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Direct-chill semi-continuous casting process of three-layer composite ingot of 4045/3004/4045 aluminum alloys

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Abstract: Three-layer composite ingot of 4045/3004/4045 aluminum alloys was prepared by direct-chill semi-continuous casting process, the temperature field distribution near the composite interface, macro-morphology, microstructure and composition distribution of the composite interface were investigated. The results show that semi-solid layer with a certain thickness forms near the interface due to the effect of cooling plate, which ensures successful implementation of casting the composite ingot. Two different aluminum alloys are well bonded metallurgically. The mechanical properties of composite interface were measured, the tensile and shearing strengths of composite interface are 105 and 88 MPa, respectively, which proves that the composite interface is a kind of metallurgical bonding.

Key words: aluminum alloys; three-layer composite ingot; direct-chill semi-continuous casting; composite interface; structures; properties

1 Introduction

Bimetallic composites have been widely used in industries due to their high strength and improved corrosion resistance compared with those obtained in monolithic alloys [1]. During the last several decades, many methods of producing multilayer composite ingots have been developed, involving diffusion bonding [2], explosive cladding [3], rolling [4] and casting. Among these methods, some are performed based on continuous casting techniques. Formation of multilayer composite plates fabricated by this technique is followed by plastic deformation processes, such as compression, rolling, extrusion or drawing, the process is more efficient and economical in comparison with other types of processing of multilayer composite ingots. More recently, several novel approaches have also been developed to produce multilayer ingots including continuous pouring process for cladding (CPC) [5], inversion casting [6], double-stream-pouring continuous casting (DSPCC) [7], continuous casting process for cladding with a level direct chill (DC) magnetic field (LMF) [8] and the Novelis Fusion^{TM} process [9]. CPC is mainly used for steel, the interface of ingots prepared by DSPCC is a kind of gradient interface, Novelis Fusion^{TM} process is a method of preparing composite ingots with a well-bonded interface, essentially free of oxides and pores.

Composite ingots of aluminum, also known as aluminum clad alloys, are generally produced by hot roll bonding [10], where the clad layer is bonded to the core by rolling under significant loads at elevated temperatures. This conventional process has many additional manufacturing steps. The clad layer must be produced via a separate route of casting, scalping, pre-heating, rolling and trimming to a necessary clad plate thickness and size. This process is very labor-consuming and also raises the cost significantly. Therefore, it is necessary to find a new method with low-cost and high efficiency to produce aluminum clad alloys. In this work, a method of producing multilayer composites by simultaneous continuous casting is proposed. One difference that distinguishes this method from conventional continuous casting is the mounting of cooling plates in traditional mold. The cooling plates served as divider walls divide the chamber of the mold into three separate ones to mate three melts with different

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alloy compositions. Another difference is that the solidification near the composite interface can be controlled. This can provide a relatively ideal temperature distribution in the region near the composite interface and make sure that three-layer composite ingots of 4045/3004/4045 aluminum alloys can be produced by semi-continuous casting. The composite ingot of 3004 and 4045 aluminum alloys can be used to produce brazing sheet after rolling. The brazing sheet consists of a lower melting point alloy clad to a higher melting point alloy, brazeable alloy core, which can be used in heat exchanger system of automobile and have a large commercial market [11].

2 Experimental

The casting process at initial and steady states are schematically shown in Figs. 1(a) and (b), respectively. The casting parameters and the chemical compositions of 3004 alloy and 4045 alloys are listed in Tables 1 and 2, respectively. During the casting process, 3004 alloy melt was firstly fed into the middle chamber enclosed by the mold and cooling plates, and held for a short time to form self-supporting surfaces adjacent to the cooling plates. Then, 4045 alloy melt was fed into bilateral chambers to contact with the self-supporting surfaces. Thus, the two alloys were joined together. With lowering the starting head, a composite ingot with three layers was cast.

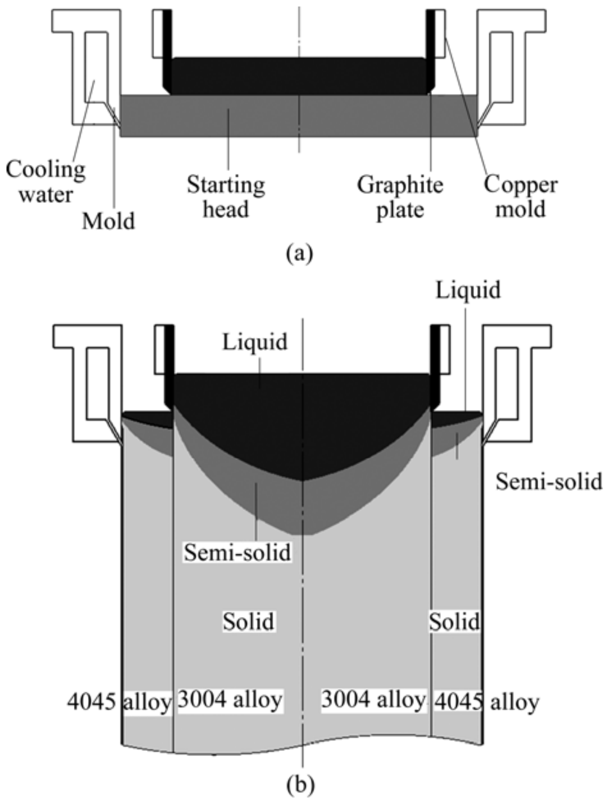

Fig. 1 Schematic diagrams of casting process at initial (a) and steady (b) states

Table 1 Casting parameters of composite ingot

Alloy	Casting temperature/°C	Casting speed/(mm·min^{-1})	Water flow rate/(L·min^{-1})
3004	715	45	80
4045	710		

Table 2 Nominal compositions of 3004 and 4045 alloys (mass fraction, %)

Alloy	Mn	Mg	Si	Al
3004	1.5	1.2	−	Bal.
4045	−	−	10	Bal.

To study the temperature field during casting, seven thermocouples were placed at different positions as schematically shown in Fig. 2 (top view). The thermocouples were vertically fixed to the stainless steel rods installed in the starting head and moved down with lowering the starting head. These thermocouples were linked to a data logger to record the temperatures every 0.5 s. When the casting was finished, the corresponding temperature data were transferred to a personal computer and then processed to yield a distance-temperature plot.

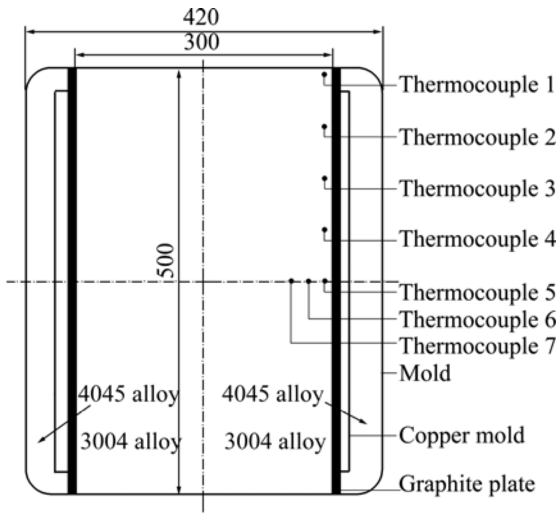

Fig. 2 Schematic diagram of thermocouple positions (top view)

Samples were cut from transverse section of the ingot. Macrostructures were observed directly. Microstructures were characterized by an SSX-50 type scanning electron microscope (SEM) equipped with an energy dispersive spectroscope (EDS). Mechanical property measurement of the composite interface was carried out on DDL Series Electronic Universal Testing Machines.

3 Results and discussion

3.1 Structures of composite interface and composition distributions across composite interface

Figure 3(a) shows the macrostructure of the transverse section in the composite ingot. The three alloy layers are revealed by two different contrasts. The interfaces separated by the three layers are planar and clean, suggesting that the composite interfaces are well bonded (4045 alloy and 3004 alloy are at the bilateral and middle parts of the transverse section, respectively). Detailed view of the composite interface is shown in Fig. 3(b). It can be seen that some needle-like primary silicon crystals (white part) are distributed at the boundaries of the coarse α(Al) grains (black part) in 4045 alloy, whereas some phases containing manganese (white parts) are embedded in the α(Al) matrix (black part) in 3004 alloy. As there are no obvious defects (such as cracks, porosities and mixture of the two alloys) observed, the two alloys are well bonded.

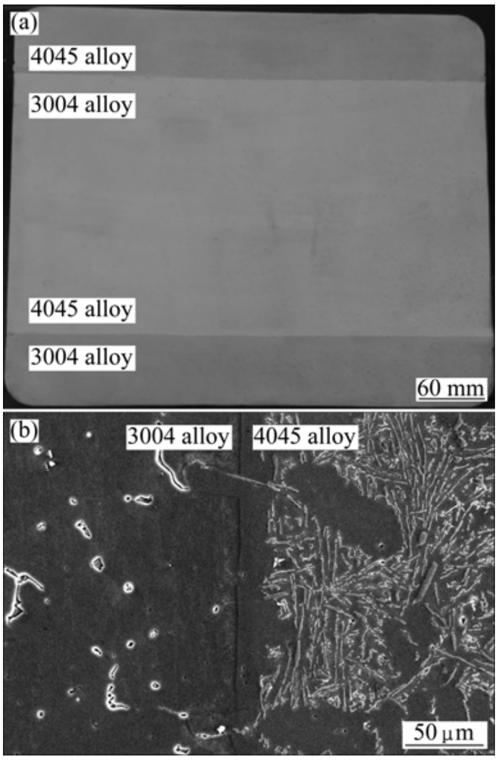

Fig. 3 Macrostructure (a) and microstructure (b) in cross section of composite ingot

Figure 4 shows the distributions of manganese, magnesium and silicon across the composite interface (denoted by black dotted line) by line scanning measurement. It can be seen that all these three elements diffuse across the interface, which implies that there is a kind of diffusion-occupied mass transport near the interface. This can ensure the quality of the bonding of the composite interface.

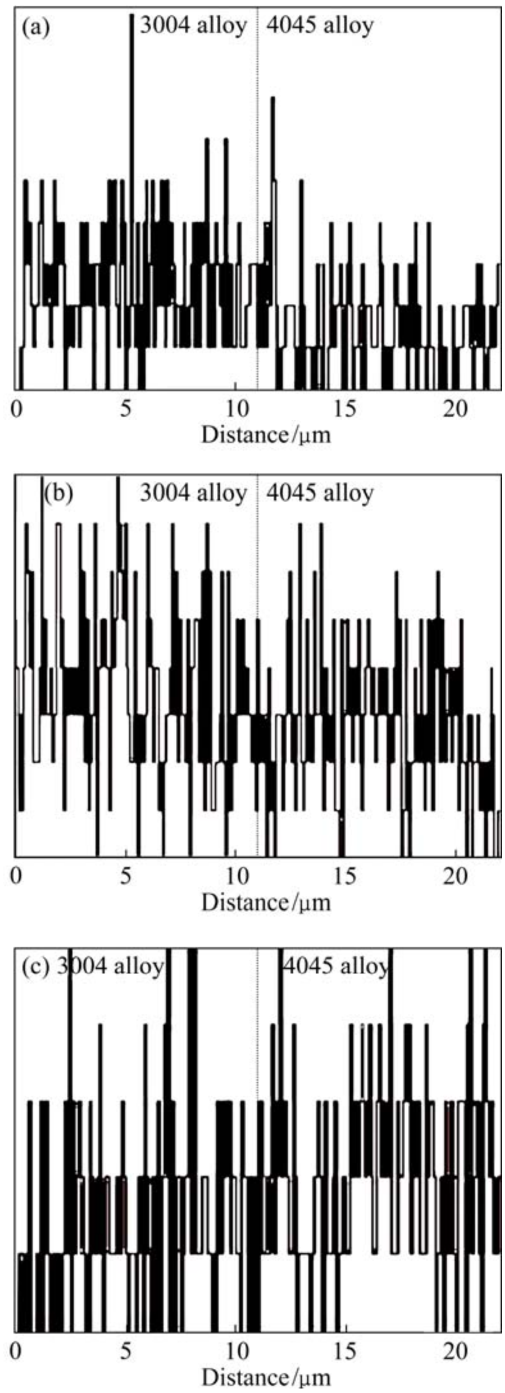

Fig. 4 Distributions of manganese (a), magnesium (b) and silicon (c) across composite interface

3.2 Mechanical property of composite interface

Figure 5 shows the conditions of tensile test and shearing test, respectively. The action area during the testing is 80 mm^2. The tensile curves are shown in Fig. 6. It can be seen that the tensile strength of the composite interface is about 105 MPa, and the shearing strength of the composite interface is about 88 MPa. The fracture position is just at the composite interface (as marked in Fig. 5). For 3004 alloy, the tensile strength is 180 MPa and the shearing strength is 110 MPa; for 4045 alloy, the tensile strength is 131 MPa and the shearing strength is 97 MPa [12], it can be seen that the strength of composite interface is a little lower than the master alloys, which indicates that the composite interface has a relatively high strength of bonding.

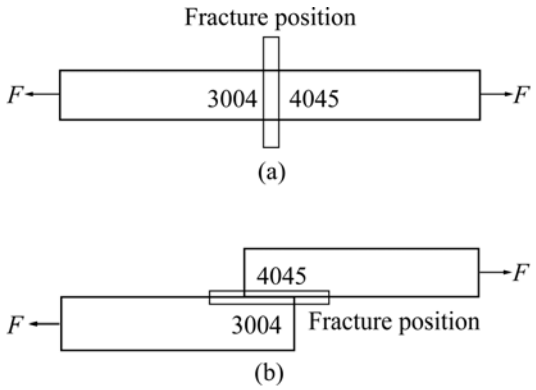

Fig. 5 Schematic diagrams of tensile (a) and shearing (b) tests

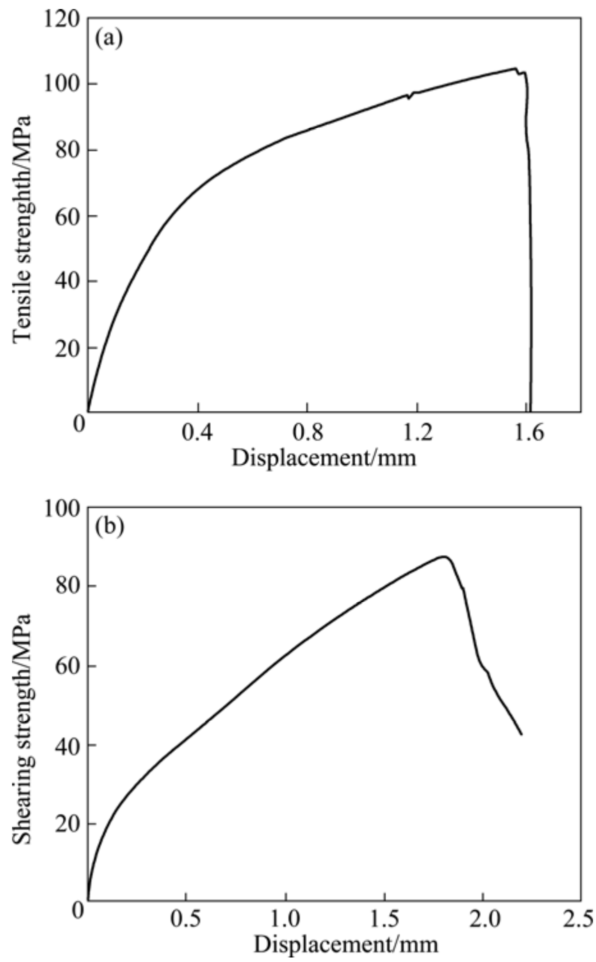

Fig. 6 Tensile strength — displacement (a) and shearing strength—displacement (b) curves of composite ingot

3.3 Cooling curves and temperature profile near composite interface during DC casting process

Figure 7 (a) shows the cooling curves (i.e. temperature change) recorded by thermocouples 5, 6 and 7 during casting. As a reference, the liquidus (655 °C) and solidus (630 °C) temperatures of 3004 alloy [13] are also given as two horizontal lines, respectively. According to the temperature fluctuation of thermocouple 5, the cooling process of 3004 alloy is divided into three phases — phase 1 (650−631 °C), phase 2 (631−636 °C) and phase 3 (636 °C−room temperature). In phase 1, it can be seen that the temperature of thermocouple 5 decreases from 650 to 631 °C (close to the solidus temperature) due to the effect of the cooling plate; whereas the temperature of thermocouple 6 is higher than that of thermocouple 5 and decreases slowly from 652 to 648 °C. This is because thermocouple 5 is adjacent to the cooling plate and thus the heat of the melt evacuates more quickly than that around thermocouple 6. As the cooling plate has little effect on thermocouple 7, the temperature almost

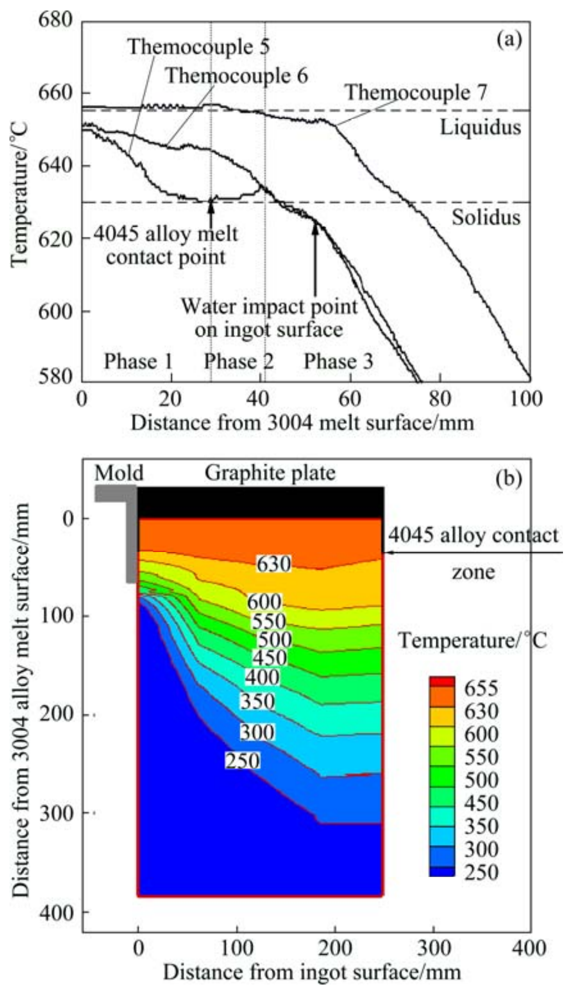

Fig. 7 Cooling curves of thermocouples 5, 6 and 7 (a) and temperature profile of composite interface during casting process (b)

remains unchanged. In phase 2, the temperature of thermocouple 5 rebounds slightly, and the rebounding should be attributed to the feeding of 4005 alloy melt into the bilateral chambers at the beginning of phase 2. The latent heat released from this melt reheats it. To prove this, the temperature of 4045 alloy melt at this moment is measured and the result shows that it is about 590 °C, which is a little lower than its liquidus temperature (595 °C), so a large amount of latent heat can be released at this moment. For thermocouples 6 and 7, mold cooling plays the major role during this process, so the temperature decreases to some extent. However, it should be noted that the temperature of thermocouple 6 drops faster than that of thermocouple 7 in phase 2, which is accounted to the fact that thermocouple 6 is closer to the mold than thermocouple 7. In phase 3, the temperatures of thermocouples 5, 6 and 7 decrease sharply due to the combined effect of mold and water cooling which are dominant in this phase. Figure 4 (b) shows the temperature profile near composite interface of 3004 alloy melt as determined from the temperature histories of thermocouples 1, 2, 3, 4 and 5. It can be seen that the temperature of composite interface is between the solidus and liquidus temperature of 3004 alloy melt when it is contacted by 4045 alloy melt, this is just the condition that composite ingot can be produced using DC casting as discussed later.

In Fig. 1, when 3004 alloy melt contacts the cooling plate, a self-supporting surface is formed adjacent to the cooling plate. 4045 alloy melt is brought to contact with the self-supporting surface. When the self-supporting surface is contacted by 4045 alloy melt, if the temperature of self-supporting surface is between the solidus and liquidus temperature of 3004 alloy, certain alloy components are relatively mobile across the interface that metallurgical bonding is facilitated. If 4045 alloy melt is contacted where the temperature of the self-supporting surface of 3004 alloy melt is sufficiently below the solidus temperature, and there is insufficient latent heat to reheat the interface to a temperature between the solidus and liquidus temperature of 3004 alloy, then the mobility of alloy components is very limited and a poor metallurgical bond is formed. This can cause layer separation during subsequent processing. If the self-supporting surface is not formed on 3004 alloy melt prior to 4045 alloy melt contacting it, then the alloys are free to mix and a diffuse layer or alloy concentration gradient is formed at the interface, making the interface less distinct. Also, the solid fraction of semi-solid layer contacted with 4045 alloy melt can be evaluated from Fig. 6(a), according to Gulliver-Scheil equation [14], the solid fraction f_s is expressed as

$$f_s = 1 - \left(\frac{T_m - T}{T_m - T_l}\right)^{1/(k-1)} \tag{1}$$

where T_m is the melting temperature of pure aluminum; T_l is the liquidus temperature and k is the partition coefficient of the alloy. For 3004 alloy, when the average temperature is 636 °C, f_s is about 0.95; when the temperature is at zero-strength temperature of 3004 alloy, f_s is about 0.81[15], this means that at this time, the self-supporting surface has some strength to support splaying forces normally causing the metal to spread out when unconfined, so the composite ingot can be produced by DC casting process.

4 Conclusions

1) Composite ingots of 4045/3004/4045 aluminum alloys are produced successfully by conventional direct-chill semi-continuous casting with cooling plates mounted in traditional mold.

2) The interface is well bonded, planar and clean with little evidence of porosity. The elements in the alloys can diffuse across the interface. The interface has a relatively high bonding strength. The bonding of the interface is a kind of metallurgical bonding.

3) Semi-solid layer with a certain thickness forms near the interface due to the effect of cooling plates, which can ensure the casting process of composite ingot.

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直接水冷半连续铸造制备 4045/3004/4045 铝合金三层复合锭

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摘 要：采用直接水冷半连续铸造法制备 4045/3004/4045 铝合金三层复合锭坯。考察复合界面附近的温度场分布，并研究复合界面的宏观形貌、微观组织及界面两侧的成分分布。结果表明，在冷却板的作用下，界面附近形成一层具有一定厚度的半固态层，从而保证半连续铸造过程制备复合锭坯的顺利实现。两种合金在界面处较好地冶金结合在一起。界面力学性能测试结果表明，复合界面的抗拉强度和剪切强度分别为 105 和 88 MPa，这进一步证明了复合界面的结合是一种冶金结合。

关键词：铝合金；三层复合锭坯；直接水冷半连续铸造；复合界面；组织；性能

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