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Elastoplastic and fatigue properties of copper in printed circuit boards: from experimental characterization to numerical simulations

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Abstract

In operation, a Printed Circuit Board (PCB) will face various and repeated thermomechanical loadings that may lead to the failure of the copper, and thus to the malfunction of the PCB itself. In order to simulate and better predict the reliability of PCBs, the constitutive behavior of copper has to be defined. In the present work, a 17 μm rolled annealed copper film frequently used in the flexible PCB industry has been tested under a cyclic tensile-compressive loading. The copper has a low elastic limit and plastic deformation plays thus an important role during straining. Under cyclic loadings, a predominant kinematic hardening has been observed. The plastic behavior of the studied copper film has been identified with a Lemaitre-Chaboche hardening model. Next, an original experimental setup has been developed, allowing to measure the fatigue behavior of thin copper films under cyclic loadings. Tests with various loading amplitudes are carried out. A Coffin-Manson model has been adopted to reproduce the experimental data.

1. Introduction

A PCB is a multi-layer, multi-material structure and its reliability mainly depends on the interactions and incompatibilities between materials. A previous study (Girard et al. [1]) concentrated on the orthotropic behavior of laminates used in PCBs. In the present study, the focus is on copper, its elasto-plastic and fatigue behaviors. Different copper grades can be found in a PCB: electrodeposited, wrought or laminated copper, each having a different mechanical behavior. In this work, a 17.5 μm thick rolled annealed copper found on commercial flexible substrates is considered.

In the literature about PCBs, many authors focused on the fatigue of plated through hole (PTH) in multilayer PCBs. The mismatch in the coefficients of thermal expansion of copper and laminates, especially in the out-of plane direction, often lead to the breaking of copper. Some authors [2], [3], [4], [5], [6], [7] address this subject to evaluate the reliability of PTHs by the mean of finite element simulations. In [3], [4], [5], [6], the fatigue behavior of electrodeposited copper was studied by submitting PTHs to thermal loadings. But this method does not permit direct strain measurements and the link between strain and failure has to be carried out through the numerical simulation of a PCB.

Copper has a relatively low elastic limit and reliability tests on PCBs rarely last more than a few thousands of cycles. Hence it is very important to identify the plastic behavior of copper to model low-cycle fatigue. The mechanical behavior of copper in PTH studies is often considered as elastic perfectly plastic, or is identified based on a tensile test [2], [4]. Some studies have conducted tests on copper films [8], [9], [5], [10], [11] but none of them during cycles. However, copper exhibits kinematic hardening. Therefore, this behavior has been taken into account by Fellner et al. [6] or Fu et al. [12] for PTH studies. Fu et al. [12] used a model identified on wrought copper, whereas Fellner et al. [6] worked on a copper grade used in PCBs.

The model of Lemaitre-Chaboche [13] accounts for combined hardening (isotropic + kinematic) and is able to accurately reproduce the cyclic behavior of materials. It is widely used and several papers depict methods to identify parameters of the model [14], [15]. For instance, Mahmoudi et al. [16] proposed a multi objective Genetic Algorithm method to determine the parameters of Chaboche kinematic hardening model.

The fatigue behavior of copper films has also been widely studied in literature, see for example the works of Merchant et al. [17], [18], Simons et al. [19], Kraft et al. [20], [21], Hommel et al. [22] Schwaiger et al. [23], Ono et al. [24], Mönig et al. [25], Watanabe et al. [7]. They proposed different methods to apply cyclic loadings on the copper film, by using bending/reverse bending or by using a compliant substrate to support the film. A conclusion of these studies is the strong dependency of the stress and the low cycle fatigue to the film thickness and grain size.

Coffin [26] and Manson [27] independently proposed an empirical relation between the number of cycles to failure and the amplitude of applied strain. This relation holds for a number of cycles to failure usually smaller than 10000 and is still widely used to describe low cycle fatigue (LCF). The simplicity of the relation and its good precision in most cases explain that it is used in most of the articles about PTHs cited above.

2. Identification of the elastic-plastic behavior

The method used to apply a tensile-compressive loading on the 17 μm copper foil is exposed in this section. A precise material characterization is described, and the

experimental results are reproduced by the Lemaitre-Chaboche model [13].

Experimentally, it is impossible to apply a compressive loading on a thin foil without buckling. Therefore, a composite specimen, made of a compliant polyimide substrate with a copper film on both sides has been designed, as shown in Fig. 1. The specimen is cyclically loaded and unloaded in tension. The substrate is chosen so as to behave elastically, whereas the copper foils may develop plasticity. Copper will plastify during the loading stage. During the unloading stage, the substrate tends to recover its elastic strain, pushing the plastically deformed copper in compression. Owing to this method, tensile-compressive loadings can be applied on a copper film. The drawback is that only the mechanical response of the assembly can be measured. The mechanical response of the copper has to be obtained via an inverse analysis. A $75\ \mu\text{m}$ polyimide substrate with $17\ \mu\text{m}$ copper films on both sides has been chosen in our tests.

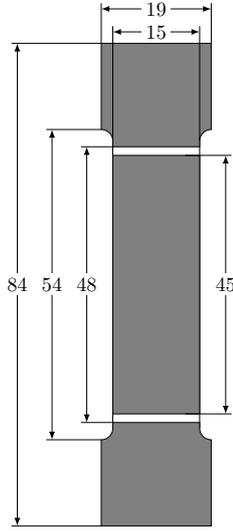


Figure 1: Layout of the specimen used for the identification of the elastic-plastic behavior of copper.

The elastic properties of the polyimide material have been determined from uniaxial tests performed at room temperature, with an Instron E3000 tensile machine (with a crosshead velocity of $2\ \text{mm}\ \text{min}^{-1}$). Samples of polyimide material are obtained from test specimens of Fig. 1 by etching copper on both faces. A speckle of spray-paint is applied on the samples so that Digital Image Correlation (DIC) technique is used to measure the longitudinal and transverse strains. Under tension, it has been checked that the polyimide substrate remains elastic when the longitudinal strain ε_{xx} is below 0.01. Subsequently, three samples have been tested below the elastic limit to measure the elastic moduli. The DIC results show homogeneous strains in the working area of the samples. The average measurements of the moduli over three samples are shown in Table 1. We assume that the substrate has an isotropic

elastic behavior for the considered strain amplitudes.

Young's modulus [GPa]	8.4	± 0.2
Poisson's ratio [-]	0.28	± 0.01

Table 1: Elastic moduli measured on the substrate at room temperature.

Next, samples of Fig. 1 are facing 100 cycles between 10 N and 130 N with a crosshead speed of $2\ \text{mm}\ \text{min}^{-1}$. The maximum force value generates a strain of approximately $\varepsilon_{xx} = 0.01$, corresponding to the upper limit of the elastic range of the substrate. The lower load value is positive in order to avoid buckling of the sample. The in-plane strains are measured by DIC, in the same way as for the substrate material. The experimental response of the substrate + copper sample is shown on Fig. 2 for the first and 100th cycles. A clear hysteresis loop is still visible after 100 cycles, close to stabilization. This is a clear effect of the kinematic hardening of the copper.

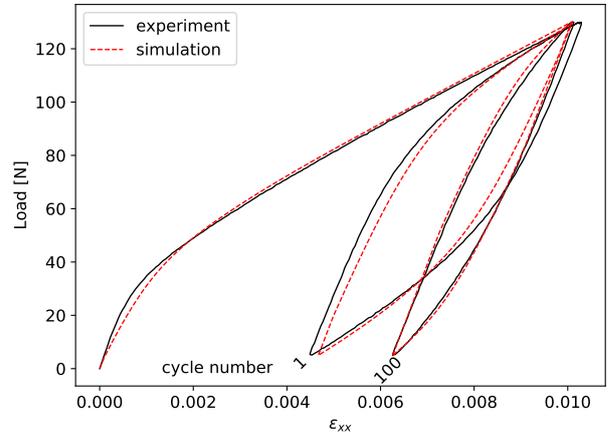


Figure 2: Comparison of experimental and simulated cyclic response after identification of the considered copper. The force versus longitudinal strain during the first and 100th cycles is plotted.

As copper presents clearly a combined isotropic and kinematic hardening in Fig. 2, the Lemaitre-Chaboche model [13] is adopted to model its elastic-plastic response. The total strain rate tensor $\dot{\varepsilon}$ is the sum of an elastic $\dot{\varepsilon}^e$ and a plastic $\dot{\varepsilon}^p$ strain rate tensors:

$$\dot{\varepsilon} = \dot{\varepsilon}^e + \dot{\varepsilon}^p \quad (1)$$

In the present paper, we assume that the elastic response of copper is isotropic. Let us denote E^{cu} and ν^{cu} , the Young's modulus and the Poisson's ratio.

A J_2 flow rule is adopted so that the plastic strain rate tensor $\dot{\varepsilon}^p$ is related to the deviator of the Cauchy stress tensor s and the backstress X by:

$$\dot{\varepsilon}^p = \frac{3}{2} \dot{p} \frac{s - X}{J_2(\sigma - X)} \quad (2)$$

where $J_2(\boldsymbol{\sigma} - \mathbf{X}) = \sqrt{\frac{3}{2}(\boldsymbol{s} - \mathbf{X}) : (\boldsymbol{s} - \mathbf{X})}$ is the effective stress and $\dot{p} = \sqrt{\frac{2}{3}\dot{\boldsymbol{\epsilon}}^P : \dot{\boldsymbol{\epsilon}}^P}$. The yield surface is defined by:

$$f_y = J_2(\boldsymbol{\sigma} - \mathbf{X}) - R - \sigma_0 \quad (3)$$

During plastic loading, $f_y = 0$. σ_0 is the initial yield stress. $p = \int \dot{p} dt$ is the accumulated plastic strain. R is representative of isotropic hardening. Its evolution law is given by:

$$\dot{R} = b(Q - R)\dot{p} \quad (4)$$

b and Q are material parameters.

In our work, the backstress is made of three components: $\mathbf{X} = \sum_{i=1}^3 \mathbf{X}_i$. The evolution law of each component of the backstress is given by:

$$\dot{\mathbf{X}}_i = \frac{3}{2} C_i \dot{\boldsymbol{\epsilon}}^P - \gamma_i \mathbf{X}_i \dot{p} \quad (5)$$

where C_i and γ_i are material parameters.

Finally, eleven parameters (E^{cu} , ν^{cu} , σ_0 , C_1 , γ_1 , C_2 , γ_2 , C_3 , γ_3 , Q and b) have to be determined by combining Finite Element calculations and an optimization procedure. A Finite Element model of the substrate-copper sample is built. Only one eighth of the sample is represented due to symmetries.

The simulated structure is subjected to the same loadings (in terms of overall force) as in the experiment and the predicted longitudinal strains are compared to the measured experimental strains. A cost function is minimized by optimizing the material parameters of the Lemaitre-Chaboche model with a Nelder-Mead algorithm. The algorithm is modified to ensure that no negative values for the material parameters are used (no cyclic softening was observed during the experimental tests).

The initial guess for the optimization is taken from the work of Salahouelhadj et al. [5] and the algorithm stops when the cost function reached a minimum. The robustness of the solution is checked by running the algorithm a second time with a new random set of parameter. It has been checked that it leads to the same solution. The simulated response of the sample is shown in Fig. 2 together with the experimental response. A very good agreement is reached.

The elastic plastic behavior is now identified. To be able to develop predictive simulations, one has to find a criterion for failure under cyclic loading. This is the goal of the next section.

3. Fatigue behavior

The aim is to study the low cycle fatigue behavior of the copper foil and to provide a relationship between the applied strain amplitude and the fatigue life. Merchant et al. [18] studied the mechanical fatigue life of thin copper foils, very similar to the one studied here. The Coffin-Manson relationship has been used to model the fatigue life.

A specific sample shown on Fig. 3 has been designed to detect the copper failure during the application of the cycles. Six copper tracks are aligned in the loading direction and are connected in a daisy chain. The two extremities of the daisy chain are connected to a four point sensing terminal. The idea is to monitor the electrical resistance of the copper path along the cycles, in order to detect the failure. The same copper pattern is present on both sides of the sample for symmetry purpose.

To localize the strains in the center of the specimen (the gauge region), the copper tracks are thinner in this area (see Fig. 3). It is thus expected that failures will happen in this central portion of the specimen.

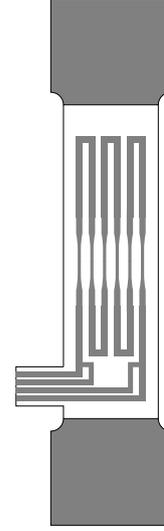


Figure 3: Fatigue test specimen with the same daisy chain on each side. The daisy chain is made of 6 tracks aligned in the loading direction. The daisy chain is connected to a milliohmmeter via the plug. A four-terminal sensing measuring technique is adopted here.

A sinusoidal force is applied to the specimen. The lower bound is set to 10 N to avoid buckling of the specimen, and the upper bound is varying with tests between 100 and 260 N. The longitudinal strain is measured with a point tracking software developed by ProViSys company. Two small dots are drawn on one copper track (see Fig. 4) and a camera (IDS USB 3 uEye CP, approximately 500 img/s) records the test. The two dots are detected by the software, which computes the current longitudinal strain.

The electrical resistance is measured only on one face of the sample by the milliohmmeter (Burster resistomat 2329) and the measured value is captured in real time.

Once one of the six tracks of the face connected to the milliohmmeter breaks, the measured electrical resistance suddenly rises. The test is paused and all of the twelve copper tracks are tested one by one with an ohmmeter. The number of cycles to failure is recorded and the test is continued by series of additional cycles. At the end of

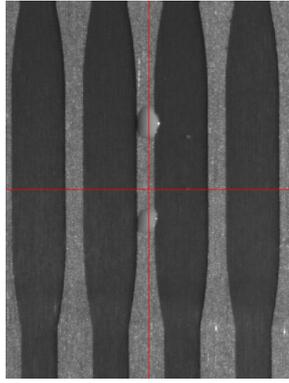


Figure 4: Experimental setup for the copper film fatigue characterization. The longitudinal strain is obtained via the monitoring of the distance between the two dots present in the central part of the specimen (two point tracking system). The electrical resistance of the daisy chain is monitored in real time, together with the longitudinal strain and the force.

each series, the remaining copper tracks are tested until all tracks show a significant increase in resistance.

From the measurements, the strain amplitude has been observed to stabilize after a few dozen of cycles. It is therefore possible to link the stabilized value of the strain amplitude to the number of cycles to failure for each track. Note that different maximum force have been applied, leading to different strain amplitudes. The corresponding numbers of cycles to failure have been measured and the obtained data are plotted in Fig. 5.

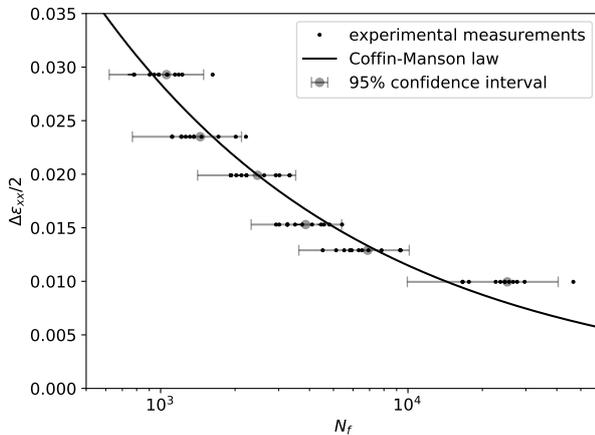


Figure 5: Fatigue results: number of cycles to failure related to the total longitudinal strain amplitude $\Delta\epsilon_{xx}/2$. The prediction of the fitted Coffin-Manson model is also plotted. The means and error bars are plotted for each sample (12 tracks). Each error bar is constructed using a 95 % confidence interval.

The Coffin-Manson relation [26], [27] is proposed to

model the link between the strain amplitude $\Delta\epsilon_{xx}/2$ and the number of cycles to failure N_f :

$$N_f = \frac{1}{2} \left(\frac{\Delta\epsilon_{xx}}{2\epsilon_f} \right)^{1/c} \quad (6)$$

c and ϵ_f are parameters to be determined. Note that this relationship has been used by Merchant et al. [18] to model fatigue of thin copper films. These parameters have been adjusted to fit the experimental data. The values of the parameters found to describe the measured data are $c = -0.394$ and $\epsilon_f = 0.567$. The corresponding curve is drawn on Fig. 5.

The adjusted Coffin-Manson model offers a good prediction of the fatigue life of the studied copper grade. Beyond 10000 cycles, the predictions of the model are seen to deviate from the measured data. This corresponds to strain amplitudes below 2 %.

4. Conclusions

Most of the models found in the literature about PCBs do not adopt kinematic hardening to describe the plastic behavior of copper. However, it has been shown in the present study that kinematic hardening plays a major role for cyclic loadings. The combined isotropic and kinematic hardening of rolled annealed copper used for flexible printed circuit boards has been experimentally observed and a Lemaitre-Chaboche model has been identified. The method presented here to apply tensile-compressive loadings on the copper foils can be adopted for other metallic foils.

The fatigue behavior of the rolled annealed copper has been experimentally determined, via the development of an original testing configuration. The Coffin-Manson model has been used to describe the fatigue life of the studied copper and the law is able to reproduce the number of cycles to failure for low cycle fatigue conditions.

It is expected that based on the proposed mechanical characterization carried out in this article, predictive simulations can be performed on flexible PCBs. This will be the subject of future work.

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