process robustness and providing low-cost assembly (Smith et al., 2000; Baldwin et al., 2000; Liu et al., 2001; Wang et al., 2001-(1); Previti and Ongley, 2002).

- In no flow underfilling, process sequences more akin to conventional SMT than conventional capillary flow underfilling and therefore easier for SMT engineers to adopt (Firmstone et al., 1999; Baldwin et al., 2000).
- The no flow underfilling process has more strict requirements on the materials than the conventional capillary underfilling process as far as rework is concerned, since there is no interval to test and inspect the assembly defects until the whole process finish (Wong et al., 1999).
- In capillary flow underfilling, lengthy capillary flow and curing time dramatically decrease production throughput and exerts significant pressure on the profit margin i.e. increase assembly cost (Liu et al., 2001; Wang et al., 2001-(1); Chan et al., 2001; Lu et al., 2002; Stoyanov et al., 2002). Although there have been numerous studies to enhance properties of the capillary flow underfill materials to shorten the underfilling and curing time (Vincent and Wong, 1999; Adamson et al., 2002; Huang, 2002), even the best underfills add a time penalty and increase the cost (Gilleo et al., 1999).
- With the trend towards increasing component size, finer pitch, high I/O numbers, lower solder bump standoff; capillary flow underfilling method has become increasingly difficult and time consuming that reveals bottlenecks in the assembly process (Wang et al., 2000; Miao et al., 2001; Liu et al., 2001).
- The novel no flow underfilling process not only eliminates the strict limits on the viscosity of underfill encapsulants and package size, but also improves the production efficiency (Hsu et al., 2000; Chan et al., 2001; Tu et al., 2001). Because there is no delay due to capillary flow and post curing processes (Wang et al., 2001-(1); Zhang et al., 2001; Previti and Ongley, 2002).
- Very sophisticated dispensing system has to be used in conventional capillary flow underfilling process to provide controllable dispensing/flow process, a minimum of incomplete fills and voids whereas no flow underfill dispensing system can be less sophisticated and cheaper (Firmstone et al., 1999).
- No flow underfilling has much reduced tendency for incomplete filling and void formation and, additional filleting process not required (assuming optimized dispense pattern) (Firmstone et al., 1999). On the other hand, flow

inhomogeneities leading to voids, filler separation and settling are some of the main drawbacks of the capillary flow underfilling (Gilleo et al., 1999).

- For no flow underfill materials, another important advantage is that the compatibility issues between flux and underfill in a capillary flow underfill process are no longer a concern (Smith et al., 2000; Zhang and Wong, 2002-(1); Kondos and Borgesen, 2004; Tonapi and Reitz, 2004), because no flow underfill materials have self-fluxing action (Chan et al., 2001; Tu et al., 2001; Previti and Ongley, 2002). Moreover, so the self-alignment feature of solder bump reflow is also retained (Firmstone et al., 1999; Chan et al., 2001).
- The no flow underfilling process does not require nitrogen inerting during reflow process, since underfilling take place before solder reflow and encapsulation of no flow underfill protects the solder/metallization from oxidation during reflow (Baldwin et al., 2000; Kondos and Borgesen, 2003).

2.5. Underfilled Component Rework Techniques and Considerations

By means of the development of new reworkable underfills nearing completion and their commercialization underway, use of underfill is considerably increasing in PCBAs (Moore and Studley, 2003). As such, over the past several years, underfilling process has essentially become one of the standard assembly processes in the electronics manufacturing environment, for ensuring high levels of product reliability (Adamson, 2001; Schneider, 2001).

Nowadays, most of the PCBAs consist of underfilled packages. As an inevitable consequence, the task shifts to designing and adopting rework equipments and techniques of PCBAs. While reworking these kinds of PCBAs, presence of underfill material must be considered. Hence, rework process techniques and its parameters must be modified according to new requirements (Moore and Studley, 2003). Moreover, in essence, due to the necessity of underfilling, it must be incorporated into the rework process of PCBAs as a standard process to reach the technological improvements. As a result, conventional rework of PCBAs has been inherently changed.

It is actually clear that not only increasing use of BGAs, CSPs, and FCs but also continuous reduction in component size, bump pitch, and interpackaging areas around the components has exerted significant pressure on the rework of PCBAs which reveals more difficulties (Dalrymple and Milkovich, 2000; Russell, 2000). From the reliability point of view, with the trends towards smaller pitch, smaller solder ball height and larger component size the use of underfill material becomes more important (Gilleo et al., 1999; Vincent and Wong, 1999; Wang and Wong, 2000; Schneider, 2001; Babiarz et al., 2001; Zhang and Wong, 2002-(1). As a result, with the inevitable addition of underfilling step, rework process of PCBAs has turned out to be more strenuous task.

As mentioned in section 2.4.1, underfilling can be implemented in two ways and if they are integrated into the PCBA rework process, accordingly, this conditions the way of rework implementation method. Consequently, the rework processes of underfilled packages could be executed in the same manner as conventional rework process with capillary flow underfilling and novel rework process with no flow underfilling.

2.5.1. Conventional Rework Process with Capillary Flow Underfilling

The rework of underfilled components is similar to the rework of non-underfilled one in which the defective component is removed, the reworked site is redressed and the new component is replaced. The main difference is being the presence of the underfill between the component and PCB, which adds a new set of issues that need to be addressed in terms of component removal and site redressing (Wong et al., 1999; Wang and Wong, 2000; Gowda et al., 2002). Detail information will be given in the further sections.

As shown in Figure 2.15, the underfilled components conventional rework process with capillary flow underfilling has the following steps:

- Preheating the PCB evenly to a temperature below the melting point of solder. Then component is heated to reflow temperatures to melt solder connections and break down the underfill.

- Next, the defective component is removed from PCB immediately.
- Afterwards, PCB site is cleaned from underfill and residual solder.
- Once the clean up of the PCB is complete, solder paste or flux is applied, and then the new component is replaced.
- Later, solder joints are reflowed, followed by the capillary flow underfilling.
- Finally underfill is cured.

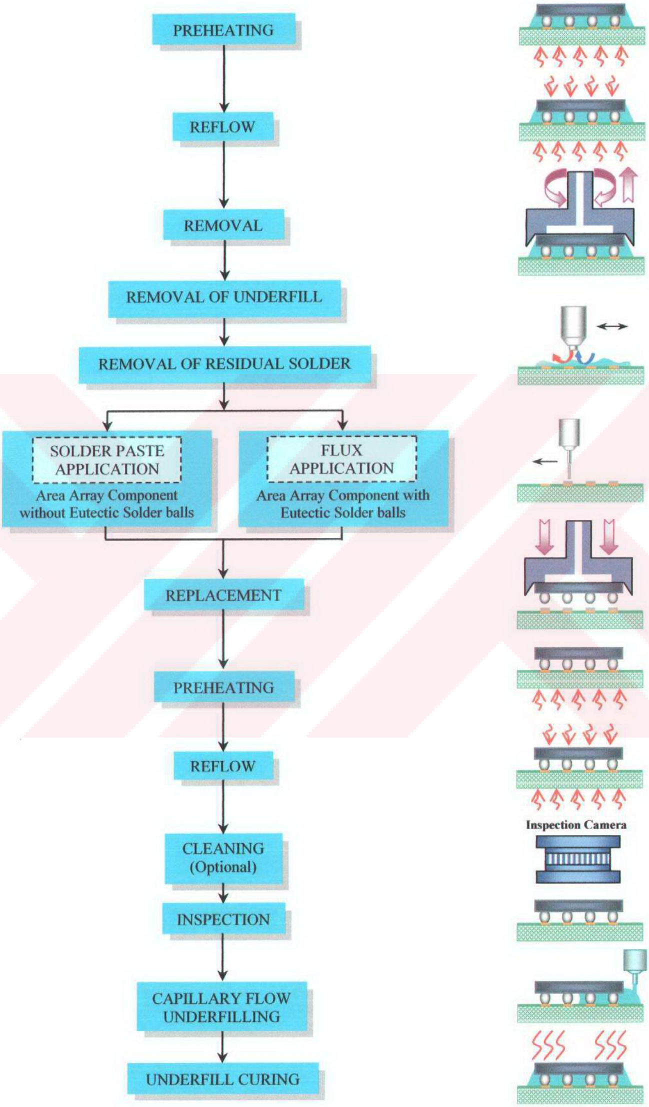


Figure 2.15. Conventional Rework Process with Capillary Flow Underfilling

2.5.2. Novel Rework Process with No Flow Underfilling

Underfilling can be implemented with the capillary flow since it has been a more widely used method in electronics over the years. Although it can be a choice as a dispensing method in the rework process, it has severe limitations mentioned in section 2.4.1.3. Hence, no flow underfilling is a better alternative to be selected as a more viable dispensing method.

Based on the researches' experimentations no flow underfilling was proven to be applicable to the BGAs, CSPs and FCs assembly, providing high assembly yields and reasonable reliability level (Shi and Wong 1999-(1); Firmstone et al., 1999; Smith et al., 2000; Zhong, 2000; Chan et al., 2001; Tu et al., 2001; Liu et al., 2001; Previti and Ongley, 2002). Moreover with the continuous improvement being made in the underfilling technology, in present, more advanced versions of no flow underfills compatible with the BGA, CSP and FC components become commercially available in the markets. Therefore, it seems to be effective to incorporate the no flow underfilling with the rework process to benefit from the no flow underfilling outstanding facilities in the rework process. As a consequence of above, implementation of the rework process of underfilled BGAs, CSPs and FCs integrated with the no flow underfilling could be an alternative solution to the rework process of these kinds of packages.

As shown in Figure 2.16, the novel rework process of underfilled components incorporated with no flow underfilling has the following procedures:

- Preheating the PCB to the temperature below the melting point of solder. Then component is heated to reflow temperatures both for melting the solder joints and breaking down the no flow underfill.
- Then, the defective component is removed from the PCB.
- Once the defective component removal, PCB site is cleaned from underfill and residual solder.
- After the PCB site cleaning, either solder paste is applied onto the PCB or not applied. It depends on the component specifications being reworked.
- Next, no flow underfilling is implemented.

- The new component is replaced precisely, compressing the liquid no flow underfill to disperse uniformly between component and PCB without causing any voids.
- Afterward solder joints are reflowed and underfill is cured concurrently.

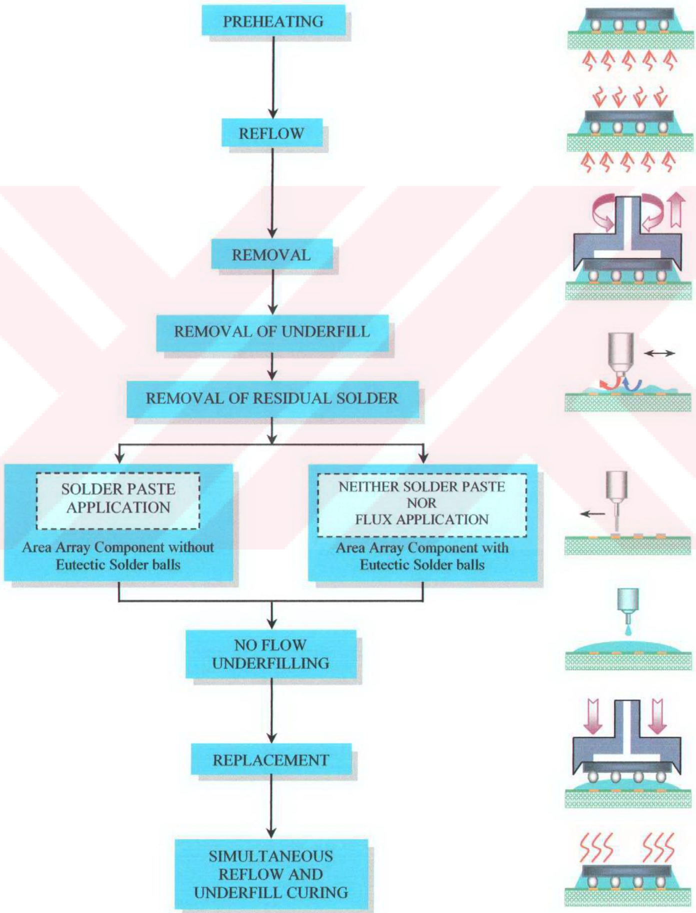


Figure 2.16. Novel Rework Process with No-Flow Underfilling

All in all, by means of integrating the no flow underfilling, its remarkable beneficial affect in the novel rework process with respect to reduced process complexity, cycle time, costs and increased process effectiveness is obviously seen from Figure 2.17.

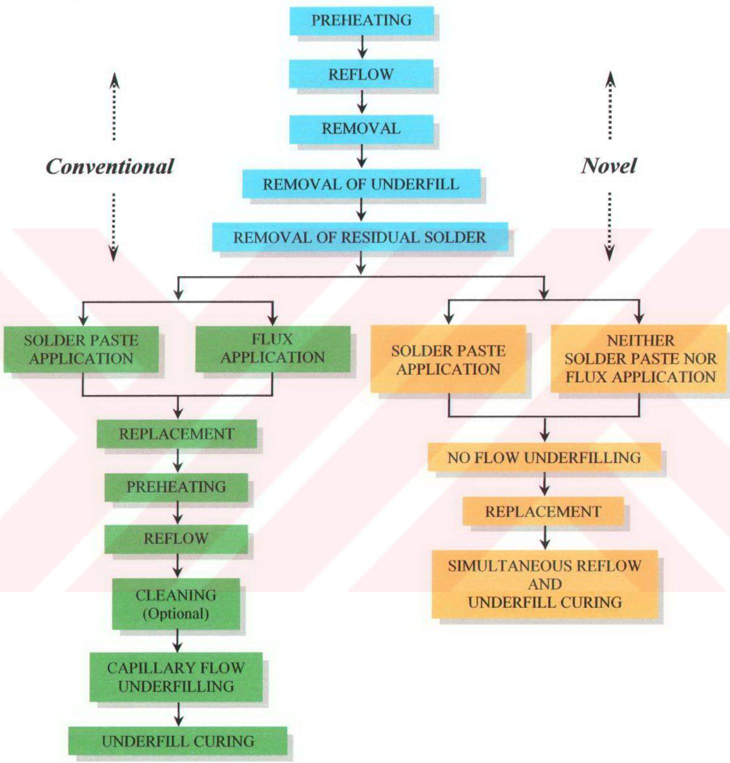


Figure 2.17. Comparison of Conventional and Novel Rework Process

With the addition of the underfilling to the conventional assembly and rework processes of the area array components, inevitably supplementary problems and considerations arise. Thus, following are detailed studies on essential process steps for conventional and novel rework implementations, respectively.

2.5.3. Considerations of Conventional Rework Process

2.5.3.1. Component Removal

Removal of the underfilled component is more challenging compared to non-underfilled one. Therefore it needs careful attention during removal process. Due to the presence of underfill during the removal stage, uniform complete component heating is required in order to accurately reflow solder joints and also break down underfill bond. Hence during underfilled component removal, reflow profile should be well established. Additionally, from the reflow standpoint, while typically a single reflow profile is used for removal and replacement of a component, the presence of underfill during the removal and its absence during the replacement, two significantly different reflow profiles are required in the conventional rework incorporated with capillary flow underfilling process (Gowda et al., 2002).

In general, from the view point of processability, the key to successfully remove the underfilled faulty component from the PCB is to heat the local working area to a temperature above the solder melting point and the glass transition temperature of the underfill material (Hannan and Viswanadham, 2001).

In order to perform successful removal process, first of all, heat is applied simultaneously from the top and underneath of the component (Tong et al., 1999; Schneider et al., 2001). According to underfill suppliers' recommendations, during removal, the assembly is simply heated to the temperatures of 210°C~220°C (component temperature) to easily remove the defective component from the board. After exposing the component to these temperatures within the sufficient dwell time (30-90 seconds for FCs and 60–100 seconds minimum for CSPs/BGAs), it is essential to twist the package when the underfill starts to melt so as to break the fillet's adhesion to the board and to remove the package easily. This can be done with a dedicated tool or tweezers. Without slightly twisting the component, the adhesive fillet is not broken, and the component remains firmly attached to the board (http://www.loctite.com, 2003).

On the other hand, it was reported that, although thermal profile was high enough to break down underfill (210°C~220°C), a vacuum suction could be insufficient to remove underfilled component from the board (Crane et al., 1999; Wang et al., 2001-(1); Gowda et al., 2002). Thus, as mentioned above, a mechanical twisting action is required to break down underfill bond and facilitates the component removal (Wang et al., 2000; Peng et al., 2001; Hannan and Viswanadham, 2001; Gowda et al., 2002). Therefore, special removal tool(s) with a gripping feature is needed to accomplish removal process successfully without damaging the PCB (Crane et al., 1999; Wang et al., 2001-(1); Gowda et al., 2002). To accomplish the removal process some researches used manual removal method with such a metal tweezers (Tong et al., 1999; Peng et al., 2001; Gowda et al., 2002; Lau and Chang, 2002), whereas some others designed and manufactured special accessories incorporated with the vacuum suction head in order to apply shear or twisting force to the component (Wang et al., 2001-(1).

Furthermore, it was stated that, even though the component removal could be easy with twister, however, some damages to the substrate materials (copper trace and solder mask peel-off) could also occur. Thus, from the processability point of view, in addition to develop a better component removing method, the vendors should develop reworkable underfills which are more user friendly and create less damage on both the component and substrate (Lau and Chang, 2002). Therefore with respect to component removal, instead of thermal based removal process, Kuerbis et al. (2003) studied on mechanical component removal technique based on the component milling approach. Test results showed that the reworked components had reasonably high quality interconnections similar to the non-reworked components. However, the milling process is not aesthetically pleasing method as the malfunctioning component is totally destroyed. Further, due to the fact that a layer of underfill is left over the circuit board between the components solder balls, the conventional capillary flow underfilling is not possible, as such this approach is not transparent to the general area array component assemblies. As for underfill material property, manufacturers and scientists, especially in the Packaging Research Center, Georgia Institute of Technology, USA by C. P. Wong et al, are carrying out extensive studies related to improving and developing capillary flow and no flow underfill materials (Shi and Wong, 1999-(1); Tong et al., 1999; Liu et al., 2001; Zhang et al., 2001; Lau and Chang, 2002; Bae et al., 2002; Moon et al., 2003).

2.5.3.2. Site Cleaning

After the defective component removal, PCB site must be redressed to replace new component efficiently. Site redressing process has two steps, removal of residual underfill and removal of excess solder (Tong et al., 1999; Wang et al., 2000; Gowda et al., 2002; Moore and Studley, 2003).

Although in most cases, the reworkable underfill materials soften at elevated temperature, allowing the component to be removed from the board, the polymer residue remaining on the rework site is rather difficult to clean (Crane et al., 1999; Wang et al., 2000; Peng et al., 2001; Gowda et al., 2002; Lau and Chang, 2002). Moreover, it was pointed out that use of variety of solvents as well as proprietary strippers either failed to remove the residual underfill material or attacked the solder mask as well (Crane et al., 1999). Additionally, as Tong et al. (1999) stated, organic solvents could not dissolve but swell the dense network structure of epoxy based underfill, even over a long period of time. Inevitably, the board will be damaged preventing the attachment of new component. As a consequence of the above, degradation or even damages to the solder mask material, vias, and copper pads/traces is not uncommon after the clean up the PCB site (Lau and Chang, 2002).

On the other hand, a combination of a gentle mechanical process and solvent cleaning application was found to be effective in cleaning the site from remaining underfill and solder residue (Crane et al., 1999; Wang et al., 2000; Lau and Chang, 2002). However, this process is highly dependent on the operator and may require one to two minutes to complete, depending on the underfill (Gowda et al., 2002). Although its sounds like a relatively simple task, care must be taken when brushing the rework area not to cause mechanical damage to PCB land, copper traces, and solder mask (Wang et al., 2000; Peng et al., 2001; Hannan and Viswanadham, 2001).

Due to the higher standoff and larger component size of BGAs and CSPs compared to FCs, more underfill residue was left on PCB site after the component removal and inherently board cleaning is tougher after BGA and CSP removal (Wang et al., 2000; Peng et al., 2001). Thus, PCB site cleaning is carefully controlled and more attention must be given so as not to cause any damages to PCB site (Wang et al., 2000). Moreover, depending on the underfill type, cleaning of the underfill residue for large BGAs would be time consuming, and brushing occasionally may lead to pad damage (Wang et al., 2000). Based on the experimental studies of Lau and Chang (2000, 2002), it was revealed that because of the taller solder mask (than the copper pad) and the very small diameter of the copper pad, the underfill residues on the copper pad were very difficult to be removed with an electrical rotary tool equipped with a stiff horsehair flat end brush. From the processability standpoint, it was advised that, in addition to have a better design of the solder mask/copper pad on the substrate and develop a better cleaning method, the vendors should develop reworkable underfills which are more easier to be cleaned-off from the substrate.

In order to obtain acceptable cleaning process, in terms of removal of underfill residue, recommendations of underfill manufacturer should be complied. The recommendations provided by the underfill manufacturer for site redressing that include (Gowda et al., 2002):

- The underfill material should be exposed to 220°C for a minimum of 60 seconds during component removal to allow enough time for decomposition of the underfill material and facilitate removal from the board;
- The residual solder and most of the underfill material is removed using site-scavenging system. The board temperature during scavenging is maintained between 120°C to 150°C;
- The remaining underfill is removed by mechanical brushing using a rotary tool (set at 30.000 rpm) and flat end stiff horsehair brush. This operation is performed at room temperature;
- The site is finally cleaned using isopropyl alcohol.

On the other hand, there is another cleaning related concern with the conventional underfill implementation. The incompatibility of the conventional underfill and flux residual creates interfacial problems in assembled component and lowers the reliability (Adamson and Klocke, 2001; Zhang and Wong, 2002-(1); Kondos and Borgesen, 2003). These problems aggravate further with the increase in component dimensions and I/O counts, and decrease in standoff height and pitch sizes (Zhang and Wong, 2002-(1).

Even so called "low-residue" or "no-clean" solders and fluxes, designed to minimize the need for cleaning of surface mount solder joints, are occasionally a source of great problems, tending to leave residues on the board (Adamson and Klocke, 2001). Hence, it is important that the amount of flux residue left after reflow soldering operation should be minimized (Adamson and Klocke, 2001) and flux cleaning is advisable, since any flux contaminant at or near a bump impede underfill flow and can cause a void and subsequently a space for the solder bump to flow (Quinones et al., 1998). As a consequence, the flux residue and underfill voiding are significant issues in the conventional underfilling of area array components and these considerations demand better process control for fluxing (Adamson, 2000).

According to Peng et al. (2001), voids at the base of the solder joint due to flux residue from the no-clean solder paste limited the thermal cycle performance of the underfilled fine pitch BGAs. The reflow atmosphere was determined to be a significant factor. Use of a nitrogen reflow atmosphere was shown to increase the underfill void content compared to reflow in air.

2.5.3.3. Component Replacement

After the site is redressed, new component is assembled either based on the flux-only or solder paste applied process. Due to the absence of the underfill between package and board, replacement thermal profile is lower than removal profile (Gowda et al., 2002).

2.5.4. Considerations of Novel Rework Process

2.5.4.1. Thermal Profiling

In the novel rework process, thermal profiling needs to be more carefully controlled and implemented in order to compensate no flow underfilling requirements and also of course to preclude any adverse affect to the reliability of the PCB due to the high reflow temperatures (Wong et al., 1998-(1); Wang and Wong, 2000; Debarros and Katze, 2000; Smith et al., 2000; Wang et al., 2001-(1). Reflow is the most complex procedure to optimize when no flow underfills are used, because several processes take place, some of them with conflicting requirements (Kondos and Borgesen, 2004). Since the underfill is dispensed prior to the component reflow soldering, high curing latency is required so that the underfill can maintain low viscosity at the solder reflow temperature, i.e. minimal curing reaction should occur at the temperature below solder bump reflow temperature (~180°C–210°C). Otherwise, the gelled underfill will restrict the solder wetting on the contact pads and hinder the forming interconnection (Wong et al., 1999; Smith et al., 2000; Liu et al., 2001; Zhang and Wong, 2002-(1); Kondos and Borgesen, 2003; Zhang et al., 2003). Figure 2.18 shows a case where the material started gelling too early, preventing this particular bump from wetting its pad, although it is clear from the shape of the bump that the other joints have collapsed and the molten solder was pressed onto the pad, trying to form a joint (Kondos and Borgesen, 2003).

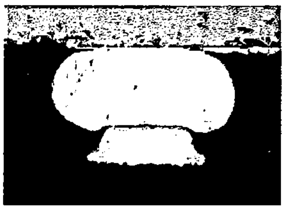


Figure 2.18. A Failed Joint due to Early Onset of Gelling of the Encapsulant (Kondos and Borgesen, 2003)

Moreover, right after the completion of solder bump reflow rapid curing reaction of the no flow underfill material should take place in the reflow cycle (Hsu et al., 2000; Smith et al., 2000; Liu et al., 2001; Kondos and Borgesen, 2003). It is not surprising then that some of these materials are quite sensitive to variations in the reflow profile, leading to opens if the temperature becomes too high too soon, or even if the heating rate is too high (Kondos and Borgesen, 2003). Reflow time and temperature are critical parameters in achieving interconnect and the required degree of cure (Debarros and Katze, 2000). It was found that the gelation was strongly dependent on the heating rate and the curing temperature, at a higher heating rate or high cure temperature, the underfill tended to gel at lower degree of cure (Zhang et al., 2003). No flow underfills cure after they reach the liquid-state phase (183°C for eutectic solder). Degree of cure is greatly influenced by the peak temperature attained and the length of time above 183°C (Debarros and Katze, 2000).

The optimum performance is obtained with reflow profiles having a soaking zone temperature no greater than 160°C and a peak of at least 220°C. In addition, it is recommended that the profile include at least 55 seconds with a temperature above 180°C and at least 45 seconds with a temperature above 200°C (http://www.loctite.com, 2003).

2.5.4.2. Component Removal

This step has the same considerations of the conventional rework process.

2.5.4.3. Site Cleaning

This step has its own considerations and also has the same considerations of conventional rework process as well.

From the processability and reliability point of view, as an important facility provided by the no flow underfill materials is that the problem of flux and underfill material compatibility is obviously eliminated. Hence, there is not a challenge of cleaning implementation between the smaller gap distance of component and circuit board (Smith et al., 2000; Zhang and Wong, 2002-(1); Kondos and Borgesen, 2003; Tonapi and Reitz, 2004).

2.5.4.4. Solder Paste or Flux Application Requirements

One of the most important parameters that conditions either solder paste or flux application necessity is the reliability constraints. As mention before, if the high level of reliability is required, which makes the reliability predominant factor, solder paste application is inevitably necessary. On the other hand, as it was previously pointed out that, substantially the goal of underfilling is to provide/increase the reliability level of the components. As such, reliability constraints are almost compensated by the underfill material rather than solder paste applied. Moreover, today commercially well established no flow underfills are available from such company as Kester and Emerson & Cuming, which completely eliminates the need for additional solder paste/flux application for the components having eutectic solder balls.

As a consequence, since not only the constraints of the PCBA harsh working environments but also economical constraints due to the high value circuit boards and components necessitate establishing consistent reliability level, all these requirements are responded by the successfully developed no flow underfills. Additionally, when the assembly of high-melt solder balled components is an issue, unfortunately solder paste application is an inevitable process.

2.5.4.5. Component Replacement

In conventional rework process, solder joints form first followed by the capillary flow underfilling, while in novel rework process no flow underfill is applied onto the PCB prior to new component replacement and then simultaneously solder joints are reflowed and underfill is cured (Wang and Wong, 2000; Hsu et al., 2000; Wang et al., 2001-(1); Previti and Ongley, 2002).

The component must be placed in a way that assists in displacing air so that voids will be minimized or completely eliminated. There is a tendency to trap air as the area array component is placed into the no flow underfill, unlike capillary underfills where the flow front displaces air (Gilleo et al., 1999; Baldwin et al., 2000;

Debarros and Katze, 2000; Kondos and Borgesen, 2004). One of the more advanced techniques, called compression flow may be a solution (see Figure 2.19).

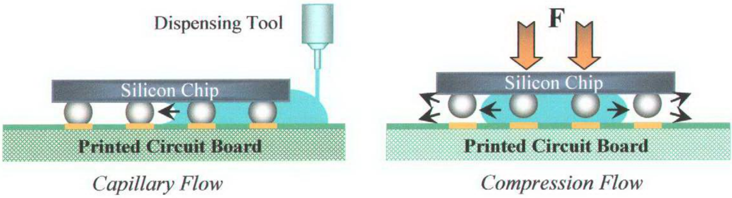


Figure 2.19. Comparisons of Capillary Flow and Compression Flow

The underfill material underneath the component resists flow, and it must be squeezed out. The downward movement causes the no flow underfill to flow outward to the edges of the component, forming fillet, which promotes component adhesion to the board (Smith et al., 2000; Kondos and Borgesen, 2003). The compressed underfill, with a generally symmetrical outward flow pattern, helps displace air (Gilleo et al., 1999; Debarros and Katze, 2000; Kondos and Borgesen, 2003). Once the underfill has reached the edges of the component, it must wet the sides and climb them to form a fillet in a range of 1/3 to 2/3 total component height (Kuerbis et al., 2003).

No flow underfill encapsulants resist the downward motion and collapse of the component. If only a few bumps are in contact with their pads initially, the force exerted by them after melting and forming joints may be too feeble to squeeze more liquid from underneath the component and to allow collapse (Chan et al., 2001; Kondos and Borgesen, 2004). The challenge of the no flow underfill implementation before reflow is that, adjustment of the bonding or placement force such that good contact of solder bump to the substrate pad and smooth compressive flow of no flow underfill can be obtained (Lu et al., 2001).

During the placement process, once the underfill material wet the sides of the component sufficiently, during that time, the component must be held in place, or it might temporarily float on the drop of underfill liquid and settle in the wrong place later. Not only must the component usually be held for a certain amount of time before the placement tool is released, but also it must be pressed down with a certain force during that time as well (Kondos and Borgesen, 2003). This means when working with no flow underfill, in component replacement step, a threshold bonding force is necessary to insure that all solder balls are in contact with the PCB pads, for good soldering (Zhong, 2000; Debarros and Katze, 2000; Chan et al., 2001; Lu et al., 2002; Kuerbis et al., 2003; Kondos and Borgesen, 2004). Placement dwell time and force have a predominant influence on continuity yield. The dwell time allows the underfill liquid rebound effect to dissipate before the pressure is released (Debarros and Katze, 2000; Kondos and Borgesen, 2003). However, bonding force and dwell time should be optimized because too much bonding force can bring about completely collapsed solder joints and even can cause bridging of solder balls and/or pads which results in short circuits (Zhong, 2000; Chan et al., 2001; Lu et al., 2002; Kondos and Borgesen, 2003).

Moreover, apart from the obvious risk of damaging the component, as seen from the Figure 2.20, excessive force may also result trapped underfill beneath the solder bumps after reflow (Lu et al., 2001).

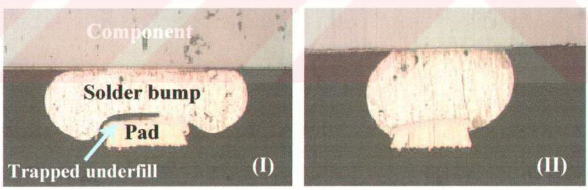


Figure 2.20. Solder Joint Cross-sections: (I) underfill trapping between solder bump and pad; (II) good bonding between solder bump and pad (Lu et al., 2001).

As a result, the component should be accurately placed with sufficient force which has to be high enough to eliminate the solder ball height differences, to remove no flow underfill between solder ball and pad, and to attain a contact between solder balls and circuit pads (Chan et al., 2001; Lu et al., 2002; Kuerbis et al., 2003). Moreover, according to no flow underfill supplier's technical data sheet, necessary placement force ranges from 150 to 350 grams, depending on size and bump count of the component and minimum recommended placement dwell time is 0.02 seconds (http://www.emersoncuming.com, 2003).

Additionally, no flow underfill liquid resists not only downward motion of the component, but lateral motion as well. Therefore, there should be reduced self-centering of the component during reflow, and accurate placement is more important when no flow reflow encapsulants are used in comparison with conventionally assembled components. When reflow with no flow underfill, large resistance force arises from the dramatic increase in viscosity of underfill reflow. Hence, self alignment ability of components, which facilitates the replacement process, is partially inhibited by the no flow underfill resistance force due to its viscosity in reflowing process and thus higher placement accuracy is inevitably needed (Kulojarvi et al., 1999; Chan et al., 2001; Tu et al., 2001; Adamson and Klocke, 2001; Kondos and Borgesen, 2003; Coderre, and Vijayamadhavan, 2003). It was resulted that during assembling, changes in placement force does not almost influence on the self alignment of no flow underfill. However, the viscosity of no flow underfill would seriously affect the self alignment (Chan et al., 2001).

The self alignment ability could be concerned with the curing process of no flow underfill, because the underfill resistant force depends on the curing process, that is, the increase of the viscosity during reflow (Kulojarvi et al., 1999; Chan et al., 2001). It is very important to keep a low viscosity during reflow for processability and reliability of application of no flow underfill (Chan et al., 2001; Shi and Wong 1999-(1, 2); Liu et al., 2001; Zhang et al., 2003). Basically, the lower the viscosity, the better the underfill (Wong et al., 1999; Chan et al., 2001). It was stated that, assembling with no flow underfill allow <25% misalignment from the pad center during reflow for micro-BGAs (Chan et al., 2001).

Air entrapment is a primary issue influenced by placement speed. The faster the placement speed, the faster the no flow underfill flows around the obstructions, bumps, and over the depressions. This action suggests that a higher degree of air entrapment will occur as placement speed increases (Debarros and Katze, 2000).

Even before the component is placed, the dispensed encapsulant may affect the choice of features for local placement correction. In some instances, instead of fiducials, it is preferable to use pad site recognition for local correction. If some of the pads are covered, this method cannot be used. Conversely, if it is necessary to use pad site recognition, care must be taken so that the encapsulant does not spread so much after dispense that it covers the pads (Kondos and Borgesen, 2003).

2.5.5. Factors Affecting Underfill Void Formation

One critical consideration in achieving reliable assemblies is making certain the PCBA is moisture-free. If there is moisture and/or solvent in the PCB and component package structure, there is a potential for voiding and delamination. Voids are frequently a source of reliability problems, particularly when located adjacent to solder bumps. Delamination can originate at voids. In capillary flow underfilling, solder may flow into voids and resultant delaminations during subsequent reflow processes, depleting the joint. Shorting results when voids extend to adjacent joints (http://www.cooksonsemi.com, 2003).

In no flow underfill processing voids are caused primarily by moisture/solvent in the substrate, entrapped air from dispensing and component placement (Baldwin et al., 2000; Debarros and Katze, 2000; Kondos and Borgesen, 2003). When voids between bumps exist and the device is subjected to thermal shock, the pressures exerted on the solder joint force the solder into the void. As it can be seen from the Figure 2.21, if the void is large enough, the resulting failure allows bridging from one I/O to the adjacent one (Debarros and Katze, 2000).

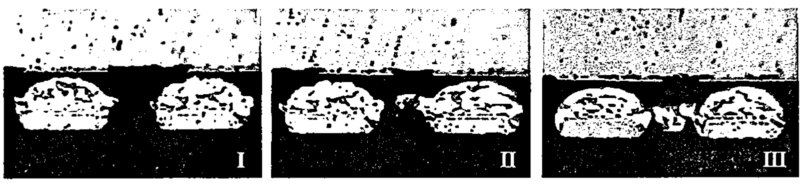


Figure 2.21. Solder Migrating into Void between Bumps (Debarros and Katze, 2000)

With no flow underfills, board dryness is even more critical, because of the much higher temperature the assembly undergoes during reflow (as high as 235°C), compared to traditional underfill curing (typically 150°C~165°C). Not only does the higher temperature increase the rate of moisture transfer from the board, but it can also cause water to come out that would have still remained bound inside the board at lower temperatures (Kondos and Borgesen, 2003). To eliminate voids related entrapped moisture and solvent, the substrate must be pre-baked (Baldwin et al., 2000; Smith et al., 2000; Debarros and Katze, 2000; Kondos and Borgesen, 2003). Debarros and Katze (2000) reports the results of an experimental pre-baking evaluation study showing that irrespective of the PCB material type, pre-baking for 2 hours at 120°C was required (see Figure 2.22)

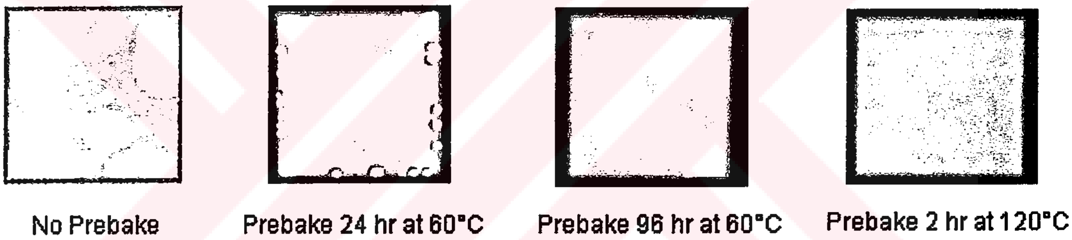


Figure 2.22. Prebaking Affect on No Flow Underfill Voiding (Debarros and Katze, 2000)

On the other hand, due to excessive ramp rates or temperature exposure during reflow outgassing can also occur within the no flow underfill itself. Higher ramp rates and elevated temperature exposure can cause the underfill constituents to volatilize and cause gas-producing chemical reactions to occur during reflow, resulting in underfill voiding (see Figure 2.23). Such voids can be extensive if the reflow profile is not designed correctly (Baldwin et al., 2000).

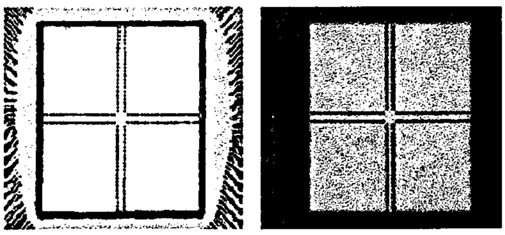


Figure 2.23. Outgassing Voids Due to Excessive Reflow Ramp Rates. (Left) High ramp rate, (Right) Low ramp rate profile (Baldwin et al., 2000)

All in all, as with any conventional underfills, voids in the no flow underfills are a potential problem. As a general aspect, researches have performed the pre-baking of 125°C~150°C at 1~1.5 hours before the implementation of electronics assembly either based on the capillary flow or no flow underfilling in order to avoid any shortcoming of the moisture or solvent induced defects (Smith et al., 2000; Tu et al., 2001; Lu et al., 2002). In addition, void formation can be eliminated through careful control of underfill properties and process parameters, accurate board preparation (Kulojarvi et al., 1999; Baldwin et al., 2000; Kondos and Borgesen, 2003).

2.6. Affect of Lead-Free Concerns on Electronics Assembly

2.6.1. Environmental Awareness in Electronics

Obviously the trend in electronics of today is not only smaller products with more functions, better performance and lower price, but also greener, more environmentally friendly products (Penttila and Kujala, 2001; Zhang and Wong, 2002-(2). In the electronics assemblies, components are generally attached to PCBs by lead-based solders over the years (Yang et al., 2001; Horsley et al., 2002). Lead, a major component in solder, has long been recognized as a health threat to human beings (Zhang and Wong, 2002-(2). The major environmental risk associated with lead in electronics is that since lead oxides from the solder can become soluble (Yang et al., 2001), the lead from disposed landfill sites could leach out into water sources (Harrison et al., 2001; Yang et al., 2001; Zhang and Wong, 2002-(2); Horsley et al., 2002).

Even though electronic solder accounts for reportedly less than one percent of the worldwide use of lead, litigation, legislation and environmental mandates have increasingly sought to make lead-based solder extinct. Thus, pending legislation and global marketing pressures driven by environmental concerns, along with the need for solders with higher temperature capability to severe service environment, have resulted in significant activities to find substitutes for lead-based solders for microelectronics assembly (Yang et al., 2001). At present, electronic packaging industry is actively searching for lead-free solders due to the environmental concern of lead-based solders. The main force of lead-free packaging were driven by legislation, but recently other forces such as commercial advantages related to environment-friendly electronics have raised more interest in industry and accelerated the process (Zhang and Wong, 2002-(2); Zeng and Tu, 2002). Hence, lead-free electronics is not only perceived as a health issue, but a result of government and commercial drivers as well (Zhang and Wong, 2002-(2).

In a global perspective, many of industry groups and collaborative organizations such as Improved Design Life and Environmentally Aware Manufacture of Electronics Assemblies by Lead-free Soldering (IDEALS-Europe), National Electronics Manufacturing Initiative (NEMI-USA), Japan Electronic Industry Development Association (JEIDA-Japan) etc. have been actively working to find out a viable alternative to Sn/Pb solder alloy as a lead-free solution. In general, high tin alloys are preferred to be the candidates of lead-free solder alloys, including Sn/Ag, Sn/Cu, Sn/Ag/Cu, Sn/Ag/Bi and various versions of these alloys with small amounts of other elements (Yang et al., 2001). However, among the others currently there is consolidated opinion on the application of tin, silver, copper (SnAgCu) eutectic alloy system (~217°C melting temperature) as such the electronics industry is leaning towards SnAgCu family of solders for lead-free applications (Yang et al., 2001; Horsley et al., 2002; Collier et al., 2002; Gupta et al., 2002; Mackie, 2003). As yet there are no industry standards on exact alloy compositions, variety of SnAgCu alloy compositions have been recommended, for example while NEMI recommends Sn3.9Ag0.6Cu as the best available option for lead-free surface mount reflow solder applications, JEIDA recommends Sn3.0Ag0.5Cu as a good choice for the replacement of lead-bearing solder (Yang et al., 2001; Collier et al., 2002).

2.6.2. Impact of Lead-Free Implementation on Assembly and Rework

One acknowledged fact is that primary change with lead-free PCBA implementation is the higher processing temperatures compared to standard tin-lead solders (Yang et al., 2001; Rupprecht, 2002; Bath, 2003; Mackie, 2003; Wood, 2003). Today most of the IC component manufacturers have announced their new green packaging products. Due to the fact that the ternary SnAgCu alloys are most frequently mentioned as solders for lead-free assemblies, they are naturally chosen to be used for solder balls on area array packages by the manufacturers with a slight differences in alloy compositions (http://www.ibm.com, 2003; http://www.nec.com, 2003; http://www.philips.com, 2003; http://www.amkor.com, 2003; http://www.intel.com, 2003). Newly developed BGAs/CSPs which can be subjected to the maximum 260°C for less than 15 seconds in a lead-free environment become available in markets (http://www.amkor.com, 2003; http://www.intel.com, 2003; http://www.motorola.com, 2003).

The lead-free alloys require reflow temperatures 30°C to 40°C higher than the temperatures used currently for standard tin-lead solders which means that the peak reflow temperatures for many lead-free solders are approximately 240°C~250°C as compared to tin-lead soldering temperatures of 210°C~220°C (Gowda et al., 2001; Rupprecht, 2002; Bath, 2003). High processing temperatures potentially degrade the PCB materials and may lead to excessive warpage, delamination, solder mask discoloration, and damage. In addition, multiple reflow cycles during rework may result in the degradation of the PCB surface finish and result in the oxidation of the copper pads. Accordingly, the assembly and rework processes need to be optimized to ensure that the integrity of the component and PCB materials is not compromised (Gowda et al., 2001). Hence, with respect to reflow soldering, even though the current components could perform satisfactorily after being exposed to a 260°C peak reflow temperature, there are many compelling reasons to limit the reflow temperatures an assembly is exposed to. Minimizing process temperatures limits the thermal stress on boards and components, reducing potential for manufacturing defects. Moreover, limiting the temperatures reduces the intermetallic growth and the potential for popcorning of components with high moisture content (Johnson et al., 2001). Therefore there are many studies conducted on trying to find out optimum lead-free reflow process window (Johnson et al., 2001; Harrison et al., 2001). Based on the experimental results of these studies, it was revealed that with the SnAgCu solder alloys reliable solder joints could be obtained with the narrowed reflow process windows ranging from 225°C~240°C peak temperatures.

From an inspection viewpoint, lead-free solder joints look distinctively different than tin-lead joints (Rupprecht, 2002; Wood, 2003) and are often erroneously rejected by inexperienced operators for quality reasons (Rupprecht, 2002). Hence there is a strong need to retrain technicians according to new inspection criteria (Rupprecht, 2002; Wood, 2003). External appearances of a lead-free and tin-lead solder ball are shown in Figure 2.24. It is obviously seen that lead-free solder ball looks grainy compared to traditional tin-lead eutectic solder ball.

Sn3.0Ag0.5Cu solder ball 63Sn37Pb solder ball

Figure 2.24. Real Photograph of the Lead-free (left) and Lead-based (right) Solder Balls (http://www.nec.com, 2003)

The shape of the reflow profiles for lead-free solders is distinctively different from those of eutectic solders (Rupprecht, 2002; Wood, 2003). Linear profiles are preferred for SnAgCu solders (IPC Roadmap, 2000). Generally, the best profile ramps from soak to reflow quickly and then leaves the component in reflow within the sufficient period of time (Rupprecht, 2002; Wood, 2003). In addition to higher temperatures, most lead-free solder pastes essentially require extended period of time at liquidus during reflowing, usually 60 to 90 seconds instead of the traditional 40 to 60 seconds to make sure the joints are properly formed (Yang et al., 2001). Efficient, controlled preheating avoids the risk of thermal damage when working expensive but sensitive components unsuitable for heating above 240°C with quick reflow times (Rupprecht, 2002). It was stated that, for lead-free reflow process, especially in the case of large assembly, the recommended reflow profile should have a preheat temperature only a few degrees below the melting point of the solder, with a dwell time long enough to allow equalization at that temperature (Mackie, 2003). As a consequence, the main differences between Sn/Pb and lead-free heating profiles are the increase of preheat and solder reflow temperature, and also the longer times at liquidus for sufficient wetting.

From the processability point of view, due to the higher processing temperature of lead-free implementation (up to 260°C) the oxidation of the solders becomes more of an issue. Conventional no-clean fluxes may dissipate or become inactive before reaching the peak solder temperature (IPC Roadmap, 2000). Moreover, flux oxidation can cause increased flux cleaning problems. It was shown that each of these problems had been reduced or eliminated with the use of nitrogen processing atmosphere, since the solderabilities of lead-free alloys were considerably improved (Mackie, 2003). In addition, the required process temperature for good wetting had shown to be reduced (up to 30°C) with the use of nitrogen, thereby reducing the potential damage to temperature-sensitive components. Therefore nitrogen atmospheres may be necessary, especially with complex boards with varying finishes and thermal requirements (IPC Roadmap, 2000).

Additional reflow issue to be considered is the cooling rate which is important in higher order alloys (more than two elements) since different metallurgical reactions can occur at high and low solidification rates. In other words, different intermetallic compounds can form within the joint depending on cooling rate (Yang et al., 2001). Another factor to consider when moving to lead-free is the temperature gradient across the surface of the component. While generally a temperature gradient of 10°C is considered acceptable, lead-free implementation requires 5°C (Wood, 2003).

As a result, in the case of lead-free reflow soldering, it should be aware of the fact that use of lead-free alloys markedly shrinks the reflow process window (Johnson et al., 2001; Rupprecht, 2002; Mackie, 2003). In essence, not only more precision is needed (Rupprecht, 2002; Wood, 2003) but also greater process control is demanded (Mackie, 2003; Wood, 2003). These concerns stem from the opposing requirements of high enough reflow temperature to melt the lead-free solder and form proper interconnection with appropriate flux activation and wetting characteristics, yet low enough to avoid PCB and/or component damage due to temperature sensitivity (Mackie, 2003; Wood, 2003). Typical lead-free reflow profile recommended by the lead-free solder supplier is shown in Figure 2.25.

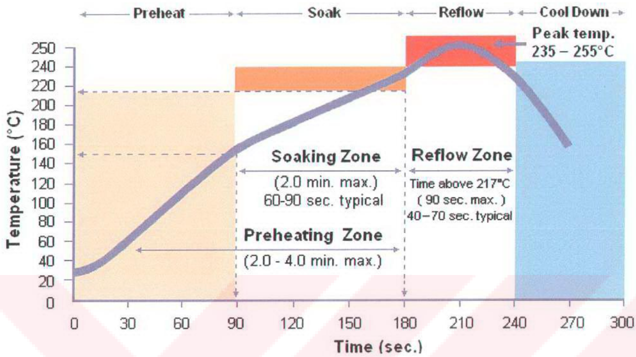


Figure 2.25. Recommended Generic Lead-Free Reflow Profile for Sn95.5Ag3.8Cu0.7 and Sn96.5Ag3.5 Solder Alloys (http://www.kester.com, 2003)

Important specifications for a successful lead-free implementation stated by Institute for Interconnecting and Packaging Electronic Circuits (IPC) Roadmap (2000) are given below;

- The ramp rate for solder paste is 1°C to 2°C/sec maximum up to soak temperatures, and may be up to 3.5°C/sec from 215°C peak temperature.
- Time above solder liquidus temperature (217°C) will typically range between 30 and 90 seconds. An extended period may be required to ensure proper wetting.
- Peak temperature will typically be between 235°C and 250°C. A lower peak temperature (closer to 235°C) is preferred to minimize component damage, but 260°C may be necessary with some designs to maximize wetting.
- Cool-down rates will typically be between 2°C and 4°C/sec.
- Atmosphere requirements for SnAgCu depend on the components and flux, therefore, should be evaluated to determine if enhanced wetting performance and reduced oxidation will be obtained.

All things considered, lead-free soldering is technologically possible, but key implementation issues need to be addressed;

- In most cases, higher process temperatures are required than for standard tin-lead solders, and this may be incompatible with some materials, components and equipments.
- The process windows for lead-free reflow soldering implementations are narrower than for tin-lead.
- Equipment and processes will have to be modified in many cases to accommodate the higher soldering temperatures.
- In some cases, cleaning processes may be modified.
- Criteria for inspection methods may need to be modified through operator re-training.

2.7. Requirements of Automated Advanced SMCs Rework

Despite the current state of art technology, defects are still common in the PCBAs because of the enormous varieties in component types and their assembly tasks. Current literature survey results revealed that there have been some automated robotic rework cell system development attempts. These rework cell systems have been designed and developed for standard SMCs at 1.27 mm (50 mil) pitch sizes (Geren and Lo, 1998) and for fine pitch SMCs at 0.635 mm (25 mil) pitch sizes (Fidan et al., 1998-(1). In addition to these, following statements have been pointed out to emphasize the need of a fully automated robotic rework;

- Manual rework on the PCBAs is unreliable, lengthy and challenging process, and operators must have combination of different skills.
- The continuous movement towards miniaturized, high lead count, fine pitch SMCs and inherently densely populated multilayer PCBs not only means that the required training and skill level for rework operators has increased but also makes even manual or semi-automated rework extremely difficult and time consuming.

- Intense dependence on the operator involvement within the current available rework stations, increases human error and overall process duration, so lowers the process yield and quality.
- The automation in the whole rework steps is essential to achieve desired consistent efficiency and quality level which cannot be achieved with the manual rework. Automation provides consistent, flawless, high quality repairs by continuous control of all rework steps.
- The increasing utilization of complex, high lead count, fine pitch SMCs with the increasing compactness of the SMC assemblies has demanded more accurate, reliable and cost effective method of rework which can only be achieved with the full automation of all rework steps.
- The costs of scrapping faulty complex PCBAs can be very high and also disposing of PCBs can be a problem when the heavy metals in most boards are classified as hazardous waste.
- The health hazards associated with the use of chemicals and the higher risk of jeopardizing the high value PCBAs during manual-assisted rework essentially necessitate to consider fully automated rework.

On the other hand, with the emergence of the advanced SMCs having much more miniaturized pitch sizes and component dimensions varying from 0.1 mm to 1.5 mm and from 3.81 x 3.81 to 50 x 50 mm respectively, the greatest challenges with the component placement and solder application have brought about. Furthermore, besides the above, in conjunction with the inevitable trends of underfill application and environmentally friendly electronic products the advanced SMCs' rework process window have become markedly narrower and the level of essential precision, accuracy, and overall process control is increased to an extent where a fully automated robotic rework system is increasingly necessary.

As a result of above, in essence, because of the more complicated natural structure of advanced SMCs coupled with the novel technological requirements there is a significantly growing need for a fully automated rework system that can carry out the whole advanced SMC rework process on the basis of a batch size of one.

3. MATERIAL AND METHOD

This study aims to design a robotic rework cell system for advanced SMCs. However, working method of the cell system is indefinite, at beginning of the study. The majority of the uncertainty is mainly due to the type of the reflow technique. Because of this, in subsequent sections, viable rework methods are developed based on the appropriate reflow techniques. Then, suitable auxiliary rework systems and tools are determined according to the rework method which is revealed to be superior.

3.1. Tooling Requirements of Automated Advanced SMCs Rework

So far, all crucial rework specifications and requirements of advanced SMCs have been extensively revealed. If these are scrutinized properly, required tooling for fully automated advanced SMCs rework system can be substantially found out. However, so as to achieve fully automated robotic rework of advanced SMCs based on the novel rework fashion, necessarily the followings are to be also reconsidered:

- Preparation of defective PCBA for rework; cleaning whole contamination from PCBA, and prebaking etc.
- Preheating; uniformly and precisely applying 70-75% of the total heat with the appropriate temperature increment to bring the assembly from room temperature up to a temperature that expedite defective component removal.
- Desoldering; exposing the defective component to the reflow temperature to melt solder joint and to break down underfill bond in a fully adjustable, closed-loop temperature controlled manner.
- Defective component removal; removing the component with a twisting action without causing any damages on PCB and/or component structure.
- Site clean up; cleaning efficiently whole remnants of residual solder and underfill from rework site without damaging the PCB.

- Solder paste or no flow underfill dispensing; applying precise and correct amount of related fluid materials to the target pad sites in a fully controlled, automated fashion.
- New component replacement; accurately placing new component with a sufficiently high enough placement force for a certain dwell-time to attain a good contact between solder balls and circuit pads by dissipating solder ball coplanarity differences and dispersing no flow underfill uniformly.
- Resoldering; precisely simultaneous reflow soldering and curing underfill material in a fully adjustable, closed-loop temperature controlled manner.
- Inspection; confirming the rework results.

In addition to these, the automated advanced SMCs rework process also needs the implementation of accurate sensory, supervisory and other control tools and systems as well.

Accordingly, except the necessary vision and cameras, and other sensory control devices for an automated rework process, substantial tooling candidates of the automated robotic rework system for advanced SMCs are give in Table 3.1.

Table 3.1. Necessary Tooling Candidates for Automating Advanced SMCs Rework

Rework Step	***Possible Tooling Candidates***
Preheating	• Hot plate • IR • Hot air preheater
Desoldering & Resoldering	• Hot air/gas • IR • Laser reflow
Component Removal & Replacement	• A special removal tool with a gripping feature
Site Cleaning	• Non-contact, convective (hot air based) vacuum desoldering tool
Solder paste, Flux, and No flow Underfill Application	• Time/pressure valves • Spray valves • Non-contact jetting valves • Linear positive displacement pumps • Rotary positive displacement pumps
Component pick & place and positioning	• An industrial assembly robot • X-Y positioning table
Inspection	• Transmission X-ray

3.2. Determination of Candidate Tooling Requirements for Automated Advanced SMCs Rework

In order to find out viable candidate tooling for fully automated, robotic rework of advanced SMCs; besides the analysis of existing manual advanced SMCs rework procedures, methods, tools, and problems, also currently available reflow technologies and technology on automation including industrial robots, sensory devices, inspection systems etc. are to be scrutinized in details.

Therefore, firstly studies are made of the prime reflow methods and possible reflow tooling candidates based on their suitability and technical feasibility for automated rework of advanced SMCs. This is done by investigating current literatures and related market segments. Afterward, proposals are outlined for determined candidate reflow tooling, followed by the determination of possible closed loop heat control mechanism and related tooling considerations for the determined candidate reflow tooling.

Secondly, studies are made of the calculation of required accuracy for essential manipulating devices which are industrial assembly robot and X-Y positioning table. Then important selection criteria and essential features that the manipulating devices must have are introduced.

In subsequent sections, studies are made of the possible tooling candidates for all other rework steps, except reflow tooling. In this section, the ideal rework requirements are reconsidered and rework tooling candidates for component removal/replacement, preheater, fluid material dispensing, site cleaning, vision and inspection are presented respectively. These tooling candidates are identified according to their suitability, adaptability, and technical feasibility for automated rework of advanced SMCs. Finally, it concludes with a determined automated rework procedure of advanced SMCs which is stated based on the previously analyzed manual rework procedures and proposed essential rework tooling candidates.

As a final conclusion, determination of candidate tooling requirements for automated advanced SMCs rework is presented in subsequent sections respectively.

3.2.1. Determination of Prime Reflow Methods

As a rule of thumb, the successful removal and replacement of a component is based on the desoldering and resoldering of its solder interconnections. Because of the nature of area array components, they are heat-sensitive and individual solder joint rework is inherently prevented, both of which significantly complicate the rework process and necessitate strict process control. Hence, the application of the heat, the selection of appropriate method, and the ability of accurate control of the required heating tooling has the remarkable merits. In essence, the reflow method must be capable of meeting the all critical specifications of the thermal processing required for the successful removal and replacement of an area array component, introduced in previous chapter.

The selection of the type of reflow soldering process required depends upon the type of components to be soldered, whether through hole; surface mount or combination of two. There are number of soldering equipments ranging from the simple handheld soldering irons to hot air/gas, infrared radiation (IR), and laser. Unfortunately, there is no one reflow method that is appropriate for all IC components, and many of the techniques are not applicable to some components due to the nature of the components and the associated PCBs (Geren, 2001). However, detailed rework studies revealed that non-contact local heating methodologies of non-focused infrared, hot air/gas and laser are commonly used for advanced SMCs. Infrared and hot air/gas reflow soldering methods are mature in technology while laser reflow soldering is a relatively new process in electronics manufacturing. The following is description of these three possible reflow soldering methods for a rework station.

3.2.1.1. Infrared Reflow

Infrared refers to that part of the electromagnetic spectrum having wavelengths lying between the visible and microwave regions, with 0.75 to 2.5 μm being near-IR, 2.5 to 25 µm middle-IR, and over 25 µm far-IR (http://www.thermometrics.com, 2003).

In IR reflow systems, either lamp emitters are used to generate IR radiation energy in a concentrated wavelength at the near end of the spectrum (namely called non-focused/iris-focused or lamp IR) or emitter panels are used to produce the IR radiation energy in the mid to far wavelength regions of the spectrum (called focused IR) (Conway et al. 1990). In the non-focused IR systems, the whole component and surroundings are heated whereas in the focused IR systems only the targeted solder joint is heated (Geren, 1993).

IR heat transfer is dependent upon wavelength energy and color of the board and component, which determines a material's heat absorption characteristics, and is selectively absorbed by the product (Lee, 2002).

IR radiation provides convenient, rapid temperature control, is relatively cheap for both investment and running costs, has no pollution or health risks, and avoids tombstoning. Hence, the IR reflow is the most commonly applied soldering process for SMT; especially the non-focused IR is proving to be more desirable (http://www.intel.com, 2003). This is why the most of currently available manual and semi-automated rework systems include non-focused IR heating units.

The non-focused IR is a contactless and tool free thermal processing technique. In this method, short wave IR energy, derived from a 150 watts tungsten-halogen spot lamp is collimated and focused through a lens system which allows the control of the heating area and also generates the red color for ease of operating. Only four interchangeable lens attachments are used which enables to project IR spot size of 4 to 70 mm in diameter, making the focused IR well-suited to differing component families ranging from BGAs, CSPs, and FCs to more traditional SMCs. The component being heated is isolated from adjacents by adjusting the IR spot to size with an iris. In addition, since there is enough free space between IR heat source and component, closed-loop control of component temperature with a non-contact remote temperature measurement technique is achievable (http://www.pdr-smt.com, 2004). However, there is still a risk of reflowing adjacent components at densely populated PCBAs and reflow might occur at higher temperatures due to the use of short wave IR (Geren, 2001).

Geren and Redford (1994) report the results of a study showing that the non-focused IR method is promising to be well suited to automated rework system for the standard SMCs with respect to costs, adaptability, suitability, flexibility, and reliability reasons. In addition, they have also successfully designed and implemented the proposed non-focused IR based system in a fully robotized manner which verifies the viability of the proposal.

Consequently, not only its advantages over the focused IR method but also encouraging demonstration of its viability and adaptability in a fully automated rework environment the non-focused IR method is promising to be appropriate for automated advanced SMCs rework.

3.2.1.2. Hot Air/Gas Reflow

In hot air/gas reflow soldering systems, convective energy is used for thermal processing of electronic assemblies. This process involves simply heating the air or an inert gas to reflow temperatures and directing it via specifically designed nozzles to accurately concentrate heat on the component and solder joints. The nozzle design is perhaps one of the most critical process parameters to be concerned in this type of heating (Primavera, 2003).

The main drawbacks of hot air systems are that interchangeable nozzles specifically designed for each component types are used to accommodate different applications (Wood, 1998; Geren, 2001), the risk of reflowing inevitably surrounding components and the requirement of sufficient interpackage spacing to accommodate hot air nozzles (Prasad, 2001-(2). Contrarily, despite its significant shortcomings, the hot air/gas is one of the major reflow methods and it is commonly offered to be used for desoldering and resoldering processes of individual SMCs.

3.2.1.3. Laser Reflow

Not only the increasing miniaturization in electronics assemblies and heat-sensitivity of components, but also greater thermal demands, higher service temperatures and need for greater reliability has remarkable impact on the demands of the soldering technology. These inherently have made soldering by laser economically viable and of interest to manufacturers of electronics assemblies (Beckett et al., 1994; Liu et al., 2002). In present, the demand of laser applications is significantly increased due to the growing applications of expensive, moisture sensitive fine pitch and advanced SMCs on densely populated PCBAs and also due to the impending use of lead-free solders (Prasad, 2004). As a result, the ability to precisely and accurately apply required heating energy to a specific component or target area without causing any damages has definite merits in thermal processing of these assemblies. Laser soldering process utilizes a focused high-power density laser beam to deliver highly concentrated energy to the components to be soldered and to the solder for a short period (Becker, 1997; Beckett et al., 2002).

In the past, the most popular sorts of lasers used in the PCBAs have been the traditional CO_2 lasers operating at a wavelength of 10.6 μm and lamp-pumped solid state Nd:YAG lasers operating at 1.06 μm wavelength (Whitehead and Foster, 1995; Beckett et al., 1997; Becker, 1997). However, these sorts of lasers have not penetrated into wide range of industrial applications due to inconvenience or mainly cost reasons (Bachmann, 2003). On the other hand, from the electronics soldering standpoint, laser soldering method has received renewed interests over the past decade by means of the fascinating improvements in semiconductor physics which have brought about the availability of diode lasers (also known semiconductor diode lasers). These novel types of lasers are capable of providing continuous wave (CW) power of several watts from single diodes and tens of watts CW from multiple emitter assemblies (Whitehead and Foster, 1995; Beckett et al., 1997). The diode lasers used for soldering purposes generally operate around 800~980 nm wavelengths (Bachmann, 2003).

The main differences between laser types for soldering applications are associated with the wavelength of the emitted energy, the level of energy absorption by the soldering materials, the energy delivery medium, the efficiency, and the ease of the energy control (Beckett et al., 1997). Far infrared energy at 10.6 µm wavelength is strongly reflected from metal surfaces but it is strongly absorbed by organics and glass (e.g. circuit board and components) (Whitehead and Foster, 1995; Becker, 1997; Beckett et al., 1997; Hwang, 1999). In addition, there is also the risk of uneven heating which may cause PCB damage. For these reasons, far infrared CO_2 lasers have not been widely used for soldering applications (Hoult et al., 2002). At the shorter, near infrared wavelengths of Nd:YAG and diode lasers, the energy is strongly absorbed by metal surfaces, solder materials and markedly less by organics and glass (Becker, 1997; Beckett et al., 1997; Hwang, 1999; Hoult et al., 2002).

The anticipated reduction in cost and improvement in performance which is associated with semiconductor devices means that diode lasers are likely to become increasingly attractive (Beckett et al., 1997; Hoult and Apter, 2001). Add to these the advantages of extreme compactness, almost completely eliminated maintenance requirement, high reliability, real-time power control, ease of integration/automation and markedly enhanced lifetime are also other attractive properties (Hoult and Apter, 2001; Hoult et al., 2002; Bachmann, 2003). As a consequence, because of their unique features, diode lasers have been gaining high interest as a new laser source for materials processing such as soldering, surface modification (hardening, cladding and the like), welding, brazing etc. as well as an efficient optical pump source for pumping the traditional solid state lasers (Li, 2000; Szweda, 2001; Hoult et al., 2002; Bachmann, 2003).

Currently, diode lasers have already been commercially available and more powerful units are promised. Diode lasers with CW output powers in excess of 0.5 watts are referred to as high-power diode lasers (HPDLs) (Li, 2000). There are also commercially available contemporary diode-pumped solid state (DPSS) Nd:YAG lasers with varying wavelengths from 0.355 to 1060 nm for different sorts of materials processing (Vanttaja et al., 2002).

From the applications point of view, among others beam quality and power of the laser define the possibilities and the applications areas (Bachmann, 2003). As can be seen from Figure 3.1, in soldering applications, a very low power density is required. Hence at low powers with moderate beam quality and high efficiency, diode lasers are well suited to soldering applications (Hoult et al., 2002; Bachmann, 2003).

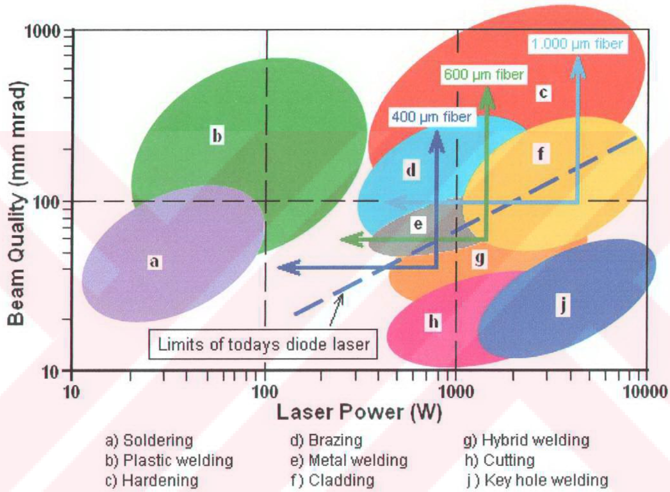


Figure 3.1. Material Processing Fields of Applications for Diode Lasers (http://www.laserline.de, 2004)

Today commercial HPDLs in the power range of 40-160 W have a size of as small as 150 x 50 x 70 mm laser head (including optics) and have a weight of only 1.2 kg, which obviously verify the superiorities of the diode lasers over the conventional CO_2 and Nd:YAG lasers (Bachmann, 2003).

The efficiency of energy absorption increases as the wavelength decreases and it was stated that laser output in the range of 785-830 nm provides the best heat absorption by metallic surfaces, minimum reflection, and minimum heating of organic board materials (http://www.speedlinetechnologies.com, 2004). Furthermore, diode lasers do not have significant wavelength advantages over conventional Nd:YAG lasers, although an improved beam absorption for metallic materials has been noticed (Li, 2000). Work by Beckett et al. (2002) reports that a number of different laser types have been experimented for soldering applications, but it has been found that semiconductor diode lasers are advantageous due to the fact that the wavelength of the energy produced is highly absorbed by the metals used in solder but less readily absorbed by common PCB materials. The higher absorption at this wavelength by metals means that a smaller power is required than CO_2 wavelength for a given joint geometry and the risk of PCB damage greatly reduced. Comparison of the lasers used for soldering is given in Table 3.2.

Table 3.2. Comparison of Lasers Used in Soldering

	CO_2	**Nd:YAG**	**DPSS Nd:YAG**	**HPDL**
Wavelength	10.6 µm	1.06 µm	0.8~1.06 µm	0.8~0.98 µm
Delivery system	Free space	Fiber optics	Fiber optics	Fiber optics
Laser Efficiency	Inferior (10-15%)	Poor (1-5%)	Very Good (25~30%)	Excellent (≥50%)
Beam quality	Good	Good	Better	Moderate
Investment and Running Cost	High	High	Moderate	Low
Size and Weight of the laser system	Inferior	Inferior	Good	Excellent
Controllability	Inferior	Good	Very Good	Very Good
Adaptability and Integration for a system	Moderate	Moderate	Good	Excellent
Wavelength suitability for soldering	Inferior	Good	Very good	Very good
Adaptability for future trends in electronics	Inferior	Inferior	Good	Excellent
Maintenance requirement (service life time)	Frequent	Frequent	No or Least Frequent	No or Least Frequent

It was stated that if a work can be done by a diode laser as well as other lasers, then the diode lasers should be used for economy, energy efficiency, reliability and processing repeatability reasons (Li, 2000).

Commercially available laser soldering systems now employ either DPSS Nd:YAG lasers or direct diode lasers for soldering. These laser systems take advantages of the unique features of the basic diode lasers which are: improved efficiency (≥30%), reliability, beam quality (focusability), and longer service life, reduced electrical power consumption, less or no maintenance requirement all of which leads to low running costs, and also extreme compactness, low weight, fiber optic energy delivery and real-time power controllability allowing integration in a system with less difficulty (Hoult et al., 2002).

These commercial systems come equipped with laser source, optical imaging accessories, CCD cameras, X-Y positioning stages and/or robots to provide precise, non-contact processing. Soldering process is taken place simply scanning the target surfaces (top of the component or leads) with the laser. Two approaches are currently used for this laser scanning process; either positioning the component beneath the stationary laser source or manipulating the fiber-coupled laser beam output. In these cases, the component can be positioned relative to laser source via precision X-Y positioning stage or laser beam is manipulated by the computer controlled galvanometer mirrors or by the robot itself (attaching the laser unit to the robot arm). Furthermore, by coupling a high speed optical pyrometer so as to read the surface temperature of the target area, completely closed loop laser soldering can be achieved.

Overall, the laser provides a controllable means of supplying localized energy for solder joint formation. The availability of low cost, high-power diode lasers now makes possible compact, flexible and controllable soldering units capable of being integrated with automatic assembly equipment. Computer control of the laser power can be achieved through direct control of the power source (low-voltage), allowing heating times and intensities to be programmed in advance to suit the work in hand (Whitehead and Foster, 1995; Beckett et al., 1997). Accordingly, the laser reflow method has become economically justifiable and more feasible for soldering and desoldering of both standard and advanced SMCs.

3.2.2. Determination of Candidate Reflow Methods

It was stated that, the determination of the appropriate desoldering and resoldering methods has the significant affect on quality and reliability of rework and also conditions the development of the whole automated rework cell. Because the selected heating methods entirely condition the layout, the procedures, the method of rework, the form of the automation, and the design and manufacturing of the whole rework cell system (Geren, 2001).

According to literature survey results, comprehensive researches have been done on the determination of accurate reflow methods for automated rework of standard SM and TH components by Geren (1993). It was revealed that, for standard SMCs the hot air/gas method has severe constrains. These stem from the required high number of nozzles (since each components need a specifically designed nozzle type), inefficient utilization of robot's manipulating facility and its working envelope, lower reliability of process result, lack of proper closed loop control, higher risk of reflowing neighboring components, and the need of enough interpackaging space for the nozzles.

Consequently, non-focused IR and diode laser methods remain to be more viable candidates. Additionally, there have also been some researches and automated system development efforts concentrated on soldering and/or desoldering based on the non-focused IR method for standard SMCs (Geren and Lo, 1998) or based on the solid state Nd:YAG laser for fine pitch SMCs (Flanagan et al., 1996; Fidan et al., 1998-(1), for PBGA components (Liu et al., 2002), and for FC components (Hanreich et al., 2001), and also for both standard/fine pitch and advanced SMCs (Russell, 2000; Wang et al., 2001-(3). There have been also some attempts for fine pitch SMCs (Laferriere and Fukumoto, 1995; Beckett et al., 1997) and both for through hole and surface mount technology components (Hoult et al., 2002) based on the diode laser.

All of above statements confirm the revealed final reflow candidates. However, these systems have limited technical capability stem from having limited component application range and some of them were not designed as a totally integrated automated system. On the other hand, these systems pioneer to find out alternative proposals for automating a rework cell system within the scope of this study.

The predominant factor of determining appropriate reflow method is the level of suitability for automation which is dependent on some substantial criteria given below:

- Cost of removal and replacement equipment
- Suitability to robotic rework
- Capability of effective local heating for desoldering and resoldering processes with the same heat source for all components
- Reliability of rework process
- Possibility for maintaining adequate and uniform temperatures across the working area in fully controlled manner
- Capability of efficiently simulating original assembly reflow profile without any disturbance
- Possibility for closed-loop control heating
- Amount of tool, head, or nozzle change requirements
- Rework cycle time

Keeping the above descriptions in mind a comparison between the non-focused IR and diode laser methods have been made (see Table 3.3) and alternative proposals are presented in the subsequent sections.

Table 3.3. Comparison of Reflow Methods for SMCs

	Non-focused Infrared (IR)	**Diode Laser**
Desoldering and Resoldering	Capable	Capable
Component application range	Group 1, 2, 3	Group 1, 2, 3
Equipment cost	High	Low
Speed of reflow	Fast	Fast
Rework results	Very good	Very good
Dedicated tooling	Only four	No
Adjacent component reflow	Possible	No
Needs desoldering/resoldering tool	No	No
Double sided PCBA repair	Capable	Capable
Suitability for future SMCs	Good	Excellent
Breaking down underfill bond	Capable	Capable
Self alignment during reflow with no flow underfill	Capable	Capable
Soldered joint quality	Good	Better
Temperature uniformity degree	±5°C to ±10°C	±5°C
Closed loop control	Possible	Possible
Temperature ramp rate control	Very Good	Very Good

Group 1: Standard SMCs (SOICs, PLCCs, QFPs, etc.); **Group 2:** Fine pitch or ultra fine pitch SMCs; **Group 3:** Advanced SMCs (BGAs, CSPs, FCs)

3.2.2.1. Non-focused IR Based Advanced SMCs Rework

The viable non-focused IR heat source commercially available on the market consists of a 150 watts tungsten-halogen spot lamp generating 1 to 1.2 μm short-wave IR energy associated with a IR lens system, interchangeable lens attachments, and iris ring adjuster. An IR spot is projected through a series of special lenses and focused on to the component. The spot size of the heat source is adjusted manually through an iris ring. To cover different sized SMCs, the system requires only four interchangeable lenses, and continues linear adjustment of the spot size for differing lenses is provided (http://www.pdr-smt.com, 2004). From the automation standpoint, following are the important factors for automating iris-focused IR method:

1) As a heat source, this method is economically justifiable.
2) The non-focused IR unit is capable of performing both desoldering and resoldering operations.
3) Since the distance between the component and IR heat source wide enough closed-loop control is possible, and the temperature rise can be closely controlled, which eliminate component and PCBA damage.
4) The manual spot size adjustment through its iris ring can be manipulated automatically by means of a mechanism consists of a stepper motor, timing belt, and pulley as shown in Figure 3.2.

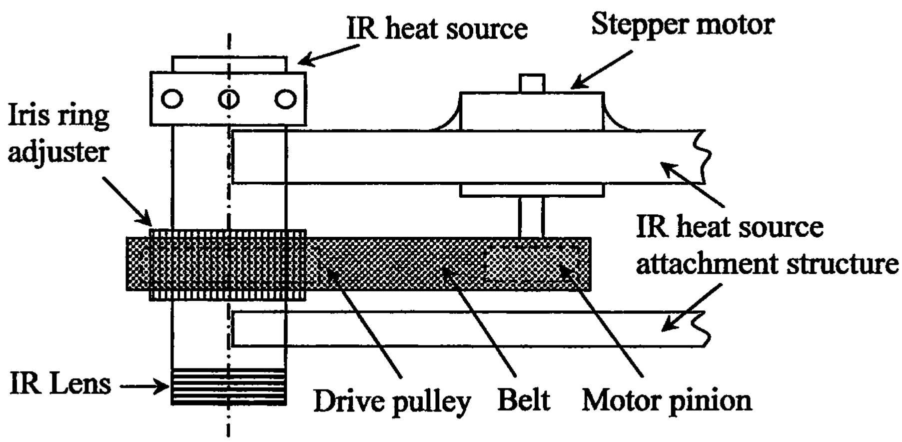


Figure 3.2. Possibility of Automating Spot Size Adjustment

5) Only four lenses are required to handle all SMCs. Although lens changing task is straightforward, it is possibly automated. The lens changing could be done by the robot itself as long as suitable gripper design and some means of easy attachment methods are implemented. Alternatively, the lenses could be changed by a rotary mechanism driven by a stepper motor underneath the IR heat source, as shown in Figure 3.3. The latter would be excellent solution to the lens change problem.

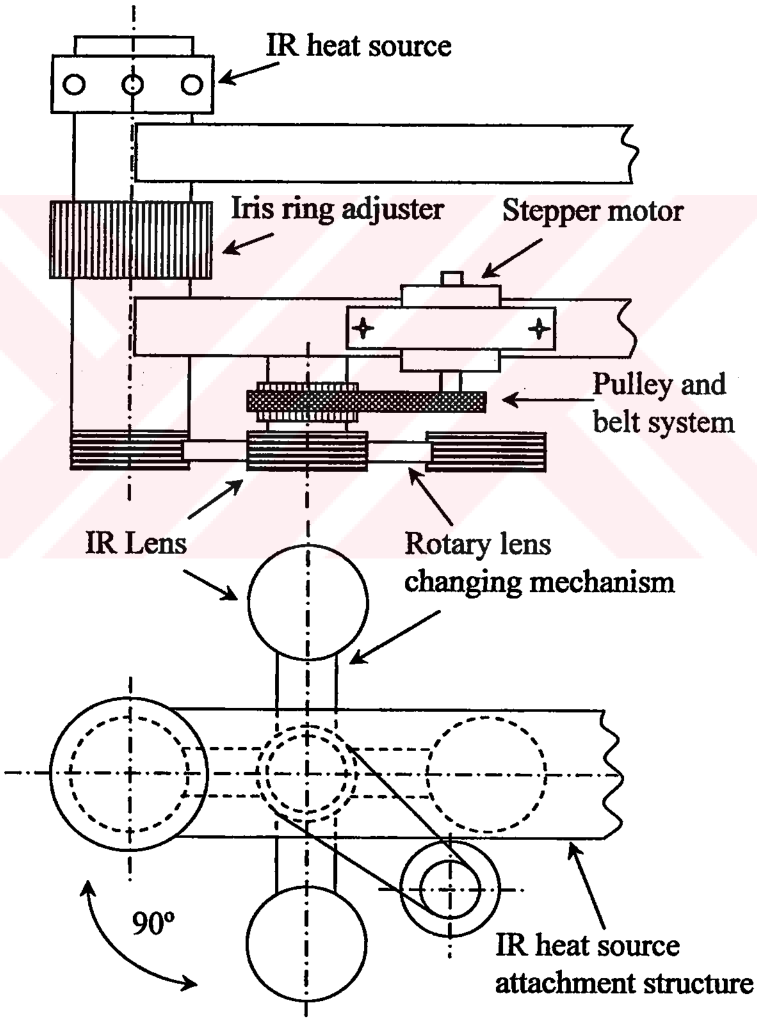


Figure 3.3. Possibility of Automating IR lens Changing

6) The IR heat source needs a discrete focusing distance for each of its lenses. From the automation point of view, the adjustment of focal distance for

differing lenses may cause a problem. Required Z axis motion for the adjustment of focal distance can be manipulated automatically via a linear guiding mechanism driven by a stepper or brushless DC servo motor. However, this needs manipulating the IR heating unit associated with the additional equipments introduced in (4) and (5), as shown in Figure 3.4.

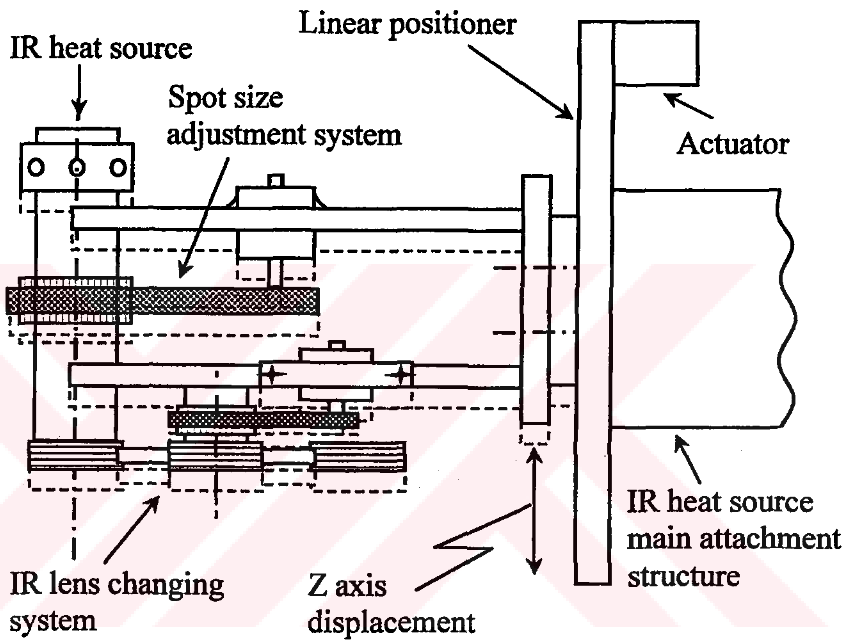


Figure 3.4. Possibility of Automating Adjustment of Focal Distance

7) This method has good potential for automation. The most suitable method for use in automated rework cell system is to fix the IR heat source in the work envelope of an X-Y positioning table so that moving the PCBA into position under the source can be done by the positioning table, enabling the robot to do other work at the same time.

8) The operation principle of this method would be simple. The PCBA is placed on an X-Y positioning table, and the table is driven to a location where the IR heat source is positioned above the table. The defective component is heated until all solder joints are desoldered and/or underfill bond are broken down and then the positioning table moves the defective component to a safe

picking location where the robot can remove the defective item (see Figure 3.5). Resoldering may be performed in reverse order.

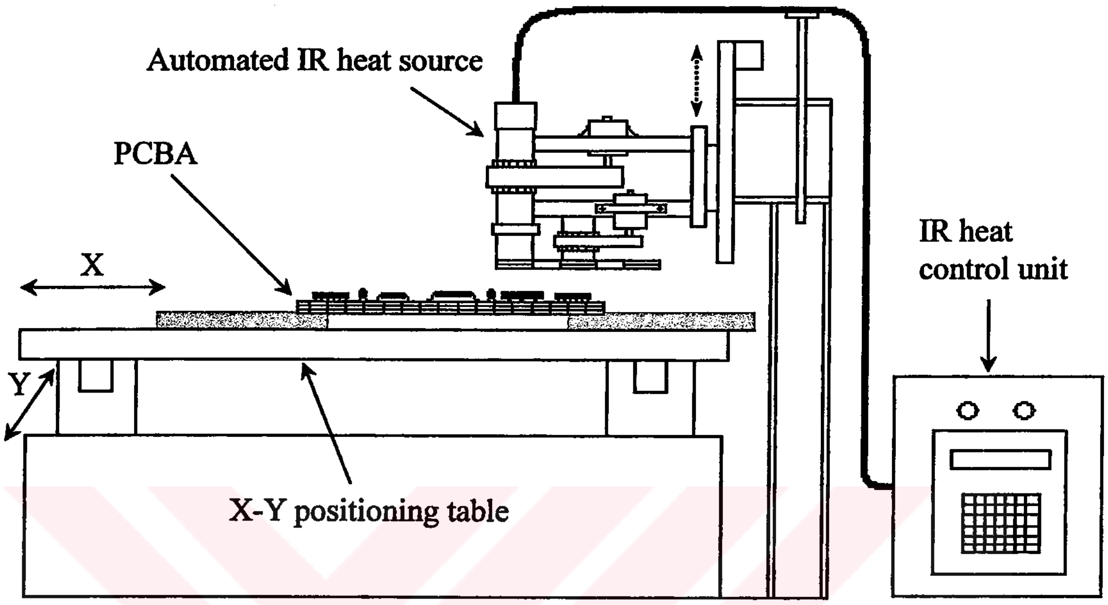


Figure 3.5. Non-focused IR Based Advanced SMCs Rework Method

9) The automated non-focused IR method is theoretically feasible, but the requirements, cost, and technical feasibility of automating spot size adjustment, lens changing and focal distance adjustment must be carefully considered.

3.2.2.2. Diode Laser Based Advanced SMCs Rework

Currently varieties of compact and robust diode laser sources operating at 808-980 nm wavelengths with an optical output power range of 25 to 6000 watts are commercially available on the market. Basically, the diode laser systems involve a diode laser source, laser drive/control unit and chiller unit. However, there are also some essential parts for the closed loop controlled, automated diode laser soldering which are; a pyrometer to precise temperature control, a CCD camera and visible guiding laser (emitting at ~400 to 700 nm) to visualize the process, and galvo scanning mirrors (galvanometer) to guide the laser output at the X and Y axes in predefined patterns.

There are commercially available modular diode laser systems on the market which allow incorporating essential pyrometer, CCD camera and a visible red laser pointer in a plug and operate manner, except essential galvanometer. However, market survey results revealed that there are also modular, highly reliable and configurable diode laser systems designed for direct laser processing which allows easily incorporating all essentials required for the fully controlled automated laser desoldering/resoldering process implementation. These diode laser systems are environmentally sealed, air-water cooled high power diode laser systems operating at 808 or 940 or 980 ±10 nm wavelengths with optical output power range of approximately 100 to 1000 watts. The dimensions of the diode laser head of 670 x 156 x 220 mm^3 and its weight of only 15 kg allow for an easy integration into production systems. Even lighter and more compact version is the fiber-coupled diode laser head, which achieves up to 1000 W output power using an optical fiber to deliver the laser beam to the scan head. With these systems, guiding the laser power in microseconds to any desired point within the working area of up to 260 x 260 mm^2 is possible. Furthermore, work distance (stand-off) of over 80 mm is offered and spot sizes as small as 0.5 mm can be achieved (http://www.laserline.de, 2004). Following are the important factors for automating diode laser method:

1) As a heat source, this method is less expensive than non-focused IR method (see Table 3.3).
2) The diode laser unit can handle wide variety of different sized components (highly contributing flexibility of the rework cell system) and powerfully driven dynamic galvanometer mirrors in a computer controlled fashion ensure fast, precise laser beam positioning.
3) By means of a high speed pyrometer; non-contact, precise temperature measurement in every few milliseconds based on the closed-loop control manner is possible, ensuring very close temperature rise control for a repeatable and reliable reflow soldering process.

4) The diode laser unit is able to both desolder and resolder the whole type of advanced SMCs by virtue of simple laser scanning of the component top surface with the computer controlled galvanometers. The scanning pattern can be customized for the specific area array component type, as shown in Figure 3.6.

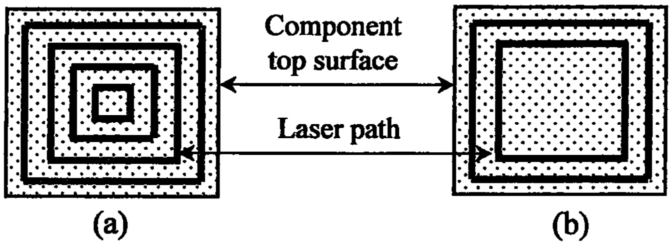


Figure 3.6. Possible Scanning Patterns for Area Array Components: (a) For Full Array, (b) For Perimeter Array Components

5) It can perform desoldering and resoldering of the components on the densely populated PCBAs without any damages to surroundings.

6) The intrinsically outstanding compactness and robustness of the diode laser head allows easy integration and reveals very good potential for automation. Like IR heat source, the diode laser head can be fixed in the work envelope of an X-Y positioning table so that the PCBA is driven into position under the laser source by the positioning table. This is the most suitable method for use in automated rework and this also allows the robot to do other work at the same time.

7) This method has simple operational principle as in the case of IR method. The PCBA is located on an X-Y positioning table, and the table is driven to a location where the diode laser head is positioned stationary above the table. The defective component is heated by the guided laser until all solder joints are desoldered and/or underfill bond are broken down and then the positioning table moves the defective component to a safe picking location where the robot can pick up the defective item (see Figure 3.7). Resoldering may be performed in reverse order.

8) The diode laser familiar slim and modular build, allowing compact integration into robotic rework system coupled with the already incorporated pyrometer, CCD camera, galvanometer scanner unit, improves the technical feasibility of this method and also provides simple process implementation facility.

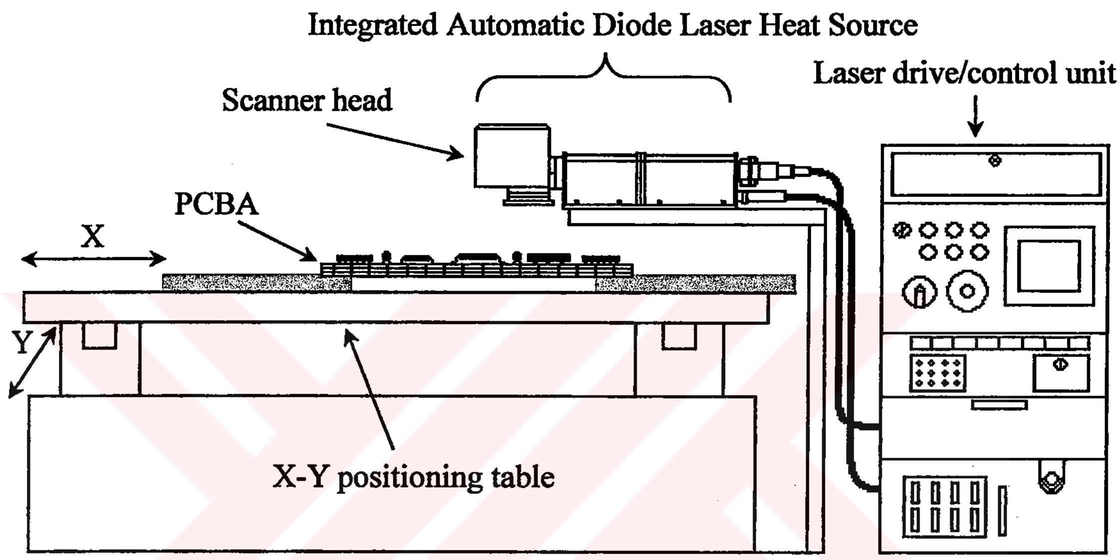


Figure 3.7. Diode Laser Based Advanced SMCs Rework Method

3.2.3. Determination of Closed Loop Heat Control Mechanism and Related Tooling Considerations

As a rule of thumb, there is an inherent need for precise control of the heating process during rework to minimize or eliminate the possible component and PCB damages since uncontrolled heating will jeopardize quality and reliability of the reworked boards. However, comprehensive studies on the manual rework procedures of advanced SMCs revealed that underfilling and lead-free processing requirements arise with the supplementary considerations and specifications which are distinctly shrinking the rework process window. Accordingly, in essence, the precision level of thermal profiling and degree of temperature control is increased to an extent where the non-contact, closed loop temperature control during the rework process in a fully automated way should be certainly attained (see chapter 2).

The main reasons for the automation of heat application during rework can be summarized as follows;

- To control the temperature increase in order to follow a desired temperature profile to meet the challenging requirements of the rework.
- To determine when to stop heat application to ensure successful removal of the defective component by accurately melting solder joints and breaking down the underfill bond.
- To determine when to stop heat application to ensure good execution of the simultaneous solder bump reflow and underfill curing on the placement of a new component.

Basically, irrespective of the reflow method used, two temperature measurement sensors are needed during the rework so as to perform fully adjustable, closed loop controlled top heating and bottom heating in an automated fashion.

In the literature, Geren and Redford (1996) reported that a real time closed loop controlled non-focused IR reflow system has been developed as part of an automated robotic rework cell system. The arrangement of the fully adjustable, closed loop heating system control structure is illustrated in Figure 3.8.

As can be seen, the complete desoldering and resoldering system consists of the IR heat source, the bottom heater, two proportional integral derivative (PID) controllers, non-contact and contact type temperature measurement sensors and interfacing devices. In this system, the reflow temperature is monitored and controlled by programmable logic PID controllers. Non-contact sensor feeds the measured target surface temperature to the controller and then the controller can adjust the power of IR source via the interface device to the preset time/temperature profile. Similar principle was also used for bottom heater.

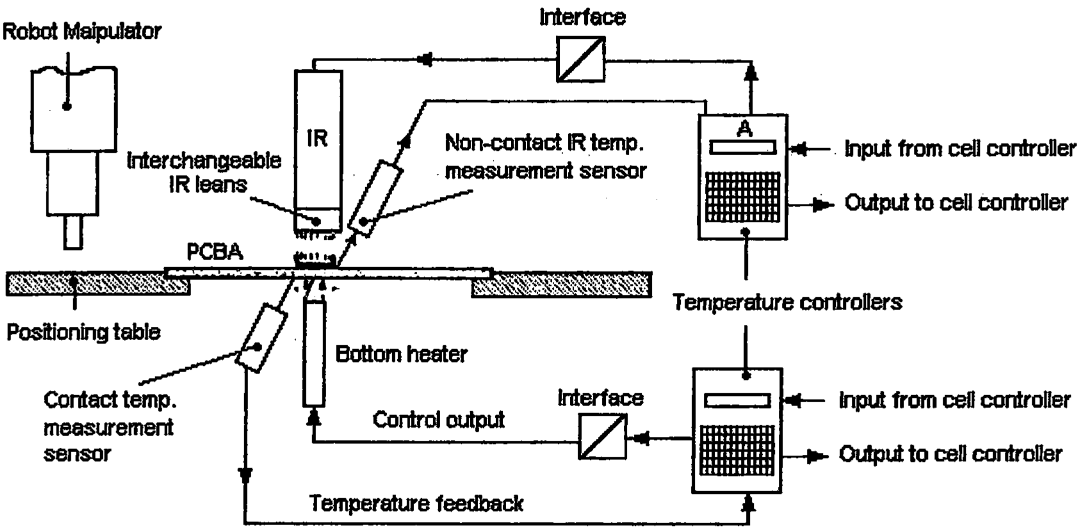


Figure 3.8. Schematic of IR and Bottom Heater Closed Loop Control Mechanisms (Geren and Redford, 1996)

In choosing a particular sensor for a given application, there may be many factors to be considered which can be divided into four major categories: environmental factors, economic factors, sensor and target object related factors. However, several important specifications in the temperature measurement sensor selection for the reflow system are given below;

- Temperature measurement range,
- Size and emissivity of the target object (advanced SMCs),
- Temperature measurement accuracy and repeatability of sensor,
- Spectral sensitivity of sensor (the wavelength region where the sensor is most sensitive),
- Sensor's speed of response,
- Sensor's resolution (the smallest change the sensor can differentiate),
- Operating environment (operating temperature, ambient conditions etc.),
- Design of the sensor (dimension, weight, and other specific properties),
- Output of the sensor,
- Life time and cost of the sensor.

Additional information on sensors and their specifications can be obtained from Stephenson et al. (1999), Smith (2000), and Lynch et al. (2002).

Geren (1995) reports the results of a study of non-contact temperature measurement and closed loop heat control in a non-focused IR based robotic SMC rework cell system. It was pointed out that potential for interference between the IR heat source and non-contact IR sensor is a significant concern. Thus, the measurement spectrum of the IR sensor must be different from the wavelength of IR heat source. Also the emissivity of the target component is another major consideration, so determination of exact emissivity of the components under the set conditions and adjustment of the IR sensor emissivity accordingly is necessary to ensure that the correct temperatures are measured at the target surface. Moreover, sensor's temperature measurement range must be sensitive from about 20°C to the solder reflow temperature. For more details about sensor selection and closed loop heat control for automated SMC rework cell system, see Geren (1993).

Basically, within the robotic rework, the objective is to simulate the thermal profile of a reflow oven and maintain thermal uniformity across the component in order for reliable thermal processing to be achieved.

To do this in laser based reflow soldering systems, a pyrometer device, which is a kind of radiation thermometer that measures the radiation energy being emitted from a body or surface in fractions of a second, is used. A schematic of closed loop controlled diode laser soldering mechanism is depicted in Figure 3.9. The pyrometer can repeatedly monitor surface temperature in every few milliseconds during the component removal or replacement process for optimal non-contact closed loop process control. As seen from figure, when the information is fed back to the computer, the related process parameters of the diode laser soldering such as laser power, scan speed can be regulated accordingly, in a fully adjustable, automated manner.

There are many types of pyrometers, for instance; narrow band pyrometers (also called as single color pyrometers), broad band pyrometers, multiple colors pyrometers (also referred to as ratio pyrometers), optical pyrometers etc.

Due to its accuracy, speed, economy and specific advantages, pyrometers are steadily gaining acceptance in new fields of industrial applications. The basic parts of a pyrometer are the lens, aperture, filter, detector, and the signal processing unit. The optics of pyrometers can be adjusted to measure temperatures of small objects. Today it is possible to accurately measure objects with a diameter of 0.2 mm (IMPAC, Pyrometer-Handbook, http://www.impacinfrared.com, 2004).

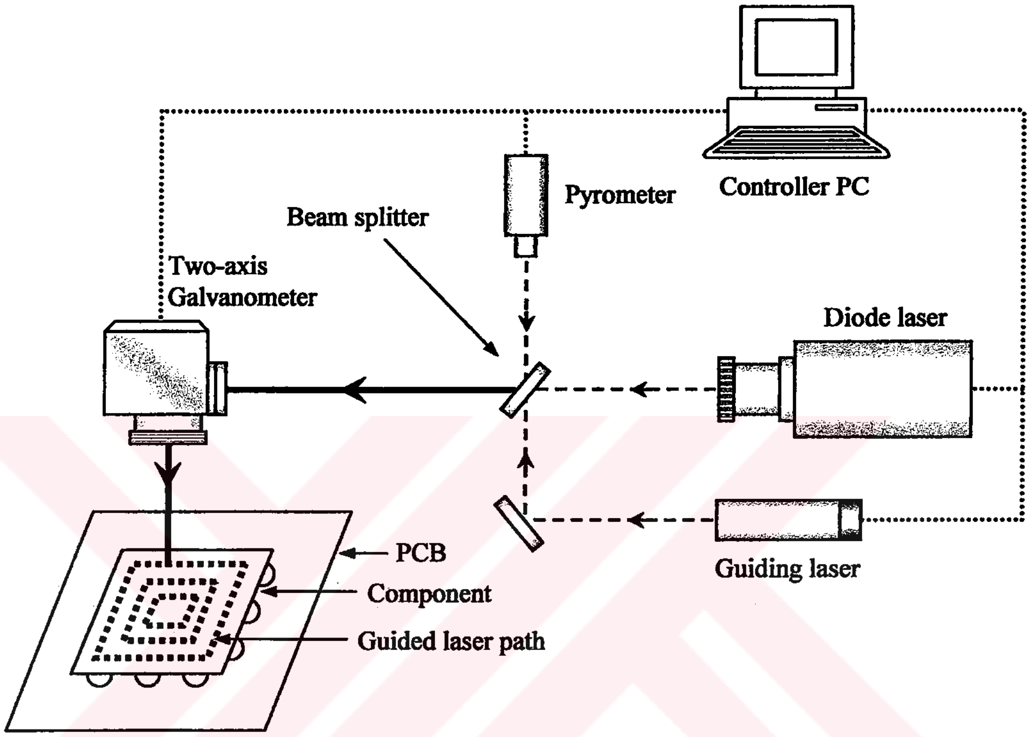


Figure 3.9. Schematic of Diode Laser Closed Loop Control Mechanism

The output signals of the today's pyrometers are either standard analogue or digital. Digital interfaces are usually RS 232 and RS 485 while analogue output signals are 4 to 20 mA, 0 to 20 mA, 0 to 10 V, etc (IMPAC, Pyrometer-Handbook, http://www.impacinfrared.com, 2004).

Among others; temperature measurement range, size and emissivity of the measured object, spectral range, temperature measurement accuracy and repeatability, response time and output signal are the most important parameters to be considered when selecting a pyrometer for diode laser reflow system.

Presently, most of the commercial laser soldering systems use the pyrometer based closed loop temperature control technique (http://www.vitechnology.com, 2004; http://www.laserline.de, 2004; http://www.dilas.com, 2004) and in the literature, there are also some successful implementations of the pyrometer in order for repeatable and reliable laser soldering process to attain computer based, non-contact, real time temperature monitoring and control (Russell, 2000; Wang et al., 2001-(3).

3.2.4. Determination of Preheater

Not only to prevent any thermal damage to the PCB and component structure due to the localized heating but also to activate the flux and expedite component removal, preheating or underside heating is essential in the rework process.

The preheater must be large enough to effectively provide uniform heating for large and massive boards (Ward, 1999; Primavera, 2003). As a preheater, currently stand-alone infrared (IR) lamp and hot plate preheat units can be used, but they may not be as effective as hot air systems for preheating the boards uniformly during rework (Prasad, 2001-(1). Presently, most of the commercially available manual and semi-automated rework systems include either IR or hot air/gas bottom heating units.

From the processability point of view, based on the previously introduced crucial specifications and results of the comparison given in Table 3.4, the hot air preheater device seems to be well suited to preheating process in order for reliable rework process implementation in an efficient and economical manner.

Table 3.4. Comparison of Preheaters

Preheater	Cost	Temperature uniformity	Closed loop control	Ramp rate control
Hot Air	Low	±2°C to ±5°C	Possible	Low
IR	High	±5°C to ±10°C	Possible	Good

Additionally, the same result was also obtained by the researches (Geren and Redford, 1996). In order to meet the preheating requirements in a fully automated robotic rework cell, a hot air device which has an air volume of 30 liter/min and a 260 W total performance was utilized.

3.2.5. Determination of Manipulating Devices

Comprehensive studies on individual rework process steps of advanced SMCs revealed that, in essence, not only more precision but also greater process control demand is increased to an extent where fully controlled, automated implementation of the rework is crucial.

Throughout the rework, automatically controlled precise movement is not only needed in X, Y, Θ axes for alignment and positioning of the component but also needed in X, Y, Z axes for fluid materials dispensing process. These are the strenuous rework requirements which make an industrial assembly robot and X-Y positioning table as the essential manipulating devices of the rework cell system.

It should be noted that the selection of the manipulating devices must be made based on the required accuracies for the rework and assembly processes. Therefore, following are the determination of the required accuracy in related axes by considering essential placement specifications presented in previous chapter.

3.2.5.1. Determination of Linear Offset in X-Y Axes

Based on the literature study, it was found out that area array components exhibit varying self centering characteristics which may be affected by the reflow temperature, structure of pad site, component weight, pitch and ball size etc. Additionally, the presence of the no flow underfill material has also some negative effect on self centering capability of the component (see section 2.5.4.5). In this respect, during the calculation of required placement accuracy self centering capability should be considered provided that a safety margin will be added in order not to rely on unforeseen self centering capability. Baartman et al. (1990) pointed out, although some level of self centering margins are considered to be acceptable in industry, designing a placement machine based only to this margin would result in a low reliability.

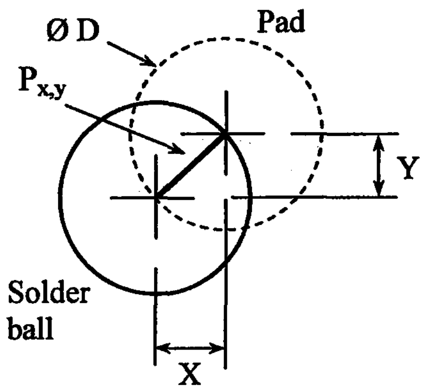


Figure 3.10. Schematic of Linear Offset

Accordingly, as shown in Figure 3.10, the linear offset is formulated as,

$$\alpha D_{pad} = \sqrt{\left(X^2 + Y^2\right)} \quad (3.1)$$

$$n P_{X,Y} = \sqrt{\left(X^2 + Y^2\right)} \quad (3.2)$$

Using Eq. (3.1) and Eq. (3.2),

$$P_{X,Y} \leq \frac{\alpha D_{pad}}{n} \quad (3.3)$$

where,

$P_{x,y}$: Linear offset

α: Maximum allowable self centering, 20% (see section 2.7)

D_{pad}: Minimum pad size

n: Safety margin to ensure successful alignment, >2 (determined based on current limits of accuracy specifications stated by the IC component manufacturers)

3.2.5.2. Determination of Rotational Offset in Θ Axis

Typical rotational misalignment of an area array component is depicted in Figure 3.11. As can be seen the amount of rotational offset is too much at the outermost ball/pad site at the corners. Accordingly, following formulations are calculated based on this criterion.

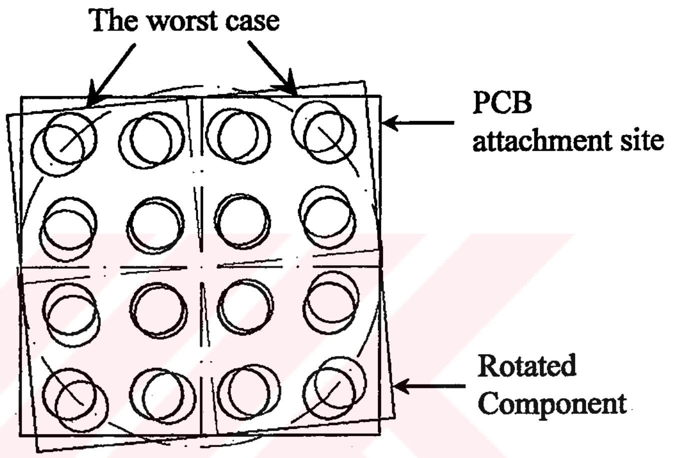


Figure 3.11. Rotational Misalignment of Component

Based on the JEDEC (2002) design standard, dimensional specifications of a typical area array component is schematically depicted in Figure 3.12 where;

A: The distance between the extreme body edges.

A_1: The distance between the centerlines of the two outermost rows of balls.

L: The distance between the centerlines of component and ball at the furthest point.

D_{ball}: Ball diameter.

e: Pitch size

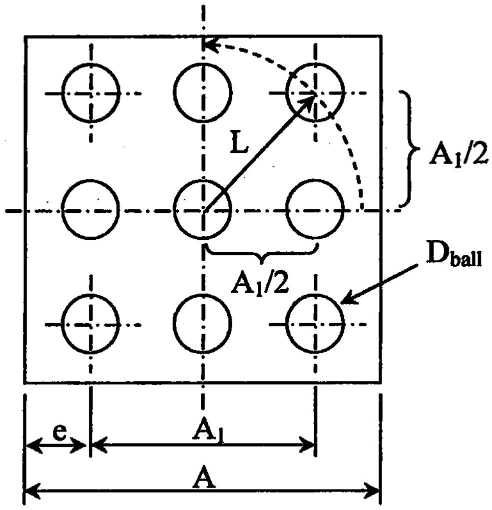


Figure 3.12. Schematic View of Component Basic Dimension

From the Figure 3.12, "L" is formulated as;

$$L = \sqrt{2}A_1 \tag{3.4}$$

where,

$A_1 = A - 2e$,

$$L = \sqrt{2}\left(A - 2e\right) \tag{3.5}$$

As schematically illustrated in Figure 3.13, maximum allowable offset due to the rotational misalignment is the distance between the centerlines of the outermost solder balls and simply formulated as,

$$K = \frac{2\pi L \Theta}{360} \tag{3.6}$$

where,

K: Linear offset due to rotational misalignment

Θ: Rotational offset

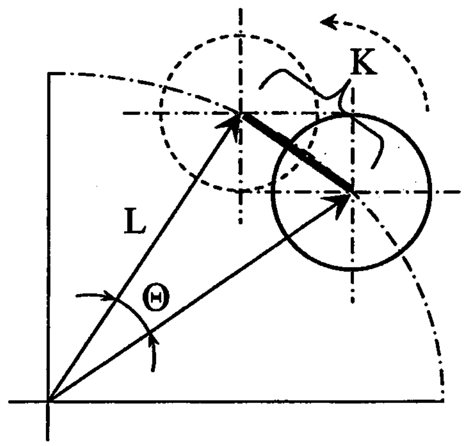


Figure 3.13. Schematic of Rotational Offset

As in the case of previous linear offset determination, the limit of the K value should be defined in the same manner. Therefore "K" is also formulated as,

$$K \leq \frac{\alpha\, D_{pad}}{n} \tag{3.7}$$

Using Eq. 3.5, Eq. 3.6 and Eq. 3.7; rotational offset "Θ" is obtained as,

$$\Theta \leq \frac{\alpha\, 180\, D_{pad}}{n\, \pi\, \sqrt{2}\,(A - 2\, e)} \tag{3.8}$$

All things considered, essential dimensional specifications for each component type based on industrial design standard guidelines are summarized in Table 3.5 and calculated essential accuracy requirements of advanced SMCs are given in Table 3.6.

Table 3.5. Dimensional Specifications of Advanced SMCs

Component type	Body size (mm)	Pitch (mm)	D_{ball} (mm)	D_{pad} (mm)
BGA	7 x 7 to 50 x 50	1.5 – 0.50	0.75 – 0.30	0.55 – 0.25
CSP	4 x 4 to 22 x 22	1.0 – 0.40	0.50 – 0.25	0.40 – 0.20
FC	3.81 x 3.81 to 12.7x12.7	0.75 – 0.10	0.20 – 0.08	0.15 – 0.06

Table 3.6. Summary of Essential Accuracy Requirements of Advanced SMCs

Component type	*Required Accuracy in*	
	Linear offset (mm) $P_{x,y} \leq \frac{\alpha D_{pad}}{n}$	**Rotational offset (°)** $\Theta \leq \frac{\alpha 180 D_{pad}}{n \pi \sqrt{2}(A-2e)}$
BGA	≤0.0167	≤0.0138
CSP	≤0.013	≤0.0255
FC	≤0.004	≤0.013

3.2.5.3. Determination of Robot Type

The PCBA requires complete agility and reliability factors only achievable with the use of robotics (Holcomb, 1995). The use of industrial robots in the PCBA is on the rise as manual assembly can be significantly more expensive than automated assembly (Wang, 1998).

Primarily robot assembly is most effective when three assembly requirements exist: high repeatability, small lot-size production, and varying part-size requirements (Rehg, 2000) which are inherently exist in the automated rework.

Since a majority of the processes involved in the PCBAs are carried out in the linear and vertical plane, robots of SCARA or Gantry construction are best suited for these assembly tasks (Lewis et. al. 1999; Rehg, 2000).

Substantially the SCARA (Selectively Compliant Assembly Robot Arm) configuration used in electronics assembly is a direct drive, four axes assembly robot (see Figure 3.14). Its first two main revolute joints allow the robot to reach any point within a horizontal planar workspace defined by two concentric circles. The third is a linear joint located at the end of the arm, providing vertical motion in the Z axis. In addition to the first three degrees of freedom (DOF), the SCARA robot include an additional revolute joint at the end of the third one, facilitating control of a part orientation in the horizontal plane (Lasky et al., 2000; Rehg, 2000).

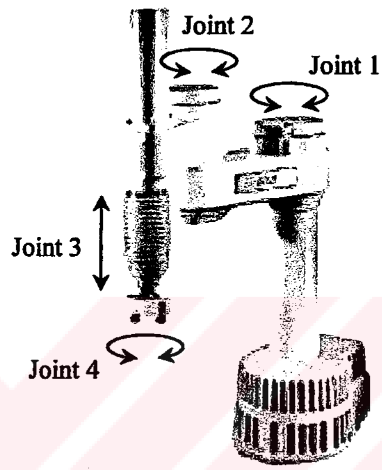


Figure 3.14. The SCARA Type Robot (http://www.adept.com, 2004)

The SCARA robots have many advantages and are quite popular in industry. Because of the vertical orientation of the joints, gravity does not affect the dynamics of the first two joints (stiffness in its vertical direction). As the name SCARA implies, this allows compliance in the horizontal directions to be selectively varied; therefore, the robot can comply to horizontal forces, facilitating insertion processes typical in assembly tasks (Sciavicco and Siciliano, 1996; Lasky et al., 2000; Hägele and Schraft, 2002). Because of the vertical linear joint, straight-line vertical motions are simple. Also, SCARA robots typically have high positional repeatability. The revolute joints allow high-speed motion (Lasky et al., 2000; Hägele and Schraft, 2002). On the negative side, the resolution (Lasky et al., 2000) and the accuracy (Sciavicco and Siciliano, 1996) of the arm is not constant throughout the workspace, and the kinematic equations are relatively complex (Lasky et al., 2000).

The Gantry configuration is geometrically equivalent to the Cartesian configuration. However, as schematically shown in Figure 3.15, Gantry robots have an elevated bridge structure and consist of three orthogonal prismatic joints so that the robot moves in X, Y, and Z directions in the joint space (Lewis et. al. 1999; Lasky et al., 2000).

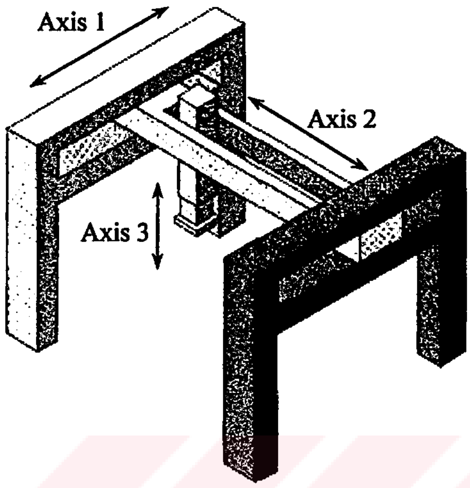


Figure 3.15. Gantry Type Robot (Lasky et al., 2000)

In addition, most gantry robot designs follow a modular system. Their axes can be arranged and dimensioned according to the given tasks. As schematically depicted in Figure 3.16, revolute wrists can be added to the gantry's z axis for end effector orientation (Lewis et. al. 1999; Hägele and Schraft, 2002).

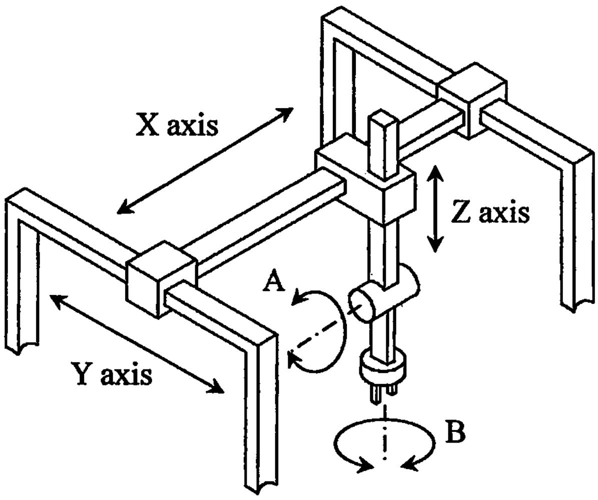


Figure 3.16. Possibilities of Gantry Robot Configuration

A large variety of linear axes can be combined. Numerous component manufacturers offer complete programs of different sized axes, drives, computer controls cable carriers, grippers, etc. (Hägele and Schraft, 2002).

In terms of work envelope, they have a rectangular volume that sweeps out most of the inner area of the gantry system (Lewis et. al. 1999; Lasky et al., 2000). Gantry robots have many advantageous properties. They are geometrically simple, like the Cartesian robot, with the corresponding kinematic and dynamic simplicity, since motion on each axis corresponds to motion of a single actuator. This eases the programming of linear motions. In particular, it is easy to do a straight vertical motion, the most common motion in assembly tasks (Lasky et al., 2000). For the same reasons, the gantry robot has both constant arm resolution (Lasky et al., 2000) and positioning accuracy (Sciavicco and Siciliano, 1996) throughout the workspace. It has also better dynamics than the pedestal-mounted Cartesian robot, as its links are not cantilevered. In general, robots with a rotary base have a speed advantage. However, they have more variation in resolution and dynamics compared to Gantry robots (Lasky et al., 2000). Gantry robots are much stiffer than other robot configurations so high payloads are possible (Sciavicco and Siciliano, 1996; Lasky et al., 2000). As noted above, due to the simple kinematic and dynamic structure; Gantry robots are very accurate, repeatable and very easy to visualize compared to revolute-base robots, such as SCARA types (Lasky et al., 2000). As with the Cartesian robot, the Gantry robot's simple geometry is similar to that of an NC machine, so technicians will be more familiar with the system and require less training time. Also, there is no need for special path or trajectory computations (Lasky et al., 2000). As opposed to high accuracy, the Gantry robots require a large operating volume for a relatively small workspace and they have slow speed of operation in the horizontal plane compared to robots with a rotary base (Lasky et al., 2000).

The choice of a robot for a selected application can be a very difficult decision. Vendor information, expert opinion, and various sources such as the robotics product database can aid in the selection. Selection needs to consider the appropriate combination of parameters suitable for the application. These parameters or technical features include the degrees of freedom, the type of drive and control system, sensory capability, programming features, accuracy and precision requirements, cost, workspace and load capacity of the selected robot (Lasky et al., 2000; Rehg, 2000). A comparison of the two robot configurations is given in Table 3.7.

Table 3.7. Comparison of Robot Configurations

Type	***Advantages***	***Disadvantages***
Scara	• Stiffness in Z axis • Large work area for floor space (efficient space utilization) • Long horizontal reach • Horizontal compliance • High speed • No gravity effect on positioning • High positional repeatability	• Two ways to reach a point • Complex kinematics • Variable resolution and accuracy • Difficult to program off-line • Medium to low payloads
Gantry	• Linear motion in X-Y-Z axes • Simple kinematics • Rigid structure • Inherently better accuracy and resolution • Very high repeatability • Easy to visualize • Easy to program off-line • Easy position control • No position dependency on gravity and inertia • Constant resolution and accuracy • Highly configurable • High payloads are possible	• Occupies large floor space for size of work envelope (poor space utilization) • Workspace is smaller than robot volume • Guiding surfaces of prismatic joints must be covered to prevent ingress of dust (all axes exposed to environment) • Low speed

Various point or weighing schemes can be applied to rate different robot models. Hence, previously stated whole assembly and rework requirements must be considered extensively. Especially an ability to attain threshold bonding force for a certain amount of time for the underfilled component assembly is curial feature that the robot must have (see section 2.5.4.5).

In the literature, the use of four-axis, adept-one SCARA robot was successfully implemented within the automated rework cell system by Geren and Redford (1996) and Fidan et al. (1998-(1).

However, within the most of the current commercially available advanced assembly and rework systems the Gantry robots are utilized extensively (http://www.air-vac-eng.com, 2004; http://www.teradyne.com, 2004). Furthermore, because of the inherent simplicity, rigidity and cost-effectiveness of the Gantry robot systems, authors also proposed a Gantry robot cell system for better cell layout and improved results of the robotic rework (Fidan et al., 1999).

3.2.5.4. Determination of X-Y Table

Besides the pointed out specifications previously, there are some additional specifications associated with the selection of the appropriate X-Y positing table for the automated rework system of advanced SMCs. These are;

- It must be open-frame,
- It must handle varying board sizes as much as possible in order to maintain or increase flexibility of the cell system,
- Technical capability of the positing table must be well suited to the determined accuracy requirements.

To conclude, with the careful consideration of the whole specifications mentioned, required X-Y positing table which is one of the most important devices of the automated rework cell system would be determined successfully.

3.2.6. Determination of Component Removal and Replacement Tool

Substantial requirement of the component removal and replacement processes is to have the ability to handle differing as much components as possible with preferable one tool. Basically vacuum suction tools are in common use for the manual, semi-automated or fully automated SMCs assembly and rework activities.

On the other hand, as mentioned previously these tools were proved to be insufficient to remove underfilled faulty component from the board (see section 2.5.3.1).

From the processability standpoint, the design and development of a special removal tool with a gripping feature is essentially needed. The most important feature of such a special removal tool would be the ability to apply sufficient twisting action to break down the underfill bond.

Based on the market survey results, currently there is no commercially available such a required removal/replacement tool (end-of-arm tooling).

In general, the tooling mounted on the robot tool plate is called an end effector or end-of-arm tooling. With respect to efficient design a suitable end effector details can be found in Lewis et. al. (1999), Lasky et al. (2000) and Rehg (2000).

Additionally, the extensive studies on the existing underfilled component rework procedure, problems, and methods revealed that there is also a growing need for the development of more user friendly underfill materials coupled with the new application methods.

3.2.7. Determination of Fluid Materials Application Methods

As a rule of thumb, no matter what type of material is to be applied with differing methods, the most important thing is to have the ability of applying precise and correct amount of material to the target area in a fully controlled manner. This is more strict for the area array components at pitch sizes ranging from 0.1 mm to 1.5 mm with the varying solder ball sizes from 80 µm to 760 µm.

For dispensing solder, flux, and underfill materials in SMT applications there are equipments that range from simple hand held units to dedicated fully automatic dispensing systems. Besides the dedicated dispensing systems in the markets such as Camalot Xyflex and Camalot 1414/1818 (http://www.speedlinetechnologies.com, 2004), Century C-720 and Axiom X-1020 (http://www.asymtek.com, 2004) there are also several dispensing valves/pumps in different configurations based on the need for dot/line specification. These are; spray valves, time/pressure valves (also known as Air/Over pumps) (http://www.techconsystems.com, 2004;

http://www.ijfisnar.com, 2004), rotary positive displacement pumps (RPDPs) (also known as Auger pumps), linear positive displacement pumps (LPDPs), and jetting valves (http://www.asymtek.com, 2004).

Each of these have positive and negative attributes making them suitable for some applications and not others because natural characteristics of the liquid materials and the design characteristics of dispensing valve/pumps have remarkable impact on the dispensing process quality. The dispensing valves/pumps and material application range are given in Table 3.8.

Table 3.8. Fluid Material Dispensing Methods

Dispensing Method	*Flux*	*Solder*	*Underfill*
Time/Pressure Valve	√	√	√
Spray Valve	√		
Rotary Positive Displacement Pump		√	√
Linear Positive Displacement Pump			√
Jetting Valve	√		√

3.2.7.1. Determination of Solder Dispenser

Most automated dispensing methods for applying solder paste are implemented using either time/pressure or rotary positive displacement pumps. The linear positive displacement pump (piston pump) and jet are not presently suitable for solder paste application because of solder paste sensitivity to separation or plugging (http://www.asymtek.com, 2004).

Time/Pressure valve or pump is the oldest technology and is still an acceptable method of dispensing in applications where high speed and smaller dot sizes are not a requirement (Piracci, 2000-(1). Hence, these pumps can still be found on systems today and are popular method of hand held dispensing (Wedekin, 2001; Peek, 2001).

Time/pressure systems consist of a reservoir of material that is pressurized to extrude material through a needle or nozzle. The amount of material is controlled by controlling the time of the air pulse and the air pressure. The primary advantage of time/pressure pumps is that they are relatively simple and inexpensive. However, with such systems high pressure cycling causes heating in the air of the syringe, accordingly, changes the viscosity of the fluid, resulting inconsistent dispensing over time. Also, high pressure pulsing can cause separation of solder particles from light flux/binder system (or filler and binder in the case of epoxies) and clogging all of which negatively effects the precise dispensing (Wedekin, 2001; Peek, 2001; Piracci, 2000-(1). Furthermore as the syringe empties, the air to material ratio changes. The air compresses easily, acting like a shock absorber, resulting in a slower and less accurate response to the air pulse. The change in pressurization time leads to the dot inconsistency and less repeatable dispensing. Dot sizes will vary depending on the amount of fluid in the syringe. There are control systems to compensate for this change in fluid level but they are sensitive to viscosity changes (Piracci, 2000-(1). As a result, the time/pressure dispensing pumps have difficulty providing consistent dispensing process.

The rotary positive displacement pump dispensing is a much more repeatable way of dispensing at a higher rate. Its primary component is an "auger" feed screw that can be turned on and off by a DC servo motor. The motor is turned on for a set time, causing the auger screw to move a precise distance. As the screw turns, it shears the fluid material, forcing the material down the thread and out the needle, producing a very precise and consistent dot deposition (Piracci, 2000-(1). In the rotary positive displacement pumps, a low pressure air supply is used to maintain a steady flow of solder paste (or epoxy) into the pump without heating the material or breaking it down (Wedekin, 2001; Peek, 2001). This means positive rotary displacement dispensing is less prone to clogging, since paste is not under repeated pressure cycling (Lee, 2002).

The advantage of these pumps with solder paste is two fold: they can dispense a very small, accurate amount of solder dot in a controlled manner and are less sensitive to viscosity variations (Piracci, 2000-(1, 2). Additionally, in the literature use of the rotary positive displacement pump for automated solder paste dispensing operation was successfully implemented within in the robotic rework cell system by Geren and Ekere (1994) and Fidan et al., (1998-(2).

It was stated that, with the increasing emphasis on miniaturistic components and densely populated PCBAs, precise application of solder material is being severely challenged by the equipment capabilities (Wedekin, 2001; Peek, 2001). However, the market survey results revealed that there are commercially well established rotary positive displacement pumps capable of dispensing dots of solder as small as 3 nanoliters and 125 μm in diameter (http://www.asymtek.com, 2004). From the dispensing standpoint, with the exponential improvements in the dispensing technology (with respect to solder rheology and equipment capability) it will soon to achieve < 125 micron dots in near future with the rotary positive displacement pump technology (Prescott et al., 2003).

3.2.7.2. Determination of Flux Dispenser

Various contact and non-contact methods can be used to apply fluxes (Behler and Hartmann, 2001). However, automated precise control of local area fluxing is critical especially for the advanced packing technologies such as CSPs and FCs. The rule of thumb is that flux must be applied in a defined pattern and film thickness so as to maximize quality, overall process efficiency and throughput (Erickson, 2003).

Flux patterns for today's electronics assembly applications often require thickness of less than 1 mil (0.0254 mm), along with consistently sharp edge definitions and minimal overspray. These escalating requirements for greater precision and consistency, coupled with much smaller component dimensions, tighter working tolerances and environmental problems (volatile organic compound emissions, flux disposal and waste from aqueous board cleaning systems etc.) already exceed the inherent limitations of contact-based traditional fluxing methods, such as dipping or screen printing and inevitably make them impractical (Lewis and Ciardella, 1999).

From the automated rework process standpoint, non-contact flux application methods of spraying and jetting are well suited for this task.

The spray fluxing is one of the more commonly used viable flux application method in electronics manufacturing environment. In this method, flux is forced through a nozzle to spray it on the planar surface of the circuit board. The flux is atomized into fine droplets (http://www.techconsystems.com, 2004; http://www.ijfisnar.com, 2004).

Commercially well established spray valves feature a needle seat design combined with an atomizing spray head. Used in conjunction with the suitable controller, a high accuracy spray shot with an elimination of over spray is possible. With such spray valves total control of the spray cycle is provided by adjustable fluid flow and precise control of pre-spray, atomizing air and post spray with the spray valve controller. Maintenance is simple. Downtime is virtually eliminated with only one seal to replace during normal maintenance. The compactness and easy-mount threaded hole features allow for easy integration into automated applications (http://www.techconsystems.com, 2004).

Flux jetting is relatively new technique. In this method, flux is dispensed via a non-atomizing high pressure jet in specific quantities with extremely thin film builds (< 10 μm) and weights with excellent edge definition. Flux can be jetted either in dot or line pattern at prefixed dispense gaps from the board surface. Since the fluid stream from the jet can be as small as 100 μm in diameter, it allows dispensing the flux in areas that it is impossible with a needle type dispenser (Lewis et al., 2003-(2).

Presently, the flux jetting valves are also commercially well established and it was reported that by augmenting the jet fluxing process with the use of "pulsed air assist" (coaxial air) techniques, even greater precision control can be achieved. In essence, the pulsed air-assist process emits a quick pulse of air after each micro-droplet or line is jetted, thereby helping to break the natural effects of surface tension on the board and smoothly spread the material onto pad surface. Unlike a traditional spraying process, pulsed air-assist jetting is a precisely controlled process that deposits more uniform flux patterns in exact locations (http://www.asymtek.com, 2004).

From the flux dispensing standpoint; wetting, speed, edge definition and film thickness are important characteristics for the successful fluxing (Lewis and

Ciardella, 1999). In this respect, a comparison of two viable non-contact flux dispensing methods is given in Table 3.9.

Table 3.9. Comparison of Flux Dispensing Methods

	Spraying	Jetting
Atomization	Possible	No
Wetting	Fair	Good
Speed	High	Can be very high
Edge definition	Poor	Excellent (speed dependent)
Film Thickness	Good control	Very good control
Over spray	No	No
Area of coverage	> 6 mm	> 5 mm
Cost	Low	High

In addition, successful implementation of the spray type fluxers within the robotic rework cell system was also demonstrated by Geren and Lo (1998).

3.2.7.3. Determination of No Flow Underfill Dispenser

Underfill material dispensing techniques can be divided into two categories; one is the contact-based needle dispensing method including, time/pressure valves, rotary positive displacement pumps, linear positive displacement pumps, and the second is the non-contact-based jetting in which the jet dispenser is used (see Table 3.8).

Since stated previously, precisely controlled repeatable material dispensing in specific quantities depends upon the inherent characteristics of the fluid material under varying conditions and the dispensing tool technical characteristics affecting overall capability of itself.

In the case of underfill dispensing, since the underfill materials are designed as premixed and frozen mixtures that change in viscosity with time and rapidly with temperature the flow output specifications of the dispense tool have to be independent of the viscosity of the material (http://www.asymtek.com, 2004).

As mentioned before, in the time/pressure valves and the rotary positive displacement pumps flow of the material is directly proportional to the material viscosity being dispensed. In addition to that, the rotary positive displacement pumps can be configured with proper pump design and advanced calibration techniques to minimize the effect of viscosity changes on the flow rate of the fluid, but the best accuracy on the smaller volumes of dispensing required for underfilling are in the range of ±10% (http://www.asymtek.com, 2004).

On the other hand, the linear positive displacement pumps have been specifically designed as an alternative to other needle based dispensing methods (Piracci, 2000-(1). In these pumps, a piston is used to change the volume of an auxiliary shot reservoir that is fed from the main syringe. The displacement of the piston in the reservoir results in an equivalent positive displacement of fluid through pump. A pneumatically controlled stop cock controls the recharge of the shot reservoir and also provides the pump with no drip performance. Since the pump's flow rate is simply a function of the piston speed and diameter, changes in viscosity, needle size and supply pressure have no effect on the material flow rate.

Consequently, for underfill material dispensing each of these contact-based needle dispensing methods offer different attributes but the most accurate method is the linear positive displacement pump. Typical dispensing accuracy of this pump is less than 1.5% for 30 mg shots and less that 1.0% for 300 mg shots (http://www.asymtek.com, 2004).

On the other hand, with all three methods of contact-based needle dispensing, precise location of the needle above the PCB surface is critical for the repeatable and good quality dispensing. Maintaining a consistent dispense gap requires contact with the board, increases cycle time and complicates the process control methodology. It also requires a precise positioning in Z axis (Piracci, 2000-(1, 2).

As for the non-contact-based underfill jetting, it is a new method of applying underfill using a ball tip pneumatic needle to force material through the jet nozzle in a rapidly cycled manner. In application, the jet is able to fly above the board at a fixed height (0.5 to 3 mm) and jet the material onto the dispense site without having to contact the board. The dot of underfill takes a ballistic path between the nozzle and its target on the board. Because of not having to move in the Z-axis to allow the fluid to contact the board the jet can be controlled for dispensing in two dimensions. This gives a significant savings in time and an increase in dispense cycle time from 10% to 50% over the rotary and linear piston pumps with equal or better consistency (up to two times). The uniformity and shape of the deposited dots are unaffected by variances in the PCB planarity or discrepancies in the needle surface and board surface tension since it never comes in contact with the board (Piracci, 2000-(1, 2). As a result, the jetting method provides non-contact, more robust, consistent and relatively simplified dispensing with a greater degree of process control at faster speeds.

By closer examination of current dispensing method and related tooling it was revealed that the linear positive displacement pump and the jet dispenser are suitable and reliable methods for automated rework. A summary of two viable alternatives for no flow underfill dispensing is given in Table 3.10 (http://www.asymtek.com, 2004).

Table 3.10. Comparison of No Flow Underfill Dispensing Methods

	Linear Positive Displacement Pump	**Jet Dispenser**
Flow rate	< 1 mg/s to >500 mg/sec	120 mg/sec
Shot size	0.002 to 2 ml	> 0.012 µl
Repeatability	Typically ± 1% except for very small dispense volumes (< 20 µl)	±3% for dot volume ±10% for dot diameter
Dispense cycle	90 msec/dot	8 to 15 msec/dot
Advantages	• Fast, efficient priming with minimal material waste. • Dispense volume proportional to piston travel, so one time calibration establishes accuracy for long production runs. • Lower initial investment cost compared to jet • Lower cost of ownership. • Tool-free disassembly and assembly for quick and easy cleaning	• Threefold improvement in consistency over needle-based method. • Low cost of ownership: easy and quick to clean in 10 min or less; maintenance is tool-free; less waste of material due to small wetted path; consumable parts are lower cost. • Outperforms needle based method with regard to speed, flexibility and process simplification
Disadvantages	• Requires periodic cleaning with limited pot life materials. • Sensitive to air in the fluid	• Requires periodic cleaning. • One dot size per jet (multiple shots for larger dot size). • High initial investment cost

3.2.8. Determination of Site Cleaning Tool

Currently, in order to achieve a clean reliable site, vacuum desoldering tools which usually have an integral heat source of either conductive, convective, or combination of both are in commonly used.

In the literature, there are successfully implemented two examples of automated site cleaning process in the robotic rework cell system. The first was employed a vacuum desoldering iron (VDI) for the site cleaning operations of surface mount and through hole technology components, which uses a combination of controlled heat and continuous vacuum in the same tip, fixed above the positing table. It was lowered and raised via pneumatically operated system whenever it was necessary and the positioning table driven each pad sequentially to VDI for cleaning action (Geren and Lo, 1998). The second was used an integrated cleaning tool for pad site cleaning of fine pitch SMCs, which combines a highly focused hot air jet and a vacuum nozzle, with an interchangeable robot end-effector adapter. During cleaning action; firstly hot air jet melts the remnant solder to allow fast and smooth motion and then vacuum nozzle draws the molten solder away from the PCB. This arrangement allows avoiding risk of delicate PCB integrity as in the case of fine pitch SMCs (Fidan et al., 1999). From the automated site cleaning point of view, the latter cleaning tool seems to be better, promising non-contact cleaning activity which is one of the essentials of reliable, high quality cleaning process.

There are also commercially available dedicated site cleaning stations, namely called automated scavenging systems, which combine a desoldering tool consisting of a vacuum tip surrounded by an annular jet of hot air with a precision motorized gantry and X-Y table. In these dedicated systems, the board is moved relative to the scavenging tip (or vice versa) in such a fashion that the whole pad site is scanned back and forth, row by row. Control of the temperature, scavenging tip height, pad dwell time, number of passes, desoldering speed are computerized while hot air/gas flow and vacuum flow are mechanically controlled within these systems. In this way, a non-contact process is performed with the individual pads being sequentially presented to the tool for the scavenging operation to take place (http://www.teradyne.com, 2004).

From the view point of engineering, vacuum desoldering tools and automated scavenging systems work on a similar principle. The difference is that scavenging systems are the automated version of the vacuum desoldering tools which is a good representative example of how the required non-contact vacuum desoldering tool can be integrated into a robotic rework cell system.

3.2.9. Determination of Vision and Inspection System Tooling

Based on the criteria introduced previously, a vision system that is able to recognize and align individual solder balls on the component to the related pads and a real-time transmission X-ray inspection system that is able to identify defects such as solder bridging, miss registration etc. are required for the automated advanced SMCs rework cell system (see section 2.7).

Typical vision systems involve cameras and digitizing hardware, a computer, and necessary interface hardware and software facilities. Accurate lighting is one of the significant facilities in the vision system of a robotic rework cell. To facilitate the interpretation of board, component, and pad site images, adequate illuminations of those are essential (Fidan and Kraft, 1999). In addition and very important, the vision system's recognition algorithms must meet the component placement accuracy requirements stated previously.

Substantially area array components placement vision system is a typically look up-look down system and consists of two cameras, one for imaging the surface of the board and other for imaging the underside of the component, coupled with the adjustable mirror(s). Such an optical system is schematically depicted in Figure 3.17. With such a vision system simultaneous imaging of component and board site is done and both images are then superimposed for the vertical alignment.

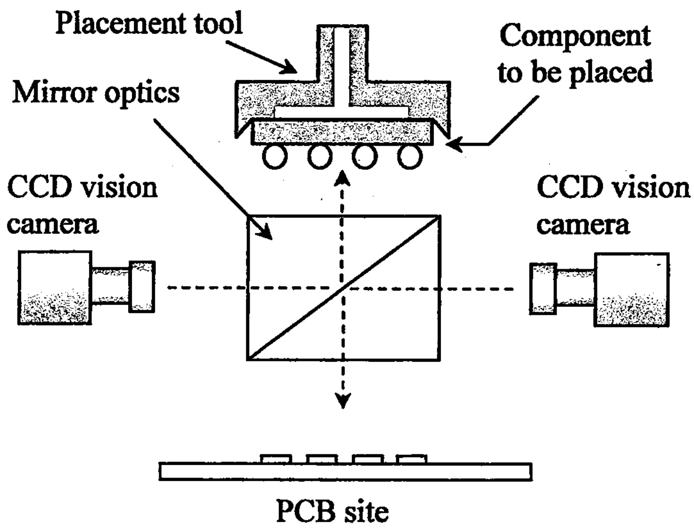


Figure 3.17. Schematic of Dual Imaging Vision Alignment System

As for X-ray inspection system, an X-ray source and an X-ray detector are its basic items. During inspection, X-rays are produced by the source and directed at the component site. The emitted X-rays from the source pass through the component, solder joints and the PCB to an X-ray detector. The image is captured and transmitted to a video camera where it is digitized. The digitized information is transferred to an image processor where it is enhanced, analyzed and prepared for display on a monitor (Rowland, 2002).

X-ray inspection systems display gray-scale images, which represent variances in the shape and thickness of an object. High density features produce a darker image than those with lesser density or thickness. The quality of the X-ray images depends upon the resolution of the X-ray tube (McClure, 1999) and type of the detector whether it is analog image intensifier or digital detector (Butani, 2002).

According to market survey results, among others there is a commercially available X-ray system which involves integrated X-ray tube source and real-time X-ray camera (http://www.glenbrooktech.com, 2004). This camera provides high resolution zoom capability, with a magnification range of 4 to 40 times without the need to reposition the devices being inspected. This unique ability to perform as an X-ray microscope eases not only the whole X-ray inspection process but also integrating it into a robotic rework cell. This also allows the addition of a vision camera to simultaneously view the inspected item along the same axis as shown in Figure 3.18.

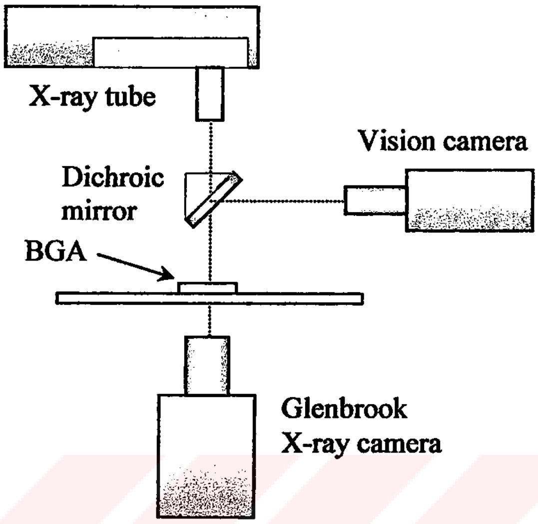


Figure 3.18. Newly Developed X-ray Inspection Technique (http://www.glenbrooktech.com, 2004)

3.2.10. Determination of Automated Advanced SMCs Rework Procedure

Based on the analyzed rework procedures in chapter 2 and proposed essential tooling requirements above for automated rework cell system, core of the possible automated advanced SMCs rework procedure has been developed as illustrated in Figure 3.19.

Detailed representation of the automated rework procedure is quite extensive and thus it is rather difficult because of the interrelated and complicated natural structure of the PCBA rework.

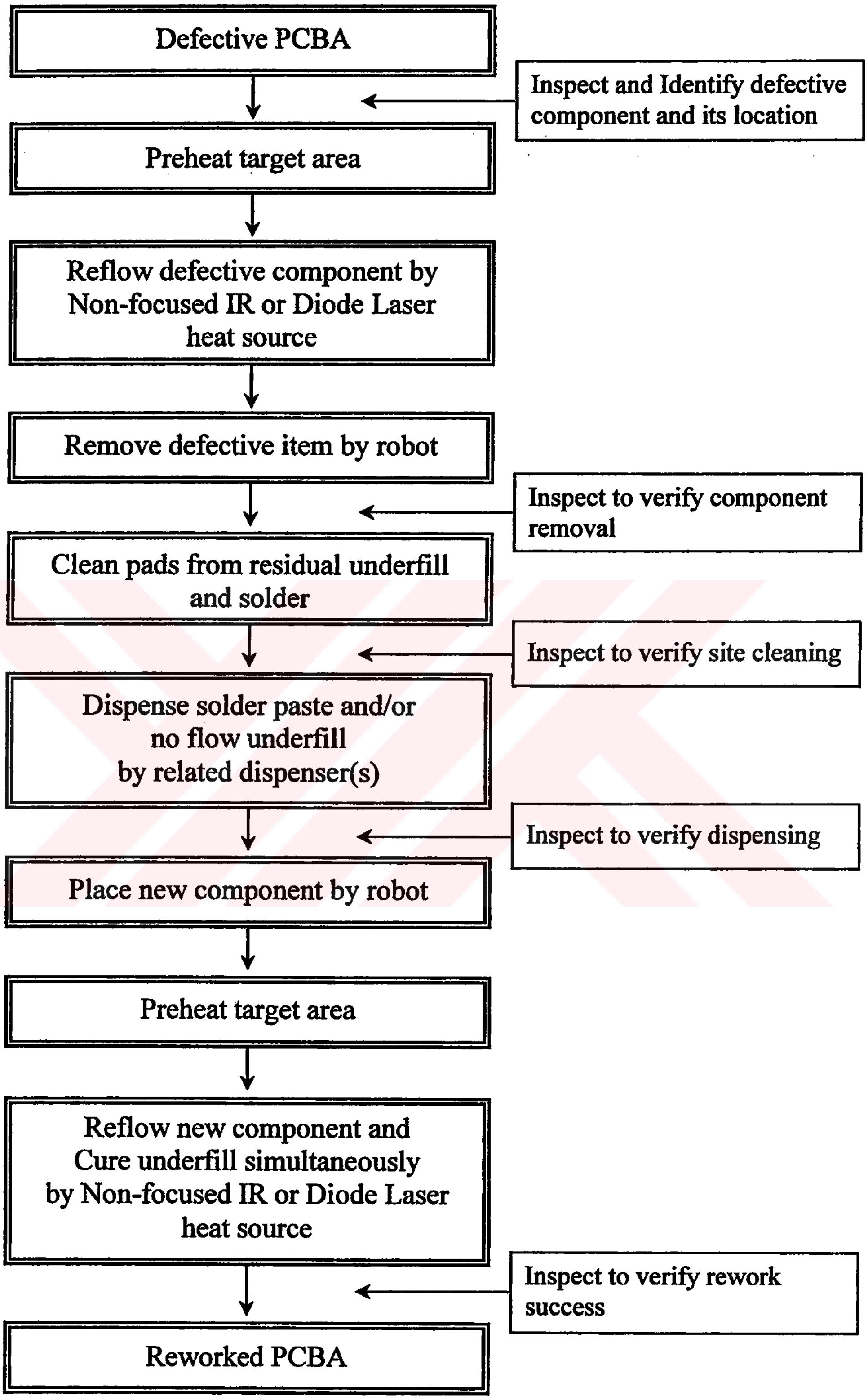


Figure 3.19. Core of the Automated Rework Procedure of Advanced SMCs

4. RESULTS AND DISCUSSION

The design and the development of a robotic rework cell system demands considerable efforts focused on the technical and economical feasibility studies.

In previous chapter, essential tooling candidates for automated robotic rework of advanced SMCs have been determined. Accordingly, based on these findings, in this section it is aimed to propose the suitable tooling selections for the automated robotic rework of advanced SMCs and also specify related tooling considerations for selection as well followed by the investigations of further tooling requirements, determination of the overall cell system layout and economic justification of the robotic rework cell system.

4.1. Selection of Reflow Method by Comparing the Reflow Candidates

Due to their suitability and technical feasibility for automated rework of advanced SMCs, the non-focused IR and the diode laser method have been determined as the possible reflow tooling candidates and viable proposals have been also made for each method so far.

On the other hand, in order to facilitate the decision making on the selection of most suitable reflow method for the automated robotic rework of advanced SMCs a comparison of the proposed methods by further investigating of their technical feasibility and suitability to automation was made as follows;

Non-focused IR Based Advanced SMCs Rework

- In the non-focused IR method, from the automation point of view, the requirements of four IR lens changing, spot size adjustment, and discrete focusing distance adjustment for each lens will arise additional design and manufacturing issues with respect to suitable hardware and software facilities. For automating all of each, a series of extra strenuous efforts should be made so as to determine important factors and criteria for related operations to identify significant tooling requirements. Moreover, appropriate tooling required for each operation may need to be newly designed and developed or additional modifications may be needed for procured tooling.

- Even though closed loop reflow temperature control and appropriate spot size adjustments will be established in a computerized manner, with the IR method there is still a risk of reflowing adjacent components at densely populated PCBAs and reflow may occur at higher temperatures due to the use of short wave IR.

Diode Laser Based Advanced SMCs Rework

- In the diode laser method, the requirements of additional tools (pyrometer, galvanometer, CCD camera, and guiding laser) for fully controlled, automated desoldering and resoldering process implementation are inherently basic parts of the reliable and repeatable laser soldering. Hence, these tooling are commercially and technologically well established in present. If necessary, the only need is to procure the essentials which are manufactured based on the simple means of plug and play method of use.
- However, there is a commercially available diode laser system manufactured by "*Laserline*". This diode laser system has intrinsically advantageous design characteristics because essentially needed whole auxiliary laser soldering tools (pyrometer, galvanometer, CCD camera, and guiding laser) have been already adapted and incorporated with the diode laser source. Hence, strenuous market survey and decision making on the selection of appropriate related tooling have been eliminated.
- The problems and difficulties with respect to automation, design and manufacturing issues which are currently concerns for non-focused IR method related to the optics changing and spot size adjustment are no longer an issue with diode laser method.
- In the diode laser method, better rework process results could be achieved in terms of the reworked joints or PCBAs reliability by virtue of the closed loop

temperature control facility in conjunction with the eliminated risk of surroundings.

- With respect to diode laser scanning pattern, the required soldering contour can be generated within its scan software or by transferring CAD data. This feature highly contributes to total system flexibility and naturally increases technical capability of the rework cell system.
- By virtue of superior design and technical characteristics, the diode laser method offers excellent suitability to the future trends in the electronics assembly and rework environments, compared to non-focused IR method (see Table 3.3).
- The diode laser method has technical and economical superiorities over non-focused IR method (see Table 3.3).

To conclude, according to further revealed comparison results, the diode laser method is promising to be well suited to automated robotic rework cell system development for the advanced SMCs due to the advantages of better cost, adaptability, suitability, flexibility, and reliability reasons.

In order to select the appropriate diode laser reflow tooling, after comprehensive market survey it has been revealed that the diode laser system namely called "DioScan 120" unit manufactured by the "*Laserline*" is suitable solution for the automated robotic rework operations of advanced SMCs, with respect to technical and economical concerns.

Based on a modular concept, the "DioScan 120" diode laser system consists of following basic parts (http://www.laserline.de, 2004);

- Diode Laser Head with Adapter for Beam Scanner
- Scanner Unit for Direct Diode Laser
- Integrated PC for Scan Head Control
- Power Supply/Control Unit

The "DioScan 120" diode laser head is an environmentally sealed, air-water cooled high power diode laser source operating at 808 ±10 nm wavelengths with the maximum 120 watts continuous wave optical output power (see Figure 4.1). Alternatively, 940 or 980 ±10 nm wavelengths are also optional. In addition, it is possible to well control the output power down to very low values (approximately lower than 10 watts).

Figure 4.1. DioScan 120 Diode Laser Head (http://www.laserline.de, 2004)

Substantially, the "DioScan 120" diode laser head consists of a beam shaping unit (for beam scanner) and it is mounted on a base plate with adapter for beam scanner head. Also in order to easily visualize laser spot size during the process, laser head has a pilot laser function. Other features of the diode laser head are presented in Table 4.1.

Table 4.1. Specifications of the Diode Laser Head (http://www.laserline.de, 2004)

Type	DioScan 120
Optical output power, max.	120 W
Beam quality	40 mm mrad
Wave length	808 ±10 nm
Overall efficiency	≥30%
Dimensions of the laser head (without optics)	480 x 145 x 166 mm3 (length x height x width)
Maximum Humidity	80% at 25 °C
Main supply voltage	230 V
Weight	12 kg (with mechanical elements for mounting)

As the name implies, the "DioScan 120" is the synthesis of the diode laser compactness and the method of moving the laser beam on the work piece using two scanning mirrors. This means that, essential 2-axis galvanometer is inherent part of the "DioScan 120" (see Figure 4.1). The PC that controls the scanner is integrated in the compact supply unit designed in 19-inch technology. Scan head control card integrated in this PC. With this system, guiding the laser power in microseconds to any desired point within the working area is possible. The scanning patterns can be generated within the scan software or by transferring related CAD data. Soldering speed and laser power can be assigned to the individual contour segment. Scan software provides fast and easy data exchange with scan head. With the alternative focusing optics, it is possible to achieve varying working area sizes from 30 x 40 mm^2 to 260 x 260 mm^2, working distance from >80 mm to >400 mm, and spot sizes from 0.5 mm to 4.0 mm (http://www.laserline.de, 2004). Some of the features of the scanner unit with standard optics are denoted in Table 4.2.

Table 4.2. Specifications of the Scanner Unit with Standard Optics (http://www.laserline.de, 2004)

Type	2-axis Galvo Scanner
Scan area	30 x 40 mm^2
Focal length	80 mm
Power supply	±24 V/4A
Working distance	90 mm
Spot size	0.5 mm
Weight	6 kg

The supply unit of "DioScan 120" is a compact, mobile supply unit integrated with power supply, water/air cooling unit (chiller), PLC control unit and scanner equipments (all-in-one concept) (see Figure 4.2). All of these units are integrated as plug-in modules. Cables leading to the diode laser head can be used for robot and cable routing (http://www.laserline.de, 2004).

Figure 4.2. Combined VG1 Supply Unit (http://www.laserline.de, 2004)

In addition, the integrated supply unit contains all necessary interfaces for the costumer's installation. The diode laser can be controlled either manually through the operator panel or from an external system. Different modes of laser operation can be chosen; continues wave, single pulse, and programmable power mode. Standard bus communication (Profibus, Interbus) as well as analog and digital interfaces enable easy integration of the diode laser into external control systems. All operating states from diode laser head to cooling system are continuously monitored. A two-stage fault management providing warning and error messages enables the operator to quickly react in the case of failures (http://www.laserline.de, 2004). Other features of the integrated power supply/control unit are given in Table 4.3.

Table 4.3. Specifications of the Power Supply/Control Unit (http://www.laserline.de, 2004)

Type	Combined VG1 Supply Unit
Dimensions	800 x 550 x 1000 mm^3 (length x height x width)
Mobility	Traveling on rollers
Power supply	230 V, 50 Hz, 1 phase
Selectable power range	10 to 100 % (max. power)
Max. power consumption	2 kW
Power cable length	8 m
Total weight	130 kg
Features of Control unit	• PLC based control unit • Integrated control panel with PLC monitor and foil keyboard • External control of diode laser power (+24 V, 0 – 10 V analogue) • Two-stage fault management • Minimum pulse length < 5 ms to CW
Features of Cooling unit	• Integrated water/air heat exchanger • Temperature range of 15-32 °C

Modularity of the "DioScan 120" diode laser system enables easy system upgrading. In this respect, in order for the robotic rework cell to carry out closed loop control/monitoring diode laser desoldering and resoldering operations for the whole range of advanced SMCs, some auxiliary tools have been also determined to be necessarily procured. These tooling given below are supplied by the manufacturer of the diode laser;

- Off-axis CCD Camera
- Off-axis Monitoring One Color Pyrometer
- Kombi F-Theta Optics (220 mm and 434 mm)

The camera is a simple, off-axis, black/white CCD camera and comes with black/white monitor. Since the CCD camera is IR sensitive, it is possible to visualize the pilot laser beam with this off-axis CCD camera.

The pyrometer is one color type and used off-axis in the diode laser assembly. To control the pyrometer, a complete Lascon controller as a separate Linux based PC system, including CD Rom, LCD monitor, mouse and keyboard comes with the pyrometer as a combined unit. Additionally, 1.5 m cables to mouse, keyboard and monitor, 5 m cable to pyrometer, multi IO PCI-card for data acquisition, and Lascon basic software on CD with manual are provided. The pyrometer delivers a signal to the controller PC. By means of the graphical interface temperature values can be recorded, but also analogue temperature signal on its consumer interface can be delivered. This is a 0 to 10 V analogue signal that can be calibrated to reflect certain temperatures. Other features of the off-axis pyrometer are denoted in Table 4.4.

Table 4.4. Specifications of the Off-axis Pyrometer (http://www.laserline.de, 2004)

Type	One Color Pyrometer
Measurement range	150°C to 550°C (adjustable measuring range)
Spectral range	1.6 to 2 μm
Measurement spot size	1 or 2 mm (depending on the requirement)
Response time	>0.1 ms (depending on signal)
Output	Digital and Analogue (0 to 10 V)
Dimensions	40 x 40 x 115 mm^3 (without optics)

With the standard optics of the "DioScan 120", it is not possible to handle whole range of advanced SMCs. Therefore, to work with the components bigger than 30 x 30 mm^2 size additional optics is essential. The selected optics is a combined F-theta optics having easily interchangeable two lenses for use with DioScan lasers. Working area (laser scanning area) of 130 x 130 mm^2 and 250 x 250 mm^2 are achieved with these two lenses respectively. Some of the features of the kombi F-theta optics are given in Table 4.5.

Table 4.5. Specifications of the Auxiliary F-Theta Optics (http://www.laserline.de, 2004)

Type	Kombi F-Theta Optics	
Focal length options	220 mm	434 mm
Scan area options	130 x 130 mm2	250 x 250 mm2
Spot size options	1.4 mm	2.7 mm
Working distance options	220 mm	440 ±20 mm
Applicable beam quality	40 mm mrad	
Power supply	±24 V/4A	

As a final conclusion, the total cost of the "DioScan 120" diode laser system is given in Table 4.6.

Table 4.6. Total Cost of the Complete DioScan 120 Diode Laser System

Item	**Cost**
DioScan 120 Diode Laser System • Diode Laser Head with Adapter for Beam Scanner • Scanner Unit for Direct Diode Laser • Integrated PC for Scan Head Control • Combined Supply Unit (including installation, training costs)	€ 61.000
Off-axis CCD Camera	€ 1.350
Off-axis One Color Pyrometer	€ 5.800
Kombi F-Theta Optics 220 and 434	€ 2.800
Total Amount	€ 70.950

4.2. Selection of Manipulating Devices and Related Tooling Considerations

Based on the market survey results, it was found out that the most advanced assembly and rework systems offer the accuracy ranging from ±0.0254 mm (0.001") to ± 0.0125 mm (0.0005"). These findings show that in order for the development of advanced SMCs robotic rework cell system based on the batch size of one, higher level of precision and accuracy are needed with respect to manipulating devices. Thus technical capability of the selected manipulating devices should meet calculated essential accuracy requirements for advanced SMCs to achieve higher reliability and throughput within in the proposed automated rework cell system.

As for robot selection, besides the previously stated criteria, the aim of total cell system design also plays an important role on the selection of the robot.

In this respect; if the robotic rework cell system is designed as an extension of a PCBA cell system in order to maximize the use of a company's resources, the SCARA type robots will be advantageous. Because such a cell system would be able to perform rework process during its free time with the efficient utilization of floor space which is in some cases an important issue. On the other hand, if the rework cell system is designed to be separate rework cell, the Gantry type robots will be viable alternative provided that there is no floor space limitation.

To conclude, while the calculated strict accuracy requirements leads to the Gantry robot to be suitable manipulator for the advanced SMCs rework cell system (see Table 3.7); the main object of the cell system design must be also carefully considered before the final decision making on the robot type selection.

As a final conclusion, of course Gantry robots have some intrinsic shortcomings, but these are outweighed by its overwhelming advantages such as high repeatability, accuracy and resolution at a constant value. Furthermore, with the continuous improvements in robotic technologies enhanced versions of the Gantry robots become currently available in conjunction with the considerably diminished poor space utilization feature. These resultant features ease to efficiently establish a Gantry robot based automated rework system as an extension of a PCBA cell system.

4.3. Selection of Component Removal and Replacement Tool and Related Tooling Considerations

Obviously, the advanced SMCs rework cell system must be capable of removing and replacing all components from a PCBA.

Extensive studies on the existing advanced SMCs rework procedures, problems, and methods revealed that in order to efficiently remove a defective underfilled component from a PCBA, special removal tool(s) with a gripping feature which enables applying sufficient twisting action to break down the underfill bond is needed. Furthermore, vacuum suction tool(s) is also required for the successful replacement of a new component. From a component removal/replacement tooling perspective, the main requirement is that the tool be able to handle the desired range of component types. Hence, the type, magnitude, and other specifications of the advanced SMCs play an important role for the design of the required tooling. Additionally, the component removal/replacement tooling design must also include appropriate robot end-effector adapter feature in order for the robot to automatically change related tools to carry out other rework operations.

Following are the determination of the essential specifications of the advanced SMCs, related tooling considerations, and proposals for the suitable removal/replacement tooling will be introduced.

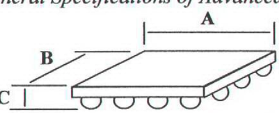
4.3.1. Selection of Component Removal Tool

From a defective underfilled component removal tooling point of view, among others magnitude of the advanced SMCs and their location onto a PCBA are predominant factors for the design of a suitable removal tool.

According to IC component manufacturers' product data sheets, advanced SMCs have varying dimensions and these are summarized in Table 4.7.

Table 4.7. Dimensions of the Advanced SMCs

General Specifications of Advanced SMCs



Package Length and Width Range (A x B)	Package Height Range (C)
4 x 4 to 55 x 55 mm	$0.5 \leq C \leq 4.0$ mm

From the engineering design standpoint, in order to remove a defective underfilled component by applying sufficient gripping and twisting action the width of the finger of the removal tool can be at least one third component width. Therefore, by accurately categorizing the current advanced SMCs, number of required removal tool can be determined. In this respect, currently available advanced SMCs can be categorized into two groups;

Group 1: Components having the length and width of 4 x 4 to 18 x 18 mm

Group 2: Components having the length and width of 19 x 19 to 55 x 55 mm

As a consequence of above, it has been revealed that two component removal tool designs having the tip width of 6 mm and 18 mm are needed to handle the whole range of advanced SMCs ("D" value shown in Figure 4.3).

Additionally, in order for the removal tool to accurately grasp the defective component, height of the component must be considered during the design of the removal tool. As seen from the Table 4.7, maximum component height is 4.0 mm and height of the finger tip lateral side where it is in direct contact with the component side must be equal or higher than this value ("F" value shown in Figure 4.3).

Moreover, the proximity of the components between each other must also be considered because densely located parts necessitate very thin removal tool tip design.

All things considered, suitable fingers of grippers for the two removal tool designs are schematically depicted in Figure 4.3 and Figure 4.4 respectively. Their related dimensions are also given in Table 4.8. First three dimensions (D, E and F) given in table are component specific and others are changeable according to further design analysis, available manufacturing technology, material, and tool etc.

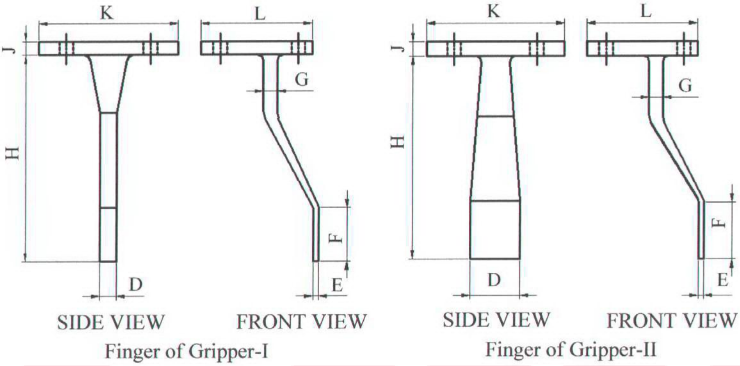


Figure 4.3. Schematic of Grippers for Advanced SMC Removal Tool

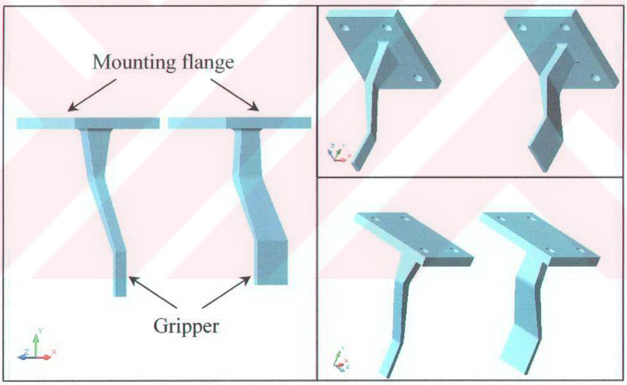


Figure 4.4. 3-D Modeling of Grippers for Advanced SMC Removal Tool

Table 4.8. Dimensions of the Grippers

Gripper Type	Dimensions (mm)							
	D	**E**	**F**	**G**	**H**	**J**	**K**	**L**
I	6	2	20	5	60	5	50	40
II	18	2	20	5	60	5	50	40

In fact, removal of the underfilled defective component requires a parallel action of the grippers in the horizontal plane. To do this, proposed gripper designs can be mounted to a sliding mechanism driven by a DC motor.

Figure 4.5 shows 3-D modeling of a suitable advanced SMC removal tool design. Modeling has been done by considering several design factors such as minimum weight, size, and high functionality, easy manufacturing, ease of use etc.

As seen from the figure, grippers are mounted to a sliding carriage which has a toothed rack feature. By means of the simple toothed rack and pinion design, grippers can be precisely driven in the horizontal plane (X axis) by the DC motors.

Smooth motion of the mechanism is provided by the use of ball bushings and additional two guiding rods contribute to robustness and prevent unnecessary rotational movement of the sliding carriage.

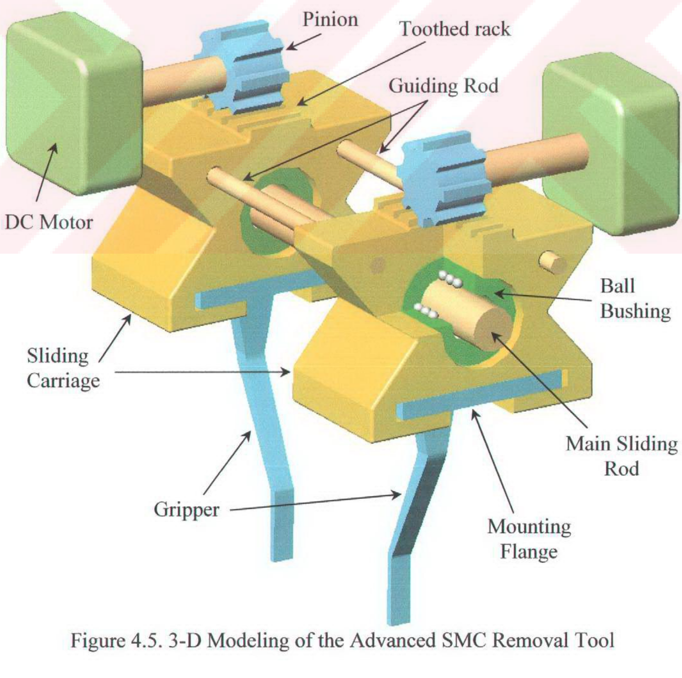


Figure 4.5. 3-D Modeling of the Advanced SMC Removal Tool

Additionally, the design of the advanced SMC removal tool coupled with robot end-effector adapter feature is also schematically illustrated in Figure 4.6.

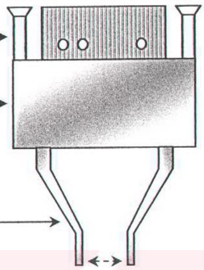


Figure 4.6. Schematic of Advanced SMC Removal Tool

4.3.2. Selection of Component Replacement Tool

As good rule of thumb, generally component replacement tasks have been done by using varying vacuum suction tools in the assembly and rework of SMCs. However, from the automated rework cell system point of view, the number of the tools used for either component removal or replacement should be kept as minimum as possible. Because each extra tool means additional cost penalty and requires additional tool parking facility, quick-exchange mechanism etc. all of which complicate the structure of the cell system design and its control architecture as well.

As stated previously, in fact, even though there are vast numbers of advanced SMCs with the varying pitch sizes and lead counts, their component packaging sizes tend to cluster around certain dimensions ranging from ~4 x 4 to 55 x 55 mm. If the tooling for the component replacement were designed by considering this, there would be a way of reducing the total number of required tooling.

As a consequence of above, a component replacement tool design having a vacuum suction nozzle sized for the smallest component, yet could generate sufficient vacuum force to lift and place the heavier component easily in the automated robotic rework operation of the advanced SMCs can be a suitable solution. As a representative example, such a replacement tool design together with robot end-effector adapter feature is schematically depicted in Figure 4.7.

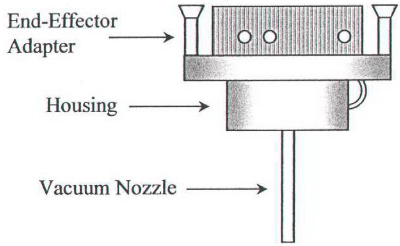


Figure 4.7. Schematic of Advanced SMC Replacement Tool

4.4. Selection of Other Rework Tooling

Making the decision on the selection of reflow method and manipulating device allows accurately selecting other rework tooling required for implementation of the automated rework of advanced SMCs. Following are the selection of the related rework tools respectively.

4.4.1. Selection of Solder Dispenser

As stated in previous chapter, use of the rotary positive displacement dispenser is more accurate and reliable method of solder application for the automated robotic rework of advanced SMCs. Presently, there are commercially available various rotary positive displacement dispensers with the differing attributes.

By virtue of advantageous design characteristics, one that is manufactured by "*Asymtek*" seems to be well suited for the robotic rework applications of the advanced SMCs at pitch sizes ranging from 0.1 mm to 1.5 mm.

It is a servo-controlled, fully programmable rotary positive displacement pump (see Figure 4.9) and available in a luer- or footed-needle design alternatives with interchangeable cartridges (see Figure 4.8). In footed needle applications, the needle has an accurate and consistent gap between the needle tip and the foot.

The pump is programmed to have a dispense height lower than the board surface. Once the needle touches the board, a spring-loaded slide in the pump body compresses to compensate for any variations in the board's surface. As a result, z-axis movement is minimized, providing fast small-dot dispensing. In luer-lock needle applications, the needle is used with a height sensor to set the gap between the board surface and needle tip. A stiff spring in the pump body eliminates any z-motion in the pump. A luer-lock needle retainer secures the needle to the cartridge (http://www.asymtek.com, 2004).

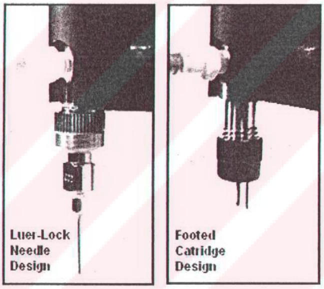


Figure 4.8. Needle Alternatives of the Rotary Positive Displacement Pump (http://www.asymtek.com, 2004)

Its quick-release cartridge design makes cleaning easy. Simply press the quick release lever on the side of the cartridge/needle holder to remove the needle and auger screw cartridge. No tools are required (http://www.asymtek.com, 2004). Special features of the dispenser can be summarized as follows;

- Footed cartridge with a fixed mechanical stand-off nozzle for extremely consistent dots and increased throughput.
- Luer-cartridge option allows use of a wide range of standard needles.
- Tool-free disassembly of wetted parts for quick and easy cleaning.
- Fast cartridge changeover.
- Closed-loop motor control with encoder feedback ensures high repeatability.

Both needle designs offer precise, reliable, and consistent solder application in a fully automated fashion. However, in the case of footed-needle design, possibility of preventing needle touch to the target board surface to be dispensed by the closely located big enough electronic devices near or around the target surface make the use of footed-needle design impractical for the automated robotic rework applications of advanced SMCs based on the batch size of one.

Consequently, Figure 4.9 and Table 4.9 presents structural view and some of the specifications of the suitable rotary positive displacement solder dispenser respectively.

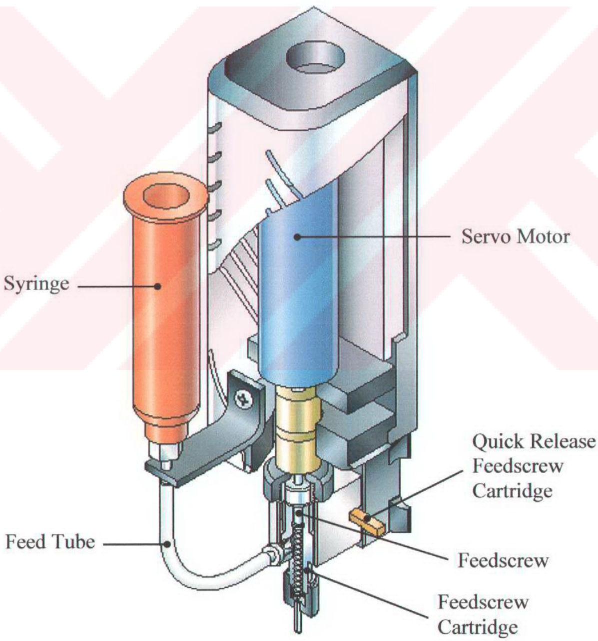


Figure 4.9. DV-7000 Rotary Positive Displacement Pump (http://www.asymtek.com, 2004)

Table 4.9. Specifications of DV-7000 Rotary Positive Displacement Pump (http://www.asymtek.com, 2004)

Type	DV-7222-SL1 (Luer needle type)
Dimensions	Length: 190-192 mm Width: 33 mm Depth: 72.6 mm
Required Air Pressure	1.0-2.1 bar (5-15 PSI)
Motor	Closed-loop control with encoder feedback
Cost	~€ 2.000

4.4.2. Selection of Flux Dispenser

In order to determine the most appropriate flux application method and related tooling for automated rework it is necessary to re-scrutinize the fluxing requirements within the advanced SMC rework process. Therefore, if essential requirements within the rework process based on the no flow underfilling are re-evaluated following are revealed;

- For soldering purposes additional flux application is eliminated, since required fluxing action is provided by the no flow underfill itself (see section 2.4.1.2).
- Throughout the rework process additional flux application is only needed within the site cleaning step.
- Flux application and cleaning of all residual remnants will already be performed before the formation of solder joint.
- High precision level of controlling fluxing is not an issue with respect to wetting, edge definition etc. However, flux must be applied to the cleaning site in an efficient and economical manner.
- An ability to handle differing sizes of component attachment sites (area of coverage) is important with respect to technical capability of automated rework system.

Based on these statements, among others flux dispensing speed, uniform film thickness, and low cost characteristics become predominant factors (see Table 3.9).

All things considered, it was revealed that for the precise and automatically fully controlled flux application process the jetting valves and spray valves can be procured for the robotic rework of advanced SMCs.

However, after careful considerations of the essential requirements and economics of the valves, the spray type valves are promising to be both technically feasible and economically justifiable.

As a final result, according to market survey results, Table 4.10 presents technical specifications and Figure 4.10 and Figure 4.11 presents external and cross-sectional view of a suitable spray valve for the automated advanced SMCs rework system respectively.

Table 4.10. Specifications of TS5520 Spray Valve (http://www.techconsystems.com, 2004)

Minimum Shot Size	6.35 mm Diameter @ 12.27 mm Distance
Maximum Flow Rate	28 ml/sec
Operating Frequency	600 cycles/min
Size	106.7 mm (Length) x 28.5 mm (Diameter)
Weight	150 g
Air Operating Pressure	50 PSI Maximum
Repeatability	±0.30%
Cost	~€ 700

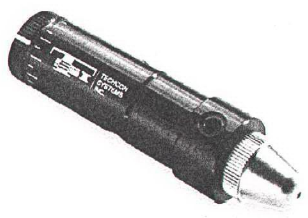


Figure 4.10. External View of the TS5520 Spray Valve (http://www.techconsystems.com, 2004)

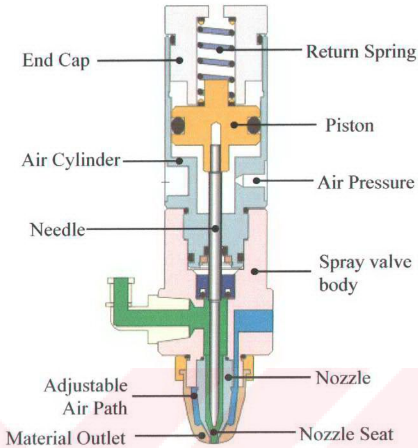


Figure 4.11. Cross-sectional view of the TS5520 Spray Valve (http://www.techconsystems.com, 2004)

The TS5520 spray valve is a normally closed, adjustable opening, needle and seat valve. Air pressure through port retracts the needle assembly from the seat allowing material to be dispensed. A separate and adjustable air path around the material dispense orifice provides an atomizing air. Spring return reverses the needle assembly travel to close the material path (see Figure 4.11) (http://www.techconsystems.com, 2004).

4.4.3. Selection of No Flow Underfill Dispenser

Before making the final decision to select the most appropriate one the underfilling requirements of advanced SMCs rework should be reconsidered as follows:

1. The rework process will be carried out based on the no flow underfilling technique (see section 2.5.2).
2. The no flow underfill material should be dispensed in a single dot/glop pattern over the center of component attachment site in specific volume (see

section 2.4.1.2). Therefore, needle size and/or adjacent component proximity in dense PCBAs is not an issue.

3. In fact, there is no need to additional sensors and/or other control devices for contact based underfill dispensing because all required control hardware and software facilities will already be procured for solder paste dispensing.
4. Choosing the right pump doesn't mean that the most complex is the best since this will be cost unnecessarily much higher.

As a final conclusion, with careful considerations of the comparison result given in Table 3.10 and stated criteria above it was revealed that the linear positive displacement pump has adequate technical capability and it is economically more viable alternative.

Current market survey results reveal that, among the others, by virtue of advantageous design characteristics, one that is manufactured by *Asymtek* seems to be well suited for the robotic rework applications of the advanced SMCs. Some of the specifications and structural view of the suitable linear positive displacement no flow underfill dispenser are given in Table 4.11 and Figure 4.12 respectively.

Table 4.11. Specifications of DP-3000 Linear Positive Displacement Pump (http://www.asymtek.com, 2004)

Type	DP-3140
Dimensions	Length: 203.2 mm, Width: 83.8 mm, Depth: 88.9 mm
Drip	No drip with 1 Cps fluid
Flow rate	0.006 ml/s to 1 ml/s
Shot size	0.002 to 2 ml
Resolution:	0.00025 ml
Accuracy	<1.5%, for 30 mg shots; <1.0%, for 300 mg shots
Dispense cycle	90 msec/dot
Cost	~€ 2.000

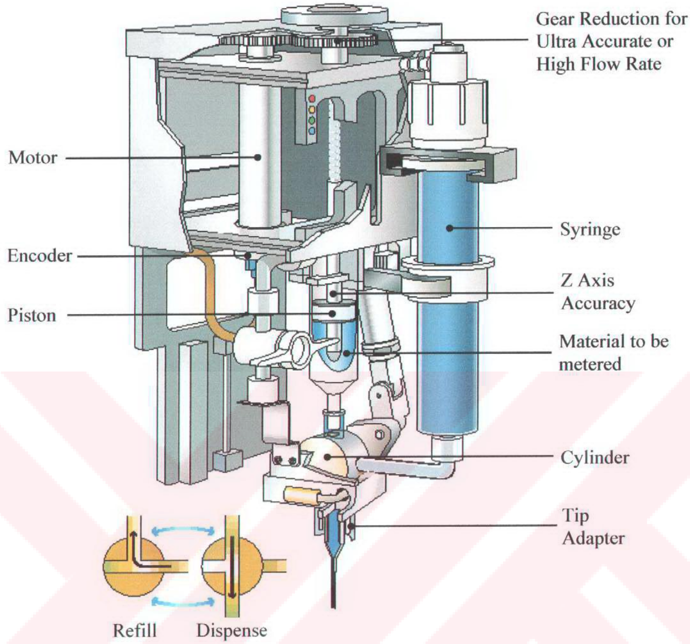


Figure 4.12. DP-3000 Linear Positive Displacement Pump (http://www.asymtek.com, 2004)

This pump design uses volumetric displacement technology and a DC servo motor with encoder to control true piston motion. The piston changes the volume of a reservoir that is fed from the main syringe. The displacement of the piston in the reservoir results in an equivalent positive displacement of fluid through the pump. A pneumatically actuated disposable valve controls the refill of the reservoir and provides integrated, no-drip performance (see Figure 4.12). The pump's flow rate is a function of the piston's speed and diameter. It delivers precise amounts of material at high speed, regardless of fluid viscosity. Performance accuracy and speed of volume deposition is precisely maintained for applications ranging from very large BGA to very small FC component. It has also quick release mechanisms for tool-free removal of the syringe, stopcock, and pump chamber (http://www.asymtek.com, 2004). Special features of the dispenser can be summarized as follows;

- Rapid refill speed for optimal underfill dispensing.
- Quick-release mechanisms of wetted parts for easy setup and removal from the system.
- Tool-free disassembly and assembly for quick and easy cleaning.
- Better than 1% accuracy for consistent dispensing with multiple programmable shot sizes.
- Fast, efficient priming with minimal material waste.
- High flow rate for high throughput.
- True positive displacement dispensing, independent of viscosity.
- Outperforms rotary positive displacement pumps with regard to accuracy, speed, and wear.

4.4.4. Selection of Site Cleaning Tool

Comprehensive studies on the manual advanced SMCs rework processes revealed the following important specifications for the site cleaning;

- Convective heating method, hot air, is a must
- An ability to efficiently melt the residual eutectic Sn/Pb or lead-free solders and to decompose the underfill material residue
- An ability to remove both residual solder and underfill by efficient vacuum suction force
- An ability of precise and fully controlled, non-contact process implementation throughout the cleaning

Moreover, the site cleaning tool should also have the ability of being attached to the assembly robot arm by using suitable interchangeable robot end-effector adapter allowing the robot to carry, perform and exchange the tool whenever needed and this also contributes to flexibility of the system.

All things considered, the non-contact, hot air-based vacuum desoldering tool is needed in order for successfully accomplishing automated site cleaning task (see chapter 2).

By considering these statements given above a market survey have been done. It has been revealed that one that is manufactured by Air-Vac Engineering Company seems to be suitable solution. This site cleaning tool has been designed as part of the semi-automated rework system. This tool has not only well suited technical capability but also has good potential for integration and adaptation to the automated robotic advanced SMCs rework cell system.

Principle of cleaning tool operation is that a composite tip is positioned just above the pad site and uniform flow of hot air or gas heats multiple solder pads while powerful vacuum draws the residuals through the vacuum passage into the high capacity collector in a safe and effective way (see Figure 4.13).

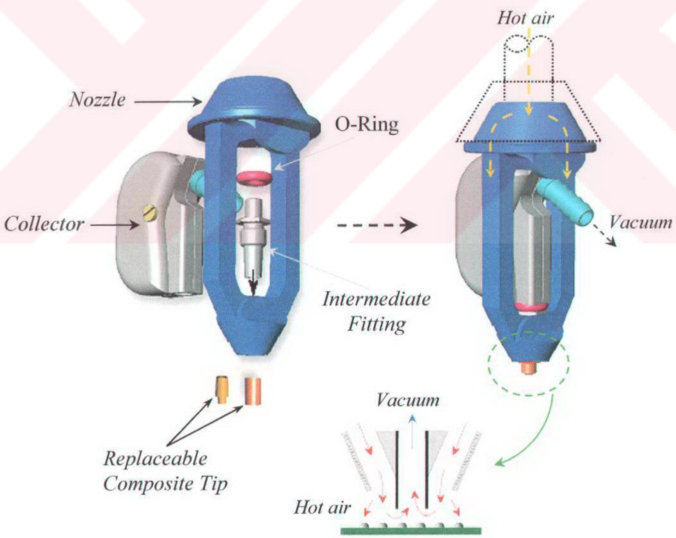


Figure 4.13. Assembly of Site Cleaning Tool (http://www.air-vac-eng.com, 2004)

Throughout the cleaning operation, tip height is automatically adjusted by a sensor and in this way a non-contact implementation is provided. Additionally, a stainless steel intermediate fitting connects the composite tip with the solder collector which allows easy cleaning and/or replacing the parts (http://www.air-vac-eng.com, 2004). Other features of the cleaning tool are presented in Table 4.12.

Table 4.12. Specifications of Site Cleaning Tool (http://www.air-vac-eng.com, 2004)

Type	High Capacity SSRS
Temperature Control	Closed loop (by a non-contact sensor feature)
Vacuum Level	28"Hg
Vacuum Flow Rate	2.4 scfm
Gas pressure requirement	80 PSI
Replaceable tips	Medium Tip: ID = 0.089", OD = 0.125" Large Tip: ID = 0.125", OD = 0.188"
Cost	~€ 4.100

Moreover, to meet clearance requirements for virtually any site cleaning operations alternatively three auxiliary tip extensions are also available in heights of 2.5", 0.75" and 0.50" respectively. As shown in Figure 4.14, installation of the extensions is quite easy. Simply screw the selected extension upward into the nozzle using the installation tool. Place spacer and O-ring on top end of fitting then install collector assembly. Tip extensions give the added height necessary for cleaning application around taller adjacent components/devices on populated PCB's (http://www.air-vac-eng.com, 2004).

To conclude, although this site cleaning tool has outstanding properties and use of this tooling is feasible in technical sense, it has economical constrain even its individual price may be justifiable. Because, as stated before, it is part of a semi-automated rework machine and unfortunately not sold separately. Therefore, to obtain this tooling economical justification of procuring whole rework machine must be considered. Because, even the basic configuration of the rework machine is to be chosen this adds unnecessary cost penalty (~€ 40.000) to the total cell system development cost.

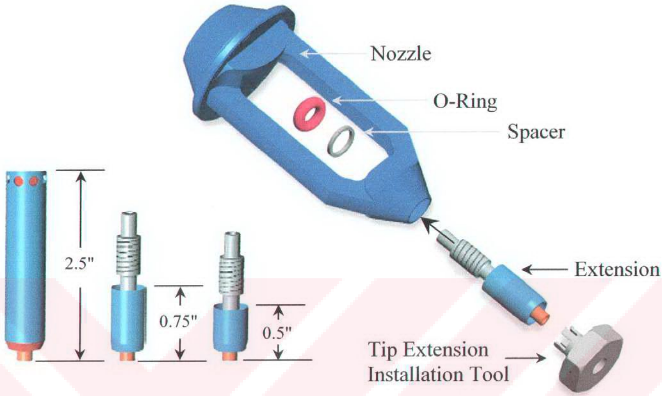


Figure 4.14. Optional Auxiliary Tip Extensions (http://www.air-vac-eng.com, 2004)

Alternatively, a suitable hot air blower and a vacuum suction tool may be procured individually. They can be appropriately combined as an integrated cleaning tool. Then this tool may be adapted and integrated to the rework cell system.

As a final conclusion, it should be emphasized that while both alternative solutions are technically feasible for the automated site cleaning operations within the advanced SMCs robotic rework cell, the second alternative thought to be also economically more justifiable solution.

4.5. Investigation of Sensory Tooling Requirements

Ideally, such an automated rework cell system needs to be equipped with the sensors for variety of tasks such as,

- *Placement force sensing,*
- *PCBA registration,*
- *Both defective and new component registration,*
- *Determination of PCBA local deflection,*

- *Inspection of solder/flux/underfill dispensing*
- *Inspection of pad cleaning results,*
- *Checking the end process results etc.*

Additionally, appropriate force sensing and control is increasingly crucial in the advanced SMC removal and replacement processes during the rework. Therefore, placement force feedback and programmable force control is required to ensure proper placement without risk of damaging delicate and expensive components.

4.6. Investigation of Auxiliary Robotic Tooling Requirements

Throughout the automated advanced SMCs rework, assembly robot must perform component pick and place operations and also handle other rework tools such as solder/flux/no flow underfill dispensers, site cleaning tool etc. Therefore, to enable the robot handle more than one tooling during the rework, an appropriate automatic tool exchanger mechanism must be incorporated to the robot end of arm tooling.

By doing this, all of the operational rework steps would be performed in a single cell environment. This also contributes to total cell system flexibility. Additionally, the choice of the end effector exchange mechanism determines the tool parking requirements for the robot.

4.7. Investigation of Overall System Control Tooling Requirements

From the automating advanced SMCs rework point of view, analyses of existing rework procedures and the rework requirements have revealed that a supervisory cell controller would be needed because of the following;

- Due to the differences in component package type, pitch size, and material composition of solder ball etc different rework procedure may be required.
- Since it is aimed to perform rework based on a batch size of one, the data and procedure requirements of rework for each defective component may be different.

- Although most of the rework activities would be carried out in a predefined sequential manner, simultaneous activation of several pieces of equipment may be inevitably required.
- The hardware required for automated rework of advanced SMCs (such as robot, vision, reflow tooling etc.) may have their own controllers and these must be supervised by a cell controller.

In addition to above, use of component- and PCBA-type related process knowledge either stored in the system or acquired during rework would be inevitably required. Hence, the presence of a knowledge-based rework process planning system is also necessary. A knowledge-based rework process planning system is essential to retrieve process information and to invoke task-oriented rework and inspection routines. Further, the planning system should be able to operate dynamically in real time prior to and throughout the rework process so that it can handle various PCBAs based on the batch size of one.

In order to control the whole advanced SMCs rework cell system, cell controller software should be generic and be able to carry out the PCBA rework without operator involvement based on the batch size of one. It relies on extensive support of data which may come from following;

- Automatic testing equipment (ATE) for the determination and identification of the defective components,
- CAD/CAM data providing the positions of the defective and surrounding components,
- In-process inspection data from installed sensory devices providing the type of defect, obstructions, location of post-desoldered defective component etc,
- Preexisting PCBA data pools that may supply various data requirements such as rework procedures and detailed data concerning tool locations etc.

The cell controller adjusts the system to automatically adapt to various conditions and activate the various tools when required.

In addition, from the rework operator point of view, user-friendly object-oriented graphical user interface facilities must also be established. The aim of implementing the graphical user interface is to reduce required operator skills and training for the operation of the automated rework cell. The function of such a graphical user interface is to receive input from the operator to guide the execution of the automated rework. Such an object-oriented graphical user interface enables the operator to perform the entire rework operation in a simple point and click method within the controlled environment.

4.8. Total Robotic Rework Cell System Layout

Based on the findings obtained from the studies of suitable tooling selections and investigations of further tooling requirements for the automated robotic rework of advanced SMCs, it has been revealed that total cell system should consist of several subsystems and/or devices as shown in Figure 4.15.

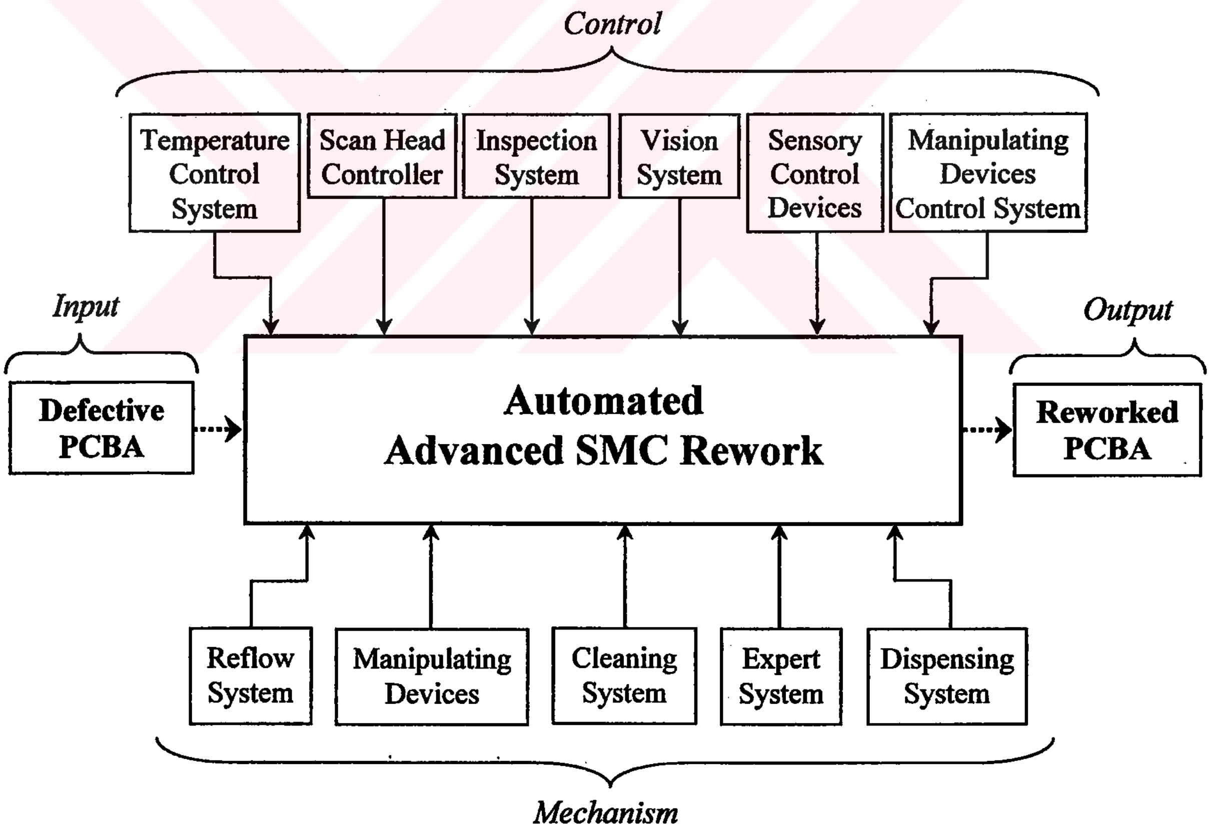


Figure 4.15. Subsystems of the Automated Advanced SMCs Rework Cell

In addition, extensive use of automation for these devices to achieve total process control is required. Also, electrical integration and interfacing these devices plays an important role in the automation process.

All things considered, Figure 4.16 and Figure 4.17 illustrate the outline of the possible hardware structure of the advanced SMCs rework cell system. The structure of the cell system may be divided into several regions;

1) Base region: Found in this area are the devices and tooling which are located within the Gantry robot's working envelope. It comprises integrated diode laser heat source, interchangeable rework tools, dual imaging vision alignment system, the open-frame X-Y positioning table, tool parking station, and hot air bottom heater. As can be seen from figures 4.16 and 4.17, the all rework tools and devices should be closely located to each other so as to decrease the size of the Gantry robot structure. The interchangeable rework tools are the dispensers for solder paste, flux and no flow underfill materials, two component removal grippers, one suction tool for component replacement, and the site cleaning tool. The tool parking station where all interchangeable tools are stored is placed at one side of the positioning table. It is placed as close as possible to the positioning table to minimize rework cycle time by decreasing automatic tool changing duration (see Figure 4.17). It is also possible to mount component feeders at the opposite side of tool parking station within the robot's working envelope (not shown in figures). The dual imaging vision alignment system consists of two mirror optic mounted-profiles, a camera and illumination source incorporated with the simple sliding mechanism.

2) Upper region: These are the devices that are located above the base region. This part includes the Gantry robot manipulator and two vision cameras located at the top of the cell and robot arm.

3) Outer region: This part include essential controllers for the rework hardware and software facilities located away from the robot's working envelope. They are robot controller, X-Y positioning table controller, combined diode laser power supply/control unit, bottom heater controller, the vision and the cell controller PC etc (see Figure 4.16).

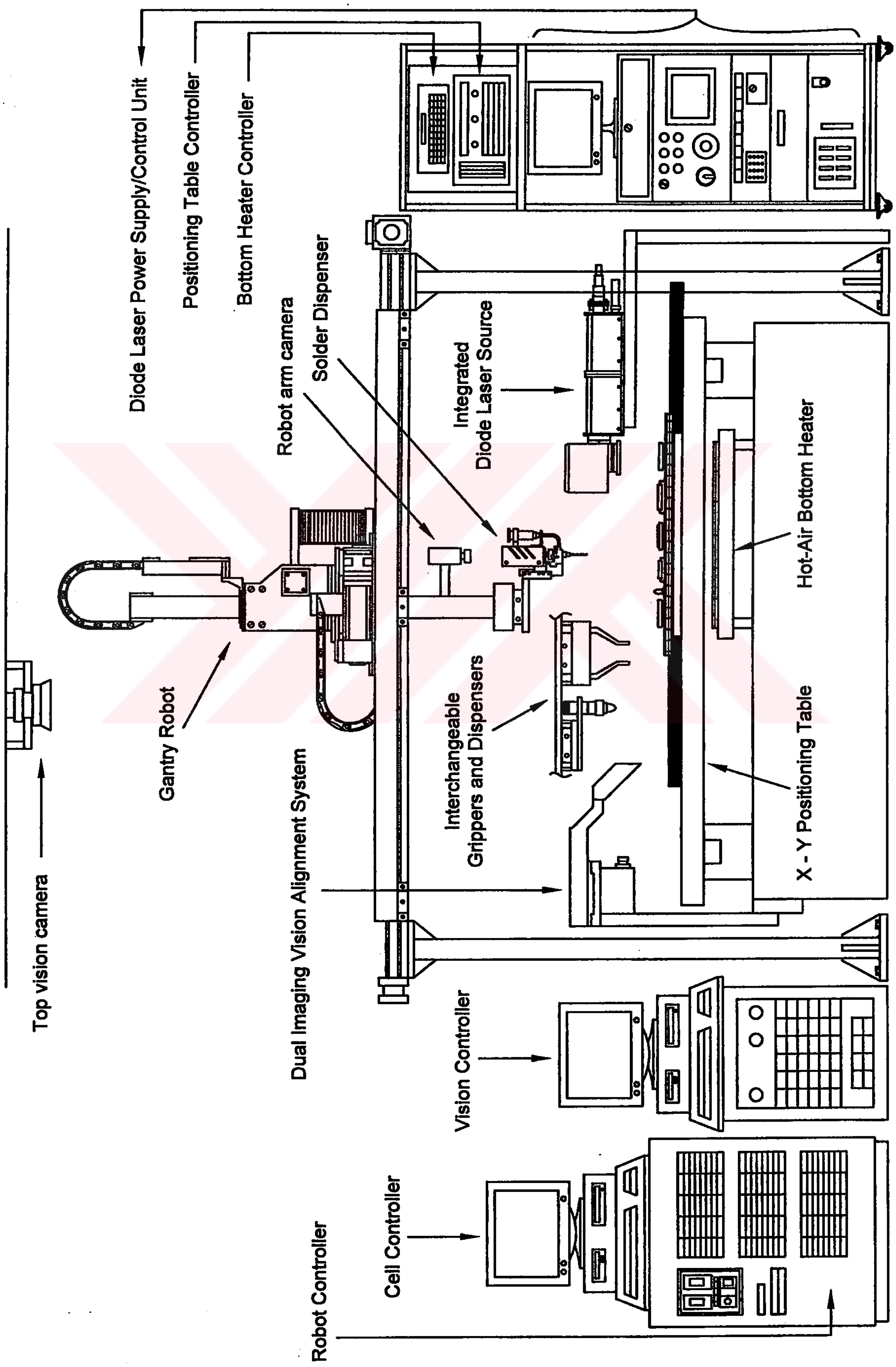


Figure 4.16. Front View of the Diode Laser Based Rework Cell Layout

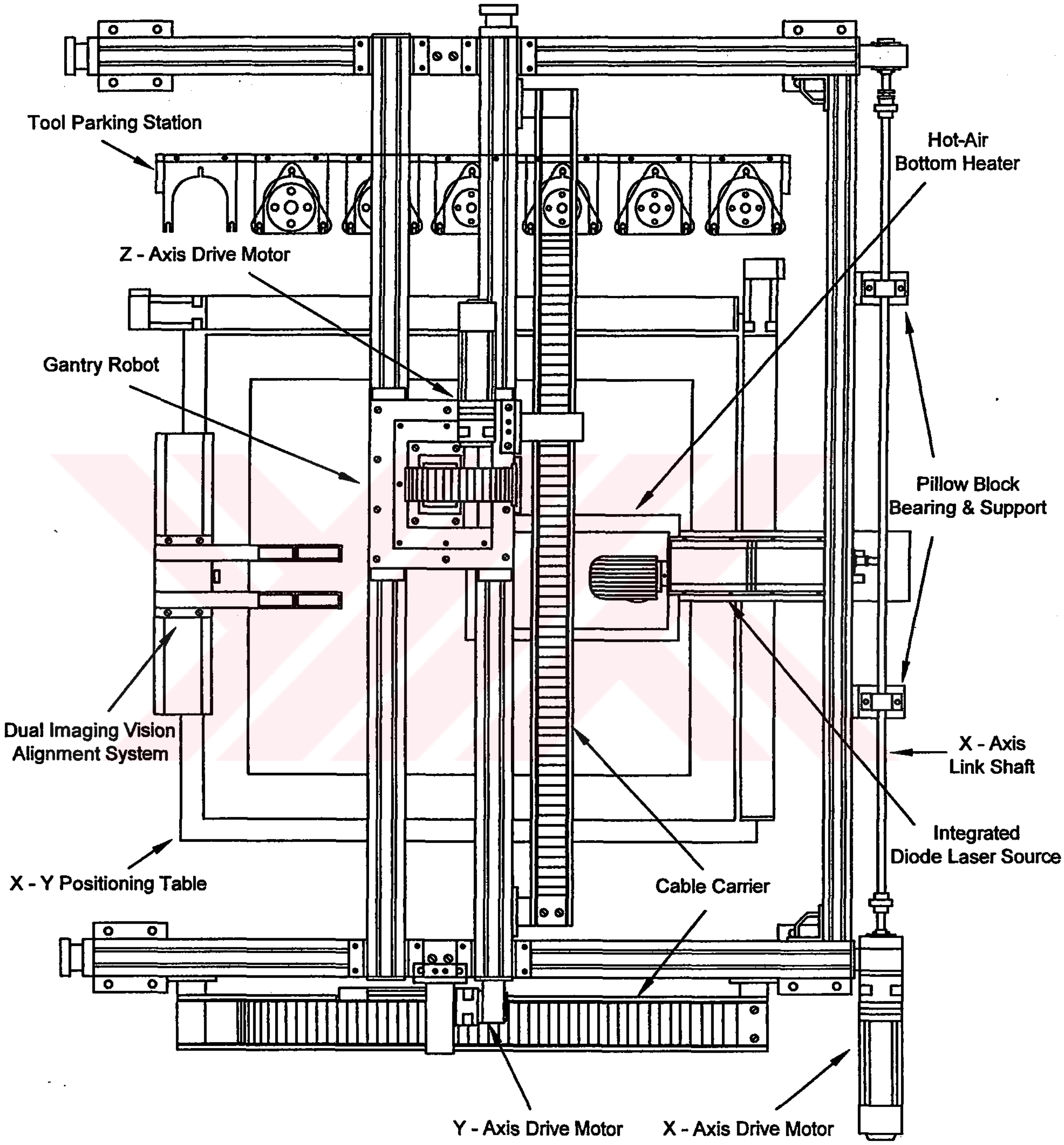


Figure 4.17. Top View of the Diode Laser Based Rework Cell Layout

On the other hand, while the robotic rework cell system hardware structure has been basically determined, automated rework procedure for the advanced SMCs can be developed as well.

As shown in Figure 4.18, robotic reworking of a defective component begins with the inspecting and identifying defective component and its location. To do this, the X-Y positioning table moves to inspection area for fiducial inspection and then locates the defective component underneath the inspection camera. After the required information about defective component location, defect type etc. is gathered, poisoning table locates the defective component between the hot air bottom heater and diode laser heat source to execute desoldering process. At the same time robot attaches gripper tool based on the cell controller instructions. When the process temperature exceeds predetermined reflow soldering temperature related controllers terminate the heating process and poisoning table moves to a location where the robot can perform removal and replacement operations. After the defective component removal, inspection of post-desoldered area is performed by the vision system. Then, robot attaches/detaches spray fluxer and hot air vacuum desoldering tool sequentially for the execution of the pad cleaning. While inspection to verify site cleaning result is executed, robot detaches cleaning tool and attaches related dispensing tool(s). Next, either solder paste or no flow underfill application is performed followed by the inspection of the dispensing result. Subsequently, robot attaches vacuum suction tool and place the new component. Afterwards poisoning table locates the newly placed component between the hot air bottom heater and diode laser heat source to execute resoldering process. Finally, after simultaneous reflow soldering and underfill cure take place last inspection process is carried out to verify rework success.

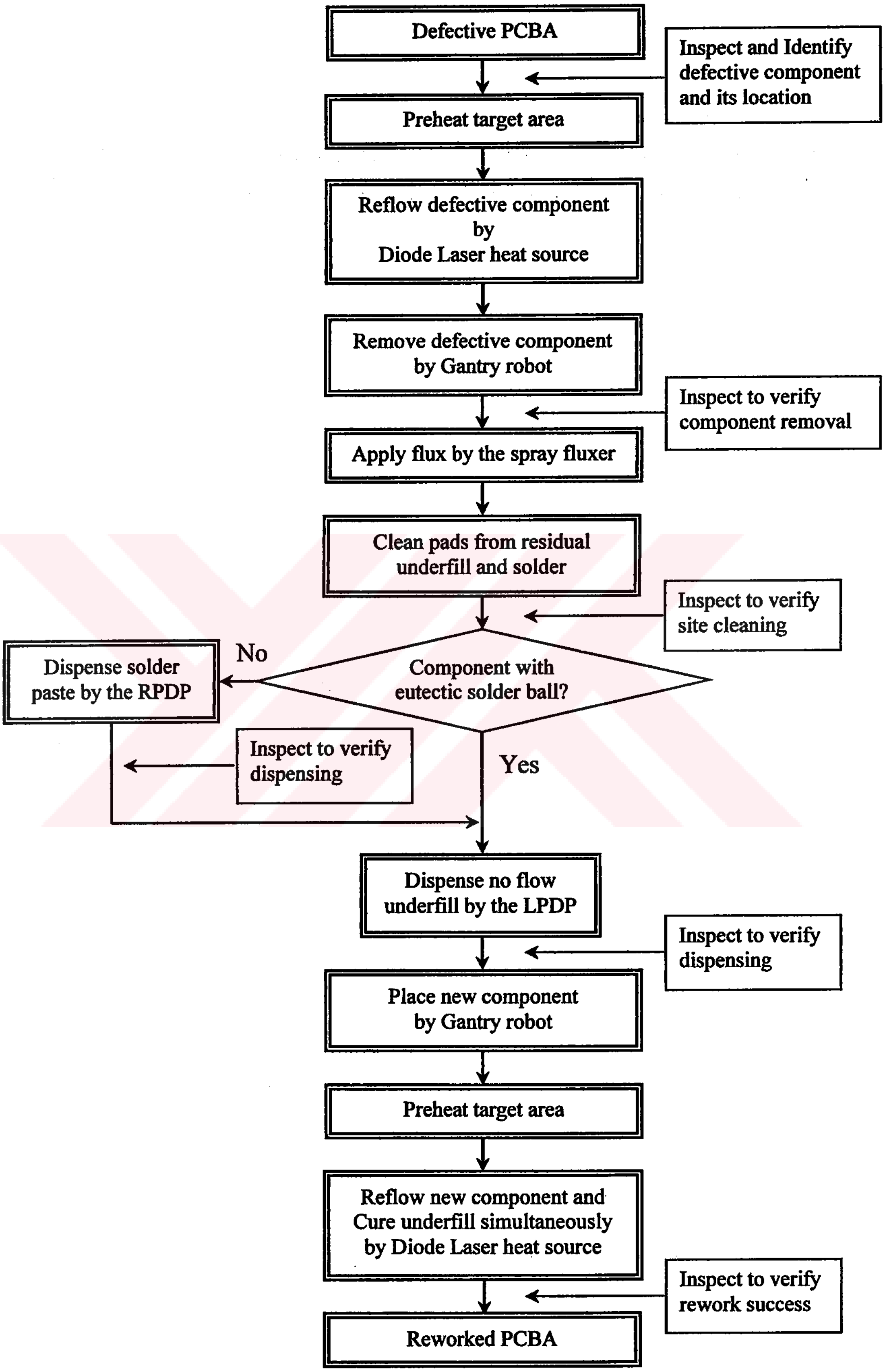


Figure 4.18. Diode Laser Based Automated Rework Procedure of Advanced SMCs

4.9. Economic Justification of the Robotic Rework Cell System

For the development of advanced SMCs robotic rework cell system based on the batch size of one, selection of the suitable rework tooling and equipments have been done as far as possible. However, for some part of the rework tooling such as X-Y positioning table, hot air bottom heater, vision and inspection system, only related tooling considerations for the accurate selection have been pointed out according to rework requirements of the advanced SMCs. This is because of the following reasons;

- The selection of the X-Y positioning table and hot air bottom heater needs further decision making on the technical capability of the rework cell system with respect to PCBA size. Their dimensional properties directly proportional to the size range of the PCBAs to be reworked. However, determination of the specific range of PCBA sizes is not the scope of this study.
- The selection of the vision and inspection system can be possible if complete installation of the rework cell system is done.

Accordingly, individual costs of possibly selected rework tooling and equipments for the advanced SMCs robotic rework cell system are presented in Table 4.13.

As can be seen from the table, total cost of selected rework tooling is around € 79.750. However, the costs of the manipulating devices, robotic tooling, bottom heater, sensory devices should be added to the total cost. Additionally, costs of the development, some of the tooling (i.e. grippers) manufacturing, integration, and interfacing of each piece of tools/equipments are also considered.

At the beginning, resultant cost of the total robotic rework cell system development can be perceived as high. However, it is thought that cost-effectiveness of the development of the robotic rework cell system can be obviously perceived when a cost comparison between the manual or semi-automated rework and the robotic rework is done based on the overall rework cost per advanced SMC. Because of the use of automation and strict process control, the automated rework cell will provide advantages of lower rework cost and consistently high level of effectiveness, quality and reliability.

Table 4.13. Total Cost of the Complete DioScan 120 Diode Laser System

Rework Tooling	**Cost**
DioScan 120 Diode Laser System • Diode Laser Head with Adapter for Beam Scanner • Scanner Unit for Direct Diode Laser • Integrated PC for Scan Head Control • Combined Supply Unit • Off-axis CCD Camera • Off-axis One Color Pyrometer • Kombi F-Theta Optics 220 and 434 (*including installation and training costs*)	€ 70.950
DV-7222-SL1 Rotary Positive Displacement Pump	€ 2.000
TS5520 Spray Valve	€ 700
DP-3140 Linear Positive Displacement Pump	€ 2.000
High Capacity Site Cleaning Tool (SSRS)	€ 4.100
Total Cost (approximately)	€ 79.750

In addition to these, if the robotic cell system is designed as an extension of a robotic PCBA cell, costs of the manipulating devices, robot tooling, and sensory control devices can be eliminated since these tooling have already been in the PCBA cell system. With this alternative, the capital investment will turn out to be more justifiable.

As a final conclusion, since the costs of existing commercial semi-automated rework systems can be as high as € 150.000~160.000, the resultant cost of development of the advanced SMCs robotic rework cell can be economically justifiable.

5. CONCLUSION

Because of inevitable increase in complexity of the PCBAs, continuing improvements in current state of art process technology, sophisticated control systems and equipments remain elusive to achieve 100 percent manufacturing yields. Hence, rework and repair of complex, high value PCBAs is inevitably essential process during their service life. Furthermore, due to the more complicated natural structure of advanced SMCs coupled with the novel technological requirements there is a significantly growing need for a fully automated robotic rework system that can carry out the whole advanced SMCs rework process based on the batch size of one.

In this study, alternative proposals for automating rework of advanced SMCs have been scrutinized in details to reach optimum solutions for a fully automated robotic rework cell system development. To do this effectively, besides the exponential studies on existing manual advanced SMCs rework procedures, methods, tools, and problems, also currently available reflow technologies and technology on automation including industrial robots, sensory devices, inspection systems etc. have been scrutinized in details. Finally, the possible alternatives have been determined and then compared between each others to investigate their adaptability to the automated rework system to reach optimum alternative solutions for the fully automated robotic rework system for advanced type SMCs.

It was found out that even though various rework methods and techniques could be applied to the automated advanced SMCs rework, diode laser method has been selected and proposed as a suitable desoldering/resoldering method because of its technical and economical superiority.

Comprehensive market survey results revealed that besides the reflow tooling, there are also commercially available other rework tooling and equipments suitable for automating advanced SMCs rework.

Related tooling considerations for selection have been specified and possibly selections of the suitable rework tooling and equipments for the automated robotic rework of advanced SMCs have been done.

Since hardware structure of the robotic rework cell system has been basically found out, appropriate automated rework procedure for the advanced SMCs has been developed as well.

It is finally concluded that:

- It was revealed that the development of a fully automated robotic rework cell system for the advanced SMCs is technically possible and if properly designed and automated it may meet the essential rework requirements of advanced SMCs and be economically justifiable.
- The cost of the selected rework tooling and equipments is approximately € 79.750. However, the costs of the manipulating devices, hot air bottom heater, and sensory equipments together with the costs of the development and some of the tooling manufacturing and automation are also considered.
- It is believed that achieving lower rework costs coupled with the consistent effectiveness, quality and reliability at high levels will be possible by means of the use of automated advanced SMCs rework cell system.
- If the advanced SMCs robotic rework cell system is designed to be part of a robotic PCBA cell, economic justification of a rework cell will be made much easier since additional costs of the manipulating devices, robot tooling, and sensory control devices can be eliminated.
- In fact, development of such an automated robotic assembly-rework station can be viable option for companies who use robots for assembling advanced technology PCBAs. Because the developed and well designed such a rework cell system being a part of robotic PCBA cell can be economically deployed for the assembly, inspection and rework of defective SMCs ranging from standard to advanced type.

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