Laser Beam Soldering Behavior of Eutectic Sn-Ag Solder

Lead-free solder combined with the laser process shows promise as an environmentally safe and fast joining method for surface-mounted components

BY W. YANG, R. W. MESSLER, JR., AND L. E. FELTON

ABSTRACT. The effect of the soldering process on the microstructure and physical properties of Pb-free, eutectic Sn-Ag is evaluated in this paper. A Nd:YAG laser soldering system was used to produce eutectic Sn-Ag joints between quad-flat pack surface-mounted components and FR-4 printed wiring boards. The wetting of solder joints was evaluated and the "process window," which provided proper laser soldering parameters, was identified. Joint microstructure and microhardness were evaluated and compared with traditional IR reflowed joints of the same configuration. The higher temperature, lower heat input, and more rapid cooling associated with laser soldering compared to IR reflow soldering produced much finer eutectic Ag_3Sn intermetallic in essentially pure Sn, considerable numbers of equiaxed dendritic Cu_6Sn_5 in the bulk solder, and thinner Cu-Sn intermetallic layers at pad and wire interfaces. Laser soldered joints were more than 50% harder than IR reflowed joints, suggesting better strength properties. It was also found that laser beam power and scan rate had a pronounced effect on microstructure and microhardness. Aging of joints at 40° to 190°C for times up to 300 days reduced process- or process parameter-induced differences in structure and properties, and generated voids and cracks at intermetallic layers which ultimately led to failure of the joints.

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Introduction

At the component-to-printed wiring board (PWB) level of electronic packaging, soldering technology is widely used to provide interconnection between electronic components and printed circuits. Solder joints are designed and produced to provide the required electrical connection, mechanical connection, manufacturability, and reliability. Sn-Pb solders (eutectic temperature 183°C at 63 wt- % Sn) fulfill most of these soldering requirements in electronic packaging. They have been used since the industry started and are still the dominant solder alloys used in the industry today.

Through the 1980s, soldering technology was driven by demands for increased function, speed, and frequency of circuit operation; increased component density; reduced cost at all packaging levels; higher reliability of joints; and ease of rework. Sn-Pb solders at or near eutectic composition (63%Sn-37%Pb) met these demands in the predominance of cases. Starting in the late 1980s, environmental concerns began to force the search for alternatives to Pb-bearing solders (Ref. 1). Niche applications, such as under-the-hood automobile electronics and avionics systems, also call for alternative solders with higher-temperature serviceability (Ref. 2).

Key Words

Laser Soldering
Sn-Ag Eutectic
Pb-Free Solders
Microstructure
Microhardness
Joint Aging
Nd:YAG Laser
Laser Beam Power
LB Scan Rate
Electronic Packaging

Sn-Ag Solder

In order to meet the new needs for finer pitch components, better joint strength, higher joint reliability, greater circuit and joint service temperature, and environmental compatibility, new Pb-free solders must be developed. Though there are many elements on which new solders can theoretically be based (due to their low melting points) such as Sn, Cd, Sb, Bi, Zn, Ga, In, Ag, Cu and Hg, only a very few combinations will meet all of the criteria stated above. Some elements are as toxic as Pb (e.g., Cd and Hg), some are in short supply (e.g., Bi and In), and some are simply impractical (e.g., Ga). The list of alternative candidates thus narrows quickly, with Sn-Ag being especially attractive.

Eutectic Sn-Ag solder (96.5%Sn-3.5%Ag) has a melting temperature of 221°C. It is an environmentally compatible solder with good mechanical properties (Ref. 3). Research has shown that eutectic Sn-Ag alloy offers among the highest shear strength, isothermal mechanical fatigue strength, creep strength, and thermal-mechanical fatigue strength of all candidates for possible use as an electronic solder (Ref. 4). Other work on the solderability of this alloy has shown that it has comparable or even better wet-

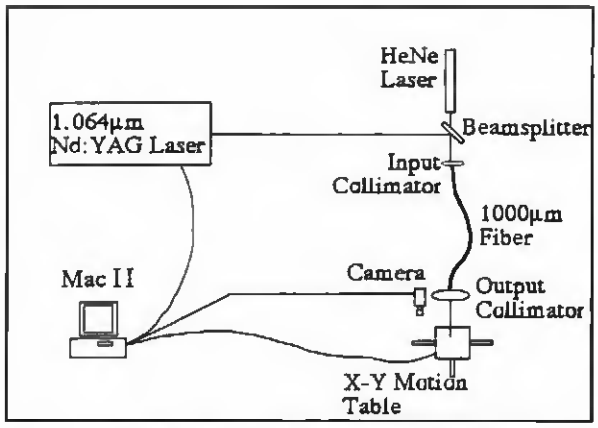

Fig. 1 — Computer-controlled 80-W Nd:YAG continuous-wave laser soldering system

ting characteristics with copper than Pb-bearing solders (Ref. 5). Though the melting temperature is only 38°C higher than eutectic Sn-Pb solder, it provides much greater potential for high-temperature applications. The additional heat required because of the higher melting temperature may be a problem when soldering temperature-sensitive electronic components and printed wiring boards. To overcome the problem of mass heating of electronic assemblies, laser soldering is an alternative.

Laser Soldering Process

The laser soldering process was developed in the early 1980s to meet the need of surface-mount technology (Refs. 6, 7). Generally, two types of lasers are used for soldering application: carbon dioxide gas lasers and Nd:YAG (neodymium/ yttrium-aluminum-garnet) solid-state lasers. The laser beam in both cases is used as a heat source to melt the solder. The beam is focused to a diameter suitable to the joint geometry, and is applied to the joints individually or by scanning continuously, depending on the materials involved and design of the joints. If a Nd:YAG laser is used with a 1.064-μm wavelength (as in this study), the laser beam is reflected by fiberglass and most polymers, while it is absorbed by most metals including copper and Sn-Ag (Ref. 8). Thus, only the solder joint area is heated during the process, while boards and components are relatively unaffected. As a result, the Nd:YAG laser soldering process can be applied to solders with wide ranging melting temperatures. This solves the problem of soldering with eutectic Sn-Ag alloy and other Pb-free solders with high melting temperatures. Since the laser beam size can be precisely controlled, laser soldering is also ideal for fine-pitch components and high-density packaging. Manufacturing defects such as bridging, solder balls, and underheating (to produce "cold joints"), which happen more often with fine-pitch components, can be largely overcome by using the laser process.

By controlling variables such as laser beam power and scan rate, reliable solder joints can be produced with minimal component heating. Due to the precise control of parameters and very short duration of the laser soldering process (*i.e.*, rapid heating and cooling), extremely fine microstructures and very thin intermetallic layers at joint interfaces can be produced; both of which should improve the mechanical properties and reliability of the joints (Ref. 9).

While there has been some industrial application of laser soldering, the understanding of solder joint formation, microstructure, mechanical properties, and reliability is still very limited. For new alloys such as eutectic Sn-Ag, this is even more true. This research studied the laser soldering of eutectic Sn-Ag solder, and contributes greatly to this understanding.

Experimental Procedure

Eutectic 96.5%Sn-3.5%Ag solder paste containing Type RMA (mildly activated rosin) flux was used in this study. All joints were made with 132-pin quad flat-pack surface-mount components on FR-4 fiberglass boards printed with pure copper pads and circuit paths. Component gull wing type, copper alloy leads were on a 25-mil (0.64-mm) pitch. This choice of solder and joint configuration enabled the simultaneous study of the soldering process (laser vs. traditional infrared reflow), fine-pitched high-density packaging, Pb-free Sn-Ag solder, and real joint reliability.

Before soldering, component leads were stripped using 33% HNO_3 to remove all traces of pretinned Sn-Pb solder, leaving bare copper alloy. Leads were further cleaned by immersion in acetone and then were pre-fluxed with Type RA (activated rosin) flux. The PWBs were cleaned using a stripping solution of 15% H_2O_2/85% acetic acid followed by rinsing in clean acetone. Immediately prior to soldering, the Sn-Ag solder paste was printed on the PWB using a manually operated stencil printer, and components were placed on the boards using a component positioner. The assembled board and components were then heated to 150°C to drive volatile organic from the paste.

An 80-W Nd:YAG continuous-wave laser system controlled through a Macintosh computer was used for soldering. The system (Fig. 1) consisted of the Nd:YAG laser source, a fiber-optic delivery system, a precision positioning system, and a control computer. When soldering, the laser beam was directed at the end of the first component lead along one side of the quad flat-pack component. The computer then simultaneously opened a shutter to allow passage of the laser beam and drove the positioning table to cause the beam to scan along one side of the component, producing joints as each lead passed under the beam. Since the copper lead has much higher optical absorption for 1.064-μm wavelength Nd:YAG laser light than the PWB polymer-matrix composite, the laser heats the solder during a scan to very high temperatures to cause melting, wetting, and flow without burning the PWB. This obviated the need to pulse the laser beam or open and close the beam shutter each time the beam passed from a lead to the board.

Laser beam soldered joints were made over a wide range of heat input by varying the beam power and scan rate independently. Beam power was varied from 10 to 60 W and beam scan rate (actually, table travel speed) from 2 to 60 mm/s. This resulted in heat inputs from 0.16 to 30 J/mm. Baseline infrared (IR) reflowed solder joints were made using a reflow temperature of 255°C and an exposure or soak time of 200 s. These conditions resulted in complete solder melting and sufficient heating to cause proper wetting and alloy flow, and they are fairly representative of the conditions

Table 1 — Microhardness of Eutectic Sn-Ag to Copper Joints Made by Laser and IR Reflow

	Microhardness (HV), (10 g, 15 s)						
Process	1	2	3	4	5	6	Average
Laser (20 W, 15.2 mm/s)	28	26.9	28	26.4	26.9	25.9	27
Laser (25 W, 38.1 mm/s)	24.1	24.5	23.7	23.7	24.5	24.5	24.2
Infrared	16	16.5	15.6	16.5	16.5	16	16.2

under which joints are made in actual production.

After soldering, the joints were cut and mounted in epoxy. Following this, cross-sections were ground, polished, and etched with 2% HNO_3-5% HCl-93% alcohol solution for several seconds. The microstructure of all joints produced was evaluated using optical microscopy, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). The microhardness of the bulk solder in joints was measured as a preliminary indicator of strength properties using a Vicker's indentor, 10-g load, and 15-s indentation time.

The as-soldered laser and IR reflowed joints were also aged in a silicon oil bath at temperatures of 40°, 90°, 140° and 190°C for time periods of 1, 3, 5, 10, 30, 60, 90, 120, 180 and 300 days. The microstructure and microhardness of these joints were evaluated as above.

Results and Discussion

Laser Soldering Process Window Development

Proper laser soldering process parameters were selected based on two criteria: 1) good wetting on the solder joints; and 2) no damage to the PWBs or components. For the same joint configuration, wetting and damage on the PWB and components are influenced only by the laser heat input to the joints, which can be controlled through the laser beam power and scan rate across the joints. A separate study was done using a wide range of beam power and scan rates to identify the proper soldering parameters (Ref. 10), and the resulting joints were analyzed using optical microscopy to characterize the wetting. Damage on components and PWBs was examined during and after the process of soldering. The results of the study were reconfirmed in this research, and the "process window" for laser soldering of Sn-Ag solder on fine-pitch surface-mount components was identified — Fig. 2.

The "process window" shows the parameters that can be used to make acceptable Sn-Ag solder joints of a defined configuration. If the laser beam power is too high or the scan rate is too slow, there will be too much heat input into the joints, causing burning and damage of components and/or PWBs. If the laser beam power is too low or the scan rate is too high, there will not be sufficient wetting to form proper joints. Proper joints with good wetting and no damage on either components or PWBs can be made using the parameters in the process window. Though this process window was developed for the specific joint configuration used here, the methodology can and should be used for the laser soldering of other solders or of other joint geometries.

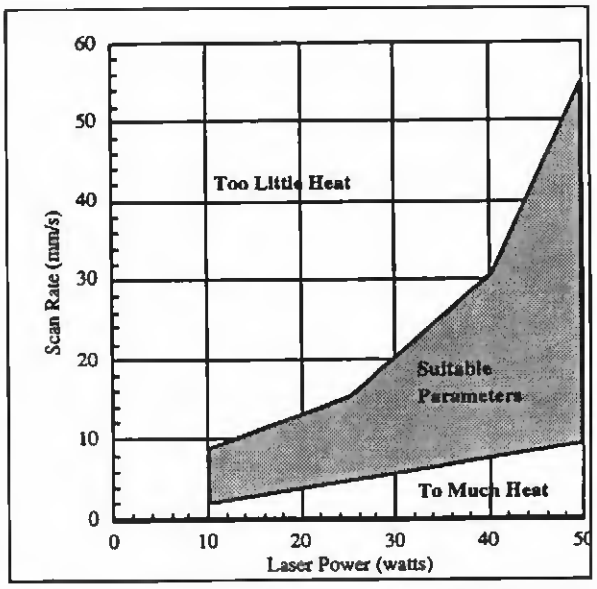

Fig. 2 —Process window for producing acceptable joints from eutectic Sn-Ag solder on bare Cu using the laser reflow soldering process.

Microstructure and Microhardness of Joints

Figure 3A shows the microstructure of as-soldered Sn-Ag joints made by laser soldering. The laser beam power used was 20-W and the beam scan rate was 15 mm/s. A large number of Cu_6Sn_5 intermetallic dendrites, as identified by EDS, were found to be dispersed throughout the solder matrix. The solder matrix consisted of almost pure Sn phase with fine Ag_3Sn intermetallics dispersed in the form of spheres or rods to produce the eutectic structure. These fine Ag_3Sn intermetallics can be resolved only at magnifications over 4000X. This morphology is expected as it minimizes the interphase surface area when the volume fraction of one phase in a eutectic structure is less than $1/\pi$. A thin layer of Cu-Sn intermetallic was also formed at the solder-copper interface. The layer was identified as Cu_6Sn_5.

Figure 3B shows the microstructure of an IR reflowed joint with the same configuration as laser reflowed joints. Here, Ag_3Sn intermetallic rods protrude from the copper-solder interface into the pure Sn matrix, reflecting the solidification direction of the solder joints. A Cu_6Sn_5 intermetallic layer was found at the solder-copper interface, but there were no Cu-Sn intermetallic dendrites in the bulk solder. The major differences for IR re-

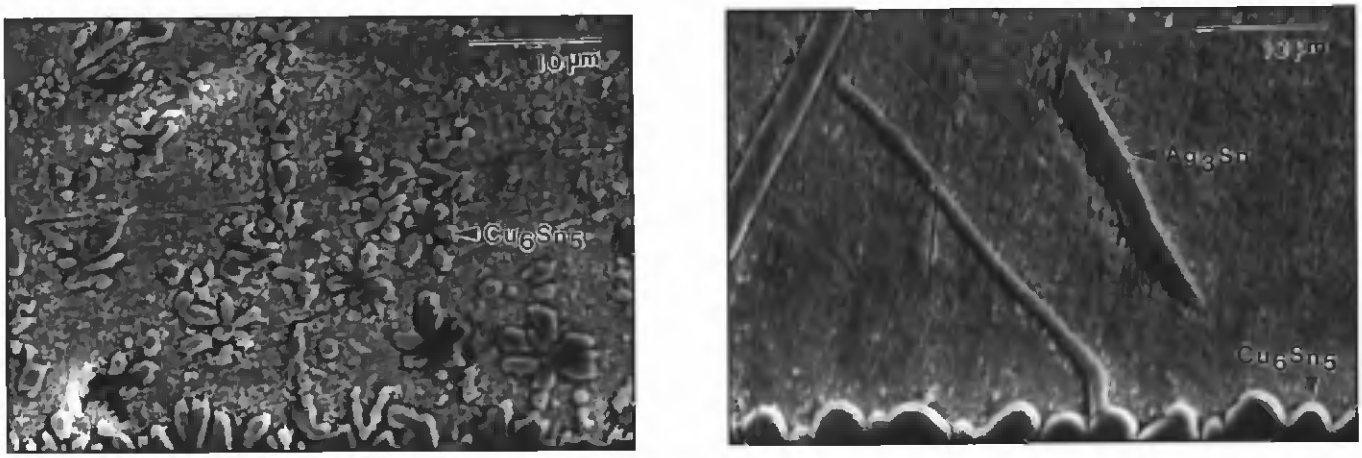

Fig. 3 — Eutectic Sn-Ag solder/copper joints made using: A — Laser soldering; B — IR reflow process.

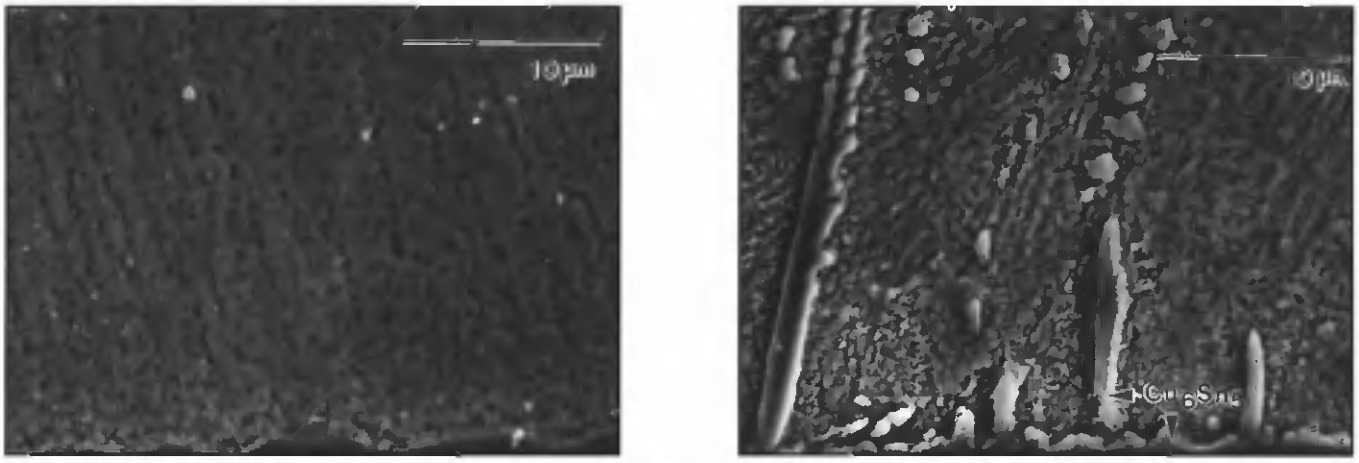

Fig. 4 — Effect of laser parameters on the microstructure of eutectic Sn-Ag solder joints. A — 20 W, 25.4 mm/s (0.79 J/mm); B — 20 W, 20..3 mm/s (0.99 J/mm).

flowed and laser soldered joints were the size and shape of Ag_3Sn intermetallics in the eutectic, the amount of Cu_6Sn_5 dendrites in bulk solder due to copper dissolution, and the thickness of the Cu_6Sn_5 intermetallic layer at the interface.

Laser soldering is a quick process. The total heating time on individual joints is less than a second. This results in a very fast cooling rate (typically 10^4°C/s) from peak temperature compared with traditional soldering processes such as IR reflow (10°C/s). The shorter heating time and faster cooling rate both limit the growth of Ag_3Sn intermetallics in the eutectic structure, as well as the growth of Cu_6Sn_5 layers at interfaces with copper leads and pads. On the other hand, due to the high energy density provided by a laser beam and the small size of fine-pitch component leads, laser heats the Sn-Ag solder to temperatures between 400–600°C during soldering (Ref. 11). This is much higher than the IR reflow process, which only heats the solder to approximately 255°C. The higher temperature caused by laser reflow leads to more rapid dissolution of Cu from leads and pads into the solder and higher solubility of Cu in Sn. As a consequence, large amounts of Cu_6Sn_5 intermetallics are able to form in the bulk solder, solidifying in the form of dendrites. Another possible but less likely origin of the Cu-Sn dendrites in the bulk solder is fragmentation of intermetallic whiskers that break off into the molten solder from the joint interface layers and float into the molten solder (Ref. 12). The uniform distribution of Cu_6Sn_5 dendrites suggests that this was likely not the case.

The difference of microstructure between laser soldered and IR reflowed joints resulted in different mechanical properties in the joints. As it is difficult to measure the static, creep, and fatigue strength of fine pitch SMT joints, microhardness was measured to give an initial evaluation of the relative strength of the joints. Higher hardness corresponds to higher strength under static tension and shear, creep, and fatigue loading (Ref. 13). Table 1 shows the microhardness of joints made by different processes. Although hardness of laser soldered joints varied with processing parameters, it is consistently higher than that of IR reflowed joints, indicating that harder Cu_6Sn_5 dendrites and finer Ag_3Sn intermetallics improve the hardness of the solder joints.

Influence of Laser Parameters on Joints

Though all the parameters tested from within the laser soldering process window produced joints with satisfactory wetting without burning either PWB or components, the microstructure and resulting mechanical properties of joints were dramatically different when using different parameter combinations. Figure 4 shows the microstructure and resulting microhardness of laser soldered joints made by A) 20 W, 25.4 mm/s (0.79 J/mm) and B) 20 W, 20.3 mm/s (0.99 J/mm). Both joints showed good wetting without any heat damage on PWB or component, but the joint made at the slower scan rate dissolved much more copper to form more Cu_6Sn_5 dendrites in the bulk solder, and exhibited higher hardness even though the size of Ag_3Sn intermetallic in the eutectic would be expected to be larger, and thus less effective as a strengthening phase. These differences indicate that to optimize the laser soldering process (or any other soldering process), the standard should not be limited to the good wetting, but must also consider joint microstructure and mechanical properties to give enhanced reliability in service.

Different laser soldering parameters result in different temperature profiles during joint formation. By measuring the temperature profile in joints during laser soldering, it was found that the higher laser beam power or slower beam scan rate increased the peak temperature and total heat input (Ref. 11). Higher peak

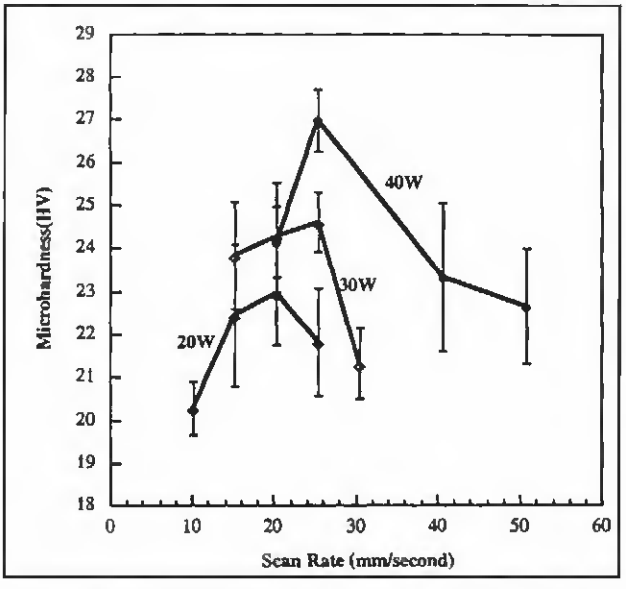

Fig. 5 — Effect of laser parameters on the microhardness of eutectic Sn-Ag solder joints.

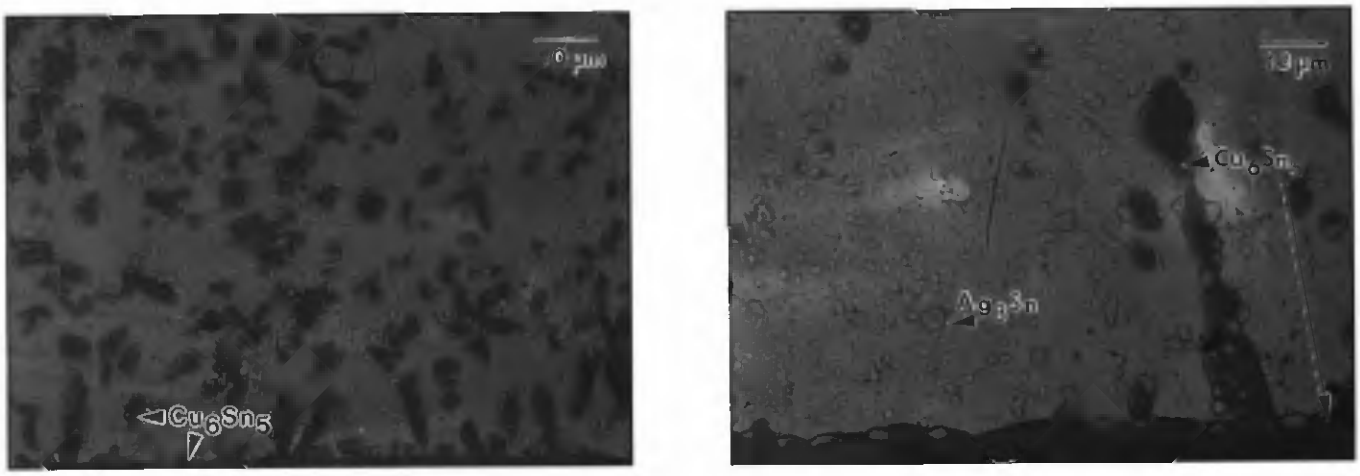

Fig. 6 — Effect of aging on the microstructure of as-soldered (laser soldering) eutectic Sn-Ag solder joints. A — 90°C, 3 days; B — 190°C, 3 days.

temperature dissolves more copper into the bulk solder and results in precipitation of more Cu_6Sn_5 dendrites upon solidification. These intermetallic dendrites have a profound influence on the microhardness and other mechanical properties of the joints. As seen in Fig. 4, with an increase in beam scan rate, less Cu_6Sn_5 dendrites were found in the bulk solder due to the lower net heat input and lower peak temperatures. The measured microhardness also decreased with decreasing amounts of Cu_6Sn_5 dendrites. As an exception, the total amount of Cu_6Sn_5 dendrites decrease at the very lowest scan rates. This is explained by the formation of larger amounts of flux vapor at these slow scan rates. These vapors probably partially block or reflect the laser beam and reduce the total heat input into the joints at these slow scan rates.

Higher peak temperature and higher heat input can also be achieved by increasing the laser beam power. Microstructure observations and microhardness data confirmed this. Figure 5 shows the joint microhardness change caused by varying laser beam power and beam scan rate. The exception of hardness drop at the slowest scan rate holds for each power level, and corresponds to the observation of greater flux vapor generation, and thus beam blocking, during soldering.

The process parameter effect on microstructure and microhardness of laser soldered joints provides a tool for controlling microstructure for better properties and joint reliability in production and service. The amount of Cu_6Sn_5 dendrites in the bulk and the coarseness of eutectic structure can be adjusted by varying the laser parameters to achieving the optimum joint reliability.

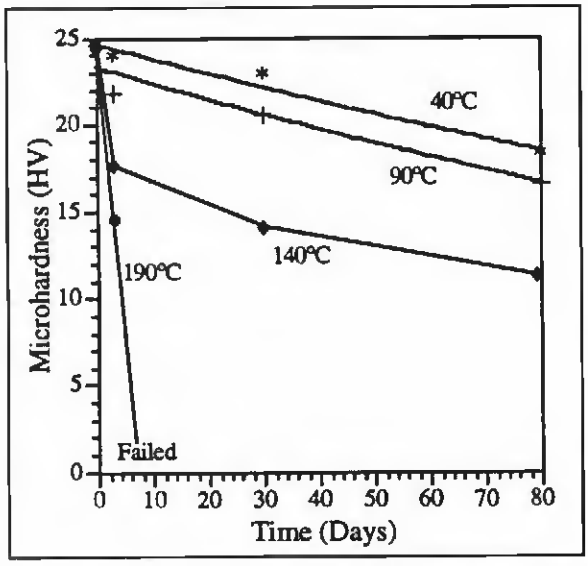

Fig. 7 — Effect of aging on the microhardness of eutectic Sn-Ag solder joints.

Aging Effect on Joints

Aging solder joints at temperatures representative of their prospective service environment is important for determining the stability of microstructure and properties, and, thus, performance and reliability in service. Joints processed by laser and IR reflow have been and are continuing to be exposed to temperatures of 40°, 90°, 140° and 190°C for times ranging from 1 to 300 days. Temperatures of 40° and 90°C were selected to allow comparison to Sn-Pb eutectic and near-eutectic solders, as these solders typically operate in this range. Exposure at 140°C was selected to represent under-the-hood automobile engine applications, while 190°C was selected to represent the very highest temperatures to which joints might be exposed (e.g., 94% T_m absolute).

Aging results to date show an evolution of microstructure with time and temperature that depends on the starting microstructural condition as determined by initial processing (e.g., soldering method). With aging, it has been found that Ag_3Sn intermetallics in the solder joint eutectic microstructure coarsen while dendritic Cu_6Sn_5 intermetallics in the bulk solder decrease in number and increase in size — Fig. 6. As expected, the rate of coarsening is greater when the initial size of Ag_3Sn particles is small, since the total interphase surface free energy is higher under these conditions. At solder-copper interfaces, the Cu-Sn intermetallic layer thickness increases with increases in the time of aging at any temperature, as expected for diffusion controlled growth. Furthermore, the Cu_3Sn ε-phase intermetallic forms in this layer nearest the copper if the aging temperature exceeds 120°C (Ref. 14).

Aging at higher temperatures accelerates microstructure evolution, as would be expected. Microhardness of aged samples correspond to observed microstructure changes. The microhardness decreases with increases in aging time, and higher temperature accelerates the softening rate — Fig. 7. Softening, in both cases, is related to coarsening of the intermetallic phases which contribute to strengthening. If aged at very high temperature (190°C), the joints failed at intermetallic layers after a very short time.

Comparing laser-soldered with IR-reflowed joints, it was found that the microstructure difference initially present in

the as-soldered joints decreases with increasing aging time and temperature, and the microhardness difference between joints made by the two processes also decreases with aging. The rate of structural change and softening is affected by temperature in an exponential way as a function of time. This confirms the expectation that although laser soldered joints may offer property advantages over IR reflow joints in the initial microstructure, these advantages may be lost after aging at elevated temperature (Ref. 9), depending on conditions. Aging of joints at lower temperatures showed much slower microstructural evolution. Samples aged at room temperature for 360 days, for example, showed very limited coarsening of Ag_3Sn and Cu_6Sn_5 intermetallics in the bulk solder, and only moderate increase in the thickness of Cu-Sn intermetallic layers at interfaces. This indicates that Sn-Ag solder microstructure is comparatively stable during low-temperature applications.

Some voids and cracks were found at the Cu-Sn intermetallic layer interface in all solder joints after aging at higher (*i.e.*, greater than 140°C) temperatures even for short times (*e.g.*, three days at 140°C and one day at 190°C). The voids have only been observed at the solder interface with the pure copper pads and not with the alloyed copper wire lead. Cracks were also observed primarily at the solder interface with the copper alloy lead of the component. These voids and cracks contribute to the eventual failure of joints, and their formation seems to be closely related to the composition of the intermetallic layers, the substrates, and the stress condition (mainly from thermal sources) in the interface region. Possible mechanisms for void formation include: diffusible hydrogen from electroplated copper substrates, Kirkendall voiding, mass imbalance, and stress-accelerated diffusion. Possible mechanisms for crack formation include: void connection; thermal stress; mismatch of thermal expansion coefficient among solder, intermetallic, and copper; and the stress concentration due to the geometric configuration of the joints. A combination of these mechanisms is most likely, but further work is needed to determine the operative mechanisms.

Conclusions

Eutectic Sn-Ag alloy is a promising alternative for Ph-containing solder due to its environmental compatibility, good wettability, and good mechanical properties. Laser soldering is particularly promising for high melting temperature solders and fine-pitch components due to its wide ranging yet precisely controlled parameters which affect the heat input. For the same reason, it offers better control of solder joint microstructure and resulting properties.

Compared with IR reflow of Sn-Ag solder, the laser soldering process generated much finer eutectic microstructure and thinner intermetallic layers at joint interfaces. The high-peak temperature associated with lasers also dissolves a certain amount of copper from interfaces and results in the formation of Cu_6Sn_5 dendrites in the bulk solder. These microstructural differences resulted in higher microhardness of the joints. The microstructure and mechanical properties of Sn-Ag laser soldered joints can be controlled through the control of laser beam power and beam scan rate.

Aging causes the microstructural evolution in both laser soldered and infrared reflowed joints, and may introduce some defects in the solder joints which could ultimately lead to the joint failure.

Acknowledgments

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