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Characterization of Electrodeposited Copper for Dynamic Flex Applications (Part 1)

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Data presented shows that electrodeposited copper from a standard production PCB bath has fatigue performance comparable to rolled-annealed copper in low-strain/high-cycle dynamic flex applications. The influence of the electroplated seed copper layer used in the construction of circuits based on Sheldahl's adhesiveless Novaclad® technology is also examined. The comparative fatigue performance of unsupported copper foils is studied by applying the Coffin-Manson relationship to fatigue-ductility data; Weibull analysis is used to compare the fatigue performance of test circuits in fatigue-ductility and rolling flex testing.

Adhesive-based circuit constructions using rolled-annealed (RA) copper have been preferred for low-strain/high-cycle, dynamic flex applications such as disk drive voice-coil circuits. Adhesive-based circuit constructions incorporating the electrodeposited (ED) copper foils more typically used in the manufacture of rigid laminate for hard-board printed circuits were known to have very poor flex life. This type of ED copper is characterized by columnar grain morphology with grain boundaries extending from the base to the surface of the foil. These boundaries have very low resistance to crack propagation. On the surface, the intersections of grain boundaries act as stress concentrators. Flexible circuits made with this type of ED copper fatigues readily and the resulting cracks easily follow the grain boundaries through the circuit trace, creating high resistance or open circuit.

Adhesiveless constructions use electroplated copper to build up circuitry, either by semi-additive pattern plating or panel plating followed by a print-and-etch step. The electrolytes used are similar and often identical to those used in rigid-board copper plating. The deposits from these electrolytes are typically very fine-grained, with good tensile strength and reasonable elongation. The additive systems were formulated to provide superior mechanical properties in plated-through holes, as well as uniform plating thickness in the holes and on the board surface.

The poor performance of rigid-laminate ED foil is often extrapolated to the performance expected from electroplated printed circuit copper. This paper will attempt to show that electroplated copper for printed circuits performs comparably to RA copper in low-strain/high-cycle, dynamic flex applications.

Experimental

Three different 5-µm seed coppers were plated on a standard G2200 Novaclad base. The coppers were plated from standard acid copper sulfate electrolytes; the additive systems were Shipley Ronal products currently used in production (see Table 1).

The seed copper was panel plated up to 17–20 µm in the production roll-to-roll process. The copper chemistry used was a standard acid copper sulfate electrolyte, using the additive system B. Copper foil was produced by masking one side of the material, etching copper off the other side, followed by stripping of the polyimide film and etching of the tie-coat layer. A sample of Rogers **R/flex®** RA copper was used for comparison.

The average copper foil thickness is given in Table 2. This table also contains relative strain values ($\%\Delta\varepsilon/2$) of the foils over a 0.375-in mandrel (calculated from the average copper thickness values). This data was used in the Weibull analysis of fatigue-ductility data for the foils.

Pattern plate circuits were also made from the three seed plated Novaclad samples. Copper was pattern plated to 17–20 µm total copper thickness in the same roll-to-roll process used for panel plating. The pattern included test circuits based on a rolling flex test coupon design supplied by Rogers Corporation. Adhesive-based, print-and-etch circuits using **R/flex** RA copper foil were made for comparison.

Table 1. Additive Systems

Designation	Copper Additive
Prototype 1	A
Prototype 2	B
Prototype 3	C

Table 2. Average Copper Foil Thickness

	Copper Thickness	$\%\Delta\varepsilon/2$ 0.375-in Mandrel
Prototype 1	15.7 µ	0.165%
Prototype 2	17.9 µ	0.188%
Prototype 3	16.5 µ	0.173%
RA Copper	17.0 µ	0.178%

The foils were cut into 0.125-in strips in the machine direction (rolling direction for the RA foil). The foil strips were tested on a Universal Mfg. fatigue-ductility tester over several different mandrel diameters: 0.040-in, 0.078-in, 0.125-in, 0.0250-in, 0.375-in, 0.500-in, and 0.750-in. An 84-g weight was used to provide tension for the test and the test frequency was 1 Hz. The strips were tested to failure with the number of cycles recorded.

Test circuits from the pattern plate runs and the adhesive-based print-and-etch run were sent to Rogers for rolling flex testing. The test was set up to roll the test circuit in a 0.125-in gap at approximately 20 Hz until failure. The bend radius of the circuits in this test was 0.625-in; the circuits were tested with the coverlay on the inside of the bend. The gap distance is the standard distance used at Rogers for rolling flex testing. For adhesive-based RA copper test coupons, this gap allows for collection of 10^6–10^7 cycles in a reasonable amount of time.

Additional test circuits from each run were flexed to failure on the fatigue-ductility tester using a 0.125-in mandrel at a rate of 1 Hz. This mandrel size was chosen so the relative strain would be the same as that experienced in the rolling flex test.

Result and Discussion

Coffin-Manson Relationship

The number of flex cycles that a circuit can tolerate is generally considered to be a measure of the circuit copper's resistance to fatigue damage, and depends in large part on an inverse relationship with strain amplitude, $\Delta\varepsilon$. Fatigue-ductility testing involves a reversible flexing over a mandrel of fixed diameter and thus the relative strain over one full cycle is represented by $\Delta\varepsilon/2$.

Fatigue of copper in a flex application is characterized by two distinct strain components. One is plastic deformation, which occurs during high-strain/low-cycle flexing; the other is elastic deformation, which occurs during low-strain/high-cycle flexing. The region of elastic deformation is also considered as the dynamic region. The total strain is simply the sum of these two components:

$$\Delta\varepsilon = \Delta\varepsilon_{plastic} + \Delta\varepsilon_{elastic}$$

The Coffin-Manson equation relates fatigue life to strain amplitude:

$$\frac{\Delta\varepsilon}{2} = \varepsilon_f' (2N_f)^c + \frac{\sigma_f'}{E} (2N_f)^b$$

Where:

$2N_f$	is the number of strain reversals
E	is Young's modulus
ε_f	is related to ductility
σ_f	is related to tensile strength

In the high-strain/low-cycle region of the curve, the first term predominates, and fatigue performance is a function of ductility. This generally favors RA copper, which typically has higher ductility than electroplated copper. Conversely, in the low-strain/high-cycle region, the second term predominates, and fatigue performance is a function of tensile strength. The bias shifts to electroplated copper, which typically has higher tensile strength than RA copper. As the relative strain amplitude decreases and the number of cycles-to-failure increases, a transition from plastic deformation to elastic deformation occurs. This transition was observed to occur around 10^4–10^5 cycles for unsupported copper foil specimens (Figure 1). This is in general agreement with data published by Gould Electronics for electrodeposited and rolled-annealed foils.

The circuit construction itself (the base laminate, adhesive(s) and coverlay) can add two to three orders of magnitude to the flex life of the copper. While this effect isn't entirely understood, it is believed that the supporting circuit construction may provide a means of crack arrestment.

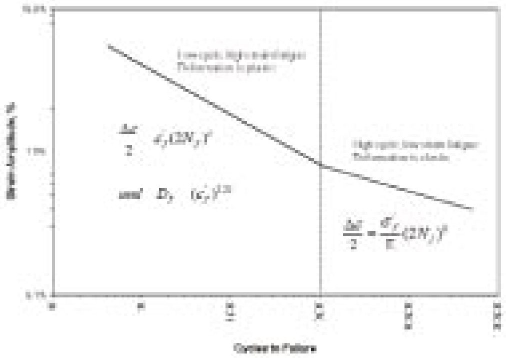

Figure 1. Coffin-Manson Plot

Figure 2 shows a comparison of fatigue-ductility data for copper foils stripped from the prototype circuit builds, along with data from an RA copper foil control. Each point represents an average of at least two high-cycle or three low-cycle values.

All three curves show reasonable agreement with the Coffin-Manson relationship. Prototypes 1 and 2 have nearly identical curves; the curves of Prototype 3 and the RA foil control are very similar in the high-strain/low-cycle region of the plot. The RA copper foil exhibits the smallest slope change when the deformation changes from an elastic-dominated to plastic-dominated mode. The foils from Prototypes 1 and 2, and the RA copper control have inflection points around 50,000 cycles; the foil from Prototype 3 has an inflection point shifted out to around 300,000 cycles. A definitive explanation for this shift will be somewhat elusive without a more detailed study. On the surface it appears that the Prototype 3 foil has a broader plastic region.

In the high-strain/low-cycle region of the curves, Prototypes 1 and 2 appear to have slightly lower cycles-to-failure for a given strain amplitude. Prototype 3 and the RA foil control have very similar performance in this region. In the low-strain/high-cycle or dynamic region, the curves converge near a relative strain amplitude of about 0.09%, which corresponds closely to a 0.750-in mandrel and approximately 3–10^6 cycles to failure. Data was not collected for mandrels larger than 0.750-in because of the extended time required at 1 Hz. Thus, it is not known if the Coffin-Manson relationship holds for strain amplitudes lower than 0.09% (mandrel sizes larger than 0.750-in). ●

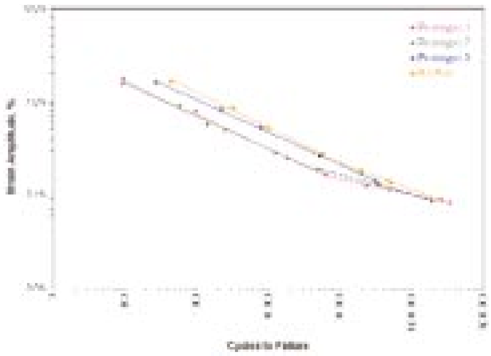

Figure 2. Cyclic Fatigue of Electrodeposited Copper Foils (Coffin-Manson Plot)

This ends Part 1 of 2 for Characterization of Electrodeposited Copper for Dynamic Flex Applications (by Charlie Hayes—Sheldahl Research & Development Group). Look for Part 2, scheduled to appear in the March/April 2001 issue of INSIGHT.

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