Torsional Property of Mg-Gd-Y-Zr Magnesium Alloy

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Abstract. The torsion behavior tests on Mg-Gd-Y-Zr magnesium alloy have performed before and after liquid nitrogen cryogenic treatment (CT) by torsional test machine. The experimental results show that the torsional strength and plasticity of the alloys have been significantly improved after CT 72h and 96h, compared to untreated test specimens. The torsion angles before breakage increase with the increase of CT duration. The SEM fracture surface morphology shows that maximum shear stresses on cross section are major reason for the damage. The torsional shear stress increases from 217.1MPa to 235. 9MPa after CT 96h, increasing by about 9%; the torsion angle increases from 499.3°to 594.5°after CT 96h, increasing by about 19%. The second precipitated phase and multi-system slip are response to the higher strength and plasticity.

Introduction

In response to the requirements of energy conservation and environmental protection, magnesium alloys attract more attentions in the automobile and aerospace industry owing to their light-weight and high specific intensity [1]. Some magnesium alloys such as AZ series and AM series have already been used to some automobile parts, namely inner door frame, valve cover and steering wheel[2]; However, the poor high-temperature strength and resistance to creep restrict wider application of magnesium alloys. Recently, magnesium alloys containing Gd and Y have attracted a great deal of attention as they have high strengths and reasonable ductility [3, 4]. In certain applications, such as steering shaft, magnesium alloys are submitted to torsional conditions, the torsional behavior of magnesium alloys is an important consideration. Cryogenic treatment (CT) is a technique wherein materials are going to be processed at about liquid nitrogen temperatures (77 K). CT is widely used for high precision parts, and has been shown to result in significant increase in wear resistance [6]. During the CT, compressive residual stress was induced with temperature below 77 K. The compressive residual stress is beneficial with respect to wear and fatigue [7].

Considerable researches have been conducted to study mechanical property and wear resistance of Mg-Gd-Y-Zr alloys [8, 9]. Few studies have been carried out to understand the torsional behavior after cryogenic treatment of magnesium alloys. The main objective of this work is to investigate the torsional properties of Mg-Gd-Y-Zr alloy and explore the effect of CT on its torsional strength.

Experimental Procedure

The Mg-10Gd-3Y-0.5Zr (wt. %) alloy was prepared from high purity Mg (99.9 wt.%), Mg-25 wt.% Gd, Mg-25 wt.% Y and Mg-30 wt.% Zr. The raw materials are melted in an electric resistance furnace at 750°C and poured into a permanent mold at 720°C. The extruded rod with a diameter of 10 mm was fabricated with a reduction ratio of 13:1 at the extrusion temperature 400°C. The torsional specimens were processed by lathe, and the specimen dimension is shown in Fig.1. The processed specimens were put into liquid nitrogen container (approximately -196°C) to conduct CT, the dipping time are 0h, 24h, 72h, and 96h respectively. The torsion tests with the loading speed of were conducted by using electronic torsion testing machine. The specimen microstructures were characterized by OM. The torsional fracture surface morphologies were observed by using SEM. Vickers hardness tests were conducted under a load of 49 N and a hold time of 20 s.

Results and Discussion

Microstructure

Fig. 1(a)-(d) shows OM images of the extruded Mg-10Gd-3Y-0.5Zr alloy before and after CT. The microstructures of the alloys mainly consist of banded microstructures that are typical characteristic of deformation structure. It is found that the alloy is consisted of α-Mg solid solution and $Mg_{24}Y_5$ secondary phase particles distributed in the intracrystalline and grain boundaries [9]. The α-Mg grains are equiaxial in shape-typical recrystallized structure, and the average grain size is about 50 μm (see Fig.1a). The fine precipitated phases distribute as streamline along the extrusion direction. After CT for 24h, the volume fraction and quantities of secondary phase particles have increased. With increasing the CT time, the matrix grains become uniform, the fine precipitated phase further increase up to 8.5% (see Fig. 1d).

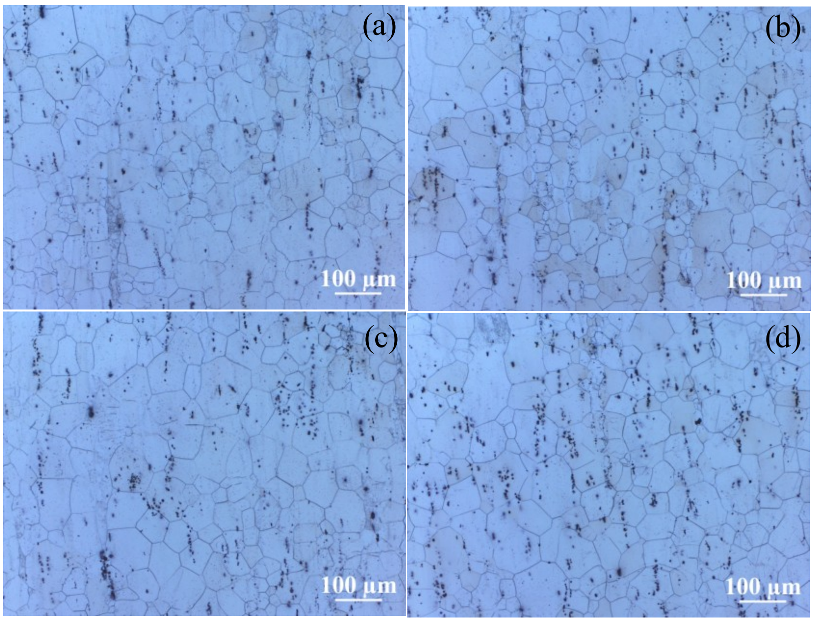


Fig. 1 Optical microstructures of extruded Mg-10Gd-3Y-0.5Zr alloys before and after CT
(a) before CT (b) CT 24h (c) after CT 72h and (d) after CT 96h

Torsional Properties

The torsion test results of the Mg-10Gd-3Y-0.5Zr alloys under the different processing conditions are shown in Fig. 2 and Table 1. The shearing stress-strain curves illustrate that the cryogenic treatment can improve the torsion resistance of the alloy, the torsional yield strength (YS) and ultimate torsional strength (UTS) increase from 215MPa and 220MPa before CT to 224MPa and 235MPa after CT 96h. The breaking torsional angles also have the similar change tendency. The maximum breaking torsional angles is just 594.45°. The possible reasons that the torsional strength of the extruded alloy is promoted are related to grain refinement and evolution of volume [10].

The decrease of temperature gives rise to thermal contracting and brings the evolution of volume. The volume change formula is:

$$\Delta V = V_T - V_0 = V_0\{\exp[\alpha(T - T_0)] - 1\} \tag{1}$$

$$\sigma_m = \frac{\Delta V}{V_0} = \exp[\alpha(T - T_0)] - 1 \tag{2}$$

Where α is the expansion coefficient under certain pressure caused by CT, V_0 and V_T are the initial volume and volume after cryogenic temperature treatment respectively, T_0 and T_T are the initial temperature and the cryogenic temperature respectively, σ_m is the contraction percentage. The volume contraction results in great compression stress and volume deformation energy, the deformation energy can provide the driving force in the second phase precipitation formation process. The second phase precipitation also plays a significant role in the following deformation process and could cause strengthening [10].

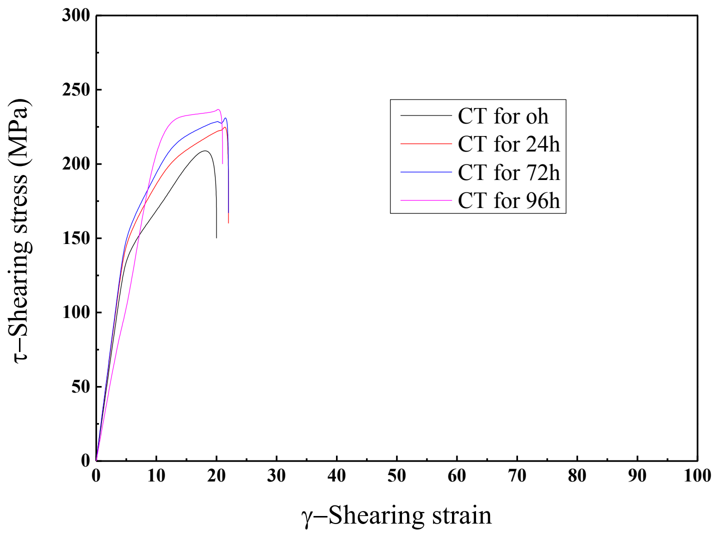


Fig. 2 The shearing shear-strain curves of the torsional specimens

Table 1 Torsion properties and hardness of as-extruded alloys.

Alloy condition	YS (MPa)	UTS (MPa)	Torsion angle(°)	Maximum Torque(N.m)	Shearing strain	Hardness Hv
Before CT	215.14	217.12	499.30	13.00	20.05	90
CT for 24h	220.86	222.11	511.75	16.03	21.91	90
CT for 72h	222.91	229.23	590.73	15.43	21.68	92
CT for 96h	224.88	235.95	594.45	17.12	20.45	95

Fractography

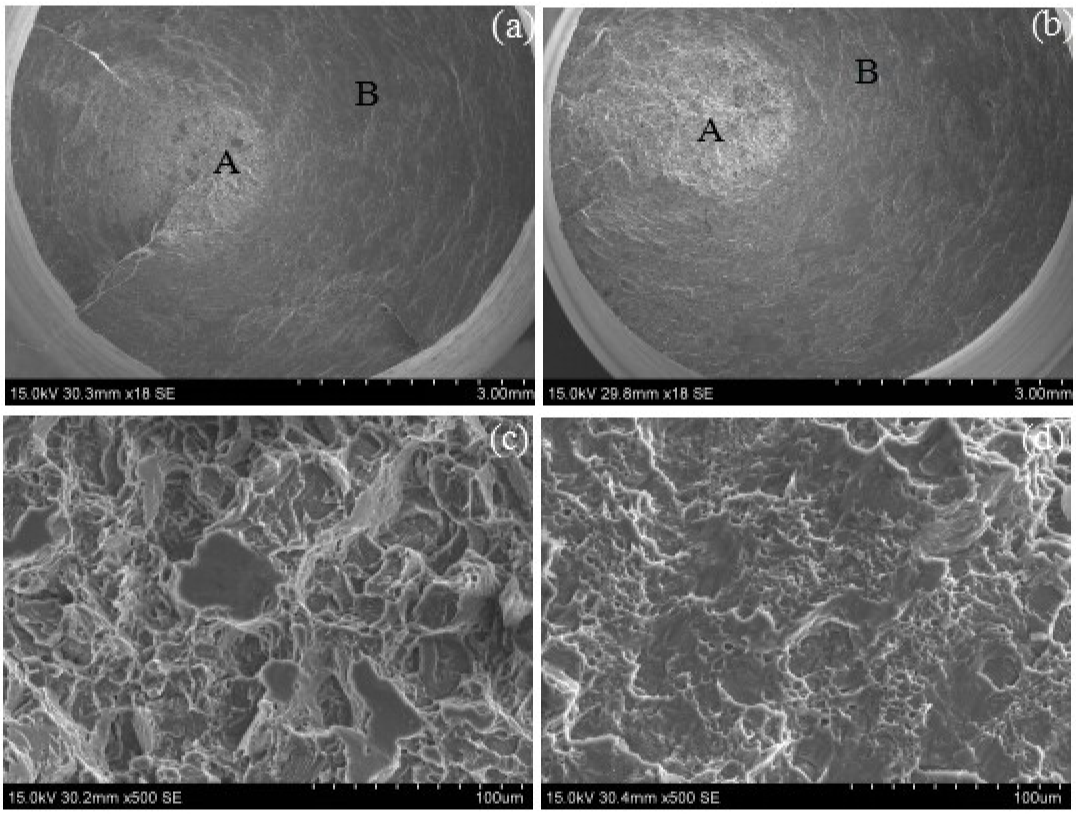
Fig. 3 shows the fracture surface morphologies of the torsional specimens. The low magnification images reveal that the torsional fracture surfaces are relatively level, (Fig. 4(a) and (b)). There are not obvious twists, which is consistent with the lower torsion angle. The torsional shearing stress formula can be expressed:

$$\tau = \frac{T\rho}{I_p} \tag{3}$$

Where T is the torque in the cross-sectional area, ρ is the distance between the calculating point and the cross section centroid, I_p is the polar inertia moment of the cross-sectional area. According to this circular shaft torsional shearing stress formula, the maximal shearing stress occurs in the circumference of the cross section, the initial cracks initiate at oxides inclusions or voids in the circumference (Fig. 3(a) and (b)), then expand to the center of the circle, the final rupture regions close to the center of the cross section. There are more fracture chine lines for CT 0h than CT 72h. The area of instantaneous fracture zone became large after cryogenic treatment.

The instantaneous fracture zone images are mainly composed of cleavage planes, some tearing ridges and fine ductile dimples. The fracture mode of the alloy untreated is cleavage rupture, some microcracks can be seen on the fracture surface (Fig. 3(c)). After cryogenic treatment, the fracture surface exhibit more obvious ductile and cleavage fracture characteristics, the number and size of the cleavage planes both decrease, and the shallow dimples with white irregular shape particles inside can be observed, indicating that crack may initiate from the broken particles and propagate by coalescence of dimples (Fig.3(d)). In addition, At -196, Some irregularly shaped rare earth particles cause stress concentration to initiate cracks, which propagate and further lead to the formation of microvoids.These microvoids accumulate together continually to form shallow flat dimples[11] The crack propagation regions of fracture surfaces have numerous grooves and randomly distributed particles due to the contact friction in the process of reverse (Fig. 3(e) and (f)). Some grooves fall off seriously.

After CT, the torsional angles have the trend toward increase, indicating that plasticity of the alloys has been improved, this may be related to the decrease of c/a value and multi-system slip. cryogenic treatment can decrease the value of lattice constant c/a from 1.6148 to1.6113, while the c/a value of the Mg-1 0Gd-3Y-0.5Zr alloy at-1 96°C will be smaller than 1.6113. The decrease of c/a will lower the critical shear stress of cylinder slip systems and make the alloy enter into multi-system slip at low temperatures [12], plasticity gets improved and the fracture mechanism show the mixture of brittle and ductile fracture.



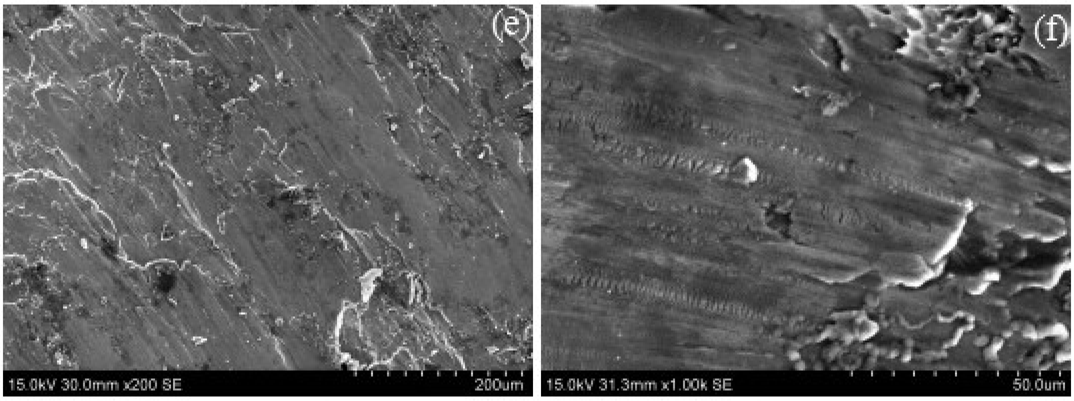


Fig. 3 SEM images of Mg-10Gd-3Y-0.5Zr alloy's torsional fracture surface (a) Low magnification before CT; (b) Low magnification after CT 72h; (c) A area magnification in (a); (d) A area magnification in (b); (e) B area magnification in (a); (f) B area magnification in (b).

Conclusions

(1) Cryogenic treatment increases the volume fraction and quantities of secondary phase particles, promotes the matrix grains uniformity.

(2) The maximum shear stresses on cross section in the external rim are the reason for the torsion damage.

(3) After cryogenic treatment 96h, the torsional shear stress increases from 217.12MPa to 235. 95MPa, increasing by about 9%, the torsion angle increases from 499.3°to 594.5°, increasing by about 19%. The second precipitated phase and multi-system slip are response to the higher strength and plasticity.

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