

Temperature Dependent Elastic and Thermal Properties of Thin Copper Foils

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Abstract

Young's modulus and coefficient of thermal expansion of free standing electrodeposited and rolled copper foils of 12 μ m to 200 μ m thickness was determined over a temperature range of 23°C to 200°C. Strain measurements were performed by using a non-contacting laser-optical strain sensor. Influence of microstructural, textural and dimensional features of thin foils on their thermo-elastic material properties is demonstrated on selected foil type and compared with bulk copper. A temperature dependent correlation between the measured values of E and CTE is found which may be used to estimate the elastic and thermal constants and thermally induced stress of these foils over a certain temperature range.

Key words: Copper foils, Young's modulus, Coefficient of thermal expansion, thermal properties, microstructure

Introduction

Thermal stresses induced by thermal excursions in electronic packages are mainly influenced by the values of coefficient of thermal expansion (CTE) and Young's modulus (E) of their constituent materials [1]. Rolled and electrodeposited copper foils are broadly used in packaging industry for printed circuit boards. The printed boards are complex multilayer structures composed of several layers of copper circuits embedded between glass fibre reinforced epoxy resin layers. During the curing process the layers are subjected to higher temperatures and pressure, inducing residual stresses in the laminate caused by mismatch of the coefficient thermal expansion of copper and the epoxy layers [2,3]. Throughout the fabrication process, depending on the thermal stability of the copper foils microstructural changes and a variation of the Young's modulus may occur resulting in thermal induced stress in the laminate core. Residual stresses coupled with asymmetries of the laminate can cause warpage, matrix cracking, delamination and circuit failure creating manufacturing problems and serious reliability concerns such as thermal fatigue during the service life [2].

Printed boards operate in general between the temperature range of -55 to +125°C which corresponds to 0.16 to 0.29 T_m of copper. Young's modulus of bulk copper shows no significant temperature dependence up to 300°C while CTE increases from 16.5 ppm/K at 23°C to 19 ppm/K at 300°C [4]. FE analysis of the electronic components based on handbook values differs substantially from temperature dependent values of the constituent materials. It is established that experimental determination of these parameters is of high significance in design and reliability of printed boards [1, 5]. Experimental studies on temperature dependant values of elastic and in particular thermal properties of free standing copper foils are limited [2,6,7].

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Though elastic properties reflect the strength of interatomic bond of a material, it is known that textural and microstructural features may strongly alter these values as observed in thin films or nano-structured materials [8,9]. Previous studies of the present authors showed that tensile and fatigue properties of thin foils are related to their thickness and microstructure [e.g.10]. Moreover the values of E and CTE as well depend on the foil type and may vary more critically for thin foils than for bulk material [6].

The aim of present study was to outline the impact of manufacturing process of thin copper foils on the temperature dependency of E and CTE up to 200°C and investigate the correlation between their properties in this temperature range.

Experimental: Materials Characterization

Commercial rolled copper foil (R) designated as TPC, electrodeposited foil (ED) designated as DF with thicknesses of 12, 18, 35µm and 200 µm were provided by Gould electronics. The foils were subjected to heat treatment at 300°C and 900°C in argon for 30 minutes and the planar grain size was determined by transmission (TEM) and scanning electron microscope (SEM) methods (Table 1).

Table 1: Average grain size of copper foils in x-y plane

Type & Grade	Thick-ness	12µm	12µm	12µm	18µm	18µm	18µm	35µm	35µm	35µm	200µm
	Heat treat-ment	none	300°C	900°C	none	300°C	900°C	none	300°C	900°C	300°C
ED-DF		0,3	2,5	11,0	0,4	1,2	15,0	0,7	1,5	19,0	50
R-TPC		2,5	8,0	29,0	3,5	8,0	35,0	4,5	8,0	44,0	

TPC rolled foils were processed by using tough pitch copper containing up to 400 ppm oxygen as dispersed oxide particles. The microstructure of the as fabricated R foils consists of highly stretched grains and a substructure of elongated cells in the rolling direction. Annealing at 300°C and 30 minutes results in formation of equiaxed grains in the x-y plane (Fig. 1). Grains mostly comparable to or larger than the foil thickness (in x-y plane) are formed after recrystallization heat treatment at 900°C. The initial strong deformation texture of the rolled foil in the x-y plane loses the <111> component following heat treatment and transforms to recrystallization texture with <100> components depending on the hold temperature [11].

The microstructure of the as deposited DF foil is characterized by a fine equiaxed grain structure, high dislocation density and large point defect concentration. Recrystallization heat treatment at 900°C results in formation of coarse equiaxed grains with fine pores generated as a result of thermal activated agglomeration of the point defects along the grain boundaries as shown figure 2. A special feature of all DF-ED foils is the random crystallographic texture which is not sensitive to recrystallization and grain growth up to higher temperatures. A detailed description of special defect microstructure of electrodeposited foils is given in [12].

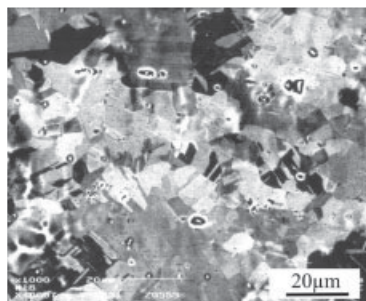


Fig. 1: Microstructure of R-TPC foil of 12μm thickness, annealed at 300°C, 30 min.

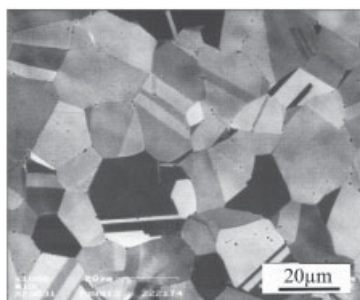


Fig. 2: Microstructure of ED-DF foil of 12μm thickness, recrystallized at 900°C, 30 min.

Testing Procedure

Young's modulus was determined by loading – unloading technique using a micro-tensile machine in combination with a non-contacting laser-optical strain sensor [13]. Displacement controlled tests were carried out using load cells with capacities of 100 and 500N at a strain rate of $5 \times 10^{-5} \text{ s}^{-1}$ with a gauge length of 40mm. A regulated stream of heated air was blown around the samples; holding the maximum temperature error within $\pm 5^\circ\text{C}$. E was obtained as an average of the slopes of several loading unloading curve with a scatter of $\pm 5 \%$ at room temperature up to $\pm 10 \%$ at higher temperatures.

Thermal expansion was measured by employing a laser speckle based dilatometer [7]. The system consists of a specially designed heating chamber filled with Argon atmosphere avoiding surface oxidation of the foils. The heating surface supports the sample which is contacted by use of a thin film of silicon thermal paste in the case of thin foils. With an equilibrium time of 10 min, a reproducibility of 1.5 % could be achieved. A temperature stability of $\pm 0.5^\circ\text{C}$ was achieved by a PID-controlled furnace. Average expansion curves were developed by fitting polynomial to the expansion data from three successive measurements. Differentiation of the polynomial at a given temperature gives the temperature specific coefficient of thermal expansion with an error of about 1 ppm per $^\circ\text{C}$. In this paper the value of CTE was calculated by fitting a quadratic polynomial to the thermal strain data which gave the most reasonable fit in the test temperature range.

Results and Discussion

The measured values of E and CTE for all the investigated specimens are given in table 2. Plots of results for selected rolled and electrodeposited foils are illustrated in figures 3 to 5 and compared with the relevant values of bulk copper taken from literature [14] [4].

Table 2: Results of E and CTE measurements for rolled and electrodeposited Cu foils as a function of test temperature

Designation	CTE(ppm/K)			E(GPa)		
	RT	100°C	200°C	RT	100°C	200°C
12µm-TPC-none	16,6	17,9	19,6	101		
18µm-TPC-none	14,8	20,3	27,6	100		
35µm-TPC-none	15,7	18,1	21,3	101		
12µm-TPC-300°C-30min	16,3	17,1	18,2	108	90	82
18µm-TPC-300°C-30min	17,1	18,1	19,7	101	84	77
35µm-TPC-300°C-30min	14,9	16,5	18,7	101	83	74
12µm-TPC-900°C-30min	15,5	17,2	19,5	87	75	68
18µm-TPC-900°C-30min	17,2	18,2	19,6	74	74	68
35µm-TPC-900°C-30min	14,3	17,1	20,9	79	61	68
12µm-DF-300°C-30min				111	98	69
18µm-DF-300°C-30min				93	87	67
35µm-DF-300°C-30min				96	79	58
12µm-DF-900°C-30min	15,8	16,9	18,39	105	84	68
18µm-DF-900°C-30min	17,1	18,0	19,2	86	77	58
35µm-DF-900°C-30min	16,9	17,4	18,1	90	69	61
200µm-DF-300°C-30min	16,7	16,8	16,9	120	106	91
Bulk copper	16,6	17,4	18,0	93	96	86

Figure 3a shows the influence of thickness and temperature on the Young's modulus of annealed R-TPC foils of 12, 18 and 35µm, with a similar average grain size of 8µm for all thicknesses. Comparing with the almost constant E of bulk copper which between this temperature range, rolled foils show a slight linear drop of about 20%.

The influence of recrystallized microstructure and grain boundary pores on the temperature dependency of E for DF-foils can be taken from figure 3b. Though the room temperature values of E for the coarse grained foils is as expected generally lower than that of the fine grained ones (Table1), a similar absolute temperature dependent E drop of 40% for both microstructures can be observed.

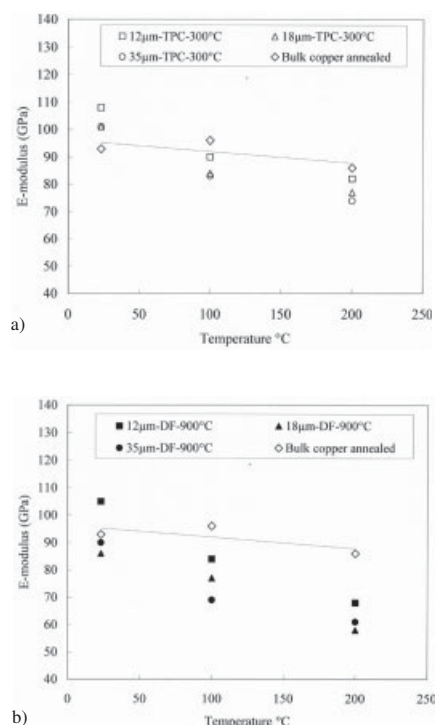


Fig. 3a and 3b: Temperature dependency of E for (a) R and (b) ED foils of various thickness

It can be concluded that for all foils a slight increase of E with decreasing foil grain size and thickness is observed. The temperature dependency of E deviates from bulk material, with more pronounced effect for electrodeposited than that of rolled foils. Grain growth as a result of recrystallization has no considerable influence on temperature dependency of E for both types of foils, but as anticipated the crystallographic orientation changes affect the values of E. The room temperature value of E for the rolled foils is higher than the bulk copper which can be attributed to the strong rolling texture of the foils remained after anneal at 300°C rather than their small grain size. As-rolled foil has a strong $\langle 111 \rangle$ deformation texture component in the x-y plane which subsequent to annealing will be altered. The hard components of the texture are reduced, depending on the exposure temperature and a recrystallization texture with $\langle 100 \rangle$ components is formed resulting in a drop in E.

The magnitude of Young's modulus for ED foils is strongly related to their point defect structure, temperature dependent stability, texture and their grain boundary porosity. For ED-DF foils, E increases with decreasing grain size which can be related to the characteristic point defect structure generated during electrodeposition. The random texture of the DF-ED foil is not altered after recrystallization and grain growth up to 900°C indicating that the temperature dependent drop of E is related to the specific microstructure specially the grain boundary pores rather than texture changes.

The temperature dependency of CTE of textured TPC foils with similar grain size and various thicknesses is illustrated in figure 4a. The CTE values are in the range of the Nist standard,

with an increasing trend at about 200°C. This behaviour is almost in conformity with the temperature dependent behaviour of Young's modulus of rolled foils. Lower values given for CTE at room temperature may be due to the higher scatter of measurements at lower temperatures. Figure 4b illustrates the temperature dependency of coarse grained DF foils of various thicknesses and random crystallographic texture. In contrast to the sharp drop of E between 100°C and 200°C, the CTE values of the foils deviate slightly from that of bulk copper in this temperature range. In contrast in previous work it was shown that instability of the microstructure, results in an remarkable increase of CTE values above 150°C. The contribution of microstructure to physical properties of the electrodeposited foils may be explained by the role of grain boundaries. Increasing the grain size due to a recrystallization treatment recovers the instable grain boundaries and reduces their volume. The impact of the isolated pores, agglomerated in the grain boundaries of a fully recrystallized ED foil seems to be more effective on modification of temperature dependent value of E than the CTE maybe due to the additional effect of grain boundary sliding.

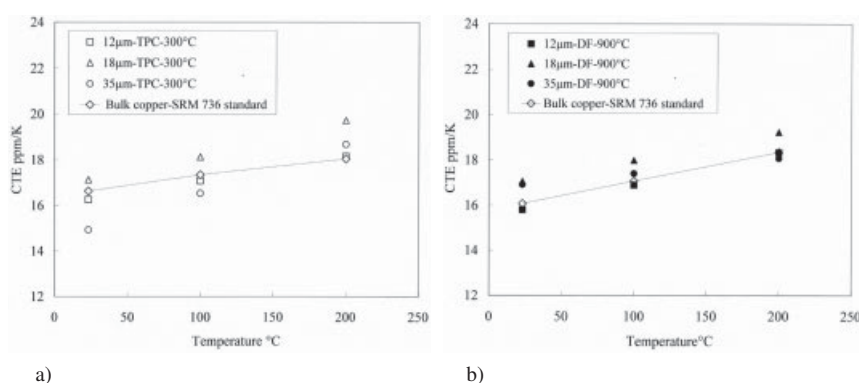


Fig. 4: Temperature dependency of CTE for (a) R and (b) ED foils of various thickness

Relationship Between E and CTE

The coefficient of thermal expansion is described by

$$\alpha = \frac{\gamma_G \rho C_v}{3E} \quad \text{Eqn.1}$$

where γ_G is the Gruneisen's constant, C_v is the specific heat at constant pressure (J/kgK) and ρ is density (g/cm³). With $\rho.C_v$ being almost constant, α (CTE) is proportional to $1/E$ [15].

The Gruneisen constant shows values in the range of 0.4 to 4 for most solids and a value near 2 for bulk copper [16]. Depending on foil type and test temperature, values in the range of 0.9 to 1.6 were calculated for all copper foils of this study, with a decreasing trend with increasing test temperature.

Thermal stress σ induced by a temperature difference ΔT in a solid surface is a function of the values of E, α (CTE) and the Poisson coefficient ν (0.2–0.3 for most materials) and can be determined by

$$\sigma = E\alpha\Delta T / (1 - \nu)$$

Eqn.2

Thermal stress σ_c induced in a thin coating (c), on a substrate (s) is expressed by

$$\sigma_c(T) = (\alpha_s - \alpha_c) \cdot \Delta T \cdot E_c / (1 - \nu_c)$$

Eqn. 3

Assuming a constant value of ν , thermal stress may be determined if the product of $E \cdot \alpha$ at desired temperature is known. Thermal stresses in multilayers can be calculated on the same basis which has been discussed e.g. in [6].

The plots shown in figures 5a and 5b, illustrate temperature dependence relationship between CTE and E, in the range between 23°C and 200°C, for selected R-TPC and ED-DF foils. The shape of the curves reflect the specific behaviour of the foil type and thickness showing a more linear relationship for recrystallized random textured DF foils than the textured TPC foils. These plots or calculated products of $E \cdot CTE$ maybe used to approximate the performance and determination of thermally induced stresses in printed boards.

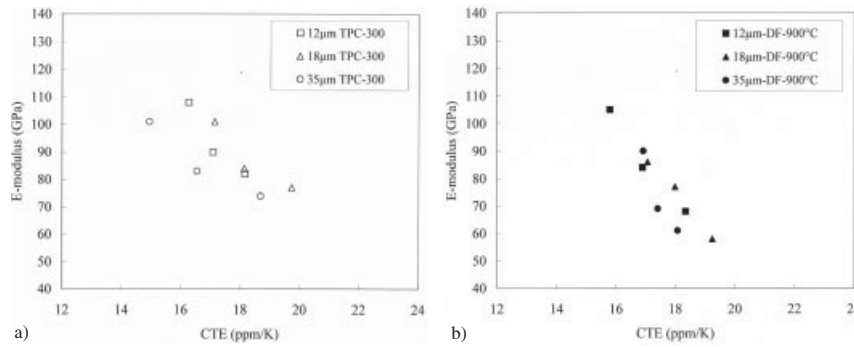


Fig. 5a and 5b: Relationship between E and CTE for (a) R-TPC foils, and (b) E-DF foils

Conclusion

Elastic and thermal parameters of copper foils are unique to the foil type and vary depending on the process parameters. A significant thickness dependency of these parameters was not observed in the range of 12–200μm.

Young's modulus of the foils is more sensitive to temperature than that of bulk copper with a greater effect for ED foils due to their special defect structure.

For ED and R foils with thermally stable microstructure CTE is almost similar to that of bulk copper up to 200°C. A deviation has been observed for fine grained foils with an instable microstructure.

A Gruneisen type relationship between CTE and E is suggested which is specific to each foil type and maybe used as an aid in numerical and FE modelling in stages of design and processing of printed boards.

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