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Low-cycle fatigue testing and thermal fatigue life prediction of electroplated copper thin film for through hole via

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ABSTRACT

A new fatigue test method was proposed for low-cycle fatigue lives of electroplated copper thin films for the through hole (TH) in a printed wiring board. And the low-cycle fatigue lives were investigated according to the proposed method. Furthermore, thermal stress analysis of the TH with the finite element method was performed to predict thermal fatigue life of the TH based on Manson-Coffin law for electroplated copper thin films obtained from the low-cycle fatigue test. Low-cycle fatigue damage in the electroplated copper thin film was occurring in the grain boundaries and the damage mechanism was found same as that for thermal fatigue damage in TH in the printed wiring board. And the fatigue life of TH predicted from the Manson-Coffin law at the maximum temperature of thermal fatigue test was good agreement with the thermal fatigue life obtained from the experimental result of thermal fatigue test.

1. Introduction

As technology to deals with high-density electronic packaging, a multi-layer printed wiring board is used. A multi-layer printed wiring board is electrically connected among layers by through hole (hereafter "TH") plated with tens of microns thick electroplated copper. In the environment of practical applications where ambient temperature varies, the TH, subject to cyclic strain occurring in association with the thermal expansion of surrounding resin material, has fatigue cracking, causing electrical disconnection. Given this condition, it is desired that mechanical properties of copper plating thin film should be clearly known and that a method of fatigue reliability analysis should also be established. To the present, there have been study reports published on static mechanical properties of copper thin films for semiconductor wiring [1–4]. As well, mechanical properties of copper thin film of a few micrometers at room temperature have been examined [5]. However, there have been no studies carried out on mechanical properties of copper thin films (tens of microns thick) for THs in consideration of temperature dependence and creep effect. The author et al. have investigated static mechanical properties of twenty microns thick electroplated copper thin films and clarified that the properties of the electroplated copper films for THs differ from those of bulk copper and copper thin films for semi-conductors [6,7]. It can be expected that static mechanical properties of copper plated thin films as well as their low cycle fatigue properties, which become important in thermal fatigue reliability analysis of TH, will differ from those of bulk copper. Though high cycle fatigue test of electroplated copper thin film of tens of microns thick have been performed [8], the method for testing low-cycle fatigue of such extremely thin films has not been established and the film's properties are not known yet.

In the situation, a test method for low cycle fatigue of electroplated copper thin films for TH was devised in this study and low cycle fatigue properties were investigated. In addition, the analysis of thermal stress on TH was performed based on the finite element method to predict thermal fatigue life of TH in a multi-layer printed wiring board from the fatigue properties found in the low cycle fatigue test.

2. Experimental and thermal fatigue life prediction methods

2.1. Low cycle fatigue test

A method for low cycle fatigue test under tension-compression loading was proposed in the study. Epoxy resin (T_g: 403 K, Hitachi Chemical: E-67) was machined into the hourglass shaped specimens,

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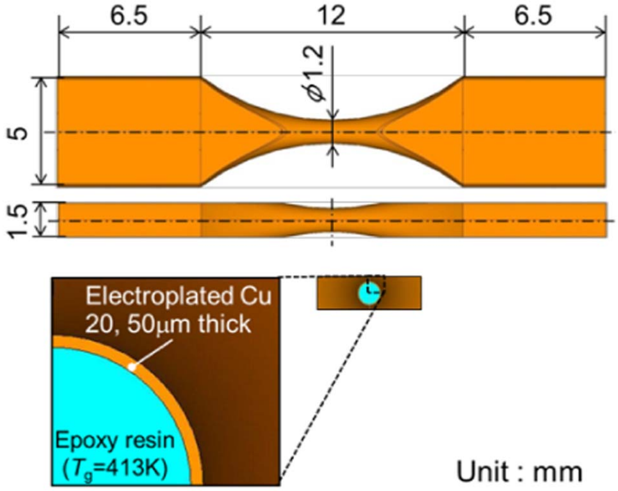

Fig. 1. Schematic illustration of specimen.

which were then plated with electroless-plated ultra thin copper films. Then, the copper films were grown to 20 μm and 50 μm respectively by electroplating. The average grain size of electroplated copper was 0.9 μm for each specimen. Fig. 1 shows the specimen shape to be used for fatigue test. Low-cycle fatigue test was set to the mode of displacement controlled tension-compression with the test temperatures of 298 K and 398 K which is equivalent to the maximum temperature in thermal fatigue testing of the printed wiring board. Three strain rates of 10^{-2}/s, 10^{-3}/s, and 10^{-4}/s were used to confirm the strain rate dependence of fatigue life in the electroplated copper thin films. The control wave was a symmetrical triangle. A linear motor-controlled fatigue testing machine (Saginomiya: LMH207–10) was used and a capacitive displacement sensor attached near a specimen fixing jig was used to control displacements. Test temperatures were controlled by the infrared ray heating equipment installed in the upper part of the testing machine and maintained ± 1 K from the set levels. Fatigue testing was continued until the load range decreased by 10% from the initial value and the fatigue life was defined as the number of cycles when the load range decreased by 3% from the maximum range.

For fatigue life, the Manson-Coffin law [9] shown in Eq. (1) was used and the inelastic strain range of electroplated copper was computed by the finite element method (FEM).

$$\Delta\varepsilon_{\mathrm{in}}\cdot N_{\mathrm{f}}^{\alpha} = C \tag{1}$$

where $\Delta\varepsilon_{\mathrm{in}}$ is the equivalent inelastic strain range, N_{f} is the number of cycles to failure, α is the fatigue ductility exponent, and C is the fatigue ductility coefficient. Fig. 2 shows a FEM analysis model of the low cycle fatigue test specimen. The analysis model was a 1/8 symmetrical reproduction made from symmetry consideration. The 10-node tetrahedron element was employed; the total number of nodes in a model regardless of the film thickness was about 60 thousands. Table 1 shows the material constants used for FEM analyses. The material constants in the constitutive equation were determined by performing the tensile test. For the fabrication of tensile test specimens, films of electroplated copper with predetermined thicknesses were formed on a plate of stainless steel, and the films removed from the stainless plate were used as specimens. The elongation was 10% or more in each condition. Young's modulus of 20 μm thick electroplated copper was much lower than that of bulk copper in this study. It has been reported that the modulus of elasticity of copper plating with low density grain boundary is lower than that of bulk copper [2,8]. Although grain boundaries in copper plating of this study are considered to be low density, the reason why the elastic modulus is low is not clear at the present time. The material properties of epoxy resin were temperature dependent elasticity, and the elastic modulus was found from the test of dynamic viscoelasticity (DMA). $\Delta\varepsilon_{\mathrm{in}}$ was calculated from the third cycle. ANSYS ver. 15.0 was used for FEM analyses.

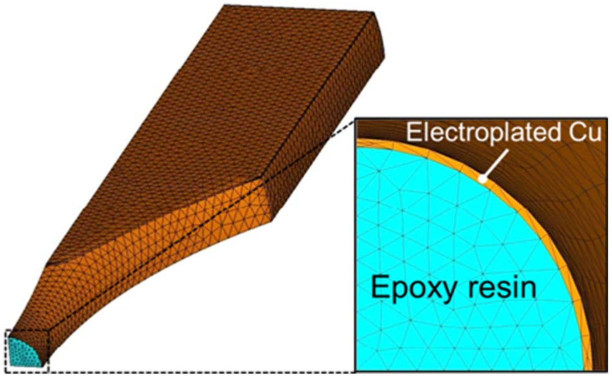

Fig. 2. FEM model of specimen (1/8 symmetry).

Table 1
Material properties of electroplated copper and resin.

	Temperature, T [K]	Young's modulus, E [GPa]	Yield stress, σ_y [MPa]	Poisson's ratio, ν	Coefficient of thermal expansion [ppm/K]
Cu (20 μm)	298	47	126	0.37	17
	323	44	124		
	348	45	114		
	373	32	125		
	398	33	125		
Cu (50 μm)	298	127	165		
	323	127	162		
	348	96	148		
	373	94	139		
	398	67	126		
Resin	233–398	3.4–2.0	–	0.17	70

Material properties are temperature dependent in either of the two materials. The electroplated copper film was an elastoplastic body and resin was an elastic body. The non-linear kinematic hardening law (Chaboche model) was used for the elastoplastic properties of electroplated copper film.

2.2. *Thermal fatigue test of TH*

Fig. 3 shows the multilayer printed wiring board for the thermal fatigue test. Table 2 shows the dimensions of the board. The insulating material was made from epoxy resin (Hitachi Chemical: E-67) and glass cloth. All THs are daisy-chain connected. The plating thicknesses of THs were 20, 30, and 50 μm. Almost no roughness was observed on specimens fabricated in this study. The conditions of thermal fatigue test were 233 K as the lowest temperature and 398 K as the highest temperature; and temperature ramp time was 600 s. A 10% increase in resistance from the initial value during the test was defined as thermal fatigue life. The number of samples was six for each thickness of the film of electroplated copper.

2.3. *Microstructural observation*

Fatigue fractures in the low-cycle fatigue test proposed in this study were compared to the thermal fatigue fractures in the multilayer printed wiring board to investigate the fracture mechanisms of these types of fractures. Microstructures were observed with a field emission-type scanning electron microscope (FE-SEM, JEOL: JSM-7100F). Moreover, analysis of crystallographic orientation was performed, using the technique of Electron Back Scatter Diffraction (EBSD, TSL: OIM). The cross sectional microstructures were prepared by Ar ion beam