Research Article

Effects of Aging Treatment on Laser-Welded Mg-Rare Earth Alloy NZ30K

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Magnesium-rare earth alloys have received extensive attention due to their attractive mechanical properties resulting from high density of precipitation. The precipitation sequence in laser-welded Mg-3Nd-0.2Zn-0.4Zr (NZ30K) alloy during aging treatment at 200°C and 225°C has been investigated using transmission electron microscopy (TEM). The results indicate that the tensile strength of laser-welded NZ30K can be improved significantly after aging treatment at 200°C for 8 h. It is found that the precipitation in laser-welded NZ30K alloy follows the sequence of supersaturated solid solution $\rightarrow \beta''(\text{DO}_{19}) \rightarrow \beta'(\text{fcc})$.

1. Introduction

Magnesium alloys have many advantages such as high strength/weight ratios and energy saving, which are considered to be the most developing potential materials in the 21st century [1, 2]. Different alloy compositions have been proposed to overcome the low corrosion resistance and the problems of high temperature applications of magnesium alloys. Because of good heat resistance and significant strengthening effect, many new magnesium alloys with addition of rare earth elements have been developed and studied [3–8]. NZ30K is alloyed by the rare earth element neodymium (Nd), which has been used for mechanical parts such as components in transportation system and hub of car wheels [9–12].

Although the alloy elements can improve the performance of magnesium alloy, the addition of elements alone is insufficient to meet some requirements in the engineering application. It is known that proper heat treatment can improve the properties of magnesium alloy obviously. Up to now, there are a lot of extensive researches investigating the precipitation sequences of magnesium-rare earth alloys [13–15]. It is reported that the precipitation sequence of magnesium alloy varies with different alloy elements. The

precipitation sequence of binary Mg-Y alloys was supersaturated solid solution (S.S.S.S.) $\rightarrow \beta''(\text{cbco}) \rightarrow \beta'(\text{cbco}) \rightarrow \beta(\text{Mg}_{24}\text{Y}_5, \text{bcc})$ [16], while that of binary Mg-Gd alloys was (S.S.S.S.) $\rightarrow \beta''(\text{DO}_{19}) \rightarrow \beta'(\text{cbco}) \rightarrow \beta(\text{Mg}_5\text{Gd}, \text{fcc})$ [17]. The precipitation sequence of Mg-Nd alloys was (S.S.S.S.) $\rightarrow \beta''(\text{DO}_{19}) \rightarrow \beta'(\text{fcc}) \rightarrow \beta(\text{bcc})$ [10]. However, there was little report about the precipitation sequence in the laser-welded Mg-Nd-Zn-Zr alloys.

In the present paper, a detailed examination of the precipitation sequence in laser-welded NZ30K during aging treatment is investigated, and the effects of different shape of precipitates on tensile strength are discussed.

2. Experimental Procedure

Test plates were the hot-rolled Mg-rare earth alloy NZ30K, which is alloyed by the rare earth element Nd, the element Zinc (Zn), and Zirconium (Zr). The chemical compositions of the alloy are listed in Table 1. The dimension of test plates was 150 mm $\times$ 75 mm $\times$ 10 mm.

A CO₂ laser source (TRUMPF TLF15000T) was used, and the experimental laser power was 8 kW. The diameter of the laser beam focus is 0.8 mm. The pure helium with the flow

FIGURE 1: TEM image and electron diffraction pattern aged at 200°C for 8 h along $[11\bar{2}0]_{\alpha}$ zone axis: (a) TEM image; (b) electron diffraction pattern.

FIGURE 2: Dark field TEM image of precipitates aged at 200°C for 8 h.

TABLE 1: Chemical compositions of the NZ30K (weight percent, %).

Compositions	Nd	Zn	Zr	Fe	Ni	Mg
Content	3.001	0.2696	0.3752	<0.002	<0.002	Balance

rate of 25 L/min was used as front-side protection, and the reverse side was protected by pure Argon gas with 20 L/min.

The surface of the plates was cleaned by wire brush and then wiped by acetone before butt welding. The welded joints were solution-treated at 540°C for 6 h and quenched into hot water at above 70°C. After the solution treatment, the joints were aging-treated at 200°C and 225°C for different hours. The parameters of heat treatments are listed in Table 2. Discs 3 mm in diameter were punched from fusion zone of welding joints, ground to a thickness of 0.1 mm, and twin-jet electropolished in a solution of 95 mL Alcohol and

5 mL Perchloric acid, at -40°C and 0.05 A. Microstructural examination was performed in a JEM-2100F TEM operating at 200 kV. As precipitation occurs in the magnesium prismatic planes, the zone axes of interest were [0001]. The tensile properties were tested by a Zwick Z020 E-stretching machine with the tensile rate 1 mm/min at room temperature. Experiment was repeated three times for each sample.

3. Results

3.1. The Prismatic Precipitation. Figure 1 displays TEM results obtained on the sample aged at 200°C for 8 h. It can be seen from Figure 1(b) that the precipitates can be identified as the structure hcp. According to the researches about the precipitates of Mg-Nd alloy [10], the precipitates are probably mainly β'' phase with DO_{19} structure. Figure 2 shows the dark field image of precipitates. It can be seen that the

FIGURE 3: TEM morphology of the precipitates aged at 200°C for 8 h: (a) rod shape, (b) tadpole shape, (c) flake shape.

TABLE 2: Parameters of heat treatments.

Sample	Parameters of heat treatments
1	Laser-welded joint with no heat treatment
2	540°C × 6 h solution treatment + 200°C × 2 h aging treatment
3	540°C × 6 h solution treatment + 200°C × 8 h aging treatment
4	540°C × 6 h solution treatment + 200°C × 64 h aging treatment
5	540°C × 6 h solution treatment + 225°C × 8 h aging treatment
6	540°C × 6 h solution treatment + 225°C × 64 h aging treatment

prismatic precipitates disperse in the matrix with the contact angle of 120 degree.

Figure 3 shows the three typical morphologies of the precipitates. The precipitates exhibit rod shape, tadpole shape

and flake shape in different regions as shown in Figures 3(a), 3(b), and 3(c), respectively. After the sample aged at 200°C for 8 h, the shape of precipitates is complex.

3.2. The Precipitation during Aging Treatment at 200°C. The precipitates of sample aged at 200°C for 2 h are shown in Figure 4. It can be seen that the precipitates exhibit both rod shape and flake shape. From Figures 4(c) and 4(e), the precipitates are almost flake shaped. The precipitates are also mainly β'' phase after aging treatment at 200°C for 2 h.

Figure 5 depicts the microstructures and the electron diffraction pattern of precipitates along $[11\bar{2}0]_\alpha$ zone axis of sample aged at 200°C for 64 h. As can be seen from Figure 5(a), there are flake shape precipitates. The electron diffraction pattern is the same as that of sample aged at 200°C for 2 h disclosing β'' phase.

3.3. The Precipitation during Aging Treatment at 225°C. The precipitates of sample aged at 225°C for 8 h are shown in

FIGURE 4: TEM image and electron diffraction pattern aged at 200°C for 2 h: (a) and (b) along $[0001]_{\alpha}$ zone axis; (c) and (d) along $[01\bar{1}1]_{\alpha}$ zone axis; (e) and (f) along $[11\bar{2}0]_{\alpha}$ zone axis.

FIGURE 5: TEM image and electron diffraction pattern showing precipitates aged at 200°C for 64 h along $[11\bar{2}]_{\alpha}$ zone axis: (a) TEM image; (b) electron diffraction pattern.

FIGURE 6: TEM image and electron diffraction pattern aged at 225°C for 8 h: (a) and (b) along $[\bar{1}11]_{\alpha}$ zone axis; (c) along $[\bar{1}12]_{\alpha}$ zone axis.

FIGURE 7: TEM image and electron diffraction pattern showing precipitates aged at 225°C for 64 h along $[012]_{\alpha}$ zone axis: (a) TEM image; (b) electron diffraction pattern.

Figure 6. It can be seen that the precipitates are rod shaped. The electron diffraction patterns in Figures 6(b) and 6(c) indicate that the precipitates are β' phase with fcc atomic structure, which are different from that of precipitates after aging treatment at 200°C.

Figure 7 depicts TEM results of samples aged at 225°C for 64 h. The electron diffraction pattern is the same as that of a sample aged at 225°C for 8 h as indicated by Figure 7(b). The precipitates are also composed of β' phase.

4. Discussion

Assuming that dislocation glide and bypass mechanisms (Orowan strengthening) only occur on (0001) basal plane, Nie amended Orowan strengthening formula according to the precipitate morphologies and habits with respect to the matrix [18]. Orowan strengthening formula is

$$\Delta\tau = \frac{Gb}{2\pi\lambda\sqrt{1-\nu}} \ln \frac{d_p}{r_0}, \quad (1)$$

where $\Delta\tau$ is the incremental of critical shear stress component, G the matrix shear modulus ($G = 1.66 \times 10^4$ MPa), b the Bo's vector mode ($b = 3.21 \times 10^{-10}$ m), ν the Poisson ratio ($\nu = 0.35$), λ the plane space between the adjacent second phase particles, d_p the average plane diameter of the second phase particles, f the volume fraction of precipitates, and r_0 the dislocation radius (here $r_0 = b$). According to the formula, the different shape precipitates can affect the tensile strength.

Here the effects of different shape precipitates on tensile strength are displayed with experimental results. The tensile strength of different samples is shown in Figure 8. It can be seen that the tensile strength of sample 3 of laser-welded joints is the largest. It is because of the fact that there are lot of prismatic precipitate plates as shown in Figure 2. The size of precipitates in sample 4 is about 100 nm. The tensile strength of sample 2 is the smallest after the aging treatment due to the basal precipitate plates after a short aging time

FIGURE 8: The tensile strength of samples containing different main particulate morphology.

as can be seen from Figure 4(c). The size of precipitates in sample 2 is about 70 nm. After 200°C aging treatment, the size of precipitates grows from 70 nm to 150 nm as the aging time increases from 2 h to 64 h. When laser-welded NZ30K is aged at 225°C, the precipitates are mainly rod shaped, which has lower strengthening effect than the prismatic precipitate plates. It is noted that the size of precipitates changes from 100 nm to 250 nm after aging treatment at 225°C for 8 h and 64 h. The strength of sample 5 and 6 is smaller than that of sample 3.

5. Conclusions

From the above results, the main conclusions can be summarized as follow.

- (1) It is found that the precipitation sequence of laser-welded NZ30K follows supersaturated solid solution ($S.S.S.S.$) $\rightarrow \beta''(DO_{19}) \rightarrow \beta'(fcc)$.
- (2) After aging treatment at 200°C for 8 h, the tensile strength of the laser-welded NZ30K can be improved significantly.

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