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Tensile Behavior of Pb-Sn Solder/Cu Joints

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Solders of nominal 95Pb-5Sn and 60Sn-40Pb were used to join Cu plates. The effect of ternary additions of In, Ag, Sb, and Bi to the near-eutectic solder were also investigated. Bulk solder and interfacial joint microstructures were characterized for each solder alloy. The solder joints were strained to failure in tension; joint strength and failure mode were determined. 95Pb-5Sn/Cu and 60Sn-40Pb/Cu specimens were tested both as-processed and after reflow. 95Pb-5Sn/Cu as-processed and reflow specimens failed in tension in a ductile mode. Voids initiated at β-Sn precipitates in the as-processed specimens and at the Cu_3Sn intermetallic in the reflow specimens. 60Sn-40Pb/Cu failed transgranularly through the Cu_6Sn_5 intermetallic in both the as-processed and reflow conditions. The joint tensile strength of the reflow specimens was approximately half that of the as-processed specimens for both the high-Pb and near-eutectic alloys. The Cu_6Sn_5 intermetallic dominated the tensile failure mode of the near-eutectic solder/Cu joints. The fracture path of the near-eutectic alloys with ternary additions depended on the presence of Cu_6Sn_5 rods in the solder within the Cu plates. Specimens with ternary additions of In and Ag contained only interfacial intermetallics and exhibited interfacial failure at the Cu_6Sn_5. Joints manufactured with ternary additions of Sb and Bi contained rods of Cu_6Sn_5 within the solder. Tensile failure of the Sb and Bi specimens occurred through the solder at the Cu_6Sn_5 rods.

Key words: Pb-Sn solder, joint tensile strength, η-Cu_6Sn_5 phase, ϵ-Cu_3Sn phase, dissolution of Cu.

INTRODUCTION

Lead-tin solder alloys are used extensively in the electronics industry to package electronic devices. In first level packaging a high-Pb alloy is utilized while a low melting eutectic or near-eutectic alloy is employed in the second level. The relatively low melting temperatures of Pb-Sn alloys minimize the risk of heat damage to devices. However, high homologous temperatures decrease the strength of the joint and reduce creep resistance. With the trend in packaging towards controlled collapse bonding and surface mount of leadless chip carriers, improved mechanical properties of solder joints have become increasingly important. Reliability of the solder joints is essential as the joints must provide both mechanical support and electrical conduction.

The Pb-Sn-on-Cu soldering process forms intermetallic compounds when the molten solder is brought into contact with the Cu base metal. The presence of intermetallic compounds is an indication of good bonding due to the mutual interdiffusion between the solder and the base metal. However, the intermetallic compounds are known to be brittle[1] and, thus, are expected to have detrimental effects on the mechanical properties of solder joints. The intermetallic phases present, their morphology, their thickness, and their grain size are possible parameters affecting mechanical properties.

Ternary additions to near-eutectic Pb-Sn alloys are sometimes added deliberately and are sometimes contaminants in the solder. Among such ternary additions are In, Ag, Sb, and Bi. Although the addition of In is rare, it improves the wetting characteristics and lowers the melting temperature of the solder. Approximately 2% Ag is added to solders in order to prevent scavenging of preexisting Ag on the surfaces to be soldered. Antimony is added in order to prevent "Sn pest," the transformation of Sn from a white metallic material to a gray powder. Antimony additions of up to 0.5% improve the wetting characteristics of the solder; however further additions of Sb reduce wettability. Bismuth resembles Sb in its behavior; up to 0.25% Bi prevents Sn pest, and up to 3% improves wettability. Variations in solder composition are expected to affect the mechanical properties of solder joints.

This work was performed to study the microstructure, tensile strength, and failure mode of joints of various Pb-Sn solder alloys between Cu plates. Both 95Pb-5Sn and 60Sn-40Pb alloys joining Cu plates were studied in the as-processed condition and after reflow. In addition, the effect of ternary additions of In, Ag, Sb, and Bi to the near-eutectic alloy were investigated.

EXPERIMENTAL

The microstructure and tensile properties of the following Pb-Sn solder alloys joining Cu plates were investigated:

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95Pb-5Sn
95Pb-5Sn: 6-hr reflow at 400° C
60Sn-40Pb
60Sn-40Pb: 6-hr reflow at 250° C
58Sn-40Pb-2In
58Sn-40Pb-2Ag
58Sn-40Pb-2Sb
58Sn-40Pb-2Bi

Specimens for microstructural analysis and mechanical testing were prepared as follows. Two 1 in × 2 in × 0.5 in Cu plates were machined, polished, etched, and fluxed. The Cu plates were bolted together with 0.020 in stainless steel spacers inserted to form a gap. The assembly was placed in a vacuum furnace which was backfilled with argon (Fig. 1). Both solder and Cu were heated to approximately 50° C above the melting temperature of the solder. During this time residual flux evaporated off the Cu surfaces. After thermal equilibrium was established, the Cu plates were slowly immersed into the solder bath. The quartz tube containing the assembly was quickly cooled in an ice water bath. The assembly of Cu plates joined by solder was then machined and sectioned into 8 specimens.

Reflow specimens were heat treated after the initial processing in an air atmosphere furnace. Specimens were held at the reflow temperatures of 400° C for 95Pb-5Sn/Cu and 250° C for 60Sn-40Pb/Cu for 6 hr, then cooled in an ice water bath.

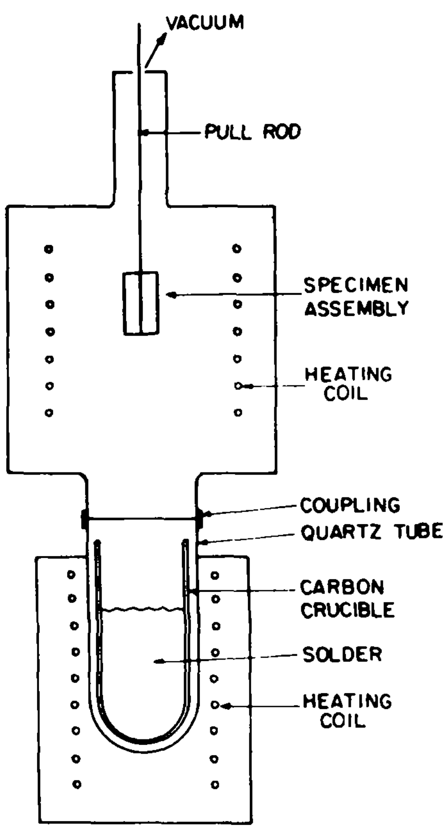

Fig. 1 — Vacuum furnace configuration used in specimen preparation.

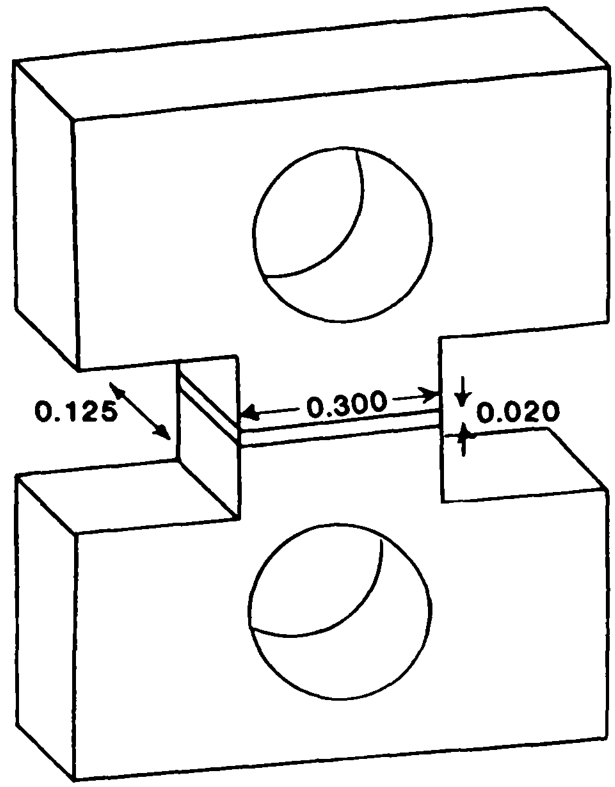

Fig. 2 — Tensile specimen configuration (dimensions in inches).

The tensile specimen configuration for mechanical testing is shown in Fig. 2. The critical dimensions are 0.020 in joint thickness, 0.300 in joint width, and 0.125 in specimen thickness. Specimens were strained to failure on a screw-driven load frame at a crosshead speed of 0.002in/min. The data reported is joint strength in tension, which represents the ultimate tensile strength of the joint. Joint strength differs from bulk solder strength since it includes the effect of constraint from the base metal.

RESULTS AND DISCUSSION

The values of joint tensile strength of the various compositions of solder alloys joining Cu plates are

Table 1. Joint Tensile Strength of Solder Alloys Joining Cu Plates

Solder Composition	Joint Tensile Strength (psi)
95Pb-5Sn	7,500
95Pb-5Sn: 6-hr reflow at 400° C	3,000
60Sn-40Pb	12,000
60Sn-40Pb: 6-hr reflow at 250° C	6,700
58Sn-40-Pb 2In	14,000
58Sn-40Pb-2Ag	13,000
58Sn-40Pb-2Sb	13,000
58Sn-40Pb-2Bi	16,000

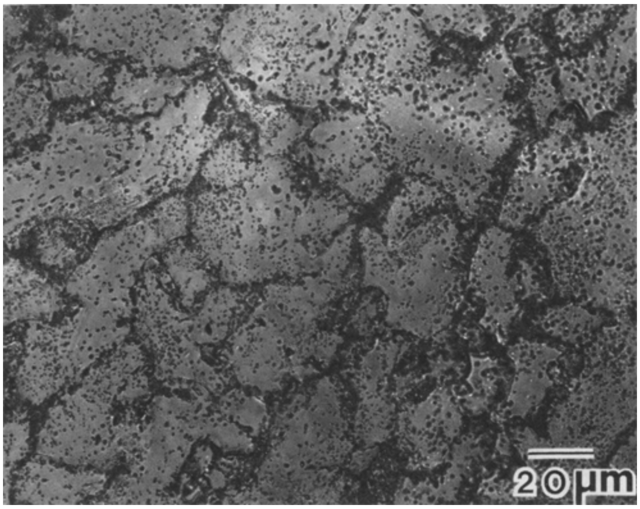

Fig. 3 — Optical micrograph of 95Pb-5Sn solder.

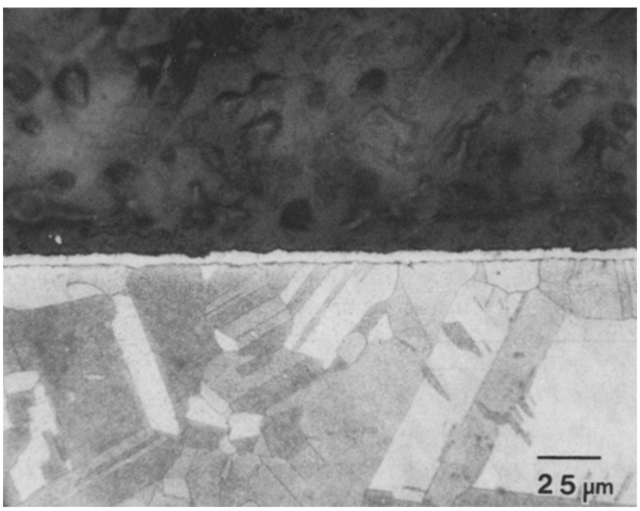

Fig. 4 — Optical micrograph of the 95Pb-5Sn/Cu joint in the as-processed condition.

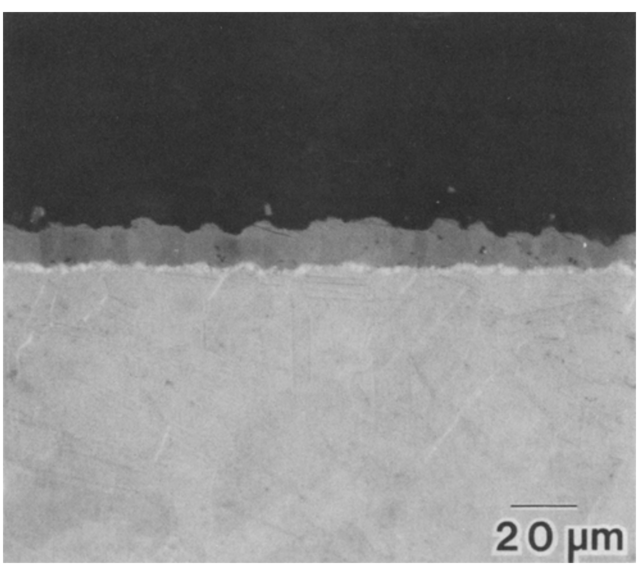

Fig. 5 — Optical micrograph of the 95Pb-5Sn/Cu joint after 6-hr reflow at 400° C.

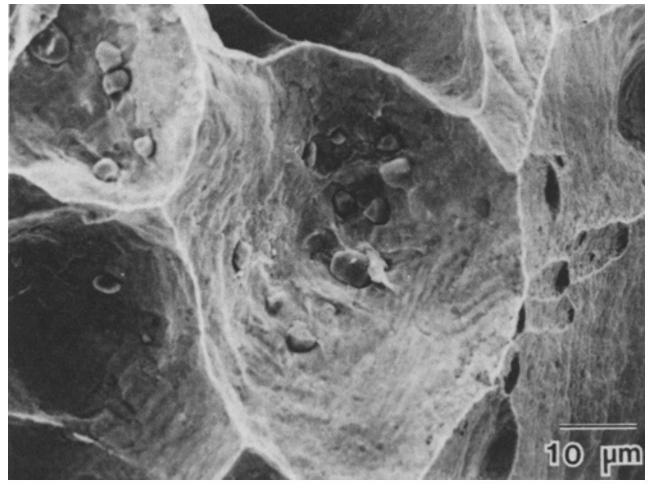

Fig. 6 — SEM micrograph of 95Pb-5Sn/Cu as-processed specimen failed in tension.

shown in Table 1. The results for the 95Pb-5Sn, 60Sn-40Pb, and 58Sn-40Pb-2X solders are discussed separately.

95Pb-5Sn

The microstructure of bulk 95Pb-5Sn solder (Fig. 3) consists of β-Sn precipitates in an α-Pb matrix.[2] When Cu is wet by 95Pb-5Sn, a thin layer of Cu_3Sn (ϵ-phase) intermetallic forms at the solder/Cu interface.[3] After reflow for 6 hr at 400° C, the Cu_3Sn intermetallic thickness increases from 4 μm to 11 μm as the solder is depleted of Sn (Figs. 4–5). The columnar structure of the Cu_3Sn is revealed in Fig. 5.

Fractography of the failed tensile specimens shows that the 95Pb-5Sn/Cu as-processed specimens failed by ductile rupture (Fig. 6). The fracture progresses through the solder by void initiation at β-Sn precipitates. The 95Pb-5Sn reflow specimens also failed

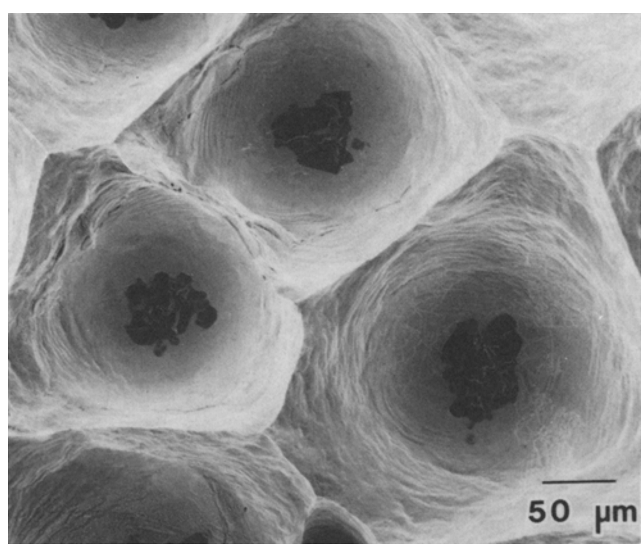

Fig. 7 — SEM micrograph of 95Pb-5Sn/Cu reflow specimen failed in tension.

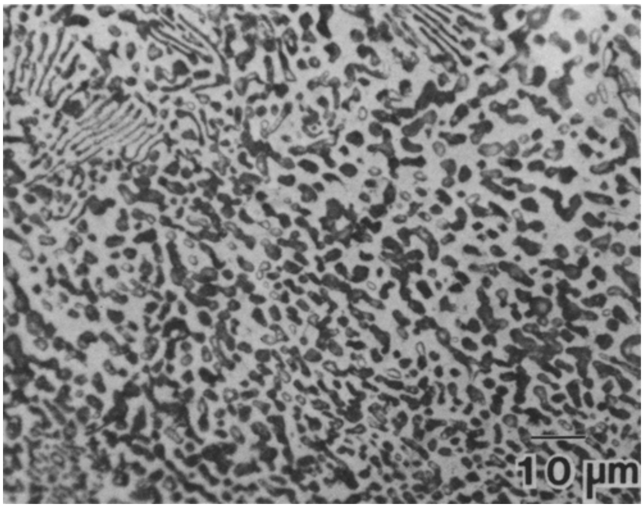

Fig. 8 — Optical micrograph of 60Sn-40Pb solder.

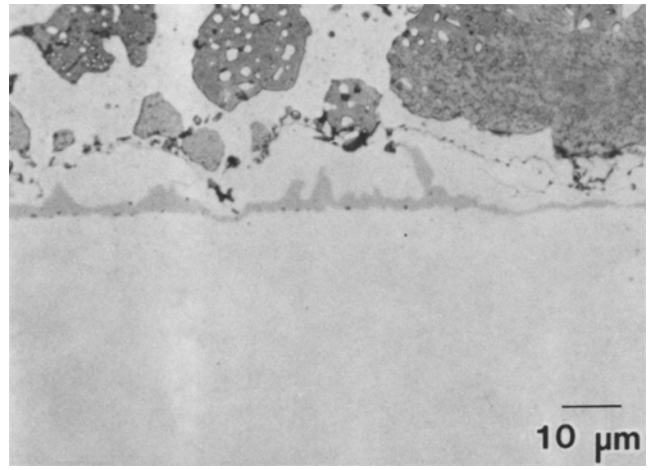

Fig. 10 — Optical micrograph of the 60Sn-40Pb/Cu joint after 6-hr reflow at 250° C.

in the ductile mode (Fig. 7). However, failure in the reflow specimens occurred at the solder/Cu_3Sn interface with void initiation at the Cu_3Sn intermetallic layer. The decrease in joint strength with reflow can be attributed to the depletion of Sn from the solder. Voids initiate preferentially at the Cu_3Sn intermetallic because β-Sn precipitates are fewer and, hence, less active as nucleation sites.

60Sn-40Pb

60Sn-40Pb solder has a two-phase microstructure consisting of a β-Sn matrix surrounding α-Pb islands (Fig. 8). Upon soldering 60Sn-40Pb to Cu, two intermetallic phases form: Cu_3Sn (ϵ-phase) forms closest to the Cu, and Cu_6Sn_5 (η-phase) forms closest to the solder (Fig. 9). The structure of the Cu_3Sn is columnar; the structure of the Cu_6Sn_5 is globular. The Cu_3Sn and Cu_6Sn_5 layers were measured to be approximately 1 μm and 3 μm thick, respectively, after the initial processing. After the 6-hr reflow at 250° C, the thicknesses of the Cu_3Sn and Cu_6Sn_5 intermetallic layers increase to approximately 3 μm and 12 μm, respectively (Fig. 10).

When the 60Sn-40Pb/Cu as-processed specimens were tested in tension, failure occurred in a transgranular mode through the Cu_6Sn_5 intermetallic (Fig. 11). The failure mode of the reflow specimens was similar to that of the as-processed specimens (Fig. 12). The joint strength decreases after reflow to approximately half that of the as-processed specimens. The decrease in strength is apparently due to the thicker Cu_6Sn_5 layer and the coarser grains of the Cu_6Sn_5 intermetallic.

58Sn-40Pb-2X

The addition of 2% In has no noticeable effect on the bulk solder microstructure of the near-eutectic solder. The solder/Cu interface is also similar to that observed for the 60Sn-40Pb/Cu. The 58Sn-40Pb-2In/Cu joints tested in tension failed both transgranularly and intergranularly through the Cu_6Sn_5 (Fig. 13). The strength was slightly higher than that of the 60Sn-40Pb/Cu specimens.

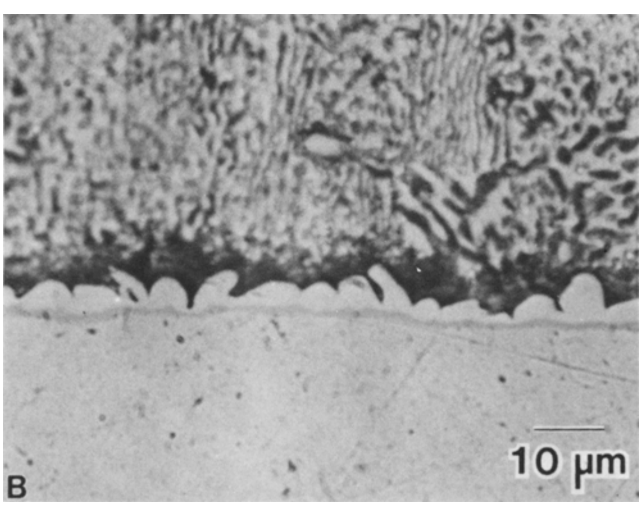

Fig. 9 — Optical micrograph of the 60Sn-40Pb/Cu joint in the as-processed condition.

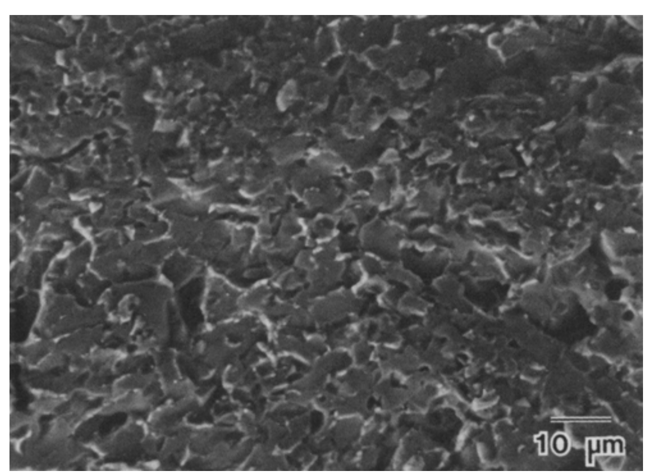

Fig. 11 — SEM micrograph of 60Sn-40Pb/Cu as-processed specimen failed in tension.

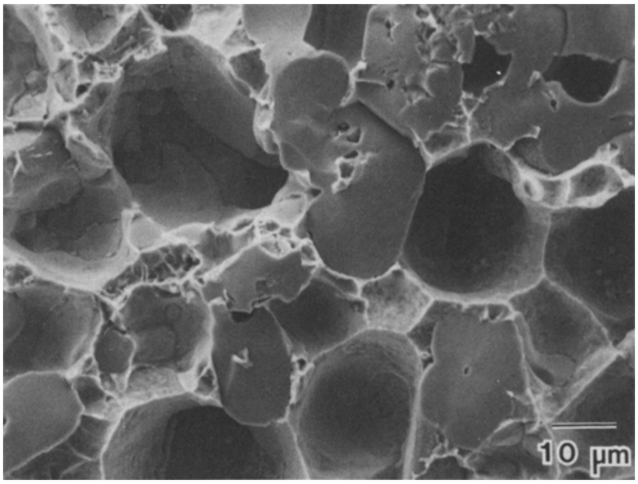

Fig. 12 — SEM micrograph of 60Sn-40Pb/Cu reflow specimen failed in tension.

The 2% addition of Ag to the near-eutectic solder results in the appearance of Sn-rich islands in the solder within the Cu plates (Fig. 14). The interface contains layers of Cu_3Sn and Cu_6Sn_5 intermetallic as well as Ag_3Sn closest to the solder (Fig. 15). The presence of the Ag_3Sn intermetallic decreases Sn availability for Cu-Sn intermetallics, resulting in thinner Cu-Sn intermetallic layers. Tensile failure of the 58Sn-40Pb-2Ag/Cu specimens was transgranular through the interfacial Cu_6Sn_5 and Ag_3Sn intermetallics (Fig. 16). The 58Sn-40Pb-2Ag/Cu specimens had greater tensile strength than the 60Sn-40Pb/Cu specimens.

The tensile failure modes of the 58Sn-40Pb-2Sb/Cu and 58Sn-40Pb-2Bi/Cu specimens were similar. The solder plates contained rods of Cu_6Sn_5 intermetallic within the regular two-phase microstructure (Fig. 17). The acicular structure of the Cu_6Sn_5 intermetallic is characteristic of the dissolution of Cu in Pb-Sn solder.[4-5] The dissolution of Cu in Sn and Pb-Sn alloys is common and has been studied.[5-7] The interfacial Cu-Sn intermetallic structures were similar to those in the 60Sn-40Pb/Cu

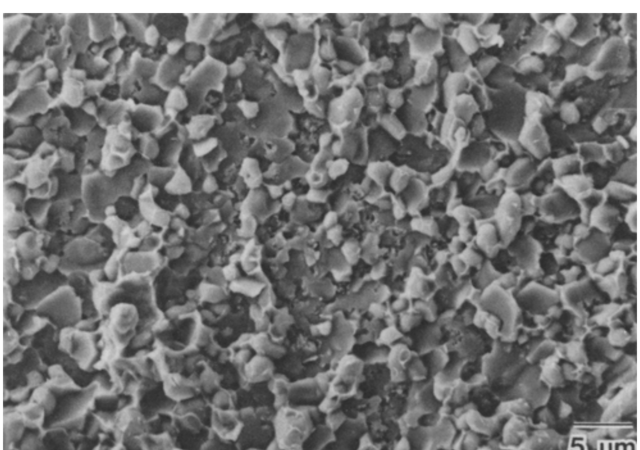

Fig. 13 — SEM micrograph of 58Sn-40Pb-2In/Cu specimen failed in tension.

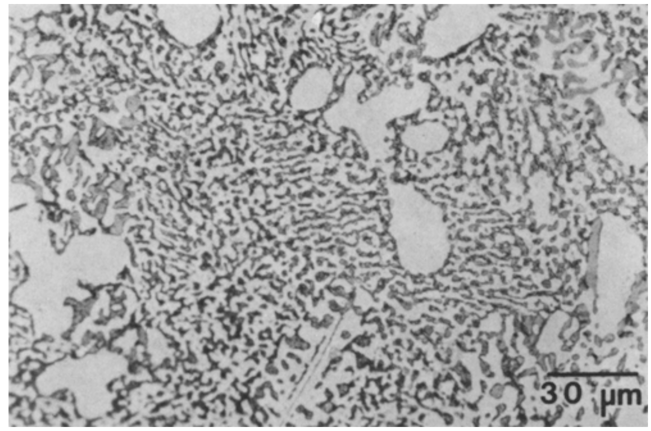

Fig. 14 — Optical micrograph of 58Sn-40Pb-2Ag solder.

specimens. When tested in tension, both the 58Sn-40Pb-2Sb/Cu and 58Sn-40Pb-2Bi/Cu specimens failed transgranularly through the Cu_6Sn_5 rods in the solder (Fig. 18). The joint strengths of the 58Sn-40Pb-2Sb/Cu and 58Sn-40Pb-2Bi/Cu specimens were greater than the 60Sn-40Pb/Cu specimens; the 58Sn-40Pb-2Bi/Cu joint strength was the highest measured for this work.

The joint strengths of the near-eutectic solder/Cu joints with ternary additions are similar. Thus, definitive conclusions on the effects of the individual alloying additions on mechanical properties cannot be inferred. However, in all cases of the near-eutectic solder/Cu joints, tensile failure was related to the Cu_6Sn_5 intermetallic. Furthermore, alloying and/or processing variations can alter the microstructure of the joint so that rods of Cu_6Sn_5 intermetallic form in the solder within the Cu plates. The presence or absence of the Cu_6Sn_5 rods determines the fracture path of the joint in tension. In the absence of the Cu_6Sn_5 rods, tensile failure occurs through the interfacial Cu_6Sn_5 intermetallic layer. In the presence of the Cu_6Sn_5 rods tensile failure progresses through the solder at the intermetallic rods. Joint strengths were slightly higher for the samples that failed in this mode.

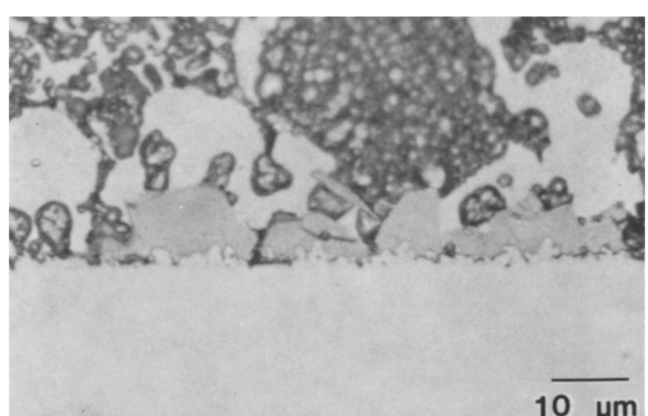

Fig. 15 — Optical micrograph of the 58Sn-40Pb-2Ag/Cu joint.

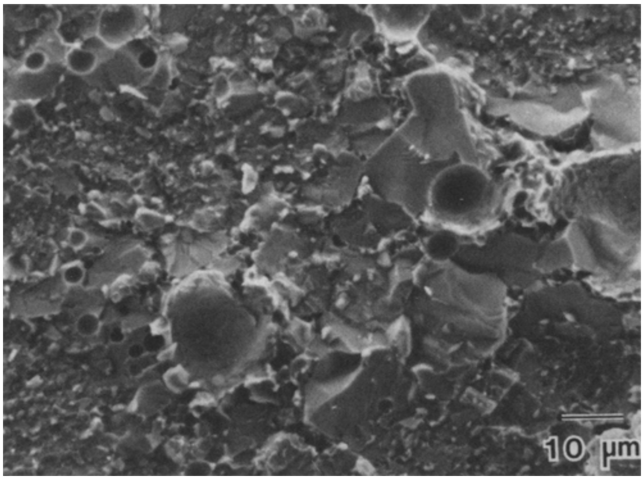

Fig. 16 — SEM micrograph of the 58Sn-40Pb-2Ag/Cu specimen failed in tension.

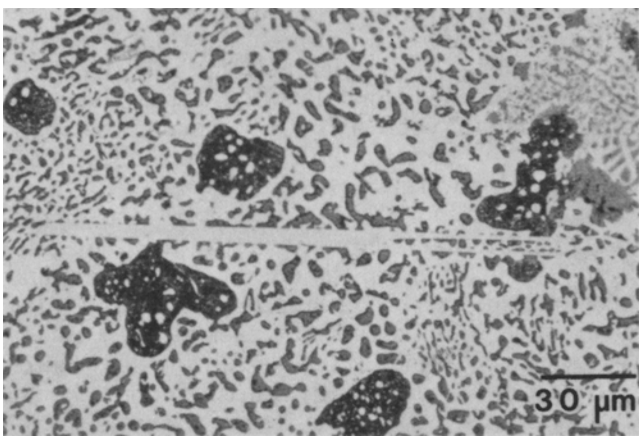

Fig. 17 — Optical micrograph of 58Sn-40Pb-2Sb solder within the Cu plates.

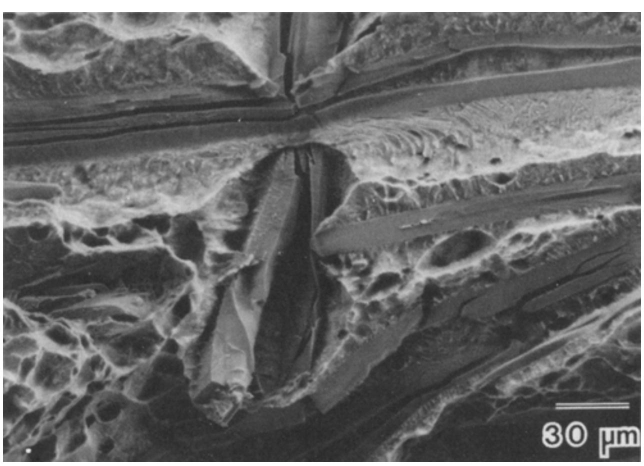

Fig. 18 — SEM micrograph of 58Sn-40Pb-2Bi/Cu specimen failed in tension.

CONCLUSION

The microstructure of 95Pb-5Sn consists of β-Sn precipitates in an α-Pb matrix. A thin layer of Cu_3Sn forms at the interface when 95Pb-5Sn is soldered to Cu. The β-Sn precipitates act as initiation sites for voids when 95Pb-5Sn/Cu joints are tested in tension. When 95Pb-5Sn/Cu is reflowed so that the Sn is depleted from the solder to form Cu_3Sn, voids initiate at the Cu_3Sn interface. Joint strength decreases as Sn is depleted from the solder.

The 60Sn-40Pb microstructure consists of β-Sn and α-Pb phases. Both Cu_3Sn and Cu_6Sn_5 intermetallics form when 60Sn-40Pb is soldered to Cu. Tensile failure of the 60Sn-40Pb/Cu joints occurs transgranularly through the Cu_6Sn_5 phase. During reflow the intermetallic layers thicken and the intermetallic grains coarsen, causing a decrease in tensile strength.

The 2% additions of In, Ag, Sb, and Bi to 58Sn-40Pb all showed an increase in strength compared to the 60Sn-40Pb/Cu. The tensile failure mode was dependent upon the presence of Cu_6Sn_5 rods in the solder. The 58Sn-40Pb-2In/Cu and 58Sn-40Pb-2Ag/Cu specimens contained only interfacial Cu-Sn intermetallics and failed through the Cu_6Sn_5. The 58Sn-40Pb-2Sb/Cu and 58Sn-40Pb-2Bi/Cu specimens contained interfacial Cu-Sn intermetallics as well as Cu_6Sn_5 rods in the joint and failed through the Cu_6Sn_5 rods in the solder. The Cu_6Sn_5 rods do not apparently cause a loss of tensile strength; the highest joint strengths were measured on samples that contained these rods.

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