COMPARATIVE STUDY OF DEFORMATION AND FAILURE BEHAVIOR OF CONVENTIONAL AND NANOCRYSTALLINE MAGNESIUM ALLOYS

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ABSTRACT

Deformation and fracture behaviour of conventional Mg alloy (AZ91) and nanocrystalline Mg alloys (Mg-5%Al-5%Nd) were investigated using tensile and impact tests. The microstructures were examined with optical microscopy (OM) and transmission electron microscopy (TEM). The fracture surfaces were observed via scanning electron microscopy (SEM). The effects of grain size on yield stress, elongation and impact energy were studied. The possible mechanism of plastic deformation in the nanostructured alloys was also proposed.

1 INTRODUCTION

Magnesium (Mg) alloys are attractive for applications in automobile, aerospace, communication and computer industry because of their very low density, high specific strength and good machineability and availability as compared to other structural materials. It also has a good conductivity and high damping capacity. However, the disadvantages of magnesium are low yield strength and limited fracture toughness. It has been perceived that the mechanical properties of Mg alloys significantly depend on the grain size [1]. Recently, mechanical alloying has been widely used to produce nano-crystalline magnesium alloys [2-4]. The deformation behavior of nano-crystalline alloys has been studied [5-8]. Normally, nanocrystalline alloys exhibit significantly higher yield strength and lower tensile elongation relative to their coarse-grained counterparts. However, relative little work has been directed to the strength, especially the fracture of Mg based nanocrystalline alloys. In this study, the deformation and fracture behaviour of conventional and nanocrystalline Mg alloys were investigated to gain insight into the dependence of mechanical properties on grain size.

2 EXPERIMENTAL PROCEDURE

A conventional cast Mg alloy, AZ91 magnesium alloy (about 9% Al, 1% Zn and 0.21% Mn added) was used in this work, which is one of the most popular magnesium alloys with a great potential for applications in automotive industry. The nanocrystalline Mg-Al-Nd alloys were produced using the mechanical alloying method. Elemental powders of Mg, Al and Nd as starting materials were weighed according to the nominal composition of Mg-5%Al-5%Nd. The powders were mixed and then mechanically milled in a Fritsch PM-5 planetary ball mill with a rotation speed of 250 rpm. Stainless balls with 15 mm diameter were used with ball to powder ratio of 20:1. To prevent the mixture from contamination, the vial was sealed and filled with pure argon (Ar) to about 2 bar pressure. To avoid agglomeration and adhesion of the powder onto the vial and the balls, 3-4% stearic acid as a process control agent (PCA) was added to the mixture. Mechanical alloying was carried out for different durations of 0, 20 and 30 h. Then, the powder was collected in a glove box filled with inert gas (Ar) and directly loaded into a die for cold compression. The green compacts were then sintered at 400 ^{o}C or 500^{o}C for 2 h followed by extrusion at 400^{o}C at an extrusion ratio of 25:1. For simplicity, the samples were named in terms of milling duration and sintering temperature. For example, C20-400 stands for a sample sintered at 400°C after 20 h milling.

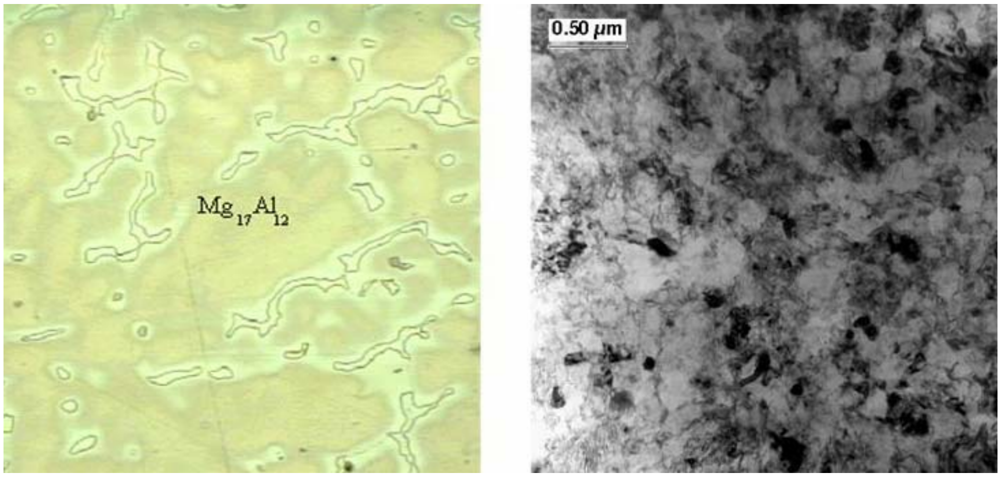
The microstructure of the AZ91 alloy was examined with optical microscopy (OM). Due to the extremely fine grain size, the microstructures of the Mg-Al-Nd alloys were observed using a transmission electron microscope (TEM).

Tensile tests were carried out using round bars with diameter of 6 and 5 mm for the AZ91 and the Mg-Al-Nd alloys, respectively. During tensile testing, an extensometer mounted on the surface of the samples was used to record the deformation. The tensile tests were carried out in an Instron machine with a crosshead speed of 1.0mm/min based on ASTM E 8M-96. The fracture behavior of the nanocrystalline Mg-Al-Nd alloy was evaluated using specially designed small notched impact specimens. For each of the tensile and impact tests, 3~5 samples were used to obtain the average values. The fracture surfaces of both tensile and impact specimens were observed using scanning electron microscopy (SEM).

3 RESULTS AND DISCUSSION

3.1 Microstructure and tensile test

The microstructure of the AZ91 alloy consists of two phases, i.e., Mg matrix and $Mg_{17}Al_{12}$ second phase, as shown in Fig. 1 (a). The average grain size is in the range of 90~140 μm.



(a) (b)

Fig. 1 Microstructure of (a) AZ91 alloy and (b) nanostructured Mg-Al-Nd alloy.

For the Mg-Al-Nd alloys, the grain size for the unmilled alloys (C0-400 and C0-500) is about 4~5 μm. After 30 h milling, the grain size was reduced to 90~150 nm, which is much smaller than the conventional AZ91 Mg alloy (90~140 μm). The bright field TEM image of the Mg-Al-Nd alloy after 30 h milling (C30-500) is shown in Fig. 1(b).

The stress-strain curve of AZ91 alloy is shown in Fig. 2. After the initial elastic response, the stress rises as a result of strain hardening and then drops. The yield stress ($\sigma_{0.2}$) and elongation are

81.4 MPa and 2.6%, respectively. Typical stress-strain relationship for Mg-Al-Nd nanocrystalline alloys is shown in Fig. 3. The yield strength ($\sigma_{0.2}$) and elongation (ψ) of the Mg-Al-Nd alloys are shown in Table 1.

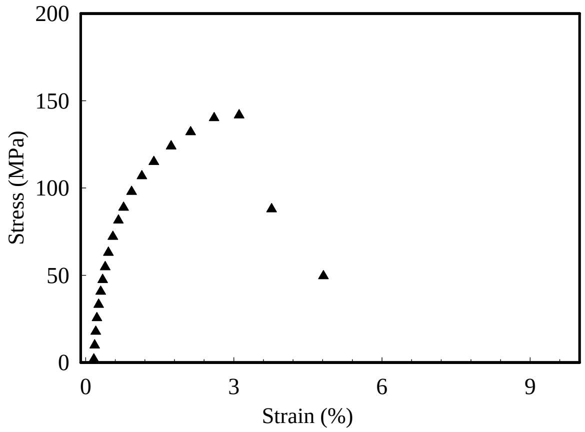


Fig. 2 Stress-strain relationship for AZ91 alloy.

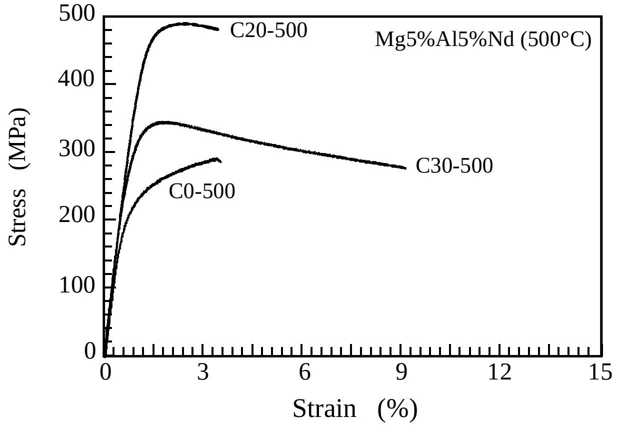


Fig. 3 Stress-strain relationship for Mg-Al-Nd alloys sintered at 500°C.

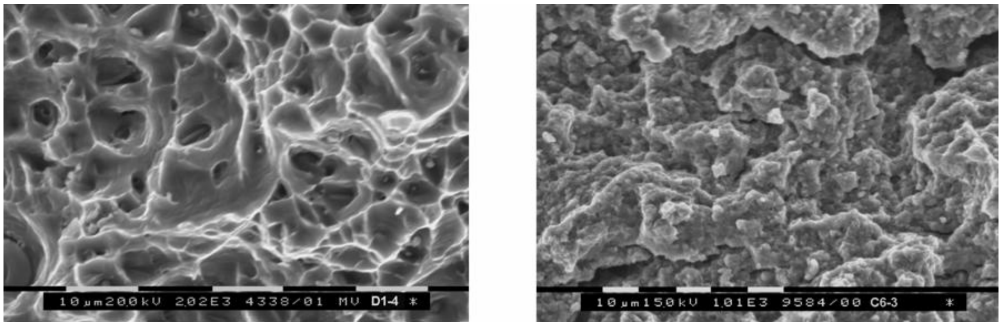
Table 1 Tensile properties of Mg-Al-Nd alloys

Specimen	$\sigma_{0.2}$ (MPa) zzz = 400°C	$\sigma_{0.2}$ (MPa) zzz = 500°C	ψ (%) Zzz = 400°C	ψ (%) zzz = 500°C
C0-zzz	190	211	2.7	3.3
C20-zzz	422	436	1.7	2.6
C30-zzz	271	333	1.6	5.9

It is clear that the yield strength of these Mg-Al-Nd alloys is significantly higher than that of conventional AZ91 alloy. The elongation (ψ) of the sample C0-zzz is generally comparable with the AZ91 alloy. The elongation (ψ) of the samples mechanically milled and sintered at 400°C is slightly lower than that of AZ91. The samples milled for 30 h and sintered at a higher temperature, i.e., 500°C exhibit a higher elongation than AZ91. As shown in Table 1, long milling duration (30 h) results in a reduction of yield strength. Based on observation of the microstructure, the reason for increase of yield strength in the Mg-AL-Nd alloys is mainly attributed to the grain refinement. The specimens sintered at 500°C have higher yield strength and elongation than those sintered at 400°C. This may be due to enhanced particle bonding at 500°C. That is, high temperature sintering at 500°C does not show any drawback in terms of strength and ductility.

In Fig. 3, it is clear that there is limited work hardening for the samples after 20 or 30 h milling although considerable strengthening has been achieved. This indicates a tendency of flow localization in these materials, which is common in nanostructured metals [9-10]. Normally, with decreasing grain size, dislocation slip and deformation twining are getting more difficult. Hahn and Padmanabhan [11] showed that for a material with very fine grains, the deformation mechanism was dominated by grain boundary sliding, which is considered to take place along some preferential grain boundaries and unsuitable boundaries can be accommodated via grain rotation. The molecular dynamics (MD) simulation on deformation of nanocrystalline copper also indicated a shift from dislocation-mediated plasticity in the coarse-grained material to grain boundary sliding in the nanocrystalline region [12]. No necking was observed in the tensile test of the Mg-Al-Nd alloys.

The fracture surfaces of the tensile specimens are shown in Fig. 4. Fig. 4 (a) shows the fracture surface of the specimen of AZ91 alloy. It is clear that the fracture surface is dominated by dimples of different sizes, formed by coalescence of microvoids. The inclusion particles can be observed in the bottom of these dimples. In contrast, no apparent dimples and tearing ridges can be observed on the fracture surface of the nanostructured Mg-Al-Nd alloy (C30-500), as shown in Fig. 4 (b).



(a) (b)

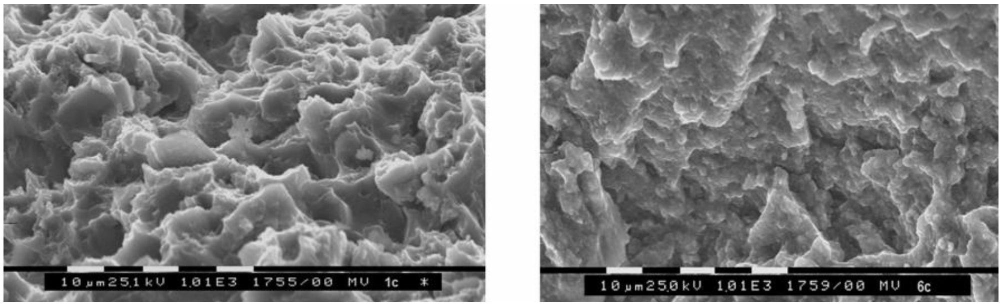
Fig. 4 Typical fracture surface of tensile specimens: (a) AZ91 and (b) Mg-Al-Nd 30h milling (C30-500).

3.2 Impact test

The average impact energy for the AZ91 evaluated by Charpy impact test is 38 kJ/m^2. The results of the impact test for the Mg-Al-Nd alloys are shown in Table 2. The impact energy for the Mg-AL-Nd samples without milling (C0-400 and C0-500) is comparable to the AZ91 alloy. However, there is a substantial reduction of impact energy for the samples after milling (C20-zzz and C30-zzz). Several studies have demonstrated highly brittle behavior of nanocrystalline metals [13-15].

Table 2 Average impact energy of Mg-Al-Nd alloys

Specimen	Energy (kJ/m^2) zzz = 400°C	Energy (kJ/m^2) zzz = 500°C
C0-zzz	22	22.8
C20-zzz	6.2	5.6
C30-zzz	5.9	5.0



(a) (b)

Fig. 5 Typical fracture surfaces of impact specimens: (a) Mg-Al-Nd without milling (C0-400) and (b) Mg-Al-Nd 30 h milling (C30-500).

Typical fracture surfaces of the impact specimens of Mg-Al-Nd alloys are shown in Fig. 5. In Fig. 5 (a), a rough surface is observed in the specimen without milling (C0-400, grain size 4~5 μm), indicating a relatively high energy dissipation during impact fracture. On the contrary, a very flat fracture surface is associated with the specimen with nanostructured grains (C30-500), Fig. 5 (b). This is consistent with the lower impact energy for the specimens after milling.

4 CONCLUSIONS

The mechanical properties of a conventional AZ91 Mg alloy and Mg-Al-Nd nanocrystalline alloys prepared by mechanical alloying were evaluated via tensile and impact tests. After 30 h mechanical milling, the grain size of the Mg-Al-Nd alloys could be reduced to below 100 nm, which led to an apparent increase in yield strength with loss of ductility (elongation) compared to the AZ91 alloy. Longer milling duration (30 h) resulted in a reduction of yield strength. Higher yield stress and elongation were associated with the specimens sintered at a higher temperature (500^{o}C). Limited work hardening was observed in these nanostructured Mg-Al-Nd alloys. Also, the milled Mg-Al-Nd alloys exhibited lower impact energy than those without milling and the conventional AZ91 alloy. Grain boundary sliding is considered to be one of the mechanisms of plastic deformation in the nanostructured alloys.

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