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ScienceDirect

Procedia Materials Science 6 (2014) 37 – 42

Procedia Materials Science

www.elsevier.com/locate/procedia

3rd International Conference on Materials Processing and Characterisation (ICMPC 2014)

Effect of Severe Plastic Deformation and Heat Treatment on Toughness of Magnesium Alloys

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Abstract

Severe plastic deformation by friction stir processing and subsequent heat treatment was carried out on cast magnesium alloys AZ91D and AE42 to obtain ultrafine precipitates size and enhance the toughness. The resultant toughness values were analyzed and correlated with microstructure. Toughness of magnesium alloys AE42 and AZ91D was doubled by friction stir processing followed by heat treatment. Ultrafine precipitates in the order of 0.1 to 0.5 micron were formed by the processing + heat treatment. Networked coarse structure was completely eliminated from cast alloys. Friction stir processing acted as severe plastic deformation and the inbuilt energy and dislocations due to the same was reason for the numerous ultrafine precipitates nucleation during the heat treatment. The precipitates were homogenously distributed in matrix.

Selection and peer review under responsibility of the Gokaraju Rangaraju Institute of Engineering and Technology (GRIET)
Keywords: Friction stir processing, severe plastic deformation, toughness, magnesium alloys, precipitates.

1. Introduction

Magnesium alloys are the lightest commercial alloys, 30% lighter than aluminum alloys. But poor toughness makes these alloys unsuitable for many advanced engineering applications. Poor toughness arises from mainly two factors viz the predominant HCP based structure and the coarse microstructure in casting [Huang et al. 2008]. The focus in this study was to make the coarse grain structure ultrafine and make the magnesium alloy tougher.

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Selection and peer review under responsibility of the Gokaraju Rangaraju Institute of Engineering and Technology (GRIET)
doi:10.1016/j.mspro.2014.07.006

Severe plastic deformation method combined with heat treatment was selected for obtaining the fine structure. Severe plastic deformation makes the cast structure refined in most of cast alloys [Huang Deming et al. 2007]. When severe plastic deformed material is heat treated at low temperature like aging treatment, nucleation of numerous fine precipitates of second phase is possible (due to the release of inbuilt energy) and controlling the same can achieve better mechanical properties [Dobriyal et al. 2008]. Friction Stir Processing (FSP) is one of the severe plastic deformation methods, which can be easily applied to magnesium alloys.

FSP is a solid state processing to improve the cast alloy properties [Thomas et al. 1991]. This is a new process based on Friction Stir Welding (FSW) in which a rotating tool with pin and shoulder is inserted in the material to be processed, and traversed along the line of interest. The heating is localized and generated by friction between the tool and the work piece, with additional adiabatic heating from metal deformation [Lina et al. 2009]. After FSP, a processed zone known as Friction Stir Zone (FSZ) is produced by movement of material from the front of the pin to the back of the pin. It changes the cast microstructure and morphology completely [Murray et al. 2007, Feng et al. 2007, Govindaraju et al. 2012].

Widely applied severe plastic deformation process like ECAP cannot be carried out at room temperature on magnesium alloys (due to HCP structure magnesium alloys need warm or hot process), but FSP which is self heating can easily be carried out on most of the magnesium alloys. Mainly two alloys were selected for the current study- AE42- the alloy developed for high temperature and automobile applications and AZ91D the widely used cast alloy. AE 42 alloy has potential application in aerospace if the toughness is improved [Mihriban O.,Pekguleryuz and ArslanKaya, A. 2005]. This is magnesium- aluminum-Rare Earth (RE) alloy in which RE elements are added for creep resistance. AZ91D is magnesium-aluminum-zinc alloy, which is gravity die cast mostly. In as cast condition this alloy has continuous network of $Mg_{17}Al_{12}$ phase. This makes the alloy casting inferior in toughness [Mihriban O.,Pekguleryuz and Arslan Kaya, A. 2005, Esparza et al. 2002].

2. Experimental procedures

AZ91D and AE42 magnesium alloys sheets (Parent Metal- PM) of 3.5 mm thick x 50 mm width x 200 mm long were prepared and used for the FSP experiments. These sheets were derived from die cast ingots. Chemical composition of the alloys is given in Table 1. FSP experiments were carried out with parameter listed in Table 2 by using tool made up of high speed steel. Multi-pass process was used and the total length of 100 mm was processed for each pass.

After processing, FSZ was separated and samples for Charpy V notch test were made for both the alloys. All the samples were heat treated at 190, 200 and 210°C for 12-16 hours (standard aging time of magnesium alloys). Before and after the heat treatment, microstructural and toughness testing were carried out. Microstructural analysis was carried out using optical microscopes after sample preparation with standard metallographic techniques.

Toughness test was Charpy v-notch test, as a standardized high strain-rate test which is important to judge the effect of FSP and heat treatment on the magnesium alloy was carried out with a sub size sample. Sample size was 3 mm T X 6 mm W with a V notch. Test was carried out on the machine with a capacity in the range of 5-15 Joules.

Table 1. Chemical composition of the alloys

Alloy	Al	Zn	RE (Ce+Nd+La+Th+Pr)	Mg
AE42	9	1	-	Balance
AZ91D	4	-	2	Balance

Table 2. FSP parameters

Alloy	Tool rpm	Traverse speed	Vertical load	Tool profile
AE42	1000 rpm	40 mm per minute	250 kg	Conical, 3 mm diameter pin and 12 mm diameter shoulder
AZ91D	1000 rpm	60 mm per minute	200 kg	

Fig. 1 Photograph of AE 42 alloy after FSP showing FSZ

3. Results and discussions

1.1. Impact test results

From the impact test results shown in Table 3, it is well established that the FSP followed by heat treatment improves the toughness of the magnesium alloy in case of both AE42 and AZ91D alloys. The reason for the same is explained that the precipitates of RE and $Mg_{17}Al_{12}$ in AE42 and AZ91D alloys respectively are in ultrafine size and well distributed. In addition, the micro defects in casting were cured during FSP so the crack initiation and failure at lower stress is stopped.

The peak toughness value was achieved for the heat treatment temperature of 200 °C. Decrease in the toughness value for the heat treatment temperature above 200°C may be attributed to the over aging.

Table 3. Impact test values of the alloys in different condition

Condition of sample	Impact energy value J (AE42)	Impact energy value J (AZ91D)
PM	6.5	4.9
After FSP (FSZ)	11 (deviation 2.2)	8.5
FSZ, heat treated at 190° C	11	10.8
FSZ, heat treated at 200° C	10.1	11.2
FSZ, heat treated at 210° C	9.8	11

1.2. Microstructural results

With the detailed analyses of microstructural results from the figures 2 to 4, the grain refinement by FSP and ultrafine precipitates by heat treatment are proved. The cast alloys (PM) has a coarse and networked microstructure (Fig. 2) which result in poor toughness. After the FSP experiments, the grain size was reduced considerably to 10-12 micron range which is shown in Fig. 3. When the FSZ is heat treated, numerous nucleations of second phases were observed as shown in Fig. 4. The precipitates are $Mg_{17}Al_{12}$ (from AZ91D alloy) and Al-RE (from AE42 alloy) ultra fine size.
The nucleation of numerous numbers of precipitates made the size of it as ultra fine (as the growth of the precipitates was limited). Dislocations and free energy introduced during the FSP was reason for more nucleation. They act as nucleation sites. In case of conventional heat treatment, the precipitates of such a fine size and uniform distribution are not possible.

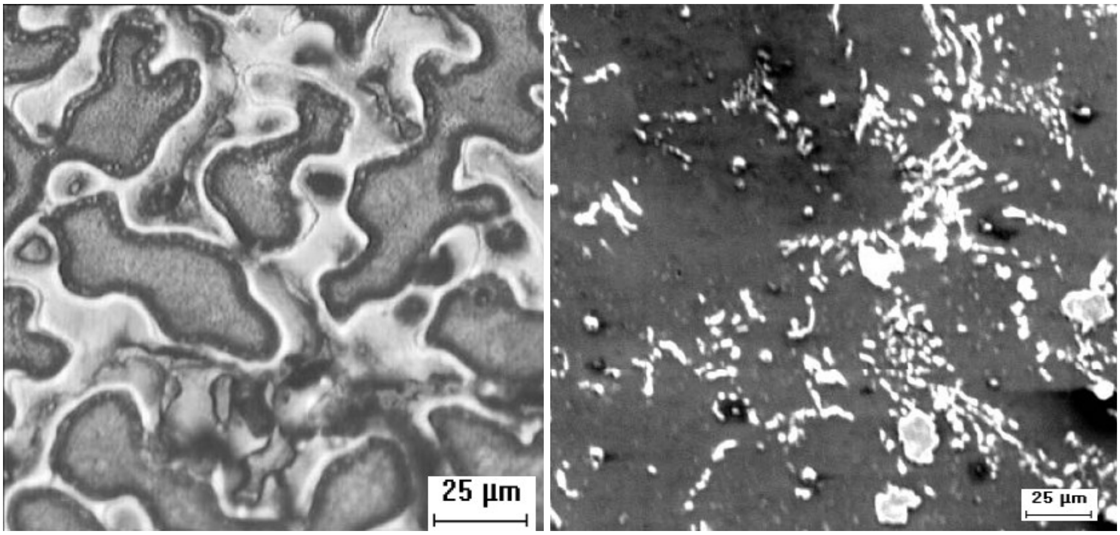

Fig. 2. Microstructure of the PM of AZ91D and AE 42 alloy

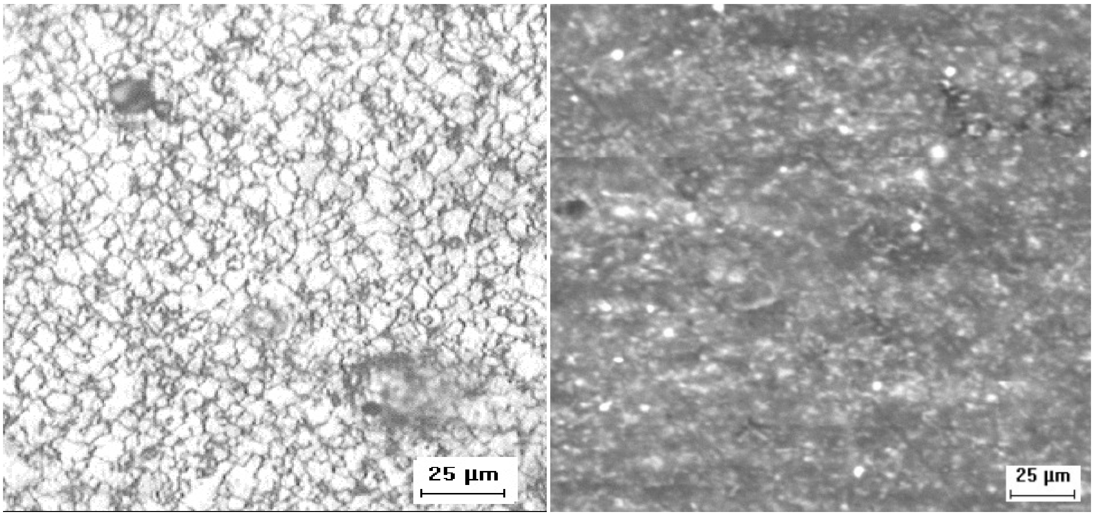

Fig. 3. Microstructure of FSZ of AZ91D and AE42 alloy

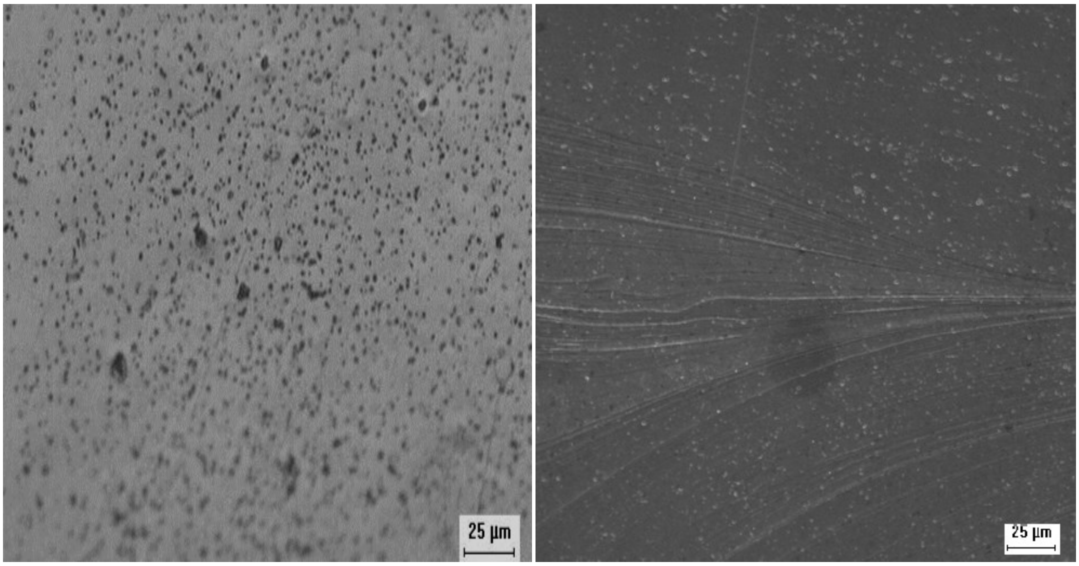

Fig. 4. Microstructure of FSZ of AZ91D and AE42 alloy heat treated at 200°C

4. Conclusions

- FSP- as severe plastic deformation process acted as grain refinement for cast magnesium alloys AE42 and AZ91D.
- FSP followed by aging treatment, in contrast to conventional heat treatment like solutionising and aging, resulted in two fold increases in toughness.

- The inbuilt energy and dislocations introduced during FSP made the precipitates numerous in number and small in size (less than 1 micron) when heated around 190-200 °C (aging temperature of most of magnesium alloy)
- The numerous ultrafine size precipitates resulted in improving the toughness of magnesium alloys by 100%.
- The process combination can be used to make commercially viable engineering parts using magnesium alloys which are lightest commercial alloys with enhanced toughness.

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