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Effects of heat treatment and plastic deformation on structure and properties of Mg-9Al-1.2Nd-0.45Y-0.7Zn Mg alloy

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Abstract: The experiments of heat treatment, hot extrusion and hard drawing were employed to study their effects on the structure and mechanical properties of Mg-9Al-1.2Nd-0.45Y-0.7Zn magnesium alloy. The results indicate that the mechanical properties of the ingot are unstable and exhibit typical brittle failure. After heat treatment (693 K, 24 h), most β-Mg17Al12 phases decomposed into the α-Mg matrix and the distribution of Rare earths compounds remained the state of as-cast, which have little effects of the mechanical properties of the alloy. As the casting defects disappeared and the grain was refined after hot extruded, the mechanical properties of the alloy were drastically increased. By hard drawing, the ultimate tensile strength and the yield strength of the alloy were sharply increased while the elongation decreased rapidly. The failure of as-cast samples was mainly brittle fracture. After plastic deformation, the fracture patterns all exhibited ductile rupture features.

Key words: magnesium alloy; heat treatment; hot extrusion; hard drawing; structure; mechanical properties

1 Introduction

As the lightest of all metals used as the basis for constructional alloys, the research and development of magnesium alloys have been greatly promoted by the lightmass requirement in lots of industrial fields[1]. However, commercial applications of magnesium alloys such as AZ91and AM60 are limited because of their poor workability and the degradation of mechanical properties at elevated temperatures. As important alloying elements to magnesium alloys, rare earths can improve casting characteristics, high temperature properties and corrosion resistance. The effects of rare earths on the mechanical properties of magnesium alloys at elevated temperatures have been analyzed by many researchers，and their results have indicated that the effectiveness of the Rare earths are obvious[2−3]. However, it is well known that materials with small grain size have excellent mechanical properties. The plastic deformation of extrusion, forging, rolling and drawing could refine the grain size and also slake the casting defects such as gas cavity, shrinkage porosity and heat cracking, which play an important role to enhance the mechanical properties of different alloys. Some studies have indicated that the deformation results in a considerable decrease of the grain size and the increase of the dislocation density, which improve the tensile strength, ductility and elongation of the alloys[4−5].

In this work, the effects of rare earths, especially the process of heat treatment, hot extrusion and hard drawing to the structure and the mechanical properties of Mg-9Al-1.2Nd-0.45Y-0.7Zn alloy were systematically analyzed. That could afford some references to prepare magnesium alloys with better mechanical properties.

2 Experimental

2.1 Experimental materials

AZ91D alloys were chosen as master alloys. Rare earths elements were melted in the form of interalloys. Chemical contents of the studied alloys are shown in Table 1. The size of ingots was d 100 mm×150 mm, which were melted in electromagnetism induction

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furnace (protected by RJ−2 flux) and cast in metal patterns.

Table 1 Chemical contents of alloy (mass fraction, %)

Al	Nd	Y	Zn	Mg
9.0	1.20	0.45	0.70	Bal.

2.2 Experimental procedures

The ingots were machined into regular cylinders with the diameter of 93 mm and were extruded on the YH61−500G horizontal extruder shortly after T4 (693 K, 24 h) treatment in the electrical resistance furnace.

The extrusion ratio was 20:1 and the mould temperature was 673 K. Chain drawing machine was used to draw the hot extruded bars at room temperature. The drawing speed was 20 m/min, and the powdered graphite was used as lubricant.

According to GB3075—82, the different state tensile samples were processed on linear cutting machine and numeric control lathe. Then the samples were tested on universal material testing machine AG-500KNE (the speed of tensile was 2 mm/s).

The microstructure of different state alloys was investigated on the microscope of Carl Zeiss AxioVision and scanning electron microscopy (SEM). The structural constituent was also analyzed by X-ray diffraction (XRD) and Energy dispersion spectrograph (EDS). The tensile fracture pattern was analyzed on SEM.

3 Results and discussion

3.1 Microstructure

As can be seen in the pictures, the microstructure of the ingot is composed of α-Mg matrix and interphases along grain boundaries (Fig.1(a)). Analyzed from the EDS (Fig.2(a)) and XRD (Fig.(4)) results, the interphases were mainly β-$Mg_{17}Al_{12}$ phases and rare earths compounds such as Al_3Nd. After T4 treated, most of β-$Mg_{17}Al_{12}$ phases decomposed into Mg matrix while The rare earths compounds which have high thermal stability basically still kept the distribution of as-cast state (Fig.1(b), Fig.2 and Fig.3). By extrusion, the distribution of interphases became streamline form and the grain size also was refined (Fig.1(c)).

The deformation mechanism of magnesium alloys were mainly slipping and twinning[6−7]. The move and reproduction of the dislocations could make themselves tangled, nailed and blocked by the boundaries in the deformation. The twinning usually occurred in the granules which were disadvantages for slipping[8−12]. The microstructure of the drawing bar in the lengthwise direction was composed of large quantity compound twins in the matrix and the microstructure of the alloy was non-homogeneous. The reticular distribution became streamlining and formed banded structure in the longitudinal direction (Fig.5).

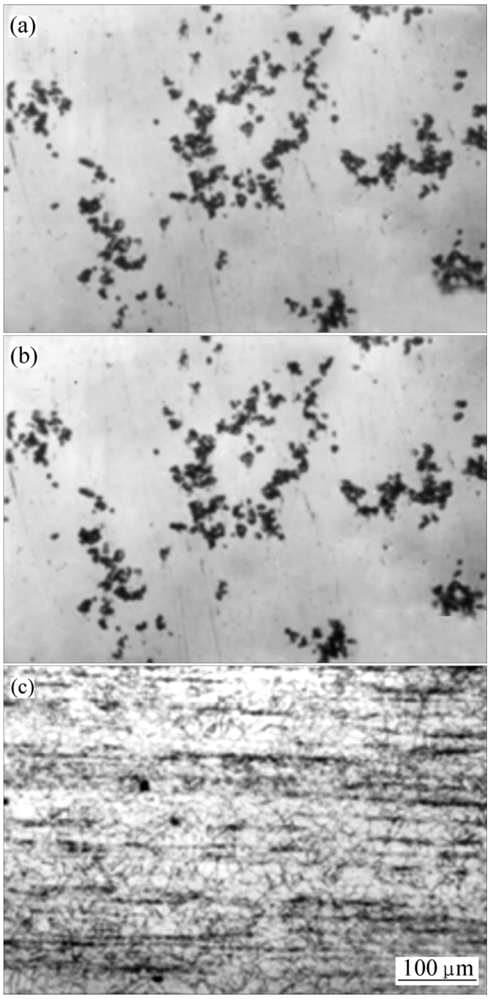

Fig.1 Microstructures of alloy: (a) As-cast state; (b) T4 state; (c) Extrusion state (lengthwise direction)

3.2 Mechanical properties

The mechanical properties along the radial direction of the ingot were low and unstable with typical brittle fracture phenomenon (Table 2). After heat treated (Fig.6), the ultimate tensile strength and elongation increased to 200 MPa and 12% respectively, but the yield strength was still as low as that of the as-cast state. Having been hot extruded (extrusion ratio 20:1), the casting defects such as gas cavity, shrinkage porosity and heat cracking basically disappeared[5−6]. The second-phases were well-distributed in the Mg matrix and the structure of the billets was refined. The mechanical properties of the alloy became homogeneous. The ultimate tensile strength, the yield strength and elongation drastically increased to 295 MPa, 195 MPa and 18% respectively.

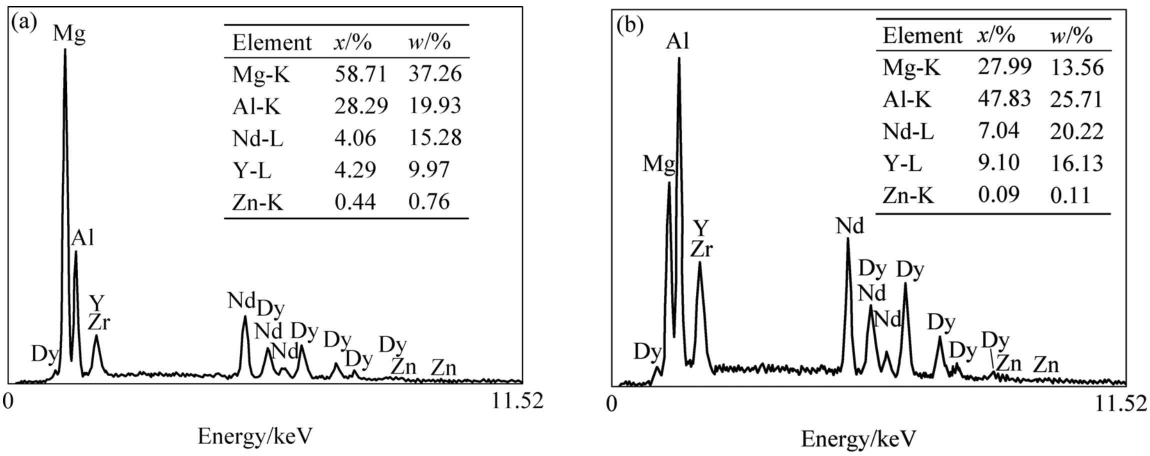

Fig.2 EDS results of interphases in alloy: (a) As-cast state; (b) T4 treated state

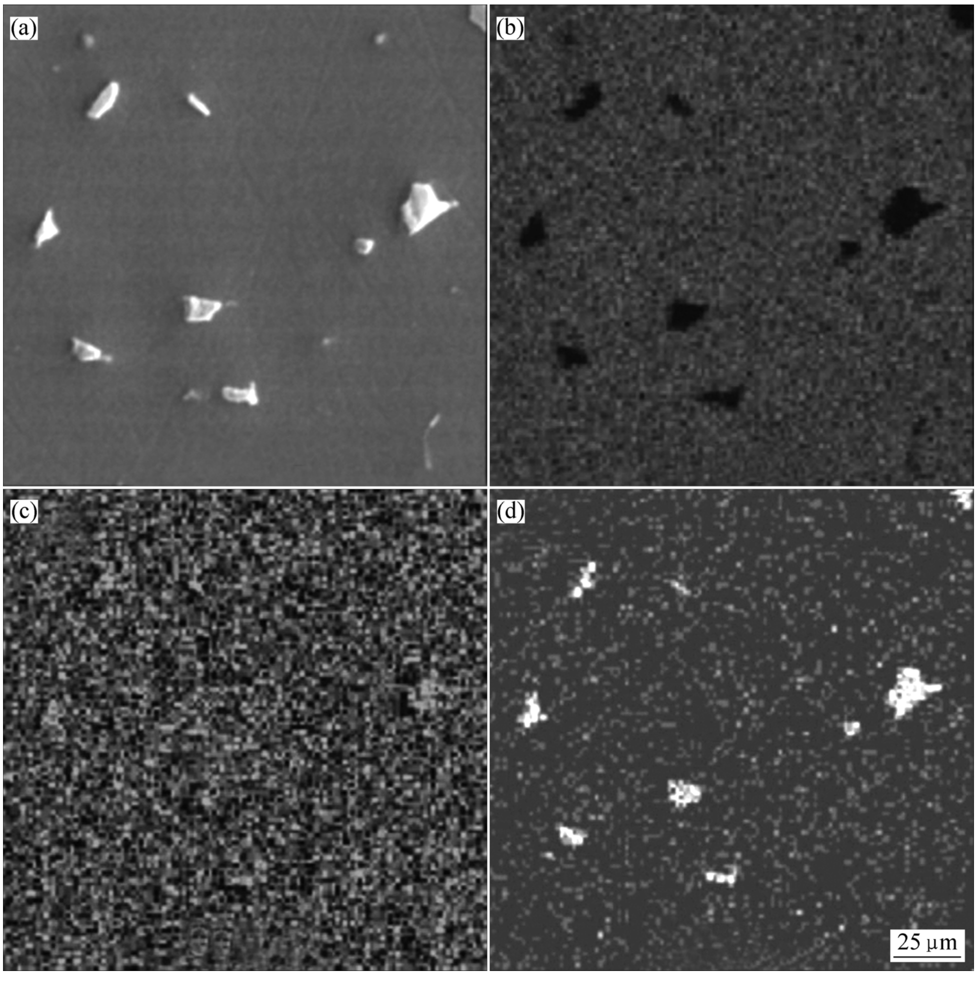

Fig.3 Plane scanning images by SEM of alloy after T4 treated

Table 2 Mechanical properties along radial direction of ingot

No.	σ_m/MPa	$\sigma_{p0.2}$/MPa	δ/%
1	101	–	–
2	109	–	–
3	175	135	5.0
4	181	122	6.0

Fig.7 shows the tensile properties of the alloy with different percent reductions in area (ψ). After the first pass of hard drawing, the ultimate tensile strength and the yield strength increased sharply while the elongation decreased rapidly from 18% to 7%. Along with the increasing of percent reduction in area (ψ), they increased with the work-hardening[4, 6, 10]. Having

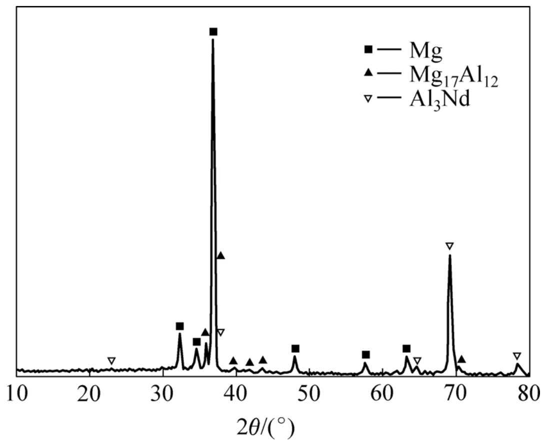

Fig.4 XRD pattern of as-cast alloy

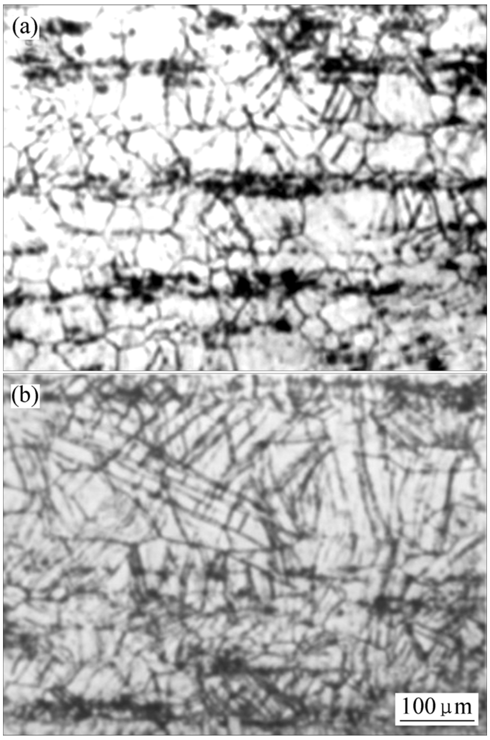

Fig.5 Microstructures of hard-drawing state alloy (Lengthwise direction): (a) *d* 19.5; (b) *d* 17.5

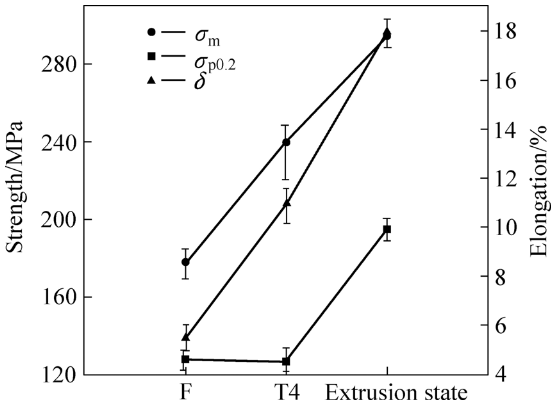

Fig.6 Tensile properties of alloy with different states

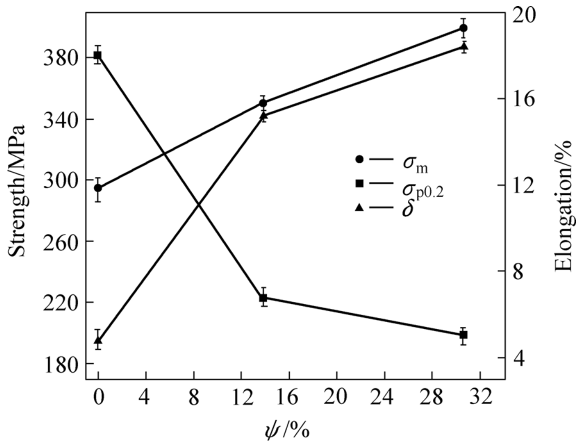

Fig.7 Tensile properties of alloy with different percent reductions in area (ψ)

been drawn for second pass, the ultimate tensile strength and the yield strength were further increased while the elongation decreased to 5%.

3.3 Fracture

There were lots of cleavage steps and inclusions on fracture surface of as-cast ingot (Fig.8(a)), and the failure was a brittle fracture. After heat treated (Fig.8(b)), the cleavage plane became wide and some tearing arris appeared that presented the feature of hybrid failure. By hot-extruding (Fig.8(c)), the tearing arris greatly increased, small dimples and fine particles could be found on the fracture surface, and ductile fracture plays an important role in the failure. Fig.8(d) shows the fracture of hard-drawing bar which was tested at 473 K. There were full of fine and deep dimples on the fracture, and also much tearing arris. That was a ductile rupture.

4 Conclusions

1) The mechanical properties of the ingot vary along the radial direction and exhibit typical brittle failure.

2) After heat treated (693 K, 24 h), most β-$Mg_{17}Al_{12}$ phases melt into the α-Mg matrix and the rare earth compounds which have good thermal stabilities remain as the state of as-cast. Both the ultimate tensile strength and elongation are greatly increased but the yield strength is still as low as that of the as-cast state.

3) After hot extruding, the casting defects disappear, the grain is refined and the second-phases are well-distributed in the matrix. The ultimate tensile strength, the yield strength and elongation drastically increase to 295 MPa, 195 MPa and 18%, respectively.

4) After subsequent hard drawing, the ultimate tensile strength and the yield strength sharply increase while the elongation decreases rapidly to 5%.

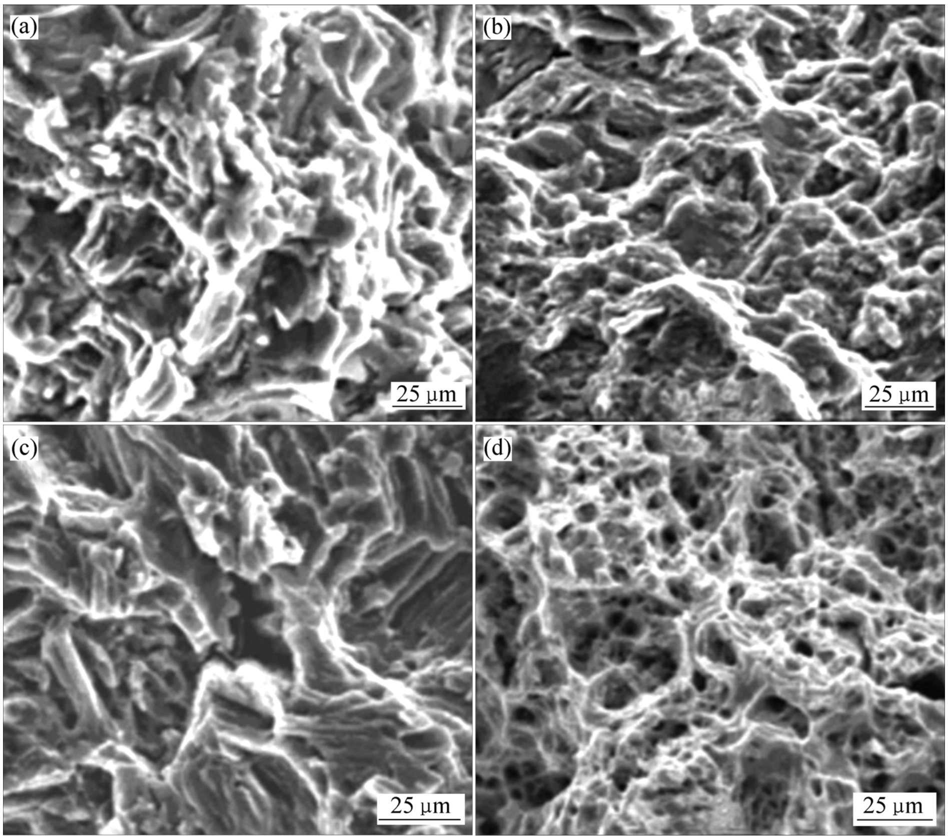

Fig.8 Fracture surface (SEM) of alloy at different states: (a) As-cast state, tested at room temperature; (b) T4 state, tested at room temperature; (c) Extrusion state, tested at room temperature; (d) Hard-drawing state, tested at 473 K

5) The failure of as-cast samples is mainly brittle fracture as cleavage fracture at room temperature. After the plastic deformation, the fracture patterns exhibit ductile rupture feature. At elevated temperature, the quantity of dimple and tearing arris on the fractures of drawn samples increases, and, the failure pattern is ductile rupture.

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