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# Microstructure, texture and mechanical properties of extruded Mg–5Al–2Nd–0.2Mn alloy

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ABSTRACT

The microstructure, texture and mechanical properties of extruded Mg–5Al–2Nd–0.2Mn alloy were investigated in the present work. The extruded alloy demonstrated a near-completely recrystallized grain structure with average grain size of about 20 μm. Intermetallic phases $Al_{11}Nd_3$ and $Al_2Nd$ were fragmented to small particles and a small amount of $Mg_{17}Al_{12}$ phase was precipitated during extrusion, which promoted grain refinement during dynamic recrystallization. A strong basal texture was formed with the basal plane parallel to the extrusion direction (ED) of the plate. The tensile strength was obviously improved after extrusion, and the difference in tensile strength of the extruded alloy in ED and transverse direction (TD) was obscure. However, the elongation in ED was higher than that in TD at both room temperature and 150 °C. It was resulted from the distribution of secondary phases along ED and basal plane texture tilting toward ED in the extruded alloy. The significant improvement in strength of the extruded alloy, compared with that of the as-cast alloy, was due to the grain refinement, the fragment of Al–Nd intermetallics, the increased interaction between the Al–Nd intermetallics and grain boundaries as well as dislocations, solid solution strengthening and texture strengthening.


## 1. Introduction

Because of the pressure of energy crisis and the reduction in environmental impact of human processes, magnesium alloys have gained more and more extended applications in automobile and aerospace industries due to their unique advantages such as low density, high specific strength and stiffness, superior damping capacity and good electromagnetic shielding characteristics. For example, Mg–Al based alloys like AZ91, AM60 and AM50 with superior die cast ability and good balance of strength, ductility and corrosion resistance, are increasingly used in automotive industry to fabricate various parts such as panel beams, steering wheel, and so on. However, their poor mechanical properties at elevated temperatures caused by discontinuous precipitation of $Mg_{17}Al_{12}$ phase from the supersaturated α-Mg solid solution and coarsening of $Mg_{17}Al_{12}$ phase in the interdendritic eutectic region at high temperatures limit their applications to temperature below 120 °C [1,2].

Alloying Mg with solute atoms, especially with rare earth (RE) elements, has received considerable attentions to improve the strength of Mg alloys. It has been proven that RE elements can enhance the strength of Mg alloys by solid solution strengthening [3] and texture strengthening [4,5]. Moreover, the addition of RE elements can also lead to the formation of different precipitated phases [6–9] and dispersoids [10] and result in the improvement in strength of Mg alloys. The strength and heat resistance of Mg–Al based alloys are obviously raised by the addition of RE elements, since they can suppress the precipitation of $Mg_{17}Al_{12}$ phase, and form highly thermal stable Al–RE intermetallics [11]. The commercial Mg–Al–RE based casting alloys AE42 (Mg–4Al–2RE) [12] and AE44 (Mg–4Al–4RE) alloy developed by the Hydro Magnesium [13] as two typical examples show higher thermal stability

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and mechanical properties compared to AM and AZ alloys due to the formation of highly thermal stable $Al_{11}RE_3$ precipitates and the complete formation suppression of $Mg_{17}Al_{12}$ phase.

Refining grain is usually regarded as another effective method to attain the desired strength and ductility. These fine grains may provide the possibility for superplasticity at relatively lower temperature and higher strain rate [14]. Severe plastic deformation (SPD) techniques, such as equal channel angular pressing (ECAP) [15], accumulative roll bonding (ARB) [16], multidirectional forging [17], hot extrusion [18] and high-ratio differential speed rolling [19] have been used to improve the mechanical properties of casting Mg alloys. It is because that compared with casting Mg alloys, wrought Mg alloys possess not only a homogenous microstructure, but also fine grains and little cast defects. Jahadia et al. investigated the effect of ECAP on AM30 Mg alloy, and the results showed that the grain structure was refined to 3.9 μm after the four ECAP passes [20]. Among these SPD methods, extrusion is a simple method for producing Mg alloys for its convenient, economical and technical advantages in fabrication of structure components. J. Meng et al. investigated the microstructure and mechanical properties of Mg–11Gd–4.5Y–1Nd–1.5Zn–0.5Zr alloy prepared via pre-aging and hot extrusion, and the results indicated that nano-scale globular $Mg_5RE$ particles were formed and promoted the DRX and grain refinement [21]. A Mg–8Al–0.5Zn alloy, which exhibits extraordinary high tensile yield strength of 403 MPa, ultimate tensile strength of 437 MPa and an elongation of 10.7% has been developed through extrusion at a low temperature of 200 °C and a slow speed of 0.07 mm/s. The superior mechanical properties are attributed to the combined effect of ultra-fine recrystallized grains, numerous nano-scale $Mg_{17}Al_{12}$ precipitates, and strong basal texture [4]. Nanostructured Mg–10Al alloys with remarkable high compressive strength (yield strength of 550 MPa, ultimate compressive strength of 580 MPa) are successfully processed via cryomilling along with SPS followed by warm extrusion. The high strength achieved is resulted from a combination of grain size strengthening, precipitation hardening and texture strengthening mechanisms [5]. However, there are few studies reported the effect of hot extrusion on Mg–Al–RE alloys. Therefore, in the present work, the microstructure, texture and mechanical properties of hot extruded Mg–5Al–2Nd–0.2Mn alloy were investigated in order to further enhance the mechanical properties based on our previous research about the addition of Nd element to Mg–5Al–0.3Mn alloy, which could decrease or even suppress the formation of $Mg_{17}Al_{12}$ phase, and improve the mechanical properties by grain refinement and the formation of high thermal stable $Al_{11}Nd_3$ and $Al_2Nd$ phases [22].

## 2. Experimental procedures

The studied Mg–5Al–2Nd–0.2Mn (wt.%) alloy was prepared from high purity Mg (99.5% wt.%), Al (99.9 wt.%), Mg–23Nd (wt.%), and Al–10Mn (wt.%) master alloys in an electric-resistant furnace under an anti-oxidizing flux protection. The melt was kept at 750 °C for 0.5 h, and then cast into a metal mould preheated to about 300 °C. The actual chemical composition of the cast ingot was Mg–5.02Al–1.87Nd–0.23Mn (wt.%) measured by an inductively coupled plasma (ICP) analyzer. The ingot with diameter of 80 mm was solid solution treated at 410 °C for 20 h followed by cold water quenching, and then hot extruded into plate of 50 mm × 8 mm in the cross section. The extrusion ratio was 12.6:1 and the extrusion temperature was 310 °C. The extruded plate was cooled by flow water.

Phase identification was conducted by X-ray diffraction (XRD, D/Max 2500V PC). The microstructures were characterized using an optical microscope (OM, Olympus GX71), and scanning electron microscope (SEM, FEI XL-30 ESEM) equipped with an X-ray energy-dispersive spectrometer (EDS). The texture analysis was performed on an EDAX-TSL electron backscatter diffraction (EBSD) system and the specimens for measurements were obtained from the mid-layer of the sheet. The samples for OM and SEM were mechanically polished and etched in a solution with 4% (volume fraction) nitric acid in ethanol. The specimens for EBSD analysis were initially ground using emery papers from #1000 to #4000, followed by the pre-polishing using $Al_2O_3$ (0.3 μm) suspension, and the final polishing on a Struers Rotopol-15 automatic polishing machine using polishing suspension OP-S (0.04 μm sized $SiO_2$ particles). EBSD data were obtained from a JEOL FESEM JSM-7000F scanning electron microscope (SEM) equipped with TSLMSC-2200. Tensile specimens with a gauge length of 15 mm and a gauge width of 5 mm were cut along the extrusion direction (ED) and transverse direction (TD) of the plates, respectively. Tensile tests were carried out using a universal testing machine (Instron-5869) at room temperature and 150 °C with an initial strain rate of $5.6 \times 10^{-4}\ s^{-1}$. The heating-plus-holding time was 10 min to equilibrate the temperature before tensile test at elevated temperatures. The fracture surfaces of the tensile specimens were also analyzed by OM and SEM.

## 3. Results and discussion

### 3.1. Microstructure

Fig. 1a shows optical microstructures of the as-cast Mg–5Al–2Nd–0.2Mn alloy. It can be seen that the as-cast alloy is composed of four phases, namely the gray α-Mg, the acicular phase, the island-shaped phase and the polygonal phase. These phases can also be observed in SEM image as shown in Fig. 1b, in which A is labeled for the acicular phase, B for the island-shaped phase and C for the polygonal phase, correspondingly. Chemical compositions of these phases are determined by EDX and the results are demonstrated in Fig. 1c–e. The atomic ratio of Al:Nd for the acicular phase A is 3.74:1, which is in quite well agreement with the stoichiometric ratio 11:3 (3.67:1) for $Al_{11}Nd_3$ phase. For the island-shaped phase labeled as B, EDX results (in Fig. 1d) reveal that it consists of Al and Mg elements. While for the polygonal particle labeled as C, EDX results (in Fig. 1e) indicate that Al:Nd ratio is 1.99:1, which is close to 2:1 for $Al_2Nd$ phase. Combining the results in the present work and previous work which has a close alloy chemical composition [22], it can be concluded that the present alloy consists of α-Mg matrix, island-shaped $Mg_{17}Al_{12}$, acicular $Al_{11}Nd_3$ phase and polygonal $Al_2Nd$ phases. After the homogenization treatment, as seen in Fig. 2a, the island-shaped $Mg_{17}Al_{12}$ particles disappeared as they were dissolved into the α-Mg matrix. The average grain size of the homogenized alloy is about 80 μm. SEM and EDX analysis for both the acicular and polygonal phases of the solid solution heat-treated alloy is also performed and the results are shown in Fig. 2b–d. The atomic ratios of Al:Nd are 3.73:1 and 2.07:1 for the acicular and polygonal phases, correspondingly, which confirms that these two phases are $Al_{11}Nd_3$ and $Al_2Nd$, respectively, and they have little change in their morphologies.

Optical microstructure of the extruded alloy on the TD–ED plane is shown in Fig. 3. At a low magnification (50x) of the optical microstructure (Fig. 3a), it is illustrated that the microstructure and secondary phases distribute directionally along the extrusion direction. It can also be seen that grains in the extruded sample exhibit two morphologies: (a) completely recrystallized fine grains with the average grain size of about 10 μm, and (b) elongated unrecrystallized grains along the extrusion direction. It is clear that recrystallization took place during extrusion. At a higher magnification (1000x) of the optical microstructure in Fig. 3b, the grains are uniform with the average grain size of about 15 μm. The secondary phases have been crashed and distributed along the