Electrical Conductivity of the Copper-Tin Intermetallic Compound Cu_3Sn in the Temperature Range −195°C to +150°C

The Cu_3Sn intermetallic has electrical resistance characteristics as good as 40% Sn-60% Pb and 60% Sn-40% Pb solder alloys at room temperature and above

BY W. J. REICHENECKER

ABSTRACT. Copper-tin intermetallic compounds exist at the copper-solder interface when tin-bearing solders are used to coat copper surfaces or to make soldered joints between copper members. The amount and thickness of the intermetallic compound layer is initially a function of the time-temperature parameters used in making the joint or "tinning" the copper. Growth of the intermetallic can occur in service with time at even moderately elevated temperatures.

Attempts to locate data on the electrical conductivity of these copper-tin intermetallic compounds were unsuccessful; consequently, a specimen of one intermetallic, Cu_3Sn, was prepared and electrical conductivity determined in the temperature range −195°C to +150°C (−319°F to +302°F).

Introduction

When copper is coated or joined with tin-containing solder alloys, a film of intermetallic compounds of copper and tin is formed at the interface between the two materials. The thickness of this film depends upon the temperature involved and the time of exposure of the copper to the molten tin-containing alloy. Longer times and higher temperatures result in increased thickness of the intermetallic film. Further exposure of the assembly to even moderately elevated temperatures of say 100°C (212°F) results in growth of the thickness of the intermetallic layer as a result of copper-tin diffusion. Given sufficient time at temperatures on the order of 100°C (212°F), a thin layer of 60% tin-40% lead solder on copper will be converted almost completely to copper-tin intermetallic compounds.

Soldering, as a means of joining copper conductors to each other or to other materials, is widely used in the electrical industry in a wide range of products encompassing the small joints in printed circuitry and "microelectronic" applications and the massive, multi-interface joints of large generators. Always, the electrical integrity of the joint is critical to the performance of the product. Although solder alloys of various compositions are used to join copper in electrical applications, tin-lead alloys are most commonly employed. Many applications expose the soldered joint to temperature excursions above room temperature and over a period of time a film of copper-tin intermetallics of significant thickness can be detected at

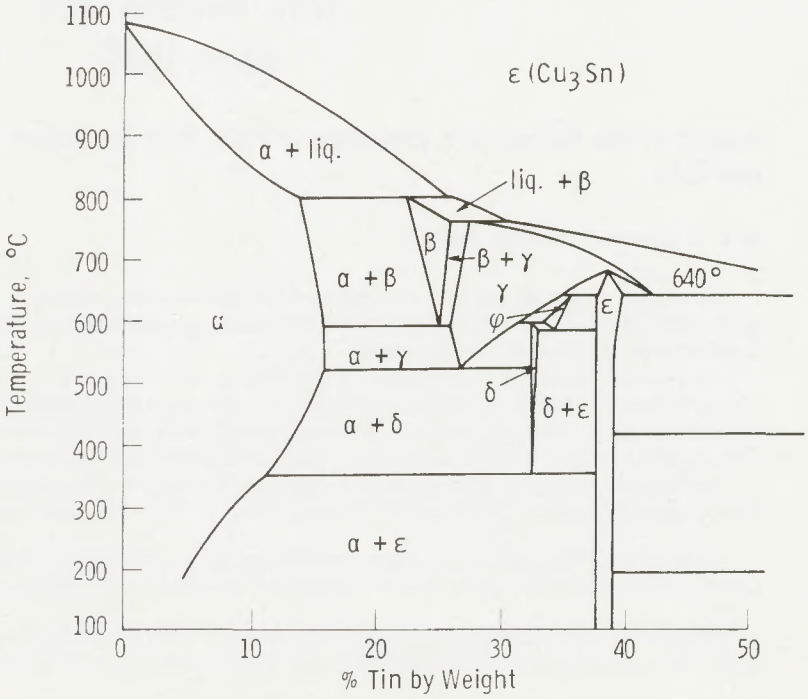

Fig. 1—Copper-rich portion of the copper-tin equilibrium diagram[1-4]

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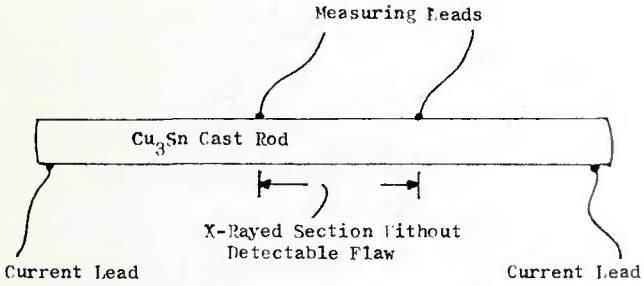

Fig. 2—Schematic of attachment of leads to Cu_3Sn specimen for electrical resistance measurements

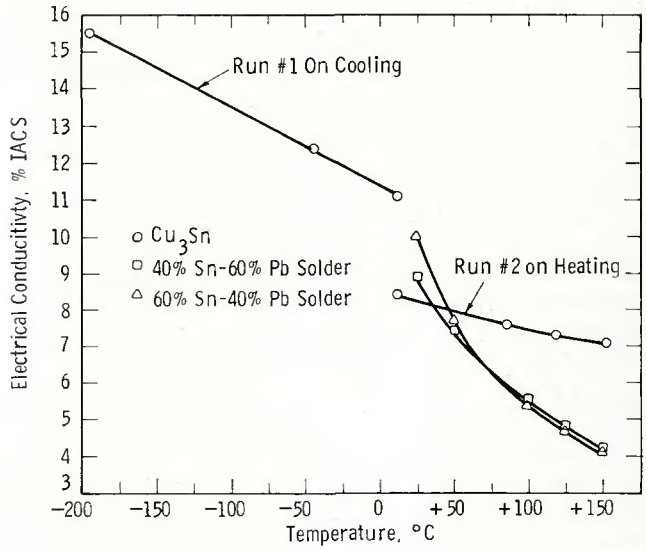

Fig. 3 (right)—Electrical conductivity vs. temperature for Cu_3Sn cast specimen compared with 40% Sn-60% Pb and 60% Sn-40% Pb solder alloys

the copper-solder interface.

Because electrical integrity is important in soldered joints, an effort was made to locate data on the effect of temperature on the electrical conductivity of the copper-tin intermetallic materials. None was found. Consequently, it was decided to experimentally obtain the data.

Experimental Procedure and Results

According to Hansen and Anderko,[1] the equilibrium stoichiometric composition of the Cu_3Sn phase of the copper-tin system is 61.63% Cu and 38.37% Sn by weight. Accordingly, OFHC copper and Straits tin were weighed in this proportion, melted under vacuum and solidified in a 6 mm (0.236 in.) ID quartz tube and then remelted under vacuum and solidified in a 7 mm (0.276 in.) ID quartz tube. In both instances, heating was by induction; however, upon remelting and solidification the second time, the specimen temperature was maintained at 600°C (1112°F) for 1 hour (h) to encourage completeness of the transformation of the γ phase to the ϵ phase—Fig. 1. The resulting specimen was approximately 7 mm (0.276 in.) in diameter × 76 mm (2⅞ in.) long. This ingot was encapsulated in evacuated quartz and annealed for 140 h at 625°C ± 10°C (1157°F ± 18°F) to homogenize it. Samples subjected to X-ray diffraction analysis after this anneal gave the characteristic diffraction pattern for Cu_3Sn.

The cast specimen of Cu_3Sn was X-rayed to assess its internal soundness since some shrinkage defects were noted in portions of the surface. Although some internal defects were detected by X-ray, a section of the specimen about 1¼ in. (3 cm) long was found to be free of detectable flaws. This portion of the specimen was used for the resistance measurements obtained in this study.

The specimen was prepared for resistance measurements by soldering four silver wire leads to it with a 40% tin-60% lead solder using an acid-type flux consisting of an aqueous solution of zinc chloride, ammonium chloride and stannous chloride acidified with 0.5% by volume of hydrochloric acid. One lead was soldered at each end of the specimen and then one lead was soldered to the surface of the specimen at either end of the X-ray sound section—Fig. 2. Electrical resistance measurements were then made at various temperatures in the range of −195°C to +150°C (−319°F to +302°F). Measurements were made below room temperature first; at 23.3°C (74°F), −40°C (−40°F) and then −195°C (−319°F), in accordance with

Table 1—Electrical Resistance and Electrical Conductivity Test Results on a Cast Rod of Cu_3Sn

Test temperature °C	Test temperature °F	Resistance, ohms	Resistivity, ohm-circ. mil/ft	Electrical conductivity, % IACS[a]
23.3	74	.0001392	93.153	11.1
−40	−40	.0001251	83.716	12.4
−195	−319	.0001002	67.053	15.5
23	73.4	.0001842	123.266	8.4
86	107	.0002041	136.583	7.6
119	246	.002120	141.870	7.3
153	307	.0002186	146.287	7.1

[a]IACS—International Annealed Copper Standard

Table 2—Electrical Resistance and Electrical Conductivity of 40% Sn-60% Pb and 60% Sn-40% Pb Solid Wire Solder[3]

Temperature °C	Temperature °F	Solder alloy	Resistivity: Microhm-inches	Resistivity: Ohms-circ. mil/ft	Electrical conductivity, % IACS[a]
25	77	40/60	7.65	116.88	8.9
50	122	40/60	9.15	139.80	7.4
100	212	40/60	12.3	187.93	5.5
125	257	40/60	14.05	214.67	4.8
150	302	40/60	16.2	247.52	4.2
175	347	40/60	18.85	288.01	3.6
25	77	60/40	6.8	103.90	10.0
50	122	60/40	8.8	134.45	7.7
100	212	60/40	12.6	192.52	5.4
125	257	60/40	14.3	218.50	4.7
150	302	60/40	16.7	255.16	4.1
175	347	60/40	19.8	302.52	3.4

[a]IACS—International Annealed Copper Standard

ASTM B-193.[2] Next, the elevated temperature data were obtained; however, the room temperature value did not reproduce the initial room temperature value obtained at the beginning of the sub-room temperature tests. Resistance measurements were made at 86°C (187°F), 119°C (246°F) and 153°C (307°F). Unfortunately, the specimen was heated by mistake above 183°C (361°F), the solidus temperature of the solder used for the lead connections; these joints were lost and as a result, a final room temperature measurement could not be obtained.

The resistance data obtained in these tests are presented in Table 1. For comparison, resistance data for 40% Sn-60% Pb and 60% Sn-40% Pb wire solders are given in Table 2.[3] Calculations of percent electrical conductivity are in all cases referenced to the International Annealed Copper Standard at 20°C (68°F) regardless of the temperature at which the test data were obtained. All data are shown graphically in Fig. 3. The data show that at room temperature and above, the electrical conductivity of the Cu_3Sn intermetallic and the two solder alloys are of the same magnitude.

No explanation is offered for the change in room temperature value of electrical resistance of the Cu_3Sn specimen observed during these experiments; however, from a practical standpoint, this situation does not alter the conclusion that the development of the Cu_3Sn intermetallic in a soldered joint in itself does not degrade the current carrying capability of the joint at least in the room temperature and above range. Since the intermetallic is a fragile, brittle material, its presence may lead to development of defects such as micro or macro cracks which could affect the overall current carrying capacity of a soldered joint.

Discussion

The interest in the electrical resistance of the copper-tin intermetallic compounds resulted from a concern that long time copper-tin diffusion effects in soldered copper joints might degrade the current-carrying capacity of a soldered joint as the thickness of the intermetallic layer increased. This does not appear to be a concern based on the electrical resistance data obtained since at least the Cu_3Sn intermetallic has electrical resistance characteristics as good as 40% Sn-60% Pb and 60% Sn-40% Pb solder alloys at room temperature and above.

No comparison at sub-room temperatures can be made because of lack of low temperature data on the solder alloys.

Acknowledgment

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Analysis of the Ultrasonic Examinations of PVRC Weld Specimens 155, 202 and 203 by Standard and Two-Point Coincidence Methods

by R. A. Buchanan, prepared for publication by O. F. Hedden

This report describes two methods of analysis of ultrasonic examination data obtained in a 13-team round-robin examination of three intentionally flawed weldments. The objective of the examinations is to determine the accuracy of independently detecting, locating and sizing the weld flaws, using a fixed procedure.

Computer programs to facilitate comparison of flaw locations with the ultrasonic data, for each of the specimens and both of the methods, are appended to the report.

Publication of this report was sponsored by the Subcommittee on Nondestructive Examination of Materials for Pressure Components of the Pressure Vessel Research Committee of the Welding Research Council.

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