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# Characteristics of clad aluminum hollow billet prepared by horizontal continuous casting

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ABSTRACT

The 3003/4045 clad hollow billets are prepared in the present study. Microstructures, solute distribution and bonding strength of the interfacial regions were investigated. The effects of plastic deformation on the evolution of microstructure and microhardness of the interfaces were also studied. The results show that metallurgical bonding between the solid and liquid Al alloys can be obtained with optimal parameters. Si and Mn atoms diffuse across the interface to form a diffusion layer with the thickness about 30 μm on average. The mean tensile-shear strength of as-cast clad hollow billet is 85.3 ± 9.2 MPa, and the strength of the interface is higher than that of 3003 alloy. Incompatible deformation between 3003 and 4045 layers occurs during rolling processes, and the needle-like Si phase transforms to the dispersive particles. The gradient distribution of microhardness across the interface is retained after the deformation.

## 1. Introduction

Bimetallic tubes which consist of layers of two different materials have been widely used in many industrial fields due to their excellent mechanical and functional properties relative to that obtained in monolithic alloy parts. These tubes can be conventionally produced by rolling (Mohebbi and Akbarzadeh, 2010), extrusion (Chen et al., 2003), ball attrition (Zhan et al., 2006), explosive bonding (Akbari-Mousavi et al., 2008), thermo-hydraulic fit method and hydraulic expansion method (Wang et al., 2005). However, the main disadvantage of these methods is that the metallurgical bonding without discontinuities along the interface cannot be achieved. Centrifugal casting (Sponseller et al., 1998) appears to be the ideal solution, but it is limited by the dimensions and shapes of the ingot. Recently, much attention has been directed to continuous casting. By this method, excellent metallurgical bonding between the two different alloys can be obtained. Meanwhile, it can offer the advantages of low energy consumption, low costs and a simple production procedure, compared with other methods. Gupta et al. (2007) and Wagstaff et al. (2006) prepared the clad ingot via Novelis Fusion process. Marukovich et al. (2006) investigated the possibility of continuous-casting of bimetallic components in condition of direct connection of metals in a liquid state. Sun et al. (2012) prepared 3003/4004 bimetal slabs by continuous casting. Wang et al. (2010) illustrated continuous casting of cladding aluminum alloys with electromagnetic brake. Fu et al. (2013) prepared Al–1Mn and Al–10Si alloys circular clad ingot by direct chill casting. However, most processes mentioned above focused on the preparation of bimetal slab or rod. Fabrication of clad hollow billet by continuous casting has not been reported due to the requirement of more complex crystallizer system and advanced technology.

AlMn 3000 series alloy and AlSi 4000 series alloy are two commonly used commercial alloys. The former has excellent corrosion resistance and the latter has good weldability. The clad tubes prepared from these two components can combine their advantages and be widely applied to many fields, such as automotive heat exchangers. However, Papis et al. (2008) indicated that an inherent difficulty in joining aluminum is its natural oxide layer, which is inert, thermodynamically stable, and not easily wettable by metallic melts. Inhibiting the formation of the oxide layer in the interface during casting process is favorable for the metallurgical bonding between the solid and liquid Al alloys.

In this paper, the clad hollow billet with internal layer of 3003 and external layer of 4045 was prepared by horizontal continuous casting. The outer and inner diameters of the billet are 80 mm and 50 mm, respectively, while the thickness of the external layer is 3 mm. Attention is paid to the properties of the interface and the bonding mechanism of the two alloys. Microstructures, composition distribution and tensile-shear strength of the interfacial regions were systematically investigated. In addition, the rolling procedures were used to study the microstructure evolution and

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**Table 1**
Chemical compositions of the commercial 3003 and 4045 alloys in weight percent.

| Alloys | Si | Mn | Fe | Al |
|---|---|---|---|---|
| 3003 | 0.2 | 1.0 | 0.3 | Bal. |
| 4045 | 10.5 | – | 0.2 | Bal. |

microhardness variation of clad billet after plastic deformation, which can offer a useful instruction for the further industrial application of the clad hollow billet.

## 2. Materials and methods

The raw materials were commercial 3003 and 4045 aluminum alloys with the chemical compositions given in Table 1. The experimental apparatus is schematically shown in Fig. 1. The 3003 and 4045 alloys were melted in their respective induction furnaces. When the temperature of 3003 reached 730 °C, the melt was poured into the line-frequency cored induction furnace. Then the drawing system started to work and the casting speed was 160 mm min$^{-1}$. After 5 min, the molten 4045 at the temperature of 690 °C was poured into the tundish and combined with the 3003 layer to form the 3003/4045 clad hollow billet. The flow rates of cooling water systems □ and □ are 1.5 m$^3$ h$^{-1}$ and 0.12 m$^3$ h$^{-1}$, respectively. During casting process, nitrogen gas was used as the shielding gas to protect the surface of internal layer from oxidation.

The rolling procedures are schematically shown in Fig. 2. The test samples were prepared with a length of 150 mm and width of 20 mm. The sample with a thickness of 15 mm was rolled at the temperature in the range of 450–500 °C to produce a 8 mm thick plate. Then the plate was cut into two sections along the dashed line. The smaller part (section A) was used for microstructure observation and hardness measurement, and the larger part (section B) was rolled into a 4.5 mm thick plate under the same rolling conditions. This process was sequentially repeated to prepare 2.1 mm and 1 mm thick plates. Thus four test plates were obtained by rolling processes.

The as-cast and rolled samples were ground, polished and etched using a solution of 1% HF + 99% $H_2O$ for 15 s. The microstructures of the interface were observed by optical microscope (MEF-3). The distribution of the Si and Mn elements across the interface in as-cast state was analyzed by electron probe microanalyses (EPMA-1600). In order to evaluate the interfacial strength, the tensile-shear tests were performed using a ZwickBZ2.5/TS1S test machine at a velocity of 1 mm min$^{-1}$. The microhardness was measured perpendicular to the interface of as-cast and rolled samples using a Vickers microhardness tester (MH-6) with an indentation load of 25 g for 5 s.

## 3. Results and discussion

### 3.1. Temperature distribution in the tundish

In order to combine the liquid and solid Al alloys by metallurgical bonding, the key issue is the temperatures of the two alloys when they contact with each other. The surface temperature of 3003 which was measured by thermocouples is in the range of 270–320 °C at the contact position. When the 3003

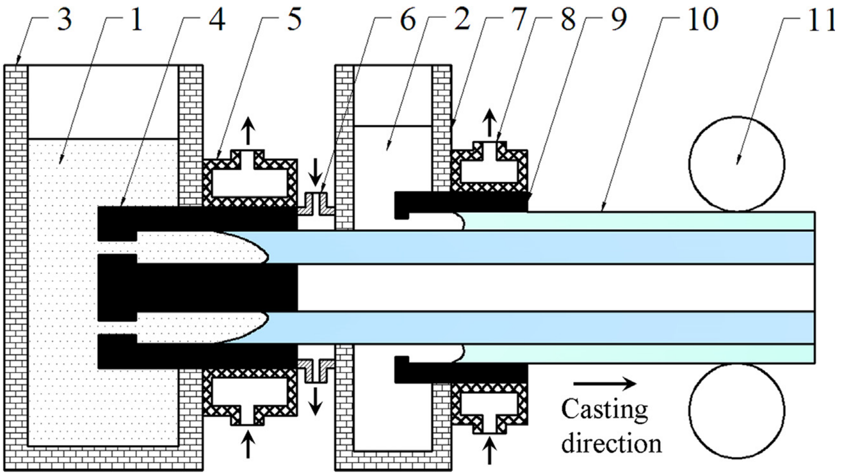

**Fig. 1.** Schematic illustration of experimental apparatus: 1 – 3003 alloy, 2 – 4045 alloy, 3 – line-frequency cored induction furnace, 4 – graphite mold □, 5 – cooling system □, 6 – shielding gas, 7 – tundish, 8 – cooling system □, 9 – graphite mold □, 10 – clad hollow billet, 11 – drawing system.

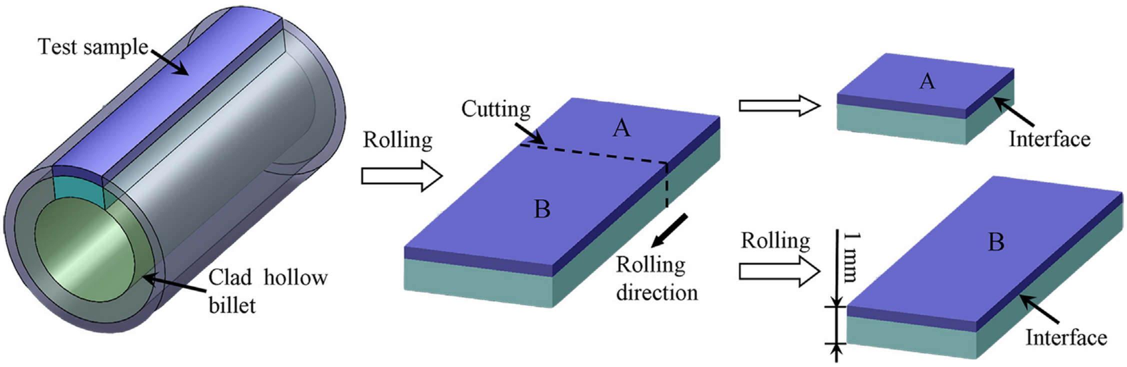

**Fig. 2.** Schematic illustration of the rolling deformation procedures of the clad samples.