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what's inside

Characterization of Electrodeposited Copper for Dynamic Flex Applications (Part 2)

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This is the second half of a 2-part series, wherein Part 1 was published in the January/February 2001 issue of INSIGHT. If you missed that issue, you may download an electronic copy (in PDF format) from the IDEMA Website at www.idema.org (INSIGHT/Back Issues—pdf files).

Weibull Analysis

The Weibull distribution is one of the more useful density functions for the analysis of reliability data. It can be used on very small data sets and has the flexibility to be widely applicable to many reliability problems.

The Weibull probability density function is generally defined as follows:

$$f(t) = \frac{\beta(t-\delta)^{\beta-1}}{\theta^{\beta}} \, exp\left[-\left(\frac{t-\delta}{\theta}\right)^{\beta}\right], \quad \underline{t} > \delta$$

However, the Weibull cumulative distribution function can be manipulated to yield a more useful relationship:

$$\ln\left[\ln\left(\frac{1}{1-F(t)}\right)\right] = \beta\ln(t) - \beta\ln\theta$$

The function is now in the form $y = mx + b$, the equation for a straight line. The left-hand term is the dependent variable y, ln(t) is the independent variable x, β is the slope m, and $-\beta\ln\theta$ is the y-intercept b.

The fatigue-ductility and rolling flex test data was collected at fixed frequencies and the specimens were cycled to failure. Thus, either time-to-failure or cycles-to-failure data can be used for t. Since we are generally more interested in the number of cycles a flex circuit can endure before failure, cycles-to-failure data was used in the Weibull calculations.

Fatigue-ductility testing of the unsupported copper foils was conducted using a 0.375-in mandrel. This mandrel size was chosen because it gives a relative strain in the transition zone from elastic deformation to plastic deformation. In this region, both terms of the Coffin-Manson equation contribute to the fatigue performance of the copper foil, and any strong bias for either foil type (RA versus electroplated) should be at a minimum.

Figure 3 shows a composite Weibull plot of the three prototype copper foils and the RA foil control. All four plots have $\beta > 1$, which is consistent with a fatigue failure. The variable quality of the line fit plots is noticeable in this composite graph. The tails of the Prototype 3 and RA copper plots seem to suggest that $\delta \neq 0$. Without the influence of the two highest cycles-to-failure points (highest ln(t) values), the RA copper plot would have a β closer to the β values of the Prototype 1 and 2 plots. The Prototype 3 plot seems to contain separate distributions that would yield similar β values. Explanations for this behavior are not readily apparent.

Figure 3 does seem to show what appear to be differences in performance of the four copper foils. Subtle differences in the positions of the plots are likely due to the slight variation in relative strains (see Table 2). However, the relative position of the copper foil Weibull plots with respect to each other is consistent with the relative position of their Coffin-Manson plots, at least for Weibull data collected over a 0.375-in mandrel.

continued on page 36

Table 2. Average Copper Foil Thickness

	Copper Thickness	%Δε/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%

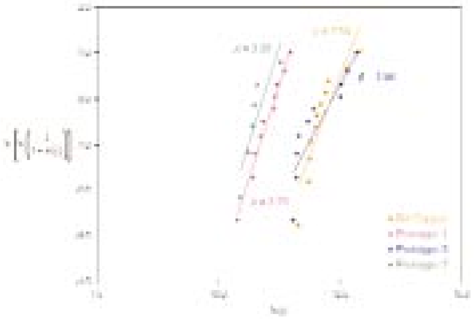

Figure 3. Fatigue-Ductility of Copper Foil (Weibull Plots, 0.375-in Mandrel).

continued from page 34

Figure 4 shows Weibull plots for fatigue-ductility testing of the Rogers rolling flex test circuits. The line fits for all four plots are much better than those observed for the unsupported foils. The values for the shape parameters are all greater than 1, which should be expected for fatigue failures. The plot for the adhesive-based, RA copper circuits has a β value similar to the RA copper foil plot. The plots of the three prototype circuit builds have higher β values than their corresponding foil plots. This suggests that the range of cycles-to-failure for the prototype circuits is narrower than the range for the RA copper circuits. It also seems to suggest that the circuit construction may be exerting an influence on the failure.

The position of the prototype circuit plots relative to the RA copper circuit plot is not consistent with the relative positions of the foil plots. Specifically, while the Prototype 3 foil yielded similar fatigue-ductility performance to the RA copper foil, the Prototype 3 test circuits did not match the performance of the RA copper circuits. This seems to reinforce the idea that the circuit construction is influencing the fatigue-ductility performance of the copper.

Fatigue-ductility failure for the prototype and RA copper starts with series of cracks developing as the copper fatigues. Eventually, at least one crack propagates completely through the trace, creating an open circuit. Alternatively, numerous cracks will reduce the effective conductor width, creating high enough resistance to cause the circuit to fail without an actual open circuit being created.

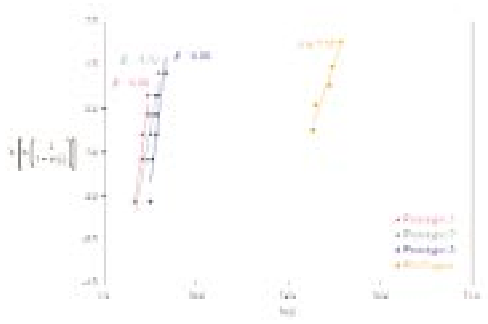

Figure 4. Fatigue-Ductility of Copper Test Circuits (Weibull Plots, 0.125-in Mandrel).

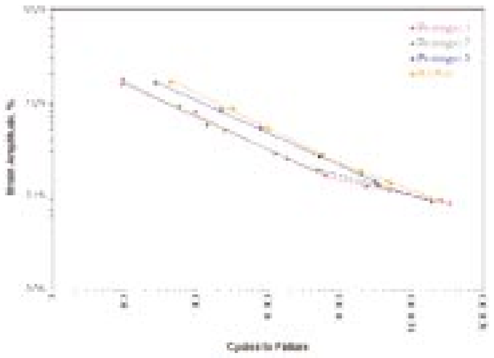

Figure 5. Rolling Flex of Copper Test Circuits (Weibull Plots, 0.125-in Plate Gap).

For a given relative strain, fatigue-ductility testing is believed to be more aggressive than rolling flex testing. This is because fatigue-ductility testing is a bi-directional or reversible flex, while rolling flex testing is uni-directional. Figure 5 shows Weibull plots of the rolling flex test data. The plots for Prototypes 1 and 2 and the RA copper have reasonable line fits and β values consistent with fatigue failures. The RA copper β is nearly identical to the RA copper β from the fatigue-ductility Weibull plot; the β values for Prototypes 1 and 2 are closer to the β values for their corresponding foils than they are to the β values from their fatigue-ductility plots.

The RA copper plot in Figure 5 is shifted to higher cycles-to-failure (higher ln(t) values) compared to its fatigue-ductility plot. This is consistent with the belief that rolling flex testing is a less aggressive fatigue test. The cycles-to-failure of Prototypes 1 and 2 are very nearly the same in fatigue-ductility and rolling flex testing, a contradiction to the above statement. Again, this may indicate a strong influence exerted by the circuit construction on fatigue performance of the copper.

The plot of Prototype 3 is very unusual. A $\beta < 1$ suggests infant mortality, which would seem to imply inadequate or defective materials. However, the adhesive and coverlay used in the construction of all three prototypes was from the same lot of materials. In addition, all three prototypes were laminated in the same press run. An explanation for the anomalous behavior of Prototype 3 in the rolling flex testing is not readily apparent.

The failure mode for all circuits in the rolling flex test was catastrophic separation of the test circuit into two parts. All failures were accompanied by some delamination of the coverlay. The prototype circuit builds generally exhibited more coverlay delamination and more severe copper fracturing than the RA copper circuits. In fact, the copper traces on the RA copper circuit failure did not show cracks on either side of the coverlay delamination boundary. The only crack appears to be the catastrophic failure line. In addition, the delamination boundary appears cleaner, with virtually no visible adhesive residue left behind. It is not known what significance these observations may have.

Conclusions and Recommendations

Evidence has been presented that 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. This is not wholly unexpected, as electroplated PCB copper tends to have higher tensile strength than rolled-annealed copper. According to the Coffin-Manson relationship, tensile strength is the dominant factor in low-strain/high-cycle fatigue performance.

There is some evidence that the seed plate from the additive C chemistry may be exerting a positive influence on the high-strain/low-cycle fatigue performance of the Prototype 3 copper foil. This influence does not appear to carry over into the dynamic flex range. However, where all three prototype copper foils exhibit similar performance in fatigue-ductility testing, the influence of the seed plate on the overall fatigue performance of a copper circuit is an area requiring further investigation.

The Weibull analysis of fatigue-ductility data from testing copper circuits gave predictable results. The failure mode observed was consistent with the generally accepted theory of copper circuit fatigue failures. It would be interesting to apply the Coffin-Manson relationship to test circuits. However, the time required to collect sufficient data in the dynamic range is prohibitive at 1 Hz. Efforts to speed up collection of this data will be undertaken.

The rolling flex test data is somewhat suspect. The anomalous behavior of Prototype 3 remains unexplained. The catastrophic nature of the failures is another concern, bringing into question the circuit construction as well as the test method itself. It is not well understood how the mechanical performances of the base film, coverlay, and adhesive behave in a high-strain, rolling flex test. It would be desirable to expand this type of testing to different relative strains (gap widths) and test circuit orientation (coverlay on the outside of the radius). Even at 20 Hz, the rolling flex test suffers from excessive data collection times at gap widths in the dynamic strain region.

Additional testing should be performed to expand the data set already collected. It would be interesting to know how easy it is to manipulate copper-deposit properties in production and thus affect mechanical performance. It would also be beneficial to understand how the copper-deposit properties vary over time as a production plating bath ages. Concurrently, the impact of circuit materials (material properties, circuit thickness, boundary adhesion, etc.) on overall dynamic flex performance needs to be better understood. Along with this is a need to understand how dynamic flex performance is affected during circuit manufacturing, principally the lamination process. ●

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