

A COMPARATIVE STUDY OF Mg-Y-Zn Rod PRODUCED BY DIFFERENT ROUTES USING SEVERE PLASTIC DEFORMATION

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Abstract

Ternary Mg-Y-Zn alloys have attracted considerable attention due to their excellent mechanical properties and unique microstructures. Microstructural variation and the resulting mechanical properties can be affected by various processing routes, particularly those involving severe plastic deformation of a cast billet. The following approach was used in this work to perform a comparative study: Cast $\text{Mg}_{92}\text{Y}_4\text{Zn}_4$ billet was subjected to severe plastic deformation by three different routes, namely ECAP, high pressure torsion (HPT) and ECAP followed by HPT with the aim of refining the microstructure. The effect of the processing route and the process parameters on the microstructure and the hardness of the Mg-Y-Zn alloy will be reported.

Introduction

Addition of rare-earth (RE) elements is known to increase the strength of magnesium alloys at high temperature and to improve their creep properties due to formation of compound intermetallic phases [1-4]. Most of the RE containing magnesium alloys have an excellent precipitation hardening response [1-4], while Mg-Y-Zn ternary alloys are not precipitation hardenable [5]. Superior mechanical properties in these alloys are achieved by other techniques, for example, warm extrusion of rapidly solidified powder (strength up to 600 MPa and 5% tensile ductility) [6, 7], or metal working of cast billet [8-10], which results in strengthening by grain refinement. The microstructure after such processing usually contains a mixture of nano-scale magnesium grains (100-200 nm) and intermetallic particles that exhibit a range of long-period stacking ordered (LPSO) structures, in which 18R and 14H are the major structures [11]. A unique feature of such LPSO structures is their lamellar morphology that comprises alternating layers of magnesium and the intermetallic lamellae. The accumulated experimental evidence indicates that mechanical properties of the Mg-Y-Zn alloys can be tailored by proper control of the volume fraction and size of the lamellae of the LPSO structures, and that an ultrahigh strength alloy could be obtained if a nano-scale distribution of LPSO structures is achieved.

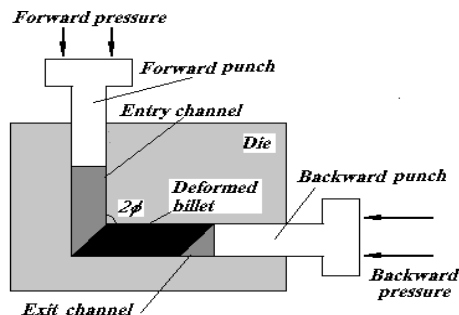
It is not possible to achieve a redistribution of LPSO structures by deformation with conventional metal forming processes as they have a geometrical limitation on the amount of strain imparted to the material. However, by severe plastic deformation (SPD) methods [12] a billet can be subjected to virtually unlimited strain without a change in its shape and dimensions. The most well-known SPD methods are Equal Channel Angular Pressing (ECAP) [13] and High Pressure Torsion (HPT) [14]. The effects of SPD on the mechanical properties of Mg-Y-Zn alloys have not been evaluated to date. It can be expected, however, that severe plastic deformation may lead to much finer grains, and therefore much higher yield strength. A comparative study of microstructure and properties of $\text{Mg}_{92}\text{Y}_4\text{Zn}_4$ cast billets severely deformed by different SPD techniques has been performed in this work.

Materials and Experimental Methods

$\text{Mg}_{92}\text{Y}_4\text{Zn}_4$ billet was prepared by permanent mould casting and homogenised for 24 hours in a

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muffle furnace at 450°C. After homogenisation the samples were quenched in water at 70°C. Cast billet was subjected to severe plastic deformation by three different routes, namely ECAP, HPT and ECAP followed by HPT.



a

b

Fig. 1 Equal Channel Angular Pressing

a – unit for isothermal ECAP with back-pressure; b – schematic of ECAP with back pressure.

Small samples 10mm in diameter and 37 mm in length were machined from homogenised billet. Four passes of ECAP (route B_c) were performed using a 90° die at 350°C with a back-pressure of 185 MPa. ECAP with back pressure was performed using a specially designed unit, Fig. 1a, equipped with a heated die to permit isothermal processing within the temperature range of 20 - 450°C. Back-pressure was controlled in a horizontal hydraulic cylinder to maintain a pre-set level between 20 and 500 MPa, while the unit was placed in a 1000kN press to exercise the forward pressure. Each pass of ECAP introduced a strain of 115% in the material.

Disk shaped samples with dimension of 1 mm thickness and diameter of 8mm were cut from as-cast and ECAP processed samples and subjected to ten revolutions in HPT die, Fig 2, under 1.9 GPa of pressure at room temperature. Each revolution introduced a strain around 1400% near the rim of the specimen.

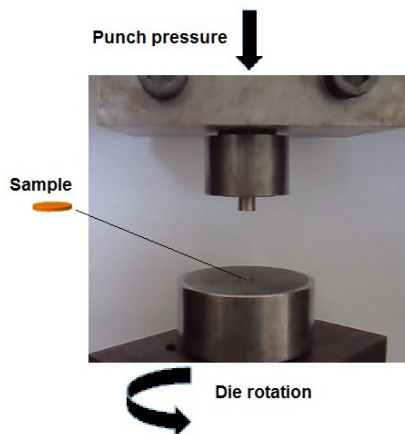


Fig. 2 High Pressure Torsion die and schematic

After all deformation routes the microstructure was examined using optical microscope Olympus GX51 and transmission electron microscope Philips CM20 at 200 kV. Vickers hardness (ASTM E384-10e2) was measured using a Struers Duramin A-300 hardness tester with a load of 0.1 kg (HV0.1). Seven indents were generated per sample. For XRD analysis, a Philips diffractometer equipped with a Cu anode at 40kV and 25 mA was used.

Results and Discussion

Microstructure

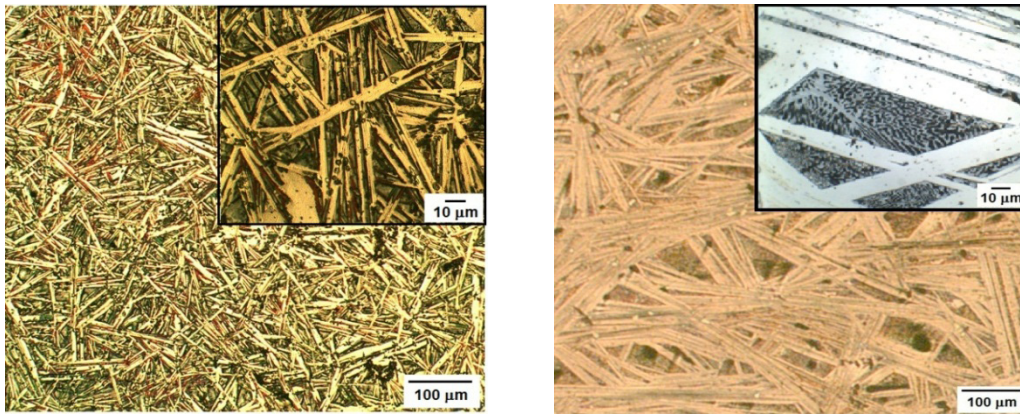


Fig. 3 Initial microstructure of cast billet before deformation
a– as-cast; b– homogenised

The microstructure of the as-cast alloy contains a large volume fraction of relatively fine-scale lamellar type product, Fig. 3a, which has high concentrations of yttrium and zinc. This microstructure is quite different from that normally observed in as-cast structure consisting of magnesium grains and secondary phase in grain boundaries [5, 11, 15, 16]. This lamellar structure has a mixture of 18R and α -Mg phases. The eutectic formed between the lamellar structures, the dark regions in Fig. 3(a), is expected to be W and α -Mg phases [19]. After homogenisation the dominating feature in the microstructure are still the lamellar plates, but they become much coarser. The eutectic is still detectable in regions isolated by the lamellar plates, Fig. 3b. The 18R phase formed in the as-cast microstructure generally transforms into 14H after prolonged heat treatments at high temperatures, Fig. 4. Since the LPSO phases have not been characterised in detail, they are designated LPSO phases in general. Apart from the LPSO phases, examination of the homogenised microstructure using TEM also reveals the existence of Mg_{24}Y_5 particles.

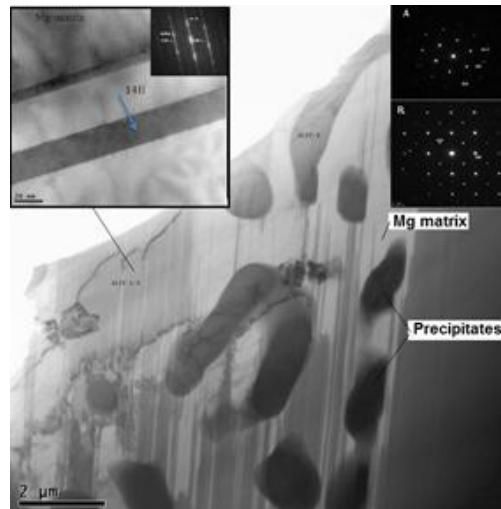


Fig. 4 TEM images of microstructures after homogenisation

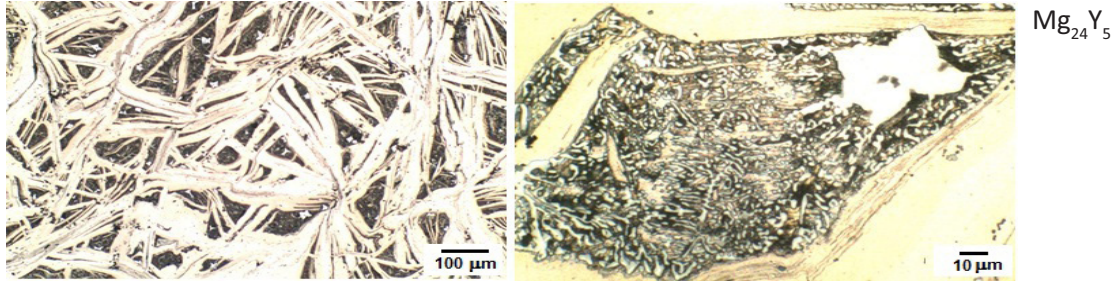


Fig. 5 Microstructure of billet deformed by one ECAP pass (different magnifications)

During severe plastic deformation the loading is distributed non-uniformly between the skeleton LPSO phase and magnesium matrix, mainly supported by LPSO phase. After the first ECAP pass, not much strain is introduced in magnesium matrix, but the LPSO structure starts to curve, as can be seen in Fig. 5. However, with the number of passes increased to four the significant amount of strain is introduced into both matrix and LPSO phase, Fig. 6. This is confirmed by profuse grain refinement (grain size around 200-300 nm) occurring in magnesium matrix, which can be seen in TEM images, Fig.7.

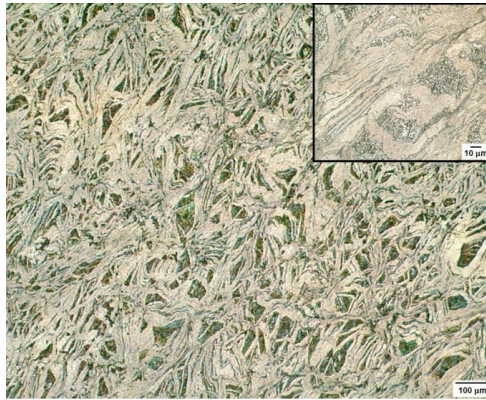


Fig. 6 Microstructure of deformed billet via four ECAP passes

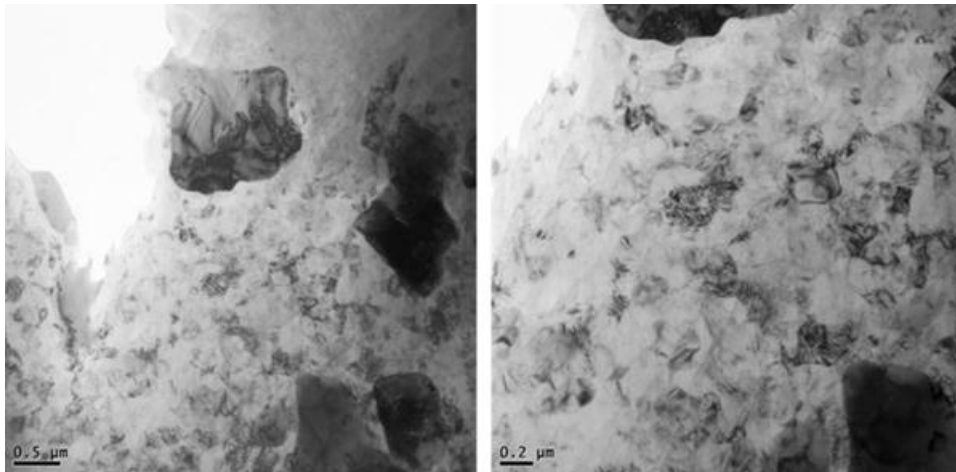


Fig. 7 TEM images of magnesium matrix (different magnifications)

More strain can be introduced if samples are subjected to additional HPT deformation. During HPT enormously high strain is produced and temperature increase is sufficient for dynamic recrystallisation (DRX) to start. The microstructure of HPT samples with as-cast or ECAP initial

conditions is shown in Fig. 8. It can be seen that if HPT is applied to as-cast sample, the plastic flow is unstable and shear bands are formed. Samples pre-strained by ECAP have plate-like oriented LPSO structure with dynamically recrystallised small grains in-between these plates.

Hardness measured for samples with all processing histories studied shows an increase due to severe plastic deformation in LPSO phase by 46 HV after four passes of ECAP and by another 61 HV resulting from HPT, Table 1. Hardness of magnesium grains increased insignificantly, by 18 – 30 HV, due to continued DRX within the magnesium matrix. The unexpected high hardness values in magnesium grains measured on HPT samples is attributed to difficulties in separating magnesium grains from the LPSO phase, as can be seen from Fig. 8a.

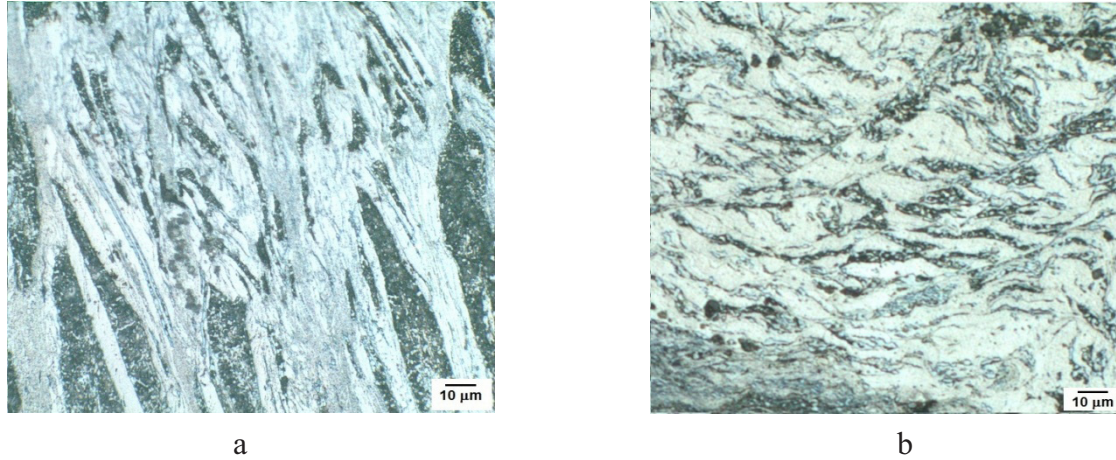


Fig. 8 Samples deformed by HPT with initial conditions:
a – as-cast; b – ECAP processed

Table 1. Hardness of differently processed cast $Mg_{92}Y_4Zn_4$ billet

Hardness, HV(0.1)		
Sample	LPSO Phase	Mg-grains
Homogenised	90±4	
ECAP 1 Pass	127±7	108±5
ECAP 4 Pass	136±6	120±5
HPT	153±5	144±7
HPT-ECAP	161±4	109±5

Conclusions

Cast $Mg_{92}Y_4Zn_4$ billet was subjected to severe plastic deformation by three different routes, namely ECAP, HPT and ECAP followed by HPT. It was shown that the LPSO phase mostly takes the load and deforms by bending and rearrangement within a soft magnesium matrix, where a substantial grain refinement down to 200-300nm takes place. Further increase of plastic strain and the associated temperature rise initiate DRX in magnesium matrix leading to its softening to some degree. However, the overall hardness of the material remains high. It can be concluded that high hardness and – by induction – high strength of $Mg_{92}Y_4Zn_4$ rod can be achieved by severe plastic deformation. As found by tensile testing, tensile ductility of the material still remains an issue, and future research will be directed at finding the temperature regimes of SPD processing leading to a better strength-ductility balance.

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