JFE TECHNICAL REPORT
No. 27 (Mar. 2022)

Development of New Cr-Cu Base and New Mo-Cu Base Materials for Heat-Sink of Semiconductor Devices

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Abstract:

Four kinds of new materials have been developed as heat-sink applications for xEV, optical communication, radio communication and others. By applying 75% or higher rolling reduction ratio, Chromium-Copper (Cr-Cu) material which comprises sintered Cr powder with infiltrated Cu acquired in-plane thermal conductivity equivalent to that of conventional W-Cu. Cr-Cu clad with Cu has made it possible to have equivalent thermal conductivity to conventional W-Cu even in thickness direction. Three-layer clad materials comprising Molybdenum or Mo-Cu on the both surfaces and Cu in the middle; Mo/Cu/Mo and Mo-Cu/Cu/Mo-Cu have been found to have improved thermal properties respectively, i.e. high thermal conductivity and low coefficient of thermal expansion, far more than conventional Cu/Mo-Cu/Cu. And for heat-sink applications requiring Cu layer on the surface, five-layer clad structure having Cu layers on the both surfaces of Mo-Cu base three-layer structure also has been found to make it possible to design thermal properties better than conventional materials using the data base of thermal properties with each Cu layer as a parameter.

1. Introduction

Further development of inverters used in xEV (HV/PHEV/PHV/FCV/EV/BEV/HEV), electric trains, power generation, robots, etc., and optical communication and mobile phones, satellite communication, radar and other high frequency communication technologies is expected in the future. Because efficient removal of the heat generated by semiconductors is necessary, heat-sinks are used in high output devices for these applications. Heat-sinks are bonded directly to the semiconductors that generate heat, or to the ceramic substrate on which the semiconductors are mounted, and dissipate the heat generated by those parts through the heat-sink to the opposite side. As requirements for heat-sink materials, the material must not cause harmful deformation when bonded to semiconductors or ceramics by solder or brazing or harmful separation of the bonded interface under the use environment, and must possess high thermal conductivity in the thickness direction for efficient heat removal and a low coefficient of thermal expansion to ensure a high level of bond reliability. Pure copper (Cu) has high thermal conductivity and is widely used as a heat-sink material. When matching of the coefficient of thermal expansion with the semiconductor or ceramic material is more strongly required, a composite material of Cu and tungsten (W) or molybdenum (Mo), which have low coefficients of thermal expansion, is used (hereinafter referred to a W-Cu[1)] material and Mo-Cu[2)] material, respectively). However, these composites have lower thermal conductivity than pure Cu. To overcome this problem, a material with a clad structure consisting of a Mo-Cu sheet positioned between Cu sheets (hereinafter, Cu/Mo-Cu/Cu) is used[3)] in applications where higher thermal conductivity is demanded and in cases where a Cu layer is necessary on the surface.

Because W and Mo essentially do not alloy with Cu, it is possible to form a two-phase composite structure that takes advantage of the low coefficient of ther-

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† Originally published in *JFE GIHO* No. 47 (Feb. 2021), p. 37−43

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mal expansion of W and Mo and the high thermal conductivity of Cu. The infiltration method is generally used to obtain this composite structure. In this method, a powder of W or Mo is formed by powder filling or powder filling and pressing, followed by sintering, and molten Cu is then infiltrated into the sintered compact.

However, the W and Mo powders used as raw materials are expensive and subject to large price fluctuations, and supply stability is also an issue, since the raw material producing regions are limited, centering on China. As problems for manufacturing, W-Cu is difficult to roll, and press-forming is impossible. It is possible to roll Mo-Cu material, but rolling must be performed in the warm temperature region, and press-forming is limited to simple shapes.

Cr, as with W and Mo, is a metal that essentially does not alloy with Cu. Cr is widely used in stainless steels and special steels, and for surface treatment; in comparison with W and Mo, both production and reserves of Cr are more than 100 times larger, and there is little geopolitical risk in the producing countries. Based on these advantages, JFE Precision Corporation focused on application of Cr to heat-sink materials, as Cr is comparatively inexpensive and supplies are stable.

On the other hand, with the progressively higher output of semiconductors, adoption of next-generation semiconductor power devices using SiC or GaN semiconductors in place of Si is also progressing[4, 5]. Due to the high hardness and high stiffness of SiC semiconductors and the brittleness of GaN semiconductors, it is more difficult to absorb thermal stress with bonded materials. Moreover, because the chip surface area has become smaller, even as operating temperatures have increased, higher thermal conductivity is required in heat-sink materials than in the past.

Against this background, the authors developed four types of heat sink materials: i) Cr and Cu composite material (Cr-Cu), ii) Cr-Cu and Cu clad material (Cr-Cu/Cu clad), iii) Mo-Cu and Cu clad material (Mo-Cu/Cu clad) and iv) Mo and Cu clad material (Mo/Cu clad). The Cr-type i) and ii) are low cost materials which can be substituted for conventional W-Cu, and the Mo-type iii) and iv) are materials with higher thermal properties than the conventional Mo-based clad materials.

Figure 1 shows the rough ranges of the thermal properties of the pure metals W, Mo and Cu, the conventional W-Cu and Mo-Cu, and the four newly-developed materials. Note that the thermal conductivity in the figure means thermal conductivity in the thickness direction.

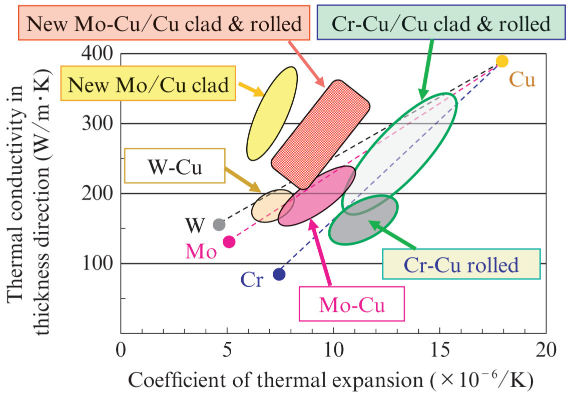

Fig. 1 Thermal properties of developed materials compared with conventional W-Cu and Mo-Cu

2. Experimental Method

Powders of W, Mo and Cr were compacted and sintered, and infiltrated compacts were prepared by dissolving molten pure Cu into the sintered compacts. With Mo-Cu and Cr-Cu infiltrated compacts, rolled sheets were prepared by rolling. These rolled sheets were stacked alternately with a pure Cu sheet and diffusion bonded under pressure while holding at a temperature which enabled sufficient diffusion of atoms at the interface between the pure Cu sheet and the Cu phase in the rolled sheets. In order to eliminate the directionality of the materials, cross-rolling was performed at the same reduction ratio in the direction orthogonal to the rolling direction of the rolled sheets before diffusion bonding. In the following, these clad materials are called Cr-Cu/Cu clad & rolled and Mo-Cu/Cu clad & rolled materials. These rolled materials were subjected to stress relieving heat treatment and processed to obtain measurement samples, and their thermal properties were measured. In the case of W-Cu, the sample for measurement of thermal properties was taken directly from the infiltrated compact due to the difficulty of rolling of this material.

The Mo/Cu clad material was prepared by stacking pure Mo and pure Cu sheets, which were then bonded at an adequate temperature and pressure for bonding, and the sample for measurement of thermal properties was taken from the bonded sheets. The cross section of the measurement sample of the Mo/Cu clad material was observed after the measurement to verify that there was a tight bond between the layers, and the bond was free of voids or other defects.

The thickness of all measurement samples was 1 mm. The composition ratio of Cu and W, Mo or Cr was obtained by measuring the density of each sample by the Archimedes method and calculating from the theoretical densities of each metal. For the coefficient of thermal expansion, the average coefficient of ther-

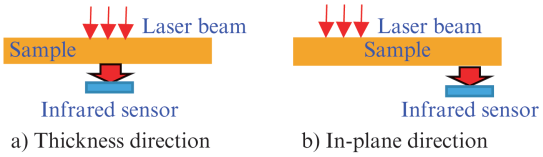

Fig. 2 Measurement method of thermal conductivity

mal expansion from 323 K to the specified temperature was measured by the push-rod displacement detection method. Thermal conductivity in the thickness direction and in-plane thermal conductivity[6] were measured by the laser flash method shown in **Fig. 2**. In-plane thermal conductivity was measured in two directions, that is, the rolling direction and the direction orthogonal to that rolling direction (transverse direction).

3. Cr-Cu Composite Material (J-C'CREP^{TM})

3.1 Cr-Cu Rolled Material

Figure 3 shows examples of the cross-sectional structure of the 50 mass% Cr-Cu material, where 50 mass% Cr indicates the composition ratio of Cr in the Cr-Cu material. With rolling reduction, the Cr particles were elongated in the rolling direction without separation of the interface with the Cu phase, and flattening in the rolling direction occurred before transverse flattening. Flattening also occurred in the transverse direction as the rolling reduction ratio increased. Cr has poor ductility, but displays high workability[7] when enclosed in Cu. In addition, cold rolling with a reduction ratio of 98% or more without intermediate annealing is also possible, as shown in Fig. 3, by controlling the sintering and infiltration conditions to obtain a residual pore free, inclusion free infiltrated structure[8].

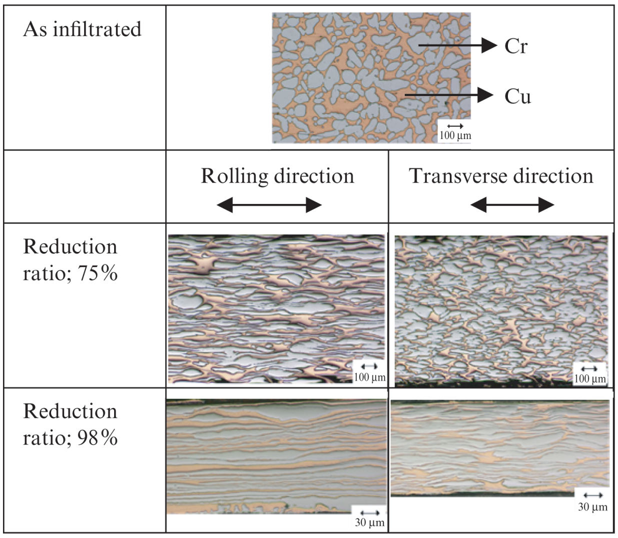

Fig. 3 Various 50 mass% Cr-Cu cross-sectional structures

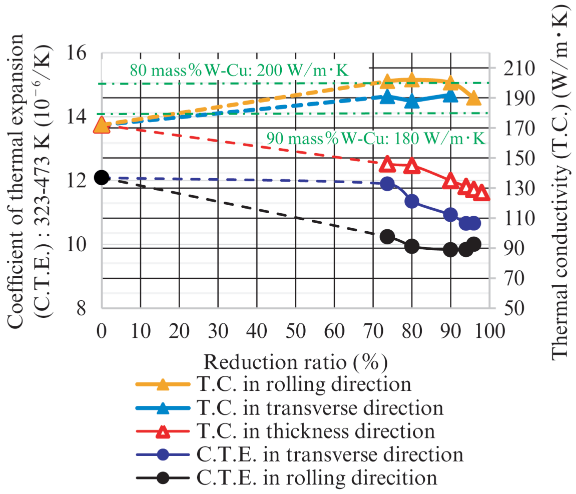

Fig. 4 Relationship between rolling reduction ratio and thermal properties of 50 mass% Cr-Cu

Figure 4 shows the relationship between the rolling reduction ratio and the thermal properties of the 50 mass% Cr-Cu material. Coefficient of thermal expansion decreases with the increase of the rolling reduction ratio. In the in-plane direction of the rolled sheets, it is thought that the coefficient of thermal expansion decreases because interfacial shearing stress occurs due to the difference in the coefficient of thermal expansion of the Cu phase, which has a high coefficient of thermal expansion, and the Cr particles, which have a low coefficient of thermal expansion, and expansion of the Cu phase is restrained by the flattened Cr particles. On the other hand, in-plane thermal conductivity increases as the rolling reduction ratio increases and becomes equivalent to that of conventional W-Cu (thermal conductivity: 180 to 200 W/m-K)[1] at rolling reduction ratios of 75% and higher. However, thermal conductivity in the thickness direction decreases as the rolling reduction ratio increases. As the rolling reduction ratio increases, it appears that the heat flux in the thickness direction becomes more difficult. That is, the thermal conductivity in the thickness direction decreases due to a preferential heat flux along the elongated Cr particles in the Cu phase. Thermal properties can be arranged in terms of the composition ratio of Cr and the rolling reduction ratio[9]. In the 50 mass% Cr-Cu rolled material, in-plane thermal conductivity equivalent to that of W-Cu can be achieved when the reduction ratio is set in the range of 75 to 98%, and it is also possible to secure the bond reliability required in devices which also dissipate heat in the sheet in-plane direction while holding the coefficient of thermal expansion to a low level.

3.2 Cr-Cu/Cu Clad & Rolled Material

As described above, in the Cr-Cu rolled material,

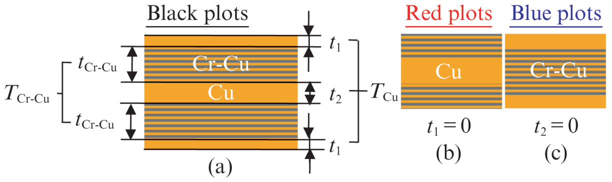

Fig. 5 Cr-Cu/Cu clad structures

the thermal conductivity in the thickness direction decreases as the reduction ratio increases. To solve this problem, in Reference[9], the authors showed that the thermal conductivity in the thickness direction is improved by cladding with pure Cu sheets. The effect of the clad structure on thermal properties is examined in the following.

As shown in **Fig. 5**, the sample comprises a five-layer structure with Cu layers on the two surfaces. The relationship of the surface Cu thickness ratio (t_1), the thickness ratio of intermediate Cu layer (t_2) and the thickness ratios of the each Cr-Cu layers ($t_{Cu\text{-}Cu}$) is defined by Eqs. (1) to (3).

$$t_1=L_{Cu1}/L_{clad} \qquad (1)$$
$$t_2=L_{Cu2}/L_{clad} \qquad (2)$$
$$t_{Cr\text{-}Cu}=L_{Cr\text{-}Cu}/L_{clad} \qquad (3)$$

where, L_{Cu1} is the thickness of the surface Cu layer (mm), L_{Cu2} is the thickness of the intermediate Cu layer (mm), L_{Clad} is the total thickness of the cladding material (mm) and $L_{Cr\text{-}Cu}$ is the thickness of each Cr-Cu layer (mm). Using the thickness ratios shown above, the total Cu layer thickness ratio (T_{Cu}) and the total Cr-Cu layer thickness ratio ($T_{Cr\text{-}Cu}$) are defined by Eq. (4) and Eq. (5), respectively.

$$T_{Cu}=2t_1+t_2 \qquad (4)$$
$$T_{Cr\text{-}Cu}=2t_{Cr\text{-}Cu} \qquad (5)$$

The above-mentioned parameters have the relationship shown in Eq. (6).

$$T_{Cu}+T_{Cr\text{-}Cu}=2t_1+t_2+2t_{Cr\text{-}Cu}=1 \qquad (6)$$

Here, the cases of t_1=0 (no surface Cu layer) and t_2=0 (no central Cu layer) are the three-layer structures shown in Fig. 5 (b) and Fig. 5 (c), respectively.

Figure 6 shows the thermal properties of the 50 mass% Cr-Cu/Cu clad & rolled material for the case of T_{Cu}=0.34 and a reduction ratio of 98%. Thermal conductivity is highest when t_1=0 (T_{Cu}=t_2), decreases as t_1 increases, and shows its smallest value at t_1=0.17 and t_2=0. The coefficient of thermal expansion does not depend on t_1 and is constant. Accordingly, the case where T_{Cu} is constant is the structure shown in Fig. 5 (b), and the thermal conductivity in the thickness direction can be maximized by adopting a three-layer structure in which a Cu sheet is positioned between two layers of Cr-Cu material.

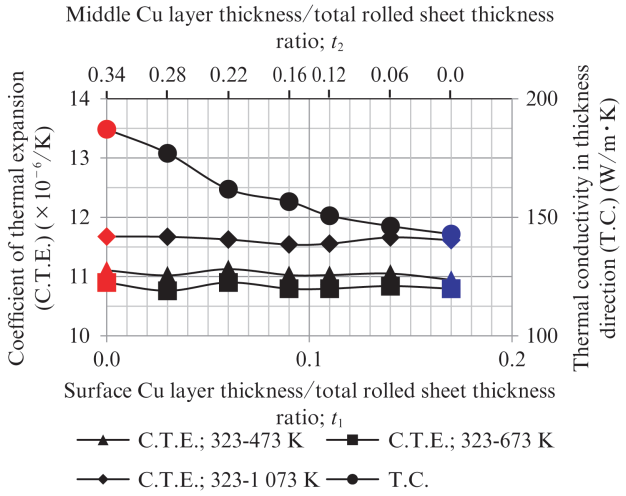

Fig. 6 Effect of Cr-Cu/Cu clad structure on thermal properties

The Cr-Cu/Cu clad & rolled material, like the Cr-Cu rolled material, has extremely good plastic workability in comparison with W-Cu and Mo-Cu materials, and press-forming of parts with a stepped geometry is also possible[10]. However, if the surface layer in a press-forming application is Cr-Cu material, the bending stress generated in the edge in press blanking, or the sag surface in press-forming of stepped parts, can cause separation at the interface between the Cr particle phase and Cu phase in the Cr-Cu material and cracks in Cr particles which are exposed at the surface, and this may cause problems in plating in post-processing in some cases[7]. In such cases, a Cu layer is provided on the surface so that $t_1>0$, although this will result in some sacrifice of thermal conductivity. In the case of T_{Cu}=0.34 in Fig. 6, the decrease in thermal conductivity in the thickness direction is less than 5%, even when t_1=0.03, and stepped press-forming is possible. **Figure 7** shows the thermal properties for t_1=0.03 as a function of the total Cu layer thickness ratio T_{Cu}. Thermal conductivity in the thickness direction shows a substantially linear relationship with the total Cu layer thickness ratio T_{Cu}, and the thermal conductivity in the thickness direction makes it possible to substitute this material for W-Cu in the range of T_{Cu}=0.35 to 0.50.

Thermal conductivity increases with increasing T_{Cu}, but at the same time, the coefficient of thermal expansion also increases. Therefore, for practical applications, T_{Cu} is decided by the balance of thermal conductivity and the coefficient of thermal expansion.

As noted previously, Cr is inexpensive and stable, and there are few geopolitical risks associated with the producing countries. In addition, the Cr-Cu/Cu clad &

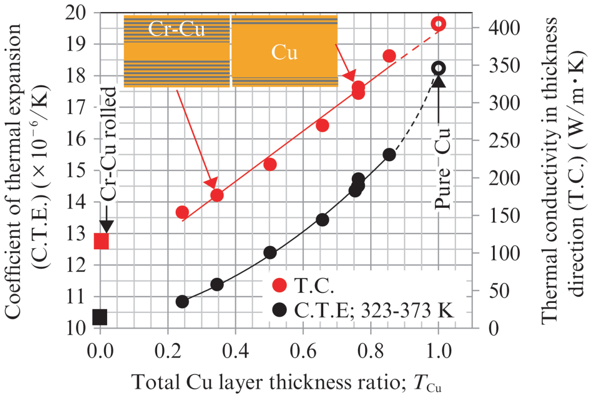

Fig. 7 Thermal properties of 50 mass% Cr-Cu /Cu clad & rolled

rolled material can improve thermal conductivity in the thickness direction while suppressing the coefficient of thermal expansion with a low content of Cr, leading to a reduction in the raw material cost of Cr, which is more expensive than Cu. Moreover, unlike W-Cu and Mo-Cu materials, it is possible to cold roll the Cr-Cu/Cu clad & rolled material. Moreover, because press-forming of stepped shapes is possible with the Cr-Cu rolled material and Cr-Cu/Cu clad & rolled material, as mentioned above, and machinability is also good[10], these materials can also contribute to cost reduction in the part manufacturing process. The Cr-Cu rolled material and Cr-Cu/Cu clad & rolled material have been applied practically as substitutes for W-Cu material, and are used appropriately depending on the application.

4. Mo-Cu/Cu Clad & Rolled Material

The Cr-Cu/Cu clad & rolled material described in the previous chapter has thermal conductivity equivalent to that of W-Cu material, but its coefficient of thermal expansion is about two times larger than that of W-Cu material. This chapter examines a composition system in which Cr is replaced with Mo, which has a lower coefficient of thermal expansion than Cr, in order to further reduce the coefficient of thermal expansion. **Figure 8** shows the thermal properties of 75 mass% Mo-Cu/Cu clad & rolled material when Cr-Cu in the above-mentioned Eqs. (1) to (6) and Fig. 5 is replaced with Mo-Cu for various surface Cu layer thickness ratios (t_1) of the Mo-Cu/Cu clad material. Here, the rolling reduction ratio is constant at 95%, and T_{Cu} is changed by adjusting the central Cu layer thickness and the thickness of the Mo-Cu layers on its two sides. At the blue plots at the right end of each group of plots with the same T_{Cu}, t_2=0 (i.e., a three-layer structure with a Mo-Cu layer in the center; Cu/Mo-Cu/Cu).

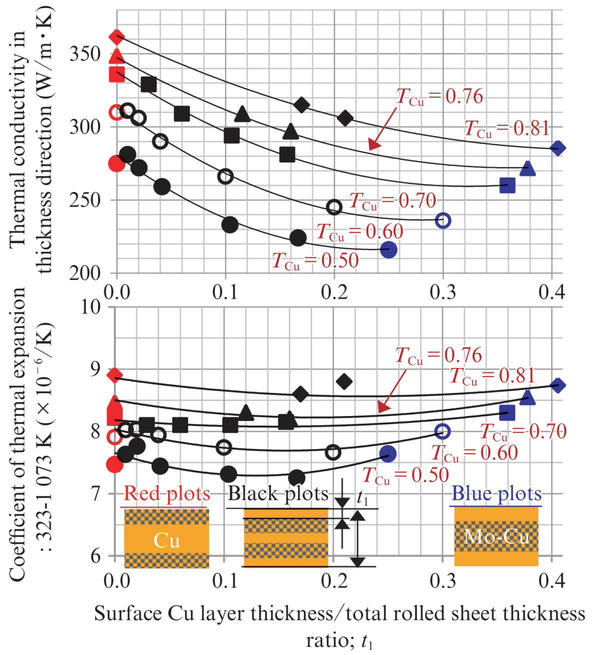

Fig. 8 Thermal properties of 75 mass% Mo-Cu/Cu clad & rolled materials

At the same total Cu layer thickness ratio (T_{Cu}), the coefficient of thermal expansion in the range from 323 K to 1 073 K shows approximately the same values for the three-layer structure with t_1=0 (red plots) and the three-layer structure with t_2=0 (blue plots) and a minimum at the value of t_1 near their intermediate positions. On the other hand, as in the case of the Cr-Cu/Cu clad & rolled material, thermal conductivity in the thickness direction shows its highest value when t_1=0 (i.e., three-layer structure with Mo-Cu layers on the two surfaces; Mo-Cu/Cu/Mo-Cu) and decreases monotonously as t_1 increases. At the same t_1, both the thermal conductivity in the thickness direction and the coefficient of thermal expansion increase as T_{Cu} increases.

This relationship between the clad structure and thermal properties appears to be influenced by the difficulty of heat flux in the thickness direction because penetration of heat in the thickness direction is difficult when heat is input from a Cu layer with high thermal conductivity into a Mo-Cu layer with low thermal conductivity, and as a result, heat flows in the sheet in-plane direction of the Cu sheet layer. However, the mechanism of this phenomenon cannot be explained convincingly at present.

In **Fig. 9**, the results in Fig. 8 are arranged with the coefficient of thermal expansion on the horizontal axis and thermal conductivity in the thickness direction on the vertical axis. At the same coefficient of thermal expansion, the thermal conductivity in the thickness direction of t_1=0 (three-layer structure with Mo-Cu layers on both surfaces; red plots) improves by approxi-

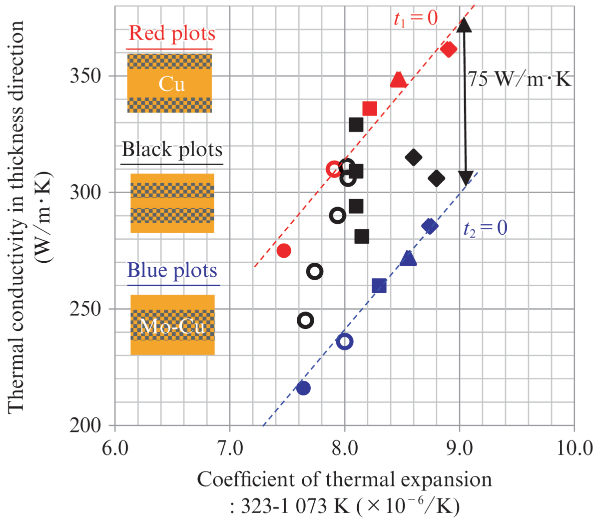

Fig. 9 Thermal properties of 75 mass% Mo-Cu/Cu clad & rolled materials

mately 75 W/m-K from that of t_2=0 (three-layer structure with Cu layers on both surfaces; blue plots).

Figure 10 shows the thermal conductivity of the 75 mass% Mo-Cu/Cu clad & rolled material as a function of t_1. Here, the reduction ratio was 95% and T_{Cu}=0.60. The thermal conductivity in the rolling direction increases by 5% as t_1 increases from 0 to 0.15, but becomes almost constant in the region where $t_1 \geq 0.15$. In contrast, the thermal conductivity in the thickness direction decreases as t_1 increases, and is 30% lower than at t_1=0 when t_1=0.30 (t_2=0). In the case of t_1=0, the anisotropy of thermal conductivity is extremely small, and thermal conductivity is substantially isotropic. In comparison with the Cr-Cu/Cu clad & rolled material, which had a coefficient of thermal expansion of 10×10^{-6}/K or more, the coefficient of thermal expansion of the Mo-Cu/Cu clad & rolled material is 7 to 9×10^{-6}/K. Thus, it can be understood that the Mo-Cu/Cu clad & rolled material reduces the coefficient of thermal expansion while also achieving thermal conductivity of 200 W/m-K or more.

Assuming hypothetically that the thermal conductivity in the thickness direction, λ, in a material consisting of multiple materials follows a simple rule of mixture, the thermal conductivity in the thickness direction of stacked Mo-Cu material and Cu sheets can be expressed by Eqs. (7) and (8).

$$\lambda=\Sigma\,\lambda_i t_i \quad \cdots\cdots (7)$$

$$\lambda=\lambda_{Cu}(2t_1+t_2)+2\lambda_{Mo\text{-}Cu}t_{Mo\text{-}Cu} \quad \cdots\cdots (8)$$

where, $\lambda_{Mo\text{-}Cu}$ is the thermal conductivity of 75 mass% Mo-Cu rolled with a reduction ratio of 95% (=175 W/m-K), and λ_{Cu} is the thermal conductivity of pure Cu (=405 W/m-K), and the functions of t_1 and t_2 in a five-layer structure are expressed by Eqs. (4) to (8).

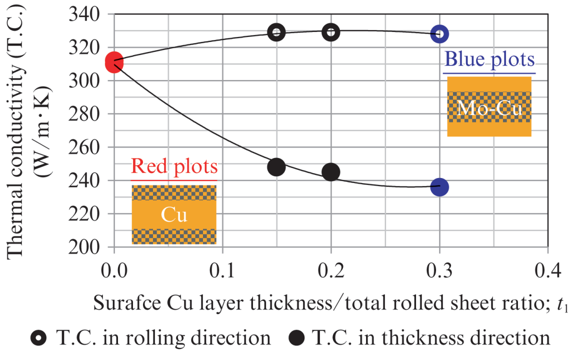

Fig. 10 Influence of clad structure of 75 mass% Mo-Cu/Cu clad & rolled materials on thermal conductivity

In case t_1=0, t_2=T_{Cu} and $2t_{Mo\text{-}Cu}=1-T_{Cu}$. Therefore Eq. (8) can be written as the following Eq. (9).

$$\lambda=\lambda_{Mo\text{-}Cu}+(\lambda_{Cu}-\lambda_{Mo\text{-}Cu})T_{Cu} \quad \cdots\cdots (9)$$

In other words, the variable can be written as the first order of T_{Cu}. The plots of t_1=0 in Fig. 9 are in good agreement with the values calculated by Eq. (9). As shown here, in the case of a three-layer structure with Cu as the central layer, it is possible to design the thermal conductivity in the thickness direction based on a simple rule of mixture.

The conventional Cu/Mo-Cu/Cu material is equivalent to t_2=0. However, as shown in in Fig. 9, when compared at the same coefficient of thermal expansion, the t_1=0 three-layer material is a clad material with superior thermal conductivity in the thickness direction. In cases where a Cu surface layer is necessary, material design for achieving the maximum thermal conductivity in the thickness direction within the desired range of the coefficient of thermal expansion is possible by adjustment based on the plots in Fig. 8.

5. Mo/Cu Clad Material with New Structure

The previous chapter showed that thermal properties can be improved by using Mo-Cu material in place of Cr-Cu material. Like Mo-Cu material, pure Mo sheets produced from Mo powder are extremely expensive. However, in this chapter, we attempted to further improve thermal properties by replacing Mo-Cu material with Mo. Here, the thermal properties of a three-layer Mo/Cu clad material are evaluated. **Figure 11** shows the thermal properties of clad materials (T_{Cu}=0.40 to 0.80) with a three-layer structure. For comparison, the following also shows the thermal properties of the t_1=0 and t_2=0 Mo-Cu/Cu clad & rolled materials in Fig. 9 and a W-Cu material prepared by the authors.

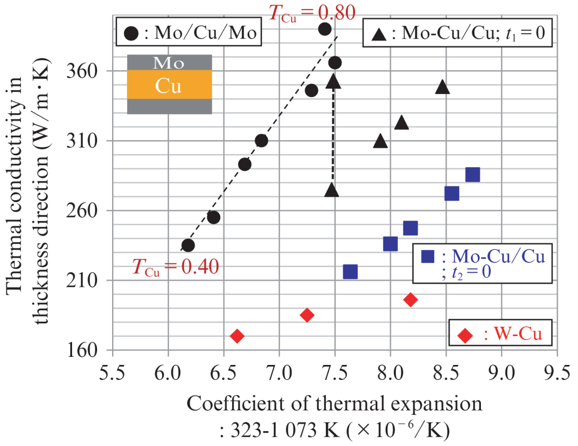

Fig. 11 Comparison of thermal properties of Mo/Cu clad with 75 mass% Mo-Cu/Cu clad & rolled materials and W-Cu

As a result, it was found that the Mo/Cu clad material has excellent thermal properties, for example, displaying thermal conductivity approximately 100 W/m-K higher than that of the Mo-Cu/Cu clad & rolled material with the same coefficient of thermal expansion of 7.5×10^{-6}/K.

The thermal conductivity in the thickness direction of this three-layer Mo/Cu clad material, like the Mo-Cu material with the $t_1=0$ 3-layer structure described above, was almost the same as the calculated values obtained by using the simple rule of mixture in the following Eq. (10).

$$\lambda=\lambda_{Mo}+(\lambda_{Cu}-\lambda_{Mo})T_{Cu} \quad \text{(10)}$$

where, λ_{Mo} is the thermal conductivity of Mo (139 W/m-K), λ_{Cu} is the thermal conductivity of pure Cu (405 W/m-K), and T_{Cu} is the total thickness ratio of the Cu layers. Property design of the Mo/Cu clad material is also possible by using the function of the parameter T_{Cu} according to Eq. (10).

It may be noted that the soundness of junctions obtained by rolling after joining has been confirmed with the Cr-Cu/Cu clad & rolled material and the Mo-Cu/Cu clad & rolled material, but rolling of the Mo/Cu clad material is difficult. Since it is necessary to verify the soundness of junctions nondestructively by ultrasonic testing of the junction interface in the production process, the Mo/Cu clad material is disadvantageous in comparison with the Mo-Cu/Cu clad & rolled material, not only in terms of the raw material cost of the pure Mo sheets, but also production costs. However, the Mo/Cu clad material it thought to be the optimum material for applications in which excellent thermal properties are required, for example, for use as inserts under SiC semiconductor chips.

6. Conclusion

As described in this report, the authors developed four types of heat-sink materials based on Cr-Cu and Mo-Cu materials, which are produced by infiltrating Cu into sintered compacts of Cr powder and Mo powder respectively.

(1) Cr-Cu rolled material: Cold rolling of defect-free Cu-infiltrated Cr-Cu material is possible at reduction ratios of 98% or more. In-plane thermal conductivity increases with the reduction ratio and is equivalent to that of the conventional W-Cu material at reduction ratios of 75% or more.

(2) Cr-Cu/Cu clad & rolled material: Thermal conductivity in the thickness direction is also improved by stacking the above-mentioned Cr-Cu material and pure Cu sheets and performing cladding. In a five-layer structure with Cu in the center of thickness, thermal conductivity in the thickness direction increases as the thickness of the surface Cu layers decreases. The thicknesses of the respective Cu layers were defined as parameters which characterize the layer structure, and the range of the parameters for achieving thermal conductivity in the thickness direction equivalent to that of W-Cu was also established.

(3) Mo-Cu/Cu clad & rolled material: It is possible to shift the material properties to a higher thermal conductivity and a lower coefficient of thermal expansion by using Mo-Cu in place of the above-mentioned Cr-Cu material. A three-layer structure with Mo-Cu as the surface material surpassed the conventional Cu/Mo-Cu/Cu. It is also possible to design a five-layer structure with a Cu layer on the surfaces by using a model and database.

(4) Mo/Cu clad material: In the Mo/Cu clad material, the Mo-Cu of the three-layer structure with Mo-Cu surface layers was replaced with pure Mo. This material displays high thermal conductivity and a low coefficient of thermal expansion. When compared at the same coefficient of thermal expansion of 7.5×10^{-6}/K, it is possible to obtain thermal conductivity of 360 W/m-K, which is approximately 100 W/m-K higher than that of Mo-Cu/Cu/Mo-Cu material.

Further evolution of inverters for automotive applications and optical communication and high frequency communication technologies is expected in the future, and the requirements for heat-sinks will also span a diverse range. To respond to these wide-ranging needs, the authors developed the four types of heat-sink materials described in this paper, and succeeded in creating a wide product lineup that enables material design corresponding to the specifications of the customer. The Cr-Cu rolled material and Cr-Cu/Cu clad & rolled material are already used practically in applications as substitutes for W-Cu.

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