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Nb Phase Position Marking for Clarifying the Formation Process of Cu-Al Composite Interfacial Phases in Continuous Composite Casting

Jun Wang 1,2, Fan Zhao 1,2,* and Xinhua Liu 1,2,3,*

1 Beijing Laboratory of Metallic Materials and Processing for Modern Transportation, University of Science and Technology Beijing, Beijing 100083, China; b20180596@xs.ustb.edu.cn
2 Key Laboratory for Advanced Materials Processing (MOE), University of Science and Technology Beijing, Beijing 100083, China
3 Beijing Advanced Innovation Center for Materials Genome Engineering, University of Science and Technology Beijing, Beijing 100083, China
* Correspondence: zhaofan@ustb.edu.cn (F.Z.); liuxinhua18@163.com (X.L.)

Abstract: Cu-Al composites are widely applied materials exhibiting advanced properties of both matrix metals. Controlling the brittle interfacial phases is a key factor in improving the interfacial strength of Cu-Al composites. This paper studied the interfacial formation process of Cu-Al composites fabricated by continuous composite casting. The phase formation sequence, growth direction and formation mechanism were clarified via element marking and thermodynamic calculations. The spatial distribution of the interfacial phases from the aluminum side to the copper side is as follows: the $\alpha + \theta$ layer ($\alpha$-Al + CuAl$_2$), the $\theta$ layer (CuAl$_2$) and the $\gamma$ layer (Cu$_9$Al$_4$). Moreover, insular $\eta$ phases (CuAl) and $\delta$ phases (Cu$_3$Al$_2$) exist in the $\gamma$ phase sublayer. The formation sequence of interfacial phases is as follows: the $\theta$ phase, the $\eta$ phase, the $\delta$ phase and the $\gamma$ phase. The $\theta$ layer and $\alpha + \theta$ layer are transformed from a liquid diffusion layer formed by scouring the surface of copper with liquid aluminum, the $\eta$ and $\delta$ phases grow towards the $\theta$ layer and the $\gamma$ phase simultaneously grows towards both the copper matrix and the $\theta$ layer.

Keywords: continuous composite casting; Cu-Al composite; interfacial phase; element diffusion; formation sequence

1. Introduction

A copper–aluminum composite is a laminated metal composite material made from certain proportions of pure copper and pure aluminum via specific composite technology. The copper–aluminum composite has received extensive attention in recent years, as it combines the characteristics of high conductivity and thermal conductivity of copper with the light weight and low cost of aluminum [1–4]. It has outstanding advantages in replacing copper with aluminum, especially pure copper, and is applied in aerospace, transportation, decorative building material and other fields [5–8].

Several technologies have been developed to prepare the copper–aluminum composite; Kim and Hong prepared copper–aluminum bimetallic materials by a composite rolling technology [9]. Liu et al. obtained copper–aluminum bimetallic strips by twin-roll casting [10]. Chen et al. made a copper–aluminum bimetallic cast through a method of pouring molten aluminum [11]. However, in the above preparation methods, it is difficult to completely remove the oxide layer on the copper plate surface and for the matrix metal to achieve tight bonding; thus, these methods have the disadvantages of low production efficiency or low composite interfacial strength. Furthermore, Hoseini-Athar et al. used explosive welding to obtain a copper–aluminum bimetallic plate with high adhesive strength [12]. However, the explosive welding method has low production efficiency and a heavy environmental
burden. Recently, a method called continuous composite casting was developed to prepare copper–aluminum composites. In this process, copper and aluminum are continuously cast simultaneously in a closed mold to realize a fully metallurgical combination. Su et al. successfully fabricated Cu-Al-clad composites by a continuous composite casting technique [13]. Wang et al. obtained Cu-Al composite plates by continuous composite casting [14]. After rolling, the interface bonding strength of a Cu-Al composite prepared by continuous composite casting is up to 60–80 MPa [15].

Interfacial strength is a key property closely related to the comprehensive performances of Cu-Al composites. It has been widely reported that interfacial intermetallic compounds (IMCs) have a significant impact on interfacial strength [16–18]. The IMC of a Cu-Al composite interface has a high hardness and almost no plasticity, which has a negative impact on the properties of the Cu-Al composite. In particular, CuAl2 and Cu9Al4 phases are the main region for crack initiation and propagation during interfacial failure. Therefore, the interfacial formation mechanism of a Cu-Al composite can be revealed by studying the interfacial migration behavior and phase formation sequence, which provides a theoretical basis for regulating the interfacial phase structure during the technological process, and finally improves the properties of the Cu-Al composite. For solid-state diffusion between Cu and Al, several conclusions have been drawn from extensive research. Guo et al. illustrated the formation mechanism and growth law of the interfacial phase through Cu-Al diffusion couple experiments at different times and temperatures [19]. Lee et al. studied the interfacial formation mechanism of a Cu-Al composite using vacuum hot-pressing technology at various temperatures [20]. However, continuous composite casting belongs to the solid–liquid composite process, in which the formation, growth and transformation of interfacial IMCs occur over a short time interval and are difficult to observe directly. Tavasoli et al. concluded that CuAl2 first formed at the interface, then a eutectic structure formed when the temperature was lower than 548 °C. Finally, CuAl2 changed into CuAl, Cu4Al3, Cu5Al2 and Cu9Al4 during the cooling process [21]. Su et al. proposed the same theory for the Cu-Al continuous composite casting [22]. However, the above theory was inferred based on the solidified microstructure and its accuracy needs to be further proven. Moreover, revealing the growth direction of the interfacial phase is important, and was not investigated in the above-mentioned studies. Therefore, seeking new research ideas and methods for the formation mechanism of the Cu-Al composite interfacial IMC in continuous composite casting is critical.

Adding other elements or making an indentation in copper and aluminum may be helpful to locate the initial composite interface position and clarify the formation process of interfacial IMCs. Tian et al. innovatively clarified the solid-state diffusion behavior of a copper alloy/aluminum alloy composite interface by position marking of the alloying elements and indentation [23]. However, alloying elements may change the properties of pure copper and pure aluminum and react with matrix metals in the solid–liquid composite process, thus reducing the reliability of research results. Therefore, choosing a reasonable addition element is crucial, and forming a pseudo-alloy may be helpful. In continuous composite casting, the copper is first solidified, then the aluminum liquid flows in and reacts with copper to form the composite interface. Therefore, it is more convenient to add elements to copper to determine the initial position of the composite interface. We consulted a large number of documents and phase diagrams based on the above ideas, and Nb is considered to meet the requirements. Firstly, the solid solubility of Nb in Cu is very low, and Nb can form a pseudo-alloy with Cu and exist in the form of a niobium phase. Secondly, the reaction of Nb and Al can be avoided in the temperature conditions of continuous composite casting, and the activity of Nb is less than that of Cu. Thirdly, the atom radius of Nb is larger than that of Cu and Al, so it is difficult for the Nb atom to diffuse into Al during continuous composite casting. As a result, the addition of a Nb phase could be a novel approach to studying the interfacial mechanism of the formation of copper–aluminum composites prepared by continuous composite casting.
In this paper, the interface migration and element diffusion behavior of Cu-Al composite interfacial phases in continuous composite casting is studied with the assistance of an added Nb phase. The formation sequence of the interfacial phase is also discussed according to the calculation results of formation kinetics. According to the above studies, the migration behavior, growth direction and formation sequence of the interfacial phases are defined, and the interfacial mechanism formation of a copper–aluminum composite is revealed. It is believed that the data obtained can provide new insight into the study of IMCs at Cu-Al composite interfaces. They provide a solid theoretical basis for the control of the copper–aluminum composite interface by solid–liquid composite technology.

2. Materials and Methods

2.1. Continuous Composite Casting

The Cu-Nb alloy was prepared by vacuum medium-frequency induction melting technology. Due to the high melting point of Nb, the weight of Nb was prepared at 5% of the total weight of the ingot, and during melting, the molten metal was kept warm for 30 min, so that more Nb could be dissolved in the copper liquid. Then, the ingot was subjected to homogenization annealing at 1150 °C for 12 h and 50 g of metal chips were removed from the ingot for composition testing. The test results showed that the actual Nb content of the ingot was 3.2 wt%.

The Cu-Nb alloy and industrial pure aluminum were used for continuous composite casting. The principle of the technology is shown in Figure 1 [24]. A copper crucible, an aluminum crucible and a composite mold were heated using a high-frequency induction heating device, respectively. After the Cu-Nb alloy and industrial pure aluminum were melted and reached the preset temperature, the plug rod of the copper crucible was taken out, the copper liquid was released and the Cu-Nb alloy tube was first solidified under the cooling action of the crystallizer. Then, the traction device was started, the plug rod of the aluminum crucible was removed and the liquid aluminum was released. The liquid aluminum filled the Cu-Nb alloy tube via the mandrel. By controlling the traction device and crystallizer, the liquid aluminum and inner surface of the copper–niobium alloy reacted and formed a composite interface of a certain thickness.

![Figure 1. Technology principle of continuous composite casting. (a) Schematic diagram. (b) Composite rod.](image)

The melting and holding temperatures of the Cu-Nb alloy were 1210–1230 °C, the melting and holding temperatures of the industrial pure aluminum were approximately
800 °C and the holding temperature of the composite mold was approximately 1050 °C. The continuous casting speed was 60 mm/min, and the flow of cooling water was 1000 L/h. The diameter of the Cu-Al composite was 20 mm, whereby the thickness of the copper layer was 2.5 mm and the diameter of the aluminum core was 15 mm.

2.2. Microstructure Analysis

The sample (length, width and height of 10 mm) was taken from the copper–niobium alloy ingot by wire cutting technology. The samples were sanded on 200#, 400#, 600#, 1000# and 1500# sandpaper, respectively, and then polished for 5 min on a metallographic polishing machine at 800 rad/min. The interface morphology and element distribution of the Cu-Nb alloy prepared by vacuum melting technology were observed and analyzed with a scanning electron microscope (HITACHI, Tokyo, Japan) and an electron diffraction spectrometer (BRKK, Boston, MA, USA). The longitudinal section of the Cu-Nb/Al composite prepared at the stable stage of the continuous casting process was cut by wire cutting, as shown in Figure 2. After sanding and polishing, the interfacial morphology and element distribution were observed and analyzed by scanning electron microscope and electron diffraction spectrometer. The transmission electron microscope (JEOL, Tokyo, Japan) sample at the Cu-Nb/Al composite interface was prepared by double-beam focused ion beam (HITACHI, Tokyo, Japan) technology. The specific process of transmission electron microscope sample preparation is as follows: the sample location is found, the protective layer is coated and then the sample is cut by a laser. Finally, the transmission electron microscope sample is welded to a special sample column and thinned to 80 nm. The microstructure observation, diffraction spot analysis and element analysis of the Cu-Nb/Al composite interface were carried out with a transmission electron microscope.

![Figure 2. Observation position of interface morphology.](image)

2.3. Thermodynamic Calculations

Thermodynamic calculations are an effective way to predict phase formation sequences at the interfaces of Cu-Al composites. R. M. Walser and R. W. Bene proposed that the new phase at the interface of the binary system is easy to form near the lowest eutectic temperature or liquid region in the phase diagram of the system, and the interfacial atomic concentration presents a “metal–glass” state. The intermetallic compound atoms or atomic groups near the melting point are obviously deviated from this region and are not easy to diffuse, nucleate and grow in the plane interface. The main reason for this phenomenon is that when the interfacial atoms are arranged in a short order from the liquid to the crystal, they will be blocked by the high energy barrier when rearranging. On this basis, R. Pretorius et al. further developed and established the effective heat of formation (EHF) model, which has successfully predicted the formation of the primary phase and the order of product occurrence at the interface of many binary systems [25,26]. The calculation formula for the effective heat formation model is given as follows:

The calculation formula of the effective heat formation model is:

\[ \Delta = \Delta H^0 \times \frac{C_e}{C_l} \]  

(1)
where \( \Delta H' \) is the effective heat of formation (the lower the \( \Delta H' \), the easier the phase formation), kJ/mol; \( \Delta H^0 \) is the standard heat of formation, kJ/mol; \( C_c \) is the content of the solvent element at the interface (this element is consumed when the phase forms), generally taken as the element content in the eutectic structure, at%; and \( C_I \) is the content of solvent elements in the intermetallic compound phase, at%.

3. Results and Analysis

3.1. Microstructure of the Cu-Nb Alloy

The morphology, element distribution and X-ray diffraction of the Cu-Nb alloy prepared by vacuum melting technology after heat treatment at 1150 °C for 12 h were analyzed with a scanning electron microscope and an electron diffraction spectrometer; the results are shown in Figure 3. Figure 3a shows the microstructure of the Cu-Nb alloy observed under the backscattering mode of the scanning electron microscope. As can be seen from Figure 3a, Nb in the Cu-Nb alloy is rod-like and uniformly distributed. Figure 3b,c shows the distribution of copper and niobium elements, respectively. As can be seen from Figure 3b,c, the distribution of Cu and Nb elements in the Cu-Nb alloy does not overlap, indicating that copper and niobium do not form a compound or solid solution, and Nb exists as a single phase. The above results indicate that the Nb phase satisfies the condition that the label element exists as a single phase at the interface.

![Figure 3](image-url)

**Figure 3.** Microstructure and element distribution of Cu-Nb alloy. (a) Microstructure; (b) element distribution of Cu; (c) element distribution of Nb; and (d) X-ray diffraction.

3.2. Interface Morphology of the Cu-Nb/Al Composite

The morphology and element distribution of the Cu-Nb/Al composite prepared by continuous composite casting technology were analyzed with a scanning electron microscope and an electron diffraction spectrometer; the results are shown in Figure 4. Figure 4a shows the microstructure of the Cu-Nb/Al composite observed under the backscattering mode of the scanning electron microscope. Figure 4b shows the distribution of Cu, Al and Nb elements, respectively. Figure 4c–f are the element analyses of the different regions in Figure 4a.

After continuous composite casting, Nb in the Cu-Nb alloy still exists as a single substance with a rod-like shape. A composite interfacial layer composed of three sublayers is formed between the Cu-Nb alloy and Al; the ratio of Cu/Al atoms is 9:4, 1:2 and 1:4, respectively. Combined with the Cu-Al phase diagram, the three sublayers are as follows: the \( \gamma \) layer (CuAl), the \( \delta \) layer (CuAl\(_2\)) and the \( \alpha + \delta \) layer (\( \alpha \)-Al + CuAl\(_2\)). Moreover, there are some insular \( \eta \) phases (CuAl) and \( \delta \) phases (CuAl\(_3\)) in the \( \gamma \) phase sublayer. It is well known that the \( \delta \) layer and the \( \alpha + \delta \) layer are transformed from a liquid diffusion layer formed by liquid aluminum scouring of the surface of copper; therefore, these two layers
have a larger thickness. Other interfacial phase layers are much thinner and form during subsequent solid-state diffusion. As shown in Figure 4, the Nb phase located between the θ layer and the Cu matrix can assist in revealing the formation process of other interfacial phase layers. Thinning of the γ layer occurs both above and below the niobium phase. This is attributed to the obstruction of the Nb phase to the diffusion of Cu and Cu atoms. Therefore, it can be concluded that the γ layer simultaneously grows towards both the copper matrix and θ layer. Moreover, it can be found that the η and δ phases mainly exist in the upper part of the γ layer; thus, these two phases grow towards the θ layer.

Figure 4. Interface morphology and element distribution of Cu-Nb/Al composite. (a) Interface morphology; (b) element distribution; and (c–f) element analysis of different regions in (a).

The morphology and element distribution of the Cu-Nb/Al composite interface containing the Nb phase were observed and analyzed with TEM, and the results are shown in Figure 5. Figure 5a displays the microstructure of the Cu-Nb/Al composite interface containing the Nb phase observed under the bright field mode of the transmission electron microscope. A diffraction analysis was carried out at four different positions in Figure 5a, and the results are shown in Figure 5b–e, respectively. Figure 5f–h show the distribution of Cu, Al and Nb elements in Figure 5a, respectively.
It can be seen from Figure 5a that the Cu-Nb/Al composite fabricated by continuous composite casting has a smooth interface fully and metallurgically bonded without casting defects. According to the diffraction spot calibration results, the phases at four positions can be determined as $\theta$, $\eta$, $\gamma$ and $\delta$. According to element analysis results, a part of Nb is contained in the $\gamma$ sublayer, and another part is contained in the copper layer. It can be found that the growth of the $\gamma$ layer towards the $\theta$ layer is slowed down near the Nb phase. This indicates that the diffusion of Cu atoms into the $\theta$ layer is blocked by the Nb phase.

![Figure 5](image)

3.3. Thermodynamic Calculation of the Interfacial Phase Formation Sequence

Thermodynamic calculations are an effective way to predict phase formation sequences at the interfaces of Cu-Al composites. Firstly, we have consulted literature to find the data on the change in the Gibbs free energy for the formation of intermetallic phases depending on temperature, as shown in the following Table 1 and Figure 6.

<table>
<thead>
<tr>
<th>Types of Cu-Al Intermetallic Compounds</th>
<th>$\Delta G$ (J/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuAl$_2$</td>
<td>$-77,100 + 22.3T$</td>
</tr>
<tr>
<td>Cu$_9$Al$_4$</td>
<td>$-334,000 + 96.1T$</td>
</tr>
<tr>
<td>CuAl</td>
<td>$-51,380 + 14.8T$</td>
</tr>
<tr>
<td>Cu$_3$Al$_2$</td>
<td>$-128,440 + 36.9T$</td>
</tr>
</tbody>
</table>
Comparing the Gibbs free energy of four kinds of copper–aluminum intermetallic compounds, it is found that the formation of free energy in the Cu₉Al₄ phase is the smallest, which should be formed first in the process of a copper–aluminum reaction. However, the interfacial formation process of a Cu-Al composite prepared by continuous composite casting is controlled by both thermodynamic and kinetic conditions, and the distribution of the copper atom concentration at the interface and the diffusion of copper and aluminum atoms have a significant effect on the interface phase formation.

The effective heat formation model takes into account the effects of thermodynamics and kinetics on the phase formation. The effective heat formation of the IMCs of the Cu-Al composite interface fabricated via continuous composite casting was calculated using Equation (1). For the Cu-Al binary system, the element concentrations are 82.9 at% Al and 17.1 at% Cu, corresponding to the lowest eutectic temperature. Under this condition, when generating the \( \theta \) phase is the highest. In Figure 6, the order of the energy barriers of phase formation from largest to smallest is as follows: the \( \gamma \) phase, the \( \delta \) phase, the \( \eta \) phase and the \( \theta \) phase. The energy barrier of phase formation of the \( \theta \) phase is the lowest, and the energy barrier of phase formation of the \( \gamma \) phase is the highest. Therefore, the phase formation sequence at the interface of the copper and aluminum solid–liquid composite is as follows: the \( \theta \) phase, the \( \eta \) phase, the \( \delta \) phase and the \( \gamma \) phase.

**Figure 6.** The curve of Cu-Al IMC Gibbs free energy with temperature.
Table 2. The effective heat formation of IMCs.

<table>
<thead>
<tr>
<th>Phase (IMCs)</th>
<th>Compound Concentration</th>
<th>ΔH° (kJ/mol·at) [28]</th>
<th>Effective Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuAl₂</td>
<td>Cu₃₀.₆₆Al₀.₃₄</td>
<td>-21.69</td>
<td>Cu</td>
</tr>
<tr>
<td>CuAl</td>
<td>Cu₃₀.₆₆Al₀.₃₄</td>
<td>-21.69</td>
<td>Cu</td>
</tr>
<tr>
<td>Cu₃Al₂</td>
<td>Cu₃₀.₆₆Al₀.₃₄</td>
<td>-21.69</td>
<td>Cu</td>
</tr>
<tr>
<td>Cu₉Al₄</td>
<td>Cu₃₀.₆₆Al₀.₃₄</td>
<td>-21.69</td>
<td>Cu</td>
</tr>
</tbody>
</table>

Figure 7. The effective heat formation map of θ phase and γ phase.

3.4. Interfacial Phase Formation Mechanism

The interfacial phase migration behavior and growth direction of Cu-Nb/Al composites prepared by continuous composite casting were determined based on the interfacial morphology and element distribution. According to the effective heat formation results of Cu-Al intermetallic compound phases, the interfacial phase formation sequence of Cu-Nb/Al composites prepared by continuous composite casting was obtained. Based on the above results, the formation mechanism of the interface was revealed. The specific process is shown in Figure 8, as follows:

1. At the initial stage of the continuous composite casting, the Cu-Nb alloy is released and solidified to form the copper alloy pipe under the cooling action of the mold. Nb does not react with copper to form intermetallic compounds, nor does it dissolve in copper to form solid solutions. Nb exists in copper in the form of a single phase, with a rod-like shape and uniform distribution, as shown in Figure 8a.

2. When liquid aluminum and the copper layer come into contact, due to the erosion of the liquid aluminum, a certain thickness of the copper layer dissolves into the liquid aluminum and forms the copper aluminum diffusion zone, the part of the exposed Nb. Due to the low effective heat formation of the θ phase, a large number of θ phase cores are formed above the solid–liquid interface. These connect together to form a continuous θ phase sublayer, which grows towards the copper aluminum diffusion zone under the control of Cu atom diffusion, as shown in Figure 8b.

3. When liquid aluminum and the copper layer come into contact, a small number of aluminum atoms diffuse into the copper layer to form the γ phase. With continuous composite casting, the concentration of copper atoms is distributed in a gradient from...
the copper side to the aluminum side, and the closer to the copper side, the higher the concentration of copper atoms. Therefore, controlled by the diffusion of copper atoms into aluminum, the $\theta$ phase is transformed into the $\gamma$, $\delta$ and $\eta$ phases, as shown in Figure 8c.

(4) When the temperature of the Cu-Al diffusion region drops to the eutectic temperature of 548 °C, the eutectic transition occurs to form the $\alpha + \theta$ phase. During the cooling process, the $\gamma$ phase gradually absorbs the $\delta$ phase and $\eta$ phase. Finally, a composite layer composed of the $\alpha + \theta$ eutectic structure, the $\theta$ phase, the $\gamma$ phase, a small amount of the $\delta$ phase and the $\eta$ phase is formed at the interface of Cu-Al composites, as shown in Figure 8d.

In summary, in the continuous casting process of copper–aluminum composites, following the contact between liquid aluminum and solid copper, the copper layer of a certain thickness was dissolved to form a diffusion zone containing copper atoms. Under the action of copper atom diffusion, a $\theta$ phase sublayer formed above the diffusion region containing copper atoms and grew into the diffusion region. Under the control of copper atom diffusion, the $\theta$ phase transformed into the $\delta$ phase and $\eta$ phase. Under the control of the interdiffusion of Cu and Al atoms, the $\gamma$ phase formed and grew laterally. The eutectic transition occurred when the temperature of the Cu-Al diffusion zone dropped to the eutectic temperature. Finally, a composite layer consisting of the $\alpha + \theta$ eutectic structure, the $\theta$ phase, the $\gamma$ phase, a small amount of the $\delta$ phase and the $\eta$ phase was formed at the interface of the Cu-Al composite.

Figure 8. Interface formation mechanism of Cu-Al composite: (a) initial stage of continuous composite casting; (b,c) stable stage of continuous composite casting (d) final stage of continuous composite casting.

4. Conclusions

In this study, the interfacial phase migration behavior and growth direction of Cu-Nb/Al composites prepared by continuous composite casting were obtained based on the interfacial morphology and element distribution. According to the effective heat formation results of Cu-Al intermetallic compound phases, the interfacial phase formation sequence of Cu-Nb/Al composites prepared by continuous composite casting was obtained. Comprehensive of the above results, the formation mechanism of the interface was revealed. The main findings are as follows:

(1) The spatial distribution of the composite interface from the aluminum side to the copper side is as follows: the $\alpha + \theta$ layer (Al + CuAl$_2$), the $\theta$ layer (CuAl$_2$) and the $\gamma$ layer (Cu$_3$Al$_4$). Moreover, there are some insular $\eta$ phases (CuAl) and $\delta$ phases (Cu$_3$Al$_2$) in the $\gamma$ phase sublayer.

(2) The formation sequence of the phase at the composite interface is as follows: the $\theta$ phase, $\eta$ phase, $\delta$ phase, $\gamma$ phase and $\alpha + \theta$ layer.
(3) The $\theta$ layer and $\alpha + \theta$ layer are transformed from a liquid diffusion layer formed by scouring the surface of copper with liquid aluminum, the $\eta$ and $\delta$ phases grow towards the $\theta$ layer and the $\gamma$ layer simultaneously grows towards the copper matrix and $\theta$ layer.

**Author Contributions:** J.W.: Conceptualization, Formal analysis, Investigation, Data curation, Writing—original draft, Writing—review and editing. F.Z.: Conceptualization, Formal analysis, Writing—review and editing. X.L.: Writing—review and editing, Supervision, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by the National Key Research and Development Program of China (grant number: 2018YFA0707303), the National Natural Science Foundation for Distinguished Young Scholars of China (grant number: 51925401) and the National Natural Science Foundation (grant number: 92066205).

**Data Availability Statement:** Data is unavailable due to privacy.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**


5. Gao, L.; Zhou, T.J.; Zhang, P.; Sun, L.X.; Cao, F.; Liang, S.H. Interfacial bonding mechanism and mechanical properties of adding CuZn alloy fibre for Cu/Al composite. *Mater. Charact.* 2022, 188, 111883. [CrossRef]


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