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Interface microstructure evolution and mechanical properties of Al/Cu bimetallic tubes fabricated by a novel friction-based welding technology

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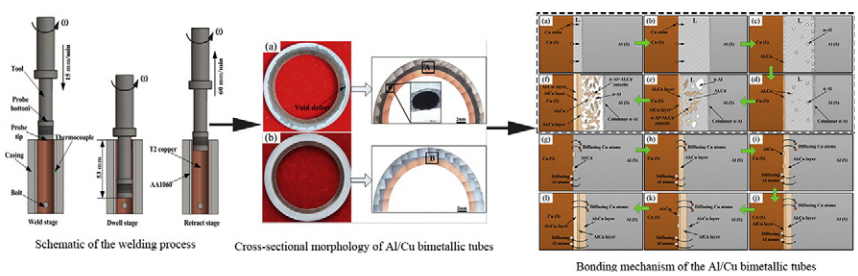
HIGHLIGHTS

- Al-Cu bimetallic tubes are fabricated by a novel friction-based welding.
- Columnar α-Al, intermediate transition layer and IMC are identified at 950 rpm.
- Al_2Cu is more significantly affected by rotational speed than AlCu and Al_2Cu_3.
- The intermediate transition layer and thick Al_2Cu weaken the bonding strength.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a novel friction-based welding technology was proposed for fabricating Al/Cu bimetallic tubes. The frictional heat and radial pressure during the friction-based welding process are used to achieve the metallurgical bonding between Al and Cu tubes in a rapid and efficient way. Successful joints indicate that this technology has the potential for fabricating bimetallic tubes. Microstructure evolution, bonding mechanism and mechanical properties of Al/Cu bimetallic tubes were also analyzed. Results reveal that columnar α-Al, intermediate transition layer and intermetallic compounds (IMC) are identified at the rotational speed of 950 rpm. While the rotational speed is decreased to 95 rpm, only solid-state diffusion occurs at the interface which results in three IMC layers, Al_2Cu, AlCu, and Al_2Cu_3. The thickness of the Al_2Cu is more significantly affected by the rotational speed than that of AlCu and Al_2Cu_3. Maximum hardness is observed at the reaction layer due to the formation of IMC. The appearance of intermediate transition and thick Al_2Cu layer weakens the bonding strength of bimetallic tubes. The joints are fractured at the reaction layers, and the fracture exhibits typical brittle characteristic. Three crack propagation paths are observed at the interface of Al/Cu bimetallic tubes.

1. Introduction

Cu tubes have been widely used as connecting pipes during the manufacture of air conditioners due to their excellent thermal conductivity. In recent years, as the price of Cu increases, the manufacturers have a great interest in the substitute of Cu tubes. Hence Al tubes have been used to replace Cu tubes in the air conditioners [1]. However, Al tubes are prone to deform during installation due to the lower strength in comparison with Cu tubes. Consequently, Al/Cu bimetallic tubes are proposed to increase the performance and decrease the manufacture cost [2,3]. Previous study showed that compared with Cu tubes, Al/Cu bimetallic tubes can reduce cost by 23–34% and weight by 36.5–46.3% [4]. Therefore, Al/Cu bimetallic tubes combine the advantages of Al and Cu, and have been used by manufacturers.

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At present, several methods have been used to manufacture bimetallic tubes, including traditional extrusion method [5], hydroforming technique [6], and magnetic pulse cladding [7], etc. The bonding mechanisms of the above methods belong to mechanical bonding, where plastic deformation resulted from the applied pressure is produced at the interface. Therefore, the interface has poor bonding strength, or is easy to fracture at high temperatures. In order to enhance the degree of bonding at atomic levels, spin-bonding [8] and shear extrusion [9] assisted by heating are successfully used to fabricate copper/aluminum composite tubes and aluminum/copper clad sheet, respectively. As described in the paper, however, the experiment system is very complex for spin-bonding, in return leads to the increase of manufacture cost. Some investigators tried to fabricate bimetallic tubes through explosive cladding [10,11]. Results show that a perfect metallurgical bonding was achieved at the interface, but uneven outer diameter and high surface roughness were also reported. Furthermore, security issues cannot be ignored during explosive cladding process. Overall, developing a new technology with a low cost and simple process to manufacture bimetallic tubes is very essential.

As a solid-state coupled thermo-mechanical process, friction stir welding (FSW) is a low cost, easy to set up and efficient welding process, which has been widely used to weld similar or dissimilar materials [12–16]. While some investigations indicated that even though Al/Cu have been successfully achieved by FSW [17,18], however, a mass of brittle intermetallic compounds (IMC) still exist at the joint interface. In comparison with butt and lap welding of plate, there are very limited investigations on the FSW of tubes. Packer et al. [19] presented FSW technology for joining ×65 pipes with a diameter of 324 mm and obtained a sound joint with superior mechanical properties. Lammlein et al. [20] tried to join Al-6061T6 pipes with a diameter of 107 mm by FSW technology, and pipe joints with sound internal and superficial appearance were obtained. More recently, Chen et al. [21] reported that the Al3003 tube and the pure Cu tube were successfully butt joined by FSW. Based on the development of FSW, friction stir back extrusion (FSBE) was proposed by Farha [22], and applied to produce pure copper tubes from solid cylindrical specimens [23]. Mathew et al. [24] have reported that AA6061 aluminum seamless tubes without any extrusion defects were successfully produced by the FSBE process.

It can be seen that FSW is feasible to realize the butt or lap joining of Al/Cu plates or tubes. To date, there is no attempt to fabricate bimetallic tubes based on the principle of FSW. In this study, therefore, a novel friction-based welding technology was proposed, where the inner tube and outer tube are fitted together by a casing and bolt. A tool with specially designed size moves downward along the centerline of the inner tube with constant rotational speed and welding speed. The frictional heat and the radial extrusion pressure are generated between the tool and the inner surface of the inner tube, and then the metallurgical bonding between the inner tube and the outer tube is achieved in a rapid and efficient manner. The Al/Cu bimetallic tubes were successfully manufactured, and the interface microstructure evolution and mechanical properties of Al/Cu bimetallic tubes were investigated.

Table 1
Procedures and chemicals for surface treatment.

Procedure	Chemicals	Operating condition
Alkali pickling	NaOH 40 g/L	50–60 °C, 2 min
Washing	H_2O	Room temperature, 2 min
Gloss finishing	HNO_3 250 mL/L	Room temperature, 2 min
Washing	H_2O	Room temperature, 1 min
Washing	CH_3CH_2OH	Room temperature

Table 2
Welding parameters.

Rotational speed (rpm)	Welding speed (mm/min)	Dwell time (s)	Retracting speed (mm/min)
950	15	2	60
600			
300			
95			

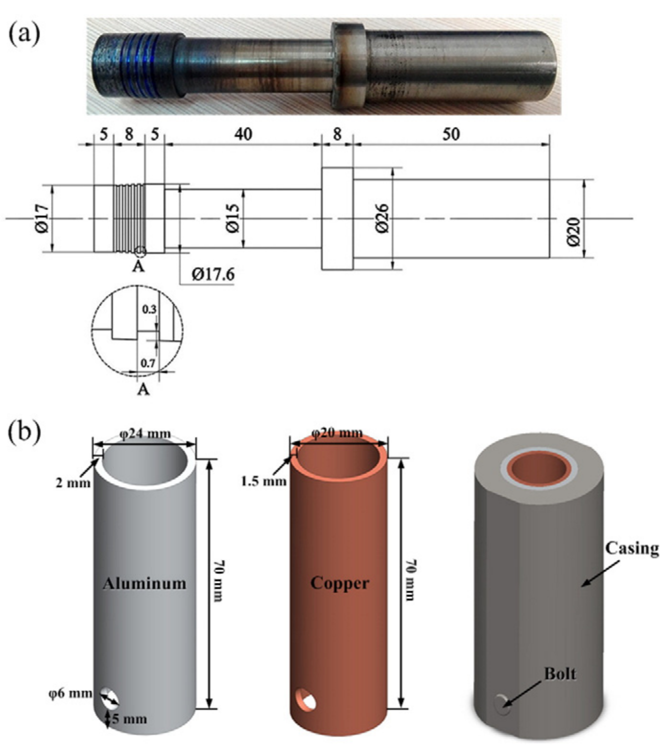

Fig. 1. (a) The welding tool, and (b) the assembled conditions of tubes.

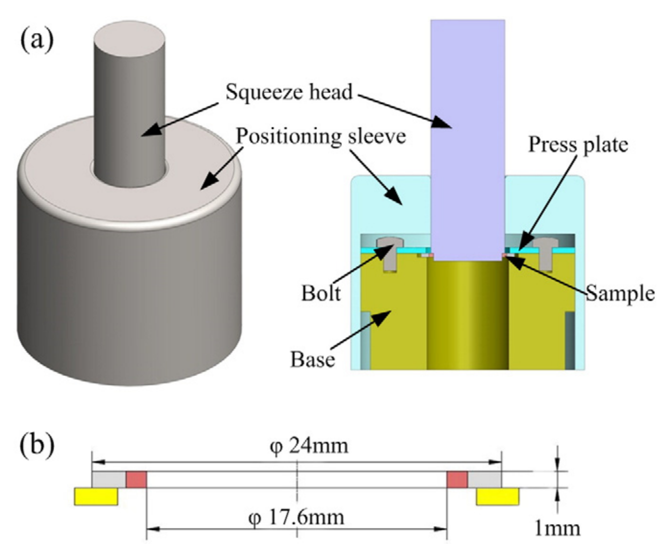

Fig. 2. Schematic diagram of (a) the shear strength test, and (b) the sample size.