Microstructure and Bonding Strength of Aluminum Bronze on ASTM 1045 Steel by CMT welding

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Abstract. The effect of welding parameters on metallographic microstructure of aluminum bronze, interfacial microstructure and bonding strength of aluminum bronze and steel substrate has been studied. A cladding of aluminum bronze was obtained on the surface of medium carbon steel by CMT welding and short circuiting transfer welding. The microstructure of aluminum bronze and the interfacial microstructure of the interface between aluminum bronze and steel substrate have been systematically investigated. Sample 1-4 are α + (α + γ₂) microstructure of typical aluminum bronze. As for Sample 5, iron-rich particles and dendrites were distributed on the α-Cu crystal matrix. The bonding strength of aluminum bronze and steel substrate has been collected according to the destructive testing method of the bimetallic bonding strength of sliding bearing. Among the five samples, Sample 4 and Sample 5 had the highest bonding strength (528.17MPa and 511.39Mpa, respectively). The reason for the enhancement of the bonding strength was discussed. In the interface of aluminum bronze and steel substrate, the transition layer will get thicker when the interdiffusion distance between Fe and Cu elements is larger, it would be more conducive to increase the bonding strength.

1. Introduction
Copper alloys have been widely used in bearing materials due to their high fatigue strength and carrying capacity, excellent wear resistance, and good thermal conductivity, of which lead bronze and copper-lead alloy are the main copper alloy bearing materials[1-3]. Owing to the severe toxicity of Pb and its compounds, many countries have prohibited the use of lead-containing materials, so lead-containing copper-based sliding bearing materials have gradually been eliminated by the times. The developed high-strength lead-free bronze alloy has a higher allowable specific pressure than traditional lead bronze materials, and can well meet the requirements of high specific pressure and high outbreak pressure of modern engines[4-7].

Researchers have tried to produce aluminum bronze/steel bimetal bearing materials by powder metallurgy method, but have not succeeded. The problem of bond strength cannot be solved due to the inherent characteristics of aluminum bronze. Some countries (Italy, the United States) have focused their research on casting method, hoping to make breakthroughs. However, there have been no reports of large-scale industrialization applications[8].

Hence, promising welding methods are considered to produce aluminum bronze/steel bimetal bearing materials. In this paper, CMT (cold metal transfer) welding method was chosen to bond
aluminum bronze to the steel substrate. CMT process is based on short circuiting transfer, or rather, on a deliberate, systematic discontinuing of arc. In a normal short circuiting transfer arc, the electrode is deformed while being dipped into the weld pool, and melts abruptly at high transfer arc current. In contrast to this, in CMT process, every time the short circuit occurs, the digital process control both interrupts the power supply and controls the retraction of the wire. The wire retraction motion assists droplet detachment during the short circuit. By ensuring minimal current metal transfer, the CMT process greatly reduces the amount of heat generated [9]. A cladding layer of aluminum bronze was obtained on the surface of steel substrate by CMT welding. The effect of different heat input on the microstructure and morphology of the interface was investigated. And the influence of the transition layer on the interfacial bonding strength was investigated too. A cladding layer of aluminum bronze was also obtained on the surface of steel substrate by short circuiting transfer welding as a control group.

2. Materials and method

The aluminum bronze wire used in this study was S215 (ERCuAl-A2). The diameter of wire was 1.2mm and the specific compositions were shown in Table 1. The ASTM 1045 steel was used as the steel substrate and its dimensions were 150 mm×150 mm×12 mm. Before welding test, the surface of substrate was polished to remove the oxidation layer. The welding wires were CMT welded and short circuiting transfer welded on the surface of steel substrate. The welding torch was perpendicular to the steel substrate. Multiple pass welding was conducted step-by-step. The schematic of welding test processes is illustrated in Figure 1. First, the welding torch moved about 120 mm along the length, then went back to the starting point immediately. After that, the welding torch walked about 13mm along the width and continued to weld along the length. A total of three welds were carried out to complete the welding process. Finally, these process were repeated in the same place once again to get a cladding layer with a height of about 4mm.

| Element | Content (wt%) |
|---------|---------------|
| Al      | 8.67          |
| Fe      | 1.04          |
| Cu      | 90.28         |

Table 1 Chemical composition of aluminum bronze alloy

The welding voltage is automatically matched with the welding current. The specific welding parameters were shown in Table 2. The scan speed was 30 cm·min⁻¹ and the shielding gas was pure argon. The sample was cut into 10 mm×10 mm×16 mm with the thickness of aluminum bronze in the
sample approximately 4 mm. Samples were polished beforehand and then corroded by ferric chloride aqueous hydrochloric acid. Finally, the microstructures of the aluminum bronze and interface were studied by the optical microscope (OM) and scanning electron microscopy (SEM). The chemical compositions were investigated by energy dispersive X-ray spectrometer (EDS).

Table 2 Welding parameters of aluminum bronze on steel substrate

| Sample No. | Welding method                  | Current/A | Voltage/V |
|------------|---------------------------------|-----------|-----------|
| 1          | CMT                             | 100       | 14.0      |
| 2          |                                 | 110       | 14.2      |
| 3          |                                 | 120       | 14.4      |
| 4          |                                 | 130       | 14.7      |
| 5          | Short circuiting transfer        | 130       | 18.5      |

In this experiment, the bonding strength of aluminum bronze and ASTM1045 steel was tested according to the destructive testing method of the bimetallic bonding strength of sliding bearing which referred to the national standard GB/T12948-1991. The schematic and digital picture of sample is shown in Figure 2.

According to the regulations, the tensile speed was controlled by means of stress, and the applied value of stress was 10 N/(mm²·s). Until the specimen was ruptured, the maximum test load was recorded. Six replicate tests were performed on each group of samples. The relative error of the value was less than 10% and the bonding strength was calculated according to the following formula:

\[ R = \frac{F_{\text{max}}}{A} \]

Figure 2 Schematic (left) and digital picture (right) of the bonding strength test specimen

3. Result

3.1 Microstructure results of aluminum bronze alloy

The metallographic microstructures of aluminum bronze alloy are exhibited in Figure 3. The microstructures of Sample 1-3 are the same as that of Sample 4. From Figure 3(a), all of Sample 1-4 are \( \alpha + (\alpha + \gamma_2) \) microstructures of typical aluminum bronze, composed of black \( (\alpha + \gamma_2) \) phase and white \( \alpha \)-Cu matrix. Since the post-weld samples were all air-cooled, the \( \beta \)-phase was transformed into black \( (\alpha + \gamma_2) \) phase by eutectoid decomposition process based on the Cu-Al binary phase diagram.
As can be seen from Figure 3(b), the microstructure of sample 5 is distinctly different from those of the other samples. Iron-rich particles and dendrites are distributed on the white α-Cu matrix. According to Table 3, it can be found that due to the dilution effect of Fe, the composition of Al was changed from original 8.67 wt% to present 7.16%, so the matrix was composed of single-phase α-Cu grains. Fe exceeded the solubility in copper-aluminum binary alloy and precipitated into iron-rich particles and dendrites.

### Table 3 The results of EDS at three positions in Figure 4 (wt%)

| Position | Al  | Fe  | Cu  |
|----------|-----|-----|-----|
| 1        | 5.6 | 80.40 | 14.00 |
| 2        | 4.40 | 86.98 | 8.63 |
| 3        | 7.16 | 3.87 | 88.98 |

3.2 Interfacial structure of the aluminium bronze alloy/ASTM 1045 steel interface

The bonding strength between aluminum bronze and steel substrate depends on the microstructure at the interface. The interfacial microstructures of welding joints were firstly observed by OM, as shown in Figure 5. The interfacial structures of Sample 1-2 are the same as that of Sample 3. As shown in Figure 5(a), the demarcation line of the steel-copper of Sample 1-3 is clear and there is no obvious transition layer. As for Sample 4 and Sample 5, it can be found in Figure 5(b) and Figure 5(c) that dendrites grew perpendicularly to the interface. According to the results in Table 4, it is known that the dendrites are rich in iron.
Figure 5 Interfacial structure at the interface: (a) Sample 3, (b) Sample 4, (c) Sample 5

The interfacial microstructure and composition of the interface were further analyzed by SEM and EDS. The SEM images of the interface of different experiment conditions and results of line scanning are shown in Figure 6. The results of EDS at different positions are displayed in Table 4.

Figure 6 SEM and EDS analysis of the interfacial microstructure: (a) Sample 3, (b) Sample 4, (c) Sample 5
According to the results in Figure 6 and Table 4, there were no iron-rich dendrites at the interface of Sample 1-3. The Fe element just diffused into the copper alloy and the interaction range was only 2mm. On the interface of Sample 4 and Sample 5, the growth of iron-rich dendrites into the copper alloy was clearly observed. The interaction range was 15 mm and 13 mm, respectively.

### Table 4 The results of EDS at different positions in Figure 6 (wt%)

| Position | Al   | Fe   | Cu   |
|----------|------|------|------|
| 1        | 7.85 | 5.05 | 87.10|
| 2        | 8.48 | 4.13 | 87.39|
| 3        | 4.76 | 82.22| 13.01|
| 4        | 9.00 | 72.99| 18.01|
| 5        | 8.23 | 76.26| 15.51|
| 6        | 7.61 | 6.19 | 86.21|
| 7        | 7.12 | 78.85| 1.34 |
| 8        | 10.59| 72.96| 16.45|
| 9        | 8.28 | 4.04 | 87.64|

3.3 The bonding strength of aluminium bronze alloy and ASTM 1045 steel

The average test results of bonding strength of different samples are shown in Figure 7. The bonding strength of Sample 1-3 were similar, being 430.63 MPa, 435.92 MPa, and 450.84 MPa, respectively. The bonding strength of Sample 4 and Sample 5 were 528.17 MPa and 511.39 MPa, which were much higher than those of Sample 1-3. It can be seen that under the same welding material, the different bonding strength was caused by different welding parameters.

![Figure 7 The bonding strength test results of aluminum bronze alloy and steel substrate](image)

4. Discussion

4.1 Effect of different welding parameters on microstructure of aluminium bronze alloy

The metallographic microstructure and interfacial microstructure of Sample 1-3 were the same. This was because Sample 1-3 were all prepared by CMT welding, and the welding current was small, meaning that the heat input was relatively low. Therefore, only a small amount of iron diffused into the copper alloy and did not affect the metallographic microstructure of the copper alloy.

Although the interfacial microstructure of Sample 4 was similar to that of Sample 5, their metallographic microstructures were completely different. The welding current of Sample 4 and Sample 5 was both 130A. However, the heat input of Sample 5 prepared by short circuiting transfer
welding was significantly higher than Sample 4 prepared by CMT welding. Due to the large amount of iron diffusing into the copper alloy, the composition of Al was changed from original 8.67 wt% to present 7.16%, so the matrix was composed of single-phase α-Cu crystal. Fe exceeded the solubility in copper-aluminum binary alloy and precipitated into iron-rich particles and dendrites. The heat input of Sample 4 was between Sample 3 and Sample 5, so there were dendrites growing perpendicularly to the interface. Meanwhile, the microstructure was still α + (α + γ₂) microstructure of typical aluminum bronze.

4.2 Effect of different welding parameters on mechanical properties of aluminium bronze alloy
The bonding strength between aluminum bronze and steel substrate depends on the microstructure at the interface. The welding parameters were different, which led to various interfacial structures and caused the changes in bonding strength.

Due to the iron-rich dendrites, the interaction range at the interface of Sample 4 and Sample 5 was relatively large, 15 mm and 13 mm, respectively. There were no iron-rich dendrites at the interface of Sample 1-3 and the interaction range was only 2mm. Therefore, the bonding strength of Sample 4 and Sample 5 was much larger than that of Sample 1-3, and the bonding strength of Sample 4 is slightly larger than that of Sample 5. Samples 1-3 were very similar in terms of metallographic microstructure and interfacial structure, so bonding strength of them was also very close.

5. Conclusion
1) Sample 1-4 are α + (α + γ₂) microstructures of typical aluminum bronze. As for Sample 5, iron-rich particles and dendrites were distributed on the α-Cu crystal matrix. The demarcation line of the steel-copper of Sample 1-3 was clear and there was no obvious transition layer. As for Sample 4 and Sample 5, dendrites grew perpendicularly to the interface.
2) A cladding layer of S215 aluminum bronze was obtained on the surface of the steel substrate by CMT welding and short circuiting transfer welding. The bonding strength of Sample 1-5 were 430.63MPa, 435.92MPa, 450.84MPa, 528.17MPa and 511.39Mpa, respectively.
3) In the interface of aluminum bronze and steel substrate, the transition layer will get thicker when the interdiffusion distance between Fe and Cu elements is larger, it would be more conducive to increase the bonding strength.

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