Journal of Electronic Materials, Vol. 23, No. 7, 1994

Resilient Metal Spring Network Silicone-Matrix Composite for Separable Interconnections

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Resilient metal spring silicone-matrix conducting composites for separable interconnections in electronics were fabricated by the impregnation of silicone into a preform comprising randomly oriented C-shaped Cu-Be springs and a small proportion of Sn-Pb solder, which served to connect the springs at some of their intersections. Composites containing 6.1–9.8 vol.% total filler exhibited volume electrical resistivity 0.5–1.0 mΩ.cm and contact resistivity (with copper) 11–17 mΩ.cm². A compressive stress of about 30 kPa was needed for the low contact resistivity to be reached. The volume 17–26% and the contact resistivity increased by 5% after heating in air at 130–150°C for seven days. Composites containing <9 vol.% total filler showed no stress relaxation for seven days at 6.0% strain.

Key words: Contact electrical resistivity, composite materials, copper springs, increased by electrical resistivity; three-dimensional interconnected network, silicone matrix, solder, volume electrical resistivity

INTRODUCTION

Due to the fact that soldering involves heating, which is not desirable for reliability and inconvenient for the disconnection of the joint, and the fact that solders suffer from thermal fatigue when they are used to join low thermal expansion components (such as silicon, substrates, and printed circuit boards), the use of separable interconnections is increasingly important for electrical connections between printed circuit boards. Such a connection is a pressure contact for which pressure is applied on a resilient electrical conductor, which must exhibit a low volume resistivity and a low contact resistivity. Furthermore, the amount of pressure needed to obtain a low contact resistivity must be low.

In addition to being highly resilient, the conductor must not suffer from stress relaxation. Moreover, the electrical properties should not degrade upon heating to 150°C, which is the ambient temperature in some applications, such as applications under the hood of an automobile.

Resilient electrical conductors in the form of crumbled metal wires (as in a Brillo pad) or conductor filled elastomers have been used for solderless interconnections.[1-3] In one configuration, these conductors are shaped like buttons, which are inserted into holes punched through an insulator board (called a button board). The positions of the holes in the board are the points at which interconnections are needed between contact pads on the printed circuit board on one side of the button board and those on the printed circuit board on the other side of the button board. In this way, the placement of a button board between adjacent printed circuit boards and the application of pressure provide the solderless interconnections. For high density electronic packaging, the buttons need to be as small as possible.

(Received December 23, 1992; revised March 14, 1994)

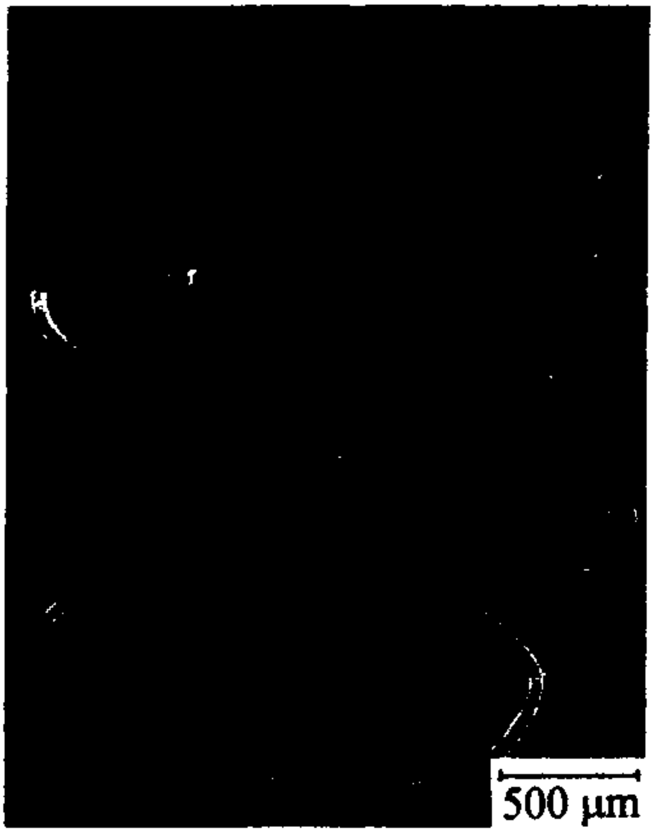

Fig. 1. Scanning electron microscopy photograph of loose C-shaped springs.

Buttons in the form of crumbled metal wires suffer from wear and the conductor particles generated by it. Moreover, they suffer from stress relaxation or sagging. Buttons in the form of a conductor filled elastomer (typically with particles as the filler) are superior in these aspects, but they typically suffer from a high contact resistivity due to the surface of the composite being covered by a layer of polymer, which is insulating.

The state of the art of conductor filled elastomers uses silver particles as the filler. This is because of the low volume resistivity and good oxidation resistance of silver. For a silicone-matrix composite to attain a low volume resistivity of 10^{-4} Ω.cm, silver particles in the amount of 35 vol.% are needed.[3] Recently, we have developed a silicone-matrix composite which uses 6 vol.% of a three-dimensionally interconnected metal (Cu + Sn-Pb) spiral spring network as the filler; this composite exhibits a volume resistivity of 10^{-4} Ω.cm in spite of its low filler volume fraction.[4]

Furthermore, because wires in the network slightly protrude from the surface of the composite, the contact resistivity is low. In addition, because of the low filler volume fraction and the low cost of Cu + Sn-Pb compared to Ag, the composite is much less expensive than the Ag particle counterpart. However, the spiral spring network composite suffers from the fact that the resulting buttons cannot be smaller than 2 mm in diameter due to the bulkiness of the spiral springs.

Therefore, in this work, we have replaced the spiral spring network by a C-shaped spring network, thereby obtaining buttons smaller than 2 mm in diameter. The fabrication, structure, and properties of the C-

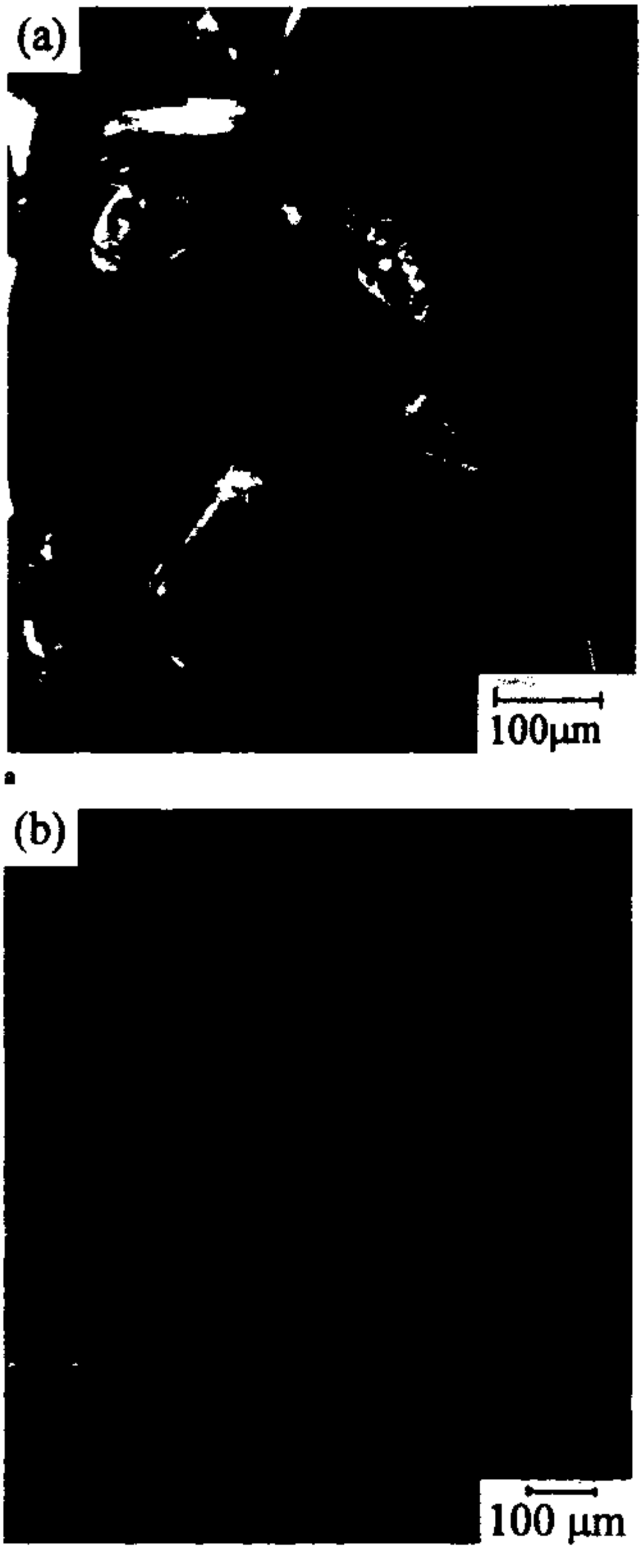

Fig. 2. Two scanning electron microscopy photographs (at different magnifications) of preform (a) before heating, and (b) after heating. The preform gave a composite containing 8.3 vol.% Cu and 1.5 vol.% Sn-Pb.

shaped spring network composite constitute the focus of this paper.

EXPERIMENTAL

Spring Fabrication

Spiral springs were first made by winding bare soft-temper alloy 172 Cu-Be (1.86 wt.% Be) wires of diameter 63 µm on a shaft, as described in Ref. 4. The wires were provided by R&F Alloys, Fairfield, New Jersey. The diameter of a spiral spring was about 0.7 mm. After that, every winding of the spiral spring was cut to obtain a large number of C-shaped springs from one spiral spring. Figure 1 is scanning electron microscope (SEM) photograph of the C-shaped springs prior to their being interconnected to form a network. Unless stated otherwise, all springs were made from 63 µm Cu-Be wires.

Preform Fabrication

The spring network prior to polymer addition is known as the preform. Its fabrication involved

- mixing a solder paste (Sn-Pb, 63 wt.% Sn, Electro-Science Laboratories, Inc., type 3702) with C-shaped springs, which had been previously cleaned by acetone, acid, and water,
- compacting the mixture to form a cylinder of diameter 3.2 mm,
- heating the compact so as to melt the solder, thereby connecting the C-shaped springs at some of their intersections, and
- washing away the remaining flux with acetone. The C-shaped springs were randomly oriented inside the compact. Figures 2a and 2b (at different magnifications) show the compact prior to heating and that after heating, respectively, for a composite containing 8.3 vol.% Cu and 1.5 vol.% Sn-Pb. Before the heating, the solder paste was observed to gather at the intersections of the springs. After the heating, the solder electrically connected the springs at most of their intersections. From Fig. 2b, we can see that some of the intersections were not connected. However, at least 60% of the interconnections were connected by solder.

Composite Fabrication

The preform was impregnated with liquid silicone resin (General Electric Co., low temperature two-part silicone, RTV511, together with dibutyl tin dilaurate as a catalyst), as described in Ref. 4.

Surface Morphology

Figure 3 shows a scanning electron microscopy photograph of the cut surface of a composite containing 6.7 vol.% Cu and 1.2 vol.% Sn-Pb. Spring wires were observed to protrude from the surface in various directions. This protrusion is due to the pull-out of spring wires when the composite was cut; it is related to the weak interfacial bonding between the filler and the silicone matrix; it is desirable for obtaining a low contact resistivity.

Volume Electrical Resistivity

The volume resistivity was measured by the four-probe method, using silver paint for the current (outer) probes and needles pushed into the sample as the voltage (inner) probes.

Two models were used to obtain the calculated values of the volume resistivity. In both models, the spring resistivity was taken to be 10.53 µΩ.cm (which is the measured value of the resistivity of the bare copper wire used in this work) and the solder resistiv-

Fig. 3. Scanning electron microscopy photograph of the cut surface of the composite (6.7 vol.% Cu, 1.2 vol.% Sn-Pb), showing spring wires protruding in different directions.

Table I. Volume Electrical Resistivity of Composites

Total Filler vol.%	Cu vol.%	Sn-Pb vol.%	Volume Resistivity (mΩcm) Measured	Model 1 Calculated	Model 2 Calculated	Ratio Model 1 Measured / Calculated	Ratio Model 2 Measured / Calculated
6.1	4.9	1.2	1.047	0.183	0.862	5.72	1.21
7.9	6.7	1.2	0.614	0.140	0.659	4.39	0.93
9.8	8.3	1.5	0.557	0.112	0.528	4.97	1.05

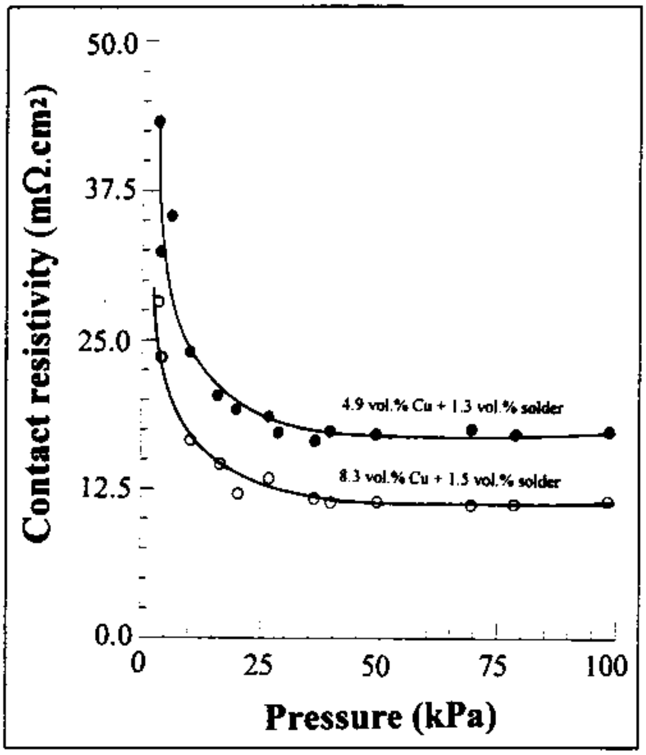

Fig. 4. The variation of the contact resistivity with pressure applied perpendicular to the plane of the contact.

ity was taken to be 14.7 μΩ.cm. Model 1 assumes that the conducting fillers are continuous and unidirectional, and uses the rule of mixtures (ROM) to yield the lower limit to the resistivity (ρ_{min}) that can be reached for a composite containing a volume fraction ϕ_1 of filler of resistivity ρ_1, a volume fraction ϕ_2 of filler of resistivity ρ_2, and a matrix of infinite resistivity. This limit is:

$$\frac{1}{\rho_{min}} = \frac{\phi_1}{\rho_1} + \frac{\phi_2}{\rho_2} \qquad (1)$$

Model 2[5] assumes that the conducting fillers are in the form of short, straight, discontinuous, randomly oriented and intersecting fibers, and it yields the resistivity ρ_c of a composite with a volume fraction ϕ_1 of filler of resistivity ρ_1, a volume fraction ϕ_2 of filler of resistivity ρ_2 and a matrix of infinite resistivity:

$$\frac{1}{\rho_c} = \frac{2}{3\pi}\left[\frac{\phi_1}{\rho_1} + \frac{\phi_2}{\rho_2}\right] \qquad (2)$$

Table I shows the measured and calculated values (based on Models 1 and 2) of the volume resistivity of composites with various filler volume fractions. An increase in the total filler volume fraction was associated with an increase in the Cu volume fraction, which was higher than the Sn-Pb volume fraction. The greater was the Cu volume fraction, the lower was the volume resistivity. The ratio of the measured resistivity to the calculated resistivity was about one when Model 2 was used, but greater than four when Model 1 was used. In the case of composites containing spiral rather than C-shaped springs, the ratio was about three when Model 1 was used, indicating that the spiral springs were totally three-dimensionally interconnected.[4]

Table II. Effect of Heating* on the Volume Electrical Resistivity of Composites

Total Filler vol.%	Cu vol.%	Sn-Pb vol.%	Resistivity (mΩ.cm) Before Heating	Resistivity (mΩ.cm) After Heating
6.1	4.9	1.2	1.047±0.04	1.322±0.06
7.9	6.7	1.2	0.614±0.02	0.719±0.03
9.8	8.3	1.5	0.557±0.03	0.694±0.05

*In air at 130–150°C for seven days.

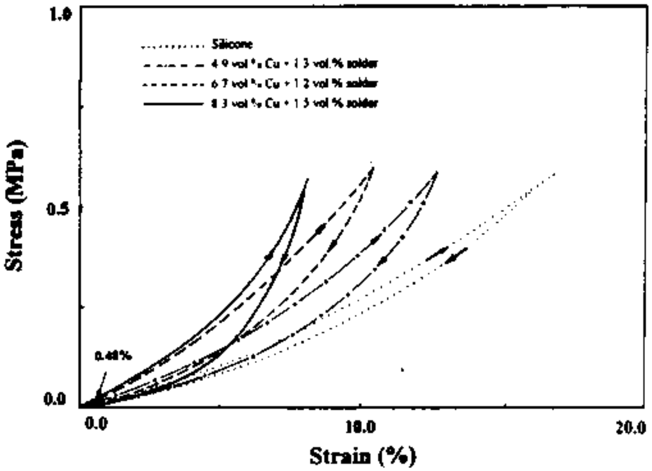

Fig. 5. Compressive stress-strain curves during loading and unloading for different filler contents.

In the case of composites containing C-shaped springs, the fact that the ratio exceeded four when Model 1 was used means that the C-shaped springs were not totally three-dimensionally interconnected; the fact that the ratio was about one when Model 2 was used means that the C-shaped springs electrically behaved as short fibers.

Contact Electrical Resistivity

The contact electrical resistivity was measured by sandwiching a cylindrical composite sample disc (3.2 mm in diameter, 4–5 mm in height) between two copper sheets, applying pressure on the sandwich in the direction perpendicular to the sandwich layers, applying a voltage between the two copper sheets, and measuring the current flowing across the sandwich, which comprised two copper-composite contacts. As the contribution of the volume resistivity of the composite to the measured resistance is orders of magnitude less than the measured resistance, it was neglected in calculating the contact resistivity.

Figure 4 shows the contact resistivity as a function of pressure for composites with different volume fractions of the filler. For each composite, the contact resistivity decreased with increasing pressure and then leveled off to a minimum contact resistivity. The greater was the Cu volume fraction, the lower was the leveled off minimum contact resistivity. The pressure required for the contact resistivity to level off was about 30 kPa.

Effect of Heating

The effect of heating (in air at 130–150°C for seven days) on the volume resistivity of composites of various filler volume fractions is shown in Table II. The heating caused the volume resistivity to increase by 17–26%.

The effect of heating (in air at 130–150°C for seven days) on the contact resistivity is shown in Table III. The heating caused the contact resistivity to increase only around 5%, and had almost no effect on the pressure required to reach the minimum contact resistivity.

Mechanical Testing

Compressive stress-strain curves and compressive stress relaxation curves (at a constant strain) were obtained by using a Sintech 2/D mechanical testing system. The crosshead movement was accurately controlled by the computer and a very sensitive load cell was used. The strain was obtained from the crosshead displacement.

Figure 5 shows the compressive stress-strain curves up to a stress of around 0.6 MPa for plain silicone and three composites of different filler volume fractions. The greater was the filler content, the higher was the modulus. The permanent set after the stress had returned to zero was zero for all composites except the one with the highest (8.3 vol.% Cu, 1.5 vol.% Sn-Pb) filler content, for which the permanent set was 0.48%.

Figure 6 shows the compressive stress-strain curves during loading and unloading of the same composite (with 4.9 vol.% Cu and 1.2 vol.% Sn-Pb), but up to two different maximum stress levels. For a maximum stress of about 0.6 MPa, the permanent set was zero. For a maximum stress of 1.5 MPa, the permanent set was 0.46%.

Figure 7 shows the compressive stress-strain curves of the same composite (with 8.3 vol.% of Cu and 1.5 vol.% Sn-Pb), but up to two different maximum stress levels. For a maximum stress of 0.5 MPa, the permanent set was 0.48%; for a maximum stress of about 1.5 MPa, the permanent set was 1.05%.

Figure 8 shows the stress relaxation curves for plain silicone and three composites of different filler volume fractions at a constant strain of 6.0%. There was no stress relaxation up to seven days except for the composite with the highest filler content; i.e., 8.3 vol.% Cu and 1.5 vol.% Sn-Pb.

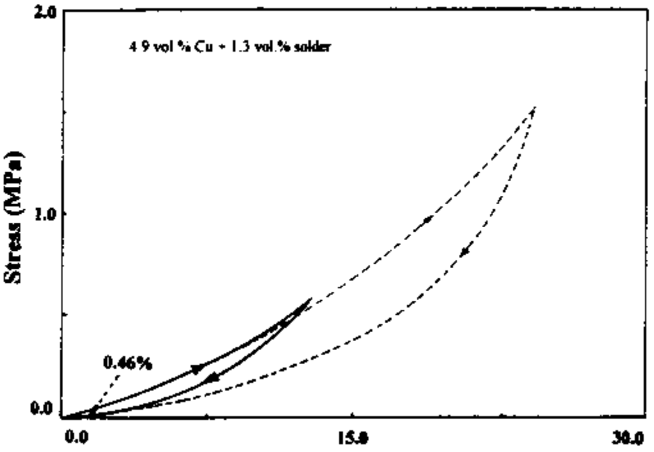

Fig. 6. Compressive stress-strain curves during loading and unloading for different maximum stresses. Only the higher maximum stress gave a nonzero permanent set.

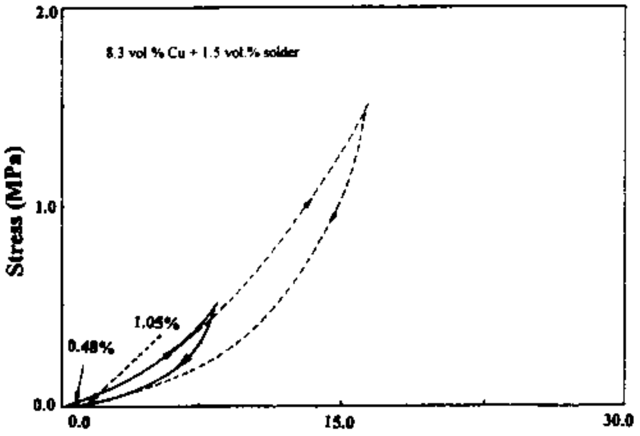

Fig. 7. Compressive stress-strain curves during loading and unloading for different maximum stresses. Only the higher maximum stress gave a nonzero permanent set.

Table III. Effect of Heating* on the Contact Resistivity of Composites

Total Filler vol.%	Cu vol.%	Sn-Pb vol.%	Minimum Contact (Resistivity mΩcm²)		Pressure Required to Reach the Minimum Contact Resistivity (kPa)	
			Before Heating	After Heating	Before Heating	After Heating
6.1	4.9	1.2	17.4	18.4	32	32
7.9	6.7	1.2	15.8	16.7	33	33
9.8	8.3	1.5	11.9	12.3	35	35

*In air at 130–150°C for seven days.

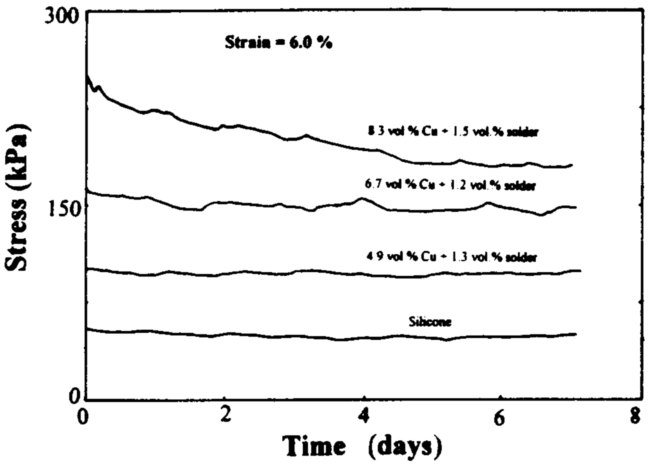

Fig. 8. Stress relaxation curves at a constant strain of 6.0% for different filler volume fractions.

Table IV. Comparison of the Electrical Properties of Spiral Sping and C-Shaped Spring Composites

Springs	Total Filler vol.%	Vol. Resistivity (mΩ.cm)	Min. Contact Resistivity (mΩ.cm²)	Pressure Req. to Reach Min. Contact Resistivity (kPa)
Spiral	6.0 (3.1% Cu+ 2.9% Sn-Pb)	0.535/ 0.536*	16.5	35
C-shaped	6.1 (4.9% Cu+ 1.2% Sn-Pb)	1.047/ 1.322*	17.5	32

*After heating in air at 130–150°C for seven days.

Comparison of the Electrical Properties of Composites with C-shaped Springs and those with Spiral Springs

The composites with C-shaped springs and those with spiral springs of the same wire diameter are compared in Table IV in terms of the volume and contact resistivities. The composites compared had about the same total filler volume fraction. The proportion of Sn-Pb in the preform was higher in the spiral spring composite than the C-shaped spring composite. This is because of the tendency for Sn-Pb to gather in the space between the adjacent nearly parallel spirals of the spiral springs. The volume resistivity was lower for the spiral spring composite than the C-shaped spring composite. The effect of heating on the volume resistivity was smaller for the spiral spring composite. The minimum contact resistivity and the pressure required to reach the minimum contact resistivity were similar for the two kinds of composites.

Lower Limit of Composite Size

In order to approach the lower limit of the composite size, C-shaped springs were fabricated from Cu wires of diameter 12.7 μm (0.0005 in). A composite of diameter 1.4 mm was successfully made using these springs. The lower limit of the composite diameter is, therefore, below 1.4 mm.

DISCUSSION

The lower volume resistivity of the sprial spring composite compared to the C-shaped spring composite is due to the more perfect three-dimensional interconnection of the springs in the former. More perfect three-dimensional interconnection occurred in the spiral spring case because of the large length of each spiral spring and the higher Sn-Pb volume fraction in the spiral spring composites. The superior resistance to heat degradation of the spiral spring composite is related to the higher proportion of Sn-Pb in this type of composite. Although a higher Sn-Pb volume fraction is desirable for a low resistivity and good oxidation resistance, it is detrimental to the resilience of the composite. The Sn-Pb volume fraction has not yet been optimized in this work. The Sn-Pb served as a coating to protect the Cu springs from oxidation. In spite of these differences, both spiral spring and C-shaped spring composites exhibited properties that are acceptable for applications. The advantage of the C-shaped spring composites lies on its lower composite size limit, which is important for electronic applications.

The compressive stress needed to reach the minimum contact resistivity was 32–35 kPa (Table III and Fig. 4), whereas a compressive stress >0.6 MPa (Figs. 6 and 7) was needed to cause a nonzero permanent set in the C-shaped spring composite with 4.9 vol.% Cu and 1.3 vol.% Sn-Pb. Thus, a stress level less than 0.6 MPa is required for the use of the composite as a separable interconnection material, such that the composite exhibits no permanent set.

In order to avoid stress relaxation, the filler content should be below 8 vol.% Cu + 1.5 vol.% Sn-Pb (Fig. 8). However, a higher filler content yields a lower volume resistivity (Table I). Therefore, a filler content of 6.7 vol.% Cu + 1.2 vol.% Sn-Pb is near the optimum. The stress required for obtaining the minimum contact resistivity is only around 35 kPa (Table III and Fig. 4), whereas the stress levels used in stress relaxation tests were above 80 kPa. It is expected that the composites will have better stress relaxation resistance when a lower stress level is applied.

The solder-copper joint strength is above 5 MPa,[6] which is much higher than the contacting pressure requirement of 35 kPa of the composite of this work. Therefore, the C-shaped spring network involving solder is expected to be reliable during usage and the electrical resistivity is expected to be stable as well.

The fabrication of the C-shaped springs can be automated, so that the springs are produced inexpensively. Compared to a composite with silver particles, the C-shaped spring composite is less expensive due to the low filler content and the low filler cost.

CONCLUSION

Resilient metal spring silicone-matrix conducting composites for solderless interconnections in electronics were fabricated by the impregnation of silicone resin into a preform comprising randomly oriented C-shaped metal (Cu-Be) springs and a small proportion of solder (Sn-Pb), which served to connect the springs at some of their intersections. Composites containing 6.1–9.8 vol.% total filler exhibited volume resistivity in the range 0.5–1.0 mΩ.cm (0.7–1.3 mΩ.cm after heating in air at 130–150°C for seven days) and contact resistivity (with copper) in the range 11–17 mΩ.cm^2. A compressive stress of about 30 kPa was needed for the contact resistivity to level off to values in the above range. To cause a nonzero permanent set, the compressive stress had to exceed 0.6 MPa. The stress re-laxation up to seven days at a constant compressive strain of 6.0% was zero if the total filler volume fraction was below 9.8 vol.%. The optimum filler content was roughly 7.9 vol.% total filler; i.e., 6.7 vol.% Cu + 1.2 vol.% Sn-Pb.

ACKNOWLEDGMENTS

This work was supported by the Defense Advanced Research Projects Agency of the U.S. Department of Defense and the Center for Electronic and Electro-Optic Materials of the State University of New York at Buffalo.

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