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An improved process for grain refinement of large 2219 Al alloy rings and its influence on mechanical properties

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A B S T R A C T

The large 2219 Al alloy rings used to connect propellant tank components of a satellite launch vehicle to each other are conventionally manufactured by radial-axial ring rolling at 460 °C with 50% deformation, but often suffer from coarse elongated grain and low ductility. An improved process (hot ring rolling at 460 °C with 30% deformation, then air cooling to 240 °C, followed by ring rolling at 240 °C with 20% deformation) was tested for ring manufacturing. The corresponding microstructure evolution and mechanical properties of the produced rings were studied. The results show that the improved process can successfully be applied to manufacture the large 2219 Al alloy rings without formation of macroscopic defects, resulting in a product with fine and uniform grains after heat treatment. The fracture mechanism of both rings was mainly intergranular fracture. With the resulting grain size refinement due to the improved process, more homogeneous slip occured and the crack propagation path became more tortuous during the tensile testing process. Thus, the elongation in all three orthogonal directions was greatly improved, and the axial elongation increased from 3.5% to 10.0%.

1. Introduction

Propellant tanks used for the storage of liquid oxygen and liquid hydrogen are important parts of a satellite launch vehicle. A connecting ring is needed to connect the components of the propellant tank to each other by welding. The connecting ring bears significant stress during operation, requiring high strength and high ductility. The 2219 Al alloy is the material of choice for the connecting ring due to its excellent weldability and good mechanical properties at low temperatures [1]. The traditional formation of the ring was by roll-bending a profile and followed by welding. However, this approach results in multi-welds, low dimensional accuracy, and poor uniformity of mechanical properties, and also requires long-term production scheduling. Compared with traditional manufacturing technologies, ring rolling offers high efficiency, processing precision, low energy consumption, good microstructure, and good performance, therefore, this technology is used for the manufacturing of large 2219 Al alloy rings.

As a typical ring rolling method, radial-axial ring rolling (RARR) adopts two radial rolls and two axial rolls to restrain both radial and axial spreads, allowing the manufacture of large scale seamless rings with high surface quality. RARR is an extremely complex dynamic rolling process with high flexibility, and the techniques to achieve stable formation condition for RARR have been studied by many researchers. For instance, Hua et al. [2] derived the stiffness condition of the ring in RARR required for a stable rolling process. Guo and Yang [3] developed a mathematical model of the steady formation condition for RARR based on the constant growth velocity condition. Quagliato and Berti [4] predicted the evolution of ring geometry during the RARR process. Hua et al. [5] established a mathematical model of ring stiffness condition for RARR based on the force method and formed a super-large ring (9500 mm) with good dimensional accuracy. Thus, methods are available for the stable rolling of large rings.

However, it remains a challenge to obtain the expected microstructures and mechanical properties for large 2219 Al alloy rings. To meet the growing needs of the aerospace industry, larger propellant tanks are required. Xu et al. [6] reported that the outside diameter of the largest connecting ring is about Ø9500 mm. To manufacture this huge ring by integral formation, an ingot with a diameter larger than Ø1200 mm is required. Yang et al. [7] found

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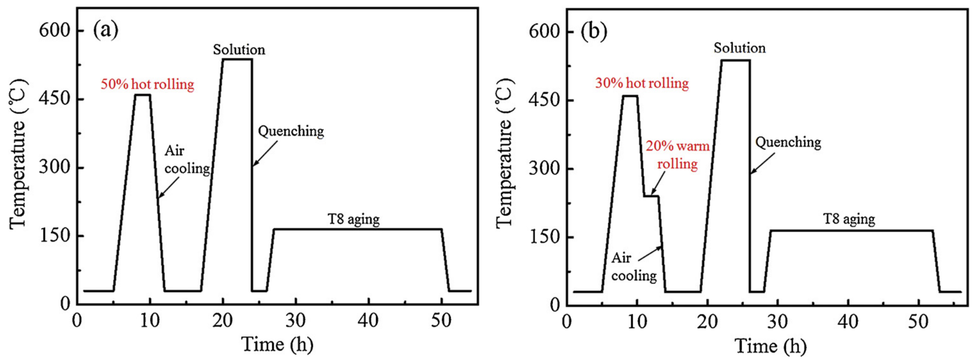

Fig. 1. Schematic of manufacturing process: (a) conventional process; (b) improved process.

that the solidification cooling rate of such a large ingot during casting is relatively low, and the cooling rate along the radial direction is not uniform, so the formed ingot may suffer from problems of coarse grain, uneven microstructure, and other casting defects that will decrease the overall mechanical properties of the material. Guo and Yang [8] also showed that the ring rolling process can result in inhomogeneous deformation in each direction (with flow mainly in the circumferential direction). Thus, it is easy to form coarse grain with an elongated shape in the final ring, causing low ductility and significant anisotropy in the large rings. Low ductility, in particular, has become the main problem restricting the application of the large connect ring, because it reduces the reliability of propellant tank systems.

Grain refinement is an important approach to improve the comprehensive mechanical properties of Al alloy products [9–11]. Therefore, grain refinement of Al alloys has been performed by severe plastic deformation [12], cryo-rolling [13], and thermomechanical treatment (TMT) [14]. Of these methods, TMT can be used to economically produce materials that are large enough for real structural applications [15]. Overall, fine-grained materials with excellent mechanical properties can be produced by TMT for a variety of applications.

Russo et al. [16] designed the first TMT strategy to fabricate fine-grained 7075 Al sheets, in a process that involved low-temperature homogenization, warm deformation, and solutionizing (static recrystallization). Ward et al. [17] refined the grain sizes of the 7075 Al alloy sheet to 15 μm by homogenization, air-cooling, cold deformation, and solutionizing, and increased the elongation of the sheet by 52%. Kaibyshev et al. [18] applied a TMT process (over-aging, low-temperature rolling, recrystallization annealing, over-aging, cold rolling, and recrystallization annealing) to refine the grain size of 2219 Al alloy, resulting in a uniform grain structure with an average grain size of 12 μm in material that exhibited superplasticity. Huo et al. [19] proposed a TMT process of solutionizing, warm rolling, continuous rolling, and solutionizing for 7075 Al alloy sheets, which significantly refined the grain size, notably improved the ductility of the material, and maintained high strength.

The common feature of the above-mentioned TMT processes used for grain refinement in Al alloy is the application of cold deformation or warm deformation to acquire high defect density. This leads to increased nucleation sites for recrystallization during subsequent annealing or solution treatment and results in a finer grain structure. In this study, based on the technical characteristics of ring-forming, an improved process with warm rolling in the final stage of ring-forming, followed by solution and T8 aging treatment, was proposed to manufacture connecting rings. Using the large Ø3350 mm 2219 Al alloy ring as an example, the effects of the improved process on grain refinement and the mechanical properties in three orthogonal directions were studied. The appropriate parameters of ring rolling for the manufacture of high-quality 2219 Al alloy large rings were described.

2. Experimental

The experimental material was a large 2219 Al alloy casting with the chemical composition of Al-6.2Cu-0.36Mn-0.11Zr-0.1V-0.10Fe-0.06Si-0.01Mg-0.10Zn-0.05Ti (wt%). The casting was supplied by Central South University, China. The manufacturing process of this casting was reported by Li et al. [20]. Casting billets with a machined dimension of Ø600 mm × 1580 mm were cut from a large casting of Ø650 mm × 4800 mm. These casting billets were processed by multidirectional forging (MDF) at 460 °C and then expanded by free forging at 460 °C, to obtain ring billets with dimensions of Ø1900 mm × Ø1500 mm × 390 mm.

Radial-axial ring rolling was performed according to two different procedures, as shown in Fig. 1. One of the rings was continuously rolled at 460 °C (hot rolling) and this expanded the ring billet to Ø3385 mm × Ø3155 mm × 352 mm (conventional process). The second ring was hot rolled to Ø2750 mm × Ø2460 mm × 352 mm at 460 °C, air cooled to 240 ± 10 °C, and then ring rolled at 240 °C (warm rolling), expanding the ring to Ø3385 mm × Ø3155 mm × 352 mm (improved process). The processing parameters of the improved process were based on experimental results of small-sample studies in the laboratory, which revealed that warm rolling at 200–280 °C with 20% deformation could significantly refine the grain structure, but warm rolling at 160 °C with 20% deformation caused the cracks. Therefore, warm rolling at 240 °C with 20% deformation was chosen to manufacture the ring with comprehensive consideration of grain refinement and cracking risk.

Fig. 2 shows the forming principle of RARR. During RARR, compression of the ring occurred in the radial direction (RD) between the main roll and mandrel, as well as in the axial direction (AD) between the upper axial roll and lower axial roll, causing reduced radial thickness and axial height, thus expanding the diameter of the ring. The addition of the axial rolls allowed the control of metal flow in that direction and prevented the fishtailing defect that can appear in the radial ring rolling process (loading only applied in the radial direction). The tangential velocity of the main roll throughout the rolling process was 1000 mm/s. The feed rate of the mandrel was 0.4–0.6 mm/s during hot rolling and ~0.1 mm/s during warm rolling. The feed rate of the upper axial roll was 0.2–0.3 mm/s during hot rolling and 0 mm/s during warm rolling. In addition, the lubricant (a mixture of water and BN) was sprayed on the ring intermittently to improve the deformation uniformity and to prevent an excessive rise in the temperature. Thus, the deformation temperature of the ring during hot rolling and warm rolling can be controlled in the range of 460–430 °C and 240–220 °C, respectively.