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Evolution of microstructure and mechanical properties of Al 6061 alloy tube in cyclic rotating bending process

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ABSTRACT

To refine the microstructure and improve the mechanical properties of metal tubes, a new concept of severe plastic deformation process of cyclic rotating bending (CRB) was newly introduced. The current study focused on the investigation of evolution of microstructure and mechanical properties of Al 6061 tube in the CRB process with different deformation conditions. For this purpose, the CRB processes were performed with different deformation temperatures, bending angles and deformation times. The tensile test and Vickers hardness test were employed to evaluate the tensile properties and micro-hardness of the tube, respectively. While the Optical Microscope and Scanning Electronic Microscope equipped with Electron Back-Scattered Diffraction were utilized for the microstructure characterizations. The results shows that the deformation temperature, bending angle and deformation time have the strong influences on the mechanical properties and microstructure of the tubes processed by the CRB process. As a result, the tube with an average grain size of about 55 μm, as well as ultimate tensile strength of 244 MPa and total elongation of 10.05% was successfully obtained with the optimized deformation condition of the CRB process with a temperature of 100 °C, bending angle of 174°, the rotation speed of 20 r/min, and deformation time of 5 min, respectively.

1. Introduction

Due to the shortage of energy and greenhouse gas emissions which resulted in the more and more serious problem of global warming, improving the fuel efficiency is a necessary way to reduce the environmental impact of using fossil fuels. In the last several decades, the lightweight technology was proposed to reduce of the weight and improve the fuel efficiency of vehicles [1]. To date, lightweight technology has gradually become the key point in the field of transportation machinery manufacturing. For this purpose, the use of structural aluminum alloys in the automotive, aerospace, and marine industry to decrease the overall weight of the mechanism implemented within the transportation devices has received the increasing attentions. Aluminum alloys have advantages of low density, excellent wear resistance, relatively low coefficient of expansion and so on. In addition, it is also an effective method to realize the lightweight of transportation machinery by using the hollow structures instead of the solid ones. Therefore, the utilization of the aluminum alloy hollow structures can significantly reduce the weight of transportation machinery. However, the low strength and ductility of aluminum alloys has limited their extensive application in industry. To meet the both requirements of the safety and lightweight, the aluminum alloy hollow structure with high strength as well as good ductility is urgently desired.

On the other hand, in the research field of material science, many researches have been dominated that the heavy plastic deformation may refine grains of metals and make them very strong [2]. And many severe plastic deformation (SPD) processes have been proposed and used to refine the microstructure and improve the mechanical properties of metallic materials [3]. The SPD processes such as Equal Channel Angular Extrusion (ECAE) [4], Repetitive Side Extrusion [5], Rotary-die ECAP [6], Parallel Channel ECAP [7], Accumulative Roll-Bonding (ARB) [8], High-Pressure Tube Twisting (HPTT) [9], Twist Extrusion (TE) [10] etc. have been widely used in metallurgy research field. Many related results have been reported in the last several decades. Furushima et al. [11] have successfully obtained the magnesium alloy tube with an average grain size of 1.5 μm by ECAP and extrusion molding process. Tóth et al. [9] proposed a new technology of High-Pressure Tube Twisting (HPTT) process that was suitable for deforming thin-walled tubes to extremely large strains. Their research results

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showed that deformation of the Al samples resulted in full plastification in the Al sample. Additionally, Arzaghi et al. [12] studied the refinement of the microstructure of pure aluminum tube by HPTT process, and the results showed that the microstructure was successfully refined and the mechanical properties of the tubes were significantly improved by the HPTT process. Munoz-Morris et al. [13] proposed that the good strength and ductile of the material of Al-Cu-Li can be obtained by the ECAP process with the reasonable deformation conditions. Horita et al. [14] and Furnkawa et al. [15] studied that expected mechanical properties and microstructure can be obtained by controlling the process parameters.

From what has been discussed above, it can be concluded that the SPD technologies is an effective method to refine microstructure and improve mechanical properties of metallic materials. However, the special tools or dies are needed to realize most of the deformation processes mentioned above. In addition, the tools or dies should be changed when the dimensions of the specimen is changed, which leads to the extremely high cost. Furthermore, most of the SPD processes focused on the microstructure refinement of metal bars. Only a few of SPD process can be used to refine the microstructure of metal tubes, but the dimension of the metal tubes are strictly limited by the tools or dies. Considering above, the exiting SPD processes are difficult to achieve large-scale industrial application. To refine and control the microstructure as well as improve the mechanical properties of metal tubes, the authors newly proposed a SPD process named cyclic rotating bending (CRB) process. The present study focused on investigating the effect of deformation conditions of the CRB process on the microstructure and mechanical properties of Al6061 tube. The CRB processes with different deformation temperatures, deformation times and bending angles were performed. The microstructure of the tubes was investigated with Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) equipped with Electron Back Scattered Diffraction (EBSD). The mechanical properties were obtained with the conventional tensile test. The results showed that the deformation temperature, time and bending angle have the strong influences on the microstructure and mechanical properties of the Al 6061 alloy tubes processed by the CRB process. The Al 6061 tube with an average grain size of about 55 μm, as well as ultimate tensile strength of 244 MPa and total elongation of 10.05% was successfully obtained with the optimized deformation condition of the CRB process.

2. Principle of CRB process for metal tubes

Fig. 1 shows the schematic illustration of the CRB process. The four-point bending method was utilized. During the CRB process,

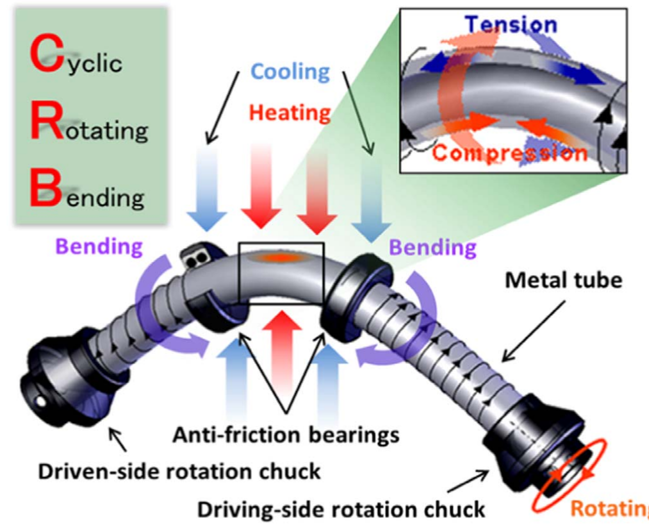

Fig. 1. Schematic illustration of the CRB process.

the high frequency induction heating technique was used to attain the different temperatures of the deformation part of metal tube. The cooling system was also used to control the temperature distribution of the tube. The implementation procedure in detail of the CRB process is presented in Fig. 2. First the metal tube is fixed by the chucks and bending bearings. Then the driving-motor starts to work at a given rotation speed to realize the rotation of metal tube. Simultaneously, the heating process of the tube also starts. When the temperature of the tube reached up to the pre-set value the bending process begins by quickly moving the up-plate to a proper position to obtain the expected bending angle. The rotating bending process will be kept for a certain time. The up-plate will return back to the original position to obtain the straight metal tube for further investigation. Then the metal tube was cooled to room temperature with water as quickly as possible (Fig. 3).

3. Experimental and material

The commercial aluminum alloy of Al 6061 is used in this study. The dimension of the sample of Al 6061 tube is φ10 (outside diameter) × 2 (thickness) × 200 (long) mm. The different deformation conditions of the CRB process, deformation temperatures of 373 K, 423 K, and 473 K, deformation time of 2.5 and

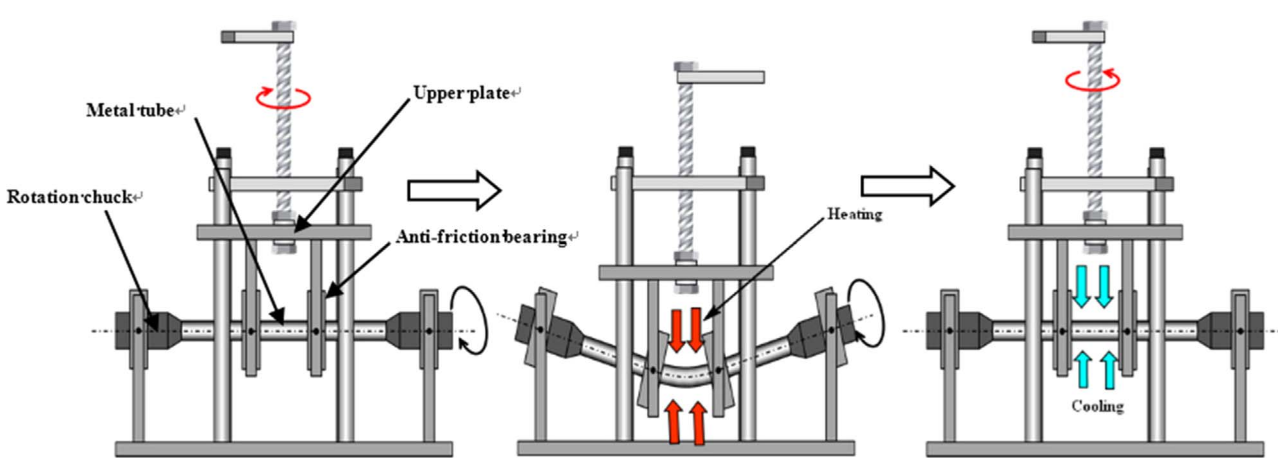

Fig. 2. Sketch map of implementation procedure of the CRB process.