Strain Controlled Mechanical Fatigue of Thin Copper Foil and Flexible Circuit

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Four modes of strain controlled flex fatigue tests are recognized: (i) bending (Bendability Test), (ii) folding (MIT Test), (iii) flexing (Bell Flex Test) and (iv) rolling through a constant gap (Roll Flex Test). For test (i), appearance of surface cracks (or a single fatal crack) is monitored after single or multiple high strain bend(s); for test (ii) – (iv), electrical resistance is monitored to determine fatigue life (N_f) that is, number of fatigue cycles to failure, defined by abrupt rise in resistance. N_f depends upon bend radius or specifically upon strain per cycle ($\Delta\epsilon/2$). For test (ii) and (iii), a plot of $\Delta\epsilon/2$ versus $2N_f$ (Coffin-Manson plot) characterizes the flex fatigue behavior in the low cycle (plastic) and high cycle (elastic) regimes. Test (iv) specifically mimics the disc drive motion whereby the flexible circuit is "rolled" back and forth at high speeds (as high as 15 to 40 Hz) through a gap (constant $\Delta\epsilon$) 3 mm or wider. Here, N_f can be as large as 10^8 and is prone to a large scatter; as many as sixty samples are simultaneously tested and failure statistics are developed for a particular PI/Cu/PI construction. Examples of rolled and electrodeposited foils, Cu/PI laminate and PI/Cu/PI flexible circuit construction in fatigue tests (i) – (iv) are provided.

Introduction

Flexible circuits during processing or manufacture are often subjected to a single or repetitive forming operation, whereby relatively large strain is localized in a small region of the circuit.[1] During service, the circuit may be subjected to stress or strain controlled cyclic motion or fatigue; examples are

(i) vibrating motion in aircraft or automobile
(ii) occasional reversible movements in cell phone or camera
(iii) relatively high strain amplitude fatigue in wrist watch or printer, and
(iv) very high speed, low strain amplitude alternating "rolling" motion through a gap in a disc drive.

The fatigue tests are conducted

a) to characterize the suitability of a given circuit design (thickness, line spacing/width) or material (substrate, conductor, adhesive, coverlayer) for a particular application such as disc drive or printer,
b) or to generalize the fatigue performance in tension/compression or bending/unbending over a large range of stress or strain amplitudes.

The fatigue life (number of cycles to failure, N_f) depends inversely upon the stress or strain amplitude per cycle ($\Delta\sigma/2$ or $\Delta\epsilon/2$). For the strain-controlled fatigue test, a linear inverse relationship (Coffin-Manson plot) between $2N_f$ and strain amplitude per cycle ($\Delta\epsilon/2$) on a logarithmic scale confirms the statistical nature of fatigue. Low cycle, high amplitude fatigue test is highly reproducible, the individual N_f readings are within a few percent of one another. High cycle, low amplitude fatigue test, however, generates considerable scatter between individual N_f readings; a statistical analysis of large number of N_f readings for a given test condition becomes essential.

Fatigue Testers

Using uniaxial servo-hydraulic tester, the stress-controlled fatigue tests in tension/tension[2, 3] or tension-compression [4,5] modes have been conducted for thin copper foil; for the latter test, the foil sample is mounted on a rigid steel substrate which in turn is subjected to cyclic stress. This type of test yields fundamental information on initiation and growth of fatigue induced cracks; its use for copper foil has been limited to only a few studies, some of which are cited above. The flexible circuits have not been tested in uniaxial fatigue mode.

Three strain-controlled bending/unbending fatigue tests, where resistance probes monitor electrical continuity of the sample, are available. A sudden order of magnitude rise in electrical resistance terminates the test, defining N_f. The available tests are described below:

(i) **MIT Fold Fatigue Test** [6] mimics printer hinge motion. A sample is cyclically folded 135° over a bend radius (a rotating spindle with curvature) at 3Hz; a small tensile load aids accurate conformation of sample surface over the curvature. Using a range of bend radii, Coffin-Manson (C-M) plot can be generated. [7] The

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a large range of stress or strain amplitudes

(i) – (iii) are provided in previous papers [11, 12, 20] and hence are not repeated here.

(i) Bell Flex Fatigue

Table 1 and Figures 1 to 4 show the tabulated data and C-M plots respectively for the 12 μm ED DF and R GR foils in the as rolled/as deposited and annealed (180°C, 30 mins.) conditions for the longitudinal (L) and transverse (T) orientations. The fatigue ductility parameter D_f (which corresponds to intercept at $2N_f = 1$ on low-cycle C-M plot), [21, 22] calculated by iteration, [23] is presented in Table 1. Heavy rolling related texturing of R foil results in considerable L/T anisotropy of D_f (Table 1), as well of N_f, in the low cycle regime (Figure 1). For the results following anneal exposure and for high cycle fatigue, the anisotropy is diminished or disappears altogether for both R and DF foils.

For the R foil, in spite of low tensile elongation (which in the as rolled state borders on brittleness), D_f is exceptionally high due to its heavy rolling reduction and considerable anneal softening. By comparison, DF foil resists

Table 1
Mechanical and Fatigue Properties of 12μm GR8 and DF Foil

	DF				GR8			
	LD		TD		LD		TD	
	AR	Ann	AR	Ann	AR	Ann	AR	Ann
UTS (KSI)	73	69	71	58	63	31	51	25
Peak Elongation (%)	3.8	3.6	4.4	4.6	1.2	9.8	0.6	5.6
Total Elongation (%)	12.2	11.3	7.9	5.4	1.2	10.3	0.6	5.9
N_f :31mil	134	150	81	76	174	91	26	57
:40	257	255	144	137	2736	327	73	124
:52	487	608	288	291	18417	889	93	272
:62	798	815	463	451	31395	3160	232	475
D_f (%)	36	38	24	25	56	94	24	47

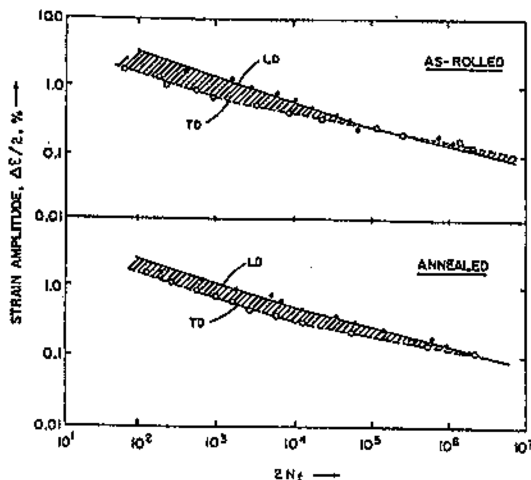

Figure 1: Coffin-Manson Plot for 12μm Rolled Foil in Bell Flex Fatigue (Anneal = 180°C., 30 mins., LD = Longitudinal Orientation, TD = Transverse Orientation)

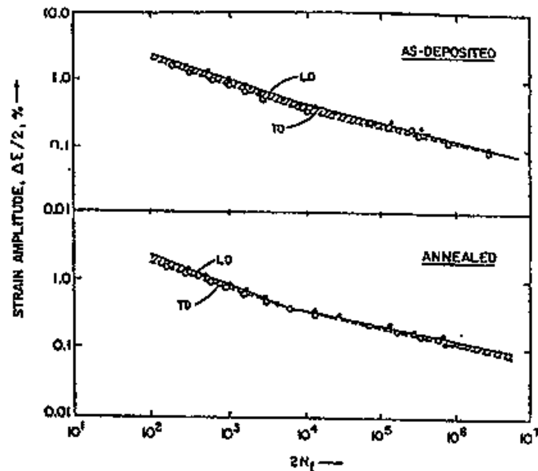

Figure 2: Coffin-Manson Plot for 12μm Electrodeposited DF in Bell Flex Fatigue (Anneal = 180°C., 30 mins., LD = Longitudinal Orientation, TD = Transverse Orientation)

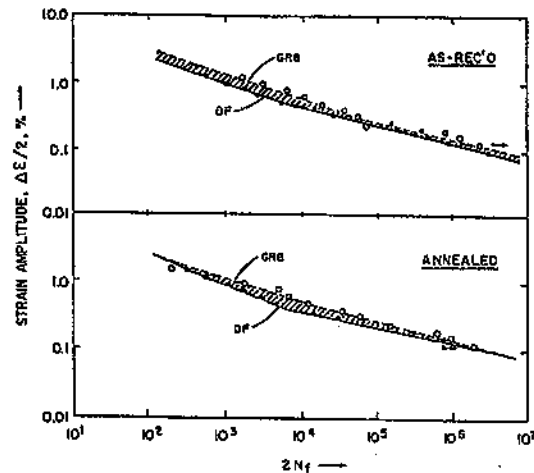

Figure 3: Comparison of 12μm Rolled GR8 and Electrodeposited DF Foils in Longitudinal Orientation in Bell Flex Fatigue.

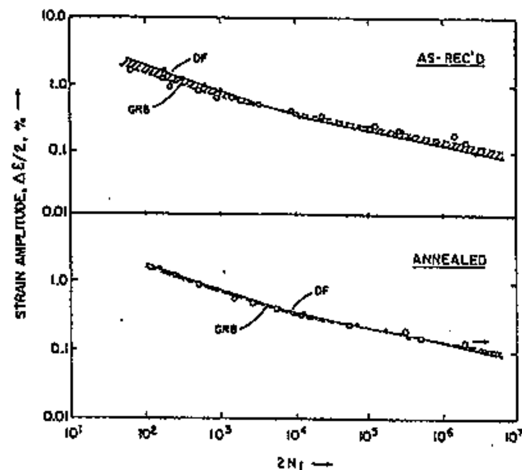

Figure 4: Comparison of 12μm Rolled GR8 and Electrodeposited DF Foils in Transverse Orientation in Bell Flex Fatigue.

Drift of data points from linearity and clustering of points in the high failure rate regime for runs 5 and 6 are apparent. These runs incorporated material changes in the adhesive and substrate types but the circuit design was left unaltered. Figure 6a shows that the results for DF foil based circuit fall within a band which is somewhat right to the single run data for the R foil circuit. The 95% confidence limits are shown in Figure 7 for the DF (7b) and R (7c) foils as well as for the DF and R foils without data points (7a). It is apparent that for the DF foil runs 4, 5 and 6, the data falls within the 95% confidence band for run 5; further, the upper band limit for runs 4, 5, 6 falls within 95% confidence limits for the R foil. Additional runs for R foil based circuit are currently under investigation so that a fairer comparison between the 18 μm DF and R foil based circuits can be ascertained.

Bendability and Springback

The bend test was conducted for circuitized copper alone, for circuitized Cu/PI laminate (copper plateup on polyimide) and for Cu/PI/Adh/PI flexible circuit for up to five successive 180° bends applying pure bending moment according to the procedure outlined in our previous study.[20] No copper conductor damage was observed visually, in optical microscopy (up to 1000x magnification) or in SEM (up to 10,000 x magnification). Occasional very fine scaled surface upheaval was observed for the Cu/PI laminate, usually a dimple at 5000x or higher but no microscopic cracking was encountered on the bent copper surface. Likewise, no damage or thinning was discerned in cross-section microscopy. The electrical resistance of the circuit, irrespective of line spacing/width, remained unaltered after bending.

Apparently, very close vicinity of the sample surface to the neutral surface of the bend (about 2.5 and 5μm for 5 and 10μm Cu plateups) respectively precluded mechanical or electrical damage to the conductor, even after repeated severe bending, since the plated copper has considerable inherent ductility. In view of the mechanical fragility of circuitized copper, superposition of tensile stress or torque on bending moment would have induced fracture damage; however, this type of complex bending, often present in practice,[1] was not attempted.

The springback after bending was monitored after each bend. The springback is due to relaxation of elastic component of residual stresses generated by bending;[24] it can be reduced to an extent by bending under tension.[25] Furthermore, it is noteworthy that the polyimide film alone is highly elastic and shows 100% springback after repeated bending. The extent of springback for Cu, PI/Cu and Cu/PI/Adh/PI is summarized in Figure 8 (where for clarity of presentation the data points are not shown).

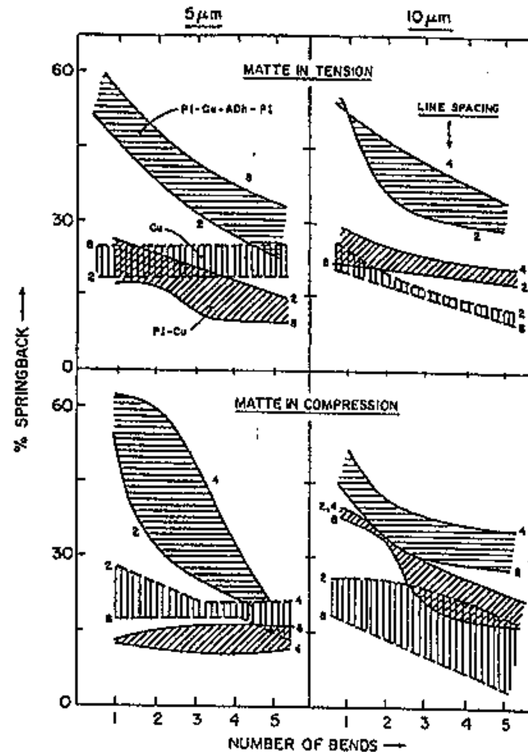

Figure 8: Effect of Number of 180° Bends on Springback of 2 mil, 4 mil, 8 mil line Spacing/Width Circuitized Cu, Circuitized Laminate PI – Cu and Flexible Circuit PI – Cu – Adh – PI.

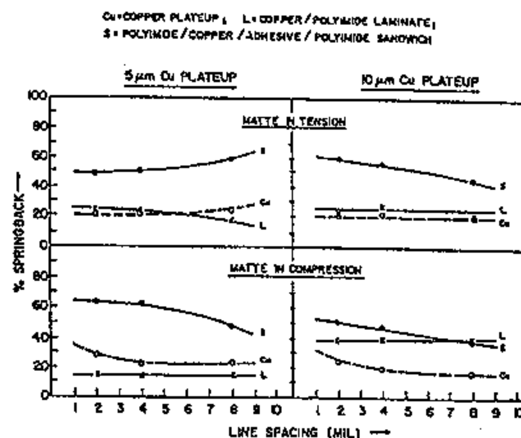

Figure 9: Effect of Line Spacing on Springback after One Bend for Circuitized Cu, Circuitized Laminate PI / Cu and Flexible Circuit PI / Cu / Adh / PI.

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