Effect of Homogenization and Extrusion on Microstructure and Mechanical Properties of Cladding Billet by Cladding Casting

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An AA4032/AA6069 cladding billet, fabricated by cladding casting process, was homogenized at 520°C for 12 h and then indirectly extruded into cladding pipe. The evolution in interfacial region was investigated in detail by the methods of optical microscope (OM), field emission electron scanning microscope (FESM), Vickers hardness, tensile and shear test. The interface region maintained original layered structure during the homogenization and extrusion process. During the process of homogenization, the eutectic silicon phases in AA4032 and Mg2Si in AA6069 became rounded markedly but still distributed dendritically. The homogenization improved the Vickers hardness and tensile strength of the interface region due to the precipitation strengthening and solution strengthening benefiting by element diffusion, and rarely affected the interfacial shear strength. The eutectic silicon and Mg2Si were spherized further and transformed into dispersive particles after extrusion process. Compared with that before deformation, the hardness of interface region got an obvious increase. The process of cladding casting and indirect extrusion is an idea method to fabricate cladding pipe. [DOI:10.2320/matertrans.MT-M2019234]

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1. Introduction

As now available and valuable industrial applications, multi-layer materials are playing increasingly roles in manufacturing industry due to the unique advantages.¹⁻³ It is an excellent comprehensive property, obtained from several single metals, that making the bimetal into an idea choice in the applications of aerospace, electronics, automobile manufacturing and so on.⁴ The bimetal can be fabricated by various methods, such as diffusion bonding,⁵ extrusion,⁶ powder metallurgy technology,⁷ rolling⁸,⁹ and casting. As a traditional technology, rolling process has been widely used to produce cladding sheets. However, there is an unsolved problem that the microscopic cracks in the interfacial region cannot be eliminated.¹⁰ Furthermore, low efficiency and high cost restrict roll-bonding process to develop.¹¹ With the development of science and technology, cladding casting is attracting more and more attention due to its efficient and economical advantages. More recently, some innovative methods have been developed including continuous pouring process for cladding (CPC),¹² inversion casting,¹³,¹⁴ continuous casting process for cladding with a level DC magnetic field (LMF),¹⁵ and Novelis Fusion⁶⁶ Process.¹⁶ However, these work and technologies mainly focus on the production process of cladding sheets. The heat treatment and the plastic deformation are rarely reported.

AA4032 owns excellent wear resistance and good high temperature strength and AA6069 is characteristic of good formability, corrosion resistance and medium strength. The combination of the two alloys just could meet the requirements of the aircraft, automotive and construction industries.

In this study, AA4032/AA6069 cladding billet was fabricated by cladding casting technology.¹⁷ The effect of homogenization and extrusion processes on interfacial characteristic was investigated.

2. Experimental Procedures

2.1 Cladding casting of AA4032/AA6069 cladding billet

The material used in this study is AA4032/AA6069 cladding billet in size φ130/φ110 mm × 2000 mm prepared via cladding casting technology. The clad-layer, AA4032, has the composition of 12.6 mass% Si, 1.0 mass% Cu, 1.0 mass% Mg, 1.0 mass% Ni and 84.4 mass% Al and the clad-layer, AA6069, has the composition of 1.0 mass% Si, 0.8 mass% Cu, 1.5 mass% Mg, 0.2 mass% V and 96.5 mass% Al. As shown in Fig. 1(a), AA6069 melt was poured into inner-mold firstly, and it started to solidify and immediately formed solid shell (i.e., supporting layer). Then, the starting head was steadily downward, and AA4032 melt was fed into outer-mold meanwhile. AA4032 melt with high temperature reheated the supporting layer. The backheating phenomenon accelerated elements diffusion across the interface. According to the optimized casting parameters, as shown in Table 1, cladding billets with a desired length was obtained. Figure 1(b) shows the feature in cross section of the as-cast cladding billet.

2.2 Extrusion of AA4032/AA6069 cladding pipe

In order to release the residual stress and eliminate the dendrite segregation of non-equilibrium phases, the cladding billet was homogenized at 520°C for 12 h, followed by air-cooled to 20°C. The temperature of cladding billets rose with heat-up rates 3°C/min in the pit-type electric resistance
furnace. Then, the cladding billet was machined into a size of $\varnothing 128 \text{ mm} \times 350 \text{ mm}$.

The extrusion process included two steps: firstly, the cladding billet was perforated by a needle perforation diameter of 50 mm; secondly, indirect hot extrusion was carried out in a 20 MN extruder with a container diameter of 166 mm and an extrusion pecker diameter of 25 mm (as illustrated in Fig. 1(c)). The hot extrusion procedure is determined as shown in Table 2. Figure 1(d) shows characteristic in cross section of the as-extruded cladding pipe.

2.3 Characterization

Optical microscopy (OM, Leica-500), Vicker hardness (452SVD automatic turret), and field emission electron scanning microscope (FESEM, Zeiss Ultra Plus 60) with energy dispersive X-ray analyzer (EDX) were carried out to examine the microstructures in the as-cast, as-homogenized and as-extrude samples. Samples for microstructure were eroded by a solution of 0.5\% \(\text{HF} + 99.5\% \text{H}_2\text{O}\) (in volume) for 20 seconds. To investigate the mechanical behavior of as-cast and homogenized cladding billet, shear tests were test by an MTS-810 universal testing machine. The mechanical samples were taken from the top, the middle and the bottom of the cladding billet, i.e., position 1, position 2 and position 3. All the tests results were averaged from three effective values.
3. Result and Discussion

3.1 Interfacial characteristic of as-cast and homogenized cladding billets

The interface, which distinctly separates the two alloys, is planar and clear, as shown in Fig. 1(b) and (d). As elaborated in our former work, firstly, AA6069 was poured into the inner-mold, some equiaxed grains formed based on the substrate and the melt solidified along the direction of heat flux, forming coarse columnar zone. In the center of billet, the isotropic heat transfer resulted in the formation of equiaxed grains. The other melt, i.e., AA4032 melt, flowed into outer-mold through the launder, contacted with the supporting layer and the outer-graphite, and then was chilled intensely. Therefore, the external of cladding-layer was composed of fine equiaxed grains, whereas the internal was consisted of coarse columnar crystals, as shown in Fig. 1(b). After homogenized, the cladding billet was extruded indirectly into clad pipe.

During homogenization and extrusion process, the interface region maintained original laminar characteristics. Figure 2 shows the interfacial microstructure of the as-cast, homogenized cladding billet and as-extruded cladding pipe. Figure 3(a) shows the interfacial microstructure and the solute distribution of elements. As shown in Fig. 2(a), the α-Al and fine acicular Si (A) distribute on AA4032 side, and some precipitated phases distribute on the other side. According to the EDS (Energy Dispersive Spectrometer) results, the precipitated phases contain Mg2Si (B), Al3Ni2 (C), AlMgSiCu (D), and so on. The elements (Mn, Ni, and Cu) distribution reveals that there is a transition at the interface, indicating that elements diffused across the interface because of the concentration gradient of elements in the two sides, as shown in Fig. 3(a).

During homogenization process, the acicular eutectic silicon and the precipitated phase at the grain boundary became rounded obviously and smooth, and still distributed dendritically at the grain boundary, which is similar to that of as-cast interfacial microstructure, as shown in Fig. 2(b). After homogenization, as shown in Fig. 3(b), the eutectic silicon phase of the AA4032 became rounded. Meanwhile, the precipitated phases of the AA6069 and Mg2Si of the two alloys were reduced because of the solution in the matrix and the redistribution of Mg, Cu and Ni elements.

3.2 Mechanical properties of as-cast and homogenized cladding billets

The as-cast hardness and homogenized is shown in Fig. 4. The mean Vickers hardness of AA4032 and AA6069 after homogenization was 121.1 HV and 94.9 HV, which improved 6.1% and 5.7% than that of the as-cast, 114.2 HV and 89.7 HV. It is the precipitation strengthening and solution strengthening that brought an obvious improvement in the interfacial hardness.

Tensile test was introduced to examine the bonding strength of the as-cast and homogenized cladding billets. Figure 5 shows tensile test results. Both the two fractures located the AA6069 side, while the interfaces were excellent without damage, as shown in Fig. 5(a). For the as-cast, the average tensile strength was 224.1 MPa, which is close to that of AA6069. After homogenized, the tensile strength rose to 231.2 MPa, as shown in Fig. 5(b). Lloyd reported that plasticity mainly occurs in the softer side of the laminated tensile samples, and failure occurs when the ultimate tensile strength of the softer side is reached. This point of view has been verified by the present results.

In order to quantitatively measure interface strength and have a profound understanding, shear test was introduced and then the fracture morphology was examined using FESEM. Figure 6 shows the shearing strength of as-cast and homogenized samples, and the shearing fractures are illustrated in Fig. 7. The mean shear strength after homogenization is 161.3 MPa, which is close to that of the as-cast, 159.3 MPa. For the as-cast, the fracture surface morphology was characterized by cleavage fracture and plastic fracture with several shallow dimples, as shown in Fig. 7(a) and (b). After homogenized, the fracture surface morphology was characterized by plastic fracture with weeny and dense dimples, as shown in Fig. 7(a’) and (b’). On the one hand, the stress caused by solidification was released during the homogenization process, resulting in the reduction of hardness and strength. On the other hand, the homogenization process promoted elements to diffuse in the interface region and the elements were functioned as solution strengthening elements. It is the inverse effect of them on the interface strength that made a negligible change of the strength value. In general, the homogenization process played a role solid solution strengthening for the Vickers hardness.
According to the detection of the interface bonding strength, it reveals that the interfacial bonding interface is high enough to prevent the relative sliding behavior during extrusion process.

3.3 Detection of as-extruded cladding pipe

After extruded into cladding pipe, the cladding pipe kept the laminar characteristic like that of the as-cast state and no defects appeared around the interface, as characterized in Fig. 8. In the two sides, larger plastic deformation occurred.

Fig. 3 EDS analysis results of elements distribution around the interface: (a) as-cast; (b) homogenized.
Fig. 4 Comparison of Vickers hardness between the as-cast and homogenized cladding billet.

Fig. 5 Tensile test: (a) fractured samples, (b) tensile strength at different regions of the cladding billet.

Fig. 6 Shear strength at different regions of the cladding billet.

Fig. 7 Morphologies of shear fracture of the interface: (a) as-cast AA4045 side; (b) as-cast AA3003 side; (a’) homogenized AA4045 side; (b’) homogenized AA3003 side.
along extrusion direction. The large needle-like eutectic silicon and Mg$_2$Si were spherized further and transformed into dispersive particles. According to the EDS analysis result, Mg$_2$Si was reduced further and some phases containing Cu and Ni were precipitated, as shown in Fig. 9.

Figure 10 shows the microhardness distribution across the interfacial region after extrusion process. Compared with the interfacial hardness before deformation, the interfacial microhardness in each side of the cladding pipe stayed almost constant and increased obviously nearby the interface, which was attributed to work hardening behavior and inner-diffusion of elements at the interface during extrusion process. In addition, there a microhardness gradient in interfacial region of the as-extruded cladding pipe, which was accorded with the interfacial characteristic of laminate composites.21)

Fig. 8 Interfacial microstructure of as-extruded cladding pipe.

Fig. 9 EDS analysis results of elements distribution around the interface of as-extruded cladding pipe.
4. Conclusions

(1) The qualified AA4032/AA6069 cladding billet was faultlessly prepared by cladding casting process. After homogenized at 520°C for 12 h, the as-cast cladding billet was extruded into cladding pipe with no pore or inclusion.

(2) During homogenization and extrusion process, the interface region maintained original layered structure. The eutectic silicon and Mg2Si became rounded obviously and still distributed dendritically during homogenization process, while they were spheroidized further and transformed into dispersive particles after extrusion process.

(3) The homogenization process, which played a role solid solution strengthening for the Vickers hardness, made an obvious improvement in the Vickers hardness and the interfacial tensile strength of the interface region, but rarely affected the interfacial shear strength.

(4) Compared with the interfacial hardness before deformation, the microhardness of the interface region got an obviously increase because of work hardening. The process of cladding casting and extrusion is an idea method to fabricate cladding pipe.

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