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Strength of tin-based soldered joints

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Single overlap joints of copper and brass soldered with tin and tin-based solders containing (wt %) 1% Cu, 3.5% Ag, 5% Sb, 57% Bi, and 2% Ag 36% Pb, have been tested in shear at 20 and 100 °C, and with strain rates of 0.05 and 50 mm min^{-1}. Six specimens were tested under each condition, and the average value and coefficient of variation of the 0.2% yield stress, ultimate shear stress, elongation, and work to fracture, determined. Brass joints were generally slightly stronger than copper joints, and tended to show more scatter. Ranking in terms of strength depended on the test conditions. The solders containing silver generally gave the strongest joints. Strain-rate sensitivities were less than 0.1, and activation energies for deformation were very low. Overall, there did not appear to be any regular pattern between the properties, solders, and test conditions.

1. Introduction

Soldered joints are an essential part of many engineering devices and structures. In both the traditional and expanding electronics and telecommunications industries, there is an increasing need for the joints to operate with higher reliability under more demanding service conditions. A soldered joint is a complex structure of the substrates bonded by an interdiffused and then quickly cooled casting. The properties of the joint depend mainly on the substrate material, solder composition, flux, soldering conditions, and the joint geometry and testing conditions.

Tin-based solders have many useful properties. They are relatively inexpensive, melt at a conveniently low temperature, and have excellent wetting characteristics with copper and brass. Soft solders are traditionally based on the tin–lead system, but increasing concern about the safety of minute amounts of dissolved lead in drinking water has prompted the introduction and use of a range of lead-free solders.

Although there is a substantial literature on the mechanical properties of tin-based soldered joints, e.g. [1–10], the interaction of the factors outlined above, makes it difficult to compare the properties and performance of solders and soldered joints. In many cases, the properties have been determined under restricted test conditions or the information may be uncertain or contradictory. For example, recent work has shown that the strength of Sn2Ag36Pb solder ring and plug joints is higher with a brass substrate compared with a copper substrate [3], while in other work the opposite appears to be the case [8]. A further difficulty in assessing the properties of soldered joints is that only rarely is a quantitative measure of the scatter determined. This seems to be particularly important because the strength of soldered joints shows significant scatter. Intermetallic compounds form by reaction diffusion between the copper and brass and the solder, e.g. [10–15]. Increasing amounts have generally been observed to decrease the strength of the joint, and hence the composition of the substrate and solder and the soldering conditions will influence the strength of the joint through the properties and amounts of intermetallic compounds that form.

It is clear that to provide measurements and meaningful comparison of the properties of various solders, two things are essential: the joint fabrication and testing conditions for each solder must be the same, and a sufficient number of joints must be tested under each condition so that a quantitative measure of the scatter may be determined. Both these restrictions have their problems. Each solder has a different solidus, liquidus and optimum soldering conditions. Nevertheless, for comparison it might be considered on balance best to use identical soldering conditions with all solders. The second point is practical rather than metallurgical. Previous work showed that about ten specimens must be tested for a confidence limit of 95% [5]. Thus for one solder to be tested at two temperatures, each with two strain rates, on both copper and brass substrates, would require 80 joints to be fabricated and tested. If six solders are to be studied the total number of joints would be nearly 500.

The present work measures the shear strength of copper and brass lap joints soldered with six commercial tin-based solders (all except one were lead-free), at 20 and 100 °C, each with a strain rate of 0.05 and 50 mm min^{-1}. For practical reasons, the requirement of a 95% confidence level was relaxed, and the number of specimens tested under each condition was reduced from ten to six.

2. Experimental procedure

Commercially pure copper and brass (30% Zn) sheet 2 mm thick (BS 2870 C101 and BS 2870 CZ106) were used for the joint members. In addition to pure tin, the tin-based binary solders contained (wt %) 1% Cu, 3.5% Ag, 5% Sb, and 57% Bi, and the ternary solder contained 2% Ag and 36% Pb. These solders and the

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TABLE I. Shear strength of copper/tin-based solder joints

Solder composition[a] (wt %)	Temperature (°C)	Strain rate (mm min^{-1})	0.2% Yield stress			Ultimate shear strength			Elongation			Work to fracture		
			Mean[b] (MPa)	S.D. (MPa)	C.V. (%)	Mean (MPa)	S.D. (MPa)	C.V. (%)	Mean (%)	S.D. (%)	C.V. (%)	Mean (J)	S.D. (J)	C.V. (%)
Sn	20	0.05	14.7	2.9	19.7	15.4	3.1	20.1	6.7	0.8	11.9	0.92	0.26	28.3
		50.0	28.5	1.6	5.7	31.7	2.7	8.5	7.6	1.5	19.7	2.25	0.71	31.6
	100	0.05	9.5	0.5	5.3	10.2	0.7	6.9	13.0	1.7	13.1	0.62	0.13	21.0
		50.0	13.9	2.6	18.7	20.3	1.6	4.9	24.5	7.3	29.8	2.88	0.76	26.4
1Cu	20	0.05	13.3	2.0	15.0	13.8	1.8	13.0	4.2	0.9	21.4	0.45	0.16	35.6
		50.0	22.7	2.3	10.1	25.3	3.2	12.6	5.2	0.5	9.6	1.23	0.31	25.2
	100	0.05	12.9	1.1	8.5	13.2	1.0	7.6	13.0	2.0	15.4	0.92	0.11	12.0
		50.0	15.3	1.8	11.8	21.4	0.8	3.7	22.6	4.4	19.5	2.56	0.31	12.1
3.5Ag	20	0.05	24.0	2.7	11.3	26.8	0.6	2.2	10.2	2.2	21.6	2.06	0.67	32.5
		50.0	30.3	1.4	4.6	36.6	4.7	12.8	7.8	1.6	20.5	1.30	2.66	204.6
	100	0.05	13.2	1.0	7.6	14.2	0.8	5.6	11.8	2.5	21.2	0.85	0.14	16.5
		50.0	14.3	0.2	1.4	25.0	2.6	10.4	20.4	7.6	37.3	3.40	0.81	23.8
5Sb	20	0.05	17.5	3.2	18.3	21.8	0.5	2.3	5.7	1.2	21.0	1.17	0.39	33.3
		50.0	24.1	2.4	10.0	29.6	4.6	15.5	7.2	2.1	29.2	1.79	0.72	40.2
	100	0.05	15.3	3.3	21.6	16.0	3.4	21.3	11.8	3.2	27.1	1.00	0.30	30.0
		50.0	14.4	2.0	13.9	24.7	2.8	11.3	17.7	1.5	8.5	3.35	0.44	13.1
57Bi	20	0.05	22.7	1.9	8.6	25.3	2.6	10.3	4.8	1.0	20.8	1.05	0.42	40.0
		50.0	18.9	4.0	21.2	19.6	4.2	21.4	3.2	1.2	37.5	0.59	0.35	59.3
	100	0.05	8.9	1.3	14.6	9.4	0.9	9.6	11.7	3.8	32.5	0.45	0.18	40.0
		50.0	13.4	1.1	8.2	17.8	1.8	10.1	12.8	1.4	10.9	1.53	0.37	24.2
2Ag36Pb	20	0.05	21.1	2.4	11.4	22.2	2.5	4.5	4.7	0.4	8.5	0.90	0.21	23.3
		50.0	25.1	1.6	6.4	29.6	3.1	10.5	6.0	0.7	11.7	1.44	0.37	25.7
	100	0.05	13.5	0.6	4.4	13.8	0.6	4.3	10.1	1.9	18.8	0.66	0.08	12.1
		50.0	13.7	2.4	17.5	25.0	1.3	5.2	17.2	2.1	12.2	3.05	0.63	20.7

[a] Sn = pure tin; others, balance tin. See text.
[b] Mean of six tests. S.D. = standard deviation, C.V. = coefficient of variation = (S.D./mean) 100.

joints made with them are designated Sn, 1Cu 3.5Ag, 5Sb, 57Bi, and 2Ag36Pb, respectively. The flux consisted of 250 g ZnCl, 25 g NH_4Cl, 10 ml HCl and 250 ml distilled water (DTD 87 1953).

Joints were made from strips of material 45 mm long and 15 mm wide with an overlap of 10 mm (the precise overlap was subject to small adjustments to ensure the wetted area was 150 mm^2). The overlap faces were polished to a 600 SiC grit finish, cleaned, fluxed, separated by two 0.2 mm diameter nichrome wires, and the assembly held together with two spring clips. A weighed amount of solder was placed next to the end of the gap, so that on melting it completely filled the gap with a minimum excess. The soldering cycle was carefully controlled. Six specimens were placed on the shelf of a cold air-circulating oven, heated to 250 °C, left at 250 °C for 1 min, and then the shelf with specimens was removed and air-cooled. Specimens were in the temperature range 220–250 °C for 5 min.

Joints were tested in tension using an Instron instrument with associated software, either at room temperature (nominally 20 °C) or 100 °C using an environmental chamber, at crosshead speeds of 0.05 and 50 mm min^{-1}.

3. Results and discussion

Six specimens were tested for each joint condition, and the average values and variation of the mechanical properties of the copper and brass soldered joints are given in Tables I and II, respectively. The ultimate strength is the property of primary interest, and typically it is the only property reported. Also included in the tables are the elongation at fracture, and the stress at an extension of 0.02 mm. Both these properties are of direct interest to the designer, and here the yield stress is required later in relation to the strain-rate sensitivity.

There is a considerable amount of information summarized in Tables I and II. First we make some general comments. The results are detailed and comprehensive. Of the 12 kinds of joint investigated (copper and brass each with six solders), comparable information obtained under the same range of test conditions is available for only five joints, copper with 3.5Ag, 2Ag36Pb, and 5Sb, and brass with 3.5Ag and 2Ag36Pb [3, 4]. In addition, these results are for a single test under each condition and hence there is no measure of the associated variation in the results [3, 4]. Information on the other joints is either partial or does not exist. A point worth emphasizing is that all the present results were obtained by one operator using the same experimental procedure, and hence any systematic error will have been kept to a minimum.

Scatter is an important measure of the reliability of a joint. The maximum variation in the ultimate shear strength was 21%, but typically the amount of scatter was substantially much lower than this value (Tables I and II). There are few studies that have tested sufficient samples to establish the scatter. From reported data on the strength of brass ring and plug joints with

TABLE II Shear strength of brass/tin-based joints

Solder composition[a] (wt %)	Temperature (°C)	Strain rate (mm min^{-1})	0.2% Yield stress			Ultimate shear strength			Elongation			Work to fracture		
			Mean[b] (MPa)	S.D. (MPa)	C.V. (%)	Mean (MPa)	S.D. (MPa)	C.V. (%)	Mean (%)	S.D. (%)	C.V. (%)	Mean (J)	S.D. (J)	C.V. (%)
Sn	20	0.05	13.9	2.8	20.1	15.3	1.7	11.1	6.0	0.7	11.7	0.78	0.08	10.3
		50.0	24.5	4.7	19.1	27.3	5.4	19.8	4.8	1.2	25.0	1.03	0.54	52.4
	100	0.05	11.8	1.2	10.2	13.0	0.9	6.9	16.9	2.6	15.4	1.00	0.16	16.0
		50.0	15.6	2.3	14.7	24.9	2.3	9.2	20.9	2.8	13.4	2.72	0.69	25.4
1Cu	20	0.05	17.1	2.3	13.5	17.5	2.5	14.3	7.7	1.5	19.5	1.10	0.18	16.4
		50.0	30.0	4.0	13.3	31.8	4.6	14.5	6.5	1.2	18.5	1.94	0.72	37.1
	100	0.05	10.4	1.9	18.3	11.6	1.3	11.2	16.0	5.1	31.9	0.91	0.32	35.2
		50.0	16.1	1.9	11.8	19.1	2.5	13.1	21.4	5.4	25.2	2.09	0.70	33.5
3.5Ag	20	0.05	20.8	1.8	8.7	22.0	2.0	9.1	6.8	2.0	29.4	1.21	0.29	24.0
		50.0	30.0	2.8	9.3	31.8	2.8	8.8	5.7	1.4	24.6	1.6	0.63	39.4
	100	0.05	10.6	1.8	17.0	11.8	2.2	18.6	16.1	3.7	23.0	0.44	0.19	43.2
		50.0	15.0	2.6	17.3	31.4	1.9	6.1	17.5	2.0	11.4	3.76	1.68	44.7
5Sb	20	0.05	24.3	2.3	9.5	24.6	2.3	9.3	7.3	0.9	12.3	1.57	0.24	15.3
		50.0	29.2	2.1	7.2	31.6	1.9	6.0	6.3	0.7	11.1	1.66	0.32	19.3
	100	0.05	15.2	1.0	6.6	17.8	2.8	15.7	18.8	2.1	11.2	1.50	0.33	22.0
		50.0	13.6	1.3	9.6	23.8	1.5	6.3	19.2	3.0	1.6	2.79	0.52	18.6
57Bi	20	0.05	18.7	3.1	16.6	18.4	3.6	19.6	3.1	0.8	25.8	0.50	0.23	46.0
		50.0	19.1	3.4	17.8	19.2	4.1	21.4	3.0	0.8	26.7	0.51	0.24	47.1
	100	0.05	10.4	1.1	10.6	10.6	1.0	9.4	10.3	2.9	28.2	0.45	0.09	20.0
		50.0	17.5	3.7	21.1	19.7	2.9	14.7	13.0	1.6	12.3	1.34	0.26	19.4
2Ag36Pb	20	0.05	21.0	2.9	13.8	21.8	2.7	12.4	4.3	0.43	10.0	0.78	0.15	19.2
		50.0	30.7	5.0	16.3	33.6	3.6	10.7	6.0	1.2	20.0	1.70	0.49	28.8
	100	0.05	15.2	2.1	13.8	15.3	2.1	13.7	9.4	2.9	30.9	0.68	0.11	16.2
		50.0	11.2	1.3	11.6	25.0	0.7	2.8	16.8	0.9	5.4	2.81	0.27	9.6

[a] Sn = pure tin; others, balance tin. See text.
[b] Mean of six tests. S.D. = standard deviation, C.V. = coefficient of variation = (S.D./mean) 100.

2Ag36Pb solder at strain rates of 0.05, 0.2, 1, 5, 20, and 50 mm min^{-1} [4], it may be calculated that the coefficients of variation are 18%, 21%, 11%, 12%, 5% and 22%, respectively. Thus the level of scatter observed in the present work may be considered good. Overall, there does not appear to be any pattern in the degree of scatter with the kind of joint or with the test temperature or strain rate.

Strength is a function of both the strain rate and the temperature. In general, with few exceptions, at any temperature an increase in strain rate increases substantially the strength and elongation, and at any strain rate, an increase in temperature decreases the strength and increases the elongation (Tables I and II). If a single mechanism of plastic deformation occurred, then the flow stress, σ, might be expected to be related to the strain rate, $\dot{\varepsilon}$, and the temperature, T, by the equations [16]

$$\sigma = C_1(\dot{\varepsilon})^m|_{\varepsilon,T} \qquad (1)$$

$$\sigma = C_2\exp(E/RT)|_{\varepsilon\dot{\varepsilon}} \qquad (2)$$

where m is the strain-rate sensitivity index measured at constant strain and temperature, E is the activation energy measured at constant strain and strain-rate, R is the gas constant, and C_1 and C_2 are constants. The flow stress (yield stress) at a constant extension of 0.02 mm and strain rates of 0.05 and 50 mm min^{-1} at constant temperature (Tables I and II) was used with Equation 1 to obtain the index m, and the flow stress at a constant extension of 0.02 mm and temperatures of 20 and 100 °C at constant strain rate (Tables I and II) was used with Equation 2 to obtain the activation energy, E. Calculated values of m and E are given in Table III.

The strain rate sensitivity indices are typically less than 0.1 (Table III). This is consistent with the general observation that at room temperature the index is less than 0.1 [16]. Enke *et al.* [6] also observed that for Sn60–Pb40 solder lap joints, m varied from 0.09–0.14 at 25 °C. There does not appear to be any other information on the values of m for solders or soldered joints. It is also observed with metals that m increases with an increase in temperature [16], and clearly the results of Table III show the opposite effect. The activation energies are very low (Table III) and typical of those for liquids. However, viscous flow is associated with a high index, and ideal viscous behaviour has an index $m = 1$ [16]. Hence we must assume that the activation energy is stress-assisted, and reduced according to the mechanism proposed by Becker [17] and Orowan [18].

Perhaps the most important conclusion from Table III is that there is no pattern in behaviour which might be associated with other mechanical properties. Equations 1 and 2 are based on a simple deformation mechanism, and clearly deformation of the joint is not such a simple process. This is reflected at least in the

TABLE III Strain-rate sensitivity and activation energy of deformation of copper and brass soldered joints at strain rates of 0.05 and 50 mm min^{-1} and at temperatures of 20 and 100 °C

Solder	Strain-rate sensitivity index[a]				Activation energy (kJ mol^{-1})[a]			
	Copper		Brass		Copper		Brass	
	20 °C	100 °C	20 °C	100 °C	0.5 mm min^{-1}	50 mm min^{-1}	0.5 mm min^{-1}	50 mm min^{-1}
Sn	0.10	0.06	0.08	0.04	5.0	8.2	1.8	5.1
1Cu	0.08	0.02	0.08	0.06	0.3	4.5	5.7	7.1
3.5Ag	0.03	0.01	0.05	0.05	6.8	8.5	7.7	7.9
5Sb	0.05	− 0.01	0.03	− 0.02	1.6	5.9	5.3	8.7
57Bi	− 0.03	0.06	0	0.08	10.4	3.9	1.0	1.2
2Ag36Pb	0.03	0	0.06	− 0.04	5.0	6.9	4.3	11.5

[a] See text for defining equations.

generally decreasing value of m with increases in temperature (Table III). It is worth pointing out, however, that the flow stress is measured at an extension of 0.02 mm, and deformation up to this extension is likely to be entirely within the ductile solder.

Any assessment of the properties of individual kinds of solder joints and comparisons between them, must have in mind the scatter and general behaviour discussed. To aid comparison of joint properties the ultimate shear strengths of the joints are shown in Fig. 1, where each condition is shown by a different symbol. Ranking the joints in terms of the strength depends on the conditions used to measure the property. A strain rate of 0.05 mm min^{-1} seems typical of conditions that occur in practice, and on this basis with copper joints at 20 °C/0.05 mm min^{-1}, the order of decreasing strength is for joints with solders 3.5Ag, 57Bi, 2Ag36Pb, 5Sb and 1Cu, with strengths of 26.8, 25.3, 22.2, 21.8, 15.4, and 13.8 MPa, respectively. At 100 °C/0.05 mm min^{-1} the order changes, and for both copper and brass joints, the average strength generally decreases in order of the joints with solders 5Sb, 2Ag36Pb, 3.5Ag, 1Cu, Sn, and 57Bi.

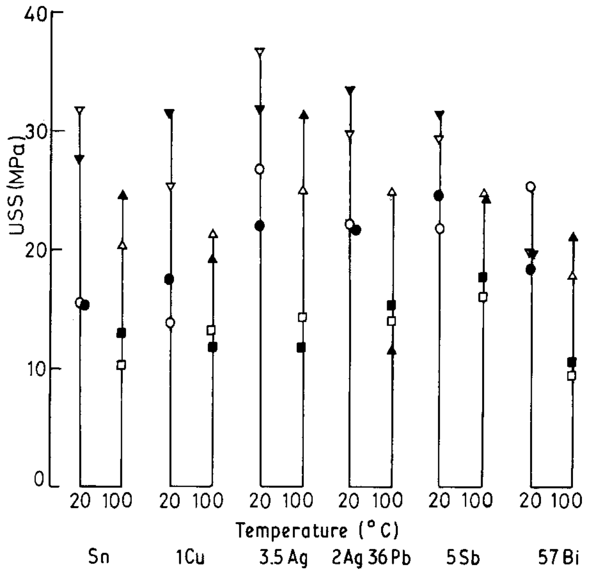

Figure 1 Ultimate shear strength (USS) of (○, □, ▽, △) copper and (●, ■, ▼, ▲) brass joints tested under various conditions. Test speed: 0.05 mm min^{-1} (○, ●) 20 °C, (□, ■) 100 °C; 50 mm min^{-1} (▽, ▼) 20 °C, (△, ▲) 100 °C.

In terms of joints with various solders, several features may be noted. Joints soldered with 3.5Ag are generally superior to those soldered with 2Ag36Pb, except for the 100 °C/50 mm min^{-1} where the 2Ag36Pb has a very low strength. Joints made with 57Bi solder do not generally follow the behaviour pattern of the other joints. At 20 °C they have acceptable properties that are least affected by strain rate. They also have a ductility comparable with some other solders. This contrasts sharply with the extreme brittleness of the solder alloy [7].

A cause of some concern over the years has been the influence of zinc from the brass on the joint strength, particularly with respect to embrittlement involving solders containing antimony. The effects of brass substrates on the strength, elongation, and scatter is given in Table IV. It is seen that brass joints generally have a higher strength and elongation. But the effect is only slight, and the present results are similar to those of Saperstein and Howes [2], who concluded that copper and brass joints had about the same strength, and that the presence of zinc in the reaction-zone layer is not particularly detrimental [2]. In fact, as noted above, the caution is not necessary, and zinc in the reaction-zone layer may be considered a small but definite advantage with these alloys. There does not appear to be any extremes in scatter, and with the antimony solder, except for the 20 °C/0.05 mm min^{-1} result which seems anomalous, the scatter is much less on brass joints than on copper joints. This is in contrast to the observation that the strength of brass joints with antimonial solder have more scatter than copper joints [3].

Finally, we comment on the strength values obtained. As mentioned earlier, comparable data over the full range of test conditions is limited. Copper ring and plug joints with 3.5Ag, 2Ag36Pb, and 5Sb solders were stronger than the present results by factors ranging from 0.9–1.3, except for tests at 20 °C and speeds of 50 mm min^{-1}, where the factors ranged from 1.5–1.9 [4]. A strain rate of 50 mm min^{-1} is nearly 1 mm s^{-1}, and it appears that any bending, which is inherent in testing the lap joint, is accentuated at this very fast

TABLE IV Ratio of ultimate shear strength and elongation of brass joints compared with copper joints

Solder composition[a] (wt %)	Temperature (°C)	Strain rate (mm min^{-1})	Ultimate strength		Elongation	
			Mean (brass)[b] / Mean (Cu)	C.V. (brass) / C.V. (Cu)	Mean (brass) / Mean (Cu)	C.V. (brass) / C.V. (Cu)
Sn	20	0.05	1.0	1.6	0.9	1.0
		50.0	0.9	2.3	0.6	1.3
	100	0.05	1.3	1.0	1.3	1.2
		50.0	1.2	1.9	0.9	0.5
1Cu	20	0.05	1.3	1.1	1.8	0.9
		50.0	1.3	1.2	1.3	1.9
	100	0.05	0.9	1.5	1.2	2.0
		50.0	0.9	3.5	1.0	1.3
3.5Ag	20	0.05	0.8	4.1	0.7	1.4
		50.0	0.9	0.7	0.7	1.2
	100	0.05	0.8	3.3	1.4	1.1
		50.0	1.3	0.6	0.9	0.3
5Sb	20	0.05	1.1	4.0	1.3	0.6
		50.0	1.1	0.4	0.9	0.4
	100	0.05	1.1	0.7	1.6	0.4
		50.0	1.0	0.6	1.1	0.2
57Bi	20	0.05	0.7	1.9	0.7	1.2
		50.0	1.0	1.0	0.9	0.7
	100	0.05	1.1	1.0	0.9	0.9
		50.0	1.1	1.5	1.0	1.2
2Ag36Pb	20	0.05	1.0	2.8	0.9	1.2
		50.0	1.1	1.0	1.0	1.7
	100	0.05	1.1	3.2	0.9	1.6
		50.0	1.0	0.5	1.0	0.4

[a] Sn = pure tin; others, balance tin. See text.
[b] Ratio of mean for the brass to the mean of the copper; C.V. (brass) = coefficient of variation for brass, etc.

speed. It would seem from both a test procedure and possible industrial use that an arbitrarily chosen test speed of 50 mm min^{-1} is too fast, and a more realistic value like 1 mm min^{-1} could be used as the upper test speed limit.

4. Conclusions

1. The maximum coefficient of variation in the ultimate shear strength was 20%. Generally the scatter was much less. Scatter with brass joints tended to be slightly higher than with copper joints. Copper and brass joints with 5% Sb solders had the lowest scatter.

2. The strain-rate sensitivity at 20 °C was less than 0.1. This is typical for metal deformation. The value was less at 100 °C. This is unusual.

3. Activation energies were very low (about 5–10 kJ mol^{-1}), and assumed to be stress-assisted.

4. Ranking in terms of strength depended on the test conditions. Generally the solders containing silver gave the strongest joints, and the 3.5% Ag solder produced stronger joints than the 2% Ag 36 % Pb solder.

5. Joints made with 57% Bi solder frequently did not follow the general pattern of behaviour with different test conditions. The joints had a ductility that was not substantially lower than some other joints.

6. Overall, brass joints had similar, or slightly better, properties than copper joints. Hence the influence of zinc in the reaction zone is not detrimental.

7. Copper lap joints had slightly lower strengths than ring and plug joints (literature values), except for the tests at 20 °C and strain rates of 50 mm min^{-1}, when the strength was substantially lower.

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