

SOLDERING

UNDERSTANDING
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BASICS



SOLDERING

UNDERSTANDING THE BASICS

Edited
by
Mel Schwartz



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Preface

THE SELECTION OF SOLDERS for specific applications is not the haphazard affair it once was. Today (2013), demanding service environments and rigorous specifications require that the precise details of a soldering process be worked out in advance rather than left to the end. The design of a soldering process has thus become part and parcel of the product design process itself.

Other trends have had tremendous effects as well. Notably, in recent years, environmental concerns have led to a widespread increase in the use of lead-free solders and much innovation in the soldering processes by which they are applied. Moreover, a drive toward miniaturization has led to sweeping changes in soldering forms and processes for electronics assembly.

There is therefore a need for a general introduction to soldering that incorporates up-to-date information on this rapidly changing field—an introduction that assumes some basic knowledge of joining processes but does not demand that the reader wade through pages of mathematical formulae.

The aim and purpose of this book is to supply practical information to the user—materials technologist, metallurgist, electronics technician and engineer, manufacturing designer and planning engineer, soldering and joining specialist, purchasing agent, tooling specialist, or quality-assurance personnel—who wishes to become familiar with the current state of the art. Its secondary purpose is to introduce interested readers to the vast and ever-growing world of online literature on soldering; for this purpose, wherever feasible, I have included the URLs of websites and pages that I believe the reader will find especially helpful. Most of these are selected from professional publications that would-be specialists would do well to follow in general, especially because no single book in this field can hope to remain completely current for very long.

The subjects to be covered include the various soldering methods and techniques as well as the latest information on solder alloys, solder films,

surface preparation, fluxes and cleaning methods, heating methods, inspection techniques, and quality control and reliability.

Again, for most of the chapters the information is geared toward soldering practice and limited with respect to the theory. The hope here is that the book will thereby be rendered useful to scientists, materials engineers, designers, manufacturing engineers, technologists, metallurgists, and so on who need immediate practical guidance rather than theoretical instruction.

Thus, this book is intended for the student, engineer, or joining specialist who wishes to learn more about all aspects of the art/science of solders and soldering as it is practiced today. Generally, anyone with some experience with soldering should be able to use the information contained herein.

Mel Schwartz
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CHAPTER 1

Soldering—Definition and Differences

SOLDER IS A FUSIBLE METAL ALLOY with a melting point (or range) of 90 to 450 °C (190 to 840 °F), used in a process called soldering, in which it is melted to join metallic surfaces (which of course must themselves have higher melting temperatures so that they remain solid when the solder is melted). It is especially useful in electronics and plumbing. Alloys that melt between 180 and 190 °C (360 and 370 °F) are the most commonly used. If alloys with melting points above 450 °C (840 °F) are used, the process is no longer called soldering but brazing. Solder can contain lead and/or flux, but in many applications, solder is now lead-free.

The word *solder* comes from the middle-English word *soudur*, via Old French *solduree* and *soulder*, from the Latin *solidare*, meaning “to make solid.”

1.1 Soldering and History

Soldering is a joining process that uses a filler metal to join parent materials that remain solid. By convention, as noted previously, soldering uses filler alloys with melting temperatures below 450 °C (840 °F). Soldering may or may not use a fluxing agent. (Fluxing agents, also called fluxes, are used to help in cleaning the interface but may leave a residue.) Because processing temperatures are lower than for brazing, soldering has been the standard assembly procedure for electronic equipment. Local heating of the joint can be done with a torch, a soldering iron (local resistance heating), induction heating, a laser, or a hot air gun. Assemblies can also be heated in an oven. There are also diffusion bonding techniques that rely on a combination of temperature and pressure (Ref 1.1).

The bond between solder and base metal is more than adhesion or mechanical attachment, although these do contribute to bond strength. Rather, the essential feature of a soldered joint is that a metallurgical bond is produced at the filler-metal/base-metal interface. The solder reacts with a small amount of the base metal and wets the metal by forming intermetallic compounds. Upon solidification, the joint is held together by the same attraction between adjacent atoms that holds a piece of solid metal together. The ease of wetting (discussed later) is related to the ease with which this solvent action occurs. The presence of the base-metal/filler-metal reaction is one factor in the wetting action of the solder. Other factors include surface cleanliness and solder surface tension (that is, capillary flow).

Soldering is an ancient joining method. It is mentioned in the Bible (Isaiah 41:7), and there is evidence of its use in Mesopotamia 5000 years ago, well before the time of Cleopatra, as well as later in Egypt, Greece, and Rome (Ref 1.2). Pliny the Elder, in his *Historia Naturalis*, written 2000 years ago, mentions (in Chapter XLVIII of Book XXXIV) that the solder connections of the pipes of the Roman aqueducts were made with a mixture called *tertarium*, an alloy of two parts lead and one part tin. The earliest solders were alloys found in nature, which meant that only a few solders, with a severely limited range of properties, were available. Because these early solders were generally used to join jewelry parts or to attach handles to decorative vessels, the primary concerns were appearance, melting point, and, to a lesser degree, strength. The materials were rare and costly, and the work was done by highly skilled artisans. Therefore, only the wealthy could hope to own articles made in this way.

It has been only in the last two centuries that some metals have become cheap and that strictly utilitarian parts are soldered. In the 1800s, low-cost steels made household tinware (which is made not of tin but of tin-plated steel, or tinplate) practical for most families, and the “tinner” became the common solder practitioner. The emergence of electrical technology required the attachment of electrical leads, which became the most common application of solders. This meant that the electrical properties of solders became a consideration; the electrical continuity of the joint was of paramount importance, where jewelry and utensils had emphasized strength and appearance. The use of solders for electrical attachments also involved simple mechanical joints and repetitive operations. The cost of the materials was much reduced, because lead-tin solders were usually used. Even today (2013), it is customary to give the tin content first when designating a solder (for example, 40/60 solder refers to a solder that is 40% Sn and 60% Pb). These new criteria promoted a new type of artisan whose skills were more oriented to engineering and production than to aesthetics, although most of the work was still done manually.

By the 20th century, metallurgical science had developed to the point that new solders could be tailored specifically for electrical, plumbing, or

structural applications. The emerging electronics industry required solders with the following properties:

- Compatibility with copper (especially with respect to alloying behavior and melting temperatures)
- Good electrical conductivity
- Workability to enable factory workers to rapidly form low-cost, reliable soldered joints

Engineers now have formal rules to govern the design of joints used in various applications to ensure the required levels of strength. The materials and processes involved in soldering have now become established in engineering practice (Ref 1.3–1.7).

1.2 Fundamentals—Alloy Formation and Phase Diagrams

Every pure metal has a crystalline state and a well-defined melting temperature. Metals also possess reasonable ductility and strength. Metals are excellent electrical conductors compared to ceramics or plastic polymer materials. Thermal conductivity generally follows electrical conductivity (that is, a good electrical conductor is usually also a good thermal conductor).

The best means for portraying the behavior of alloys is the equilibrium phase diagram (also called equilibrium diagram or constitution diagram), which represents the phases present under equilibrium conditions in a given alloy system. Phase diagrams are plots of alloy equilibrium composition versus temperature. The diagrams are generally worked out by measuring the melting and solidification behaviors of alloys of different compositions and then observing the resultant microstructures. Understanding phase diagrams is essential to working effectively with solders, because they are used to predict solder microstructure and behavior.

When two or more metals are melted together, they form an alloy that behaves as a unique material with specific properties that can significantly differ from the properties of the individual pure metals. Alloy properties depend on the atomic structure and thermal-physical properties of its constituent elements. For example, the addition of tin to lead will result in an alloy that has a lower melting point than either tin or lead—perhaps more surprisingly, so will the addition of lead to tin. The physical and mechanical properties of the alloys will also differ from the properties of the pure metals.

Some combinations of metals, such as gold and silver, form alloys simply because they are mutually soluble; that is, each can be dissolved in the other. An alloy formed in such a way is called a solid solution.

Two metals that have greater differences in their basic properties may have limited solubility in one another and may not dissolve completely. One such combination is silver and copper. Combining these two forms a eutectic alloy, which, by definition, is an alloy with a melting temperature significantly lower than either of its component metals alone. In addition, the eutectic alloy composition itself exhibits a unique type of melting and solidification behavior: melting and solidifying at a single, specific temperature just as a pure metal does. The solid eutectic alloy is a mixture comprising two phases, rather than a solid solution. Eutectic alloy structures and behavior are of critical importance in soldering.

The concepts behind the use of soldering are as follows:

- Solder is used to hold two (or more) conductors in electrical contact with each other.
- Solder is not used to make the electrical contact.
- Solder is not used to provide the main mechanical support for a joint.
- Solder is used to encapsulate a joint, prevent oxidation of the joint, and provide minor mechanical support for a connection.

1.3 Process Description and Wetting

In the soldering process, heat is applied to the parts to be joined, causing the solder to melt and to bond to the workpieces in an alloying process called wetting. In the soldering of stranded wire, the solder is drawn up into the wire by capillary action in a process called wicking. Capillary action also takes place when the workpieces are touching or very close together. The joint strength is dependent on the filler metal used. A soldered joint has electrical conductivity and is water- and gastight (Ref 1.8).

Solder wetting necessarily involves the metallurgical reactions between the filler metal and the base metal. This interaction at the solder/base-metal interface can result in a covalently bonded layer of a material called an intermetallic compound. Examples include tin and gold (AuSn_4), copper and tin (Cu_6Sn_5 and Cu_3Sn), or nickel and tin (Ni_3Sn_4). Unlike the metallic bond of metals and alloys, the covalent bond causes the intermetallic to be hard and brittle, to have a high melting point, and to be resistant to chemical attack. Excessively hard intermetallic layers can jeopardize the physical and mechanical integrity of soldered joints.

1.4 Intermetallics in Solders

Many different intermetallic compounds are formed during solidifying of solders and during their reactions with the solder surfaces (Ref 1.9).

The intermetallics form distinct phases, usually as inclusions in a ductile solid-solution matrix, but they can also form the matrix itself and contain metal inclusions or form crystalline matter with different intermetal-

lics. Finely distributed intermetallics in a ductile matrix yield a hard alloy; coarse structure gives a softer alloy. A range of intermetallics often forms between the metal and the solder, with a higher proportion of metal on one side and of solder on the other, for example, forming a structure of $\text{Cu-Cu}_3\text{Sn-Cu}_6\text{Sn}_5\text{-Sn}$ (Table 1.1).

Layers of intermetallics can thus form between the solder and the parent material. These layers may cause any of several problems. They may cause mechanical unreliability in the form of weakening and brittleness; they may increase the electrical resistance of the joint; or they may be susceptible to electromigration and the formation of voids. The gold-tin intermetallic layer, for example, is responsible for the poor mechanical reliability of tin-soldered gold-plated surfaces when the gold plating does not completely dissolve in the solder.

Gold and palladium readily dissolve in solders. Copper and nickel tend to form intermetallic layers during normal soldering profiles. Indium forms intermetallics as well.

Indium-gold intermetallics are brittle and occupy approximately four times more volume than the original gold. Bonding wires are especially susceptible to indium attack. Such intermetallic growth, together with thermal cycling, can lead to failure of the bonding wires (Ref 1.11).

Copper plated with nickel and gold is often used. The thin gold layer facilitates good solderability of nickel because it protects the nickel from oxidation; the layer must be thin enough to dissolve rapidly and completely so that bare nickel is exposed to the solder (Ref 1.12).

Lead-tin solder layers on copper leads can form copper-tin intermetallic layers; the solder alloy is then locally depleted of tin and forms a lead-rich layer. The tin-copper intermetallics then can become exposed to oxidation, resulting in impaired solderability (Ref 1.13).

Two processes play roles in a soldered joint formation: interaction between substrate and molten solder, and solid-state growth of intermetallic compounds. The base metal dissolves in the molten solder in a quantity that depends on its solubility in the solder. The active constituent of the

Table 1.1 Intermetallics in solders

	Tin	Lead	Indium
Copper	Cu_4Sn , Cu_6Sn_5 (a), Cu_3Sn (b), Cu_3Sn_8	...	Cu_3In , Cu_9In_4
Nickel	Ni_3Sn , Ni_3Sn_2 , Ni_3Sn_4 (c), NiSn_3	...	Ni_3In , NiIn , Ni_2In_3 , Ni_3In_7
Iron	FeSn , FeSn_2 (d)	...	...
Indium	In_3Sn , InSn_4	In_3Pb	...
Antimony	SbSn	...	...
Bismuth	...	BiPb_3	...
Silver	Ag_6Sn , Ag_3Sn	...	Ag_3In , AgIn_2
Gold	Au_5Sn , AuSn , AuSn_2 , AuSn_4 (e)	Au_2Pb , AuPb_2	AuIn , AuIn_2 (f)
Palladium	Pd_3Sn , Pd_2Sn , Pd_3Sn_2 , PdSn , PdSn_2 , PdSn_4	...	Pd_3In , Pd_2In , PdIn , Pd_2In_3
Platinum	Pt_3Sn , Pt_2Sn , PtSn , Pt_2Sn_3 , PtSn_2 , PtSn_4	Pt_3Pb , PtPb , PtPb_4	Pt_2In_3 , PtIn_2 , Pt_3In_7

(a) Common on solder-copper interface; forms preferentially when excess of tin is available; in presence of nickel, $(\text{Cu,Ni})_6\text{Sn}_5$ compound can be formed. (b) Common on solder-copper interface; forms preferentially when excess of copper is available; more thermally stable than Cu_6Sn_5 ; often present when higher-temperature soldering occurs. (c) Common on solder-nickel interface. (d) Very slow formation. (e) Phase brittle; forms in excess of tin; detrimental to properties of tin-base solders to gold-plated layers. (f) Forms on the boundary between gold and indium-lead solder; acts as a barrier against further dissolution of gold. Source: Ref 1.10

solder reacts with the base metal at a rate that depends on the solubility of the active constituents in the base metal. The solid-state reactions are more complex; the formation of intermetallics can be inhibited by changing the composition of the base metal or the solder alloy, or by using a suitable barrier layer to inhibit diffusion of the metals (Ref 1.14).

All electrical/electronic applications require soldering to a base metal. This base metal can be the metal that makes up the physical structure of the electrical/electronic lead, or it can constitute an underplate or a barrier metallization. In all cases, the metal must be metallurgically wettable by the solder.

Intermetallic compounds are more like chemical compounds than like metallic alloys. In soldering, intermetallic compounds in thin and uniform layers represent the “glue” that forms the structural bonds between the solder and the metal being soldered. Therefore, the base metal must be metallurgically compatible with at least one of the metallic components in the solder.

This intermetallic compound formation can occur by a solid/liquid reaction (molten solder against a solid base metal) or a solid-state diffusion reaction (solder plate against a solid base metal). In either case, the solder and base metal react to form a film of intermetallic compound between the two metals, which holds them together. For example, when tin-lead solders are used with copper, a widely used base metal, the tin reacts with the copper. Two intermetallics discussed previously can form in this metallurgical system. The compound Cu_6Sn_5 will primarily form during liquid/solid reactions. In addition, Cu_6Sn_5 continues to grow in the solid state at elevated temperatures. The compound Cu_6Sn_5 will be present during any solid-state reactions.

Every base-metal solder system forms at least one such compound. For example, soldering to nickel instead of copper will result in tin-nickel intermetallics (Ni_3Sn_4) at the interface. The Ni_3Sn_4 layer grows very slowly in the solid state and is typically difficult to observe.

The ability of base metal to form a stable intermetallic compound layer with a solder limits the number of base-metal/solder combinations that are suitable for the majority of applications. The formation kinetics of intermetallic layers must permit the thorough wetting of the solder for efficient processing. Therefore, some metals are more readily soldered than others.

1.5 Passivation

The passivation characteristic of the base metal is another factor to be taken into account. In passivation, a material forms an outer corrosion layer that shields it against its environment and causes it to become more chemically passive. Such a layer forms a physical barrier against metallurgical wetting. Before the base metal can be metallurgically wetted by

the solder, the solder must make intimate contact, on an atomic scale, with clean base metal. Passivation layers are normally oxide films that may be only a few atomic layers thick. Even so, they affect the ability of the solder to contact the base metals underneath them. Many metals will passivate extremely rapidly. Even when very active fluxes are used, stainless steel becomes unwettable after only a short exposure to atmosphere at room temperature.

Another issue is the chemical and mechanical stability of a passivation layer. Because the passivation layer that forms on solder is chemically weak, it can be reduced by weak fluxes. Nickel, on the other hand, forms a passivation film that is strong both chemically and mechanically. It is adherent to the base metal and requires much stronger fluxes to remove chemically.

1.6 Solderability

Solderability, or the ease with which a material can be joined by a given soldering method, is a property of electronic and other components that is crucial both to the efficiency of manufacture and to the reliability of the product (Ref 1.15). Good component solderability is important for three basic reasons:

- It allows the use of less active fluxes, thereby reducing the requirement for cleaning flux residues. (This is an environmental benefit. In addition, the removal of flux residue eliminates potential corrosion problems caused by that residue.)
- It produces greater first-pass soldering yields and consequently requires less hand working of the soldered joints (important because reworking can reduce the fatigue performance of a joint, compared with a successful first-pass joint).
- It results in a greater uniformity of solder fillet, with a geometry that is close to the ideal for maximum fatigue performance.

Solderability depends on the wettability of the two surfaces being joined. Poor component solderability can, to some extent, be overcome by using more active fluxes, but the trend toward denser component packing makes it difficult to remove flux residue after assembly; therefore, less active fluxes are preferable. Environmental concerns (such as those about the use of chlorofluorinated carbon solvents) are also reasons to avoid fluxes. The cost of inspection, testing, and component replacement or solder fillet rework increases the desirability of defect-free soldering. Therefore, solderability is an increasingly important manufacturing issue.

The solderability of a component is a complex processing parameter. The relationship between wettability and solderability represents a major unresolved gap in the understanding of the soldering process. Wettability

can be measured directly. Solderability, however, cannot be directly measured in a quantifiable way, and its relationship to wettability has not yet been explicitly defined.

There are three important aspects to solderability:

- Thermal demand
- Wettability
- Resistance to soldering heat

The thermal characteristics of the component must allow the joint to be heated to the soldering temperature within the specified time. To be solderable, surfaces must allow the molten solder to wet and spread during the available time without subsequent dewetting (a phenomenon discussed later). The soldering heat and the induced thermal stresses associated with it must not affect the functioning of the components. Each of these aspects of solderability can be engineered to fit a particular application by the suitable choice of solder alloys and process control parameters. With regard to design for performance, the aspect that imposes the strictest restraints is component wettability.

When discussing the wetting characteristics of a surface by molten solder, there are two important factors to consider: the extent of wetting and the rate of wetting (Ref 1.15). The extent of wetting (as indicated by the contact angle) is an equilibrium governed by the laws of thermodynamics and depends on the surface and interfacial energies involved at the liquid/solid interface (Fig. 1.1) (Ref 1.16). The rate of wetting (that is, how rapidly the solder wets and spreads) is governed by the thermal demand of the system, the ability of the heat source to supply heat, the efficacy of the flux, the viscosity of the solder, and the chemical reactions that occur at the interfaces.

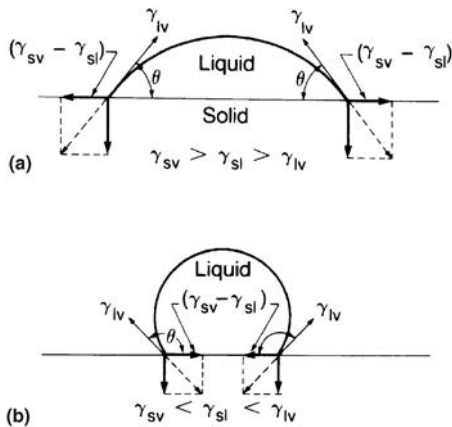


Fig. 1.1 Liquid solder droplets on a solid surface under two conditions. (a) Wetting. (b) Nonwetting. Arrows indicate surface tension. Source: Ref 1.16

The physics of wetting is governed by Young's equation (also known as Young-Depre equation, because Young described the problem quantitatively in 1805 and Depre put it in mathematical terms in 1869). A detailed discussion of the aforementioned equations and wetting can be found in Ref 1.16.

A typical example of nonwetting occurs when a liquid metal droplet is placed on a nonmetallic surface, such as copper oxide. Because there are no metallic bonds at the oxide surface, the liquid metal will have little tendency to interact with that surface. The metal droplet will behave as though it is repelled and will try to ball up to minimize the area of contact with the nonmetallic surface. One method for quantifying wettability is to observe the behavior of solder droplets on the metal surface. The contact angle formed between the surface of the liquid solder and the surface of the solid can be measured (Fig. 1.1). If the solder droplet forms a contact angle of less than 90° , then the solder is said to wet the metal. If the angle is greater than 90° , the solder is nonwetting. This is one method used to qualitatively assess solderability.

The formation of intermetallic compounds can affect Young's equation because it alters the value of the solid-liquid phase. The influence of this term has been recognized (Ref 1.15), but the magnitude of its influence has not yet been calculated quantitatively.

The surfaces of a metal crystal have a higher free energy than the bulk of the crystal, because of the existence of unsatisfied metallic bonds. When a liquid metal or alloy is brought into contact with this solid surface, the liquid will proceed to interact with the solid to satisfy those dangling surface bonds and thus reduce the surface free energy of the system. To the extent that a liquid solder can satisfy the surface bonds, it will wet the solid metal and spread across its surface. If no exchange of bonding energy takes place, then wetting will not occur and the solder will tend to ball up on the surface of the solid, minimizing the area of contact between liquid and solid.

1.7 Joint Design and Guidelines

Soldered joints provide both electrical connection and structural support in the microelectromechanical systems and electronics industry. Solders can join dissimilar materials of varied thickness. Proper joint design can bring the strength of the joint near that of the parent material. Typically, the processing temperature is slightly above the melting temperature (T_m) of the solder, and the surface temperature usually must be below T_m .

Because soldering has a 5000 year history, the process has subtleties that are often not appreciated. To optimize results, the choice of alloy, the form of alloy (wire, rings, foil, paste), surface preparation (cleaning and coating), flux (if any), jigging, heat source, joining atmosphere, heating cycle, and posttreatment each play a significant role. Solder alloys are also used to form fusible balls for ball grid array process connections.

Joints should be designed to fulfill the requirements of the finished assembly as well as to permit the application of the flux and solder. Joint design should maintain proper clearance during heating and upon solidification of the filler metal. Sometimes the units can be crimped, clinched, wrapped, or otherwise held together, but in some cases, special fixtures may be needed.

The selection of a joint designed for a specific application will primarily depend on the service requirements of the assembly. It may also depend on such factors as the heating method to be used, the fabrication techniques used prior to soldering, the number of items to be soldered, and the method used to apply the solder. In general, solders have low strength when compared with the metals they are used to join. Therefore, the soldered joint should be designed to avoid dependence on solder strength. The necessary strains can be provided by shaping the parts to be joined so that they engage or interlock, requiring the solder only to bond, seal, and stiffen the assembly.

Figure 1.2 shows joint designs commonly used for soldering applications. The lap joint and the lock seam joint are used when soldering sheets. Lap joints are also used to join pipes. The lap joint should be used whenever possible because it offers the best chance to obtain joints with maximum strength; it should also be used whenever a seal is required. Butt joints should be avoided whenever possible.

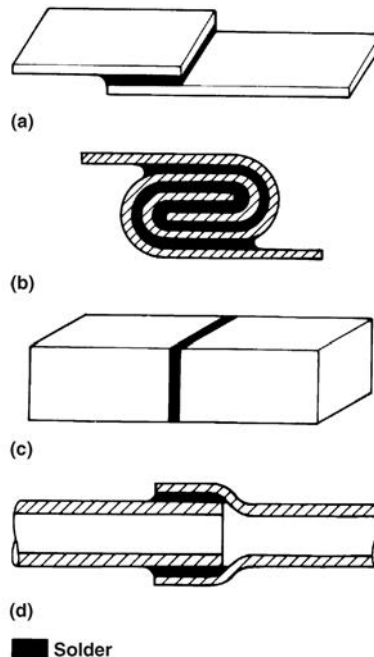


Fig. 1.2 Basic joint configurations used for soldering applications. (a) Lap joint. (b) Lock seam joint. (c) Butt joint. (d) Pipe joint. Source: Ref 1.16

An important factor in joint design is the manner in which the solder will be applied to the joint. The designer must consider the number of joints per assembly and the number of assemblies to be manufactured. For limited production using a manual soldering process, the solder can be face-fed into the joint with few problems. However, for a large production lot of assemblies containing multiple joints, an automated process such as condensation/vapor-phase reflow soldering can be advantageous (Ref 1.17–1.19). In this case, the design must provide for accessible joints that are suitable for automated fluxing, soldering, and cleaning.

There should be enough clearance between the parts being joined to allow the solder to be drawn into the space by capillary action, but not so much that the solder is unable to fill the gap. Joint clearances ranging from 0.075 to 0.150 mm (0.0030 to 0.0059 in.) are preferred for optimum strength, but variations are permissible in specific cases. It is often necessary to fabricate sample parts and to test the joints to ensure their producibility and their strength properties (Ref 1.3, 1.4, 1.20–1.22).

Other commonly used soldered joints are shown in Fig. 1.3, and self-jigging joints are shown in Fig. 1.4. Conservative joint design requires that only 50% of the joint be considered filled. However, under normal conditions, it is good soldering practice to have 70% or more of the joint consist of sound joint material (Ref 1.3–1.6, 1.21, 1.23, 1.24).

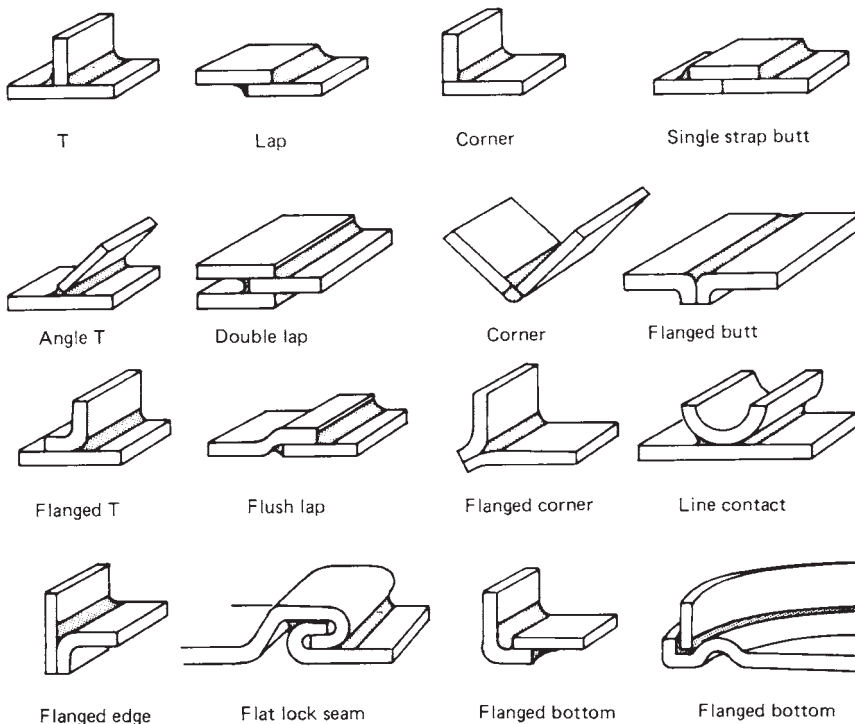


Fig. 1.3 Joint designs frequently used in soldering operations. Source: Ref 1.6

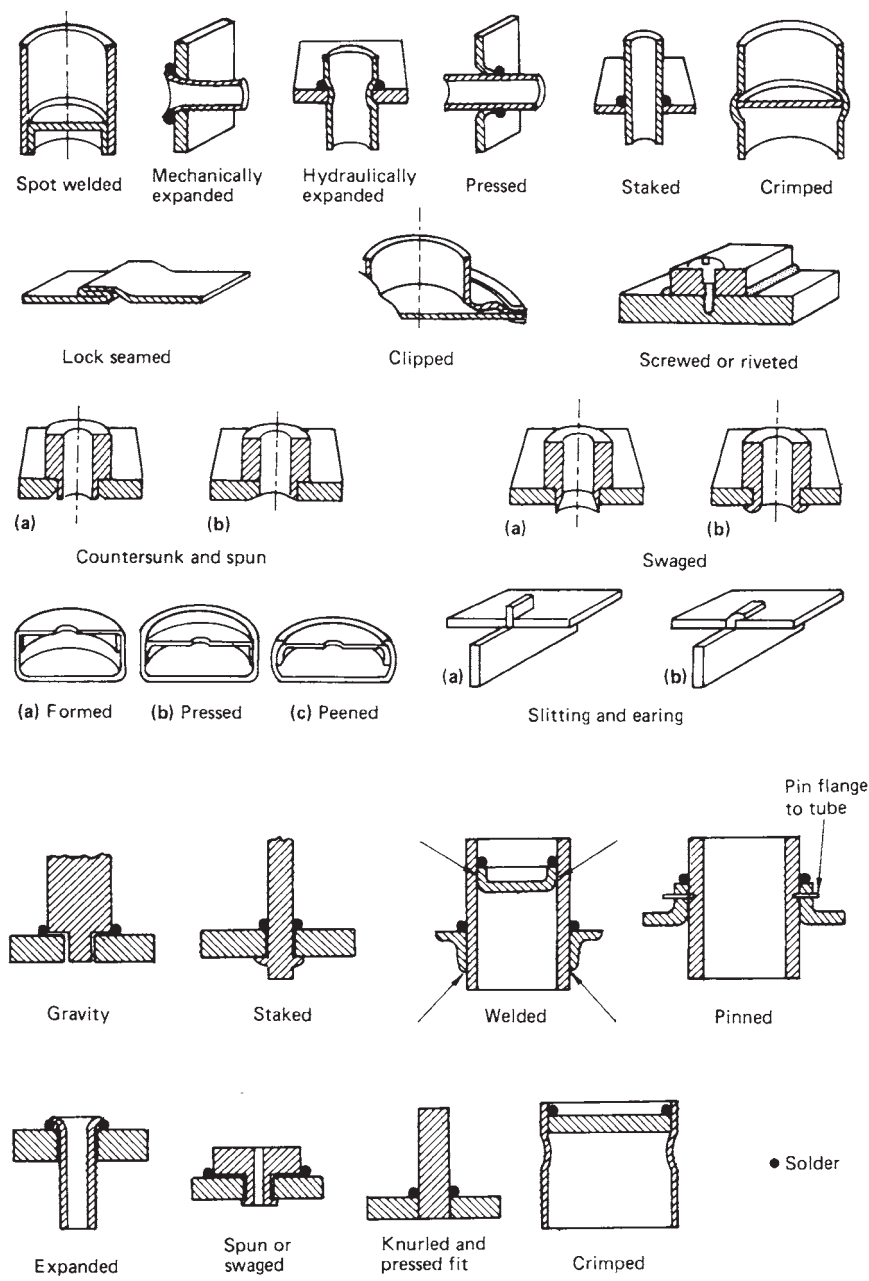


Fig. 1.4 Methods that can be used to make solder joints self-jigging. Source: Ref 1.6

1.8 Soldering Process Parameters

The parameters that affect wetting and spreading phenomena include the following:

- Temperature
- Time
- Vapor pressure
- Metallurgical and chemical nature of the surfaces
- Geometry of the solid

The manipulation of each parameter can provide some control of the wetting and soldering processes.

Temperature is important to wetting and spreading for several reasons. Higher temperatures result in greater atomic activity and provide some of the energy needed to overcome surface barriers. Higher temperatures also increase reaction rates exponentially. Temperature determines phase relationships for a given alloy composition, whether for the formation of a solid solution or for that of an intermetallic compound. The fluidity of the liquid solder is also increased with increasing temperature. In addition, higher temperatures promote the formation of oxides, which can be troublesome when soldering.

Time. Wetting is time-dependent because of the rate of kinetics of the solder-substrate interaction, the flux action, and the heat conduction of the substrate. The soldering process is time-sensitive, because time is needed to provide sufficient opportunity for the solder to wet, penetrate, or wick up into the various areas of the substrate that must be incorporated into the soldered joint. It is clear that measures of the time to initiate wetting and of the time it takes for spreading to occur are needed.

Vapor pressure is considered to be negligible for lead-tin solders, but it can be a significant factor when working with certain solders. Caution must be exercised when selecting and working with alloys that have appreciable vapor pressures.

The metallurgical and chemical nature of the surfaces affects wetting and spreading in several ways. Both the content of the alloy and the fluidity of the liquid affect wetting and thus the rate of spreading. Grain boundaries are wet differently than the bulk of the metal. The formation of solid solutions or intermediate compounds can also have a considerable effect on wetting and spreading.

The presence of oxide skins will prevent wetting and spreading, because the solder generally will not wet oxides. Likewise, films or particles of organic matter will interfere with wetting. Oils and silicones are frequent offenders and usually require different types of cleaning materials for their removal from those used for oxides.

Surface Geometry. Because contact angle is a critical measure of wetting and spreading behavior, surface geometry is an important factor in the control of spreading. Soldering artisans have long used a wire brush not only to clean the surface to be soldered but also to aid the spreading of the solder by providing sharp grooves that act as small capillaries to assist wetting. The ideal is for the spread to be isotropic, that is, the same in all directions.

Another condition of surface interaction that is sometimes encountered in soldering is dewetting, where a metal surface is initially wet by solder, but as the solder cools, its cohesive forces exceed the forces involved in wetting, and the solder balls up on the metal surface. This problem usually results from surface contamination of the metal or from the entrapment of foreign particles in the metal surface, leading to weak wetting or possibly only local wetting.

Base-Metal Selection. A sound soldered joint is achieved by selecting and using the proper materials and processes. Base metals are usually selected to meet the specific property requirements of a component: strength, ductility, electrical conductivity, weight, corrosion resistance, and so forth. When soldering is required, the solderability of the base should also be a factor in the selection. Both flux selection and surface preparation will be affected by the solderability of the base materials to be joined.

The solderability of metals and alloys is not simply a matter of chemical nobility, as may be supposed when regarding the good solderability of the noble metals, which do not readily form oxide or tarnish films. Although both cadmium and tin readily form oxides, they are considered easy to solder. On the other hand, chromium, nickel, and aluminum also form oxide films readily but are difficult to solder. The differences lie in the extremely adherent, protective nature of the oxides formed on chromium, nickel, and aluminum, compared with the oxides that form on tin and cadmium (Table 1.2).

Chromium, nickel, and aluminum are all soldered regularly with good results, but the fluxes used must be very active. In many cases, the use of active fluxes is either restricted or not allowed, so these hard-to-solder metals and alloys always require special consideration in order to be soldered in a reproducible manner. Numerous tests and methods to measure solderability are available. The tendencies of solder to wet or spread on a given material are critical when evaluating candidate soldering systems. When hand soldering on single, large-dimension bodies was the norm, the skilled artisan could adjust parameters while watching the results develop. In most cases, visual determinations of wetting and spreading characteristics provided a sufficient basis for process control. Today (2013), operating parameters must be controlled very carefully, because the soldering of components and/or electronic assemblies can involve many joints that are

Table 1.2 Relative solderability of selected metals and alloys

Easy to solder	Less easy to solder	Difficult to solder	Very difficult to solder	Most difficult to solder	Not solderable
Platinum	Lead	Galvanized iron	Chromium	Aluminum	Beryllium
Gold	Nickel plate	Tin-nickel	Nickel-chromium	Aluminum bronze	Titanium
Copper	Brass	Nickel-iron	Nickel-copper		
Silver	Bronze	Mild steel	Stainless steel		
Cadmium plate	Rhodium				
Tin	Beryllium copper				
Solder plate					

soldered at one time, joints that are hidden, dimensions that are extremely small, or situations where joint-to-joint accommodations cannot be made. As a result, it is necessary to use automatic soldering systems. Moreover, conditions must be uniform over the whole structure being soldered. In this environment, it is essential that the processes be based on measurements of wetting and spreading behavior, so that the controlling parameters can be accurately set.

ACKNOWLEDGMENT

This chapter was adapted from M. Schwartz, “Fundamentals of Soldering,” *Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, p 128–129.

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CHAPTER 2

Solder Filler Materials

SOLDERING OFFERS SEVERAL ADVANTAGES as a joining process. Solders can be processed at relatively low temperatures and provide hermetic sealing and joining of metals, ceramics, and glasses. Preforms can be used to automate the process. The technology is well known in the electronics industry, so processes and tooling can be readily adapted. The process also lends itself well to multistep manufacturing.

However, the process is complicated by the need for surface preparation, the need to prevent surface oxidation, and the possible need for fluxes. The process temperatures, although low in comparison to other joining processes, may still exceed the limits of the materials being joined (Ref 2.1). Moreover, the maximum surface temperature to which the resulting assembly can be subjected is limited by the melting point of the solder.

This chapter discusses the basics of solder selection and the main types of commercially available solder, deferring a discussion of lead-free solders to the next chapter in this book.

2.1 Solder Specification

The main families of solder filler metal, in increasing order of melting range, are based on gallium, bismuth, indium, tin, lead, and gold. Figure 2.1 (Ref 2.2) shows typical compositions and their melting ranges.

Alloys in the Ga-In-Sn family are not used as solders because they are liquid at room temperature; their main applications are as nontoxic replacements for liquid mercury and nonreactive replacements for sodium-potassium alloys. They are marketed under the trade name Galinstan (from *gallium*, *indium*, and *stannum*) by Geratherm Medical AG (Geschwenda, Germany).

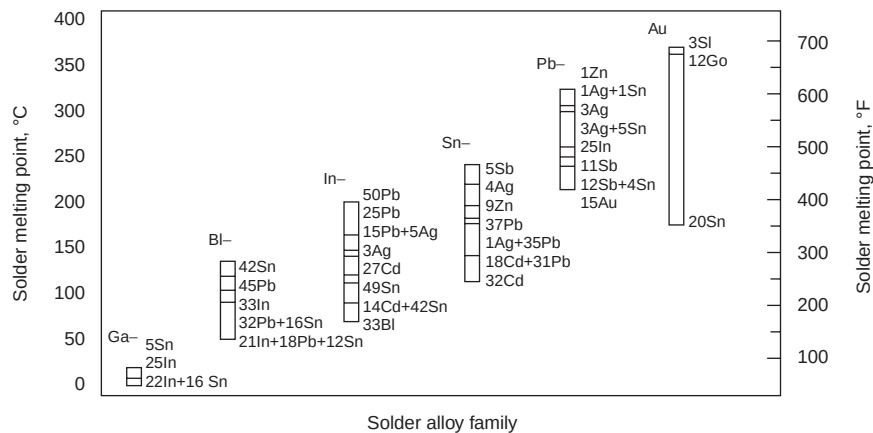


Fig. 2.1 Principal soldering alloy families and their melting ranges. Source: Ref 2.2

It is helpful to use, when feasible, a solder of eutectic composition, which is a composition that solidifies at a lower temperature than any other composition in the same alloy system. (Not all alloy systems have such a composition; gold-silver, for example, does not.) The advantage of such a composition is that it solidifies at a single temperature, called the eutectic temperature, and therefore both wets (during heating) and sets (during cooling) quickly. Moreover, because the eutectic composition has the lowest possible melting point for its alloy system, the heat stresses on the components being joined are kept to a minimum.

In contrast, the components of a noneutectic alloy solidify at different temperatures, so that the solidus (freezing temperature) and liquidus (melting temperature) of the alloy are not the same. When such an alloy solidifies, it passes through a plastic phase in which it is partly solid and partly liquid; any movement during this phase may produce cracks—obviously an undesirable feature in a soldered joint.

Different applications naturally require different formulations. For example, consider a manufacturing process in which soldered joints are produced and are themselves soldered together in further operations. It is obviously desirable to use a solder with a higher melting temperature for the initial joining operation and solders with lower melting temperatures for the subsequent steps; otherwise the initially soldered joints would tend to come unsoldered upon reheating. Silver tends to raise an alloy melting temperature and bismuth tends to lower it, so in such multistep operations it is typical to use a silver-containing solder in the first joining operation and a bismuth-containing solder in the last. Of course, for applications in which a specific property is desirable, for example, high strength or good corrosion resistance, special alloys can be used.

Useful soldering guides are available from professional organizations. Of particular relevance to the soldering of electronic components is the

American National Standards Institute (ANSI) publication J-STD-001 and its revisions, which provide standards for the soldering of electrical and electronic assemblies. (At the time of this writing, the latest revision is J-STD-001E.) The Institute for Interconnecting and Packaging Electronic Circuits (IPC) publishes IPC-HDBK-001, a companion and supplement to J-STD-001 that provides additional explanations and tutorials (Ref 2.3).

The two primary U.S. specifications for solder alloy compositions are ASTM B 32 (Ref 2.4) and Federal Specification QQ-S-571E (Ref 2.5); in the European Community the primary specification is the International Organization for Standardization's (ISO's) ISO/DIS 9453 (Ref 2.6). Not all commercially available solders are listed in these specifications, and in some government and military projects, certain solder compositions are required by contract. The physical and mechanical properties of the main types of bulk solders and solder joints are described in Ref 2.7; however, for information on ISO/DIS 9453, the current version of the standard should be used. (Cost, another important factor in solder selection, is discussed in that source as well, but the price information dates from 1992.)

In 2008, the American Welding Society (AWS) released AWS B2.3/B2.3M: 2008, *Specification for Soldering Procedure and Performance Qualification*, covering the specifications for a wide range of manual, mechanized, and automatic soldering processes. This is the first set of specifications devoted specifically to the requirements of soldering. To date, however, most soldering specifications have been generated within the electronics industry, and there are no separate standards and specifications for structural soldering, a process sufficiently different from electronics assembly to require its own specification (Ref 2.8).

2.2 Lead Solder

In lead solders, lead is ordinarily paired with tin, and the resulting solders, which are offered commercially with tin contents ranging from 5 to 70% by weight, are also known as soft solders. As is clear from the equilibrium phase diagram of the tin-lead system (Ref 2.9), there are no intermetallic compounds or solid solutions in a tin-lead solder; it therefore solidifies into fine, almost pure grains of its two component metals (Ref 2.10). The tensile and shear strengths of these solders increase and their wetting properties improve with increasing tin content. However, tin also costs more than lead, and because a less expensive high-lead alloy can usually be found that has similar workability properties to a high-tin alloy, solders with the highest tin content have only limited application (Ref 2.11).

In electronics assembly, the most common solder has historically been a lead-tin eutectic alloy with a composition consisting of 63% Sn and 37% Pb. In practice, the composition actually used is typically 60/40, which exhibits almost exactly the same behavior: 63/37 melts at 183 °C (361 °F), and 60/40 melts in the range of 183 to 190 °C (361 to 374 °F). It should

be noted that alloys of lead and tin can contain radioactive impurities that may generate “soft errors” when used in computing applications (Ref 2.12, 2.13).

In other applications, notably plumbing, other, noneutectic compositions are used. One such composition in common use is 50/50, which melts in the range of 185 to 215 °C (365 to 419 °F). This ratio solidifies more slowly, with the consequence that it is easier to make a fitted pipe joint watertight by wiping the solder over it.

However, lead solders are being phased out due to environmental and health concerns, in part because of such regulations as the European Restriction of Hazardous Substances Directive. In consequence, lead-free solders are coming into widespread use. These are, of course, less hazardous in applications where they are likely to be rinsed into the groundwater (or to come into contact with children), but they are generally not of eutectic composition, and they have higher melting temperatures than lead-base alloys—typically approximately 250 °C (482 °F). It is therefore harder to produce reliable soldered joints with these alloys. A discussion of these is deferred until Chapter 3, “Lead-Free Solders,” in this book.

2.3 Flux-Core Solder

Fluxes assist in the formation of a soldered joint by promoting proper wetting of the surfaces to be joined. They do this by chemically reducing the metal oxides that form when the metallic surfaces are exposed to air, and protecting them against further reoxidation. In traditional soldering, a bar or coil of pure solder is used, and flux, if needed, is added manually. However, since the middle of the 20th century, some hand soldering has used flux-core solder—coiled wire solder with flux actually embedded in it along its length, released onto the surfaces as the solder itself melts.

Flux-core solders use nonacid fluxes. (Fluxes are discussed in detail in Chapter 4, “Fluxes,” in this book.)

2.4 Hard Solder

A hard solder is one with a relatively high melting point; medium and easy solders have, respectively, midrange and relatively low melting points. Technically, because of their high melting temperatures, hard solders generally qualify as brazes. However, because the brazing of jewelry is generally called soldering, it is discussed briefly here.

In the making of gold and silver jewelry, hard solders are selected to match the assayed quality of the joined metals as closely as possible and therefore generally contain high amounts of the relevant precious metal. (Contrast this with the making of costume jewelry, in which typically only easy solders are used.) For more complex pieces that are assembled in steps, a hard solder can be used in the first step, a medium solder in the

intermediate step(s), and an easy solder in the last. However, individual practice varies: some jewelry makers prefer to avoid easy (and even medium) solder altogether, counting on careful torch control to keep previous joints from coming undone as they solder new ones. (Easy solders should not be confused with soft solders, the latter being an alternative name for tin-lead solders. Because of their lead content, soft solders are not used in jewelry making.)

The torches used with hard solders are usually of the oxy/propane or oxy/acetylene type. Hard solders are sold in 0.25 oz sheets, and they require the use of flux.

Much useful information on gold solders can be found in Ref 2.14. It discusses, for example, a 22 karat solder foil for yellow-gold jewelry alloys, with a composition of 90Au-8Ge-2Si and a melting range of 362 to 382 °C (684 to 720 °F). In jewelry making, one of the most important considerations is color matching; in electronics, joint mechanical integrity (shear strength and peel resistance, for example) and corrosion resistance are more important. Typical binary and ternary gold solders come from the Au-Ge-Si and Au-Ag-Cu systems. Some gold-base eutectic solders are shown in Table 2.1 (Ref 2.15).

Gold-tin, gold-germanium, and gold-silicon alloys with the compositions shown in Table 2.2 (Ref 2.16) are used for attaching integrated circuit chips to packages. They are also used in the construction and hermetic sealing of packages that house delicate sensors and instrumentation. Their high melting temperature also allows them to be used in the step-soldering process with conventional tin-lead and lead-indium solders (Ref 2.16).

The silver solders most commonly used in jewelry making and metal fabrication are cadmium-silver, lead-silver, and tin-silver. The first two are

Table 2.1 Gold-base eutectic solders

Eutectic composition	Actual caratage	Color	Melting point	
			°C	°F
Au-3.2Si	23.2	Light yellow	363	685
Au-12.5Ge	21.0	Pale yellow	361	682
Au-20.0Sn	19.2	White	278	532
Au-24.0In	18.2	Gray	458	856
Au-25.4Sb	17.9	White	360	680

Note: Some of these solders are used for engineering applications and are possible candidates as filler metals for jewelry. Source: Ref 2.15

Table 2.2 Gold solders used for integrated circuit chips

Alloy	Eutectic melting point	
	°C	°F
80Au-20Sn	280	536
80Au-12Ge	356	673
97Au-3Si	363	685

Source: Ref 2.16

toxic and should be used only in a well-ventilated area with an exhaust hood and a breathing mask; they must also not be used on items that will come into contact with food or drink. Tin-silver solder is nontoxic and is often used as an alternative to lead-silver solder or tin-lead solder.

Even higher than hard solders in melting temperature is enameling solder, which has a melting point close to that of the joined material itself and is designed to withstand the enameling process.

Hard solders in other applications are typically based on copper and contain either zinc or tin.

2.5 Glass Solder

Glass solders are used to join glass to glass. They ordinarily achieve proper flowing and wetting in the 450 to 550 °C (840 to 1020 °F) range.

They come in two types: vitreous solders, which keep their amorphous structure when remelted, and devitrifying solders, which do not. Vitreous solders are generally transparent; devitrifying solders are usually translucent or even opaque. Devitrifying solders generally form stronger joints than vitreous solders but are more sensitive to temperature and likely to form imperfect seals (Ref 2.8).

Vitreous solders can be reworked, a useful feature in some applications. Devitrifying solders have a complementary advantage, useful in other applications, in that they form glass-ceramics and are therefore often thermosetting: their melting temperature increases significantly when they first solidify, so subsequent baking does not remelt the joint.

For obvious reasons, glass solders find frequent application in electronics, for example, in the production of cathode ray tubes, for which devitrifying solders based on $\text{PbO-B}_2\text{O}_3\text{-ZnO}$ are commonly used. Other glass solders are used for other purposes. For passivation, for example, zinc-silicoborate glasses may be employed (Ref 2.17). Glass solders are also used in electronic packaging and in sealing vacuum components. For the latter application, a typical glass solder consists of a binary or ternary mixture of thallium, arsenic, and sulfur (Ref 2.18). Conductive glass solders have been developed as well.

Glass solders also have applications outside of electronics. For example, in the joining of materials that have very different coefficients of thermal expansion, glass solders are sometimes used as intermediate layers (Ref 2.19), and glass solders are used to join glass panels in the fabrication of evacuated windows (Ref 2.20).

2.6 Effects of Alloying Elements and Impurities

This chapter closes with a brief and necessarily incomplete list of some of the main effects of some important alloying elements and impurities. It should be borne in mind that an alloying element that is desirable in one application or concentration may count as an impurity in another.

Aluminum. The solubility of aluminum is low, and it forms oxides easily, making solder sluggish and gritty. In the presence of antimony, it contributes to cross through the formation of aluminum-antimony intermetallics.

Antimony. At concentrations of up to 0.3%, antimony can improve wetting, but beyond that concentration, wetting starts to degrade again. It improves strength and prevents tin pest but forms brittle joints when used to solder zinc, cadmium, or galvanized metals (Ref 2.21).

Arsenic degrades mechanical properties by forming intermetallics, and it causes dewetting of brass.

Bismuth. On the positive side, bismuth improves wettability and causes a significant reduction in the melting point, the latter property being useful in the final step of a multistep soldering operation. At concentrations of greater than 47%, the resulting soldering alloy will expand when cooled and can thereby help to offset the stresses caused by joining components with different coefficients of thermal expansion. It also helps to prevent tin whiskers. However, when used in alloys containing lead and tin, bismuth can form crystals of $\text{Sn}_{16}\text{Pb}_{32}\text{Bi}_{52}$, which melt at only 95 °C (203 °F), and can cause joints to fail at relatively low temperatures. It is also fairly expensive, and its availability is relatively low.

Cadmium makes solders sluggish, and it is prone to tarnishing and oxidation.

Copper lowers the melting point, improves fatigue resistance under thermal cycling, improves wetting, and reduces the rate of dissolution of copper from the parts being soldered. However, it forms intermetallics, promotes tin whiskers, makes solders sluggish and gritty, and degrades wetting.

Germanium. At concentrations below 0.002%, germanium increases the formation of oxides in tin-base lead-free solders. This tendency is lowest at a concentration of 0.005% (Ref 2.22).

Gold dissolves easily, forms intermetallics, and lowers the melting point of tin-base solders. At concentrations above 0.5%, it makes solders sluggish and degrades wetting. Alloys with higher proportions of tin can accept more gold without becoming brittle (Ref 2.23).

Indium increases ductility and lowers the melting point. It is susceptible to oxidation and should be avoided if possible in applications where oxide-removing flux cannot be used during repair. It dissolves gold much less than tin does and is therefore useful in soldering gold parts, although it also forms intermetallics with gold and thus should not be used at high concentrations. Indium can solder many nonmetals, including glass. It tends to cause unwanted doping in semiconductors. It diffuses through metals readily at high temperatures. Indium has a low vapor pressure and thus can be used in vacuum systems; it is also used in cryogenic applications. Indium costs several times as much as silver, and its availability is low.

Iron forms intermetallics and makes solders gritty. It has a low rate of dissolution in general but dissolves easily in lead-tin alloys at temperatures above 427 °C (801 °F) (Ref 2.24).

Lead is being phased out because of concerns about its toxicity. It helps to prevent both tin whiskers and tin pest. Lead reduces the solubility of copper and other metals in tin but does not wet as well as tin.

Nickel makes solders gritty and has low solubility in tin-lead.

Palladium. Interconnect solder joints in integrated circuits are subject to electromigration, the movement of atoms in the direction of electron flow, a phenomenon that can lead to fracturing, voids, and joint separation. According to Intel Corp. (Santa Clara, CA), palladium may be useful in tin solders as a barrier component, an element that provides electromigration resistance by reacting with tin rapidly enough to keep it from reacting with other metals, notably copper and nickel.

Phosphorus forms phosphides with tin and lead, makes solder gritty, and causes dewetting.

Silver provides mechanical strength, although lead has better ductility. It improves resistance to fatigue from thermal cycling except in the presence of lead. In tin, it significantly lowers the solubility of silver coatings. At high concentrations, silver forms intermetallics, makes solder gritty, and causes pimples on the surface of the solder.

Sulfur forms sulfides with lead and tin and causes dewetting.

Tin wets well and tends to provide good joint strength. It is susceptible to tin pest and tin whiskers unless other alloying elements are present to inhibit them. Tin dissolves gold and silver easily and other metals (including copper) less easily but still fairly well. It is most commonly the main metal in a soldering alloy.

Zinc lowers the melting point and is available inexpensively, but its corrosion and oxidation resistance are low, and it tends to form dross. When in contact with copper, zinc forms brittle intermetallic layers; when it is used to solder brass, it may be necessary to use barrier layers of copper and nickel to keep nickel from migrating to the surface.

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CHAPTER 3

Lead-Free Solders

THIS CHAPTER DISCUSSES the main types and properties of lead-free solder. In view of the newness and importance of this material, links are provided to online resources that seem to be especially helpful and informative. That these are available online at the time of this writing is, of course, no guarantee that they will remain so. The World Wide Web is not as volatile as it once was, however, and I have tried to limit my selections to archived resources that appear unlikely to vanish. I also include corresponding print references where these are available.

3.1 Changing to Lead-Free Soldering— Reasons and Resources

In 2002, the European Union approved the Waste from Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) Directives, declaring that as of July 2006 lead, cadmium, mercury, and hexavalent chromium (as well as the brominated flame retardants polybrominated biphenyl and polybrominated diphenylether) would not be permitted in new electronic equipment in the European Union. Other governments have adopted similar restrictions.

According to AIM Solders (Providence, RI), in the early 2000s it was not obvious why there was such concern about lead-free solders. They suggested that the best explanation was simply fear of possible legislation, trade barriers, and competition. See their “Lead-Free Soldering Guide,” published in 2003 during the runup to RoHS and still a useful resource today (Ref 3.1).

AIM noted that there was a good deal of resistance to the changeover and attributed this resistance mainly to concerns about cost and reliability. As for cost, most other elements are more expensive than lead, so nearly any substitution will increase the price. As for reliability, AIM suggested

that engineers had become so comfortable with tin-lead solder that it would not be easy to get them to trust lead-free solder readily. As is shown subsequently, reliability is a special concern with lead-free solders.

There is little question about the toxicity of lead. However, says IPC (formerly the Institute for Interconnecting and Packaging Electronic Circuits), “Although lead, when inhaled or ingested, is certainly toxic, many questions have been raised regarding the lack of evidence that lead in electronics represents an environmental or human health concern” (Ref 3.2). The organization provides several references relevant to this question, notably an Environmental Protection Agency (EPA) life-cycle assessment of lead-free solder (Ref 3.3).

One of IPC’s references compares the environmental effects of seven lead-free solder alloys (tin-silver-copper, tin-silver, tin-copper, tin-antimony, tin-indium, tin-silver-bismuth, and tin-bismuth) “tested,” says E. Smith III, “in the various physical forms most likely to occur from printed circuit board fabrication, assembly, and finished product disposal” (Ref 3.4). Smith ranks the specific alloy compositions studied in the following order, from least environmental impact to greatest:

- 43Sn-57Bi
- 80Sn-20In
- 99.3Sn-0.7Cu
- 90Sn-5Bi-5Ag
- 98Sn-2Ag
- 96.5Sn-3.5Ag
- 96.3Sn-3.2Ag-0.5Cu
- 95Sn-5Sb

The National Institute of Standards and Technology (NIST) maintains a page with links to several helpful resources at <http://www.metallurgy.nist.gov/solder/>. Among the resources at the time of this writing are pages on “Phase Diagrams and Computational Thermodynamics of Solder Systems,” “Review and Analysis of Lead-Free Solder Material Properties,” “NIST Recommended Practice Guide on Test Procedures for Developing Solder Data,” and “Mechanical Properties of Intermetallic Compounds Formed Between Tin (Solder) and Copper or Nickel,” as well as two collaborations with the National Electronics Manufacturing Initiative on the subject of lead-free solder (Ref 3.5).

R. Schueller, in a helpful overview of the transition to lead-free products, discusses material specification, component specification and qualification, rework, failure analysis, and remedial action (Ref 3.6). These issues are discussed in later chapters in this book. IPC also provides online resources for those seeking to implement lead-free technology (Ref 3.7).

3.2 Types of Lead-Free Solder

The main practical difficulty with lead-free solders is that their melting temperatures are not as low as tin-lead (the eutectic composition of which, as recalled from Chapter 2, “Lead-Free Solders,” melts at 183 °C, or 361 °F). Tin, the base metal most commonly used for lead-free solders, melts at 232 °C (450 °F), and the main tin-base solder families typically melt in the range of 217 to 229 °C (420 to 445 °F). That means that the materials to be joined must be able to withstand higher temperatures during the soldering process. Albert Capote of Aguila Technologies (San Marcos, CA) says that even with such a comparatively small increase in melting temperature, the materials used in electronics fabrication begin to crack and degas (Ref 3.8). Table 3.1 shows the melting points of the metals most commonly used in electronic assemblies as substitutes for lead (Ref 3.9, 3.10).

According to IPC, tin-silver-copper (SnAgCu, or SAC) and tin-copper (SnCu, or SC) are the alloy families receiving the most attention as replacements for tin-lead (Ref 3.11). IPC’s Solder Products Value Council has recommended 96.5-3.0-0.5 SAC alloy as the best choice for use in the electronics industry (Ref 3.12).

Since RoHS went into effect, the SAC alloy family has become the industry-standard lead-free solder family (Ref 3.13). In this alloy system, the eutectic composition has a melting point of 217 °C (420 °F), lower than the melting points of the tin-silver and tin-copper eutectics. The patent on this alloy and its use in electronics assembly is held by a group of researchers from Ames Laboratory (Ames, IA), Iowa State University (Ames, IA), and Sandia National Laboratories (Albuquerque, NM).

Useful information on the melting and freezing behavior of these alloys—including Sn3.0Ag0.5Cu (SAC 305) and Sn4.0Ag0.5Cu (SAC 405), which are both near the eutectic point, as well as low-silver alloys—can be found in Ref 3.14. Microstructure, discussed there, is a crucial consideration in the fabrication of reliable soldered joints; a detailed study

Table 3.1 Melting temperatures of metals used in electronic assemblies

Metal	Melting point (°C)
Bismuth (Bi)	271
Copper (Cu)	1083
Gold (Au)	1063
Indium (In)	157
Lead (Pb)	327
Nickel (Ni)	1453
Silver (Ag)	960
Tin (Sn)	232
Zinc (Zn)	419

Source: Ref 3.9

of the solidification behavior and dendrite formation of several near-eutectic alloys is available in Ref 3.15. It is important to be aware that small changes in composition can lead to large differences in microstructure.

It is possible to use a SAC alloy as a base and to improve its properties by adding further components. Adding a fourth alloying element (for example, zinc or manganese) has been found to reduce the melting point. Naturally, researchers are continually investigating other possible alloying additives and their effects on SAC alloys.

Henkel (Düsseldorf, Germany), for example, working with a group of industry users, materials suppliers, and members of the academic community, has added bismuth, antimony, and nickel to a base of SnAg3.8Cu0.7 (SAC 387) to produce Innolot, which reportedly improves on SAC 387 with respect to “spread, solder balling, thermal cycling reliability, shear strength, vibration and voiding.” Because the alloy contains bismuth, it cannot be used to join components or boards that contain lead: the combination will form a eutectic with a melting point of only 98 °C (210 °F), and the joints will therefore begin to fail at that temperature (Ref 3.16, 3.17).

Similarly, Ames Laboratory and Iowa State University have tested single-element additions to Sn-3.5Ag-0.95Cu (SAC 3595) to improve eutectic solidification (Ref 3.18). Also, in an effort to overcome the tendency of lead-free solders to become brittle upon repeated or prolonged exposure to heat, Ames has tested a series of Sn-Ag-Cu alloys modified with additions of silicon, titanium, chromium, manganese, nickel, zinc, and germanium. They report that for retention of ductility, shear strength, and impact strength, zinc seems to offer the best results. Ames has also tested alloys modified with iron, cobalt, and other similar elements for higher-temperature applications (Ref 3.19).

Silver is expensive, so it is economical to use as little of it as possible; of course, the extreme case is to leave it out altogether and use SC alloys. However, the properties of these alloys are generally not as good as those of SAC alloys (Ref 3.9, 3.10). At a content of approximately 0.7% Cu, the melting point is reduced from pure tin’s 231 °C (448 °F) to 228 °C (442 °F), but additions of trace elements such as nickel and germanium do not reduce it further. According to Ray Prasad, “Since Sn-Cu alloys with or without Ni-Ge drastically narrow the reflow process window, they should be considered only in low-thermal-mass applications such as cell phones and personal digital assistants, where it is possible to maintain uniform temperature across the board. They are not a wise choice in applications such as large desktop motherboards and server boards that require much wider process windows” (Ref 3.20).

Even if silver cannot be completely omitted from the alloy, its presence can be reduced to save costs. Indium, which has been found to have good wetting characteristics and to increase strength and fatigue resistance

(Ref 3.21), has shown promise as an additive to tin-copper eutectic solder (Sn-0.7wt%Cu) when used in combination with silver (Ref 3.9, 3.10).

R. Schueller has provided a valuable discussion of some alternative lead-free alloys (Ref 3.22). Among the alloys he discusses are SnAgCuBi, SnAgCuIn, SnAgBiIn, and SnNiCu, which he says are the most popular; Table 3.2 shows his summary of the melting points of these alloys, which indicates that bismuth and indium are the elements that make the most difference.

Schueller warns that (as with Innolot mentioned previously) contamination with lead can create a lead-bismuth eutectic with a dangerously low melting point and can have other negative effects on mechanical properties. He also emphasizes the importance of precise control over the alloy constituents, noting that “silver content greater than 4.0 wt% could lead to degradation of mechanical properties” and that “bismuth content greater than 1.0 wt% could lead to embrittlement.”

Regarding mechanical properties, Schueller says that alternative lead-free alloys, notably the bismuth-indium-base alloys and especially the Sn-CuNi alloy, improve on SAC alloys in one important respect: there are studies indicating that SAC alloys can fail at loads up to 50% lower than SnPb under static board bending. The presence of indium, however, tends to lead to the formation of intermetallics that degrade reliability under mechanical shock, and to lead to corrosion in the presence of halides and moisture. He also notes that some alternative lead-free alloys undergo a ductile-to-brittle transition at low temperatures, a concern in outdoor applications.

Because of their higher melting temperatures, lead-free solders tend to reduce the useful life of soldering tips. Stannol GmbH (Wuppertal, Germany) has developed a family of lead-free solders intended to help overcome this problem. Marketed under the name FLOWTIN, they are microalloyed variants of SAC and SC alloys and are said to increase the number of soldering cycles significantly as compared to their nonmicroalloyed counterparts (Ref 3.23).

Table 3.2 Melting temperatures of the four alloy systems

Alloy	Solidus	Liquidus
Sn37Pb	183 °C	183 °C
Sn3.5Ag0.7Cu	216 °C	220 °C
Sn(3–4.5)Ag(0.5–2)Cu(0–5)Bi	208 °C–217 °C	
Sn3.0Ag2.5Bi6.0In	188 °C	203 °C
Sn3.0Ag2.5Bi2.5In	190 °C	210 °C
Sn3.0Ag2.0Cu8.0In	195 °C	201 °C
Sn3.0Ag0.5Cu8.0In	196 °C	202 °C
Sn3.0Ag2.5Bi3.0In	197 °C	208 °C
Sn3.5Ag0.5Bi8.0In	197 °C	208 °C
Sn3.5Ag0.5Bi6.0In	202 °C	211 °C

Source: Ref 3.22

For some applications, tin-base solders other than SAC and SC can be used. For example, there is a need for low-temperature solders in applications where higher processing temperatures can damage the components being joined. The melting point of a tin alloy can be reduced by adding gallium, indium, bismuth, or cadmium. However, cadmium is toxic (and prohibited by RoHS), indium is expensive, and gallium-containing alloys are generally liquid at or near room temperature, so the only real low-cost option is bismuth. Indium Corporation (Clinton, NY) has reported good results with 57Bi-42Sn-1Ag (Ref 3.24).

In general, these low-temperature solders are often called fusible alloys and are typically made from some combination of bismuth, tin, and indium (as well as lead and cadmium, but for electronics assembly these are prohibited under RoHS). These alloys generally have low vapor pressure, good thermal conductivity, and fluidity, and they tend to be easy to handle and reuse. They also allow a high degree of control over thermal expansion and solidification shrinkage. Bismuth expands 3.3% in volume when it solidifies; alloys containing more than 55% of bismuth expand upon solidification, and those with less than 48% contract (Ref 3.25).

Other lead-free solder families include the following.

Sn-Cu-Al-Ag. Matsushita Electric Industrial Company (now Panasonic) (Kadoma, Japan) has invented and tested lead-free solders in this family. One contains 25 wt% Cu and 1 wt% Al, with tin as the balance; another has 3.5 wt% Cu, 1.5 wt% Al, and 5 wt% Ag, again with tin as the balance. Another possible composition consists of 20wt%Sn-0.7Cu eutectic alloy, 70wt%Ag-30Al alloy, and 10wt%Bi-35In eutectic alloy. Their soldering temperatures are, respectively, $\geq 300^\circ\text{C}$ (572°F), $\geq 330^\circ\text{C}$ (626°F), and $\geq 450^\circ\text{C}$ (842°F) (Ref 3.26).

Sn-Zn-Ag-Ga-Al-Ce. The solderability and the formation of intermetallics between Sn-9Zn-0.25Ag-0.2Ga-0.002Al-0.15Ce solder and three types of common substrates have been studied. The substrates were copper, Au-Ni-Cu, and tin-plated copper. Figure 3.1 shows the solderability of the solder wetted on each of these. It appears to be a viable candidate for use in the electronics industry (Ref 3.27).

Au-Cu-Sn. Alloys in this family are regarded as candidate lead-free solders for high-temperature (above 250°C , or 480°F) applications, and some, including high-gold-content (20 wt% Sn) eutectic alloys, are already used. It is desirable to lower the gold content to reduce costs, but tin-rich alloys in this system are brittle because of the presence of gold-tin intermetallic phases (especially AuSn_4). More research is needed before an optimal alloy composition in this system can be determined. So far, the thermodynamic properties of liquid Au-Cu-Sn alloys have been studied via calorimetry (Ref 3.28), and in a complementary study, tin activities in liquid Au-Cu-Sn alloys have been determined via an electromotive force method using solid electrolyte galvanic cells (Ref 3.25).

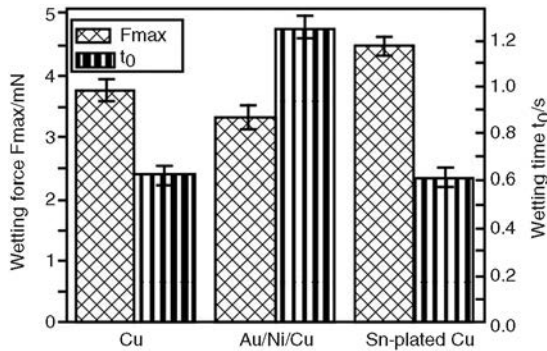


Fig. 3.1 Solderability of Sn-9Zn-0.2Ga-0.002Al-0.25Ag-0.15Ce solder wetted on different substrates. Adapted from Ref 3.27

Sn-Ag-Fe. A nontoxic solder consisting of tin-silver alloy and iron particles has been developed at the Yale School of Engineering and Applied Science at Yale University (New Haven, CT). This magnetic lead-free solder is strengthened by the iron particles and can be strengthened further by aligning the particles with an externally applied magnetic field. The solder can also be selectively heated by magnetic fields, thus avoiding the problems otherwise caused by the higher melting temperature of tin as compared to lead (Ref 3.29).

In-Sn-X. PPG Industries, Inc. (Pittsburgh, PA) has developed a solder with a composition of 61 to 65 wt% In, 30 to 34 wt% Sn, and 0 to 5 wt% of other miscellaneous metals, including 3.0 to 4.95 wt% Ag, 0.25 to 1.25 wt% Cu, 0 to 0.75 wt% Sb, 0 to 0.08 wt% Au, 0 to 0.2 wt% Pb, 0 to 0.25 wt% Bi, and others. This solder composition has a liquidus temperature of 119.6 °C (247.3 °F) and a solidus temperature of 118.6 °C (245.5 °F) and is intended for joining electrically conductive materials to glass windshields without damage by thermal stresses to the glass sheets (Ref 3.30).

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CHAPTER 4

Fluxes

SUCCESSFUL ESTABLISHMENT OF A SOLDER JOINT requires that the liquid solder make contact with the metal to which it is to be joined, so that wetting can be initiated. Unfortunately, almost all of the metals involved in soldering are oxidized during exposure to elevated temperatures in air. This prevents metal-to-metal contact as well as the wetting and formation of a metallurgical bond, unless the oxides are removed. Fluxes are used in soldering to remove such films and to protect the surfaces against reoxidation during soldering.

4.1 Flux and Its Functions

Fluxes are chemicals (liquid, solid, or gaseous materials) that remove oxide layers from the base metal and solder. When heated, fluxes either promote or accelerate the wetting of metals by solder.

The major role of the flux is the removal of thin tarnish layers during the initial stages of the soldering process, thereby permitting the molten solder to react with the substrate and to spread. Fluxes do not effectively displace organic contaminants, so the substrate underneath such films will remain untouched by the flux and will therefore be unsolderable. A degreasing step should precede flux application. Even the strongest fluxes cannot remove thick oxides or heavy scales, so a mechanical or chemical precleaning procedure may be required.

The flux has two additional functions. One is that it lowers the surface tension of the solder, allowing it to more readily fill gaps and holes by capillary action. The other is that the flux coating protects the metal surface from reoxidation during the heating steps just prior to soldering.

A flux also aids in the wetting process, improves heat transfer (especially in solder pastes), and carries oxides and solid debris away from the joint.

Fluxes contain three principal ingredients: an active chemical compound, such as a halide, for oxide removal; wetting agents to improve surface coverage; and a vehicle to dilute and mix together the cleaning compound and wetting agents. The vehicle, which is removed by evaporation during the soldering process, is typically water, isopropyl alcohol, glycerin, glycol (for liquid fluxes), or petroleum jelly (for flux pastes or creams). Fluxes are characterized by their cleaning agent and are assigned to one of these categories of increasing activity: rosin-based fluxes, organic-acid fluxes (also called intermediate or water-soluble fluxes), and inorganic-acid fluxes.

Flux selection usually depends on the ease with which a material can be soldered. Rosin fluxes are used with solderable base metals or with metals that are precoated with a solderable base metal or with metals that are precoated with a solderable finish. Inorganic fluxes are often used on metals such as stainless steel. Table 4.1 indicates the relative ease with which a number of alloys and metals can be soldered, based on flux requirements.

Table 4.1 Relative solderability of selected metals and alloys as a function of flux type used

Base metal, alloy, or applied finish	Flux type				Soldering not recommended(a)
	Rosin	Organic	Inorganic	Special flux and solder	
Aluminum	...	...	...	X	...
Aluminum-bronze	...	...	...	X	...
Beryllium	...	...	...	...	X
Beryllium-copper	X	X	X	...	...
Brass	X	X	X	...	...
Cadmium	X	X	X	...	...
Cast iron	...	...	...	X	...
Chromium	...	...	...	...	X
Copper	X	X	X	...	...
Copper-chromium	...	...	X	...	...
Copper-nickel	X	X	X	...	...
Copper-silicon	...	...	X	...	...
Gold	X	X	X	...	...
Inconel	...	...	...	X	...
Lead	X	X	X	...	...
Magnesium	...	...	...	...	X
Manganese-bronze (high tensile)	...	...	...	...	X
Monel	...	X	X	...	...
Nickel	...	X	X	...	...
Nickel-iron	...	X	X	...	...
Nichrome	...	...	...	X	...
Palladium	X	X	X	...	...
Platinum	X	X	X	...	...
Rhodium	...	...	X	...	...
Silver	X	X	X	...	...
Stainless steel	...	X	X	...	...
Steel	...	...	X	...	...
Tin	X	X	X	...	...
Tin-bronze	X	X	X	...	...
Tin-lead	X	X	X	...	...
Tin-nickel	...	X	X	...	...
Tin-zinc	X	X	X	...	...
Titanium	...	...	...	...	X
Zinc	...	X	X	...	...
Zinc die castings	...	...	...	...	X

(a) With proper procedures, such as precoating, most metals can be soldered.

The removal of flux residues depends on the specific application as well as the potential corrosivity of the residues left behind. If residues are specified for removal, then the workpiece should be cleaned as soon as possible after processing. Rosin residues become particularly difficult to remove with time.

4.2 Types of Flux

Fluxes can be categorized by their chemical makeup (Ref 4.1–4.6):

- Rosin-based fluxes
- No-clean or low-solids fluxes
- Organic fluxes
- Inorganic fluxes

These materials vary in their activity (that is, aggressiveness). Rosin-based fluxes are very mild, whereas inorganic fluxes can be extremely active and corrosive. Because of the potential for corrosion by inorganic fluxes in electronic assemblies, the rosin-based fluxes (with their low flux activity) are favored by the electronics industry.

Flux specifications are most numerous for the rosin-based materials, because of the criticality of their properties in the assembly of electronic products. Sample specifications include military standards MIL-F-14256E and MIL-STD-2000; federal specification QQ-S-571 E; and the industry standards ASTM D 509, IPC-S-815A, and IPC-TM-650 (test methods). Fluxes are tested for bulk corrosivity (copper mirror test), concentrations of Cl^- and F^- (halide content), and solids content. Tests of residues left by the flux on the substrate (typically a printed wiring board) include surface insulation resistance and ionic residues. The ISO/DIS 9454-1 document includes organic- and inorganic-acid flux specifications and test procedures (ISO/DIS 9455-X, where $X = 1, 2, \dots, 14$) in addition to rosin-based flux specifications.

Rosin-based fluxes contain water-white rosin, a distillation product from pine tree sap, dissolved in a suitable organic solvent. Rosin fluxes possess important physical and chemical properties that make them particularly suitable for use in the electrical industry. They are solid and chemically inactive at room temperature, but at soldering temperatures they gain sufficient activity to remove weakly adherent oxides from the noble metals gold and silver, as well as copper.

When used alone, rosin-based fluxes are referred to as a nonactivated, or type R, grade. Rosin is solid, noncorrosive, and insulating at room temperature. Heating causes it to liquefy and become slightly chemically active, because of its abietic and pimaric acid components. The rosin is typically dissolved in an organic vehicle, such as isopropyl alcohol, to form the liquid solution.

Although its noncorrosive nature has led to its widespread use in microelectronics, rosin-based flux is lacking in chemical activity, which essentially limits its use to precleaned parts and to only a few metals that do not have adherent oxides. The active constituent, abietic acid ($C_{20}H_{30}O_2$), with a melting point of 173 °C (343 °F), becomes mildly active at soldering temperatures ranging from 177 to 316 °C (350 to 601 °F). The residue is hard, nonhygroscopic, electrically nonconductive, and noncorrosive.

The addition of an activator to rosin fluxes increases their chemical activity. Activators can be organic halogenated compounds, such as amine hydrohalides that contain chloride, fluoride, or bromide ion groups, or halide-free activators, such as oleic, stearic, or lactic acids. Halide-free fluxes are recommended for materials that are sensitive to stress-corrosion cracking. The concentration of activators, which defines the corrosivity of the flux, determines the flux category as being one of the following: rosin based, mildly activated (RMA), fully activated (RA), and superactivated (SA). Generally, rosin-based fluxes have poor high-temperature stability; that is, the fluxes degrade rapidly after excessive exposure to elevated temperatures (for example, >25 s at 260 °C, or 500 °F).

The RMA flux is still essentially noncorrosive but is sufficiently active to remove oxides more reliably than the rosin-based flux. In addition, the residues are noncorrosive. However, care must be exercised in cases of high-reliability applications. It is advisable to specify that these fluxes be halide-free, to ensure that specific safety requirements are met in critical components. Even so, cleaning is now required to remove the flux residue. Both polar and nonpolar solvents have been used. These RMA fluxes are preferred for military, telephone, and other high-reliability electronic products.

Activated fluxes were developed to provide more chemically active fluxes for mass-produced electronics, such as packaged components. Most mass-produced electronics are manufactured using RMA fluxes. The use of chlorides in these fluxes requires effective cleaning after soldering to prevent corrosion and electrical leakage, because the presence of chloride ions in flux residue makes it conductive. Because of the chemistry of the activators, a double solvent cleaning is normally required. Activated rosin fluxes are widely used in commercial electronics and in high-reliability applications where the residue can be completely removed after soldering.

The R-type fluxes are used on electronic assemblies, where the benign residues are left on the soldered assembly. However, the substrate(s) must have excellent solderability, because the weak activity of these fluxes offers a very small window of variability for oxide thicknesses. The R-type fluxes are effective on lightly tarnished copper surfaces and on precious-metal substrates, as well as on tin- and solder-coated base metals. Residues can be removed by nonpolar solvents, organic solvents (isopropyl alcohol, 1,1,1-trichloroethane), semiaqueous solutions (terpenes), and aqueous baths or detergent solutions.

The residues left by R-type fluxes can be reduced by dilution with an organic solvent (for example, isopropyl alcohol). Such fluxes are termed low solids because the solids, which are responsible for the residues, are significantly reduced so that cleaning steps are not required. These fluxes are also referred to as no-clean; however, the term *no-clean* covers a much wider range of flux formulations that must simply comply with residue corrosivity, irrespective of the solids content. (See the following.)

The increased activity of the RMA fluxes improves solder wetting on more heavily tarnished copper substrates. Residues are relatively benign and only require removal when the fluxes are used on high-reliability electronic systems (for example, in military applications) or when the fluxes contain potentially harmful halide activators. Residue cleaning is a two-step process. The first step requires the use of organic solvents to remove the nonpolar rosin, and in the second step, a polar solvent (water or polar alcohols) is used to rinse away activator residues. Aqueous and semiaqueous products can perform both functions.

The greater corrosivity of RA and SA fluxes is due, primarily, to higher levels of the activators that are used in RMA fluxes. These fluxes are used on base metals such as nickel (and nickel plate), lightly tarnished low-carbon steels, copper, iron-base alloys, and copper-base alloys (brasses, bronzes, and beryllium-copper).

Residues of the RA and SA fluxes must be removed to prevent the corrosion of the substrate later in service. Cleaning procedures similar to those identified for RMA fluxes are used. Cleanliness testing for ionic residues should be implemented to verify the adequate removal of flux deposits, particularly for the stronger fluxes.

No-Clean or Low-Solids Fluxes. Flux formulations for which the residues do not pose a corrosion concern after soldering are called no-clean fluxes. The fluxing activity of these materials can approach that of traditional RMA fluxes (Ref 4.7). It should be noted, however, that *no-clean* has become a misnomer, because in many applications they do need to be cleaned.

A second approach to eliminating the need for postprocess cleaning is to use a low-solids flux, that is, a flux with limited solids content. (Solids form the residue after soldering.) However, low-solids fluxes have reduced oxide-removal potential. Therefore, substrate tarnishes and contamination, flux density, and process conditions (inert atmospheres may be necessary) must be more tightly controlled to ensure consistent solderability.

Organic fluxes (or organic-acid fluxes) are also called water-soluble or intermediate fluxes. Although less active than inorganic fluxes, they are effective at soldering temperatures ranging from 90 to 320 °C (195 to 610 °F). They contain one or more organic acids, such as lactic, oleic, or stearic acid. Chemical activity can be enhanced by adding organic halogen compounds (amine hydrohalide, which may contain chloride and bromide derivatives) or nonhalogenated substances, such as one of the amines

or amides (urea or thylene diamine). Typical vehicles include water, isopropyl alcohol, polyglycols, or petroleum jelly for pastes.

Organic fluxes have a chemical activity range that varies from the levels associated with RMA fluxes to those that exceed the activity of RA fluxes. They are active at soldering temperatures, but the period of activity is short because of their susceptibility to thermal decomposition. Their tendency to volatilize, char, or burn when heated limits their use with torch or flame heating. They have better high-temperature stability than rosin-based fluxes, which makes them good candidates for solders with melting temperatures that exceed 184 °C (363 °F).

Organic fluxes are particularly useful in applications where controlled quantities of flux can be applied and where sufficient heat can be used to fully decompose or volatilize the corrosive constituents. Caution is necessary to prevent undecomposed flux from spreading to insulating sleeving. Care must also be taken when soldering in closed systems where corrosive fumes can condense on critical parts of the assembly.

Organic fluxes are used in many electronic applications involving machine processes and hand assembly, as well as the hot tin or solder dipping of nickel- and iron-base alloy leads and devices. These fluxes are also used on structural applications with copper and copper alloy workpieces that have light-to-moderate tarnishes.

Whether the fluxes are used in structural or electronic applications, their residues should be removed. When they are properly used, the residues are water-soluble and relatively inert and, in some applications, can be removed by rinsing with water or a polar organic solvent.

Inorganic fluxes (or inorganic-acid fluxes) are composed of inorganic acids and salts that are highly corrosive and extremely active. In many instances, they are not acceptable for use on electronics but are suitable for plumbing and industrial applications. Inorganic fluxes do enable the soldering of ferrous alloys and high-nickel alloys used in electronic packages and hermetic enclosures. The difficulty of chloride ion removal has led to the gradual abandonment of inorganic fluxes, even for tinning purposes.

Inorganic fluxes are used to optimum advantage where conditions require rapid and highly active fluxing action. They can be applied as solutions, pastes, or dry salts in many general soldering applications. They function equally well with torch, oven, resistance, or induction soldering methods, because they neither char nor burn. These fluxes can be formulated to provide stability over the entire soldering temperature range.

Inorganic fluxes have the highest levels of chemical activity. There are two categories of these fluxes:

- Pure acids, such as hydrochloric, hydrofluoric, or phosphoric acids, which have surfactants added to enhance coverage

- Inorganic salt mixtures or solutions, which may also contain surfactants

The pure acids are very strong and are capable of removing heavy oxide layers and scales. However, they offer the clean surface limited protection from reoxidation during the soldering process. Binary inorganic salt alloys are formed from the combination of zinc chloride (ZnCl_2), ammonium chloride (NH_4Cl), stannous chloride (SnCl_2), or sodium chloride (NaCl) components. The inorganic salt combinations form simple eutectics with minimum temperatures near the melting point of solders. (The melting temperatures of the single salts are too high for them to flow at typical soldering temperatures.) For example, the $\text{NH}_4\text{Cl}:3 (\text{ZnCl}_2)$ eutectic composition has a eutectic temperature (T_e) of 177°C (351°F). Other eutectic salt combinations include $\text{SnCl}_2\text{-CuCl}$, $T_e = 170^\circ\text{C}$ (338°F); AgCl-CuCl , $T_e = 260^\circ\text{C}$ (500°F); and CuCl-ZnCl_2 , $T_e = 230^\circ\text{C}$ (446°F).

Proper flux selection is based on the salt mixture having a melting temperature that is less than that of the solder. The molten salt reduces the surface oxides and coats the base metal to prevent reoxidation during the soldering process. Flux activity is further increased by dissolving the flux in a water vehicle. The salts break down to release Cl^- ions, which combine with water to form a hydrochloric acid (HCl) activator. The fluxes, particularly the water solutions, may contain surfactants to assist the complete coverage of the joint area. A paste form of the flux uses petroleum jelly as the vehicle.

Inorganic fluxes are limited to structural applications, such as plumbing or mechanical assemblies. Their corrosive activity is unacceptable for electronic devices or substrates, or for their assembly. These fluxes are effective on nickel and nickel alloys, stainless steels, chromium, and heavily tarnished copper and copper alloys. The inorganic fluxes are very stable at high temperatures. The flux residues and the fluxes themselves are extremely corrosive and must be thoroughly removed after processing.

One distinct disadvantage of inorganic fluxes is that their residue remains chemically active after soldering. If this residue is not removed, then severe corrosion can occur at the joint. Adjoining areas can also be attacked by residues from the spray of flux and from flux vapors. Fluxes that contain ammonium salts can cause stress-corrosion cracking when soldering brass as well as most iron-nickel alloys.

It should be noted that chloride-containing residues and small amounts of water are particularly damaging to aluminum and aluminum alloys, because of the potential for stress-corrosion cracking. Residues are removed with hot-water rinses and follow-up polar-solvent rinses. Neutralizing solutions (mild caustics) can be used on nonsensitive substrates. A list of selected inorganic flux solutions for particular base metals is provided in Table 4.2.

Table 4.2 Typical inorganic fluxes for selected base metals

	Composition Amount		Composition Amount
For stainless steel and galvanized iron		Paste flux for soldering aluminum	
Zinc chloride, mL (oz)	2510 (85)	Stannous chloride, mL (oz)	2450 (83)
Ammonium chloride, mL (oz)	190 (6.5)	Zinc dihydrazinium chloride, mL (oz)	210 (7)
Stannous chloride, mL (oz)	270 (9)	Hydrazine hydrobromide, mL (oz)	295 (10)
Hydrochloric acid, mL (oz)	60 (2)	Water, mL (oz)	295 (10)
Wetting agent (optional), wt%	0.1		
Water(a)	...	For soldering aluminum	
For stainless steel		Cadmium fluoboride, mL (oz)	150 (5)
Zinc chloride, mL (oz)	1420 (48)	Zinc fluoboride, mL (oz)	150 (5)
Ammonium chloride, mL (oz)	150 (5)	Fluoboric acid, mL (oz)	180 (6)
Hydrochloric acid, mL (oz)	90 (3)	Diethanol amine, mL (oz)	590 (20)
Wetting agent (optional), wt%	0.1	Diethanol diamine, mL (oz)	120 (4)
Water(a)	...	Diethanol triamine, mL (oz)	295 (10)
For Monel		Potassium chloride, mL (oz)	1330 (45)
Zinc chloride, mL (oz)	470 (16)	Sodium chloride, mL (oz)	890 (30)
Ammonium chloride, mL (oz)	470 (16)	Lithium chloride, mL (oz)	440 (15)
Glycerin, mL (oz)	470 (16)	Potassium fluoride, mL (oz)	210 (7)
Water, L (gal)	0.5 (0.125)	Sodium pyrophosphate, mL (oz)	90 (3)
For high-tensile-strength manganese, bronze, copper, or brass		Triethanolamine, mL (oz)	740 (25)
Orthophosphoric acid (85%), mL (oz)	1000 (34)	Fluoboric acid, mL (oz)	90 (3)
Water, mL (oz)	470 (16)	Cadmium fluoborate, mL (oz)	60 (2)
For cast iron		Stannous chloride, mL (oz)	1300 (44)
Zinc chloride, mL (oz)	950 (32)	Ammonium chloride, mL (oz)	150 (5)
Ammonium chloride, mL (oz)	120 (4)	Sodium fluoride, mL (oz)	30 (1)
Sodium chloride, mL (oz)	240 (8)	Zinc chloride, mL (oz)	1300 (44)
Hydrochloric acid, mL (oz)	240 (8)	Ammonium chloride, mL (oz)	150 (5)
Water(a)	...	Sodium fluoride, mL (oz)	30 (1)
For cast iron			
Zinc chloride, mL (oz)	1180 (40)		
Ammonium chloride, mL (oz)	120 (4)		
Hydrofluoric acid, mL (oz)	40 (1.25)		
Water(a)	...		

(a) To make 3.8 L (1 gal)

4.3 Postassembly Cleaning Procedures

After the soldering operation, the workpiece is cleaned, primarily to remove flux residues that can cause corrosion of the part while in storage or during service. Other cleaning procedures include the removal of solder-stop materials as well as stray solder particles, which can interfere with mechanical or electrical performance of the assembly. Flux residues should be removed as soon as possible after the soldering process, because their ability to be removed decreases with time, whereas their tenacity and potential for corrosive damage increase with time.

Cleaning fluids and solvents to be used are determined by the particular flux residues. (Guidelines are presented in the previous section.) The selection of organic solvents is rapidly changing as chlorofluorocarbon materials are phased out by environmental regulations and new materials (and processes) become qualified as replacements.

Some general practices must be considered when establishing cleaning procedures. First, assess the compatibility of substrate materials and filler metals with the cleaning solutions. Organic solvents are benign toward metal surfaces. Alkaline solutions used to neutralize strongly acidic fluxes can affect some base-metal finishes (for example, copper alloys, iron alloys, and some steels). When in doubt, samples of the substrate should be exposed to the cleaning agent prior to use on final assemblies.

Second, determine whether the cleaning solutions leave undesirable residues. Mineral deposits from tap water can corrode or stain substrate surfaces (especially in the continued presence of water vapor). Tap-water rinses should be followed with rinses in either deionized or distilled water. All traces of water can be removed by a final alcohol rinse. Isopropyl alcohol is generally used. Denatured alcohol and acetone should be avoided, because they also can leave residues.

Third, the drying of solvent or other cleaning-solution residues should use dry, clean gas, such as bottled or cryogenic nitrogen gas. Compressed “house” air may contain water particles or compressor oils that can quickly recontaminate the workpiece.

Fourth, limit the contact of the assembly with oily rags and fingerprints. Many instances of cosmetic staining or pitting of the workpiece surface have been traced to fingerprints.

Fifth, test for the effectiveness of postcleaning operations. Unlike the well-specified procedures used by the electronics industry, such procedures are not well standardized for structural applications. Temperature-humidity chambers can be used to assess the propensity for corrosion on the workpiece (a destructive test).

Cleaning effectiveness can be enhanced by thermal and mechanical assistance. Cleaning solvents and solutions have higher solubility for residues at elevated temperatures. Caution should be observed when heating solutions, because of the generation of vapors that can result in health or fire hazards. The use of solvent vapors at their boiling point in vapor degreasers can remove residues from remote locations on the workpiece. However, the solvents that have been popular for vapor degreasing are being restricted from use by environmental statutes.

Mechanical agitation of cleaning solutions is obtained by ultrasonic activation, high-energy sprays, and manual scouring procedures. Ultrasonics are very effective for loosening residues, particularly in hidden locations. Although generally safe for the cleaning of structural members, care must be exercised when using ultrasonics on electronic assemblies, because of the possible damage to internal connections. The use of sprays or jets to force the cleaning solution into crevices and hidden areas of the workpiece can increase cleaning efficiency. Batch and in-line equipment based on spray and jet technology is currently available. Because the cleaning material passes through a jet, aerosols and mists are generated, which may create an explosion hazard.

Manual scouring can remove residues on exposed surfaces only. Cleaning with sandpaper or vapor blasting metal surfaces with abrasive particles should be avoided in the postprocess cleaning steps for three reasons: First, the base-metal oxide layer protects the surface from corrosion or excessive oxidation later in service. For example, stainless steels are particularly susceptible to corrosion attack after abrasive treatments, particularly those that use steel wool or a steel brush. Second, solders are generally much softer than the base metals. Therefore, inadvertent damage can be easily done to the joint fillets, possibly jeopardizing monotonic strength and fatigue resistance. Third, abrasive grit particles can become embedded in the substrate and particularly in the softer solder. Dislodged particles can damage mechanical actuators that are part of the soldered assembly. The abrasive particles can also deteriorate surface solderability of the workpiece during subsequent assembly, repair, or rework procedures. Damage occurs readily to circuit boards (solder masks, coatings, and the laminate itself) by abrasive particles.

Finally, storage of the parts must be considered. The extent of storage control depends on factors such as the type of assembly and its service requirements, the cost of rework, repair or scrapping of damaged parts, and the environment of the factory. Acute contamination or corrosion of finished parts can be prevented by their enclosure in bags. Popular containers are polyethylene plastic bags, which can provide short-term storage (<1 year) when properly sealed. Solderability may deteriorate for longer storage times because of the outgassing of polymer components contained in the plastic. Only new bags should be considered for the storage of solderable parts because contamination of the bag interior from previous usage may deteriorate solderability. Plastic bag material should be a minimum 0.1 mm (0.004 in.) thick. The bags can be filled with an inert gas (nitrogen) to further limit oxidation of solderable surfaces. Paper bags should be considered only for the transport of devices, because their inability to be sealed from the environment, as well as contamination of solderable surfaces by chemicals in the paper, limit their appropriateness as storage containers. Metal foils can be used as storage media, although greater effort is required to seal the material. The use of desiccants that comply with MIL-D-3464E, “Desiccants, Activated, Bagged, Packaging Use and Static Dehumidification,” is acceptable.

More elaborate and expensive storage measures include the construction of special facilities that control temperature, humidity, and air-particulate counts. The prevention of mechanical damage that results from the movement of inventory must also be addressed. Storage conditions are of particular concern for electronic devices and circuit boards in which solderability loss can severely hinder subsequent automated assembly processes.

4.4 Fluxes in Electronic Assembly

The role of fluxes in electronic soldering is to reduce thin tarnish layers on the substrates and solder, lower the surface tension of the solder to improve capillary flow and optimize fillet geometries, and protect the substrate surfaces from reoxidation during preheat prior to reflow. Electronic-grade fluxes for assembly processes can effectively remove only light oxide layers. Precleaning steps with chemical etchants should be used to remove heavy oxide films and scales prior to assembly. Surface oxide removal by the flux is inhibited by organic films that can be present on the surface. Therefore, surfaces must be degreased prior to application of the flux coating. In electronics applications, the least chemically active flux that satisfies production yields is preferred, to minimize potential corrosion from unremoved residues.

Fluxes are applied to a printed circuit board (PCB; also sometimes printed wiring board, although this term is less commonly used today) by spraying, immersing the board into a bath of flux, passing it through a flux wave, or coating it with a flux foam. The condition of the flux, which changes with use because of solvent evaporation and contamination buildup, is typically monitored by tracking its density. Density can also be used to indicate the viscosity of fluxes used in foaming applications, which in turn determines the ability of the flux to form a foam. Manufacturer recommendations should always be strictly followed, because formulation variations are often proprietary.

Safety and health concerns should be considered in flux usage. Alcohol is a widely used solvent in fluxes, which makes the baths and vapors flammable. Fluxes, like corrosives, can cause acute and chronic irritation to the respiratory tract and skin. Because rosin-based fluxes break down at soldering temperatures to produce fumes of compounds from the aldehyde family, adequate ventilation of the work area is required.

Flux usage must address three materials compatibility issues. First, the potential for damage to device packages (header material, glass-to-metal seals, and such), base materials, and plated surfaces prior to assembly will increase with more-active fluxes. Second, postassembly corrosion may arise from flux residues with high ionic contents, necessitating their removal by postassembly cleaning measures. Third, the cleaning agents and processes used to remove flux residues must be compatible with the devices, substrates, and environmental regulations. Organic solvents, such as 1,1,1-trichloroethane and Freon (E.I. du Pont de Nemours & Company), are very effective in removing rosin-based flux residues. However, these hazardous materials are being restricted from use due to potential environmental damage. Although aqueous and semiaqueous cleaning systems based on water, polar alcohols, and terpenes can be very effective, their compatibility with all electronic materials has not been fully charac-

terized. It should be noted that ultrasonic cleaning processes may damage active and passive devices. Therefore, the compatibility of this technique with assemblies must be verified prior to its implementation. Designers and process engineers must address these concerns at the early stages of process development to prevent costly production errors.

The most critical aspect of PCB cleanliness is ionic residues from the fluxes. When combined with atmospheric moisture, these residues can generate structural corrosion between the dissimilar metals found in the solder joint. The residues can also create metal whiskers by the electromigration of metal ions between lands or conductor lines at different voltage potentials, causing leakage currents that disrupt electrical performance. Ionic flux residues on PCBs are measured by the extraction method, in which the residues are rinsed into a bath, the resistivity of which is converted into the equivalent amount of ionics removed from the board (expressed as $\mu\text{g NaCl}/\text{cm}^2$ of board surface).

The potential for leakage currents, which are a function of substrate material, moisture, and the ionic content of the flux residues, is assessed by the surface insulation resistance (SIR) test. A conductive comb pattern is constructed on the test board. A voltage difference is applied between adjacent legs, and the resistance breakdown is monitored under different temperature-humidity-time conditions. Ionic residue and SIR tests are recommended in the process development stages of soldered assemblies. Several industrial, military, and federal specifications that quantify flux activity and PCB cleaning procedures and criteria for electronic applications have been established. For fluxes used in electronics assembly, the most important specification at the time of this writing is ANSI/IPC J-STD-004B.

Rosin-based fluxes are the most widely used fluxes for electronics assemblies. The RMA flux residues must be removed from most products designated for high-reliability applications. The RA flux residues should be removed from all PCBs, except those used in low-end commercial electronic products. The RSA fluxes are extremely corrosive, and their residues must be thoroughly removed from all products.

Activators are typically halide ions (Cl^- , F^- , and Br^-), which increase the activity of the rosin-based flux. However, halide-free activated fluxes are available and will lessen the corrosion potential of flux residues. Visible residues are tan or white in appearance (Ref 4.8). Black residues indicate that the flux has been exposed to excessive heat, and they are consequently very difficult to remove. Ionic residue determination and SIR tests are strongly recommended for flux activities that exceed those of RMA materials.

No-clean fluxes are also used for electronic assembly, but in this application the demands for substrate cleanliness are sufficiently high that these fluxes do require cleaning. Wack and Becht provide a helpful summary of the relevant technical and economic issues (Ref 4.9).

Organic fluxes require residues to be removed from the product by use of aqueous or semiaqueous cleaning methods. Although in some applications the residues are water-soluble and relatively inert, in electronics assembly it has become more common to use chemicals rather than just deionized (DI) water—in part because the use of lead-free solders requires higher soldering temperatures and therefore causes more burnt-in fluxes. There are chemical cleaning agents that have been found to outperform DI water in this application (Ref 4.10).

Flux activity can be provided by halide-containing compounds. The fluxes are also available in halide-free forms. Although they are more heat resistant than rosin-based fluxes, organic-acid fluxes will char, producing hard-to-remove brown or black deposits. Ionic residue determination and SIR tests are strongly recommended for prototype development and lot sampling in assembly production to ensure adequate flux residue removal.

Inorganic fluxes are not used in PCB assembly operations.

M. Konrad of Aqueous Technologies Corp. (Rancho Cucamonga, CA) writes, “There are forces that have combined to mandate a defluxing process. These modern trends include adoption of lead-free alloys, board and component miniaturization, increased reliability expectations, increased reliance on quality standards, and the increase in product liability. Be it by requirement (military/IPC cleanliness specifications) or by necessity, defluxing is once again part of mainstream assembly processes” (Ref 4.11). His article provides helpful advice on developing a defluxing roadmap, focusing on type of flux, type of assembly, product flow, volume, staff competency, facility restrictions, environmental restrictions, and budget. Probably the best solution for any given assembly operation is to develop a single integrated cleaning process that works for any fluxes that are used, whether clean or no-clean.

Components mounted flush with the surface of a PCB pose special cleaning problems; M. Bixenman of Kyzen Corporation (Nashville, TN) and M. Konrad of Aqueous Technologies discuss flux removal from under such components in an article specifically applied to quad flat-pack devices. They say, however, that “the information presented may be applied to all post-reflow defluxing applications,” and the defluxing methods they describe “may be applied generally to all defluxing applications” (Ref 4.12). The information they present may therefore be helpful in setting up an integrated cleaning process suitable for electronics assembly.

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CHAPTER 5

Solder Pastes

THE RAPID DEVELOPMENT of surface-mount technology processing, which can involve very dense populations of devices and leads, necessitated a method to precisely place controlled amounts of solder on a substrate, either for lead attachment or for bonding of the device to attain more effective heat transfer. Solder pastes that are applied by screening or printing through a mask or by application through a fine tube can fulfill these needs.

Solder paste is a mixture of solder particles with a binder composed of flux, rheological components (such as thickeners), and a solvent material. It is used primarily in printed circuit board (PCB) assembly based on surface-mount technology. Processes such as vapor phase (condensation) and infrared furnace reflow are well suited to solder paste use. Solder particle shape, size distribution, and concentration, along with binder properties, determine the flow properties of the paste.

A solder paste must contain solder particles of the desired composition to yield the melting and joining requirements of the application. The metal particles must be sized to provide good screenability and to avoid excessive oxide content. The shape of the particles is important. Spherical particles are lower in oxide content because there is less surface area, and they are able to flow more freely in screening applications.

A paste must also contain a vehicle to control its rheological, or flow, properties, its drying behavior, its surface activity (wetting behavior), and the solubility of the residues left after reflow. The vehicle usually consists of a rosin (pine derivative) or a synthetic resin, solvents to adjust drying time and temperature, modifiers to control rheological behavior, and an activator, or flux, to remove oxides from the solder and to protect the liquefied solder from oxidation.

As shown in Fig. 5.1, the paste is deposited by screen printing, stencil printing, or bulk dispensing techniques. The screening method, although ancient, has been modernized by the development of new high-precision

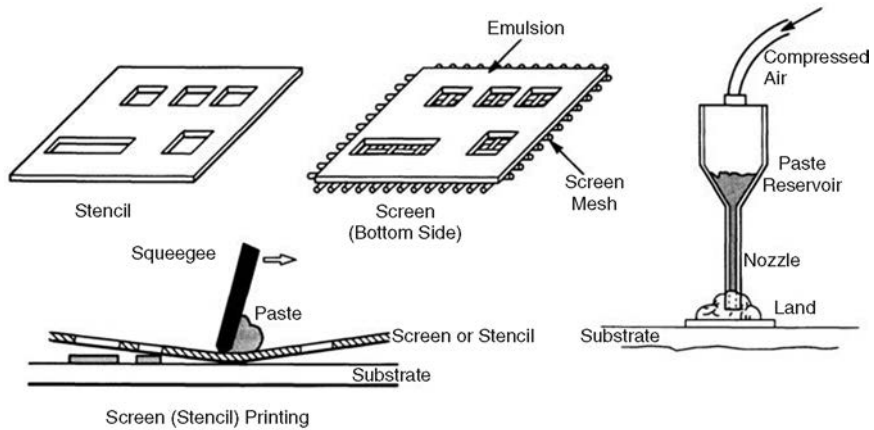


Fig. 5.1 Stencil printing, screen printing, and bulk dispensing of solder paste

screens, solder pastes, and equipment for screening and curing the screened materials. Solder paste also can be applied through a metal mask, or stencil. Although the location of the solder is not as precise as that obtained with screening, the metal masks are more durable and provide better control of solder thickness as it is applied. Another paste-placement method is to use fine tubes or nozzles to deliver the paste to precise locations. This method is ideal for placing discrete dots of paste, rather than covering large areas.

Paste properties (whether applied using screen or stencil) affect the number and kinds of defects observed on the finished solder joint. The PCBs with 1.25 mm (50 mils) pitch require 0.20 to 0.25 mm (0.008 to 0.010 in.) of paste thickness, whereas fine-pitch PCBs (630 μm , or 25 mils, or less) typically use 0.08 to 0.20 mm (0.003 to 0.008 in.) of paste.

The paste must set and hold its shape and location after screening so that subsequent processing maintains the solder in the desired locations and amounts. The assembly is then subjected to heat, and the solder is melted and joined to the part being soldered. This reflow can be conducted either as the final step in soldering or as a separate step. The parts must generally be cleaned after soldering.

Printability can be affected by the distribution of the solder particles, metal content, slump, and viscosity of the paste. For example, smaller solder particles pass more easily through stencil or screen openings. However, the higher oxide content of the smaller particles (larger surface-to-volume ratio) creates a greater number of postassembly solder balls, which are small spheres of solder that fail to coagulate with the larger solder mass in the joint (Fig. 5.2). Solder balls that are not removed by the cleaning process can cause short circuits during device electrical operation.

Metal content refers to the mass percentage of the paste, that is, the solder component. Slump is a measure of the tendency of the paste to

spread away from the deposited configuration prior to reflow. Excessive slump causes the deposits to contact one another (Fig. 5.3a), resulting in solder joint bridges (Fig. 5.3d), which can short circuit electrical signals (Ref 5.1).

Viscosity determines the fluidity of the paste. When viscosity is too high, the paste will not pass through the screen or stencil and will cause skips (Fig. 5.3b). When viscosity is too low, the paste will run out under

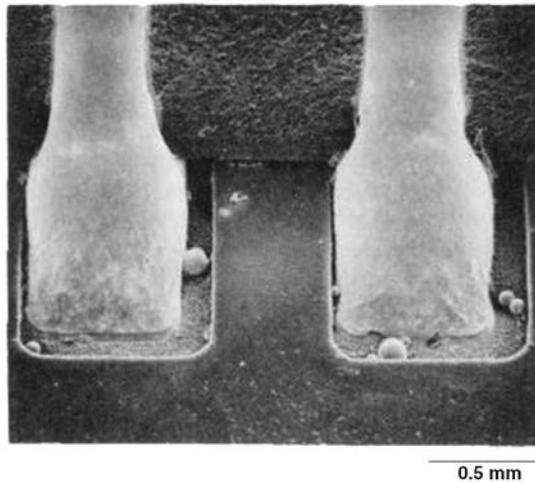


Fig. 5.2 Scanning electron micrograph of solder balls on a leadless ceramic chip carrier solder joint. Courtesy of Sandia National Laboratories

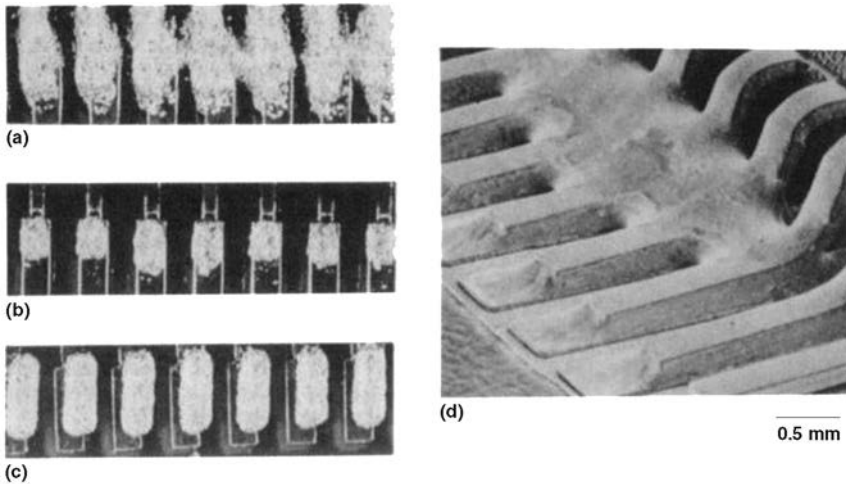


Fig. 5.3 Defects of solder paste deposits. (a) Appearance of paste with poor slump (optical microscopy). (b) Skips in paste deposits (optical microscopy). (c) Paste deposit/land misregistration (optical microscopy). (d) Solder bridges (scanning electron microscopy). Source: Ref 5.1, 5.2

the screen or stencil and will deteriorate the slump properties. Tackiness refers to the ability of the paste to hold devices onto the board prior to the reflow cycle. Paste with poor tackiness causes components to become displaced or to fall from the board during handling prior to reflow, resulting in part misalignment after assembly.

Test procedures that have been developed to quantify solder ball formation, slump, tackiness, and viscosity are identified in IPC-SP-819, “General Requirements and Test Methods for Electronic Grade Solder Paste.”

Solder pastes deteriorate with storage time, which increases viscosity. The addition of thinners will reduce viscosity. Solder particles can further oxidize, leading to increased solder ball formation during reflow. Pastes that contain indium deteriorate more quickly than those based on other alloys. The shelf life of solder pastes can be extended by storage under refrigerated (not freezing) conditions, where the paste surface is sealed from the atmosphere. Manufacturer recommendations should be strictly followed.

Process factors that affect the quality of the printed deposit include:

- Stencil or screen thickness
- Damage and wear to the stencil or screen
- Squeegee stiffness and pressure
- Snap-off distance
- Drying conditions following dispensing
- Stencil (screen) substrate registration (Fig. 5.3c)
- Pressure and orifice size on bulk dispensing equipment

Table 5.1 provides typical solder paste properties for the noted delivery techniques (Ref 5.1, 5.3). References 5.4 to 5.8 provide valuable advice on solder paste selection. Flower (Ref 5.5) in particular also provides data (current as of 2009) about the shift from leaded to lead-free solder paste in the global market; at that time, Asia was over 80% lead free by market share, whereas North America was only approximately 25% lead free.

The traditional methods of dispensing solder paste are by a time-pressure method, in which air pressure from a syringe forces paste through a needle tip for a predetermined period of time, and the more common auger valve method, in which a rotating auger forces paste through a needle tip. More recently it has become possible to use piezoelectric actuators to control dispensing (Ref 5.9).

Table 5.1 General solder paste parameters for dispensing techniques

Dispensing technique	Particle diameter		Metal content, %	Viscosity, Pa · s(a)
	μm	μin.		
Screen printing (–80 mesh screen)	45–75	1800–3000	85	250–550
Stencil printing	45–75	1800–3000	85–90	400–800
Bulk	30–75	1200–1800	80–85	100–400

(a) 1 Pa · s = 1 kcps

ACKNOWLEDGMENT

Most of this chapter was adapted from M.M. Schwartz, *Fundamentals of Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 126–137; and P.T. Vianco, *Soldering in Electronic Applications, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 985–1000.

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CHAPTER 6

Soldering Processes and Equipment

THE PROPER APPLICATION OF HEAT is of paramount importance in any soldering operation. The solder should melt while the surface is heated, to permit the molten solder to wet and flow over the surface. The choice of heating method is therefore an important consideration.

6.1 Iron Soldering

Iron soldering was the earliest soldering method. The hand-held soldering iron used in this process continues to be popular and is the most cost-effective tool for:

- Prototype and short production jobs
- Rework of defective solder joints and/or components
- Soldering of components that are too delicate or specialized to solder using mass-production techniques

Essentially, a heated metal tip is used to raise the temperature of the metals to be joined or of the joint. As the temperature increases, flux becomes activated, which allows the solder to wet the base metals.

The traditional soldering tool is the soldering iron, or bit, with a tip (usually copper) that can be heated electrically, by direct flame, or in an oven. Because soldering is a heat-transfer process, the maximum surface area of the heated tip should contact the base metal. The solder itself should not be melted upon the tip of the iron when a joint is being made. To lengthen the usable life of a copper tip, a coating of solder-wettable metal, such as iron with or without additional coatings, is applied to the surface of the copper. The rate of dissolution of the iron coating in molten

solder is substantially less than the rate for copper. The iron coating also shows less wear, oxidation, and pitting than uncoated copper.

The modern soldering iron consists of an electric resistance heater, a temperature controller, and an iron-plated copper tip. Many different materials, such as high-resistance metal alloys and ceramic and ferromagnetic materials, are used to develop the high resistance of the heater. The soldering tip conducts the heat from the heater to the joint. A temperature controller is required for stable tip temperature. When the tip is placed in contact with the joint substrates, heat is conducted to them, and the tip temperature decreases. The temperature controller senses the decrease in tip temperature and increases the heat generated by the heater. Once the tip temperature has increased to the controller setpoint, the heat being generated is reduced. A typical soldering iron is shown in Fig. 6.1.

Soldering irons are available in a large variety of sizes and designs, ranging from a small pencil to special irons or bits that weigh 2 kg (5 lb) or more. The selection of the iron depends on the application and the quantity of heat needed at the joint. The heat recovery time of the iron should be fast enough to keep up with the job.

The most common soldering iron tip consists of a copper core with protective iron or nickel plating. Although copper is an excellent conductor of heat and has a high caloric heat content, it is soluble in common tin-base solders. The iron/nickel plating protects the copper from dissolving in the molten tin alloys. Because this plating does not react with the molten solder, the life of the copper tip is extended greatly. In its non-working area, a tip is usually plated with chromium, which serves two purposes: It provides a nonwetting surface to prevent the solder from migrating away from the working surface of the tip, and it minimizes tip oxidation. Because tip life is a common concern among soldering iron users, most soldering iron manufacturers produce tip care guides that can extend tip life.

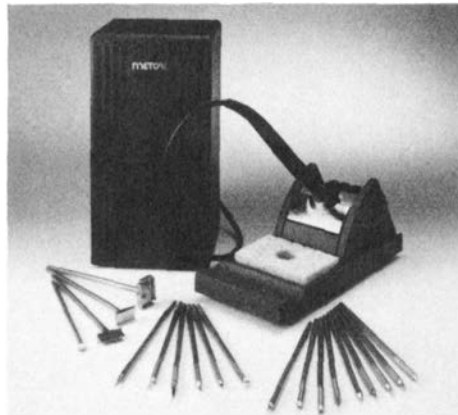


Fig. 6.1 Typical soldering iron

The lowest possible tip temperature, the largest tip working area, and the shortest tip length should be chosen. A wide variety of tip geometries is usually needed to provide the specialized component contact for which soldering irons are advantageous. Soldering iron sales personnel can usually help the user choose the most flexible and useful tip geometry for the specific task.

Regardless of the heating method, the tip performs the following functions:

- Storing and conducting heat from the heat source to the parts being soldered
- Storing molten solder
- Conveying molten solder
- Withdrawing surplus molten solder
- Bringing the workpiece joint area to the soldering temperature

The angle at which the copper tip is applied to the work is important in terms of delivering maximum heat. The flat side of the tip should be applied to the work to obtain the maximum area of contact. Flux-cored solders should not be melted on the soldering tip, because this destroys the effectiveness of the flux. The cored solder should be touched to the soldering tip to initiate good heat transfer, and then the solder should be melted on the work parts to complete the solder joint (Ref 6.1).

Equipment. Hand soldering equipment can be broadly classified by its temperature-control method. There are constant-voltage, variable temperature, and tip-temperature-controlled soldering iron types, each of which is described subsequently.

Constant-voltage soldering irons are temperature-limited but do not incorporate a temperature sensor. Temperature calibration of the tip is not possible, because these irons depend on the increasing resistance of the heating element to limit tip temperature. Line voltage fluctuations and ambient temperatures greatly affect the temperature of the soldering tip. A constant-voltage soldering iron is the least expensive hand soldering tool. However, this type of soldering iron requires highly skilled operators to create reliable joints.

Variable-temperature soldering irons incorporate a temperature-control device in the soldering handle. A control knob on the power source provides a means for the user to vary the tip temperature. When the soldering tip achieves the prescribed temperature, current to the heater is turned off. The tip cools to the lower-temperature setpoint of the controller, and current to the heater is turned back on. Tip temperature calibration is possible with variable-temperature soldering irons. This type of iron can be adjusted so that its temperature is balanced with the thermal requirements of the joint. However, one of its drawbacks is that an unskilled or inattentive operator may leave the temperature at the highest setting, in an at-

tempt to solder more quickly, damaging heat-sensitive components or printed circuit boards (PCBs). Damage can also occur when the heat is too low and an operator stays on the termination too long while adding pressure.

Temperature-controlled soldering irons incorporate a temperature sensor in the soldering tip. These soldering irons operate at a manufacturer’s preselected temperature, and tip temperature calibration is not required. Tips are selected for their shape, as well as their operating temperatures. At the preselected temperature, either the resistance of the heating element changes or the current supplied to the heating element is turned off. The resulting reduction in heat generation stabilizes the tip temperature at its setpoint. Temperature-controlled soldering tips help ensure that the proper tip is used in a production environment, thus eliminating costly damage to PCBs and components. This tool requires the least amount of operator training.

Soldering Iron Selection. When selecting a soldering iron, potential damage to the PCB and its components must be considered. Damage can result from excessive joint temperatures or electrical overstress. Thermal damage can result from an iron that is not temperature controlled or is operated at too high a temperature, whereas electrical overstress results from the flow of electrical energy (leakage or electrostatic) when the iron is placed in contact with the component, which damages or weakens an electrical component.

Figure 6.2 illustrates a typical soldering iron tip and joint thermal profile for repetitive joints. When an iron and tip have been properly selected, the tip temperature will decrease when the tip is placed in contact with the joint and solder is applied. When the temperature of the joint is from 28 to 55 °C (50 to 100 °F) greater than the solder liquidus temperature, the tip is removed from the joint. The tip temperature recovers (increases) to its setpoint as the solder joint cools.

When a soldering iron is improperly selected, each successive joint connection decreases the working temperature of the tip. After several solder joints have been completed, the tool may be unable to form reliable

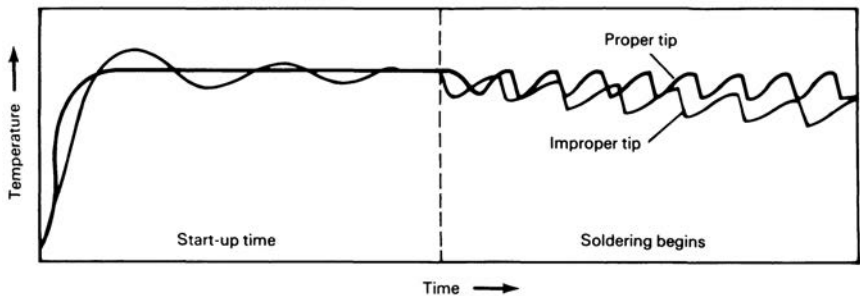


Fig. 6.2 Typical soldering iron tip and joint thermal profile

joints. A properly selected soldering iron will stabilize the tip at a temperature that does not damage components, while providing a working temperature sufficient for soldering successive joints reliably.

References 6.2 to 6.4 detail complete construction and soldering iron techniques for PCBs, including component mounting and soldering steps. Also given are qualities and descriptions of good and bad soldered joints, including graphics of air pockets, floaters, dimples, excess solder, balling, blowholes, and dull or crystallized surfaces. Point-to-point prototyping techniques are described in the design of a PCB as well as flea clips and spacers and chassis.

Reference 6.5 contains a good introductory lesson on how to solder with a soldering iron, and Ref 6.6 provides much helpful advice on achieving consistent results in hand soldering operations requiring high throughput and productivity.

6.2 Torch Soldering

Torch soldering uses a fuel-gas flame as the heat source in the soldering process. The fuel gas is mixed with either air or oxygen to produce the flame, which is applied to the materials to be soldered until the assembly reaches the proper soldering temperature. Solder filler metal, which melts at temperatures below 450 °C (840 °F), is added to the assembly to bond it. Successful torch soldering is accomplished when parts are clean and fit together closely and when oxides are not excessive.

The selection of a gas torch is controlled by the size, mass, and configuration of the assembly to be soldered. When fast soldering is necessary, a flame is frequently used. The flame temperature is controlled by the fuel mixture used. Fuel gas burned with oxygen gives the highest flame temperature possible with that gas. The highest flame temperatures are attained with acetylene. Lower temperatures are obtained with propane, butane, natural gas, and manufactured gas.

Multiple flame tips, or burners, often have shapes that are suitable to the work. They can be designed to operate on oxygen and fuel gas, compressed air and fuel gas, or Bunsen-type torches.

When adjusting tips or torches, care should be taken to avoid adjustments that result in a sooty flame, because the carbon deposited on the work will prevent the flow of solder (Ref 6.1, 6.7).

Torch soldering is used in numerous industries that utilize a variety of base metals. It is most often used to produce a leaktight assembly with some degree of mechanical strength. This process does have several advantages when compared with other metal-joining methods. These advantages include:

- Relatively low temperatures, which result in minimal distortion and heat discoloration of the soldered assembly

- Flexibility, such that one torch can be used to solder a variety of assemblies
- Relatively inexpensive capital equipment cost
- Ability to solder most base metals and base-metal combinations with an appropriate flux
- Local heating of small joints on large assemblies, which precludes the need to heat the entire assembly
- Process automation, in many cases

The limitations of the process are that:

- A flux is needed because the process is accomplished in air, and this flux often must be removed to prevent part corrosion.
- Highly reactive materials, such as titanium and many refractory metals, cannot be soldered, because no suitable fluxes are available.
- Soldered joints do not normally exceed the strength of the parts being soldered; that is, the process produces relatively weak joints when compared with brazed and welded assemblies.

Torch soldering is used extensively on copper, brass, and other copper alloys. Steel, stainless steel, aluminum, gold, and other metals, as well as many combinations of these, also can be soldered by this process.

The plumbing industry uses this process extensively on residential copper tubing for water lines, primarily because of its flexibility and ease of use. Soldered copper water lines provide leaktight joints with the requisite strength. Torch heating is also used for liquid and gas conduit in industrial processing applications.

This process is also used by many other industries in assembly processes, such as the soldering of jewelry, aluminum heat exchangers, radiators, and pressure-sensing devices. Tube-to-fitting types of assemblies also are commonly torch soldered, as are butt and lap joints.

Equipment. Typically, the equipment required for torch soldering is simple.

Torch. Single torches are often used for hand soldering, whereas multiple torches can be used together on automated systems.

Gases. Fuel gas and air systems are frequently used for torch soldering because of the low heat requirements. The plumbing industry often uses a simple hand-held propane/air torch that is attached to the top of a small, rechargeable cylinder. Surrounding air is mixed with the propane from the cylinder in the appropriate ratio.

Gas/oxygen systems can also be used for torch soldering, although they produce more heat than gas/air systems. This amount of heat is not normally required for torch soldering.

A reducing flame—that is, a flame where excess fuel is present and surrounding air is used to complete combustion—is typically used when sol-

dering. A reducing flame helps keep the assembly clean by reducing surface oxides.

Filler Metals. Many different filler metals are used in the torch soldering process. Tin-lead, tin-silver, and tin-antimony filler metals are commonly used on copper alloys, steel, and stainless steels. Zinc-aluminum is used exclusively on aluminum-base metals. The solders that are commonly used as filler metals are shown in Table 6.1.

Basic Heating Techniques. The key to torch soldering, as in all methods of heating, is to equally heat the components that need to be soldered. This may require directing the torch to a larger mass component of an assembly. Because the filler metal will flow to the hottest portion of an assembly, the flame should be applied so that the filler metal will flow in the intended direction. Also, movement of the torch is required to avoid overheating or burning the assembly.

Figure 6.3 shows the appropriate wire and torch placement for the soldering of tubing. Proper heating will result in the flow of filler metal through the joint, resulting in a fillet both inside and outside the joint. This ensures that a leaktight joint has been produced.

Torch soldering techniques are easy to learn with proper training and experience.

6.3 Dip Soldering

Dip soldering is accomplished by submerging parts to be joined into a molten solder bath, which supplies both the heat and the solder required to produce the joints (Fig. 6.4a).

The molten bath can be any suitable filler metal, but the selection is usually confined to the lower-melting-point elements. The most common dip soldering operations use zinc-aluminum and tin-lead solders.

The molten bath can be heated by electricity or gas. The bath container is made from ceramic materials or a metal that is nonreactive to the filler metal used for dipping. The dip baths, which can range in size from very small to large, are used in a wide range of industries.

This method is useful and economical, because an entire unit comprising any number of joints can be soldered in one operation after proper

Table 6.1 Common solders for torch soldering

Composition	Solidus temperature		Liquidus temperature		Comments
	°C	°F	°C	°F	
63Sn-37Pb	183	361	183	361	Eutectic composition; most fluid of the SnPb alloys
40Sn-60Pb	183	361	238	460	Long melting range; good for filling gaps
96.5Sn-3.5Ag	221	430	221	430	Fluid solder; strongest of low-temperature solders
95Sn-5Sb	233	452	240	464	For copper- and iron-base alloys; not for use on zinc-bearing alloys, such as brass
98Zn-2Al	376	710	385	725	For soldering of aluminum; used extensively on heat exchangers

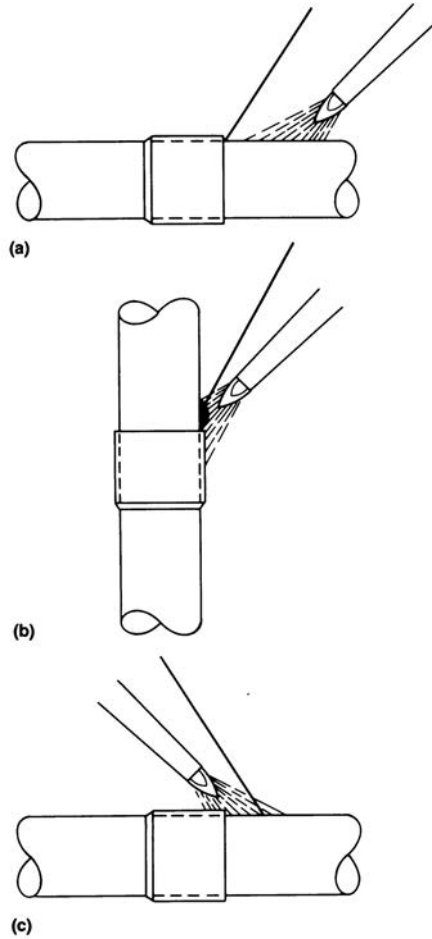


Fig. 6.3 Examples of placement of filler-metal wire and flame. (a) and (b) Proper placement. (c) Poor placement

cleaning and fluxing. Fixtures are required to contain the unit and maintain proper joint clearances during solder solidification. The soldering pot should be large enough so that, at a given rate of production, the units being dipped will not appreciably lower the temperature of the solder bath.

The process of dip soldering is simple to carry out. The joint areas are cleaned and then coated with an appropriate flux. The parts are then lowered into the molten filler metal, and joining takes place by capillary attraction into the joints. The solder does not wet surfaces that are not coated with flux. Jigs and fixtures are normally essential to hold components at proper clearances for joining purposes and to maintain overall dimensions of the finished product. They should not be wetted by the solder. Furthermore, any substrates that must be submerged should be able to tolerate the solder temperature.

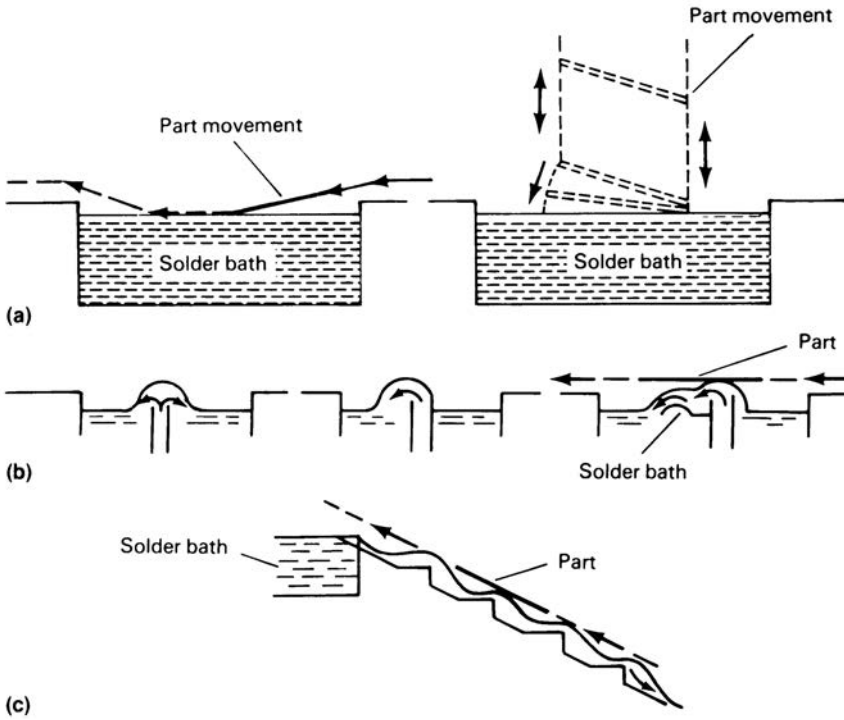


Fig. 6.4 Selected soldering techniques used for high-volume production applications. (a) Dipping on a static bath. (b) Wave soldering system. (c) Cascade soldering system

The molten bath supplies both the heat for raising the temperature of the part and the filler metal to make the joints. It is therefore important that the dip soldering pot capacity be large enough to allow heating of the part and joining without significantly reducing the temperature of the molten filler metal. For some applications, soldering pots are designed for specific production rates.

An advantage of the dip soldering process is the wide range of part sizes, shapes, and thicknesses that can be accommodated by the same apparatus and still result in satisfactory joints. Larger parts require a preheating operation to reduce thermal shock when the part enters the dip pot. The preheat also allows quicker attainment of equilibrium between the molten metal in the pot and the part being joined. Atmosphere protection of the dip soldering pot is necessary when the filler metal has oxidation tendencies. Surface oxides on the workpieces must be removed prior to dip soldering, because they can interfere with a proper joining operation.

Dip soldering is used in job shops as well as high-rate production situations. Therefore, the parts joined by dip soldering vary from individually designed products to mass-produced items. Dip soldering is ideal for the production of prototype engineered products, which are often made for

test purposes. The process also can be used to join limited-production items for the automotive, aircraft, consumer, electronic, and other industries. High-production products are typically heat exchangers for automotive use, high-volume telecommunications equipment, and appliances.

Joints produced by dip soldering techniques are usually sleeve, lap, or T-joints that fill by capillary attraction. The parts to be joined are assembled with gaps appropriate to the particular filler-metal surface tension and viscosity characteristics. The joint/fixture design must accommodate thermal expansion that is due to heating the entire substrate or part. Joint gaps also depend on the reactions of the molten filler metal with the material to be joined. For example, aluminum filler metals (or those with zinc, tin-zinc, or zinc-aluminum alloys) react more quickly with aluminum than a tin-lead solder will with copper and therefore require larger gaps for joining.

Equipment. Dip soldering equipment is very basic, comprising a bath made of metal or ceramic to hold the molten filler metal and a means to heat and control the molten filler-metal temperature. In the radiator industry, job shops use gas heating with their pots for the sake of economy. Much equipment is made to operate electrically, either because of space considerations or because the pots are used in conjunction with other equipment on a production line that may be affected by a gas heating system. Some systems include a metal pump that raises the level of the liquid metal in areas smaller than the overall pot to ensure that no surface oxides are present during the dip operation. This type of equipment is used in automotive radiator manufacture. A typical installation is illustrated in Fig. 6.5.

Solder pots should be run by production personnel who are trained to handle and care for equipment that contains molten metals. A substrate that has been raised to the soldering temperature represents a high-temperature hazard. Parts must be dry upon entering the dip solder pot to avoid splashes or explosions. Suitable protective wear (with guards, where

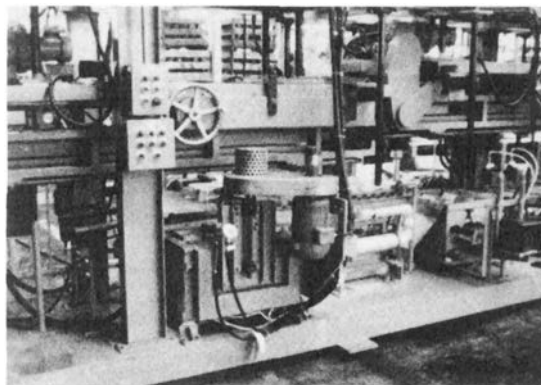


Fig. 6.5 Dip soldering pot in a radiator production line

possible) is necessary. Good ventilation is important, because of flux and possibly metal fumes. Generally, operators of tin-lead solder dip pots are now checked for lead content in the blood, because of possible health hazards.

6.4 Wave Soldering

Wave soldering is one of the primary techniques for mass assembly of printed wiring boards involving through holes, surface-mount devices, or a combination of these two technologies. A schematic of the wave soldering process is shown in Fig. 6.6. A solder “fountain” or wave is created by a pump located at the bottom of the solder pot; suitable baffles are mounted in the pot to direct the flow of solder into the desired configuration. The printed wiring board is placed onto a conveyor, which brings it into contact with the wave surface. Note from Fig. 6.6 that the circuit boards travel along the surface of the solder; molten alloy does not flow on top of the board. As the PCB passes on the wave, the solder wets the surface-mount package leads, terminations, and exposed metal surfaces in the circuit board and also fills plated through holes. This technique can produce several thousand solder joints in a matter of minutes.

Electronic components are commonly soldered to printed wire boards (PWBs) by wave soldering (Fig. 6.4b). The solder is pumped out of a narrow slot to produce a wave or series of waves. This approach, which lends itself to automatic soldering, involves a continuously pumped crest of solder that peaks at the PWB. Another method is drag, or planar, soldering. This method uses a bath, into which the board is automatically dipped with controlled conveyors (Ref 6.8, 6.9).

In cascade soldering (Fig. 6.4c), the solder flows down a trough because of gravity and is returned by pump to the upper reservoir. Both of these wave solder systems are excellent in that a virtually oxide-free solder surface is presented to the part, and the flux and vapors are dislodged by the flow of the solder.

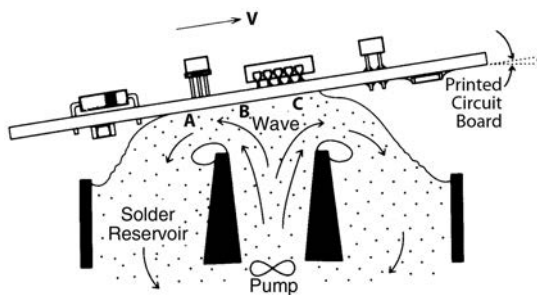


Fig. 6.6 Schematic of the wave soldering process. The three important process-control regions are the entry (A), the interior (B), and the peel-back region (C).

Integrated wave soldering systems for printed wiring assemblies provide units that can apply the flux, dry and preheat the board, solder components, and clean the completed assembly. Some systems have special features that apply the flux by passing the assemblies through a wave, by spraying, by rolling, or by dipping. Several systems use oil mixed with the solder to aid in eliminating icicles and bridging between conductor paths. Another system features dual waves that flow in the opposite direction to the travel of the board.

The implementation of wave soldering for surface-mount technology requires that the devices be glued to the substrate prior to wave soldering. Moreover, the entire surface-mount package must be able to withstand contact with the flux and temperatures of the molten solder without a loss of reliability. Small-outline transistors and discrete components (chip resistors, capacitors, etc.) are readily attached by wave soldering; larger packages (e.g., leaded or leadless chip carriers) may be damaged by exposure to the harsh environments (flux and molten solder) and may be more prone to solder defects (Ref 6.10).

The wave soldering technique encompasses a sequence of processes, all of which are typically contained in the same apparatus. First, the substrate receives a coating of flux. Flux application methods include:

- A wave technique similar to that shown in Fig. 6.6
- Coating the circuit board by a flux foam created by passing air or nitrogen through a flux bath to generate the foam (or froth) on the bath surface
- Directly spraying the flux onto the board surface

After flux is applied, the substrate is passed through a preheating stage. Warming the board promotes activation of the flux, accelerates the evaporation of volatiles from the flux (which can cause voids and solder balls by spattering on contact with the hot solder bath), and reduces thermal shock to the substrate and devices when it passes onto the solder wave. Then, the circuit board contacts the solder wave for the formation of the joints. After passing the wave, the board cools through natural heat loss or, more quickly, by the use of forced air.

The successful assembly of a PCB by the wave soldering technique relies on the proper process parameters and the layout of the board for the respective technology (through hole, surface mount, or mixed). The hole or via size (diameter) must permit adequate capillary filling by the molten solder and form the joint or the interconnect within the short time period (5 to 7 s) that the board contacts the wave. Holes with small diameters (<0.076 mm, or 0.003 in.) and long length joints with very thin gaps restrict the elimination of flux volatiles, causing voids and insufficient solder quantity. Excessively large holes (>1.0 mm, or 0.039 in.) and gaps (>0.40 mm, or 0.016 in.) decrease the capillary driving force of the solder

to fill the volume and create the joint; in some cases, the solder simply drains from the hole under its own weight.

In addition to insufficient solder in holes and vias, other defects in wave-soldered products include bridges, icicles, and skips. Bridges are defects in which a quantity of solder forms a short across two conductors (leads, lands, or traces). A piece of solder that does not short two conductors but rather hangs from one surface is an icicle. Skips refer to the failure of solder in the wave to reach the metal surface and form the joint.

Design considerations, such as the orientation of through-hole leads and surface-mount devices with respect to the direction of travel past the wave, as well as the proximity of packages to one another, can dramatically affect yields (Ref 6.10, 6.11). Figure 6.7 is a diagram showing the preferred orientation of through-hole and surface-mount packages.

Through-Hole Technology. In the case of through-hole assemblies, the leads on the side of a through-hole 16-pin dual in-line package should be oriented perpendicular to the travel direction of the conveyor to prevent bridging between them. Moreover, the bridging of leaded packages can be limited by maintaining the lead extension beneath the circuit board at less than 1.0 mm (0.039 in.). Leads that are too close to each other also increase the chances of solder bridges. Solder skips are less frequently observed on through-hole products (assuming adequate wettability of the metal surfaces), because the device package body is on the top surface and therefore does not shadow joints from the wave.

Surface-Mount Technology. The circumstances of solder defect function are different for surface-mount technology because the entire package passes through the wave. Solder joint skips are more common because the package body can shadow nearby leads or terminations from contact with the wave, causing an inadequate supply of solder at the joint. Therefore, the joint areas of the package should be fully exposed to the wave, as suggested by Fig. 6.7. Packages with leads or terminations on all four sides experience an increased propensity for defects on the leads in the nonpre-

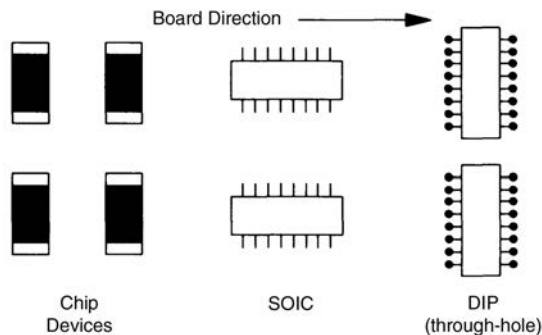


Fig. 6.7 Schematic of preferred device orientation for wave-soldered assemblies. SOIC, small out-of-line integrated circuit (surface mount); DIP, dual in-line package (through hole)

ferred orientation. Also, the greater density of devices on surface-mount circuit boards increases the frequency of solder skips due to the closer proximity of the packages. Finally, the finer lead pitch used on surface-mount leaded and leadless (chip carrier) packages limits or prohibits their assembly on boards by wave soldering.

Process Parameters. The second factor critical to successful implantation of wave soldering of PCBs is the process parameters. Process parameters can be divided into three groups: the fluxing operation, the solder wave properties, and the process schedule.

The fluxing operation includes not only the particular parameters (wave or foam height, spraying pressure, etc.) needed to ensure adequate flux supply to the board for solder wetting but also the condition of the flux. In-line fluxing techniques (wave or foam) frequently use the same quantity of flux to process a large number of boards. Deterioration of the flux due to board contaminants, as well as loss of the flux vehicle, must be monitored to minimize defects in the final product. Specific gravity is used to indicate flux condition.

Low-solids fluxes are gaining popularity as a no-clean alternative to rosin-based fluxes, including their use in wave soldering. The low-solids contents (typically less than 5%) make these fluxes difficult to foam, so spray or wave applications are preferred (Ref 6.12). Tighter control of the flux chemistry, reduced solder pot temperatures (by 10 to 15 °C, or 18 to 27 °F), shorter solder dwell times (by 1 to 2 s), and the use of inert or reducing atmospheres (Ref 6.3) can reduce the number of defects.

Solder Wave Properties. The second process factor is the solder wave properties. The simple wave geometry (also called the T-wave) is shown in Fig. 6.6. Three regions of the wave are identified. The entry region (on the left with the board moving to the right) should be sufficiently turbulent to supply solder to all of the exposed metal surfaces and should permit the escape of flux volatiles that may cause voids in the joint. In the case of surface-mount assemblies, fluid motion must be sufficiently active to force solder close to the packages for adequate wetting of terminations and leads, thereby avoiding solder skips. The interior region of the wave acts as the heat source and solder supply to promote wetting of the substrate features. The exit or peel-back region is the point at which the board leaves the wave and is critical in preventing solder bridge and icicle defects on the circuit board. For example, defects are reduced by having a smooth wave that separates very slowly from the board. This effect is achieved by matching the solder flow velocity with the speed of the circuit board (Ref 6.13) as well as by making adjustments to the wave configuration. Hot air knives positioned after the wave have been used to remove solder bridges and icicles prior to solidification of the solder.

Figure 6.8 shows several equipment modifications used to produce different wave geometries. The extended T-wave and lambda-wave modifications to the standard T-wave cause a smooth surface at the exit region to

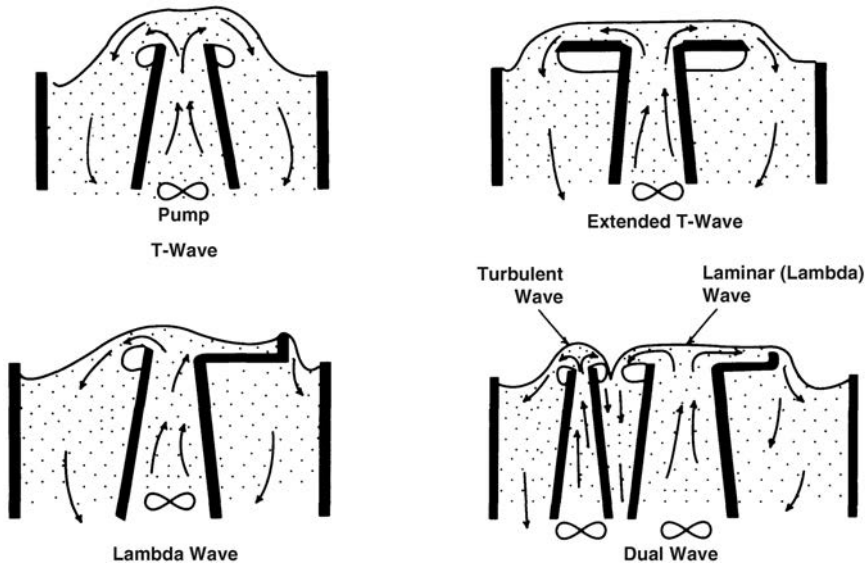


Fig. 6.8 Equipment modifications used to produce different wave geometries. The nomenclature describes the profile geometry of the wave.

limit bridges, icicles, and the formation of excessive dross. The dual-wave configuration provides separate turbulent and smooth (laminar) waves to effect the desired solder joint qualities. Note that these modifications generally require that the circuit board laminate and devices withstand a longer period of contact with the molten solder.

Dross formation tends to be high in wave soldering due to the large surface areas of solder exposed to the atmosphere (which is further aggravated by the turbulent flow of the solder in the pot). Dross particles can become embedded in the solder joints as well as disturb the peel back of the solder upon exiting the board. The use of inert atmospheres, reduced solder temperatures, and oils to cover the solder surface limit the formation of dross.

Solder temperatures are typically higher than those used in reflow processes. The higher temperatures are required to provide sufficient heat transfer to the substrate for adequate wetting as well as to reduce the solder surface tension to limit defects at the peel-back region. Solder pot temperatures are typically 50 to 80 °C (90 to 145 °F) above the liquidus temperature of the alloy; higher values are required for thicker substrates (e.g., multilayer or controlled-expansion substrates). The potential for damage to the laminate, including warpage and distortion as well as delamination of the conductor, increases with higher solder temperatures. Continuous processing with wave soldering equipment can cause a buildup of contaminants in the solder pot (e.g., nickel, copper, and gold from circuit board and lead finishes).

In addition to the traditional tin-lead alloys, wave soldering has been adapted to other solders, including the eutectic tin-bismuth solder and the tin-lead-bismuth alloys (Ref 6.14).

Process Schedule. The third factor in the wave soldering technique is the process schedule, which includes the preheat zone temperature profile, the solder wave temperature, the conveyor tilt angle (α in Fig. 6.6, which affects the exit geometry of the board), and the conveyor speed. The conveyor speed determines the dwell time of the circuit board in the preheat zone and solder wave. Although specific settings depend on the type of equipment and the product being assembled, some general guidelines can be applied. First, the preheat stage should bring the board temperature to the range of 100 to 150 °C (210 to 300 °F). These temperatures provide suitable activation of the flux and lessen thermal shock to the circuit board (and devices) upon contact with the solder wave. The dwell time in the molten solder wave should be limited to 3 to 5 s. Dwell times at the molten solder temperature can reach 5 to 10 s for dual-wave systems. Time-temperature exposure limits for soldering processes are typically specified for devices and the laminate; manufacturer recommendations should always be followed. Also, dwell times should be minimized to limit the leaching of conductor or lead finishes (e.g., copper, nickel, or gold) into the solder.

Defects. Certain defect trends can be identified with particular process conditions (Ref 6.15). For example, voids and blowholes are more frequent at fast conveyor speeds and higher solder temperatures. These process conditions generate an excessively fast heating rate, which causes the rapid volatilization of the flux components and subsequent void formation. Rapid conveyor speed can be responsible for several other defects:

- An increased propensity for poor filling of holes and vias caused by insufficient dwell time in the solder wave. As a result, the wetting kinetics may not fill the volume (this is further exaggerated by low solder temperatures).
- The presence of solder bridges and icicles due to poor matching of the substrate speed and flow of the solder wave at the peel-back region upon board exit
- Cracking of surface-mount ceramic chip capacitors caused by thermal shock

High solder pot temperatures and slow conveyor speeds (i.e., long dwell times) can create difficult-to-remove flux residues. Also, excessive warp or distortion of the board results from inadequate support of the substrate by the conveyor system; this is particularly acute with thinner laminates, higher soldering temperatures, or longer dwell times (e.g., dual-wave systems). Thicker circuit boards (backplanes) may also warp due to the

large thermal gradients through the thickness of the laminate due to inadequate preheating of the board.

Clearly, the various process parameters can interact to produce certain defects. Therefore, optimization experiments and statistical process control are required to obtain and maintain acceptable product yields. The qualitative guidelines cited previously provide a first measure of correlating defects to process conditions for subsequent improvement to the assembly procedure.

6.5 Induction Soldering

Induction or radio-frequency soldering is a versatile means of providing heat to the joint area. Heating is caused by electrical resistance to eddy currents induced in the workpiece. These currents are induced by the rapidly changing magnetic field generated by a coil supplied with an alternating current. The eddy currents are generated at the surface of the workpiece (skin effect) and diminish toward the interior. The depth of direct heating by eddy currents depends on the electromagnetic properties of the workpiece material, the frequency of the alternating current (higher frequency results in shallower penetration depth), and the power level of the magnetic field (i.e., the current in the coil).

The only requirement for a material that is to be induction soldered is that it be an electrical conductor. The rate of heating depends on the induced current flow. The distribution of heat obtained with induction heating is a function of the induced current frequency. The higher frequencies concentrate the heat at the surface of the workpiece.

Induction heating is generally applicable for soldering operations, with the following requirements and attributes:

- Large-scale production
- Application of heat to a localized area
- Minimum oxidation of surface adjacent to the joint
- Good appearance and consistently high joint quality
- Simple joint design that lends itself to mechanization

The induction technique requires that the parts being joined have clean surfaces and that joint clearances be maintained accurately. High-grade solders are generally required to obtain rapid spreading and good capillary flow. Preforms often afford the best means of supplying the correct amount of solder and flux to the joint.

When induction soldering dissimilar metals (particularly joints composed of both magnetic and nonmagnetic components), attention must be given to the design of the induction coil in order to bring both parts to approximately the same temperature.

The advantages of induction heating include the ability to supply heat uniformly over the entire joint area while maintaining a localized temperature rise so heat-sensitive materials or devices neighboring the joint are not damaged. Induction heating is a compromise between global heating processes such as furnaces, which warm the entire part, and more concentrated heat sources, such as torches or soldering irons, which warm only a very localized area. A second advantage of induction heating is that the temperature rise can be very rapid, thereby limiting heat loss into the workpiece, oxidation of the substrate, and thermal degradation of the flux. Limitations that must be considered with the application of induction heating are the cost of the equipment and the need for specially trained personnel. These personnel are needed to ensure proper equipment setup so that efficient transfer (coupling) of energy between the coil and the workpiece take place.

In the induction process, heat energy is not delivered to the workpiece; instead, it is generated within the material by electromagnetic field coupling between the workpiece and the alternating current in the coil (i.e., the workpiece and the coil form an inductance-capacitance-resistance circuit with the power supply).

Several types of equipment are available for induction heating: the vacuum tube oscillator, the resonant spark gap, the motor-generator unit, and solid-state units.

The coupling efficiency is optimized over a narrow range of operating parameters (frequency, coil turns, coil proximity, etc.) in accordance with the given workpiece parameters (electromagnetic properties and part geometry). The first consideration regarding the use of induction heating in a soldering operation is the electrical and magnetic properties of the materials to be joined. First, the energy coupling is more efficient in ferromagnetic materials, that is, materials with large magnetic permeability values (e.g., iron, low-carbon steels, nickel, etc.). Permeability being the same, materials with higher electrical resistivity heat more efficiently than low-resistivity materials. Therefore, heating efficiency is optimized by joints having metals with large permeability and high electrical resistance as opposed to low-permeability, low-resistance metals (e.g., copper, brass, or aluminum). Figure 6.9 illustrates the energy input required to bring several ferrous and nonferrous materials to 188 °C (370 °F) (Ref 6.16). These differences become especially critical when joining dissimilar materials, where one part may heat up more quickly than the other.

Resistivity Effects. The coupling efficiency changes as the material warms up due to the temperature dependence of the electrical and/or magnetic properties. Resistivity increases with temperature for most metals and is the most important concern in nonmagnetic materials. Table 6.2 shows the resistivity changes in materials over the typical range of soldering temperatures. Unfortunately, changes to the overall coupling efficiency (and therefore heating rate) caused by resistance changes are not

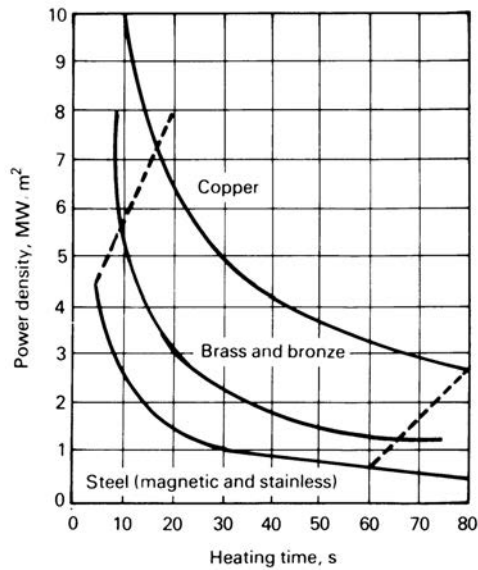


Fig. 6.9 Power inputs and heating times for selected ferrous and nonferrous materials. Source: Ref 6.16

Table 6.2 Relationship of temperature to electrical resistivity, the product of specific heat and material density, and thermal conductivity for selected materials

Temperature		Electrical resistivity (ρ), $10^{-6} \Omega \cdot m$	Product of specific heat and material density ($c\gamma$), $10^6 W \cdot s/m^3 \cdot K$	Thermal conductivity (K), $W/m \cdot K$
$^{\circ}C$	$^{\circ}F$			
Mild steel (0.23% C)				
20	68	0.160	3.65	52.0
100	212	0.220	3.85	51.0
200	392	0.290	4.10	49.0
300	572	0.380	4.40	46.0
400	752	0.483	4.77	43.0
500	932	0.610	5.19	39.3
Stainless steel (19.11% Cr, 8.14% Ni, 0.60% W)				
20	68	0.695	4.04	15.9
100	212	0.776	4.15	16.3
200	392	0.850	4.24	17.2
300	572	0.915	4.36	18.0
400	752	0.976	4.51	19.7
500	932	1.030	4.83	21.4
Copper				
20	68	0.017	3.39	395
100	212	0.022	3.48	387
200	392	0.033	3.57	380
300	572	0.037	3.65	373
400	752	0.044	3.72	366
500	932	0.052	3.77	360
Aluminum				
20	68	0.027	2.52	211
100	212	0.0364	2.59	219
200	392	0.0478	2.65	224
300	572	0.0599	2.71	223
400	752	0.073	2.78	216
500	932	0.087	2.84	209

Source: Ref 6.16

easily predicted because part geometry and penetration depth of the electromagnetic field have a synergistic effect.

Curie Temperature Effects. In magnetic materials, a significant reduction in coupling efficiency occurs when the material passes through its Curie temperature upon heating (i.e., changes from ferromagnetic to paramagnetic). Curie points for iron and nickel are 770 and 358 °C (1418 and 676 °F), respectively (Ref 6.17). Clearly, only nickel would be of concern at soldering temperatures. The magnitude of the coupling loss depends strongly on the geometry of the part and the coil configuration. Lost coupling efficiency due to resistance or magnetic property variations can be regained by changes to the power supply frequency during the soldering procedure. However, in the case of the Curie transition, the exceptional heating rate of ferromagnetic materials can never be wholly recovered.

Temperature rise in the workpiece is also affected by the thermal mass of the part(s) as reflected by thermal conductivity, specific heat, and size of the part. Heat loss from the joint area due to thermal conductivity as well as excessive part size can lengthen heating times, making it difficult to uniformly heat joints containing dissimilar metals. Thermal mass is often expressed quantitatively by the product of the specific heat (c) and the material density (γ). Values of $c\gamma$ are given in Table 6.2.

Workpiece Geometry. Induction heating is more efficient and more easily practiced on workpieces with simple, axisymmetric geometries because they, in turn, require simple coil geometries. Electromagnetic energy is more easily coupled into the part due to closer proximity to the workpiece and the generation of a more uniform magnetic field. Uniformity, as well as field strength, improves as the number of turns in the coil is increased. A larger coil also provides a more uniform field but at the expense of delocalizing the heating area. Some sample coil configurations for typical part geometries are shown in Fig. 6.10. Finally, uniform heating of the workpiece can be achieved in relatively nonuniform magnetic fields by rotating the part within the coil.

Use of induction heating becomes more limited as the workpiece geometry becomes complex. First, the placement of the coils about or near the joint area becomes more difficult. Secondly, corners and protrusive shapes in the magnetic field may develop hot spots caused by proximity to the coil or low thermal mass, thereby possibly damaging the material at those locations. To accommodate complex part configurations, coil shapes can be altered to vary the local magnetic field strength and hence change the localized heating of the part. For example, the overheating of a corner or protrusion can be reduced by locally decreasing the number of coil turns in that area or by positioning the coil farther from the workpiece. The opposite actions apply to part configurations with large thermal mass that require additional power input to prevent heat-sinking effects.

In addition to surrounding the part with the coil to maximize coupling, coils can be used as proximity sources for localized heating. In this tech-

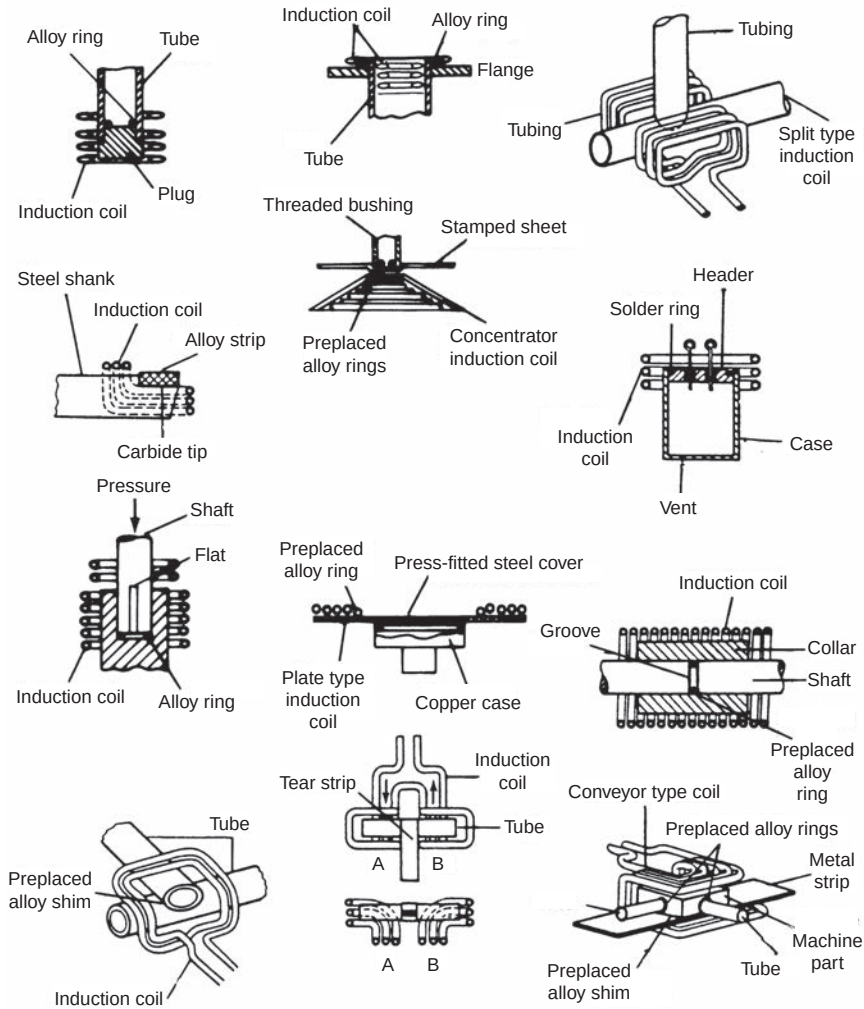


Fig. 6.10 Coil configurations for typical joint shapes. Source: Ref 6.16

nique, a coil (typically smaller than the part) is located next to the joint area to be heated. As expected, the limited magnetic field intensity causes this technique to have very low coupling. The heating area can be extended by manually scanning the coil over a larger area (such as is done in torch heating).

Preplaced Solder. Soldering by induction heating necessarily implies joints designed for the use of solder preforms or paste; these items are introduced into the joint area prior to applying heat. The amount of solder is much less than the mass of the parts, so the effect of the preform on the induction heating process is typically negligible. Space restraints, as well as the danger of electrical shock and severe burns, prohibit manual inter-

action with the workpiece during heating. Therefore, certain practices associated with the use of preplaced solder must be followed:

- An adequate supply of solder alloy must be present to completely fill the gap.
- Provision must be made for solder flow through the joint and the escape of flux volatiles from the joint.
- Design considerations must allow for an increased propensity of void formation due to limited capillary fill with preplaced solder.
- Fixturing that secures the workpiece during soldering must maintain substrate alignment and the joint gap specified for the final product.

Wetting of the parts can be enhanced by hot solder dipping or by electroplating a coating of tin-lead solder on the joint surfaces prior to final assembly. Although typically performed in air, induction soldering can also be practiced in inert atmospheres or in vacuum (e.g., localized cover gas blankets or more sophisticated equipment such as glove boxes and large chambers). Induction heating is well suited for robotic automation, including bench-top systems as well as larger-scale factory production lines. Monitoring the workpiece temperature by optical pyrometry can provide a feedback signal for real-time control of the induction power source, thereby improving reproducibility of the heating schedule parameters.

Setup Parameters. The heating requirements of some simple workpiece geometries (and accompanying simple coil geometries) have been calculated, and performance parameters have been tabulated in charts (Ref 6.16). However, maximizing the energy coupled into a particular workpiece is more often the result of trial-and-error experiments with coil configurations, power supply frequency, and voltage. Nonoptimum coupling causes greater current to be drawn from the power supply to achieve the desired heating of the part, possibly exceeding the power capacity of the generator. Joints between dissimilar metals further lessen optimum coupling and diminish efficiency.

Although induction heating may require some trial-and-error efforts to optimize the process for a given product, some preliminary calculations can provide approximate design criteria from which to begin process development.

The first parameter required to set up an induction system is the power required to heat the workpiece(s). For localized heating, heat is lost to the remaining mass of the part as well as through radiation, conduction, and convection with the atmosphere. For a first-order approximation, ambient heat loss can be neglected, particularly with the relatively low temperatures necessary for soldering processes. However, conduction into the solid away from the joint area can be significant; moreover, the calculations to quantify the effect may be very complex. An estimate of the power, P , required to heat a section of material can be determined from:

$$P = \frac{\gamma c \Delta T V}{t} \quad (\text{Eq 6.1})$$

where V is the volume to be heated, c is the specific heat of the material, ΔT is the temperature rise, γ is the density of the material, and t is the time for the temperature increase to take place. Of course, the power rating of the induction heating equipment must be higher than that calculated in Eq 6.1 to account for coupling inefficiencies and the heat-loss mechanisms noted previously. The overall efficiency of induction heating nonferrous metals is 50 to 75%. Values are approximately 75% for magnetic metals that are below the Curie temperature (i.e., in the ferromagnetic state).

Selection of a power frequency depends on the type of soldering material and the size of the workpiece. Table 6.3 gives typical frequencies for the through heating of nonferrous metals. The representative geometry is that of round bar. A similar range of values can also be used for magnetic materials below the Curie temperature. Heating the material above the Curie point requires a frequency increase to maintain reasonable power coupling, particularly as the part size increases (power input to the workpiece is proportional to the square root of the frequency). Frequency values at temperatures exceeding the Curie point are 3 to 10 kHz for part sizes of 5 to 40 mm (0.20 to 1.6 in.) diameter and 1 to 3 kHz for diameters of 40 to 150 mm (1.6 to 5.9 in.).

A parameter of particular interest to induction heating is the penetration depth of heating (also called the skin depth), and this is denoted by the symbol δ . The skin depth is defined as the position in the solid away from the surface at which the magnitude of the magnetic field falls to approximately 37% of its value at the part surface. The skin depth is given by:

$$\delta = \frac{\rho}{\pi \mu f} \quad (\text{Eq 6.2})$$

where ρ is the resistivity of the part, μ is the absolute magnetic permeability, and f is the frequency. The absolute permeability is equal to the product $\mu_r \mu_0$, where μ_r is the relative permeability of the material (e.g., pure iron = 18,000 and nonmagnetic copper = 1), and μ_0 is the permeability of free space, which equals $1.257 \times 10^{-6} \text{ V} \cdot \text{s/m} \cdot \text{A}$ (a universal constant). Skin depth increases as the material resistivity increases and as the fre-

Table 6.3 Frequencies for the through heating of nonferrous metal round bars

Bar diameter		Frequency, kHz
mm	in.	
0–12	0–0.5	450
12–25	0.5–1	10 and 3
25–75	1–3	1
>75	>3	50

quency decreases. For magnetic materials at temperatures below the Curie point, the value of μ_r is not a constant; it is dependent on the magnetic field intensity, H_0 . For example, the value of μ_r for a low-carbon 1044 steel is $734,000/H_0^{0.92}$.

Safety Concerns. The safety hazards accompanying the use of induction heating include electrical shock from contact with the coils as well as burns caused by the heated workpiece. A third hazard is the danger of steam explosion caused by arcing between the coil and the part. Typically, the heating coils are hollow copper tubing; they are cooled by the internal flow of water or a water-based coolant. The vapor cloud accompanying the spatter of flux during soldering can cause an electric arc that may puncture the copper tubing if the induction coil is close to the workpiece. Arcing can also be caused by movement of the coil windings through forces generated by the magnetic field. Water contacting the hot part produces an immediate, violent steam explosion. To prevent this occurrence, adequate clearance should be maintained between the coil and the part (typical minimum spacing is 6.4 to 13 mm, or 0.25 to 0.50 in.). Moreover, trial heating runs, in which the current is slowly increased to assess coil movement and part-to-coil shorting, should be performed prior to product assembly.

6.6 Furnace and Infrared Soldering

Furnace soldering encompasses a group of reflow soldering techniques in which the parts to be joined and preplaced filler metal are put in a furnace and then heated to the soldering temperature. There are many applications, especially in high-production soldering, where a furnace will produce consistent and satisfactory soldering. Although this method is not widely used, furnace heating should be considered under the following circumstances:

- When entire assemblies can be brought to the soldering temperature without damage to any of the components
- When production is sufficiently large to allow expenditures for jigs and fixtures to hold the parts during the soldering process
- When the assembly is complicated in nature, making other heating methods impractical

The proper clamping fixtures are very important during furnace soldering. Movement of the joint during solder solidification can result in a poor joint.

Another important consideration in furnace soldering is flux selection. Rosin and organic fluxes are subject to decomposition when maintained at elevated temperatures for an extended period of time. When either rosin or organic flux is used, the part must be brought rapidly to the liquidus tem-

perature of the solder. It is sometimes beneficial to dip the parts in a hot flux solution before placing them in the oven. When using rosin-based flux, it is generally necessary to use a solder with a tin content of 50% or more.

The reducing atmosphere used in the furnace does not allow joints to be made without flux, because the temperatures at which these atmospheres become reducing are far above the liquidus temperature of the solders. The use of inert atmospheres will prevent further oxidation of the parts, but flux must be used to remove the oxide that is already present.

The furnaces should be equipped with adequate temperature controls because solder flow begins at approximately 45 to 50 °C (80 to 90 °F) above the solder liquidus temperature. The optimum condition exists when the heating capacity of the furnace is sufficient to heat the parts rapidly to the liquidus temperature of the solder.

Five reflow technologies are currently certified for use in surface-mount technology (SMT) applications:

- Type A: vapor phase
- Type B: area conduction (that is, linear conduction)
- Type C: hot bar
- Type D: convection and convection/infrared
- Type E: laser

Mass Reflow Techniques. Of these five methods, three are considered to be mass reflow techniques (types A, B, and D), because all of the solderable interconnections on the surface of a PWB assembly are brought through the reflow heating cycle simultaneously.

Vapor-Phase Reflow. Also known as condensation heating, vapor-phase reflow had early prominence as an SMT reflow soldering method. A fluid that has a boiling point higher than the solder melting point is heated and the vapor is contained in a chamber, through which the PWB assembly is passed. Heat transfer is achieved through the heat of vaporization released by the fluid as it condenses on the PWB surface. The fluids are compatible with most substrate and device packaging materials. The process is relatively insusceptible to variances in component distribution and assembly densities. Additional information can be found in the “Vapor-Phase Soldering” section of this chapter.

Area Conduction. This comprises multiple hot plates with a substrate conveyance system. This method can also be combined with other energy-transfer techniques, including convection and infrared, when appropriate for specific applications.

Infrared Heating. Infrared (IR) technology has been very successfully adapted to SMT reflow soldering. Area IR emitters, that is, radiant panels, and lamp radiant emitters that are arranged in arrays with reflectors are incorporated in a conveyORIZED oven to provide the source of heat. By

using mid- to far-IR emissions and presenting a large heated surface area to heat the resident atmosphere in the oven, the dual heat-transfer technologies (that is, IR heat provided by the direct lamp heat and conduction-generated heat provided by the indirect heating of the atmosphere) can achieve a very controlled rate of heating, which is ideal for SMT reflow soldering.

Optical soldering systems that focus IR light (radiant energy) on the joint by means of a lens are available. Lamps with power ratings that range from 45 to 1500 W (140 to 4700 Btu/h) can be used for different application requirements. The devices can be programmed through a silicon-controlled rectifier power supply with an internal timer.

The most common sources of IR heating for soldering applications are heated filaments. The quartz-iodine tungsten-filament lamp is widely used because it is very stable and reliable over a wide range of temperatures.

In general, IR soldering systems are simple and inexpensive to operate. One of the most critical operating parameters is surface condition. Variations in the condition of the solder surface can be compensated for, to some extent, by adjusting the heating power. Advantages are process repeatability, ability to concentrate or focus the energy with reflectors and lenses, economy of operation, and absence of contact with the workpiece.

Infrared reflow has continued to evolve. Emphasis has been placed on enhancing heat transfer through forced convection (class 3), also known as convection-dominant reflow soldering (Fig. 6.11, 6.12). Convection

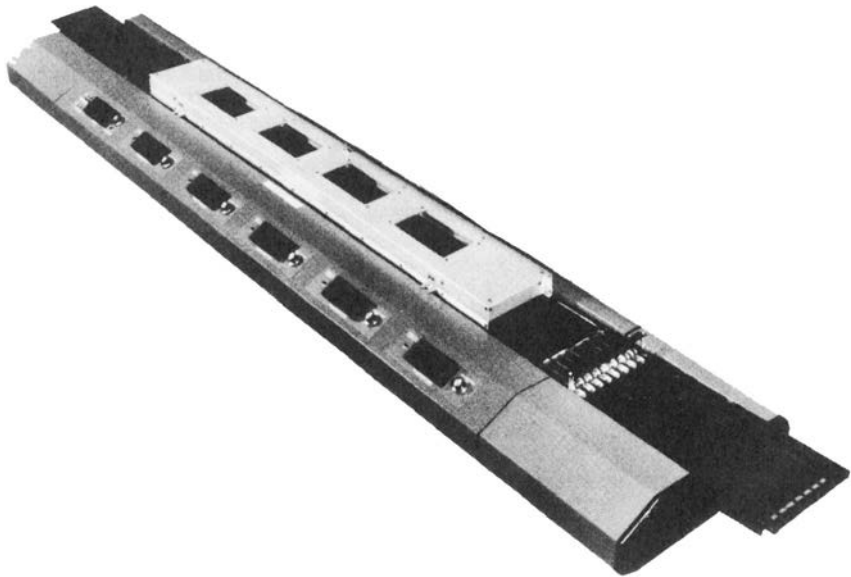


Fig. 6.11 Conduction reflow soldering oven with forced convection enhancement. Courtesy of Sikama International

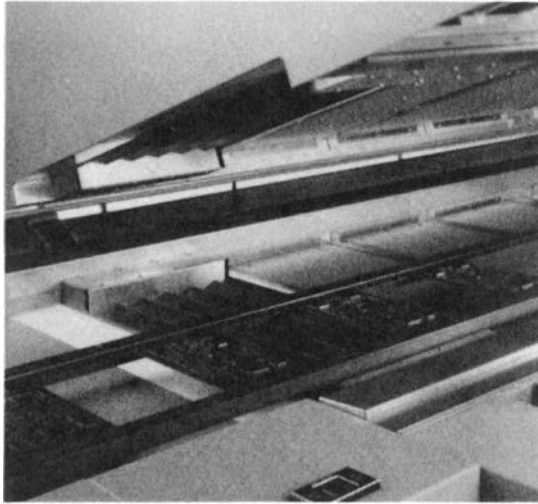


Fig. 6.12 Forced convection reflow soldering oven used to solder printed wire board components. Courtesy of Vitronics Corporation

evens out the hot and cold spots caused by different surface adsorptivity. The intent is to approach the beneficial near-equilibrium aspects of vapor-phase reflow but with the multizone profile control that has been traditionally offered by the convection/IR method. This objective is driven by the more-complex soldering applications, in terms of assembly mass and surface geometries.

Reflow Profile. The heating cycle of the PWB assembly should be precisely controlled. The reflow profile is composed of four regions (Fig. 6.13):

- Preheat (prebake)
- Preflow (soak)
- Reflow
- Cooldown

Preheat. As the PWB assembly enters the oven tunnel (at ambient temperature) and energy is introduced to the assembly, the heat-transfer process begins. The interconnection temperature is brought up to approximately 100 to 120 °C (212 to 250 °F) to reduce the risk of thermal shock to the components and PWB delamination. The control of the rate of heating is most critical in the preheat portion of the profile. Many component manufacturers, particularly suppliers of ceramic capacitors, recommend a preheat rate of heating that is less than 4 °C/s (7 °F/s). The rate of heating should be based on the application, and the component complement should be considered.

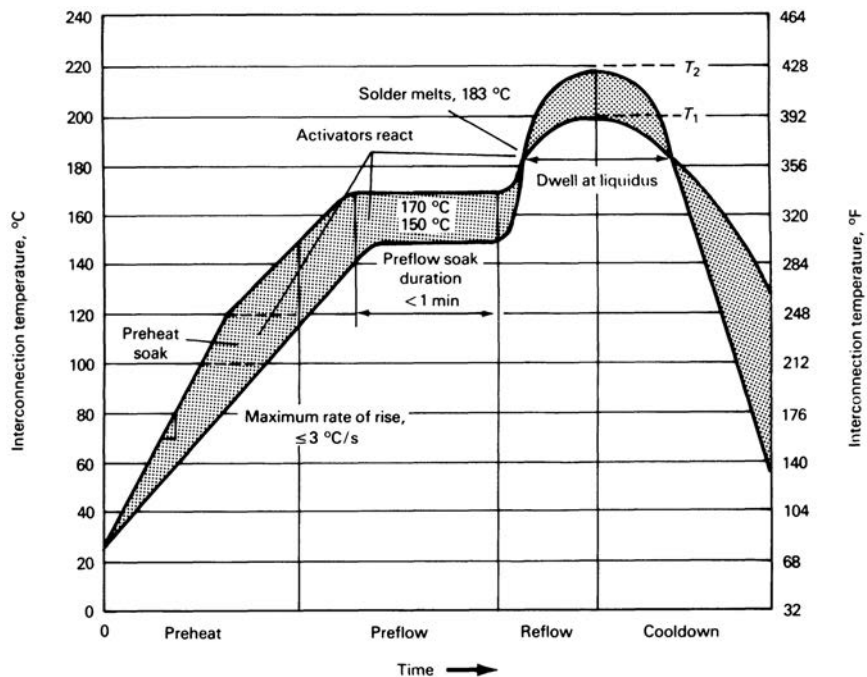


Fig. 6.13 Plot of interconnection temperature versus elapsed time showing four regions that constitute reflow profile. Total elapsed time from preheat to cooldown varies from 3 to 6 min.

Throughout the preheat stage, activators commence scrubbing and some solvents begin to evaporate. In certain solder paste formulations, some of the flux activators may begin oxide reduction at this stage.

Preflow. Before it attains reflow temperatures, the assembly is allowed to soak for a period of time. Those PWB assemblies that have polymer-based substrates require time to allow the transfer of heat throughout the assembly, to reduce thermal gradients. The remainder of the noncontributing solvents contained in the solder paste is driven off. As the temperature of the solderable interconnections is brought to just below the solder melting point, flux activators react with the surface to clean component and pad interfacing surfaces.

The temperature range and duration of this stage varies among flux types and the solder paste formulations that different manufacturers produce. Generally, rosin mildly activated (RMA) fluxes become fully activated in a preflow soak at temperatures between 150 and 170 °C (300 and 340 °F). Some RMA formulations achieve optimum results when the preflow soak is held to less than 1 min (Fig. 6.13).

Some organic acid (OA) fluxes exhibit preflow characteristics that are similar to those of the RMA fluxes. Many OA formulations are optimized with a gradual slope in which temperature rises from approximately 100

to 170 ± 15 °C (212 to 340 ± 30 °F) (Ref 6.18). The duration of preflow is very critical to OA fluxes and will typically be approximately 1 min, although this will vary among different formulations (some manufacturers recommend minimizing the duration). If the preflow time interval is too long, paste oxidation and flux degradation can occur.

Reflow. As the temperature of the solder paste on the interconnect passes the melting point of the solder alloy and enters a molten state, the reflow portion of the process begins. With 63Sn-37Pb, a eutectic solder that represents the most commonly used alloy in SMT assembly, reflow occurs at 183 °C (361 °F). During the reflow stage, all solderable portions of the PWB assembly reach their desired peak temperatures. Most solder manufacturers recommend bringing the interconnect temperature to approximately 15 to 30 °C (27 to 54 °F) above the alloy melting point to ensure complete melting, as well as good solder flow, and to aid fillet formation. This is designated T_1 in Fig. 6.13. The supplier should be consulted to provide the actual temperature for a particular formulation.

The duration of time at which a solderable interconnect resides above the melting point of the solder paste is called the dwell at liquidus. The liquidus dwell extends through the reflow portion of the profile and into the cool-down portion until the solder reaches solidus. This is the most critical portion of the reflow profile. Because these are the highest temperatures endured by the assembly during the process, the duration at these elevated temperatures should be minimized. Intermetallic growth occurs while the solder is in the molten state, as well as a result of diffusion over a period of time. A sustained liquidus dwell period essentially gives it a head start. The longer the duration, the more intermetallic growth takes place. Because cooling the interconnection to below the solidus temperature is also part of this duration, the actual dwell for a particular application will be affected by the mass and surface geometry (and expediency of heat dissipation) of the assembly and the resulting thermal gradient.

Cooldown. As the assembly passes its peak temperature and leaves the heated tunnel, it begins to cool, eventually passing the point where the solder solidifies. Cooling can be aided by fans, blowers, inert gas curtains, refrigeration, normal exposure to ambient air, or a combination of several of these mechanisms. To avoid thermal shock to components, it is currently recommended that the rate of cooling not exceed -4 °C/s (-7 °F/s). However, rapid cooling does promote a finer grain growth in the joint and contributes to a stronger interconnect.

The actual time and temperature duration range for each zone not only varies among the different types of fluxes used in SMT soldering but also among similar flux designation formulations of different manufacturers. The user should consult his supplier to obtain the actual time and temperature durations that are recommended for the specific solder paste being used. It is important to note that most fluxes have a fairly substantial en-

velope in terms of temperatures at the different stages. In some cases, however, actual duration can be more stringent.

Reflow Schedule. A reflow specification should be required for any facility that uses mass reflow techniques. This procedure should mandate the temperatures that the PWB assembly will be exposed to at the peak of the reflow cycle. The full peak liquidus temperature, T_1 , is the minimum peak temperature that any solder and interconnection must be exposed to for proper joint formation and is a parameter of the reflow schedule. It is affected by factors such as solder paste alloy, metal content, particle size, flux, surface tension, and fluidity of the solder. As noted earlier in the section “Reflow Profile” in this chapter, this value will vary among different formulations and should be specified by the solder paste manufacturer.

The most vulnerable component (MVC) maximum peak temperature is represented by the value T_2 . It identifies the component that has the lowest thermal threshold and is most likely to be thermally damaged. The MVC may be an inserted component with a low material melting point (that is, an electrolytic capacitor), a plastic connector, a switch, a label, or some other heat-sensitive part or material. The lowest common denominator within the assembly will determine the highest temperature to which any part should be exposed. A buffer of -5°C (-9°F) should be taken from that threshold to establish the MVC temperature used in the specification. In some applications, the MVC temperature may be determined by the internal heat sensitivity of an active device. Hence, the internal temperature tolerances should also be taken into consideration.

Processing in Inert Atmosphere. Reflow soldering in an inert atmosphere can, in some instances, be beneficial to improved wettability. However, implementing nitrogen in the reflow oven is being driven by two specific factors: no-clean fluxes and the bare copper assembly process.

No-clean (or low-residue) fluxes represent one solution to the search for alternatives to cleaning PWB assemblies with environmentally damaging chlorofluorocarbon solvents. The result is the development of solder formulations that do not require cleaning.

A number of factors will ultimately affect feasibility for a given application. Besides external cosmetic appearance requirements, both solder joint quality and testability (in light of remaining residue) will be dictated by other user standards and requirements. Although some low-residue solder paste formulations that work well in ambient (oxygen-laden) atmosphere are available, many very-low-residue no-clean solder pastes require that reflow take place in an inert (N_2) atmosphere. Some no-clean solder paste formulations have been successfully tested at approximately 300 ppm of O_2 , but the higher the concentration of inert atmosphere, the wider the process window. Optimum results, in terms of very low residue, have been attained with nitrogen atmosphere of less than 20 ppm O_2 .

Bare Copper Assembly Process. Development of this process has been prompted by the need for coplanarity on the PWB substrate when placing

fine-pitch devices. Hot-air leveling of solder during PWB fabrication has not attained adequate levels of coplanarity when components of 0.51 mm (0.020 in.) pitch or finer are being attached. In the bare copper assembly process, the PWB is fabricated in the usual manner, except that the tin-lead solder coating is omitted. Instead, the substrate is coated with a sealant (that is, inhibitor) that prevents the copper from oxidizing. In assembly, solder paste deposition (screened or stenciled) and component placement are accomplished as usual. During reflow, the sealant vaporizes between 100 and 120 °C (212 and 250 °F) (during the preheat stage), which exposes the copper to the solder paste. Because the copper is exposed, the furnace must contain an inert atmosphere to prevent excessive oxidation of the lands. Just how oxygen-free the oven atmosphere needs to be varies among users. Some obtain successful results in atmospheres composed of approximately 500 to 700 ppm O₂. The most stringent specification requires a nitrogen atmosphere with less than 50 ppm O₂ at any point in the process where the PWB assembly becomes elevated above 150 °C (300 °F).

6.7 Resistance Soldering

Resistance soldering is a soldering process in which the heat needed to melt the solder is developed by the resistance of the material when a large electrical current is supplied. Resistance soldering can be applied to electrically conductive materials that allow the passage of electric current. The process can be used for selective spot soldering of small components, for the soldering of closely placed parts on an assembly, or for heat restriction when necessary. It is similar in many ways to resistance brazing.

Resistance soldering involves placing the workpiece either between a ground and a movable electrode or between two movable electrodes as part of an electrical circuit. Heat is applied to the joint both by the electrical resistance of the metal being soldered and by conduction from the electrode, which is usually carbon. When the current is applied, rapid local heating occurs, melting the solder. This molten solder wets the surface. As a result, the resistance in the material falls and the current increases, tripping a control. The heat rapidly dissipates into the surrounding area, and the solder quickly solidifies.

Production assemblies can use multiple electrodes, rolling electrodes, or special electrodes, depending on which setup offers the most advantageous soldering speed, localized heating, and power consumption. Resistance soldering electrode bits generally cannot be tinned, and the solder must be fed directly into the joint.

Process Applications. The resistance soldering process can be used in all soldering operations and with all solderable metals. The only limitations are the thickness and the design of the parts to be soldered. Resistance soldering is used to join steels (for example, carbon, low alloy, and stainless) and nonferrous alloys (for example, aluminum and aluminum alloys,

nickel and nickel alloys, and copper and copper alloys) up to 3.2 mm (0.125 in.) in thickness (Ref 6.19).

The resistance soldering process is suitable where:

- An open flame constitutes a potential hazard in the workplace.
- The heat needed for soldering must be confined to a specific area.
- The oxidation attributed to heating of the solder must be minimized.
- The components to be joined are inaccessible with a conventional soldering iron.
- The bead produced can be adapted to automated processing/mass production methods.

Equipment. Resistance soldering equipment typically consists of two electrodes that have been modified for use with a specific part configuration. These electrodes are made of a high-resistance electrical conductor (for example, carbon, graphite, or tungsten). The geometry of the electrode can assume any one or a combination of the following forms (Fig. 6.14):

- Pencil
- Twin-pencil
- Roller
- Clamp
- Plier-type

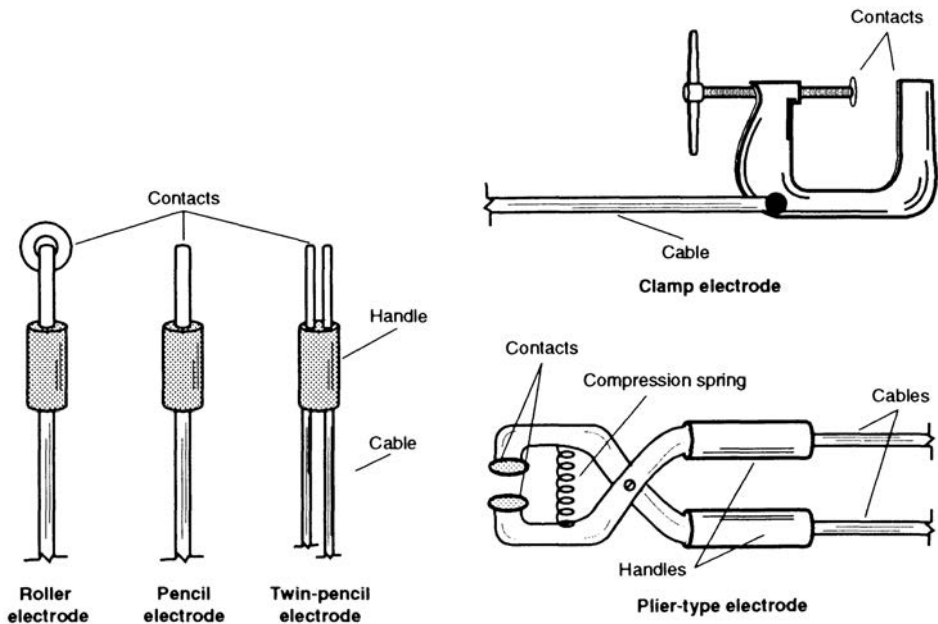


Fig. 6.14 Typical electrode configurations used in resistance soldering applications

The electrodes are connected to the transformer by oversized current-carrying conductors. The heart of the system is a heavy-duty, variable, step-down transformer designed to develop an output of 2 to 25 V_{ac} and a current of 5 to 500 A (Fig. 6.15). A footswitch, a timer, or an adjustable-resistance bridging device across the electrodes can be used to provide a method for the parts to reach the desired solder temperature and shut-down. This allows the solder to solidify and the parts to return to ambient temperature in a 4 to 6 s cycle.

Personnel Training. Soldering personnel with a strong basic training will need some additional special training to operate a resistance soldering system. The operator's function is to load and unload the parts and to maintain or replace the electrode heads when required. General soldering health and safety rules should be observed to avoid electrical shock and the potential for overheating solder to cause spatter. Typically, the engineer who originally designs the electrode heads is responsible for the initial startup of the equipment.

Resistance Soldering Practice. The resistance soldering process requires preassembly of the workpiece components. Because the workpiece and the solder are integral parts of the current loop, care must be taken to ensure that the current path is not blocked by any foreign or nonmetallic substance. Hence, the preassembled workpiece requires a clean, deburred surface and the proper solder alloys (preform or in paste form). The use of wire solder and flux is not recommended because of the rapidity of heating and the potential hazard of electrical shock.

The preassembled workpieces are positioned in a grounded jig or clamp, and the movable electrode is brought in contact with the workpiece to complete the circuit. When the power is turned on, the operator waits for signs that the solder is starting to flow and then immediately turns the power off. When using automatic soldering equipment, the duration of the current flow is monitored by sensors that determine the length of the on

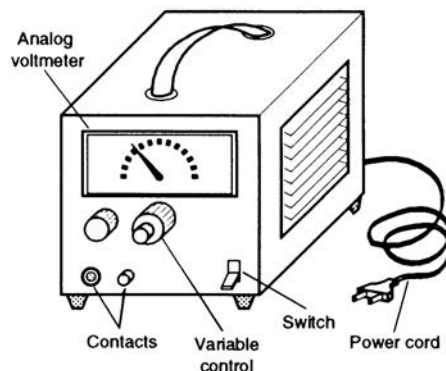


Fig. 6.15 Typical variable step-down transformer with 2 to 25 V output (at 5 to 500 A current) used in resistance soldering processing

cycle. As the workpiece cools, the solder solidifies, and the workpiece is removed from the jig. The next assembly can then be placed in the jig. A properly designed movable electrode head allows multiple solder connections to be produced in a single operation.

6.8 Hot Gas Soldering

Hot gas soldering uses a fine jet of inert gas, heated to above the liquidus of the solder. The gas acts as a heat-transfer medium and as a blanket to reduce access of air at the joint. This method is commonly used in applications where the workpiece thermal mass is small and the melting temperature of the solder is relatively low. The efficiency of heating large-mass substrates with hot gas is low in comparison to radiative or conductive methods of heating. The electronics industry uses hot gas soldering to reflow or melt solder in localized areas on circuit assemblies. A common application is the reworking or removal of electronic components.

Process characteristics of hot gas heating that are critical to its effectiveness in soldering are:

- Focus of gas flow
- Gas flow rates (velocity and volume)
- Temperature control
- Gas media or constituent

The focus of gas flow defines the area of localized heating, determines the efficiency rate of heating a defined area, and controls the excessive heating of adjacent areas. In most electronic applications, because the areas that need to reach the solder melting temperature are relatively small, confining thermal energy to a small area is critical. The focus of gas flow is usually controlled via nozzle design or the use of baffle plates. The nozzle collimates the gas stream to optimize the gas impingement across one or more solder interconnects, whereas the baffle plates attempt to block the gas from impinging on adjacent areas or on a component body directly. Common nozzle materials are stainless steel or quartz glass.

Gas flow rates primarily determine heat-transfer efficiency (that is, the temperature and heating rate of the workpiece) and may affect the total area being heated. Insufficient gas flow will reduce the efficiency of thermal energy transfer, whereas excessive gas flow will disperse heat across the assembly, which may result in the overheating of adjacent areas. On some hot gas soldering systems, the flow rates are adjustable in both volume and velocity and can be used to establish the most appropriate heating profile for soldering. The selection of optimum flow rates usually depends on the gas temperature selected for the soldering process and on the size of the openings in the nozzle, as well as the configuration of the workpiece or circuit board.

The gas temperature also affects the heat-transfer efficiency and ultimately the time required to form the solder interconnect. Typically, the gas is heated by passing it through a set of resistive heating elements. The usual temperature of interest for soldering process control is the temperature at the exit aperture of the nozzle. Because air is a poor heat conductor, the gas temperature will fall off rapidly as the distance from the nozzle to the solder interconnect increases. In electronics applications, the component body tends to heat more rapidly than the actual interconnect; therefore, excessive nozzle-exit temperatures with a high flow rate may thermally damage components or circuit boards.

Typical gas media used in hot gas soldering are air, nitrogen, and a nitrogen-hydrogen mix (75N₂-25H₂). Air is the most common gas used because of its ready availability and low cost. Nitrogen is sometimes used to minimize the oxidation of the component and board metallizations and to potentially improve solder wetting performance and interconnect reliability. In some cases, a nitrogen-hydrogen mixture is used to capitalize on its lower density relative to air. The lighter gases allow for the same heat-transfer performance and inert nature while reducing the force of the gas against the area being soldered. This reduction in the force of the gas decreases the dispersive effects upon impingement. In addition, some no-clean flux materials perform better in an inert atmosphere, such as nitrogen, during the soldering process.

Process Parameters. Heating profiles are established in hot gas soldering by using a combination of gas flow rates, gas temperatures, and time. Some systems use lower flow rates and higher temperatures, whereas others use higher flow rates and lower temperatures. The actual selection of flow rates and temperatures depends on the physical and dimensional characteristics of the item being soldered, as well as component mounting density. Figure 6.16 illustrates a thermal profile of a component being soldered and the temperature across adjacent components.

Reliability concerns do exist when hot gas soldering techniques are used in electronics assembly. There is a potential for solder joint fracture when melting or reflowing a portion of a multileaded component. Fractures in solder joints occur when the joints are thermally cycled in use because of the induced stress caused by partially reflowing the component. If the hot gas process excessively heats adjacent components, causing a percentage of the interconnects on a component to reflow, then a residual stress may be established, which can significantly reduce the overall fatigue life of the solder interconnects. Therefore, gas flow rates and focus are critical to the overall reliability of the solder interconnects. The use of properly maintained equipment and trained operators should minimize these concerns.

Processing concerns also exist when using hot gas soldering in electronics assembly. Because this technique has inefficiencies relative to conductive and radiative methods, it is difficult to reflow solder joints that

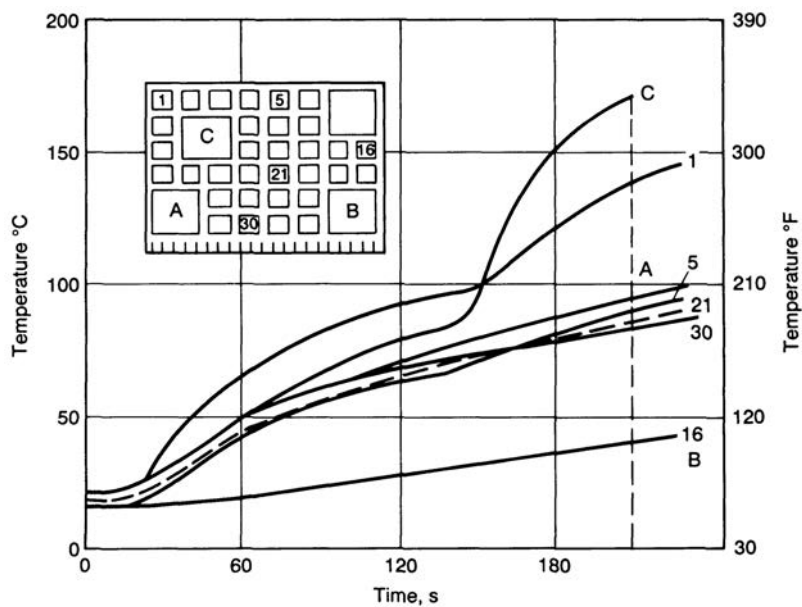


Fig. 6.16 Time-temperature relationship of component being soldered (line C) and adjacent components (lines A and B). Locations of specific sensor components are shown in inset diagram.

have large heat sinks. Therefore, an additional heating process may be needed to reduce the total hot gas heat energy required to reflow the solder interconnects. There are four methods of preheating the assemblies: oven bake, diffused hot gas, radiant, and conduction (edge rail or hot plate) heating. All methods are effective. However, the working time of assemblies preheated in an oven is very short. The selection of the preheating technique depends on the physical characteristics of the assembly being soldered and on the process equipment.

6.9 Vapor-Phase Soldering

Vapor-phase soldering (also known as condensation soldering) is a process of condensation heating in which a product prepared for soldering is passed through or into a layer of saturated vapor. The process uses the latent heat of vaporization of the condensing saturated liquid to provide the heat required for soldering. A reservoir of saturated vapor over a boiling liquid provides a constant controlled temperature with rapid heat transfer. The vapor condenses on the relatively cool part, which transfers the latent heat of vaporization to the part and heats it rapidly and uniformly. The process reaches thermal equilibrium in a few seconds at a temperature that is limited only by the boiling point of the fluid used in the process. Typically, newer equipment uses a single perfluorocarbon fluid

vapor layer, which does not contain chlorine or bromine and is environmentally safe. This fluid is also chemically inert, thermally stable, and has very low solvent action.

This method is useful for large assemblies, as well as for temperature-sensitive parts. Although the process is used in a variety of heating applications, such as curing epoxies and polymers or stress relieving various platings, it is primarily useful when soldering surface-mounted components to various substrate materials. Because of the precise temperature control that this process offers (by virtue of a fixed boiling point), multi-level soldering is possible using up to three solder compositions with three different melting temperatures. Fluid temperatures that range from 100 to 265 °C (212 to 510 °F) are available. The most common fluid used boils at 215 °C (420 °F) and is used for 63-37-type solder, which melts at 183 °C (360 °F). A 30 °C (55 °F) differential is typical, to enable the heating process to proceed rapidly. Temperature precision also prevents the assembly from overheating.

Typical materials that are joined by this process are solder-coated substrates made from various ceramic materials and G10 or FR4 epoxy laminates mated with surface-mounted components. Solder paste is typically applied to the substrate by screening, stenciling, or using X-Y dot placement. Components are then placed in the correct position in the solder paste, which temporarily holds them until they are soldered. The assembly is then passed through the vapor-phase setup, where the solder is melted, joining the components to the substrate. Typical surface-mount lead density is 1.25 mm (0.050 in.) on centers. Fine-pitch components as small as 0.38 mm (0.015 in.) on centers can also be processed. There is no inherent lead-pitch limitation in the vapor-phase process, because it is essentially an oxygen-free soldering process. Because of its uniformity, rapid heating, precise temperature control, and oxygen-free environment, the process is preferred for high-value assemblies. Also, because of the thermal capacity, ease of profiling, and forgiving nature of the process, it is also used when high throughput is required from limited floor space or when a large number of different types of boards must be run in a given time period.

Equipment is normally configured for either batch or in-line operations (Fig. 6.17, 6.18). The majority of machines available are of single-vapor design (Fig. 6.19). Earlier models had vertical access and used less-expensive fluid as a cover layer. These machines also lacked a preheating capability, which was found to be necessary in order to reduce the temperature differential at the point of solder melting. This measure prevents wicking and other undesirable characteristics that can develop when one part of a solder joint heats faster than the other. Both a preheating capability, typically provided by IR panels, and a cool-down stage have been incorporated in newer models. The cool-down stage brings the solder joint through the liquidus phase more quickly (Fig. 6.20). This procedure re-

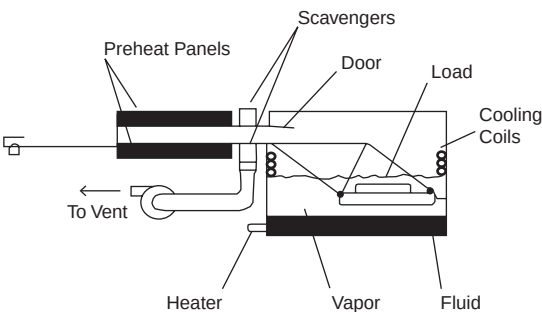


Fig. 6.17 Pelletized vapor-phase batch system

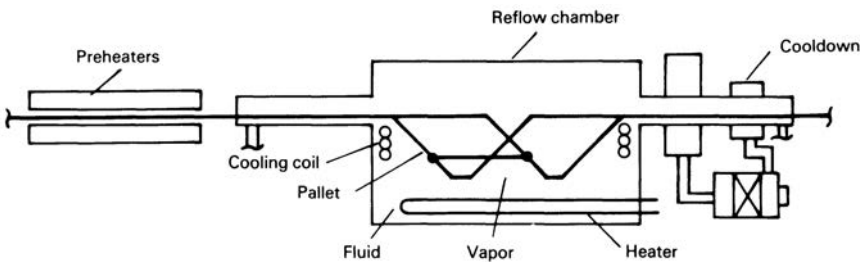


Fig. 6.18 Third-generation vapor-phase reflow system

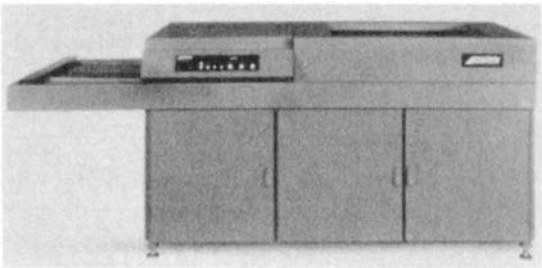


Fig. 6.19 Single-vapor batch-type equipment

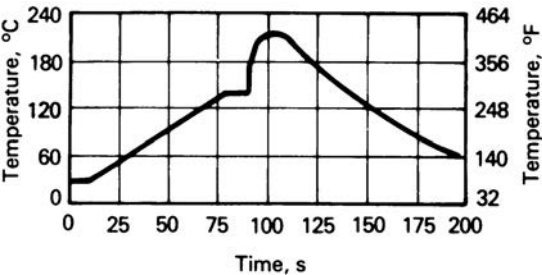


Fig. 6.20 Thermal profile

duces the time that the joint can form undesirable intermetallic layers and simultaneously improves the grain structure of the joint, thus improving its capability to withstand thermal cycling.

The stability of the vapor-phase process and its ease of profiling means that machine operators require little training. If the overall process is established correctly, then there are few elements that require adjustments. A smooth, vibration-free conveying mechanism enables defect-free soldering and assembly.

The proper setup procedure is to attach a thermocouple to a strategic location on the printed board, such as a sensitive component or a solder joint. Then, the board is processed to reach a preheat temperature of between 125 and 150 °C (255 and 300 °F) in 50 to 60 s. A desirable heating rate is approximately a 2 °C/s (4 °F/s) rise to within 100 °C (180 °F) of the reflow temperature. Major parameters are dwell time (batch machines), conveyor speed (in-line machines), and preheat panel temperature. Reflow time is established by observing the solder melt through the window in the chamber. In the batch machine, the dwell times can be set from those obtained and the process replicated. With in-line machines, the reflow time is established by the conveyor speed, and the preheat temperature is adjusted with the panel temperature. Similar board assemblies can be processed using very similar profiles, which minimizes lost machine time due to the complex repetitive profiling that is common with other reflow methods.

Because vapor-phase soldering depends on the series of processes that precede it, every parameter leading to the actual soldering process must be carefully controlled to ensure a high yield. For example, thickness, viscosity, and location accuracy are just some of the parameters involved in solder paste application. Pad design and board layout are equally important to the process, as is the accurate placement of components. With proper controls, it becomes possible to solder with defect rates under 50 ppm using the vapor-phase process. Information on guidelines for parameter control can be obtained by contacting the Institute for Interconnecting and Packaging Electronic Circuits.

6.10 Spray Gun Soldering

Spray gun soldering is a heating method used when the contour of the part to be soldered is difficult to follow with either a wiping or drop method or when the part is placed in the assembly in such a way that the solder cannot be applied after the parts are assembled.

Gas-fired or electrically heated guns are available. Each type is designed to spray molten or semimolten solder on the work from a continuously fed solid solder wire. Soldering guns use either propane mixed with oxygen or natural gas mixed with air to heat and to spray a continuously fed solid solder wire of approximately 3.2 mm (0.12 in.) diameter. About

90% of the solder wire is melted by the flame of the gun. The solder contacts the workpiece in a semiliquid form. The workpiece then supplies the balance of the heat required to melt and flow the solder. Adjustments can be made within the spray gun to control the solder spray.

6.11 Ultrasonic Soldering

Ultrasonic soldering uses a transducer as the source of ultrasonic energy. The transducer is energized in a bath of molten solder, and sound waves are coupled between the transducer and the workpiece, allowing the oxides in the base metal to be disrupted so that the solder melts the base metal. Sound waves are transmitted throughout the base metal, permitting wetting to occur on surfaces that are “blind” to the source. Ultrasonic soldering is also used to apply solderable coatings on difficult-to-solder metals.

ACKNOWLEDGMENT

Most of this chapter has been adapted from M.M. Schwartz, *Fundamentals of Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 126–137; M. Cowell, *Iron Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 349–350; C.E. Fuerstenau, *Torch Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 351–352; R.E. Beal, *Dip Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 356; P.T. Vianco, *Wave Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 366–368; P.T. Vianco, *Induction Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 363–365; P. Zarrow, *Furnace and Infrared Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 353–355; K. Lazar, *Resistance Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 357–358; M.D. Frederickson, *Hot Gas Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 361–362; and D.L. Linman, *Vapor-Phase Soldering, Welding, Brazing, and Soldering*, Volume 6, *ASM Handbook*, ASM International, 1993, p 369–370.

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CHAPTER 7

Soldering in Electronics Assembly

THIS CHAPTER ADDRESSES some general considerations in the soldering of electronic devices and some topics of importance specifically to electronics assembly. A table at the end of the chapter includes important physical and mechanical properties of some commonly used packaging and substrate materials.

7.1 Design and Manufacture of Electronic Assemblies

There are several joint designs and assembly techniques commonly used in the manufacture of electronic devices.

Substrates. A substrate is the platform on which the electrical/electronic circuitry is built. Many different types of substrates are used in the electronics field. Early substrates were sheets of material to which insulated, stand-off terminals were attached by bolting or riveting. The circuitry was then obtained by point-to-point wiring between these terminals. Although this approach is still used, the most common substrate in use today (2013) has circuitry that is laid on it in planar form, with the components already attached. Attachment is normally accomplished through the soldering process. The most common form of this substrate is the printed circuit board (PCB).

A substrate can have numerous forms. There are many methods of applying the conductive patterns that make up the circuitry, and each has its own specific soldering solutions. Substrate materials are discussed later in this chapter.

Through-Hole Technology. This term typically refers to the use of leaded device packages. The leads are inserted into holes in the PCB and

are soldered in place. Several package/lead configurations are shown in Fig. 7.1. Device leads are typically copper or one of the iron-base alloys (typically coated with a solderable layer). Substrates for through-hole technology include organic laminates, metal-clad substrates, and ceramics for hybrid microcircuits. Through-hole PCBs are categorized as:

- Single-sided, with circuitry on one surface only
- Double-sided, with circuitry placed on both surfaces
- Multilayer, with circuit layers on both external surfaces as well as conductive paths within the laminate

The solder joint configuration for each case is shown in Fig. 7.2. Lands (and conductor lines) are constructed of copper foil bonded to the laminate; the foil thicknesses are typically 0.017, 0.035, or 0.071 mm (0.0007, 0.0014, or 0.0028 in.) and are designated as 0.5, 1, and 2 oz, respectively. The surfaces of lands (and lines) can be built up with a combination of electroless and electroplated copper to a thickness that ranges from 0.013 to 0.076 mm (0.0005 to 0.0030 in.) to satisfy final thickness requirements and enhance solderability.

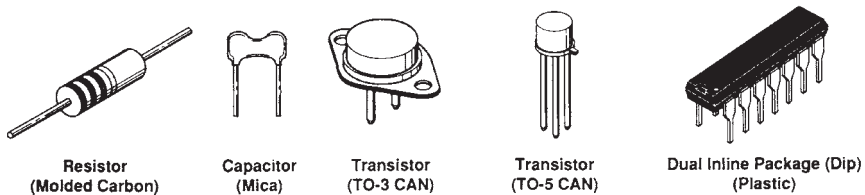


Fig. 7.1 Package and lead configurations for through-hole devices

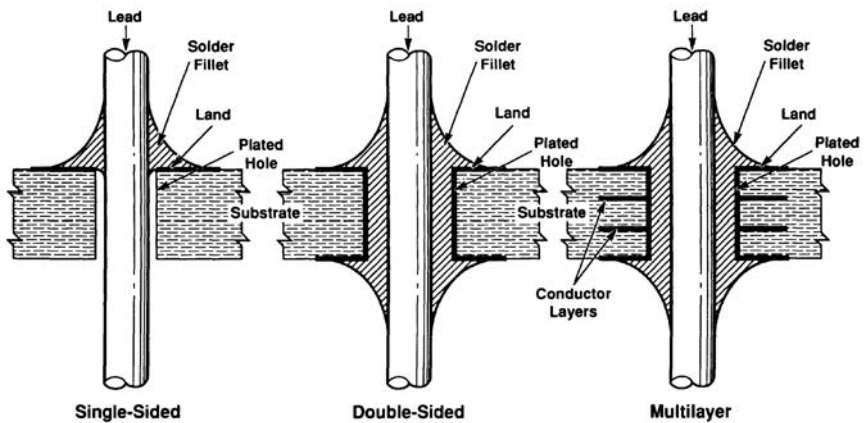


Fig. 7.2 Single-sided, double-sided, and multilayer solder joint configurations for through-hole technology

Although the role of holes on single-sided circuitry is to mechanically secure the electronic devices, holes on double-sided and multilayer boards have an expanded role of providing electrical signal conduction between the two surfaces and internal layers. Holes used for interlayer signal transmission, but without a device lead, are called vias. The hole walls are deposited with copper to establish electrical conductivity and promote solder flow. The walls are coated with from 0.0003 to 0.0025 mm (0.00012 to 0.00010 in.) of electroless copper, followed by 0.025 to 0.076 mm (0.001 to 0.003 in.) of electroplated copper (Ref 7.1). General guidelines for hole design are provided in Fig. 7.3. Vias can also be designed to assist in heat transfer (Ref 7.2).

Loss of electrical continuity in the through hole can arise from cracking (termed barrel cracking) of the hole plating layer because of the large coefficient of thermal expansion (CTE) in the thickness dimension of the laminate (nearly a factor of 10 higher than in the laminate plane). This phenomenon is particularly severe for via holes with large aspect ratios (the board thickness/hole diameter). Aspect ratios should be kept to a value smaller than 3 to ensure adequate reliability by typical assembly processes (Ref 7.3). The use of holes with larger aspect ratios requires additional attention to reliability.

A plated via is one that is plated with a conductive metal (usually copper but sometimes gold or silver) but left unfilled. Such vias provide electrical connections but are not well suited for component placement: if a component is placed over a hole, the solder may flow through the hole and create an unreliable joint. If such a via is also filled with a nonconductive material (usually an epoxy) to block such solder flow, the result is a filled

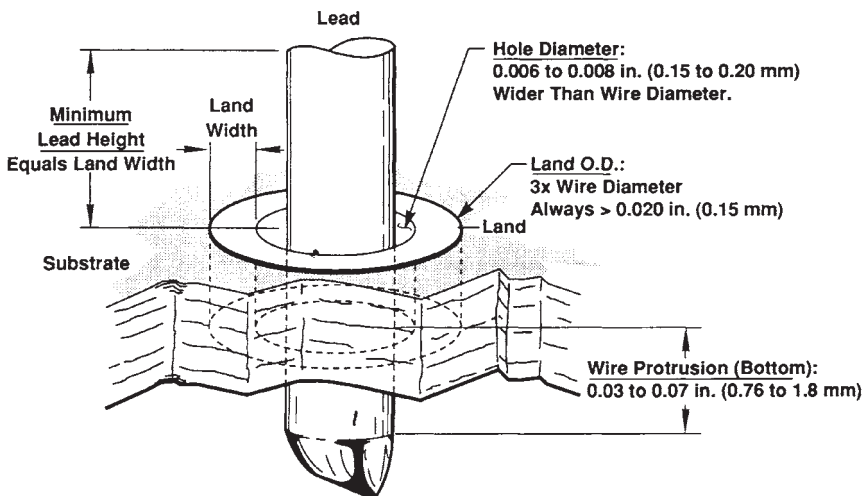


Fig. 7.3 General guidelines for lead and substrate geometries used in through-hole technology

via. Filled vias save space on a PCB by allowing a multilayer connection and a component pad to occupy the same physical location.

The process of circuit design using vias ordinarily includes several steps. First, a substrate material is selected; then a via diameter is chosen based on the substrate material. The placement of the vias is then determined in one of two ways. The older, more conservative method is to place the vias at most one-eighth of a wavelength apart (measured center to center) in every direction within a chip mounting pad (where the wavelength computation takes account of the dielectric constant of the substrate material). Today (2013), however, advances in software have made it possible to optimize via placement through modeling and simulation. Layout issues are then reviewed and thermal and assembly issues addressed (Ref 7.4).

Microvias (vias with diameters in the range of 50 to 100 μm) can be filled with copper rather than a nonconductive material. There is some evidence that such copper-filled microvias may help to reduce solder voids (Ref 7.5).

Calculations have shown that the mechanical strength of the through-hole joint is limited primarily by PCB properties, specifically, the peel strength of the copper foil/laminate bond and the adhesion between the plating layer of the hole and the laminate (Ref 7.6). Similarly, the bond strength between the thick-film network and the ceramic substrate limits the strength of solder joints on hybrid microcircuits. Mechanical integrity can be lost through thermal fatigue. However, CTE mismatch between the device package and the PCB is not a principal source of thermal fatigue damage to through-hole solder joints, because the leads take up much of the displacement difference. Rather, thermal fatigue arises primarily from the difference between the lead CTE (for example, copper, at $9.4 \times 10^{-6}/\text{K}$, or $5.2 \times 10^{-6}/^\circ\text{F}$) and the through-thickness thermal expansion value of PCB laminate (as much as $175 \times 10^{-6}/\text{K}$, or $98 \times 10^{-6}/^\circ\text{F}$). Fatigue damage (Fig. 7.4) in through-hole solder joints is lessened by the CTE of the solder ($25 \times 10^{-6}/\text{K}$, or $14 \times 10^{-6}/^\circ\text{F}$), which is between those of the lead and PCB materials, as well as through proper assembly practices such as the incorporation of strain-relief bends or loops placed in leads.

Plated through holes are soldered from one side. Multilayer boards are more difficult to solder, because the interior conductor lines act as additional heat sinks that inhibit board heating. Solder assembly techniques for through-hole PCBs include hand soldering and larger-scale, automated processes such as dip, drag, or wave soldering. Solder pot working temperatures for the latter processes range from 240 to 260 $^\circ\text{C}$ (464 to 500 $^\circ\text{F}$) for 63Sn-37Pb and 60Sn-40Pb solders. A good rule of thumb is to limit contact between the assembly and the molten solder to 3 to 10 s to minimize damage to the laminate and flux charring.

Heat damage to the attached device, neighboring components, and the substrate material must be considered when reworking through-hole sol-

der joints. When a part is intended to be removed after assembly, it can be attached by hand soldering techniques with one of the lower-melting-temperature solders (Table 7.1). This technique is generally reserved for prototype assemblies; military and most commercial products specifications do not allow this operation.

Conformal coatings must be removed prior to reheating a solder joint. Clinched leads, that is, leads that are bent slightly on the opposite surface of the board to provide mechanical rigidity during assembly, hinder the removal of components. Generally, heat inputs will be greater when re-

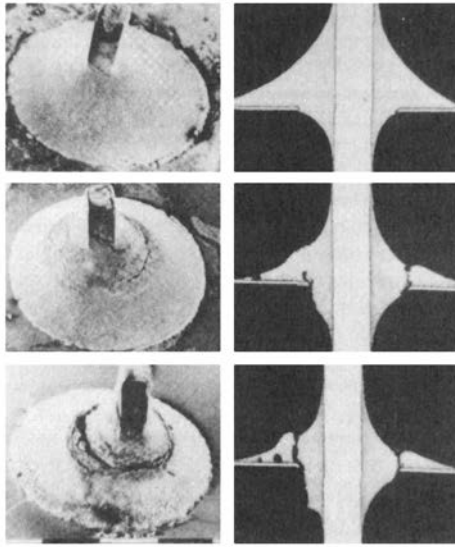


Fig. 7.4 Progression of fatigue damage in a through-hole solder joint (optical and scanning electron microscopy). Source: Ref 7.7

Table 7.1 Commonly used solders in electronic assemblies

Solder alloy, wt%	Solidus/liquidus temperatures	
	°C	°F
52In-48Sn	118/118	244/244
50In-50Sn	118/125	244/257
58Bi-42Sn	138/138	281/281
43Sn-43Pb-14Bi	143/163	289/325
97In-3Ag	143/143	289/289
70Sn-18Pb-12In	162/162	324/324
63Sn-37Pb	183/183	361/361
60Sn-40Pb	183/190	361/374
62.5Sn-36.1Pb-1.4Ag	170/179	338/354
50Pb-50In	180/209	356/408
60Pb-40In	195/225	383/437
96.5Sn-3.5Ag	221/221	430/430
95Sn-5Pb	233/240	451/464
97.5Pb-1.5Ag-1.0Sn	304/309	579/588
90Pb-10Sn	268/299	514/570
95Pb-5Sn	270/312	518/594

working a joint because the solder, lead, and land must be heated, which increases the likelihood of damage to the land/substrate bond or to the device. Cleanliness specifications must be followed after reworking to prevent functional failures caused by corrosion from flux residues.

The reliability of double-sided and multilayer circuit boards depends strongly on the plating quality of the hole walls. Water vapor and contaminants from the plating solutions can become entrapped in the deposited film. Plating layers should be free of embrittling contaminants that make them unable to adapt to board thermal expansion. The coating must have adequate thickness (and uniformity) so as not to be totally consumed by the metallurgical reaction with the solder. Contaminant materials vaporize at the soldering temperatures, causing cracks in the plating layer. Although plating cracks and voids, or delamination, do not necessarily jeopardize joint strength, they can interrupt electrical continuity between layers and surfaces.

A plated through hole that is coated with a hot-dipped or plated-and-fused solder layer will have a very thin film of solder around its edge upon reflow. This phenomenon is a consequence of the surface physics of molten liquids. The limited protection offered by the thin solder film can cause nonwetting of the hole edge during assembly, in which case the joint is said to have a “weak knee.” The effects of a weak knee on joint reliability are largely cosmetic for plated through holes.

Surface-mount technology (SMT) uses several types of assembly techniques. The technology generally refers to products that use conventional PCB assemblies, which include organic laminates, clad-metal substrates, as well as ceramic substrates for hybrid microcircuits. Although the architecture differs between organic laminates and hybrid substrates, the package configurations for electronic devices are similar. Surface-mount technology also includes chip (silicon)-on-board technologies (such as tape-automated bonding, discussed subsequently) and controlled collapse chip connection, also known as flip chip (which uses bump bonding, also discussed later).

PCB Assemblies (Organic Laminate and Ceramic). Denser board populations and adaptability to fully automated assembly processes have increased the popularity of SMT. Figure 7.5 shows several leaded and leadless surface-mount packages. Lands on surface-mount PCBs are constructed with the same conduction layer material specifications used on boards with through-hole components:

- Land thicknesses (copper) are between 0.018 and 0.071 mm (0.0007 and 0.0028 in.).
- Protective finishes on PCBs include hot-dipped solder with hot-air leveling or organic coatings (inhibitors) on bare copper.
- The control of solder thickness on hot-air-leveled lands is critical with surface-mount PCBs.

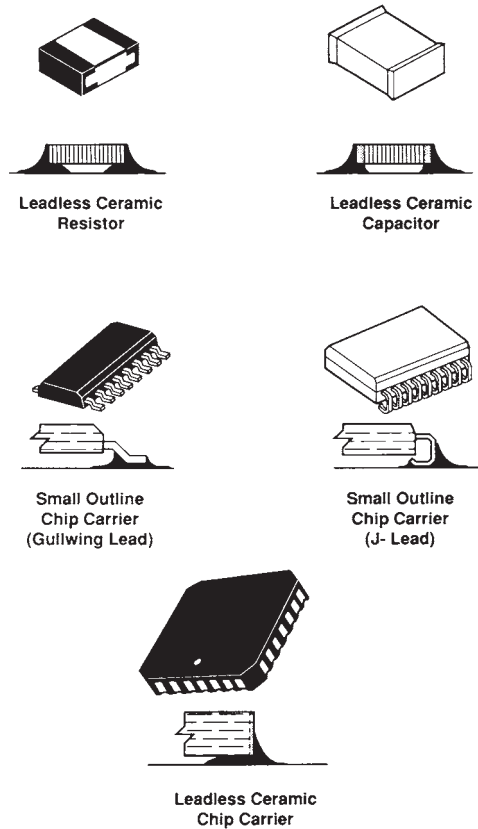


Fig. 7.5 Package and lead configuration of surface-mount devices, including solder joint profiles

- Excessive solder quantities will interfere with part alignment during placement, damage fine leads during automated setup of components on the board, and increase the likelihood of nonsymmetric fillets on devices.
- Nonsymmetric fillets can lead to misalignment (“tombstoning”) of devices during automated soldering processes.

A variety of land geometries are used to accommodate the range of package input/output (I/O) configurations. Holes, or vias, may be required on the PCB to permit signal transmission between the two external surfaces or between internal conductors of multilayer boards. In some cases, through-hole components are also found on the same PCBs. These assemblies are known as mixed technology. The quality of the plating layer in the hole is critical to system reliability, whether in vias for signal transmission or component holes for mixed-technology applications.

Conductor lines and lands on ceramic boards are composed of one of the thick-film inks. The pattern is screen printed into the circuit configura-

tion and fired to promote adhesion. Lines are usually formed from a single printed layer, with a thickness of approximately 0.01 mm (400 $\mu\text{in.}$). Lands to which soldering will take place may receive a second printing (double-printed), which improves solder joint reliability by reducing porosity in the film and limiting the dissolution of the conductive layer that is due to the formation of intermetallics between the solder and the precious metal. Double-printed layers are typically from 0.02 to 0.025 mm (0.0008 to 0.0010 in.) thick, depending on the porosity of the first layer.

Leadless surface-mount resistors and capacitors use terminations to form the solder interconnect. Terminations are regions on the package surface that are coated with a solderable layer to promote wetting by the solder. Leadless chip resistors and capacitors have a silver-bearing thick-film ink that is fired onto areas of the ceramic substrate; these areas are connected to the active electrical elements. Dissolution, or scavenging, of the thick film is reduced by adding more than 35% Pd to its composition (Ref 7.8). More commonly, the thick film is coated with a solderable nickel or copper finish to prevent the scavenging of silver by the solder. Candidate protective layers for the solderable finishes include electroplated tin or tin-lead and hot-dipped tin-lead solder.

Leadless ceramic packages for integrated circuits have multiple I/O terminations composed of metallized grooves on the package sides (castellation) and a metallized bonding area on the bottom of the package (blind lap joint). The metallized surfaces have a refractory layer (tungsten or molybdenum) that provides the electrical feedthrough to the interior. The refractory layer is then coated with a nickel solderable layer (1.3 to 3.8 μm , or 50 to 150 $\mu\text{in.}$). A protective layer of gold (1.3 to 2.5 μm , or 50 to 100 $\mu\text{in.}$) coats the nickel. The gold finish is removed by a hot-dipped solder coating step to prevent gold embrittlement of the solder joints. Gold embrittlement is of particular concern in surface-mount solder joints, because the limited amount of solder required to form the small joints can easily exceed the 4 wt% maximum gold content observed to degrade solder properties. Lower potential gold contents are preferred as a safety factor.

Leaded packages for surface-mount assembly have conductors fabricated from copper or one of the iron-base alloys and formed into the appropriate configuration (J-lead, gullwing, and others). A solderable layer of electroplated or electroless nickel, followed by a protective coating of electroplated gold, is deposited onto the iron-base alloy leads, in accordance with the recommended thicknesses. The leads are hot dipped in tin-lead solder to remove the gold coating prior to assembly or to protect the copper solderable finish; however, tin or tin-lead electroplated coatings are preferred with fine-pitched leads and packages to eliminate the “crown” of solder on the lead. This crown causes the lead to deform and slide off of the similar crown of solder on the land when the part is placed

on the PCB, causing component misalignment, solder joint distortion, or electrical failure.

Historically, until the shift toward lead-free soldering, the predominant solders used in surface-mount PCBs were the tin-lead alloys. The tin-lead-silver solder (62.5Sn-36.1Pb-1.4Ag) has improved flow and a slightly improved isothermal fatigue life (for service conditions with limited temperature variations), when compared with the eutectic tin-lead alloy. The silver component of this solder improves creep strength. Silver-bearing solders also restrict the scavenging of silver from silver-bearing thick-film terminations on leadless ceramic devices that do not have a solderable (barrier) coating. A noneutectic Sn-Pb-Ag alloy formed by the addition of 2% Ag, or the use of 60Sn-40Pb solder, will reduce the occurrence of solder wicking on leaded devices. Solder wicking, also called solder creepage, is a phenomenon on leaded devices whereby the entire quantity of molten solder is drawn away from the pad to the lead because the lead heats up faster than the pad, causing the pad to be insufficiently wetted. This problem is particular to the vapor-phase reflow process and is compounded by leads that are noncoplanar with one another.

The noneutectic solders melt more slowly than eutectic alloys because they melt over a temperature range. This allows the lead and bonding pad surfaces to reach the same temperature, so that solder will simultaneously wet both surfaces. A longer melting sequence of the noneutectic alloys also decreases the incidence of “drawbridging,” or “tombstoning,” on leadless chip components (Fig. 7.6). A cause of drawbridging is the non-simultaneous melting of the solder at the two terminations, causing the component to be drawn toward the molten joint by the surface tension of the solder. Other factors in drawbridging are paste tackiness, paste quantity, part location, and land design.

Other solders that have been used for surface mounting include lead-indium alloys, which are used in hybrid microcircuit systems. The lead-indium solders limit the leaching of precious metals from thick-film networks and finishes on devices, and reduce the formation of brittle intermetallic compounds that jeopardize solder joint integrity. In addition, these alloys are more ductile than the tin-lead solders, thereby limiting the loads on the more-fragile thick-film/substrate ceramic bond. The low-temperature ductility of these solders provides a niche for them in cryogenic applications (for example, space vehicle electronics).

The low-melting-temperature tin-bismuth solders are used on PCBs with heat-sensitive devices or with those components that must be removed and replaced on the board one or more times to satisfy testing or operational modes.

The high tin-silver solders are well suited for surface-mount assemblies because of their improved fatigue properties as compared to those of the tin-lead alloys. Their higher melting temperatures (96.5Sn-3.5Ag eutectic,

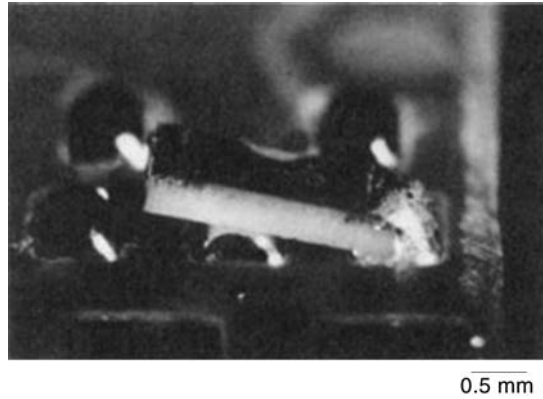


Fig. 7.6 Drawbridging of a leadless ceramic chip resistor (optical macroscopy). Courtesy of Sandia National Laboratories

221 °C, or 430 °F) increase the service temperature window of assemblies as well. It is critical that the finishes on substrate lands and device leads or terminations be compatible with the solder alloy. The mixture of different metals, which is due to nonsimilar pastes and finishes, can produce lower-melting-temperature phases that can deteriorate the physical and mechanical properties of the solder joints. For example, mixing bismuth-containing solders and lead finishes with tin-lead solder causes a low-melting-temperature Sn-Pb-Bi phase that melts at 96 °C (205 °F).

The use of alternative solders implies solder joint cosmetics that are different from those of the tin-lead alloys. Cosmetics should not be relied upon to judge service performance. Typically, the tin-bismuth, lead-indium, and tin-silver solders have a grainy solder fillet. The fillets of lead-indium and tin-silver will be less concave than those of tin-lead, because of their higher surface tensions.

Altera Corp. (San Jose, CA) has made available a useful reference on SMT assembly board processing that compares the processing requirements for tin-lead versus lead-free soldering (Ref 7.9). According to Altera, one key difference is in reflow soldering, which has a narrower processing window for lead-free than for conventional solder. For lead-free reflow soldering, Altera recommends that nitrogen be included in the process in order to achieve better wettability and make the processing window wider, and that reflow profiles be carefully analyzed with close attention to JEDEC/IPC standard J-STD-020 revision D.1 (Ref 7.10). Altera also notes that because lead-free solders have higher surface tension than conventional tin-lead eutectics, stencil designs for screen printing should be modified accordingly to allow the lead-free solder to spread more easily.

Typical fluxes used for surface-mount assembly are the rosin-based materials, usually the rosin mildly activated (RMA) forms. Water-soluble

fluxes (organic acids) are being used increasingly in electronics, because of the variety of aqueous cleaning processes available to remove their residues. Although flux residue removal is determined by the reliability required of the assembly and flux activity, surface-mount technology requires additional attention to cleaning requirements and procedures. The high density of devices places conductors closer together, so that ionic residues are more likely to cause electrical shorts by the electromigration mechanism. In addition, flux residues can be easily entrapped in the 0.05 to 0.013 mm (0.002 to 0.0005 in.) gap between the package and the substrate. For lead-free processing, Altera recommends taking into account flux activation temperature, activity level, compatibility with the lead-free alloy, and such reliability-related properties as surface insulation resistance and electromigration (Ref 7.9).

Surface-mount PCBs are manufactured by mass production techniques, such as vapor-phase reflow, heating in infrared furnaces, or wave soldering. A typical assembly sequence for reflow techniques (that is, using vapor-phase or furnace processes) involves:

- Depositing solder paste on the substrate lands by either screen printing, stencil printing, or bulk dispensing techniques
- Baking the paste to drive off volatiles
- Placing the electronic components on the paste deposits, over the lands (manually or with robotics)
- Reflowing the solder
- Cleaning the boards of flux residues, if necessary

The use of alternate solder alloys depends on their availability in paste form (with the optimum flux and flow properties). Preforms or wires of nontypical solders are more readily available. For vapor-phase reflow, working fluids that would accommodate solders with higher melting temperatures than tin-lead alloys may have limited availability. Infrared heating is more versatile in this regard. Damage to heat-sensitive components must be considered when higher-melting-temperature solders are used. Wave soldering uses a solder bath, which requires that an ingot form of the solder be available to fill the pot. Surface-mount parts are typically secured to the PCB with epoxies prior to being passed through the wave.

Some surface-mount PCBs are hand soldered. This technique is reserved for larger-pitch assemblies and runs of small quantities or for very high-reliability electronic systems. It is also used as a means of repair and rework. For component placement, the conventional soldering iron tip has been replaced by hot bars or rectangles that conform to the various I/O configuration of surface-mount packages in order to simultaneously melt the solder in all joints. Heating rates should be minimized on chip capacitors and resistors to prevent cracking of the ceramic chip or thick-film termination. Total heat input from the iron must not damage the land/

substrate bond. An intermetallic layer formed between the copper land and molten tin-lead solder generally is not sufficient to restrict rework operations. However, solder removal that exposes the intermetallic layer to atmospheric oxidation can deteriorate solderability. Hand soldering processes may improve solder joint fatigue life by resulting in a finer solder microstructure, because of the fast cooling rate of joints after reflow (Ref 7.11). However, the fine microstructure coarsens with time and temperature, causing the strength advantage to be lost.

Solder joints for surface-mount technology fulfill electrical and mechanical attachment requirements. Adequate joint configurations have more than sufficient bonding strength to secure the device to the board. Shear tests (load application parallel to the board surface) are typically performed on leadless chip resistors and capacitors or on leadless ceramic packages to quantify the joint strength. Shear loads of chip resistors on polyimide-quartz PCBs are shown in Table 7.2 for as-fabricated, thermally cycled, and thermally shocked units (Ref 7.12). Leaded packages are more often tested in tension; that is, the load is applied perpendicular to the PCB surface.

A particular concern with surface-mount solder joints is thermal fatigue damage caused by the CTE mismatch between the PCB laminate and the device package. Figure 7.7 shows scanning electron micrographs of fatigue cracks on several different device packages. Thermal fatigue damage is of greater concern on leadless packages than on leaded configurations, because the latter can accommodate some of the displacement mismatch through the leads. For leadless packages (resistors, capacitors, or chip carriers), cracks begin under the package, as shown in Fig. 7.7(e), and grow toward the outer surface. Thus, cracks are well established prior to being visually detected on the fillet surface.

Fatigue deformation that occurs under variable temperature conditions greatly complicates the prediction of solder joint failures. However, the thermal fatigue life of surface-mount solder joints can be estimated from isothermal fatigue test data when the microstructural damage is not strongly temperature dependent.

Table 7.2 Shear strength of surface-mount leadless ceramic chip resistor

Test identification	Shear strength	
	N	lbf
As-fabricated	84 ± 8	19.0 ± 1.7
300 thermal cycles	72 ± 6	16.2 ± 1.3
100 thermal shock cycles	97 ± 4	21.9 ± 1.0

Resistor dimensions, 2.67 × 1.27 × 0.457 mm (0.105 × 0.050 × 0.018 in.); termination width, 0.25 mm (0.010 in.); thermal cycle, -55 to 125 °C (-67 to 257 °F), 120 min hold period, 6 °C/min (11 °F/min) ramp; thermal shock, -55 to 125 °C (-67 to 257 °F), 10 min hold period, liquid-to-liquid transfer; displacement rate, 10 mm/min (0.41 in./min). Source: Sandia National Laboratories

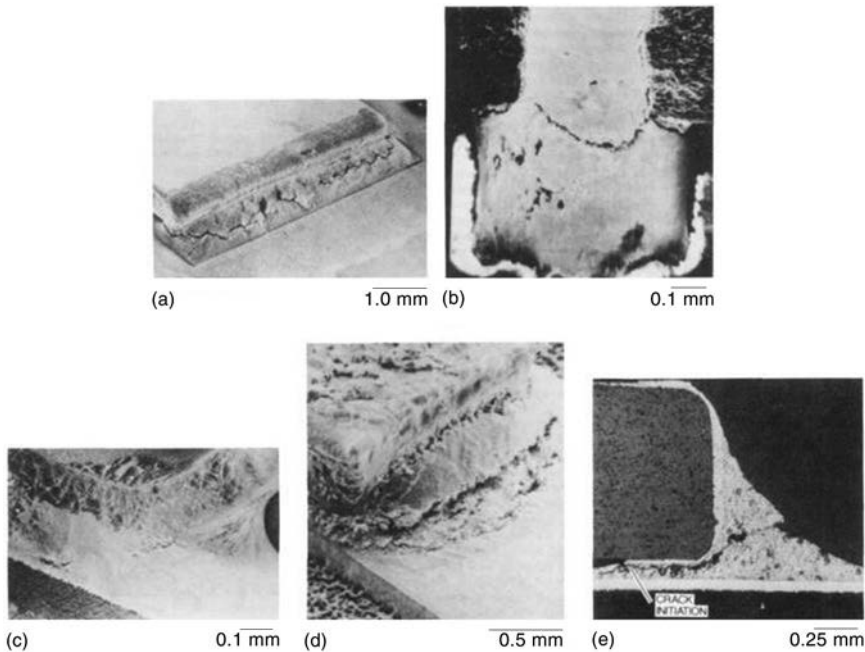


Fig. 7.7 Fatigue cracks in surface-mount solder joints. (a) Leadless capacitor. (b) Leadless ceramic chip carrier. (c) J-leaded package. (d) Gullwing leaded package (scanning electron microscopy). (e) Cracking in a leadless ceramic chip resistor solder fillet. Source: Ref 7.7

Thermal fatigue life can be lengthened by matching the CTE of the substrate to that of the package material (Table 7.3). Fatigue resistance is improved by increasing the stand-off distance between the component and the substrate (that is, increase the value of t). Other techniques include the use of nonmelting balls in the solder paste or protrusions on the bonding surface of the package, both of which act as spacers to control the gap. In addition, it has been shown that fatigue life increases as the solder joint cooling rate is increased (Ref 7.13). The cooling rate can be controlled on automated assembly equipment such as infrared furnaces and some vapor-phase units. However, thermal shock to the electronic devices and the substrate must be considered when increasing the cooling rate. Fast cooling rates are an inherent feature of localized heating techniques, such as hand soldering with an iron, hot gas or hot bar techniques, and laser soldering. However, room-temperature aging of the solder may counteract any fatigue life improvement.

Tape-automated bonding refers to bonding the silicon integrated circuit (IC) chip to a metal lead frame that, in turn, is soldered to the PCB. This technique is shown in Fig. 7.8. The $\text{Au}_x\text{Sn}_{1-x}$ solder inner lead bond, which attaches the silicon chip to the lead frame, is formed by the intermixing of gold and tin diffusing from corresponding metallizations deposited on the

chip and lead, respectively, under elevated temperature and pressure. The outer lead bond, which attaches the silicon chip plus lead frame to the circuit substrate, is a tin-lead solder joint formed by one of the conventional assembly processes. A lead exists for each of the I/Os on the silicon chip. The thermal fatigue of solder joints is reduced by the lead, which takes up the thermal strain mismatch between the silicon IC and the substrate. Additional compliance is added to the lead by jogs or bends in the geometry.

Controlled collapse chip connection (C^4) describes the process whereby the silicon IC chip is bonded directly to a ceramic substrate by small solder bumps that also serve as the signal I/O path (Fig. 7.9). This technique, known as bump bonding, is widely used in computer assembly technology. The solderable surface on the silicon is a vacuum-deposited copper layer.

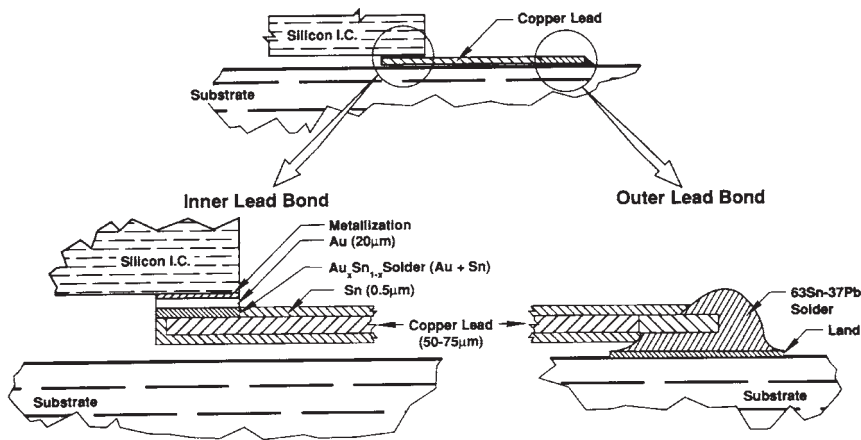


Fig. 7.8 Tape automated bonding of a silicon chip to the substrate. IC, integrated circuit

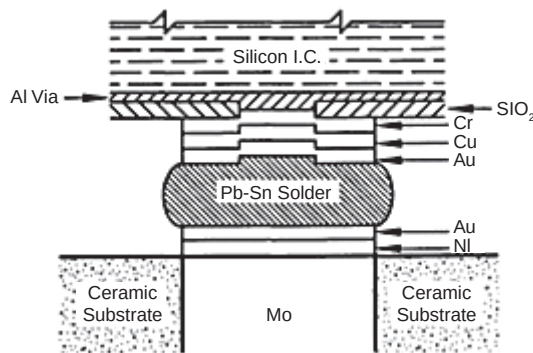


Fig. 7.9 Solder bump joint used in controlled collapse chip connection. IC, integrated circuit

A vacuum-deposited chromium film promotes adhesion of the copper to the SiO_2 layer. A gold layer (also vacuum deposited) is the final protective finish. The ceramic substrate can be single layered or multilayered.

When working with solder bumps to molybdenum vias, the molybdenum is coated with vacuum-deposited nickel and gold films, where nickel is the solderable surface and gold is the protective finish. The solder can be one of the lead-rich, tin-lead alloys (90Pb-10Sn or 95Pb-5Sn) or a lead-indium alloy (50In-50Pb). The lead-tin alloys are suited for assemblies that will later be processed with eutectic tin-lead soldering. More recent developments also allow the use of indium (Ref 7.14) or metal-coated carbon nanotubes (Ref 7.15). The solder films are vacuum deposited onto the silicon chip in thicknesses ranging from 0.100 to 0.123 mm (0.004 to 0.005 in.). The units are passed through a belt furnace under a protective atmosphere to melt the solder.

The solder joints of C^4 interconnects must accommodate the thermal strain mismatch between the silicon IC and the substrate. Fatigue damage is reduced by maximizing and controlling uniformity of the silicon IC chip stand-off distance above the substrate (hence the term *controlled collapse*), limitation of the chip size, and the use of substrates with CTEs similar to that of silicon.

Additional information on recent trends and developments in bump bonding can be found in Ref 7.16.

Underfilling. Underfill technology was originally developed to deal with thermal mismatches between PCBs and silicon devices by providing a gradient in CTE between the silicon chip and the substrate. Underfills also strengthen the mechanical connection and help to protect against shock and vibration. Underfill materials used in electronics assembly are generally electrically insulating adhesives, typically epoxies (filled or unfilled). They are used in a wide range of component types, including flip chips, ball grid arrays (BGAs), and micro-BGAs (discussed subsequently).

Capillary underfills are low-viscosity liquids that flow under a component by capillary action. According to B. Toleno of Henkel's electronics group (Irvine, CA), they are "the choice materials for advanced chip-scale package and BGA devices that require a high level of reliability, particularly those in handheld devices that will be exposed to higher-than-normal stress" (Ref 7.17).

The next generation of underfill technology includes epoxy flux materials: dual-function materials that provide both flux and underfill. According to some of the developers of such materials, they provide a high level of versatility and manufacturing flexibility (Ref 7.18).

Connector Technology. In the signal analysis of an electronic product, the backplane forms the hub through which PCBs "talk" with one another and receive electrical power to operate devices mounted on them. As a result, the physical requirements placed on the backplane construction

cause it to be a unique PCB. The backplane must mechanically support numerous PCBs and connector-cable assemblies that are frequently removed and reinserted, in addition to heavier devices such as large capacitors or transformers. Therefore, the backplane is typically much thicker (2.4 to 3.2 mm, or 0.093 to 0.125 in.) than conventional PCBs (Ref 7.19). As the hub of electrical signal transmission, the backplane is often multilayered with thick conductor lines (0.071 to 2.8 mm, or 0.0028 to 0.11 in.), depending on the power transmission requirements of the system. Connector pins may be soldered on the substrate using preforms and vapor-phase assembly or manual processes. The thicker laminate and conductors as well as the multilayer construction can be a formidable heat-sink to soldering processes in addition to being susceptible to warpage by overheating or inadequate support. Connector pins may also be press-fit onto the substrate.

Signal transmission between devices that are not electrically connected via the PCB, between PCBs themselves, or between PCBs and the backplane require the use of wires, cables, and connectors. Connectors are manufactured using attachment modes of soldering or a combination of soldering and mechanical fastening techniques. Examples of various connector techniques and design guidelines are shown in Fig. 7.10. The solder joints in connectors must be mechanically robust to accommodate loads caused by rigid, unyielding cables, as well as their frequent disconnection and reinstallation.

Base materials for connectors, wires, and cable conductors include copper alloys (for example, oxygen-free, high-conductivity copper and electrolytic pitch-grade copper; brass; beryllium-copper; and others), iron-base alloys (Kovar, stainless steel, and others), and aluminum alloys. Because connector assemblies typically use larger quantities of solder to form the joint, the electroplated gold that serves as the protective layer may not have

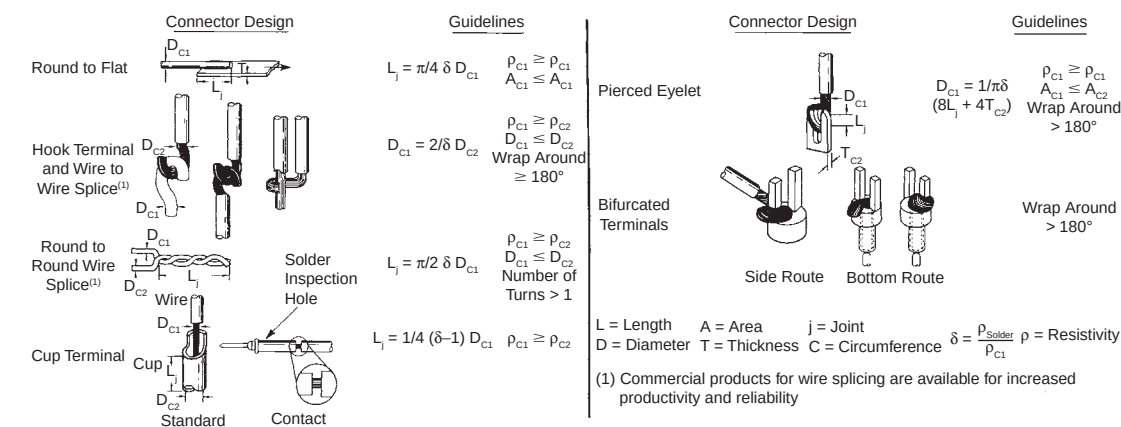


Fig. 7.10 Connector methodologies

to be removed by a hot-dipped solder coating prior to assembly. The solder joint may have a frosty appearance, because of the dissolved gold in the solder. However, a hot-dipped coating should be applied if the thickness of gold electroplating and the estimated quantity of solder used in the joint indicate a dissolved gold content in the solder that will potentially exceed the 4 wt% limit, which causes embrittlement in tin-lead solder joints.

Pins, which are part of a plug-and-socket connection, can be gold plated with so-called hard coatings, that is, the gold electroplate contains approximately 0.3 wt% Co or Ni to improve abrasion resistance during removal and installation cycles of the connector. However, the cobalt or nickel additions can cause the solderability of the pin to be poor.

Silver coatings are preferred on some connector parts in order to lower contact resistance. Unfortunately, silver is tarnished by the formation of sulfides from airborne sulfur compounds, which also deteriorate solderability. For grounding applications, soldering processes to aluminum connector housings should be followed with an electroplated coating of zinc or cadmium to guarantee adequate corrosion resistance.

Solders used in connector assemblies have historically been tin-lead alloys. Additional strength, particularly for products exposed to elevated temperatures or mechanical loads, is obtained with the tin-silver and tin-antimony solders, and in any case, the recent shift toward lead-free assembly has led to the use of such alternatives. The higher melting temperatures of these alloys, coupled with the generally massive structure of connectors (when compared with electrical components), require greater heat input into the assembly for proper joint fabrication. Joining can be facilitated by first hot dipping the mating substrates in the particular solder prior to final assembly. The use of preforms can facilitate the introduction of solder into joints, particularly those of very small assemblies.

The preferred fluxes for connectors are the rosin-based materials. Residues from pure rosin need not be removed. The RMA flux residues are removed for high-reliability applications. Residues of more-active fluxes (fully activated, superactivated, or water soluble) must be removed. Hand soldering with low-solids fluxes in air can give inconsistent solderability, because only very thin layers of tarnish can be removed by the flux. The higher heat inputs required for connector structures can degrade rosin-based fluxes, necessitating the use of water-soluble and synthetic fluxes that will tolerate the higher working temperatures. In either case, the residues must be removed, because they are corrosive.

Connectors are typically assembled by localized heating, such as by soldering iron, hot gas jet, or hot bar techniques. The use of automated assembly processes that exploit vapor-phase reflow or infrared furnaces is prohibited in order to prevent the exposure of heat-sensitive structural materials in the connector to elevated temperatures. Moreover, the generally cumbersome assemblies are not well suited for batch or continuous processes.

7.2 Substrate Materials for Electronic Component Applications

Many different materials are used for substrates. Substrates used for electrical/electronic applications must be insulators to allow the conductive circuitry to function in the manner of a network made from separate insulated wires. Common substrate materials for this application include ceramics and organic laminates. Metals can also be used as substrates if they are coated with a substantial insulating material that can withstand the rigors of assembly.

Ceramic Substrates. Many types of ceramics can be used as substrates. The most common is a high-fired alumina that is either 96 or 99% Al_2O_3 . Others include beryllia (BeO) and silica (SiO_2), as well as several of the engineered ceramics, such as silicon nitride (Si_3N_4).

Solders do not readily wet ceramic-based materials, because of the low surface energy of the substrate and the absence of a solder-ceramic metallurgical reaction. Solderable surfaces are provided by thick-film metallization inks. These inks contain a powder of electrically conductive metals or alloys (for example, copper, nickel, gold-palladium-platinum, platinum-silver, platinum-gold, and others), an oxide powder and glass binder that bond the conductive component to the substrate by a high-temperature firing process, and an organic carrier comprising resin and solvents to give the ink “body” for printability on the substrate. The thick films have excellent solderability, because of their noble metal content. However, the 10 to 20 μm (400 to 800 $\mu\text{in.}$) thick film can be consumed by intermetallic formation with the tin component of the liquid solder, as well as through solid-state reaction at the solder-film interface of the solidified joint. The use of lead-indium solders greatly reduces the growth of intermetallic compounds. Copper and nickel thick films are not as quickly consumed by the tin-base solders and are less costly. However, these coatings must be protected from excessive oxidation during firing, solder processing, and contaminated atmospheres during storage.

Other thick-film systems are based on moly-manganese and refractory metals (Ref 7.20). The moly-manganese process uses an ink of molybdenum and manganese that is printed onto the selected location(s) and fired to bond the film to the ceramic. Next, a layer of copper or nickel is electroplated onto the moly-manganese film to form the solderable coating. Then, a protective layer of electroplated gold is added. Alternatively, some refractory metal thick-film systems use molybdenum or tungsten as the ceramic binder. Gold is electroplated onto the refractory metal binder. The resulting metallized layer is heated to partially consume the gold as gold-molybdenum or gold-tungsten alloy at the interface. The alloys form the solderable surface, while the remaining gold serves as the protective finish. Electroplated nickel can be used to create the solderable surface in place of gold-molybdenum or gold-tungsten.

The 96% Al_2O_3 material is usually employed when thick-film materials are placed on the surface to form the circuitry. The 99% Al_2O_3 material is most often used for the evaporation or sputtering of thin materials. The materials that are laid down for terminal and component bonding pads are usually gold (or alloys high in gold), silver, and copper. Because these metals are laid down in thin layers, a soldering problem called leaching occurs. Leaching is the migration of the components of a substrate into a working solution. The process must be controlled because soldering results in bonding between the solder and the metals being attached. If the soldering process is not controlled, it can literally dissolve the metallization from the surface of the substrate. A gold-platinum alloy is more resistant to leaching than pure gold.

Thin-film (10 to 500 nm, or 100 to 5000 Å) deposits are more susceptible to leaching than are thick-film (10 to 25 μm , or 400 to 1000 $\mu\text{in.}$) deposits, because the thin layer is more susceptible to being consumed by the leaching. Therefore, the time at temperature and the maximum temperature become very important. In leaching, temperature is more important than time. Significantly more leaching will be generated by a small increase in temperature than would be produced with even a moderate increase in time.

Composite Laminates. The most popular composites are the copper-clad laminates used for PCB substrates. The metal cladding is usually copper but could be nickel or some other metal. Copper cladding can be either a plated material or wrought rolled foil. From a soldering standpoint, the rolled material is preferable, but it is more costly and more difficult to bond to the laminate material. Many PCBs are passed through numerous heat cycles during the manufacturing process. In addition, the use of multilayer designs is increasing dramatically. Plated foil, contaminated with co-deposited organics, can become brittle at elevated temperatures. Hence, foil coppers are available in several classes, depending on their application.

Printed Wiring Laminate Materials. The laminate upon which the metal cladding is applied is available in many composite forms. Originally, layers of paper or cloth impregnated with a phenolic resin and designated XP, XXP, or XXXP were used. The latter became the standard in the mid-1950s.

The selection of organic-based laminate materials as electronic substrates has certain limitations, the most common of which is temperature. In addition, soldering must not degrade the material by burning or charring. Laminate selection should depend on the application of the electronic hardware. A glass-epoxy laminate material known as FR-4 is commonly used in consumer and industrial electronics. The “FR” designation indicates that the material is fire resistant.

Metal Substrates. There are some applications in which metals can be used as base substrates. Because the presence of an insulating material is

required, the metal must be coated with a suitable material (for example, porcelain enamel).

The surface layer of a substrate comprises the so-called solderable layer to which the molten solder metallurgically reacts and, frequently, an additional coating or protective layer to prevent the formation of excessive oxidation and/or contamination by organic films on the solderable layer. This solderable surface can be either the base material surface itself or a coating deposited by electroplating, electroless plating, evaporation, pre-tinning (solder dip coating), sputtering, or chemical vapor deposition. The protective layer is typically an electroplated film that is entirely consumed by the solder during wetting. It is primarily the condition of the surface of the solderable layer (base material or a separate coating) on the component lead, termination, and PCB lands that accounts for joint solderability during assembly. Base material bulk properties, such as thermal conductivity or heat capacity, indirectly affect solderability, particularly the time-dependent wetting performance.

Coatings that serve as the solderable layer must be sufficiently thick to ensure that:

- The coating completely covers the base material surface.
- The layer is not dissolved by the liquid solder.
- The layer is not consumed by solid-state growth of intermetallic compounds with the solder.

On the other hand, excessive thickness can lead to residual stresses that cause delamination of the coating and the entrapment of organic plating compounds and gases that in turn cause the deterioration of solderability. Coatings used as solderable surfaces are typically the elemental metals, that is, nickel or copper. Multielemental thick-film layers are used as solderable surfaces on ceramic substrates (for example, conductor networks for hybrid microcircuits or terminations on discrete leadless ceramic devices or chip carriers).

The protective layer must be of sufficient thickness to protect the wettability of the surface of the solderable layer. Nickel that has been coated by a protective coating can be wet by the molten solder using the rosin-based fluxes. An unprotected nickel film requires much more active fluxes to promote solder wetting. Because the protective coating is absorbed into the solder, its thickness must be limited to prevent excessive contamination of the solder, thereby affecting its physical and mechanical properties.

Protective layers are often made from precious metals, the most popular of which is gold. It is imperative that gold coatings be removed by hot solder dipping the leads twice in flowing or nonflowing solder baths prior to assembly in order to prevent solder joint embrittlement (MIL-STD-1276D). However, three immersions in solder at 250 °C (480 °F) are recommended to ensure the complete removal of all thicknesses of gold from beam-leaded, surface-mount devices (Ref 7.21).

Other protective layers include electroplated tin (the production of which is termed tin plating) and electroplated tin-lead solder (for example, 60Sn-40Pb). The tin and tin-lead solder platings can be heated above their respective melting temperatures of 232 and 183 °C (450 and 361 °F) to remove pores or gaps. These layers are then referred to as fused tin or fused tin-lead coatings, respectively. A protective layer of tin or tin-lead solder can also be added by applying flux to the solderable surface and immersing it into a molten bath of tin or tin-lead solder. These finishes are referred to as hot-dipped tin or hot-dipped solder layers, respectively.

Organic coatings, such as benzotriazole and imidazole, are used as protective finishes on solderable surfaces. They are popular for protecting bare copper surfaces on PCBs during storage prior to soldering.

Examples given subsequently are described according to the base materials used most frequently in electronics applications. In general, properly prepared and protected solderable surfaces (base material or deposited layer) can be readily wetted by the solders listed in Table 7.1 using standard electronic fluxes and assembly practices.

Copper and copper-base alloys are used in electronic applications as wire leads (individual or as frames) on through-hole components, electroless/electroplated layers in PCB holes, or thin foil in the construction of lines and lands on PCB surfaces. In some PCB fabrication processes, copper foil surfaces can be built up with electroless and electroplated copper as well. The thickness of copper layers that coat PCB through holes is approximately 0.025 to 0.076 mm (0.001 to 0.003 in.). Typical foil thicknesses for PCB surface patterns range from 0.018 to 0.071 mm (0.0007 to 0.0028 in.). The most common thicknesses are termed 0.5 oz copper (0.018 mm, or 0.0007 in.), 1 oz copper (0.036 mm, or 0.0014 in.), and 2 oz copper (0.071 mm, or 0.0028 in.).

Copper is readily wetted by tin-lead solder using rosin-based fluxes, provided that the surface is not heavily oxidized. Oxide removal is performed by immersion in dilute hydrochloric acid or sulfuric acid solutions or another type of mixture. Protective finishes for copper and copper alloys include layers of electroplated silver of a thickness from 3.8 to 8.9 μm (150 to 350 $\mu\text{in.}$), electroplated tin (7.6 to 13 μm , or 300 to 500 $\mu\text{in.}$), and electroplated tin-lead (7.6 to 23 μm , or 300 to 900 $\mu\text{in.}$). The latter two layers can be fused; the preferred thicknesses range from 2.5 to 13 μm (100 to 500 $\mu\text{in.}$). The silver coating is usually covered by a tarnish layer caused by a reaction with sulfur in the air. The resulting sulfide film causes the solderability to deteriorate with time of exposure. Silver coatings must be removed, similar to the gold coatings, to prevent embrittlement of the solder joint by silver-tin intermetallic formation.

A hot-dipped tin-lead finish (5.1 μm , or 200 $\mu\text{in.}$, minimum) is most often specified for copper-base metal. A solid-state reaction takes place between copper and tin (or the tin component of solders) to form a layer of intermetallic compounds, Cu_3Sn and Cu_6Sn_5 , at the solder-copper interface. The thickness of the intermetallic layer increases as exposure tem-

perature and time increase. The total intermetallic layer thickness (Cu_3Sn + Cu_6Sn_5) as a function of time and temperature is shown in Fig. 7.11(a) for electroplated tin, Fig. 7.11(b) for electroplated tin-lead coatings, and Fig. 7.11(c) for hot-dipped tin-lead coatings. Growth kinetics at room temperature are illustrated in Fig. 7.11(d) (Ref 7.22, 7.23).

Intermetallic layers have low ductility and, depending on their thickness, can affect the mechanical integrity of the solder joint (Fig. 7.12). In addition, the solid-state growth of the intermetallic film may consume very thin layers of tin or tin-lead alloy. The exposed intermetallic layer of Cu_6Sn_5 can readily oxidize and is difficult to wet with molten solder. Parts stored for over 1 or 2 years or those that will experience elevated temperatures (as in testing requirements) should be covered by a solderable layer of electroplated nickel (1.5 to 3.8 μm , or 60 to 150 $\mu\text{in.}$), followed by one of the aforementioned protective finishes. This coating structure will prevent the excessive formation of copper-tin intermetallic compounds at the

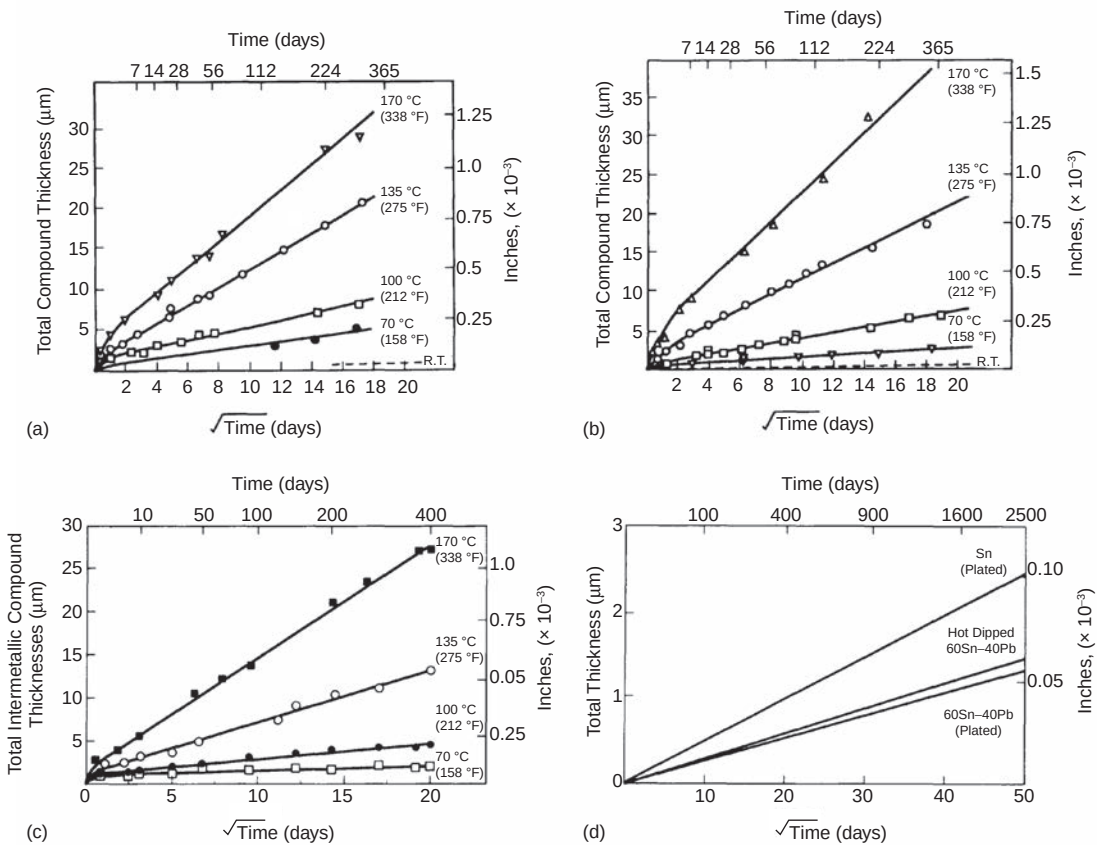


Fig. 7.11 Copper-tin intermetallic layer (Cu_6Sn_5 + Cu_3Sn) growth kinetics. (a) For electroplated tin coating. (b) For electroplated 60Sn-40Pb coating. (c) For hot-dipped 63Sn-37Pb coating. (d) For tin-lead coatings at room temperature. Source: International Tin Research Institute and Sandia National Laboratories

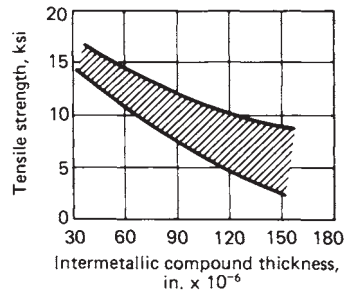


Fig. 7.12 Effect of intermetallic compound thickness on room-temperature tensile strength of solder joints (copper/copper-base metals)

solder-substrate interface, which may consume the tin or tin-lead protective finish and cause subsequent solderability to deteriorate.

Copper lines and lands on PCBs are protected with a hot-dipped solder coating that is generally applied by the hot-air leveling technique. The bare copper can also be protected with an organic inhibitor. Alloys of copper, including brasses, bronzes, Cu-Fe-Zn, Cu-Fe-Sn, and Cu-Zn-Al-Co, should be plated with a solderable layer (and protective coating) to overcome difficult-to-remove oxides or to act as a barrier against the diffusion of base-metal constituents (for example, zinc) into the solder. Finishes include either a minimum 2.5 μm (100 $\mu\text{in.}$) of copper or a nickel layer with one of the protective coatings (described previously).

Beryllium-copper forms a tenacious oxide. Solder wetting with the use of activated rosin-based fluxes requires that the surface oxide be reduced by etching with strong acids. The soldering operation should immediately follow surface-preparation steps to prevent reoxidation. Beryllium-copper with very thin oxides can be wetted by solder if inorganic acid fluxes are used. However, a thorough cleaning of residues is required. The inorganic acid fluxes are used only to apply a protective layer of hot-dipped tin-lead solder. They are not recommended for PCB assembly.

Nickel and nickel-base alloys are used as the base metals on package leads. However, the most common electronics application is electroplated pure nickel used as the solderable coating on nickel-and iron-base lead materials that cannot be subjected to the cleaning measures and aggressive fluxes required to promote solderability. Nickel and its alloys are difficult to wet, because of the formation of a thin, tenacious oxide layer. Substrates must be chemically etched with aggressive solutions. The soldering operation or the application of a protective layer must immediately follow the etching treatment in order to minimize reoxidation of the surface. Freshly deoxidized leads made with nickel or nickel-containing alloys, or those that are electroplated with a solderable layer of nickel (1.3 to 3.8 μm , or 50 to 150 $\mu\text{in.}$), require one of the following protective layers prior to assembly on the PCB:

- Electroplated (matte) tin (7.6 to 13 μm , or 300 to 500 $\mu\text{in.}$)
- Electroplated tin-lead coating (7.6 to 23 μm , or 300 to 900 $\mu\text{in.}$)
- Hot-dipped solder coating (5.1 μm , or 200 $\mu\text{in.}$)

The electroplated layers can be fused. The hot-dipped solder coating step may require the use of more-aggressive fluxes (organic acid or inorganic acid fluxes) to achieve a satisfactory finish. These fluxes must be compatible with the device package construction, and their residues must be thoroughly removed after coating. It is very important that hot-dipped solder (or tin) layers on device leads and terminations contain neither lumps nor icicles, because these defects can interfere with the automated placement of components on the PCB, particularly with the use of fine-pitch devices. However, a properly applied hot solder dipped lead finish is superior to most tin or tin-lead plated surfaces.

The nickel solderable coating is protected by a finish of electroplated gold, particularly if the base metal is subject to temperatures that exceed the melting points of tin or tin-lead finishes prior to assembly. The MIL-G-45204C thickness recommendation for solderability is from 1.3 to 2.5 μm (50 to 100 $\mu\text{in.}$). However, general specification of gold thickness (MIL-STD-1276D) can be as high as 2.5 to 7.6 μm (100 to 300 $\mu\text{in.}$), so that complete removal for soldering should be verified if the thinner layers do not offer adequate protection.

A less-expensive silver coating (3.9 to 8.9 μm , or 150 to 350 $\mu\text{in.}$) can also be used. However, silver tarnishes upon atmospheric exposure, causing a deterioration to solderability. As already mentioned, silver coatings must be removed, just as gold coatings are.

Electroplated copper (3.8 to 7.6 μm , or 150 to 300 $\mu\text{in.}$), followed by one of the tin or tin-lead protective finishes, can also provide excellent solderability to nickel and nickel-alloy base metals. Although nickel forms an intermetallic compound layer with tin (primarily Ni_3Sn_4), its growth rate is much slower than that of copper and tin. Therefore, it does not significantly affect the mechanical properties of solder joints in electronic assemblies. An ultrasonically activated solder pot can be used to apply a hot-dipped solder (or tin) coating to the lead without the use of aggressive fluxes. The ultrasonic energy disrupts the oxide layer, thereby allowing the solder to wet without the use of aggressive fluxes. Ultrasonics should not be used on devices that can be damaged by the ultrasonic energy.

Aluminum and aluminum-base alloys are used as connector housings that attach cables to PCBs or other cable assemblies. A strap or lead is soldered to the housing to provide an electrical ground.

Aluminum alloys are difficult to wet, because of a tenacious surface oxide. Although aggressive fluxes, such as the inorganic acids, are required to promote solderability, they leave behind extremely corrosive residues that must be thoroughly removed to prevent corrosion in service.

Another issue when solder joining aluminum is galvanic corrosion between aluminum and a dissimilar substrate (for example, copper or nickel) or between aluminum and solder constituents (for example, tin). Solder alloys, such as 80Sn-20Zn ($T_1 = 270^\circ\text{C}$, or 518°F ; $T_s = 198^\circ\text{C}$, or 388°F) and 95Zn-5Al (382°C , or 720°F), were developed for compatibility with aluminum. However, their high melting points require localized heating techniques and prohibit joining to organic materials or hybrid thick-film networks. The high thermal conductivity of aluminum alloys requires large heat input into the substrate to promote wetting.

Although solderable and protective finishes were not cited by the specifications noted previously, adequate solderability can be obtained with coatings of electroplated nickel or copper to thicknesses of 1.3 to 3.8 μm (50 to 150 $\mu\text{in.}$) and 7.6 to 25 μm (300 to 1000 $\mu\text{in.}$), respectively. A zincate coating is applied to the aluminum prior to the nickel or copper finishes to promote adhesion. Once the soldering operation has been performed, it is recommended that the exposed nickel or copper layer be coated with an anodic finish (for example, cadmium or zinc) to reduce the potential for a corrosion couple with aluminum. Ultrasonic activation of the solder pot provides a means of depositing a hot solder or tin-dipped finish to aluminum substrates without a flux.

Iron and iron-base alloys constitute the base materials for leads on a number of through-hole and surface-mount device packages. These alloys include Kovar, 29Ni-17Co-0.2Mn-balance Fe; alloy 52, 0.5Mn-0.25Si-50.50Ni-balance Fe; and alloy 42, 0.5Mn-0.25Si-5.5Cr-42Ni-balance Fe. Solder wetting of the iron-base alloys requires the removal of a thick, tenacious surface oxide by such procedures as the use of etchants and chemical brighteners or aggressive electropolishing treatments (Ref 7.24).

The hot-dipped solder coating may require the use of more-aggressive fluxes (organic acid or inorganic acid fluxes) to achieve a satisfactory finish. These fluxes must be compatible with the device package materials, and their residues must be thoroughly removed after coating. Surfaces must be protected from reoxidation after surface preparation, typically by a hot-dipped tin or solder coating.

However, the most common technique to achieve solder wetting of these materials is the use of combined solderable and protective layers. The most frequent approach is to electroplate device leads with a solderable layer of nickel (1.3 to 3.8 μm , or 50 to 150 $\mu\text{in.}$), followed by a protective layer of electroplated (matte) tin (7.6 to 13 μm , or 300 to 500 $\mu\text{in.}$), electroplated tin-lead coating (7.6 to 23 μm , or 300 to 900 $\mu\text{in.}$), or hot-dipped solder coating (5.1 μm , or 200 $\mu\text{in.}$, minimum). The electroplated layers can be fused. Silver (3.9 to 8.9 μm , or 150 to 350 $\mu\text{in.}$) can also be used as a protective finish. As previously mentioned, hot-dipped solder (or tin) finishes on package leads should not contain lumps or icicles, because they can interfere with the automated placement of components on the PCB.

The nickel solderable coating can be protected by a finish of electroplated gold, particularly if the base metal is subject to temperatures that exceed the melting points of tin or tin-lead prior to assembly. The recommended thickness for soldering operations ranges from 1.3 to 2.5 μm (50 to 100 $\mu\text{in.}$), in accordance with MIL-G-45204C. Gold coatings must be removed in the manner previously described.

Alternative solderable coatings include electroless nickel (1.3 to 3.0 μm , or 50 to 120 $\mu\text{in.}$), palladium-nickel (1.3 to 2.5 μm , or 50 to 100 $\mu\text{in.}$), or copper (3.8 to 7.6 μm , or 150 to 300 $\mu\text{in.}$). Electroless nickel is not recommended for flexible or semirigid leads or substrates exposed to high-temperature testing procedures prior to PCB assembly. Phosphorus from the plating bath may become entrapped in the layer, resulting in film embrittlement or poor solderability because of its diffusion to the nickel surface at elevated temperatures. A palladium-nickel coating does not require a protective finish because the palladium component imparts oxidation resistance to the alloy coating. The electroless nickel and electroplated copper coatings require one of the protective finishes noted earlier.

Precious metals (gold, silver, palladium, platinum, and others) and their alloys have excellent solderability with tin- and indium-base solders, because of a strong metallurgical reaction at the solder/base-metal interface. This metallurgical reaction results in the formation of intermetallic compounds at the interface. Their growth can take place when the solder is in either the liquid or solid state. In either case, intermetallic compound growth can quickly consume wires, leads, or the entire thick-film layer.

Silver wires or silver coatings on other metals have been used in place of gold to reduce cost. Silver has a lower dissolution rate in tin-lead solders than gold. The rate can be further diminished by adding from 1 to 2 wt% Ag to the solder. However, silver rapidly tarnishes from airborne sulfur pollution, causing the surface to tarnish rapidly and lose solderability. The dissolution of precious metals is significantly less when lead-indium solders are used.

Wetting of precious metal base materials is assisted by the limited oxide layer that forms on them, which sometimes allows wetting by solders without the use of a flux. Wires or ribbons are used as jumper leads on PCBs by virtue of their low resistance. Pastes that contain precious metals or their alloys as the conductive component are used as thick-film networks for hybrid microcircuitry.

7.3 Storage

The base material or surface finish solderability is strongly affected by storage conditions (time, temperature, humidity, gases, and packing materials) and the integrity of the protective coating. Recommended electroplated and hot-dipped solder finishes that pass specified solderability tests are considered to preserve solderability for 1 to 2 years under typical in-

dustrial environments (Ref 7.25, 7.26). Longer periods may require special storage conditions, such as inert atmospheres in containers, controlled temperature and humidity levels, or additional solderability testing prior to assembly. Plasticizers and silicon-base mold releases in plastic containers, as well as sulfur compounds in paper products and factory atmospheres, can degrade solderability. Inventory-control practices, including “first in, first out” and “just-in-time,” can prevent solderability deterioration caused by excessive storage periods.

7.4 Corrosion

Solder alloys have necessarily dissimilar compositions, when compared with the base materials that they join together. Therefore, solder joints have a potential for corrosion activity. Water vapor from the atmosphere can provide the electrolyte medium, particularly given that most PCB laminates (and ceramic materials) are hygroscopic to varying degrees.

Sources of ionic species to form the electrolyte medium are flux residues, processing chemicals that remain in the PCB (laminates), or external contamination by handling or service environments. The electromotive series provides a preliminary estimate of corrosion potential for the metal systems in the joint. However, the series cannot describe the kinetics (rate) of corrosion.

Assembly processes for high-reliability electronics or those systems destined for harsh service conditions (for example, saltwater spray or high-humidity locations) must be thoroughly assessed for corrosion potential. Issues include the compatibility of the solder and base material, the activity of the flux and the need for its residue removal after assembly, and the use of either conformal (organic) coatings to exclude atmospheric moisture or coatings with metal finishes (zinc or cadmium electroplating) to act as sacrificial anodes.

7.5 Solder Application

Because of the small distances between components, when soldering electronics, it is often necessary to measure carefully the amount of solder that must be applied to form a satisfactory joint. It is not only a matter of providing a sufficient amount of solder for a good fillet, but it is also important to not have excess solder in the joint. This can sometimes be accomplished by plating the area to be soldered to a predetermined solder thickness, so that the solder forms a good fillet when it is reflowed. This is often the method used to accomplish flip-chip bonding to produce tape-automated bonding assemblies (Ref 7.27).

Solder resists enable control over the PCB areas that will be wet by the solder. The resist, or mask, is an organic coating placed selectively on the board. Only the uncoated areas are exposed to and are wettable by the

solder. The higher interconnect densities now being attained by SMT processing make solder resists a valuable method.

Solder resists can be either permanent or temporary, depending on the application. The permanent resists must resist not only the solder but any fluxes or solvents applied later in the manufacturing sequence. Compatibility with the process and the circuit materials is a consideration, as is the ability to withstand soldering temperatures. In addition, the solder resist offers the circuits some protection against dirt and contamination. Commonly used resist materials are polystyrene, epoxides, and acrylics, although more-costly materials, such as polyimides, are sometimes used because of their greater thermal resistance.

Screened Materials. Solder masks are commonly applied by screening. The films are subsequently dried and cured thermally. The elevated temperatures involved in the curing cycle can cause oxidation of the conductors on the PCB, resulting in a loss of solderability. Lower curing temperatures are desirable. Some of the resists are cured by exposure to ultraviolet light rather than by heating. This approach is very fast, involves less emission of volatile pollutants, and does not cause oxidation of the metal surfaces.

Photographic Films. A second method of applying solder resists is to use sheets of photosensitive material laminated to the surface of the circuit. Although these are more expensive than screened materials, the photographic films enable much higher pattern resolution. Dry film resists are much stronger and more resistant to damage during soldering and cleaning operations. The use of these photosensitive materials increases the complexity of the process.

Temporary solder masks are often used as production aids, offering local protection from solder at locations such as:

- Contact pads that have been gold plated
- Plated through holes that must be soldered in a later operation
- Pads that must be kept free of solder

Adhesive solder-mask tapes that specifically protect edge connectors on PCBs are also available, and numerous mechanical approaches to limiting solder contact exist (Ref 7.28).

Preforms. Solder can also be apportioned in proper amounts to individual joints by using preforms. In the case of SMT, the solder is often screened onto the substrate in the form of solder paste, or it is dispersed in small quantities in precise locations by using tiny nozzles or tubes.

Solder pastes, discussed in Chapter 5 in this book, are the most common form of solder in electronic assembly, especially in SMT. However, in some applications, particularly those involving through-hole components or large devices, solder paste alone may not be sufficient. It is common in PCB assembly to use mixed technology, that is, solder paste for

the surface-mount components, and solder preforms for attaching leads. A combination of paste and preform may also be used to make a joint strong enough to meet requirements that cannot be met with paste alone.

As the name suggests, a solder preform is a preformed shape of solder, designed to be uniform and to deliver a consistent amount of solder to each joint. Preforms can be used in many applications besides SMT; they can be purchased in many standard shapes including spheres, discs, and rings, as well as in customized designs. They are available in all of the alloys used for solder paste and are governed by the same specifications.

In applications where both paste and preforms are used, the same alloy should be used for both. This will avoid undesirable consequences of mixtures and also allow the use of the same reflow method and temperature profile. Most often, no additional flux is needed because the flux in the solder paste will suffice for the preform as well, but if additional cleaning is required, the same flux should be used for both paste and preform.

When preforms are used alone, however, fluxing is required. Generally, preforms can be coated with a flux that will be activated when the alloy is heated.

In handling preforms, gloves should be used so as not to contaminate the surface with organic chemicals. They should be stored in their original containers in nitrogen-dry boxes, opened only just before use, and kept not more than approximately 2 years from date of manufacture, unless the end-user is able to certify their quality (Ref 7.29). (This reference also provides valuable advice on whether a given application requires a preform.)

In using preforms, when a square or round lid is attached to a device, but solder is not desired in the enclosed area, the solder application is often accomplished by using squares or annular rings that are punched from solder sheet. The solder quantity is usually sufficient to fill the asperities in the surfaces. The thickness and the lateral dimensions are determined by the location and the amount of solder needed to make a satisfactory joint. The solder preform is placed in the space between the parts to be joined, and then this assembly is subjected to sufficient heat to fuse the solder and hermetically seal the assembly. The entire body is then cooled. If the parts were clean and the proper amount of solder was supplied, a good solder joint results.

Heat for soldering can be applied in a number of different ways. In automated processing, the parts to be soldered are often passed through the hot zone of a furnace on a belt. This makes it possible to provide adequate preheating of the parts, the proper maximum temperature, and a gentle cooling cycle to minimize stresses. This method is fast and allows easy control of the measured amounts of solder to precise locations in a variety of geometric shapes. However, the cost of the preforms is a drawback.

Solder balls (or solder spheres) are commonly used in the processing of microelectromechanical systems (MEMS), particularly those assembled on wafers. The usual method of creating them is to make a reusable

silicon mold by way of deep reactive ion etching and put a controlled amount of solder paste in each cavity, then reflow it in vacuum so that the solder paste, which coheres with itself more than it adheres to the silicon, forms a sphere. Then the mold is placed over the wafer and the solder reflowed a second time, so that the solder is attracted to the MEMS underbump metallization. This process has the advantage of allowing the device to be sealed at the same time its electrical interconnections are made, which is especially helpful in the manufacture of multichip modules (Ref 7.30).

7.6 Common Types of Electronic Assembly

The ball grid array is a descendant of the pin grid array (PGA), a type of IC packaging with pins arranged in an array on the underside of a (roughly) square package.

The PGAs were developed to increase the number of pins that could be mounted on an IC. They are often mounted on PCBs either by being inserted into a socket or by through-hole methods. The PGA types include plastic, flip chip, ceramic, organic, and others.

As the number of pins on PGAs increased, however, the pins were placed closer and closer together and became harder and harder to solder. The solution was to replace the pins with tiny solder balls.

The result was the BGA, a surface-mount package that uses an ordered array of preplaced solder balls as its connectors. The BGAs, similar to PGAs, are generally classified by material, form, or size; types include flip chip, chip-scale package, super ball grid array, plastic, cavity plastic, and ceramic, as well as numerous others.

The BGAs allow for a high degree of automation; automated flip-chip bonding machines, for example, can process 500 chips/h (Ref 7.31). Their very short connection distances also make for good electrical properties. With package-on-package designs, they can be stacked to provide greater functionality with the same footprint as a single BGA. They can, however, be difficult to inspect.

The pitch of a BGA is the distance between one ball and the next, measured from center to center. The standard pitch is 1 mm; a BGA with a smaller pitch is called a micro-BGA.

Assembling BGAs, especially micro-BGAs, is an exacting process that requires tight tolerances, high precision, and great care in determining the reflow profile, creating printing stencils, and choosing solder paste and flux. The proper thermal profile depends on several factors, including PCB layer count, the number of planes inside the board, the type of PCB material, the component types, the component density, and the PCB thickness, length, and width. The correct stencil thickness depends on the density of the components on the board and helps to determine the amount of solder paste that will be dispensed on the surface-mount pad; too much paste can cause shorts between fine-pitch BGA balls, and too little can

cause insufficient wetting and cold solder joints (Ref 7.32). There is no simple formula for determining stencil thickness, and its selection is a matter of experience. Reference 7.33 provides a brief and helpful guide to stencil printing for electronics assembly, including BGAs.

Solder Charges and Solder Charge Grid Arrays. An alternative mounting method is the use of a solder charge, described by H. Endres as “a blanked solder mass that is extruded through a hole near the tip of a terminal until it fills a volume on the opposite side of the pin” (Ref 7.34). According to Endres, solder charges prevent solder wicking during reflow and achieve cheaper, stronger, more reliable interfaces than BGAs while also using standard reflow processing. The method uses stamping equipment to adhere the solder charge to the terminal. (In Ref 7.35, T. O’Neil provides a helpful overview of stamp soldering and suggests that it can be used in high-speed manufacturing processes.)

A solder charge grid array consists of a solder charge mounted to a terminal. Its geometry is reported to make x-ray inspection easier and more reliable (Ref 7.36).

A package-on-package (PoP) device is made by stacking components on top of one another, resulting in three-dimensional (3-D) integration. As noted earlier, such a device can provide greater functionality than a single BGA with the same footprint. When manufactured by solder paste printing, generally the bottom layer is handled as in ordinary BGA assembly; the upper layers then require very accurate placement as well as dipping. Either paste dipping or tacky flux dipping may be used, although paste is generally more forgiving and easier to inspect. In reflow soldering, the thicker the device, the greater will be the role of the difference in temperature between the device and the board surface; as always, careful temperature profiling should be performed. The PoP devices also present special inspection issues (Ref 7.23).

The production of PoP devices is a form of what is sometimes called mixed assembly, although the term has different meanings to different manufacturing engineers. Another example is stacked-die chip-scale packages, which use a combination of C⁴ and wire bonding (Ref 7.37).

Wafer-Level Packaging. Closely related to the BGAs, a wafer-level package uses solder balls to connect an IC, mounted face down, to a PCB. Unlike other BGAs and similar technology, it does not use bond wires or interposer connections (Ref 7.38). The technology lends itself well to stacking and 3-D integration (Ref 7.39) and can also be performed successfully with dielectric substrates (Ref 7.40).

7.7 Properties of Common Packaging and Substrate Materials

An assessment of solder joint performance requires knowledge of several physical and mechanical properties of the solder alloy, package, and substrate materials. Strength calculations based on bulk solder properties

typically provide a conservative estimate of solder joint performance (Ref 7.41); more accurate predictions are made from solder joint properties. The properties of those materials commonly used in electronics packaging and substrates are summarized in Table 7.3.

Organic materials used in PCB laminates soften significantly at temperatures that exceed their glass transition point. Time periods at temperatures greater than the transition value should be minimized to prevent permanent warpage or twist to the PCB, which can cause debonded lands and conductor lines or fractured joints and packages due to misfit in cabinet frames.

Coefficients of thermal expansion are required to assess the thermal fatigue resistance of solder joints, a principal source of failure for leadless surface-mount components. The CTEs of PCB laminates are specified for the in-plane dimensions. It is important to note that the through-thickness CTEs of PCB laminates can be as much as an order of magnitude larger than the in-plane values. Because CTEs of PCBs are very sensitive to the resin content, resin type, and fiber weave of the laminate, precise values should be obtained by measuring them directly, rather than relying on generic information from the manufacturer. Thermal conductivity is important in solder joint design for high-power applications.

Excessive moisture retention by the PCB (organic laminate or ceramic) can lead to voids in solder joints that are due to water vapor formed at

Table 7.3 Selected properties for electronic assembly materials

Material	Glass transition temperature		Planar coefficient of thermal expansion(a), 10 ⁻⁶ /K	Thermal conductivity		Planar tensile modulus	
	°C	°F		W/m · K	10 ⁻⁴ Btu/ft · s · °F	GPa	10 ⁶ psi
Printed board substrates							
Epoxy fiberglass	125	257	13–18	0.16	0.26	17	2.5
Polyimide fiberglass	250	482	12–16	0.35	0.56	19	2.8
Epoxy-aramid fiber	125	257	6–8	0.12	0.19	30	4.4
Polyimide-aramid fiber	250	482	3–7	0.15	0.24	28	4.0
Polyimide quartz	250	482	6–8	0.30	0.48	...	...
Fiberglass/synthetic fluorine-containing resin	75	167	20	0.26	0.42	1.4	0.2
Ceramics							
Alumina, 86%	...	...	6.0	20	32	300	44
Beryllia, 99.5%	...	...	6.4	200	320	350	51
Silicon	...	...	2.3	150	240	115	17
Metals							
Copper	...	...	17.0	370	590	130	19
Nickel	...	...	13.0	89	140	220	32
Aluminum	...	...	24.0	230	370	70	10
Brass, 33 wt% Zn	...	...	20.0	120	190	112	16
Bronze, 5 wt% Sn	...	...	18.0	75	120	121	18
Low-carbon steel	...	...	12.0	58	93	210	30
Stainless steel, 18-8	...	...	15.0	16	26	210	30
Kovar	...	...	5.2	17	27	210	30
60Sn-40Pb solder	...	...	25.0	51	82	32	4.6

(a) Thermal expansion of circuit board substrates in the z (thickness) dimension can be an order of magnitude greater than in the xy (planar) dimensions. Source: Ref 7.3

soldering temperatures, or it can cause movement of surface-mount parts during reflow that results in misaligned packages on the assembly.

ACKNOWLEDGMENT

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CHAPTER 8

Quality Control, Inspection, and Reliability

MANY SOLDERING DEFECTS are the result of problems in processing or in materials selection and storage. By correctly identifying defects in soldered joints, materials- or process-related problems can be determined and solved. The continuous monitoring of manufacturing processes and the inspection and evaluation of soldered joints can lead to significant improvements in a soldering process. Statistical process control can be used to monitor processes and materials and to correlate these data with the quality of the final product. Variations in product quality that are linked to variations in materials and processes can be used to make continuous improvements in final quality.

8.1 Quality Control—Assessing Solderability

Table 8.1 lists methods that are commonly used to evaluate the solderability properties of selected soldered components.

Dip Test. The most useful test for assessing solderability is the dip test, because of its accuracy and simplicity. It is conducted with the additions of cams and timers so that standardized conditions are established. The dip test is a reasonable simulation of practical soldering conditions and starts with a test specimen that has been dipped in a mild flux, as is usually the case with soldering tests. The dip test involves immersing the test specimen into a clean solder bath, waiting an appropriate length of time, and then withdrawing the specimen from the bath. In most cases, the test is automated to ensure reproducibility. The results are evaluated by means of visual inspection and comparison with a set of standards. Thus, the dip

Table 8.1 Test standards used to evaluate solderability

Basic method	Test standard
Dip and look	ANSI/IPC-S-804 (boards) ANSI/IPC-S-805 (components) IEC 68-2-20 MIL-STD-202, 750, 883 EIA RS-186-9E
Rotary dip	ANSI/IPC-S-804 (boards) IEC 68-2-20 BS 4025 (British standard)
Wetting balance	ANSI/IPC-S-805 (components) IEC 68-2-20 MIL-STD-883
Globule test	ANSI/IPC-S-805 (components) IEC 68-2-20 BS 2011 (British standard) DIN 40046 (German standard)
Meniscus rise	No standards to date
Timed solder rise	ANSI/IPC-S-804 (boards)

test is operator sensitive, somewhat subjective, and of limited value, because it is not quantitative.

The rotary dip test was devised to provide a better simulation of the dynamic conditions that exist in machine soldering operations. It is used to evaluate the solderability of printed wire boards and involves bringing the specimen into moving contact with the molten solder for a specified period of time. This is a “go/no-go” test that requires complete wetting of the specimen surface within a set time and is thus dependent on visual inspection of the test specimen.

Wetting Balance (Meniscograph). Another common test employs the wetting balance, which gives a numerical result. The equipment consists of a balance that records the forces exerted on a fluxed test specimen during a controlled dipping cycle in a clean solder bath. From the values obtained, it is possible to compare the rate of wetting as well as the forces involved for various flux formulations.

The speed of wetting is an especially important factor in the wave soldering process, where automation requires a time-based response of flux and solder as the work moves through the process machine at a constant speed.

The wetting balance test cannot be used on finished, etched printed circuits or on single-sided circuits. It is often used on specimens cut from double-sided clad materials prior to etching. Although this test gives numerical results, they are not strictly quantitative. However, the results do provide the basis for a meaningful comparison among fluxes.

Additional Tests. There are several other tests that provide practical information for special purposes, such as the spreading test and the globule test. These tests are sometimes used to evaluate incoming materials or to aid in the selection of materials. They are not universally employed.

The spreading test is used to provide a numerical rating for both fluxes and solders. It is described in detail in MIL-F-14256, “Flux, Soldering,

Liquid (Rosin Base),” and in QQ-S-571, “Solder, Electronic,” which are national-level specifications.

The *globule test* was once widely applied but is now limited to being used to determine the wetting of component leads and wires (Ref 8.1).

8.2 Inspection

The overall quality of a soldered joint can be determined by visual, automatic, and destructive inspection techniques. However, it is important to remember that quality is a function of materials, processes, and application requirements. An inspection of joint shape and structure may reveal defects that result from process- or materials-related problems.

Visual Inspection. Most solder joints are currently evaluated by visual inspection criteria that are defined in numerous standards, both commercial and military. Soldered joint surfaces should be smooth and free of cracks, pores, and holes. The joint should have complete fillets that completely cover the substrates, because that is indicative of good wetting and a sound metallurgical bond. The acceptable alignments between electronic component leads and pads for a surface-mount leaded component are shown in Fig. 8.1.

Most companies involved in soldering operations use either an internal or commercial-quality standard of some type, or they use standards developed by independent organizations. The IPC’s standards J-STD-001, “Re-

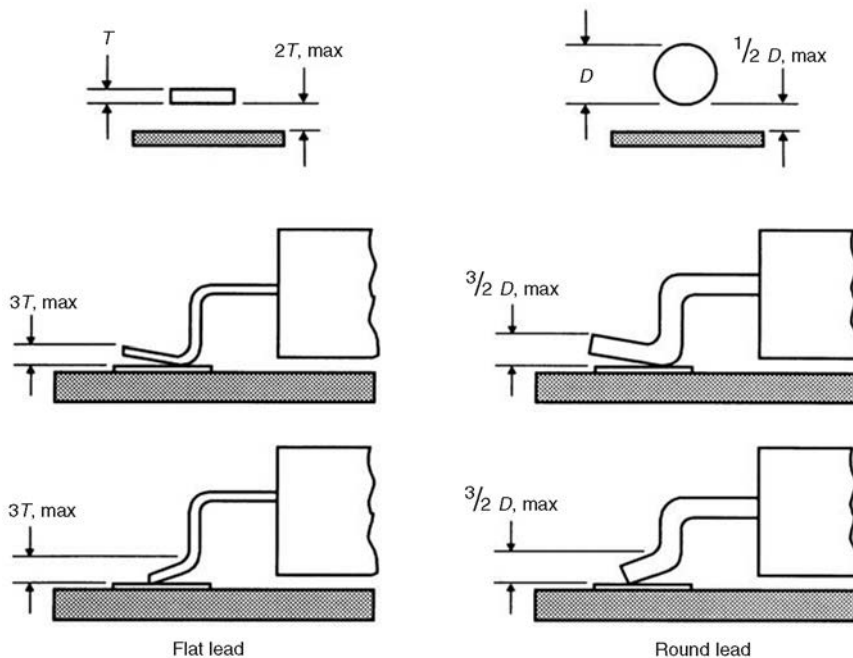


Fig. 8.1 Planar-mounted device lead height off land. Source: MIL-STD-2000

quirements for Soldering Electrical and Electronic Assemblies,” and IPC-A-610, “Acceptability of Electronic Assemblies,” have been approved by the American National Standards Institute. Figure 8.2 illustrates a preferred solder joint for a surface-mount leaded component.

Some problems that are common to all soldering operations, and which are usually identified by visual inspection, are discussed as follows.

Nonwetting (Fig. 8.3) is a condition in which the molten solder has contacted the substrate, but no reaction has occurred. The solder does not completely cover the substrate, and the substrate exhibits no change in color or appearance. Nonwetting can be due to an unsolderable surface; insufficient, improper, or inactive flux; insufficient temperature; insufficient solder; or some combination of these. In Fig. 8.3, the substrate is Kovar, plated with 95 wt% Sn and 5 wt% Pb and dipped into a pot of molten eutectic tin-lead solder.

Dewetting (Fig. 8.4) results from either a poor or an incomplete reaction between the solder and either the substrate or the lead. The solder may wet the substrate, but the surface tension of the solder or a change in solder or substrate composition causes the solder to withdraw, leaving

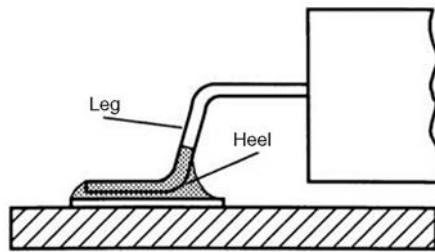


Fig. 8.2 Preferred solder joint for a surface-mount assembly. Source: IPC-A-610

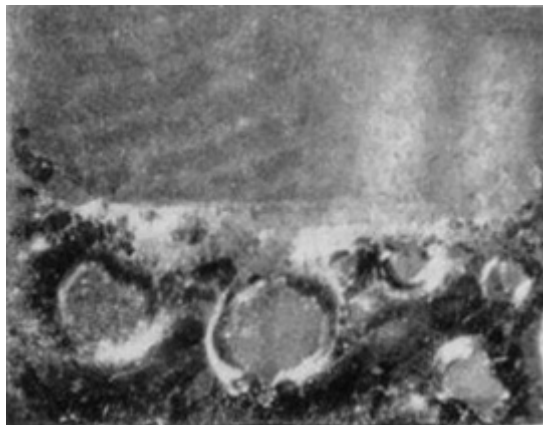


Fig. 8.3 Nonwetting condition

areas of partial wetting and irregular solder contours. The substrate retains the color of the solder but does not exhibit a sound metallurgical bond. Some causes of dewetting include excessive intermetallic growth from improper storage or processing conditions, unsolderable particles within the substrate, and unsolderable residues from fluxing or plating operations. The sample in Fig. 8.4 is also Kovar, plated with 95 wt% Sn and 5 wt% Pb and dipped into a pot of molten eutectic tin-lead solder.

Bridging occurs when a span of solder exists between adjacent leads. Bridging cannot be tolerated on electronic assemblies, because it forms a conductive path that can cause electrical shorts. The probability of bridging increases as the spacing between joints decreases. It is of particular concern with fine-pitch electronic leaded devices. Manufacturing problems in electronic surface-mount assembly, such as smearing, misregistration, slumping, and poor printing of solder paste, increase the possibility of bridging. In a through-hole assembly process, bridging is a factor based on many variables, including solder temperature, molten solder dynamics, alloy composition, joint orientation, and substrate temperature. Excessive oxidation in the solder can also aggravate the problem. Bridging is related to a problem known as icicling, which occurs in wave-soldered assemblies as incomplete bridges or spikes that trail from the joint. Depending on its precise cause, it can be dealt with in any of various ways (Ref 8.2).

Rough Solder Surfaces. Dull or rough solder surfaces can indicate processing or materials problems, or they can be a result of the alloy selected. Most solder joints should have a shiny, metallic surface, although lead-free solder joints are not as shiny as eutectic solder joints, and inspectors must be trained to tell the difference. Dull or rough surfaces can be caused by either overheating or underheating. Although overheating usually results in a sound joint, it can cause the solder joint to oxidize, and it may damage heat-sensitive components. Underheating results in a poor solder-substrate



Fig. 8.4 Dewetting condition

bond. Other causes of dull solder surfaces include vibration during solidification, which can result in a weakened solder joint, and contamination. Elemental additions, both intentional and unintentional, can affect the wetting behavior and reliability of soldered joints. Contamination is a particular problem in wave soldering and tinning operations in which a molten solder comes into continuous contact with a variety of materials. Gold, copper, aluminum, nickel, iron, and other elements can cause dull, rough, or gritty solder surfaces and can affect joint integrity. The specific elements that affect the soldered joint depend on the solder and the substrate that are used.

Porosity within the solder joint can weaken it by decreasing the amount of solder. Porosity at the joint surface, often referred to as voids, pin holes, or blow holes, can either trap corrosive chemicals or allow oxidation or corrosion of the base metal. Porosity is caused by air, flux vapor, plating residues, or water vapor that is trapped within or beneath the solidifying solder.

Although any individual can perform a visual examination, training and experience are necessary for good and consistent evaluations. Visual inspection suffers from inconsistencies between inspectors as well as from evaluation variations when inspectors suffer from fatigue or eye strain. The visual inspection of each soldered joint also requires a considerable amount of time. Another disadvantage of visual inspection is that it can only be used to evaluate the surface of the joint. Automated inspection equipment attempts to solve some of the problems associated with visual inspection.

Automated Inspection. Laser inspection adds a known quantity of heat to a soldered joint using laser energy. The quantity of heat radiated by the joint is then measured and used to calculate the mass of the soldered joint. This nondestructive method of evaluation is useful in determining excessive solder, insufficient solder, and porosity. It cannot be used to examine joint configuration. However, wetting behavior can be estimated by the amount of heat that passes into the substrate.

Structured-light, three-dimensional vision systems use a number of lasers to form a plane of light and a number of detectors to record the curve that forms as this plane intersects the surface of a soldered joint. The system scans soldered joints by moving an x-y table back and forth under the laser assembly. The entire inspection system, including the laser optics and table, is attached to a granite block that floats on a bed of air to eliminate outside interference from vibration. Each soldered joint contains from 3,000 to 20,000 data points. If data collection is obstructed by nearby components, then the approach angles of the lasers can be adjusted. The data are then sent to a knowledge-based software system, where the joint is detected and analyzed. The software algorithms for joint detection and analysis vary, depending on the configuration of the selected soldered joint. Although this system is capable of repeatable and consistent evalu-

ations, it can only be used to examine the joint surface. This system is also limited by the software algorithms. New joint configurations require additional programming before joint recognition is possible.

Figure 8.5, an image from a structured-light, three-dimensional vision system, shows a good joint between a leaded surface-mount device (SMD) and a copper pad or substrate on an epoxy-glass laminate. The center-to-center spacing between adjacent joints is 0.635 mm (0.025 in.).

X-ray laminography is based on conventional x-ray technology, except that the x-ray beam and detector are rotated to produce a cross section of the soldered joint. The beam rotates magnetically while the detector mechanically spins beneath the assembly to be inspected. The material above and below the focal point is blurred, so that the image is sampled over a number of rotations to produce a section that is approximately 0.18 to 0.51 mm (7 to 20 mils) thick, depending on the field of view. Solder recognition and analysis software process the image, and the solder-joint characteristics are measured and recorded. This system can be used to examine the interior of the joint and its components.

Voids, porosity, and cracking are detectable with x-ray laminography systems. Because this system uses x-rays, it is limited in the same manner as other x-ray devices. It cannot detect organics or elements with low atomic weights, nor can it identify atomic or molecular structures. It is very limited in its ability to evaluate the surface of a soldered joint.

Figure 8.6 shows an x-ray image of a leadless ceramic SMD. The white areas are soldered joints between the component and the circuit board. The small black dots represent voids within the joint, underneath the component. The distance between adjacent joints is 1.27 mm (0.050 in.).

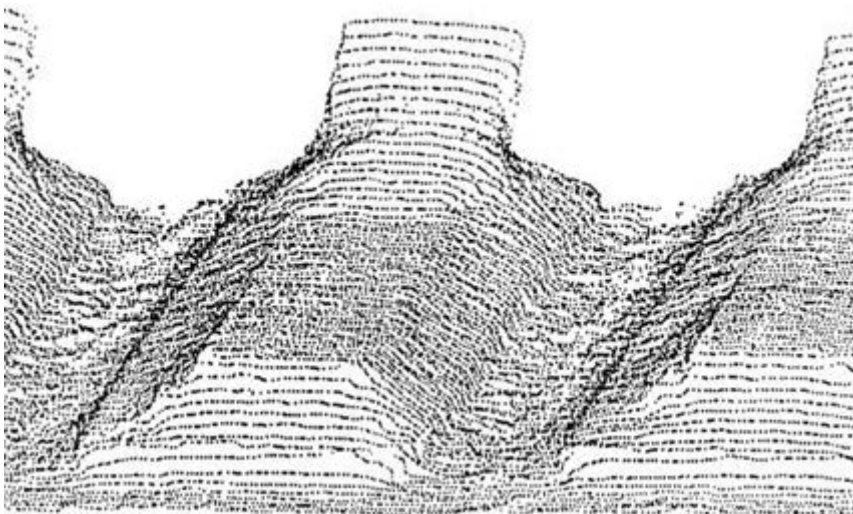


Fig. 8.5 Solder joint image from a structured-light, three-dimensional vision system

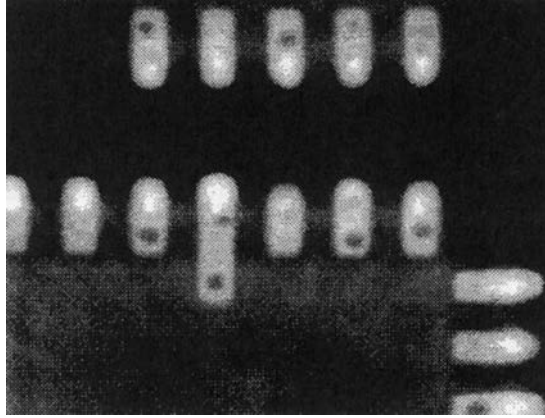


Fig. 8.6 X-ray laminography image of soldered joints and a leadless ceramic surface-mount device

Automated systems are much more consistent than human inspectors, and they have greater capabilities. However, they are limited by hardware and software constraints. They also require large capital expenditures and trained operators. The principal advantage of visual and automated inspection systems is that they are nondestructive, which means that joints that meet the quality standards can be used in finished products.

Nonlaminographic (two-dimensional) x-ray inspection of package-on-package devices requires viewing at an oblique angle, so that one layer does not obscure another. Laminographic x-ray inspection of such devices may not be feasible, however, if the system does not have sufficient vertical resolution to discriminate between layers (Ref 8.3).

Destructive Evaluation. Destructive techniques, such as microsectioning, can reveal additional information about soldered joints. The configuration, integrity, and microstructure of the joint are easily visible for analysis and evaluation. However, because destructive inspection techniques destroy the soldered joint, this method of inspection may be best suited for joints that have failed to meet visual quality standards or for soldered joints that have failed in service. The sectioning of soldered joints may be the only method available for evaluating the overall quality of the joint. Porosity, cracking, excessive intermetallic growth, and phase coarsening are conditions that are found within the interior of the joint and which may only be revealed by destructive evaluation.

Extreme care must be taken when preparing microsections for optical evaluation. Smearing and cracking can be caused by improper sawing or grinding. The polishing of solder-joint microsections can also be difficult. Solder joints are often used to bond harder metals, such as copper or Kovar. Ceramics or epoxy-glass laminates also are often part of solder-joint microsections. When several materials of varying hardnesses are present, smearing the solder over the solder-substrate interface is possible.

Excessive relief between materials is another problem encountered in polishing. Yet another difficulty is the etching of soldered joints. Most solders join materials that are resistant to many etchants. A general-purpose etchant for tin-lead solder bonded to copper is a mixture of ammonium hydroxide (NH_4OH) and hydrogen peroxide (H_2O_2) in water. In the proper concentrations, this etchant will attack tin, lead, and copper at equal rates.

Figure 8.7 shows a leaded SMD soldered to a copper pad on an epoxy-glass laminate. A lamellar or globular structure of tin and lead-rich regions is visible within the joint. An intermetallic between the solder and the substrate is created when the joint is formed. For tin-lead solders on copper, the intermetallics formed are Cu_6Sn_5 and Cu_3Sn . Tin forms a variety of intermetallics with most substrates. Although this intermetallic is evidence of a good metallurgical bond in a solder joint, excessive intermetallic growth may be detrimental. Most intermetallics are brittle and may serve as paths for crack propagation. Intermetallic growth also depletes tin from the solder joint, which leaves a weakened, lead-rich region near the substrate and the intermetallic.

An example of intermetallic growth is shown in Fig. 8.8. This joint was aged at 125°C (255°F) for 12 weeks. An alternate etchant, which will attack and darken the solder but leave the intermetallics bright and visible, is acetic acid. Because this etchant will rapidly attack lead and phases that contain it, short etch times and dilute solutions are recommended.

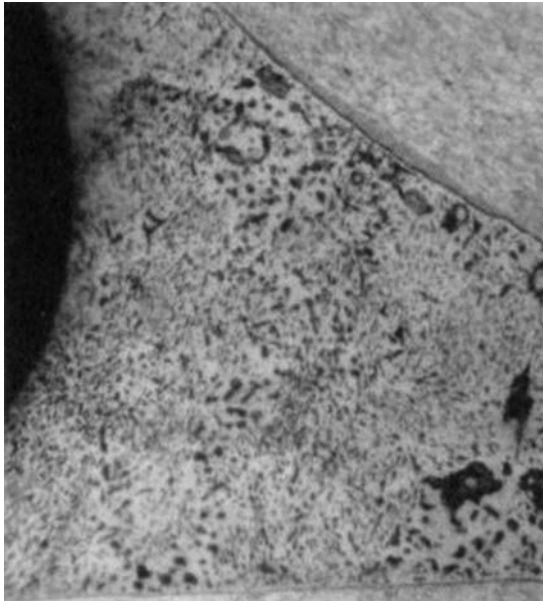


Fig. 8.7 Soldered joint between a surface-mount device copper lead and a copper pad, as-soldered condition

Intermetallic growth can be fit to the following equation, where total intermetallic thickness is a function of time and temperature:

$$x(t,T) = x_0 + A t^n e^{-Q/RT} \tag{Eq 8.1}$$

where t is the time, T is the temperature in Kelvin, x_0 is the initial intermetallic thickness, R is the universal gas constant, A and n are constants, and Q is the apparent activation energy for a particular growth process. The constants A , Q , and n are determined by the solder substrate system.

Figure 8.9 depicts intermetallic growth for 60 wt% Sn and 40 wt% Pb plated on pure copper at various temperatures. The intermetallic thickness

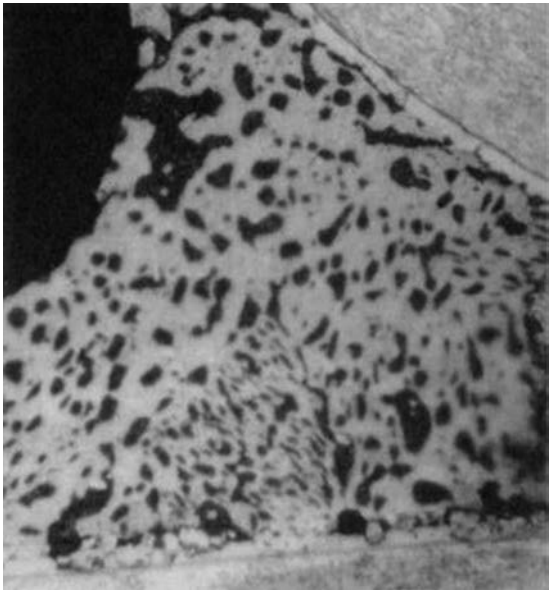


Fig. 8.8 Soldered joint between a surface-mount device copper lead and a copper pad. Aged for 12 weeks at 125 °C (255 °F)

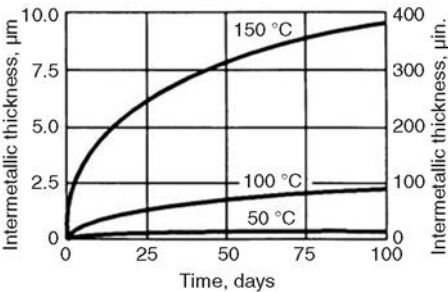


Fig. 8.9 Intermetallic thickness versus time

can be used to gage the approximate time or temperature that a joint has been in service.

Another method of estimating the age and service environment of a soldered joint is to evaluate the degree of phase coarsening. Figure 8.10 is a phase diagram of the tin-lead system. At the solidification temperature of 183 °C (360 °F), the solubility of tin in lead is 28.1 at.%. At room temperature, this solubility drops to approximately 2 at.%. This supersaturated solid solution rejects the excess tin at a slow rate at room temperature. Energy, in the form of heat or stress, drives this reaction at a higher rate. Long aging times and high temperatures will lead to the development of a soldered joint that consists of uniform, coarsened regions of tin and lead. A soldered joint that exhibits coarsening in only certain regions or bands has experienced some form of stress. Coarsening occurs in the regions of greatest strain. Because the coarsened areas are often weaker, the coarsened band will often become a path for crack propagation. Differences between the coefficients of thermal expansion for the various materials that compose the soldered joint will strain the joint during changes in temperature. These strains are usually concentrated in the solder in the area of the least volume. Although the strains that cause coarsening can be a result of mechanical stresses, they are usually due to thermomechanical stresses from thermal cycling.

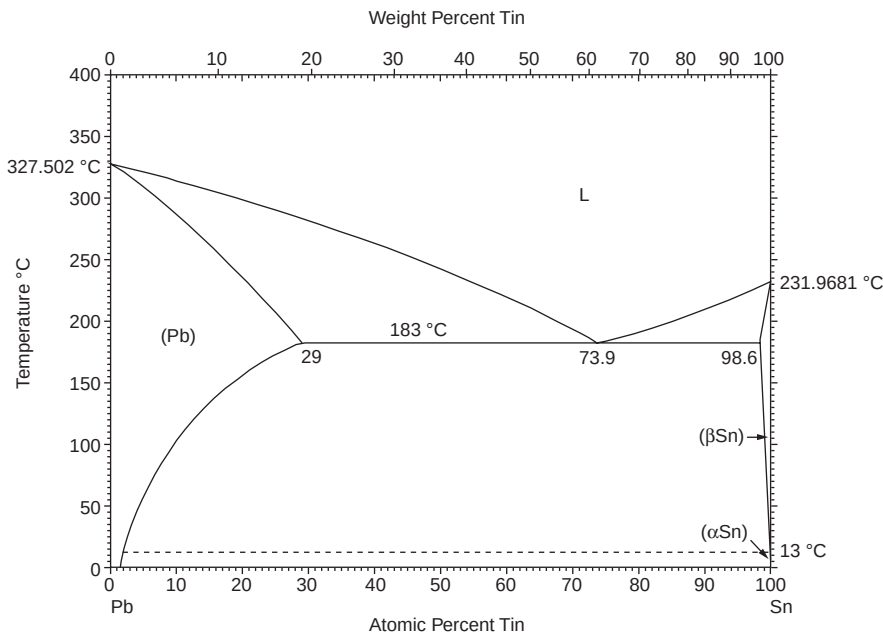


Fig. 8.10 Lead-tin phase diagram

8.3 Reliability

The reliability of a product is a measure of how well it fulfills its required functions for a specified time under its expected service conditions. A product is only as reliable as its “weakest link.”

The making of a reliable soldered joint is, in large measure, a matter of identifying the optimal reflow process, and this depends on the precise solder paste used. Suppliers of paste will generally provide recommendations as to how to achieve the best performance. The general principle is that the temperature must be high enough that the solder paste can wet all the components, be low enough that the components themselves are not damaged, and allow for a controlled cooling phase. It is also important to treat all the soldered joints on the board alike and to make sure that all the components, as well as the board, reach the reflow temperature at approximately the same time. Reflow profile, obviously important here, was discussed in Chapter 6 in this book, and additional details can be found online in Ref 8.4.

To maximize the reliability of a product, one must plan from the beginning and handle the design, materials selection, part selection, and manufacturing processes accordingly. This requires identifying likely failure sources, which, in the case of electronic assembly, include failure of soldered joints, failure of components or parts, failures in the internal structure of printed circuit boards (PCBs), and failures caused by extended time, voltage, and extreme external conditions. Some examples of common sources of such failures are discussed in Ref 8.5.

The most common reliability tests are described as follows.

Thermal Cycle Testing. In thermal cycle testing, a thermal expansion mismatch is repeatedly created in the soldered joints, resulting in thermal fatigue.

Mechanical Shock and Vibration (S&V) Testing. The purpose of such testing is twofold. First, it simulates the worst possible shipping conditions a product may undergo; second, it simulates the shock and vibration to which the product is likely to be subjected during use.

Highly Accelerated Life Test (HALT). In HALT, a product typically undergoes simultaneous thermal cycle testing and vibration testing, with the vibration stress increasing with each thermal cycle. Ordinarily, the duration of the test is no more than one week. Because the acceleration factor is unknown, HALT does not do well in predicting product lifetimes, but it is quite effective in quickly causing failures that are likely to occur during use. It is therefore useful for discriminating between product configurations and identifying design weaknesses.

Corrosion Testing. Corrosion tests for electronic assemblies generally focus on creep corrosion caused by hydrogen sulfide. The sulfur clay test is effective in determining whether a product is susceptible to such corro-

sion and in examining the effectiveness of such improvements as changes in surface finish or enclosure.

In reliability audits, sample sizes are generally smaller than in full-blown reliability tests, and some less-critical tests can be omitted. Both HALT and S&V testing work well for reliability audits. Thermal cycle testing works less well because it requires longer times and larger sample sizes (Ref 8.6).

Among the reliability issues specifically affecting electronic devices is one previously discussed: bridging, the misconnection of two adjacent pads. Another is gold embrittlement (Ref 8.7), which is especially problematic in such high-reliability applications as military electronics and medical devices. In such applications, gold embrittlement is typically avoided by lead tinning, a process in which components with a gold finish are dipped in a pool of solder to remove the gold (Ref 8.8).

The reliability of lead-free soldered joints presents difficulties. For example, lead-free soldered joints have a stronger tendency toward voiding than tin-lead joints, and there is no clear consensus of opinion as to what effect such voiding has on joint reliability. A study by Henkel (Irvine, CA) suggests that the amount of voiding in such joints is affected by flux formulation, surface finish, and choice of solder (Ref 8.9). Among Sn-Ag-Cu alloys, those with low (less than 3 wt.%) silver content appear to be the most effective in preventing fracture from mechanical shock (Ref 8.10).

Lead-free solders are also especially susceptible to tin whiskers, brittle filaments of monocrystalline tin that can cause intermittent or permanent short circuits when they form in the surface finish of an electronic device. These pose a critical problem in military and aerospace applications, where very high reliability is especially important. One obvious way to avoid them is not to use tin; another is to use barrier materials to encapsulate any whiskers that have started to form since plating was completed.

Studies on the mechanisms of tin whisker formation have revealed other ways to avoid or reduce them. In one such study, two different heat treatments—annealing at 220 °C (430 °F) and reflowing at 260 °C (500 °F)—have been found to curb tin whisker growth (Ref 8.11). In another, an anticorrosion treatment (Protectostan LF, Atotech Deutschland GmbH) has been found to be effective (Ref 8.12).

For ball grid arrays (BGAs), mixing tin-lead parts with lead-free solders can result in reliability problems. Also, lead-free BGAs are especially prone to head-in-pillow defects, caused when the solder paste wets the pad but does not fully wet the ball; these defects result in soldered joints that provide sound electrical connections but are low in mechanical strength.

Repairing or reworking an electronic circuit in which not all connections are accessible requires desoldering, the removal of solder from the circuit, so that the component(s) to be reworked can be removed. Desoldering is typically performed with a desoldering pump or a solder wick

under the application of heat. In the case of BGAs, reworking is complicated by such factors as hidden joints and temperature sensitivity. Rework on BGAs is a multistep process that includes removing the component, cleaning the BGA site (and PCB), attaching new solder balls, and resoldering the BGA to the PCB (Ref 8.13). It can be performed using either focused infrared (IR) technology or hot gas; IR is reported to be the more reliable and safe of the two (Ref 8.14). Quad-flat no-lead devices, and leadless devices in general, also pose special problems, but inexpensive automated solutions are available (Ref 8.15). Reference 8.9 provides detailed descriptions of various new tools and systems for repair and rework as of 2010, along with manufacturers and websites.

The reliability problems posed by leadless near-chip-scale packages in lead-free processing are discussed in Ref 8.16. Reference 8.6 provides guidance on reliability testing in the manufacture of lead-free medical devices under the *restriction of hazardous substances directive*.

While the reliability of lead-soldered joints is well understood, the shift toward lead-free solders has created a need for finite-element models that can be used to evaluate the reliability of lead-free components. ABAQUS/Standard is said to provide advanced features that make it a useful design tool for such components (Ref 8.17).

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9

CHAPTER

The Future of Soldering

THIS CHAPTER PROVIDES a brief overview of some developing technologies that are likely to have a significant impact on the future of soldering.

9.1 Plastic Electronics

One technology could completely eliminate the need for soldering in some electronics applications. Plastic electronics involves the deposit of an electrical circuit directly onto a polymer substrate as a printable ink. This technology, first discovered in the 1970s, is still in its early stages, and its commercial potential has been limited by its low speed and high power consumption. However, the Cavendish Laboratory at the University of Cambridge (Cambridge, United Kingdom) has developed a way to fabricate such circuits with higher performance and lower power consumption. This new technology, although unlikely to replace silicon-chip technology altogether, could lead both to new products and to more lightweight and flexible versions of existing products (Ref 9.1).

9.2 Single-Molecule Electronics and Chemical Soldering

Another emerging technology that could obviate the need for conventional soldering is the development of very small electronic devices, sometimes called single-molecule electronics. Okawa et al. report that they have found a way to create conductive nanowires and attach them to molecular components, through a process they call chemical soldering. The method involves using the tip of a scanning tunneling microscope to initiate the formation of a chain of molecules. Development of this technology could, the researchers say, lead to “cheaper, higher-performance,

and more ecological alternatives to conventional silicon-base devices” (Ref 9.2).

9.3 Thermal Dip-Pen Nanolithography

Yet another fabrication technique for producing very small electronic devices is thermal dip-pen nanolithography. In this technique, developed by the U.S. Department of Energy’s Lawrence Berkeley National Laboratory, the tip of an atomic force microscope is used as a nanoscale soldering iron. It is reported that it can be used to fabricate patterns as small as 20 nm (Ref 9.3).

9.4 Nanotechnology in Electronic Assembly

As the previous two examples suggest, applications of nanotechnology in electronic assembly are growing in general. One possible application is the use of nanoparticle sintering to fill printed circuit board microvias. Another is the reduction of the melting point of solder pastes; it is thought that achieving a particle size of 5 nm could reduce the melting point by as much as 5%. Yet another is the directed self-assembly of very small ($<100\text{ }\mu\text{m}$) electronic components into connected systems for use in, for example, cell phones and computers; components with such small dimensions are hard to assemble with robotic manipulators because capillary forces make it difficult to release the resulting assemblies from the manipulators.

9.5 Dissimilar Material Joining

The soldering of dissimilar materials is often problematic, generally owing to differences in their material properties or to the difficulty of finding a solder suitable for both, and it is the subject of much ongoing research. As examples of innovation in this area, this section summarizes three recent advances among many.

Soldering of Magnesium Alloys. Magnesium alloys offer a combination of useful properties: low density, desirable casting properties, recyclability, high damping capacity, and high electrical shielding. In consequence, it is a good choice of material for lightweight components in the automotive, aerospace, and other industries, so long as there is a joining technology suitable for the application. In one study, the feasibility of soldering magnesium alloys to themselves and to dissimilar metals has been demonstrated by soldering AZ31 and AZ91 magnesium alloys to AlMgSi1 aluminum alloy and C15 low-carbon steel, using newly developed filler materials based on the Al-Mg-Zn system. Aluminum- and zinc-base coatings were used for corrosion protection. The use of ultrasonic activation made fluxing agents unnecessary (Ref 9.4).

Ultrasonic Soldering with a Tin-Aluminum Solder. A new solder developed by the Edison Welding Institute (EWI) (Columbus, OH) is reported to allow the ultrasonic joining of aluminum, copper, titanium, glass, ceramics, and other materials that are otherwise difficult to join. Called EWI SonicSolder, it is a tin-aluminum solder that is said also, because of its high tin content, to provide a degree of biocompatibility suitable for medical devices. Reportedly, when used in ultrasonic soldering, it requires no fluxes and no metallization of nonmetal joining materials. Its mechanical properties are said to rival those of industry-standard lead-free solders such as Sn-3.0Ag-0.5Cu. Because it contains no noble metals, it is said to offer cost advantages as well. It has been used in the aerospace industry for large-area joining of aluminum parts (Ref 9.5).

Active Soldering of Indium-Tin Oxide to Copper. A new active solder has been reported to achieve good results in the soldering of indium-tin oxide (ITO) to copper. The ITO is a transparent conductive oxide commonly used in such electronic devices as flat-panel displays and solar cells, where it is ordinarily sputtered onto a target substrate joined to a copper backing. When such a device is recycled, the old, spent ITO target is removed, and a new one is attached to the recycled copper backing via a soldering process. The ITO and copper have very different coefficients of thermal expansion, so to avoid thermal stresses in such a joint, it is necessary to use a low-melting-temperature solder. It has been reported that an active filler metal Sn56Bi4Ti (Ce,Ga) has been developed with a melting temperature of 148 °C (298 °F), low enough to serve as a solder in this process. According to the report, the joining of ITO with ITO and copper at 180 °C (355 °F) in air has been successfully performed with this filler metal (Ref 9.6).

9.6 New Applications

New applications of electronic packaging technology are constantly being developed, and it would be hopelessly unrealistic to try to provide even a representative sample in a short space; moreover, even if that task were feasible, any such sample would be outdated before it reached publication. Here, just one example is discussed: a surface-mount technology (SMT) lamp, developed by Avago Technologies (San Jose, CA, and Singapore), that combines through-hole and surface-mount technologies in a single light-emitting diode (LED). Said by Avago to provide the advantages of each of the two technologies, the device is intended mainly for outdoor video wall applications, for which conventional through-hole LEDs have historically offered better brightness and other optical properties than their SMT counterparts despite being more laborious to manufacture. The SMT lamp, Avago says, can be processed and reflow-soldered in a single run, with no loss of performance and with more compact board designs (Ref 9.7).

9.7 Conclusion

The field of soldering, like so many others, is changing at a rapid pace as new technologies and applications are developed. This book has tried to present an up-to-date guide to the essentials of the field, incorporating the latest information, standards, and industry practices, with (where relevant) URLs for useful online resources. It should be borne in mind, however, that no single printed volume can possibly contain all the most current information, and that ongoing research results in fresh innovation every day. My hope is that by the time the reader has finished studying this book, he or she should be equipped to study the current field him- or herself.

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