Effect of the precipitated phase of MgZn_2 on surface nanocrystallization of Al-Zn-Mg alloy based on high-frequency impacting and rolling

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Abstract

Al-Zn-Mg alloy specimens before and after aging treatment were processed through high-frequency impacting and rolling. Grain refinement and work hardening were achieved in a certain depth from the top surface of specimen. Surface nanocrystallization mechanism was analyzed by TEM. The effect of precipitated phase of MgZn_2 on grain refinement process was investigated in detail. The schematic illustration of grain refinement process of aging Al-Zn-Mg alloy was established. Results show that the role of precipitated phase is the crossing point of sub-grains boundaries and the obstacle of dislocation motion.

Keywords: Precipitated phase; Surface; Nanocrystalline; Grain boundaries

1. Introduction

Surface nanocrystallization (SNC) by severe plastic deformation (SPD) might significantly improve the mechanical properties of materials without changing their chemical compositions [1-3]. Since SNC was first proposed by K. Lu in 1999 [4], many researchers have succeeded in producing nano-sized grains in the surface of low carbon steel, copper alloy, titanium alloy and magnesium alloy specimens. Meanwhile,

the SNC mechanism and microstructure evolution also have been characterized [5-9]. Previous studies have demonstrated that SNC mechanism of metal materials is mainly related to stacking fault energy (SFE). SNC process of high SFE metal is completed by dislocations movement [7, 10], and SNC process of low SFE metal is completed by twins deformation [11, 12]. The reason is that the number of slip systems of low SFE metal is fewer, and twins play a leading role in the plastic deformation process.

The above SNC mechanisms of metal alloys were all studied from the angle of SFE, and the corresponding rules have been obtained. Yet, some kinds of metal alloys have aging strengthening effect. The aging strengthening, therefore, should also be paid close attention when discussing the SNC mechanism. A large of studies [13-15] have showed that some strengthening phases were precipitated out at the grain interior and grain boundaries after aging treatment, and the strength and hardness will be improved. But after aging strengthening treatment, what is the role of precipitated phase in the SNC process? Whether the precipitated phase plays a leading role? These researches are rarely reported.

2. Experiments

The experimental material was the aging strengthening type of hot rolled aluminium alloy with the chemical composition of (in wt.%): 4.2066Zn, 2.2642Mg, 0.1287Cu, 0.3113Mn, 0.12445Zr, 0.2278Cr, 0.2954Fe, 0.2352Si and balance Al. The mechanical properties include yield strength of ≥ 345 MPa and tensile strength of ≥ 410 MPa. The parameters of 120 °C and lasting 24 hours were used to finish the aging treatment. High-frequency impacting and rolling (HFIR) was adopted to treat

the material surface of not-aging and aging specimen (see Fig. 1). The following processing parameters, frequency of 27 kHz, amplitude of 7.0 μm , coverage rate of 300%, static pressure of 200 N and feed quantity of 10 mm/min, were adopted based on HFIR physical mechanism [16] and experimental optimization in this study.

The cross-sectional microstructures were examined by the Zeiss Axio Imager A1m microscope. Transmission electron microscopy (TEM) of a JEM-2010 type was used to observe 80, 50, and 20 μm regions from the top surface of the treated aging specimen. Hardness distribution along the depth was determined by MH-3 vickers hardness tester with a load of 100 gf and a loading time of 10 s.

Fig. 1. The basic principle and working schematic of HFIR

3. Results and discussion

Fig. 2a and Fig. 2b show that the hardened layer of aging specimen is thinner than that of not-aging specimen under the same HFIR parameters for the obvious increase of precipitated phase. Fig. 2c is high resolution TEM and Fourier Transformation of precipitated phase (see the red arrow in Fig. 3c). Two dimensional lattice fringe can be clearly seen. The spacing of two crystal planes is $d = 0.1445 \text{ nm}$ and 0.2036 nm , respectively, identical to the PDF standard card of MgZn_2 phase. It is known that the interfacial angle is about 46.8° through calculation, while the actual measured value is 46° . The calculated value is approximately the same to the

measured value, which meets the requirements of calibration, so we can know that the crystal zone axis is [100]. The Fourier Transform image is shown at the top right corner, each set of diffraction spots corresponds to lattice plane of MgZn_2 along [100] crystal zone axis, and conforms to the interfacial angle formula. Fig. 2d indicates that micro-hardness of the top surface of aging specimen is improved by 68% after HFIR (from 140 HV to 235 HV). However, the value for not-aging specimen is only about 38% (from 130 HV to 180 HV). This phenomenon shows that the precipitated phase plays an important role during the surface strengthening process.

Fig. 2. Hardened layer, precipitated phase characterization and hardness distribution of the treated specimen before and after aging treatment

The precipitated phases of aging specimen were easily observed after HFIR in Fig. 3. The size of original grains shown in Fig. 3a is about 2-4 μm. In Fig. 3b a lot of dislocation lines are generated, and the motion of dislocation lines stops when they meet with the precipitated phases. Under the effect of continuous plastic deformation, dislocation lines gradually mingle and original grains are divided into some non-uniform sub-grains. At this point, the role of precipitated phase is the crossing

point of sub-grains boundaries (Fig. 3c). Grain morphology of 20 μm from the top surface was shown in Fig. 3d, and this region consists of nano-sized grains which are randomly distributed. The continuous diffraction rings in the selected area diffraction pattern indicate that randomly oriented grains were obtained. The average grain size determined from the TEM micrographs is about 20 nm. Meanwhile, Fig. 3d also shows that nano-sized precipitated phases are randomly distributed in the nano-grains matrix after HFIR. At this time the crossing point role of precipitated phase is gradually weaken, because the size of the refined grains is nearly equal to that of precipitated phase. Comparing with the precipitated phase in Fig. 3b-d, the size of precipitated phase nearly does not change at any different regions. So the precipitated phases after aging treatment have not produced an obvious fragmentation phenomenon.

Fig. 3. The morphology of the treated aging specimen at different region

For the SNC mechanism of Al-Zn-Mg alloy without considering precipitated phase has been detailed studied. For example, R. Gnanamoorthy et al [17], H.Q. Ye et al [18] and X. Wu et al [19] studied the surface strengthening mechanism of

non-aging aluminum alloy. The formation, pile-up and arrangement of high density dislocation dominate the SNC process. However, SNC mechanism of Al-Zn-Mg alloy considering precipitated phase of MgZn_2 has not been studied and summarized.

In this study, the detailed schematic was shown in Fig. 4a. SPD produces on the material surface under the continuing action of impacting and rolling. Then the high concentrations of dislocations gradually produce in the grains. The corresponding dislocation walls and dislocation cells are also formed for a part of dislocations tangling and dislocation pile-up, respectively (Fig. 4b). At the same time, the other part of dislocations stop motion when they meet the obstruction of precipitated phase (red point shown in Fig. 4a), and dislocation lines gradually intersect, which speed up the segmentation and refinement of grains (Fig. 3b and Fig. 3c). Therefore, the precipitated phase plays an important and obvious role for grain refinement of the aging Al-Zn-Mg alloy. With the continuous effect of impacting and rolling, plastic deformation continues to increase. The high density of dislocation walls, dislocation cells (Fig. 4c) and small angle substructures are formed. The grains will be further divided and refined. Especially, the precipitated phases always exist in the form of independent nano-sized structure.

Fig. 4. Schematic illustration of grain refinement process of aging Al-Zn-Mg alloy

4. Conclusions

In summary, Grain refinement and work hardening were successfully produced in the surface of Al-Zn-Mg alloy before and after aging treatment by HFIR. The schematic illustration of grain refinement process of aging Al-Zn-Mg alloy was established through considering precipitated phase. The role of precipitated phase is the intersection point of sub-grains boundaries and the obstacle of dislocation motion. The study of SNC mechanism based on precipitated phase will effectively promote the development of surface strengthening mechanism and technology.

Acknowledgments

This work was supported by the National Science Foundation [grant no. 51305160].

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Figure captions

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