Thermal Expansion Control of Printed Circuit Boards Using Copper-Molybdenum Composite Materials

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Abstract

In recent years, there has been a strong demand for electronic devices to be miniaturized, lightweight, and high-performing. As a result, there has been progress in downsizing and increasing the output of components, as well as high-density mounting of components, leading to an increase in heat generation on the printed circuit board (PCB). Since rising component temperatures can lead to component failure, efficient heat removal is an urgent issue. Damage caused by thermal stress is also a major problem. Repeated temperature changes can cause fractures or cracks inside the PCB or in the joints between the PCB and mounted components, resulting in poor conduction. The main factor contributing to this thermal stress is the mismatch in coefficients of thermal expansion (CTE) between materials. To ensure the reliability of PCBs with mounted components, it is necessary to reduce the thermal stress that occurs between the PCB and the components. We have focused on Cu-Mo composite materials with high thermal conductivity, high elastic modulus, and low thermal expansion, and have developed PCBs with low thermal expansion and high heat dissipation by utilizing these materials. In this study, we concentrated on the low thermal expansion of PCBs made with Cu-Mo composite materials and demonstrated the possibility of controlling the CTE of PCBs by adjusting the volume content of the Cu-Mo composite in the inner layer.

Key words

Printed circuit board, thermal expansion, copper-molybdenum composite materials

I. Introduction

In recent years, there has been a strong demand for electronic devices to be miniaturized, lightweight, and high-performing. As a result, there has been progress in downsizing and increasing the power output of components, leading to an increase in heat generation in printed circuit boards (PCBs) due to high-density component mounting. The increase in heat generation can lead to a rise in component temperature, potentially causing malfunctions, defects, and failures. Therefore, efficient heat dissipation has become an urgent issue.

In addition to temperature rise, damage caused by thermal stress is also a major problem[1,2]. When used in environments with significant temperature fluctuations or high heat densities, the PCBs, on which the components are mounted, are subjected to repeated large temperature changes. This can cause breaks or cracks in the solder joints within the PCB or between the PCB and semiconductors or electronic components, leading to poor conduction. The main cause of solder fatigue is the mismatch in the coefficient of thermal expansion between materials.

When a difference exists in the coefficient of thermal expansion between materials, temperature fluctuations can cause strain. Repeated temperature fluctuations can induce repeated strain in the solder joints between the mounted components and the circuit board, potentially leading to cracking, breakage, and destruction. To ensure the reliability of the mounted printed circuit boards, it is essential to minimize the thermal stress generated between the printed circuit board and the components.

We have been focusing on Copper-Molybdenum (Cu-Mo) composite materials, characterized by high thermal conductivity, high elastic modulus, and a low CTE [3,4], for the development of PCBs. Thus far, we have prototyped multilayer PCBs, incorporating Cu-Mo composite materials in the inner layers, evaluated their thermal characteristics, and confirmed the feasibility of achieving both high heat dissipation and low thermal expansion [5].

In this paper, we report the results of our investigation into controlling the thermal expansion of PCBs by adjusting the volume fraction of Cu-Mo composite materials within them, with emphasis on the low thermal expansion of PCBs made from Cu-Mo composite materials.

II. Overview of Printed Circuit Boards Using Copper-Molybdenum Composite Materials

This section provides an overview of PCBs utilizing copper-molybdenum composite materials. Fig. 1 shows a schematic of a PCB where the copper-molybdenum composite material is applied. The PCB depicted in Fig. 1 has Cu-Mo composite material inserted into its inner layers. In this case, two layers of the Cu-Mo composite material are shown.

Cu-Mo composites are materials whose properties can be tuned by varying the molybdenum content. They are known for their high thermal conductivity, high Young's modulus, and low CTE. Examples of the properties of CuMo composites and related materials are shown in Table 1.

There are two types of Cu-Mo composite materials: a laminated type consisting of copper foil and molybdenum foil, and a particle-dispersed type in which molybdenum particles are dispersed in copper. Prototype PCBs with both laminated and particle-dispersed Cu-Mo composites in the inner layer have been fabricated, and their thermal conductivity and CTE have been evaluated. The results showed that the thermal conductivity of the PCB with copper-molybdenum composite material ensures 60-70% thermal conductivity, and 60-70% CTE compared to a PCB with a similar configuration but with copper replacing the copper-molybdenum composite material. Table 2 shows the results of thermal conductivity and CTE obtained in the evaluation of the prototype PCBs. The particle-dispersed Cu-Mo composite material, laminated Cu-Mo composite material, and Cu content in the entire PCB were approximately 12.2%, 9.6%, and 10.2%, respectively.

It is known that at the same molybdenum content, the laminated Cu-Mo composite material has a lower CTE than the particle-dispersed Cu-Mo composite material. This can be rephrased to say that the laminated Cu-Mo composite material can achieve the same CTE as the particle-dispersed Cu-Mo composite material with a lower molybdenum content. Even in the above evaluation, the same CTE was obtained for the PCB using the laminated Cu-Mo composite material, despite the lower content of Cu-Mo composite material, as compared to the PCB using the particle-dispersed Cu-Mo composite material. In this study, it was decided to use the laminated copper-molybdenum composite material.

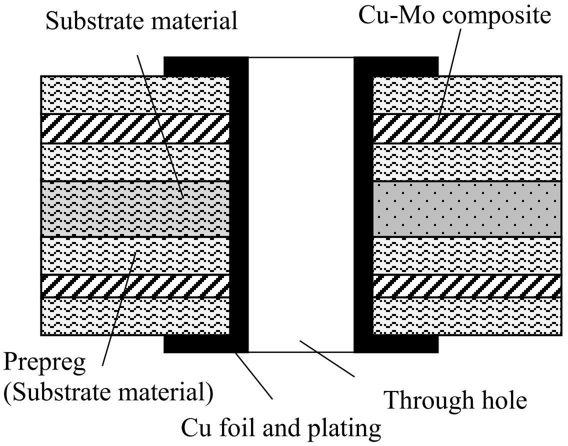


Fig.1 Schematic of the layer structure of a PCB with copper-molybdenum composite material inserted in the inner layer.

III. Methods for controlling the CTE of printed circuit boards

This section outlines the methods used to control the CTE of the copper-molybdenum PCBs examined in this study. Two methods were considered.

Table 3 Properties of inner layer materials

Material	κ (W/mK)	CTE ($\times 10^{-6}$/K)	Young's modulus (GPa)
Cu	398	17.1	120
Mo	142	5.2	320
Cu-Mo Composites (Particle-dispersed type)	220	8.8	210

Table 4 Thermal conductivity and CTE of prototyped PCBs

Type of Prototyped PCB	Thermal conductivity κ(W/mK)	CTE ($\times 10^{-6}$/K)
Particle-dispersed Cu-Mo PCB	40.4	11.4
Laminated type Cu-Mo PCB	34.6	11.4
Cu PCB	56.9	16.4

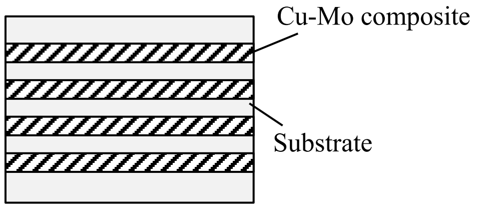
The first method involves adjusting the CTE of the entire PCB by altering the number of Cu-Mo composite material layers, which changes the composite's content in the PCB. Fig. 2 illustrates the layer structure of a PCB with varying numbers of Cu-Mo composite material layers. As depicted in Fig. 2, the number of composite material layers inserted into the PCB's inner layer varies.

The second method modifies the CTE of the entire PCB by changing the copper-molybdenum composite material's content in-plane of the PCB. This is achieved by creating through-holes in the composite material inserted into the PCB's inner layer.

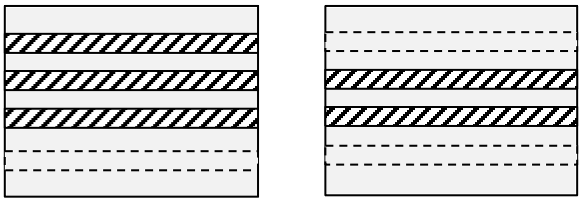
Fig. 3 shows the pattern of the Cu-Mo composite material with through-holes. The through-holes, a combination of small and large diameters, are arranged in a grid pattern.

VI. Coefficient of thermal expansion measurement

Evaluation test specimens of PCBs were fabricated with the Cu-Mo composite layer structure shown in Fig. 2, as well as PCBs with four layers of Cu-Mo composite material, each layer conforming to the shape depicted in Fig. 3. Then measurements of their CTE were conducted. The approximate size of the test specimens is 5mm x 5mm with a thickness of 2mm. The copper-molybdenum composite material used in this study has a molybdenum content of 63.6%. Table 3 shows the content of the copper-molybdenum composite material in the fabricated test specimens.



(a) 4 layers of copper-molybdenum composite material (Type A)



(b) 3 layers of copper-molybdenum composite material (Type B)

(c) 2 layers of copper-molybdenum composite material (Type C)

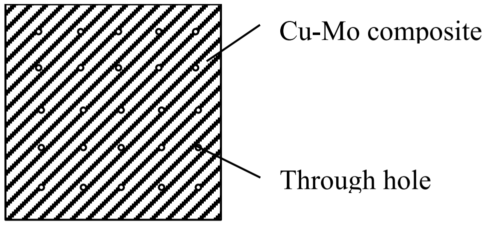
Fig.2 Copper molybdenum PCB with varying number of layers of copper molybdenum composite material

Types A to C are variations of the number of layers of copper-molybdenum composite material in the inner layers of the printed circuit board shown in Fig. 2. Types D to H are those in which through-holes have been formed in the copper-molybdenum composite material of the inner layers of the printed circuit board shown in Fig. 3.

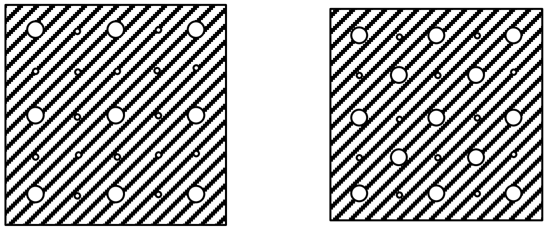
The CTE of the test specimens was measured using a horizontal dilatometer. The measurement temperature range was set from 30°C to 150°C, with a heating rate of 1°C/min. The CTE was calculated using Eq. (1).

$$\alpha = \frac{1}{l}\frac{\Delta l}{\Delta T} \tag{1}$$

where l is the length of the test specimen, Δl is the change in length of the test specimen, and ΔT is the change in temperature. The ratio of Δl to ΔT was calculated from the slope of the graph, which shows the relationship between the measured temperature and the rate of dimensional change.

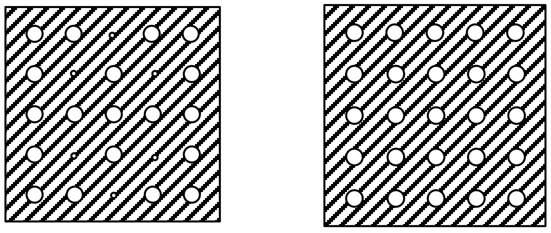


(a) Type D



(b) Type E

(c) Type F



(d) Type G

(e) Type H

Fig.3 Shaped pattern of copper-molybdenum composite material with through holes inserted in the inner layer of PCBs

Table 3. Copper-molybdenum composite content of test specimens

Type of test specimens	Copper-molybdenum composite content (%)
A	10.5
B	7.9
C	5.2
D	10.1
E	8.1
F	7.2
G	6.1
H	4.5

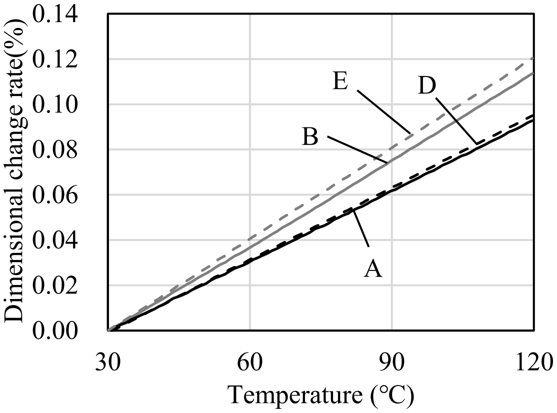


Fig.4 Relationship between temperature and rate of dimensional change of test specimens (type A, B, D, E).

Table 4 CTE of test specimens

Type of test specimens	CTE (10^{-6}/K)
A	10.9
B	12.2
C	13.5
D	11.2
E	12.9
F	13.4
G	14.9
H	15.6

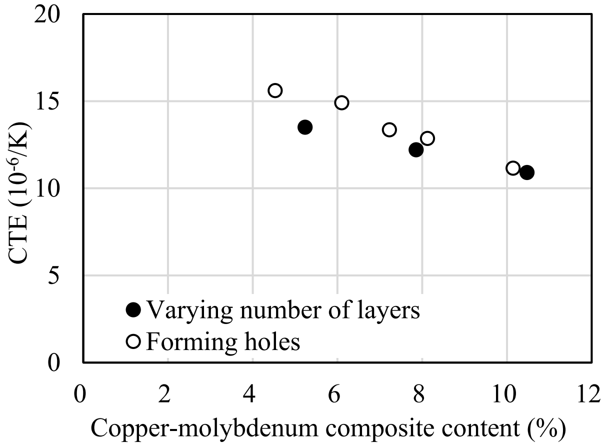


Fig.5 Relationship between the content of the copper-molybdenum composite and the coefficient of thermal expansion

V. Result and Discussion

The relationship between temperature and rate of dimensional change for test specimens A and B, as well as D and E, which are close to the Cu-Mo composite content, is shown in Fig. 4. These test specimens are detailed in Table 3. It can be seen that linearity was obtained in both cases where the content was varied by changing the number of layers of the Cu-Mo composite and where the content was varied by forming through holes in the Cu-Mo composite. The same trend was observed for the other test specimens.

The CTE calculated from the relationship between temperature and rate of dimensional change for test specimens A through H is shown in Table 4. It can be seen that the CTE of the PCB test specimens changes when either the number of layers of the Cu-Mo composite material is varied or when through holes are formed in the Cu-Mo composite material, thereby varying the content.

Fig. 5 shows the relationship between the content of Cu-Mo composite material in the PCB test specimens and the CTE. It can be seen that there is a linear relationship between the content of Cu-Mo composite material and the CTE, whether the number of layers of the Cu-Mo composite material is varied or through holes are formed in each layer of the Cu-Mo composite material.

Additionally, it can be confirmed that the coefficient of thermal expansion is lower when the number of layers of the copper-molybdenum composite material is varied, compared to when holes are formed in the copper-molybdenum composite material.

Here, we will discuss the CTE of the prototype PCB test specimens those were developed this time. The CTE of a laminate material, such as a PCB, is expressed by Eq. (2) [2].

$$\alpha_l = \frac{\sum_{i=1}^{n} \alpha_i V_{f\,i} E_i}{\sum_{i=1}^{n} V_{f\,i} E_i} \tag{2}$$

where α represents the CTE, V_f denotes the volume fraction, E stands for Young's modulus, the subscript l indicates the entire laminate, and i refers to the material i.

Next, the CTE of the Cu-Mo composite layer with through-holes is considered. The copper-molybdenum composite material has through-holes formed in the thickness direction.

Therefore, it can be considered as a flat plate with unidirectional voids in the thickness direction. The Young's modulus and porosity of a flat plate with unidirectional voids are shown to be expressed as in eq. (3) [6].

$$E = E_0(1-p)^m \tag{3}$$

Here, E_0 is Young's modulus of a flat plate without voids, m is an exponent that depends on the direction of loading and the Young's modulus of the base material, and p is the porosity. In the direction parallel to the vacancies, $m \approx 1$. In the direction perpendicular to the vacancies, $m \approx 2.3$-2.7. Young's modulus decreases rapidly with increasing porosity. A model for the CTE of metal matrix composites was derived by Schapery[6]. In this model, the CTE of the composite is given as in Eq (4).

$$\alpha_c = \alpha_p + \left(\alpha_p - \alpha_m\right)\frac{\left(1/E_c\right) - \left(1/E_p\right)}{\left(1/E_m\right) - \left(1/E_p\right)} \tag{4}$$

where α_c is CTE of composite, α_p is CTE of particle, α_p is CTE of matrix, E_c is Young's modulus of composite, E_p is Young's modulus of particle, and E_m is Young's modulus of matrix. In the case of porous metals, E_p in Eq (4) is zero, so $\alpha_c = \alpha_m$.

From the above, the thermal expansion coefficient of the copper-molybdenum composite layer with holes is the same as that of the original copper-molybdenum composite, but Young's modulus is reduced. The CTE of the laminate is expressed in Eq. (2). As the Young's modulus of the copper-molybdenum composite material layer with vacancies decreases, the effect on the CTE of the entire printed circuit board is reduced. Therefore, the CTE is higher for PCBs with the through holes in the Cu-Mo composite material than for PCBs with varying numbers of Cu-Mo composite material layers.

VI. Conclusion

We are developing printed circuit boards with a high thermal conductivity, high elastic modulus, and low thermal expansion using Cu-Mo composite materials in the inner layer. In this study, we focused on the low thermal expansion of the copper-molybdenum PCBs and verified the possibility of controlling the CTE of the PCB by changing the volume fraction of the Cu-Mo composite material inserted in the inner layer of the PCB. The following results were obtained from this study:

- Changing the number of layers of the Cu-Mo composite material, as well as forming holes in the Cu-Mo composite material, both result in changes to the CTE of the PCB by altering the content ratio of the Cu-Mo composite material.
- There is a linear relationship between the content ratio of the Cu-Mo composite material and the CTE of the PCB.
- Compared to forming holes in the Cu-Mo composite material, changing the number of layers of the Cu-Mo composite material results in a lower CTE.
- Forming holes in the Cu-Mo composite material reduces the Young's modulus of that layer, thus minimizing its impact on the overall CTE of the PCB.

The method examined in this study allows us to adjust the CTE of the PCB at each individual component mounted on it. This makes it possible to control the difference in thermal expansion between the printed circuit board and the mounted components, and it is expected that this will enable the reliability of the mounted components to be maintained consistently on the PCB. Going forward, we plan to proceed with demonstrations of this method on PCBs with mounted components.

References

[1] R. Satoh; K. Arakawa; M. Harada , K. Matsui,," Thermal fatigue life of Pb-Sn alloy interconnections“, *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, 14, 1991, pp.224 – 232

[2] H. Nakayama, H. Kawazoe, S. Shiota, M. Nakao and A. Shimizu, "Design of Thermal Expansion Coefficient for Multilayer Printed Wiring Boards", *Circuit technology, Japan,* 8, 1993, pp. 201-208.

[3] T. Arikawa, A. Ichida and E. Takegoshi, "Mechanical Properties of Cu-Mo Composites", *J. Soc. Mat. Sci., Japan*, 48, 1999, pp. 295-300.

[4] J. Reiser, A. Hottmann, J. Hain, U. Jantsch, M. Klimenkov, J. Hohe, T. Mrotzek, "Thermal management materials based on molybdenum (Mo) and copper (Cu): Elucidation of the rolling-induced evolution of thermophysical properties (e.g. CTE)", *J. Alloys and Compounds*, 776, 2019, 387-416.

[5] Yohei Ito, Takanishi, Tatsuya Sakamoto, Keisuke Fujiwara and Hitoshi Arai, "Development of Printed Circuit Boards with High Thermal Conductivity and Low Thermal Expansion by Applying Cu-Mo Composite Materials", *Proc. of 56th International Symposium on Microelectronics*, 2023.

[6] H. Nakajima, "Fabrication, properties and application of porous metals with directional pores", *Progress in Materials Science*, 52, 2007, pp. 1091-1173.