Journal of ELECTRONIC MATERIALS, Vol. 38, No. 2, 2009
DOI: 10.1007/s11664-008-0568-3

The Influence of an Imposed Current on the Creep of Sn-Ag-Cu Solder

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The work reported here included preliminary tests on the influence of an imposed current on the creep rate of the Pb-free solder Sn-Ag-Cu 305 (Sn-3Ag-0.5Cu in wt.%). The samples employed were double-shear specimens that contained paired solder joints, 400 μm × 400 μm in cross-section, 200 μm in thickness on Cu. Three tests were done. In the first, samples were tested under stress at room temperature with imposed current densities that ranged from 1×10^3 A/cm^2 up to 6.5×10^3 A/cm^2. As expected, because of Joule heating, the results show a sharp increase in creep rate with the imposed current density. A second set of tests was done to determine whether Joule heating fixed the creep rate. The steady-state temperature of the solder joints was measured under current, and samples were creep-tested at that temperature. Surprisingly, the creep rate under current was significantly below that measured in isothermal tests at the same temperature. The third set of tests studied the influence of microstructure. Samples were prepared with three starting microstructures: as cast, thermally aged by long-term isothermal exposure, and current aged by long-term exposure to a fixed current density. The three microstructures were then tested with and without current at two ambient temperatures. The different microstructures had very different creep rates in the absence of current but, surprisingly, imposing a current (5.5×10^3 A/cm^2) increased the creep rate by very nearly the same factor (~7×) in every case. Neither of these results is well understood at this time.

Key words: Current, creep, solder joint, electromigration, Joule heating

INTRODUCTION

The emergence of Sn-rich Sn-Ag-Cu solders as leading candidates to replace leaded solders has led to a considerable body of work on their microstructure and properties. This work has included research on the development of interfacial intermetallics during solidification and aging,[1–4] the generation of microstructural damage by the action of high current densities,[1,5] and the rate of creep deformation as a function of temperature and load.[1,3,4,6–8] Since solder joints in service carry current while under load at moderate temperature, the coupling between these factors is important to joint reliability, and is the subject of the present investigation.

It is inevitable that temperature, load, and current will be coupled. Current raises temperature via Joule heating; both temperature and current induce microstructural changes, particularly in the nature and distribution of precipitates and interfacial intermetallics; and the current induces the electromigration of vacancies, which may significantly affect the diffusional processes that govern creep. None of these coupling terms are well understood.

The present paper presents the results of three experiments that explore aspects of temperature–

(Received April 15, 2008; accepted September 12, 2008;

load–current coupling in the candidate alloy Sn-Ag-Cu 305 (Sn-3Ag-0.5Cu in wt.%). In the first experiment, we explore the influence of the current density on the creep rate at a typical load and temperature. In the second we recognize that the first-order effect of the current density is to increase the temperature via Joule heating. To specifically test the influence of Joule heating, we compare the creep rates of samples under current to those of samples without current at the same steady-state temperature. In the third we examine the influence of microstructure on the creep rates, and compare the effect of current on samples with three different microstructures derived from three typical service histories. In all these tests we used a simple sample geometry to facilitate the eventual interpretation of the results. The range of conditions explored is very limited, so the results are not definitive. Nonetheless they reveal some very interesting features of the load–temperature–current coupling in solder joints.

EXPERIMENTAL PROCEDURE

The specimens used in the work reported here were double-shear creep specimens like that shown in Fig. 1. The specimens were made in the following way. Copper blocks were cut to 11 mm × 13 mm × 6 mm size, and their broad faces were polished to 4,000 grit. The polished faces of three blocks were coated with flux, then matched together while separated by 200 μm spacers. The composite block was placed in molten Sn-Ag-Cu at 360°C for 45 s, then removed and cooled in air. Once cool, the block was polished to examine the quality of the solder joints. The block was placed in a precision cutter and cut into sheets roughly 500 μm thick. The sheets were polished, then cut into rods. These rods were then polished to create double-shear samples with square cross-sections, approximately 400 μm × 400 μm, and a length of roughly 18.4 mm. The lengths contained three Cu segments 6 mm in length connected by two solder joints of 200 μm length, as illustrated in Fig. 1.

To study the influence of current on the creep rate samples were tested in the creep apparatus shown in Fig. 2. The samples were tested in the as-cast condition. A constant load was placed on the sample, and the displacement was measured using an Omega linear variable displacement transducer (LVDT). The displacement was then converted to strain for analysis. Samples were tested under 8.3 MPa stress at room temperature with imposed current densities ranging from 1×10^3 A/cm^2 up to 6.5×10^3 A/cm^2. The tests lasted 48 h.

Fig. 1. Sample configuration. The cross-section is a square, approximately 400 μm × 400 μm.

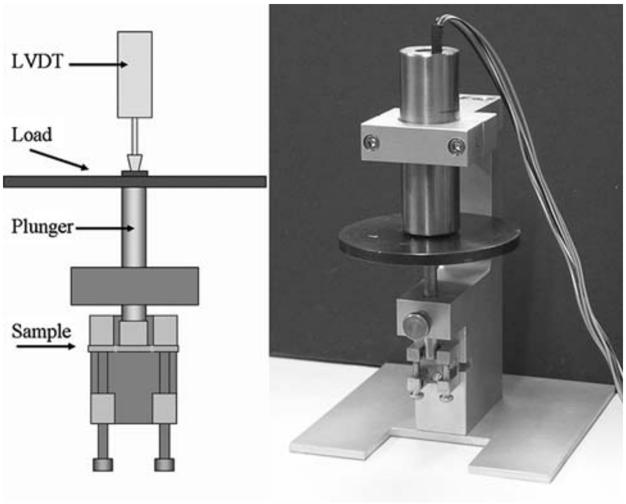

Fig. 2. The creep-testing apparatus. The sample is loaded in shear as shown in the drawing on the left. The displacement is measured by the LVDT. Controlled current is fed through the plunger and passes through the solder joints.

To study the influence of current on creep rate at a given temperature, the steady-state temperature of the solder joints under current was measured both by attaching thermocouples and by infrared (IR) imaging. Samples were then creep-tested in an isothermal environment at the measured temperature.

To study the influence of microstructural evolution on the creep behavior, samples were aged in two ways. First, samples were thermally aged in an oven at 180°C for 200 h. As will be described below, this treatment produced samples with coarsened intermetallic layers at the interfaces and coarse precipitates through the bulk. Second, samples were aged under current by applying a current density of 4×10^3 A/cm^2 at room temperature for 200 h. The three sets of microstructurally different samples, these two and the as-cast samples, were then creep tested with no current and with an imposed current of 5.5×10^3 A/cm^2. Creep tests were done both at room temperature with an 8.3 MPa load, and at 80°C with a 3.5 MPa load.

RESULTS

The Influence of Current on Creep Rate

To test the influence of electrical current on the steady-state creep rate, samples were tested in the as-cast condition while carrying current densities that ranged from 0 to 6.5×10^3 A/cm^2. The tests reported here were done at ambient temperature under a fixed shear stress of 8.3 MPa. The results are presented in Table I and in Fig. 3. The strain rate measured in the absence of current is comparable to that published elsewhere.[1,3,4,6] As expected, the creep rate increases substantially with

Table I. Creep Rates of As-Cast Samples, 8.3 MPa at room temperature

Current Density (A/cm^2)	Steady-State Strain Rate (1/s)
0×10^3	1.7×10^{-7}
1×10^3	3.3×10^{-7}
2×10^3	4.9×10^{-7}
3×10^3	6.1×10^{-7}
4×10^3	7.0×10^{-7}
5.5×10^3	1.5×10^{-6}
6.5×10^3	9.7×10^{-6}

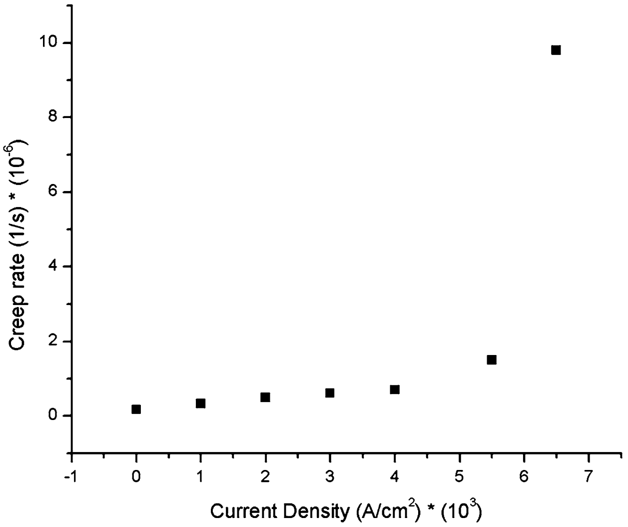

Fig. 3. Logarithmic creep rate as a function of current density.

increasing current density. The limited data taken here suggest a roughly linear increase until the current density reaches about 5.5×10^3 A/cm^2, at which point there is a dramatic increase in the slope of the curve, suggesting a possible change in mechanism.

Separating the Effect of Joule Heating

It is, of course, expected that the steady-state creep rate should increase with current density. The current through the solder joint raises its temperature via Joule heating, and the steady-state creep rate ordinarily varies exponentially with the temperature according to the Dorn equation:

$$\frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{A}{kT}\tau^n \exp\left[-\frac{Q}{kT}\right] \tag{1}$$

where $\mathrm{d}\gamma/\mathrm{d}t$ is the steady-state strain rate, τ is the shear stress, T is the absolute temperature, and A, n, and Q are constants. To correct for the overall temperature increase due to Joule heating the average temperature of the solder was measured by attaching a thermocouple, and confirmed by infrared measurement with an IR camera. For a sample in the as-cast condition, the temperature increased from 20°C (room temperature) to about 40°C at a current density of 4000 A/cm^2, and 50°C at a current density of 5500 A/cm^2. Samples were then tested without current in an oven at controlled temperatures of 40°C and 50°C. The creep rates at these temperatures are compared to the creep rates due to 4000 A/cm^2 and 5500 A/cm^2 in Fig. 4.

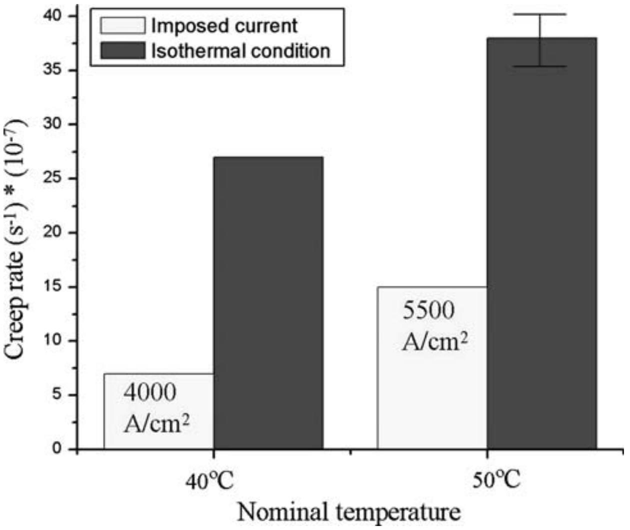

Fig. 4. Comparative rates of creep with an imposed current density, and during isothermal hold at the temperature imposed by the current.

Surprisingly, the steady-state creep rates under current were significantly below the isothermal creep rates at the same temperature, which suggests that the effect of current-induced electromigration is to reduce the rate of creep.

The Influence of Microstructure

It is well known that the creep rate of solder is influenced by the microstructure of the joint, and that this microstructure evolves during service under the action of temperature and current. It is important to know whether the natural evolution of the microstructure causes any significant change in the effect of current on creep rate. To test this, samples with three different microstructures were prepared as described in the previous section: as-cast samples, thermally aged samples that were exposed to high temperature for an extended period, and current-aged specimens that were held under current for an extended period.

The microstructures of these different specimens are illustrated in Figs. 5–8. Figure 5 shows the as-cast microstructure. There is a small layer of Cu_6Sn_5 present at the Cu/Sn-Ag-Cu interface which forms during reflow of the solder joint.[2] Both thermal and current aging led to much thicker and more developed intermetallic layers (Figs. 6 and 7, respectively), and also produced dispersions of coarse Ag_3Sn precipitates in the β-Sn matrix. Cu_3Sn

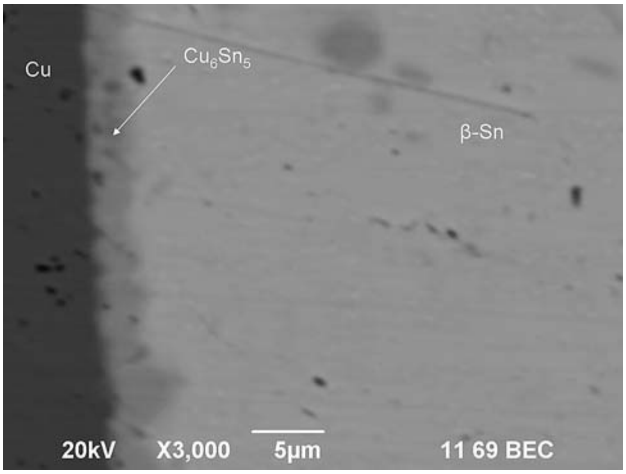

Fig. 5. Cu/Sn-Ag-Cu interface of an as-cast sample.

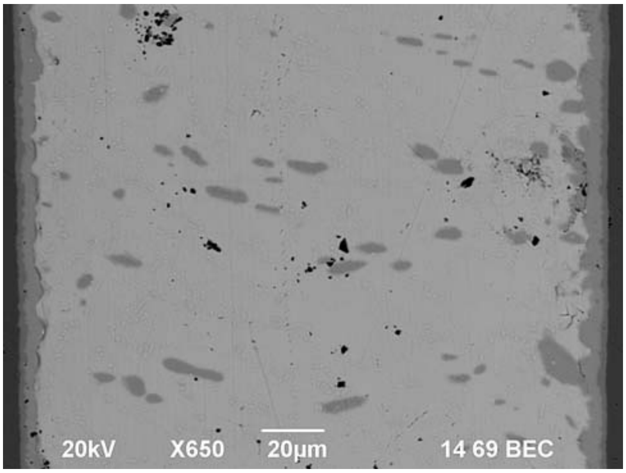

Fig. 6. An SEM image of a thermally aged solder joint. Note the formation of intermetallic layers on both sides of the joint.

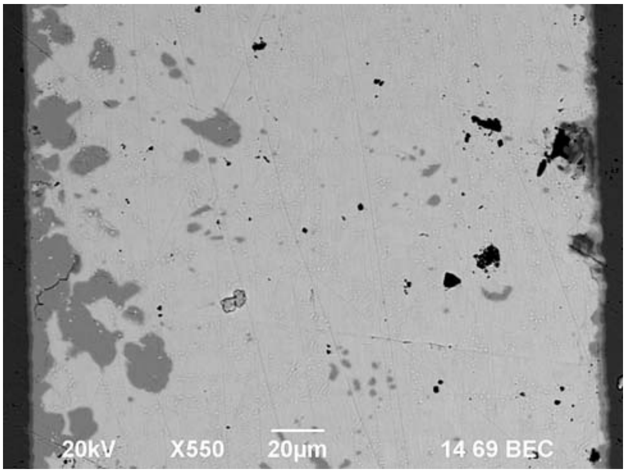

Fig. 7. An SEM image of a current-aged sample. The intermetallic growth is concentrated on the anode side.

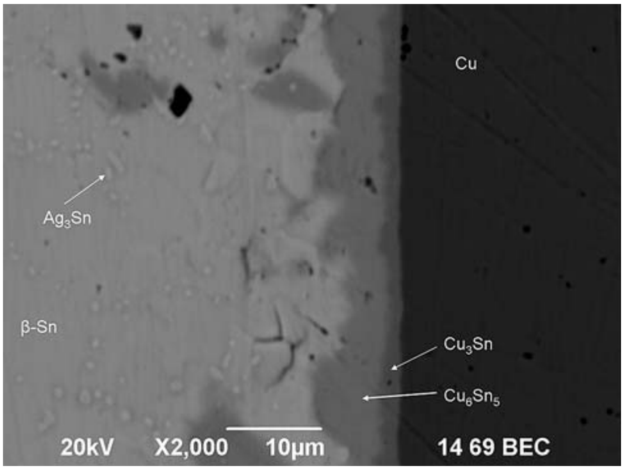

Fig. 8. A close-up image detailing the IMC layers in a thermally aged sample.

can be seen in a thin layer along the copper interface, while Cu_6Sn_5 is present between Cu_3Sn and the β-Sn matrix. These are identified in Fig. 8. In the thermally aged samples, well-developed intermetallic layers appear on both sides of the solder joint. In the current-aged samples, the intermetallic layer is thicker, but is essentially confined to one side of the joint, the anode, which is the downstream side with respect to electron flow. These intermetallic structures have been observed previously and are documented in the literature.[2,3,5,8]

The effect of an imposed current density on the creep rates of these microstructurally different samples was measured under two conditions: a shear stress of 8.3 MPa imposed at ambient room temperature and a stress of 3.5 MPa imposed on samples at an ambient temperature of 80°C. The results are plotted in Figs. 9 and 10. As expected, the creep rates in the absence of current change with the microstructure. However, the proportional increase in creep rate due to an imposed current of 5.5×10^3 A/cm^2 is, surprisingly, nearly the same in every case. For all three microstructures and both test conditions, the imposition of a current density of 5.5×10^3 A/cm^2 increases the creep rate by a factor of about 7.

A possible explanation for this surprising result is suggested by the Dorn equation (Eq. 1). Prior work[6] suggests that the microstructural changes associated with aging and interaction with the metallized substrate of the joint change the pre-exponential factor, A, in Eq. 1. Assume that an equation of this form continues to govern creep under current (though with some as yet unknown modifications, as shown by the results of the previous section), and further assume that the temperature increase due to the imposition of the current is independent of microstructure (at least to first order). Then the ratio of the creep rates with and without current

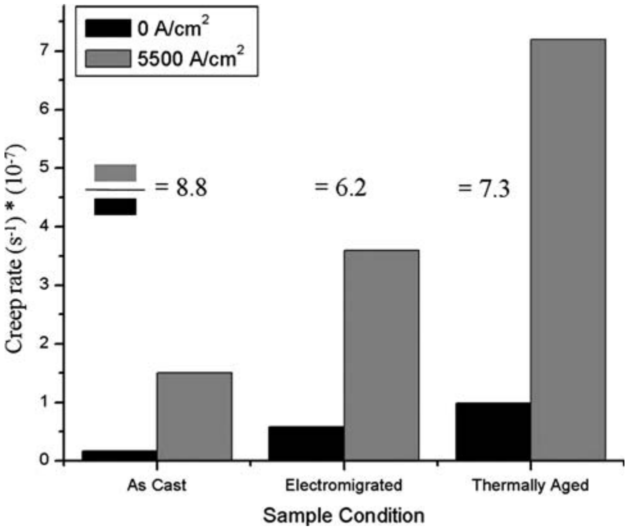

Fig. 9. Steady-state creep rates for three joint microstructures, with and without imposed current, under a shear stress of 8.3 MPa at ambient room temperature.

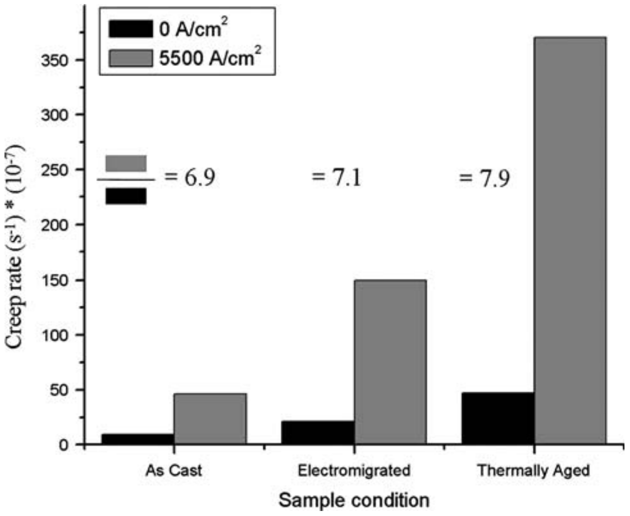

Fig. 10. Steady-state creep rates for three joint microstructures, with and without imposed current, under a shear stress of 3.5 MPa at an ambient temperature of 80°C.

will be determined by the ratio of the temperature-dependent terms on the right-hand side of Eq. 1 and will, therefore, be roughly independent of the microstructure.

DISCUSSION

The results presented here are limited, but contain several interesting features. The increasing creep rate with current density is expected, if for no other reason than the temperature increase from Joule heating. However, a comparison between the increase due to current and the increase due to isothermal heating to the same steady-state temperature suggests that the current-induced creep enhancement is less than would be expected on the basis of temperature alone. This result is surprising, and needs to be confirmed and explained.

Assuming that the relatively low value of the current-induced creep is real and reproducible, it is possible to identify several factors that might contribute to this result. One relevant factor is the temperature distribution. The inhomogeneous microstructure of the solder joint produces an inhomogeneous pattern of Joule heating which is likely to produce an inhomogeneous temperature distribution with significant thermal gradients. Evidence from prior work,[1] for example, suggests that the temperature is peaked near the intermetallic layers, presumably because of the higher electrical resistivity of these intermetallic compounds. Thermal gradients may affect the creep rate in either direction; the colder regions should creep at a significantly lower rate, while the possible enhancement of diffusion may tend to increase the creep rate.

A second relevant factor is the electromigration that occurs at high current density. Electromigration induces vacancy flows and controls the direction of those flows, a behavior that is evidenced by the asymmetry of the intermetallic layers developed in the current-aged samples as shown in Fig. 7. Since the common mechanisms of creep require lattice diffusion, which is driven by vacancies, a change in the vacancy concentration or flux can certainly have a significant effect. Clarifying the precise nature of that effect will require further research.

Finally, the observation that, at least in the limited set of tests done here, the imposition of a current causes very nearly the same proportional increase in creep rate for a variety of microstructures and test conditions was initially surprising. As suggested above, this result may simply indicate that a given current density produces roughly the same temperature increase, irrespective of microstructure and starting temperature. However, whatever its source, if this result is reproducible it may be of considerable value in predicting the behavior of joints under current since it may provide a simple way of inferring behavior under current from isothermal tests on joints with similar microstructures.

ACKNOWLEDGEMENT

This research reports results from a joint project between the Component Quality and Technology Group, Cisco Systems and the University of California, Berkeley. Work at Berkeley was supported by Cisco Systems, and by the Korean Ministry of Commerce, Industry and Energy through Next-generation Microsystems Packaging Program.

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