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Effect of plastic deformation on microstructure and hardness of 2024/3003 gradient composite ingot prepared by continuous casting

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ABSTRACT

The effects of plastic deformation on the evolution of microstructure and micro-hardness were studied on plates made from a cylindrical composite ingot of 2024/3003 aluminum alloys. This ingot was produced by double-stream-pouring continuous casting. The results show that the as-cast microstructure has a dominant influence on the evolution of microstructure and the distribution of micro-hardness of the composite ingot. The three layers in as-cast composite ingot were maintained after compression and roll processing. The micro-hardness in all three layers in the composite increased and the grain size in these layers appeared to decrease as the number of compression or rolling passes increased. The microstructure evolution in the direction parallel to the applied load can be evaluated qualitatively using a simplified lamination model. The distribution variation in micro-hardness measured along the direction normal to the applied load can be attributed to the movement of transition layer and diffusion of alloying elements.

1. Introduction

Multilayer composite plates, also called sandwich strips, bimetallic or cladding plates, consist of layers of two or more different materials. There are many industrial applications for these bimetallic composite ingots and sheets due to their high strength and improved corrosion resistance relative to that obtained in monolithic alloy parts. A variety of other properties are also improved in such bimetallic ingots [1–9]. During the last several decades, many methods of producing multilayer composites ingots have been developed. These involve diffusion bonding [2], explosive cladding [3], rolling [4], and casting [5–9]. Some of these methods are based on continuous casting techniques. The formation of multilayer composite plates by continuous casting followed by plastic deformation processes, such as compression, rolling, extrusion or drawing, is more efficient and economical in comparison to other types of processing of multilayer composite ingots. Moreover, several novel approaches have recently been developed to produce multilayer ingots. These include continuous pouring process for cladding (CPC) [5], inversion casting [6,7], continuous casting process for cladding with a level DC magnetic field (LMF) [8], and the Novelis Fusion™ Process [9].

Recently, a method named double-stream-pouring continuous casting (DSPCC) was proposed to produce multilayer composites. This method is based on the concept of producing gradient materials by the simultaneous continuous casting of two different alloys [10,11]. One difference that distinguishes the DSPCC method from the conventional continuous casting is that the pouring system uses two sets of ladles, instead of one, to mate two melts having different alloy compositions. Another difference is that the crucial control of melt solidification is possible using the DSPCC method and these provide a means of changing the dimensions and properties of the interfacial zone. The dimensions and properties of interfacial zone can be controlled by adjusting the alloy composition and solidification processing parameters, such as the temperature of the melts, the cooling rate of the mold, the casting speed and the depth of the inner submerged nozzle in the mold. Under the right set of conditions these two streams of melts achieve a steady or quasi-steady mass and heat flow and partially mix in the mold. The degree of mixing obtained in the composite ingot depends largely on the aforementioned casting parameters.

The melt streams solidify in a sequential manner proceeding from the mold wall to the interior of the mold. The outside solidifies first, followed by the solidification of the transition zone and then by the solidification of the interior most liquid. Besides the strong metallurgical bonding between the two alloys, the main feature of DSPCC is that the composite ingots made using this method can achieve a macro-scale composition gradient in the casting cross section. When such kind of composite ingot endures plastic defor-

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mation, the width of the composition gradient can be adjusted over large range. As has been reported in many functionally gradient materials, the width of composition gradient in this transition zone plays an important role in determining the properties of the composites, such as the relaxation of the residual stress [12–14]. The ability to adjust the width and composition of the transition zone, thus provides the major benefit for the DSPCC casting method relative to the aforementioned alternate methods.

Preliminary work of DSPCC was carried out with binary Al–Si and Al–Cu alloy systems [15–16]. A system involving either an Al–Cu–Mg–Mn alloy or an Al–Mn alloy was studied after which a novel gradient composite ingot named 2024/3003 was prepared [17–19]. Since the 3003 aluminum alloy possesses excellent corrosion resistance and the 2024 alloy is a high strength aluminum material, the gradient composite ingot prepared from these two components is expected to combine their respective advantages. Microstructure and composition distribution of as-cast 2024/3003 composite ingots were previously reported [17], as was their heat treatment and the diffusion behavior of alloying elements [19]. An understanding of the evolution of microstructure and micro hardness after deformation processing is also important to the potential use of the 2024/3003 and similar composite ingots in commercial applications. The main purpose in this paper is thus to study the evolution of microstructure and property variation of as-cast 2024/3003 composites after plastic deformation. Attention is paid to the variation of microstructural appearance and micro-hardness distribution in the multilayer section of plates formed from the composite ingots after having been deformed first by compression and then by rolling.

2. Experimental

2.1. Materials and ingot preparation

The raw materials used in this paper were Al–1.5% Mn (nominal chemical composition, in mass%), similar to 3003 aluminum alloy, and Al–5.0% Cu–2.0% Mg–1.0% Mn, similar to 2024 aluminum alloy. The 3003 and 2024 aluminum alloys were prepared separately by melting the commercial, pure aluminum, manganese, magnesium, and copper metals and/or Al–10% Mn and Al–50% Cu master alloys. The processing procedure of preparing 2024/3003 gradient composites by DSPCC was described in our previous papers [17]. Several composite ingots, having a diameter of 65 mm and length about 500 mm, were prepared and used for a variety of tests including tensile testing and heat treatment response. Only one of these composite ingots was used in this paper. The casting parameters are as previously reported in literature [19].

2.2. Plastic deformations

The compression and rolling procedures that were used are schematically shown in Fig. 1. The test specimens were prepared by cutting a column having lengths of 150 mm from the 65 mm diameter ingot, 60 mm from the top of the ingot. The cut column was free compressed into a 16.5 mm thick plate with the rate of the movement of the upper punch rate set to 1.6 mm/s, and at temperatures within the range of 723–773 K. The compressed plate, about 15 cm in width and about 20 cm in length, was then cut into two parts, one-third of length of the plate, along dashed line B illustrated in Fig. 1. The smaller part was used as a specimen for microstructure observation and hardness measurement. The larger part was compressed into a 7 mm thick plate under the same compression conditions used for the initial, 16.5 mm thick free compression. This process was sequentially repeated to form 3 mm thick plates. Each was cut into two sections, again approximately one-third the distance along the length of the plate, a direction corresponding to the radial direction in the ingot. The smaller section was used for microstructural observation and micro-hardness testing while the larger piece was compressed into a thinner plate, repeating the previous compression procedure. Three test plates were thus prepared by compression processing.

The 3 mm thick plate was then used to prepare three more plates by roll processing. The edges of the 3 mm thick plate were milled prior to rolling. The 3 mm thick plate was then rolled at temperatures in the range of 723–773 K to produce a 2 mm thick plate. This process was sequentially repeated to form 1.3 mm and 1.0 mm thick plates. Again, each was cut into two sections, approximately one-third the distance along the length of the plate. A total of six plates were thus prepared from the composite ingot section, first by compression and then by rolling.

2.3. Structure observation and hardness testing

The surface of the sample for structure and hardness test is schematically shown by arrow C, as illustrated in Fig. 1. Keller's reagent and 0.5% HF reagent were used to etch the specimens for macro- and microstructure examination. The Vickers hardness in the specimen's transverse section was measured by an HVS-1000 micro-hardness tester under the load 4.9 N and a contact time

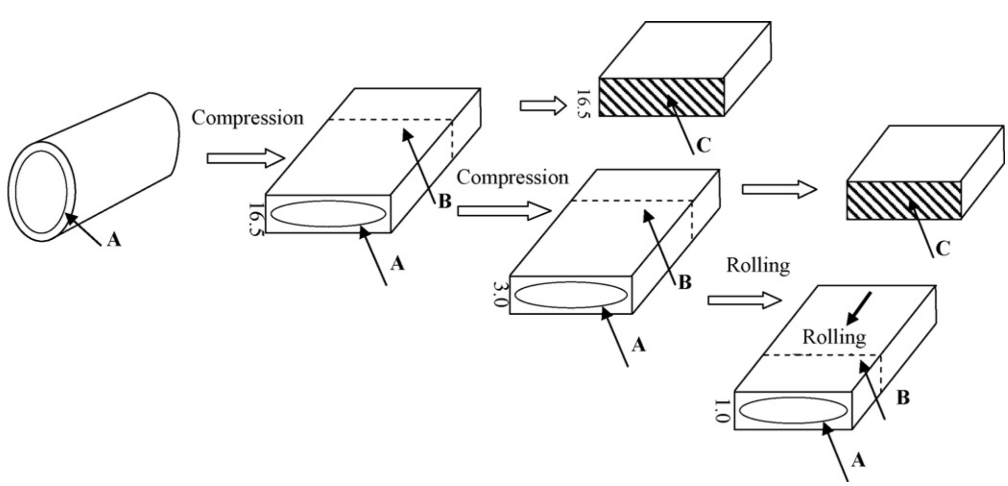

Fig. 1. Schematics of the plastic deformation procedures of the 2024/3003 composites. (A) The location of the transition region between internal and external region, (B) the location of the cutting of the plate, and (C) the surface for microstructure and hardness testing.