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Mechanical property of AZ61/nano-Al_2O_{3p} ECAEed MMCs

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Abstract. The effect of equal channel angular extrusion (ECAE) on the mechanical behavior of AZ61/Al_2O_{3p} magnesium metal-matrix nanocomposites was investigated. ECAE is a useful technique to produce bulk nano-structured materials through severe plastic deformation. The present magnesium metal matrix composites (Mg MMCs) with 1, 2, and 5 wt% nano-sized Al_2O_3 particles for ECAE were fabricated using stir-casting method. The significantly enhanced mechanical behavior of AZ61/Al_2O_{3p} magnesium metal-matrix nanocomposites at room temperature, for instance, yield strength (YS), ultimate tensile strength (UTS) and ductility, can be obtained after ECAE process. AZ61/5wt% Al2O3p MMCs ECAEed exhibits the maximum ultimate strength up to 335Mpa, whereas AZ61 MMCs (with addition of 0, 1, 2, 5 wt% Al_2O_3) have tensile strength of about 200 - 240Mpa.

Keywords: *ECAE, metal-matrix composites, magnesium alloy, nano-sized aluminum oxide, nanocomposites, nanoparticles, extrusion.*

I. Introduction

Magnesium (Mg) alloys have been successfully used for light-weight applications in the transportation industries in order to reduce vehicles‘ fuel consumption. Mg alloy exhibits excellent damping capacities, low densities and very good recycling capabilities. Mg alloy has major disadvantages of low ductility, decreasing strength as arising temperature. Therefore Mg alloys have not been used for critical performance applications because of their inferior mechanical properties compared to other engineering materials. Hence, many researchers attempt to fabricate Mg-based metal-matrix composites (Mg MMCs) by varied methods to obtain light-weight materials with excellent mechanical properties [1-3]. To improve the quality of MMCs, a method preserving high technological ductility with efficient and multiple strength enhancements has been developed on the basis of severe plastic deformation (SPD) technique. SPD is a common method for refining the grain size of metallic materials into submicrocrystalline- and nano-scale and enables manufacturing high-strength metallic materials. The SPD technique used in this study is Equal channel angular extrusion (ECAE) [4-7].

Ceramic nano-particles have been used to strengthen metallic materials in recent years. Based on the Orowan strengthening theory, finer particles are efficiently to enhance mechanical behaviour. Regarding to the fabrication of Mg MMCs, S.F. Hassan et al. [8] prepared the composite of pure magnesium by adding reinforcement phase Al_2O_3 with different particle sizes and weight percentages. The result showed yield strength (YS), ultimate tensile strength (UTS) and ductility would increase apparently when the reinforcement phase particle was 50nm. And nano-Al_2O_{3p} also significantly refined grains of magnesium matrix when added in higher weight percentage. M. Paramsothy et al. [9-10] reported AZ31 nanocomposite presented smaller grain sizes than monolithic AZ31, and higher strength than monolithic AZ31. M. Habibnejad-Korayem et al. [11] studied various weight percentages of nano-scale Al_2O_{3p} being added to pure magnesium and Mg alloy AZ31 by a stir-casting method. The nano-scale particulate can make the grain size of Mg MMCs be refined, and the mechanical behavior will be enhanced. Jiang Jufu et al. [12] studied AM60 semi-solid melt being

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*corresponding author, Email: sgjghuang@mail.ntust.edu.tw produced via new strain induced melt activated (new SIMA). Microstructure observation indicated that grain size of as-cast AM60 was reduced to 8μm after ECAE process. However, there were none researchers investigating AZ61 Mg MMCs extruded by ECAE.

From previous studies, it is found that the Mg MMCs using different kinds of particles can refine the grain size. At room temperature, Mg MMCs exhibit restricted ductility and low formability ascribed to their HCP crystal structure. Therefore, it is required to ameliorate poor workability of Mg MMCs for the evolution of plastic forming technology by ECAE. But the research of AZ61 MMCs added with nano-sized Al_2O_3 particle and extruded by ECAE is rare. This study selects nano-sized Al_2O_3 particle material as the reinforcement particle and uses the melt stirring technique to integrate the reinforcement particles into AZ61 melt in order to form AZ61 MMCs. Finally the properties of Mg MMCs are improved by ECAE passes to obtain the best mechanical behavior.

II. Materials

The matrix used in this work is magnesium alloy AZ61 with ~6.0% aluminium and ~1.0% Zinc. Its chemical composition is shown in **Table 1**. Al_2O_3 particles with weight fraction of 1, 2, and 5% within MMCs are used as the reinforcement phase. The commercially-available Al_2O_3 powder with a particle diameter about 50nm, purity of ≧99.8%, is added into AZ61 to form Mg-based metal-matrix composites.

Table 1 Chemical composition of AZ61

Elements	Al	Mn	Zn	Si	Fe	Cu	Ni	Mg
Wt%	5.83	0.549	0.794	0.013	0.005	0.01	0.008	Balance

III. Processing

The melt-stirring technique is used to fabricate the present Mg MMCs. Experimental setup is shown in **Fig. 1**. The AZ61 is initially placed inside a graphite crucible and heated to 760°C in a resistance-heated furnace. The molten alloy is stirred with a vane operated at 450rev/min for 10 minutes. Preheated Al_2O_3 particles are simultaneously added to the stirred alloy. Then the composite melt is finally poured into a metallic mold. The AZ61 MMCs containing Al_2O_{3p} with different weight fraction of 1, 2, and 5 wt% are prepared for further mechanical testing. The AZ61 MMCs were homogenized at 400°C for 20 h and water quenched. These ingots are hot extruded by an extrusion ratio of 12.25:1 on a 500 ton hydraulic press, and the extrusion is carried out at 300°C. The preforms are held at 300°C for 90 min in a constant temperature furnace before extrusion. Colloidal graphite was used as lubricant when extrusion was executed. During extrusion, the plunger speed was about 2.0 mm/s. Rods of 20mm diameter were obtained following extrusion. The extruded rods are shown in **Fig. 2**.

Bars of 11.0 × 11.0 × 90 mm are processed from the AZ61 and AZ61 MMCs' rods. The bars before extrusion are shown in **Fig. 3**. The scheme of ECAE is shown in **Fig. 4**, which is carried out in a die with the die angle $\Phi = 120°$ and the outer die angle $\Psi = 0°$. The extrusion temperature was set at 300℃±5°C. During extrusion, the plunger speed was about 1.0mm/s. After each extrusion pass, the billet was quenched into water. The billet was rotated counterclockwise about the exit extrusion axis by 90° between each pass, the so-called route Bc, and each bar is extruded for 4 times. The specimens of AZ61 was extruded by ECAE as shown in **Fig. 5**., the specimens of AZ61+1%Wt Al_2O_3 was extruded by ECAE as shown in **Fig. 6**., the specimens of AZ61+2%Wt Al_2O_3 was extruded by ECAE as shown in **Fig. 7**., and the specimens of AZ61+5%Wt Al_2O_3 was extruded by ECAE as shown in **Fig. 8**. The red arrow marks on the specimens indicate the extrusion direction after 4 pass, which consist with the Z direction shown in **Fig. 9**. The picture of ECAE machine is shown in **Fig.10**.

IV. Result and discussion

A. Metallographic observation

Figs. 11 shows typical optical microstructures at the centre of the examined cross sections of the as-cast ingots of AZ61 MMCs with different weight percentage of $Al_2O_{3p.}$ From **Fig. 14** it can be seen the addition of Al_2O_{3p} reduced the grain size from 73.5 μm to 27.2 μm for ingot. **Fig. 12** shows the microstructures of the MMCs extruded, and the average grain size data of the MMCs as a function of different manufacturing process are shown in **Fig. 14**. From **Fig. 13**, the average grain sizes of MMCs decreased evidently with the increase of the weight percentage of Al_2O_{3p} additions and ECAE passes. A more uniform microstructure consisting of grains with a average grain size of 5μm is observed in the AM60/5wt% Al_2O_{3p} MMC after 4 passes (Fig. 13d). In the case of ECAEed AM60 MMCs, grain growth restriction might have been preferred by the presence of nano-Al_2O_{3p}. The grain refinement is caused by capability of nano-Al_2O_{3p} nucleating MMC grains during recrystallization, and the nano-Al_2O_{3p} also hinders the movement of the matrix and retards the growth of crystalline grains when the melt soup is solidified so that grain refinement is resulted.

B. Hardness

Fig.15 presents the results of the microhardness measurement conducted on as-cast ingpts of AZ61 and AZ61/Al_2O_{3p} MMC after different manufacturing process, which revealed an increase in MMCs hardness with an increase in weight percentage of nano-Al_2O_{3p}. The hardness data of the MMCs as a function of different manufacturing process are shown in **Fig.15**. From **Fig.15**, the hardness of MMCs increased evidently with the increase of the weight percentage of Al_2O_{3p} additions and ECAE passes. The optimal hardness appears at AM60/5wt% Al_2O_{3p} MMC after 4 passes, and the maximum hardness is 97.6 HV. The comparison of ingot and rod shows the hardness increases with decreasing the average grain size. The relationship of grain refinement and hardness could be discussed on the basis of the Hall-Petch equation:

$$\mathrm{H} = \mathrm{H_o} + \mathrm{k}_H \mathrm{d}^{-1/2} \tag{1}$$

Where *H* is hardness, *d* is the matrix grain diameter and K_H is the Hall-Petch coefficient. Hence, the hardness of Mg alloy can be improved both by adding reinforcement particles and grain refinement.

C. Tensile strength

Fig.16~18 shows the tensile properties of the MMCs as a function of different manufacturing process. From the experimental results can be found in the room temperature, the trends of the ultimate strength, yield strength and hardness are similar. Without the extrusion of AZ61 MMCs (with addition of 0, 1, 2, 5 wt% Al_2O_3) at room temperature, the tensile strength is about 200 - 240Mpa. After extrusion, the ultimate tensile strength were increased to between 315 - 328Mpa. After ECAEed，the ultimate tensile strength can be increased to up 325 - 335MPa. AZ61/5wt% Al_2O_3p MMCs ECAEed exhibits the maximum ultimate strength up to 335MPa.

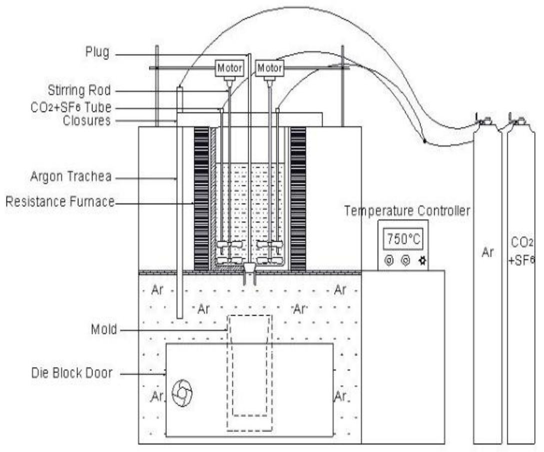


Fig.1 Setup configuration

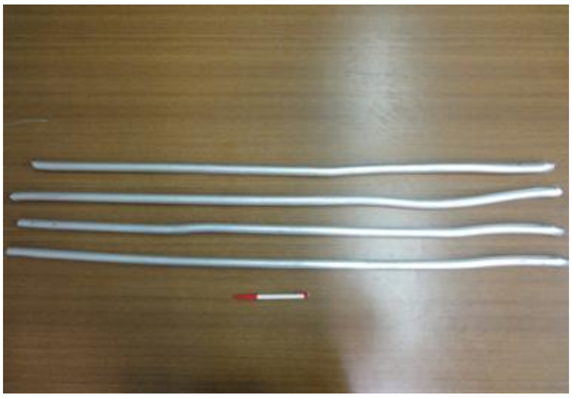


Fig.2 Extruded rods of the AZ61 MMCs

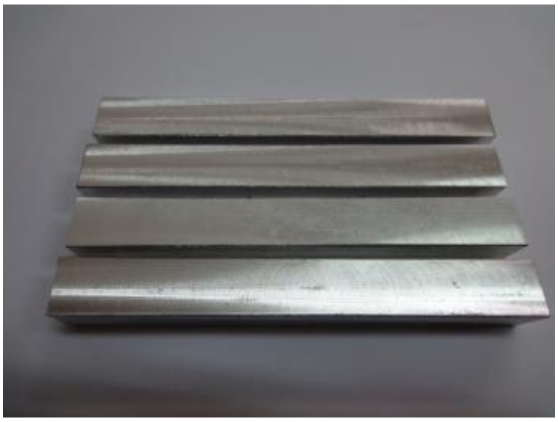


Fig.3 The specimens before ECAE

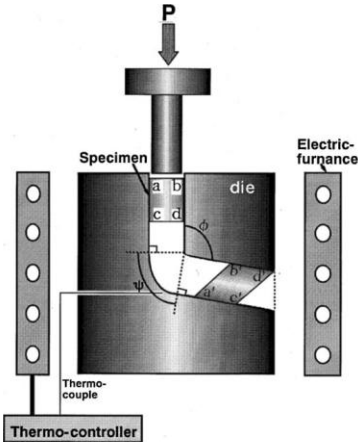


Fig.4 The scheme of equal-channel angular pressing (ECAE)

Fig.5 The specimens after ECAE(AZ61)

Fig.6 The specimens after ECAE(AZ61+1%Wt Al_2O_3)

Fig.7 The specimens after ECAE(AZ61+2%Wt Al_2O_3)

Fig.8 The specimens after ECAE(AZ61+5%Wt Al_2O_3)

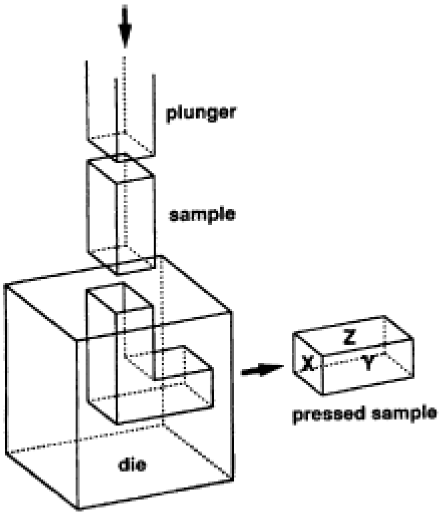
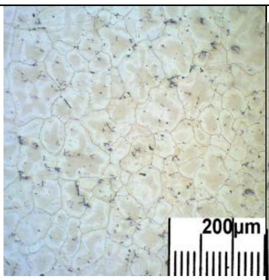
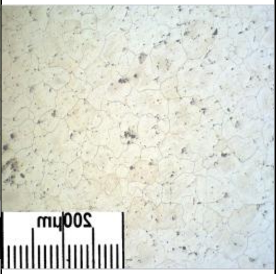
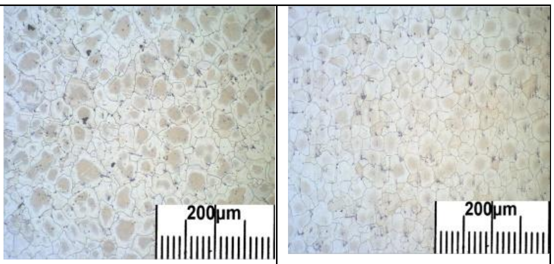


Fig.9 Schematic illustration of a typical ECAE facility: the X, Y and Z planes denote the transverse plane, the flow plane and the longitudinal plane, respectively

Fig.10 The ECAE machine

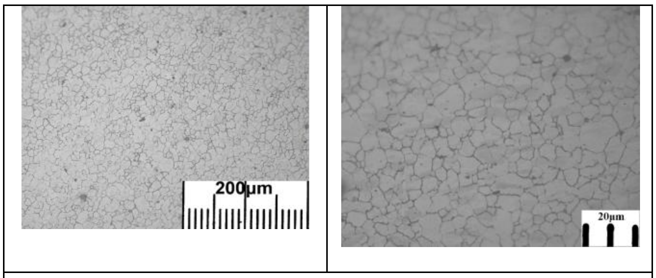
	
(a)AZ61 100X	(b)AZ61+1wt%Al_2O_{3P} 100X



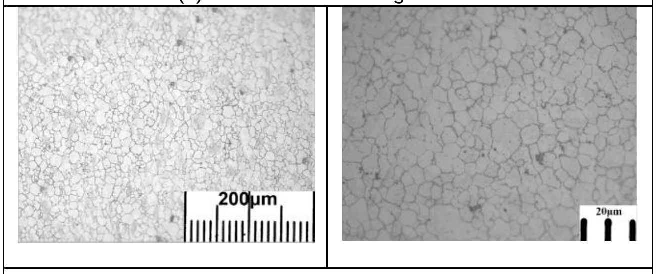
(c) AZ61+2wt%Al_2O_{3P} 100X

(d) AZ61+5wt%Al_2O_{3P} 100X

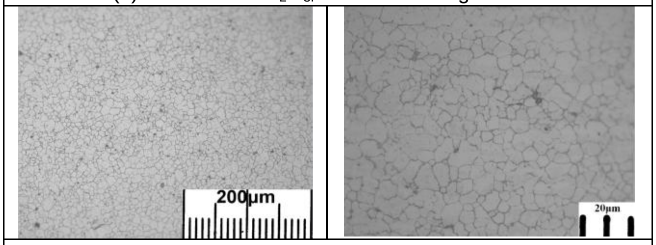
Fig.11 Microstructure of as-cast ingot (a)AZ61,(b)AZ61+1wt%Al_2O_{3P},(c) AZ61+2wt%Al_2O_{3P},(d) AZ61+5wt%Al_2O_{3P};100X



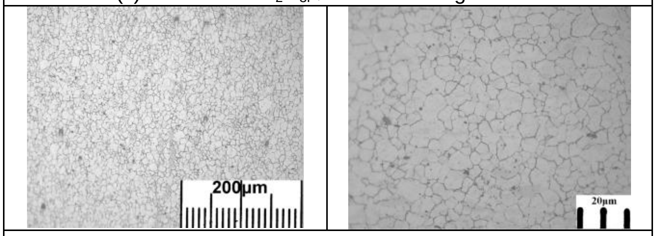
(a)AZ61，left:200X、right:500X



(b) AZ61+1wt%Al_2O_{3P}，left:200X、right:500X

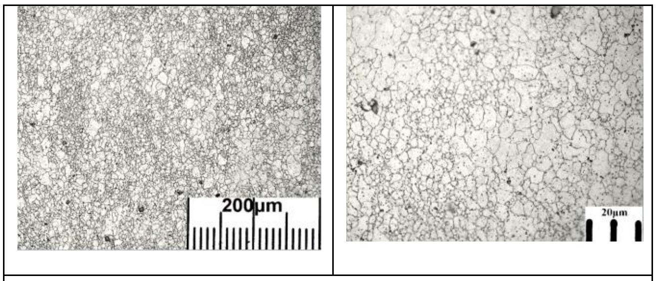


(c)AZ61+2wt%Al_2O_{3P}，left:200X、right:500X

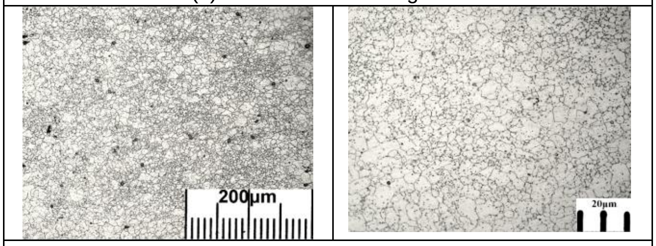


(d) AZ61+5wt%Al_2O_{3P}，left:200X、right:500X

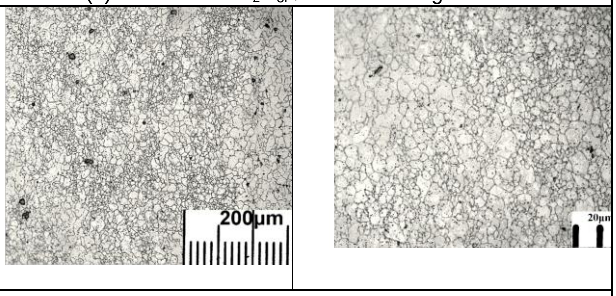
Fig.12 Microstructure of extruded rod (ECAE,N=0)(a)AZ61,(b)AZ61+1wt%Al_2O_{3P},(c) AZ61+2wt%Al_2O_{3P},(d) AZ61+5wt%Al_2O_{3P}



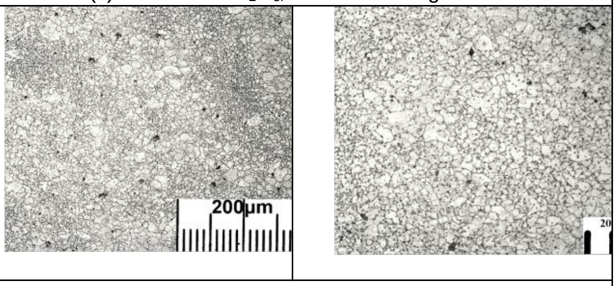
(a)AZ61，left:200X、right:500X



(b) AZ61+1wt%Al_2O_{3P}，left:200X、right:500X

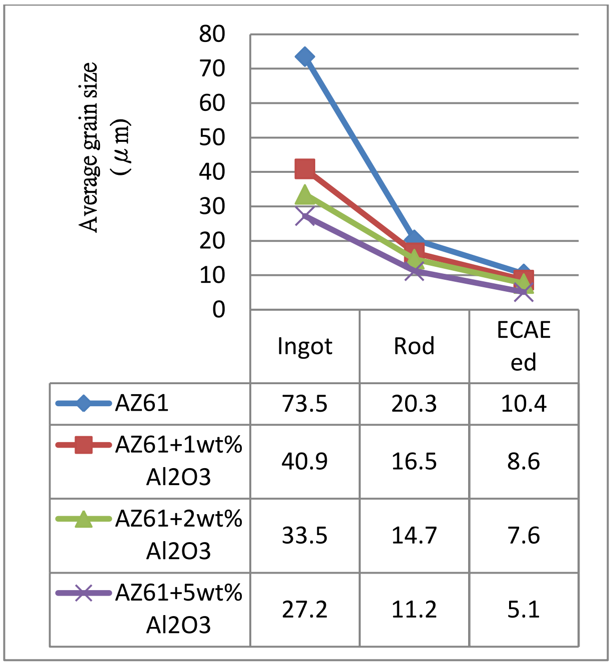


(c)AZ61+2wt%Al_2O_{3P}，left:200X、right:500X



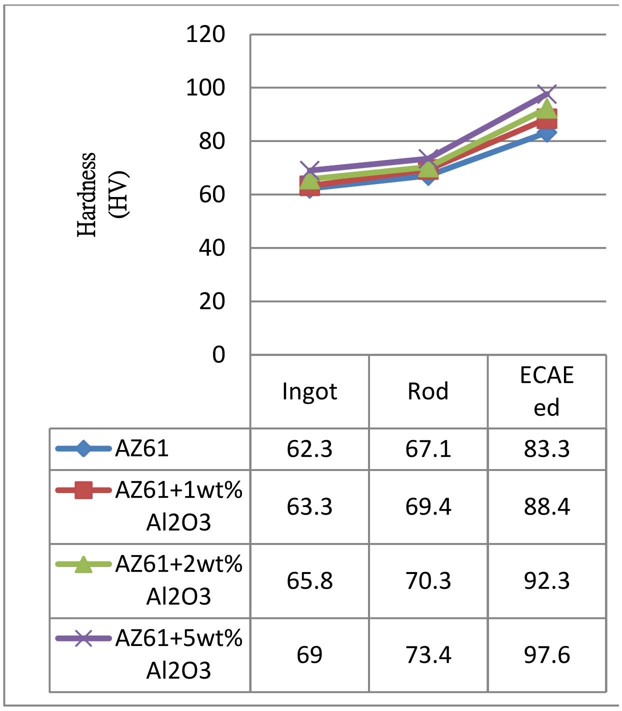
(d) AZ61+5wt%Al_2O_{3P}，left:200X、right:500X

Fig.13 Microstructure of ECAEed billet(ECAE,N=4)(a)AZ61,(b)AZ61+1wt%Al_2O_{3P},(c) AZ61+2wt%Al_2O_{3P},(d) AZ61+5wt%Al_2O_{3P}



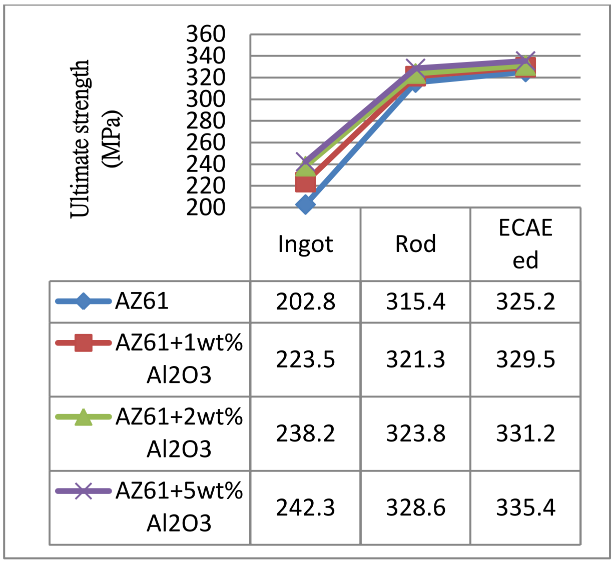
	Ingot	Rod	ECAEed
AZ61	73.5	20.3	10.4
AZ61+1wt% Al2O3	40.9	16.5	8.6
AZ61+2wt% Al2O3	33.5	14.7	7.6
AZ61+5wt% Al2O3	27.2	11.2	5.1

Fig.14 Effect of different manufacturing process on the average grain size of AZ61/Al_2O_3p magneisum matrix composites



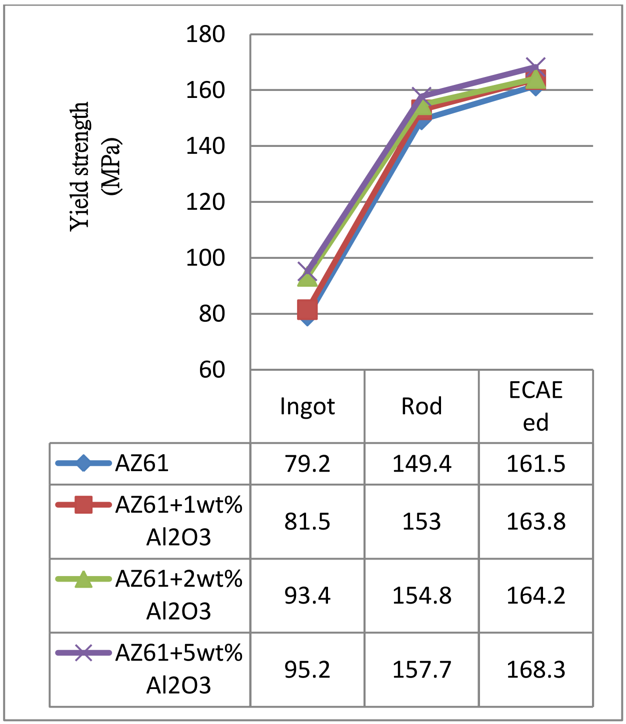
	Ingot	Rod	ECAEed
AZ61	62.3	67.1	83.3
AZ61+1wt% Al2O3	63.3	69.4	88.4
AZ61+2wt% Al2O3	65.8	70.3	92.3
AZ61+5wt% Al2O3	69	73.4	97.6

Fig.15 Effect of different manufacturing process on the hardness of AZ61/Al_2O_3p magneisum matrix composites



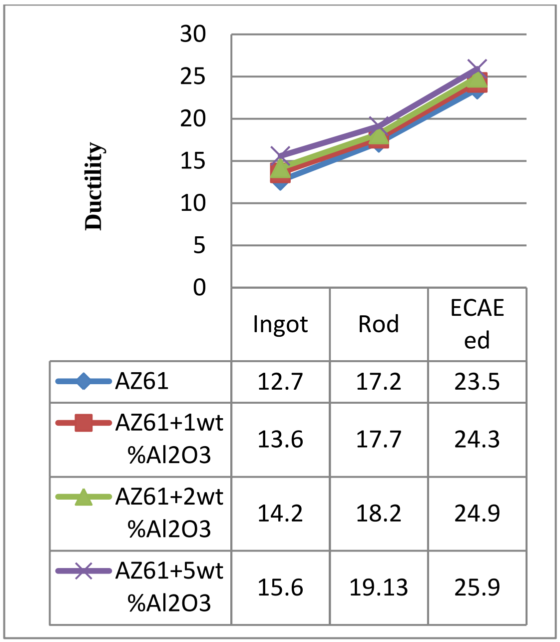
	Ingot	Rod	ECAEed
AZ61	202.8	315.4	325.2
AZ61+1wt% Al2O3	223.5	321.3	329.5
AZ61+2wt% Al2O3	238.2	323.8	331.2
AZ61+5wt% Al2O3	242.3	328.6	335.4

Fig.16 Effect of different manufacturing process on the ultimate strength of AZ61/Al_2O_3p magneisum matrix composites



	Ingot	Rod	ECAEed
AZ61	79.2	149.4	161.5
AZ61+1wt% Al2O3	81.5	153	163.8
AZ61+2wt% Al2O3	93.4	154.8	164.2
AZ61+5wt% Al2O3	95.2	157.7	168.3

Fig.17 Effect of different manufacturing process on the yield strength of AZ61/Al_2O_3p magneisum matrix composites



	Ingot	Rod	ECAE ed
AZ61	12.7	17.2	23.5
AZ61+1wt %Al2O3	13.6	17.7	24.3
AZ61+2wt %Al2O3	14.2	18.2	24.9
AZ61+5wt %Al2O3	15.6	19.13	25.9

Fig.18 Effect of different manufacturing process on the ductility of AZ61/Al_2O_3p magneisum matrix composites

V. Conclusions

This study proposed and investigated the microstructure of nano-Al_2O_{3p} reinforced and ECAEed AZ61 Mg based metal-matrix composites. The present Mg-based MMCs were fabricated by the melt stirring technique. Based on the experimental results, the following conclusions and some important novelties could be drawn:

1. Severe plastic deformation by equal channel angular extrusion technique was shown to enhance efficiently the hardness of AZ61 MMC due to its grain size refinement.
2. Observing the microstructures of MMCs, the more uniform microstructure consisting of grains with a average grain size of ~5μm is observed in the AZ61/5wt% Al_2O_{3p} MMC after 4 passes.
3. The hardness of MMCs increased evidently with the increase of the weight percentage of Al_2O_{3p} additions and ECAE passes.
4. The optimal hardness of AM60/5wt% Al_2O_{3p} MMC after 4 passes has achieved to be 97.6 HV.
5. The tensile property of MMCs increased evidently with the increase of the weight percentage of Al_2O_{3p} additions and ECAE passes. The ultimate strength of AM60/5wt% Al_2O_{3p} MMC after 4 passes has increased to 335 MPa.

VI. References

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