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ORIGINAL ARTICLE

On the precipitates and mechanical properties of magnesium–yttrium sheets

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Abstract Light-weight wrought magnesium alloys is an important part of the weight reduction in automobiles industry for improve their fuel efficiency. Yttrium containing magnesium alloy is a potential material in this perspective. In this work, two magnesium–yttrium alloys (C and D alloys) were cast and rolled to 2 mm thick sheets. The mechanical properties of these hot rolled and annealed sheets were determined. Optical microscope and scanning electron microscope equipped with EDX were used to investigate microstructure evolution during thermo-mechanical processing in the studied alloys. Precipitates evolution during hot rolling and annealing processes were analyzed and compared with those calculated using thermo-chemical software (FactSage). Schiel phase distribution diagrams of C and D alloys were calculated using FactSage.
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1. Introduction

As the lightest of all metal materials, magnesium alloys continue to offer tremendous potential for automobile and aerospace industries. The existing magnesium applications are mainly die castings and the use of wrought magnesium sheets is limited. Recently, there is great interest in the development of wrought magnesium alloys to produce Mg sheet. However the limited range of properties that is available for magnesium sheet is hindering widespread industrial use of this material. Hexagonal crystal structure of magnesium precludes high formability at room temperature, with the result that further development is required in order to enhance the rolling and forming properties of magnesium. Mg–Y-based alloys display excellent mechanical properties at service temperatures [1–3]. Mg–Zn–Y system particularly is promising because it exhibits a superior mechanical performance with respect to the commercial Mg–Zn–Zr (ZK) system [1]. In Mg-rich region, Mg–Zn–Y alloys precipitate icosahedral phase (I-$Mg_{43}Y_4Zn_3$) and long period stacking order (W-$MgYZn_3$). These phases have a remarkable strengthening effect at room temperature as well as elevated temperature [2–4]. Many research activities have been carried out including grain refinement and precipitates of Mg–Zn–Y alloys containing I and W phases [5–7].

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Table 1 Chemical compositions of Mg–Y based alloy.

Alloy	Al	Zn	Mn	Y	Ce[a]
C (Mg–2%Y)	0.57	0.4	0.29	2.05	
D (Mg–2%Y–0.17%Ce)	0.58	0.41	0.29	2.04	0.17

[a] Ce added as Mishmetal (%Ce = 55.90, %La = 30.50%, %Pd = 6.80, %Nd = 5.20, Others = 1.60).

In 2010, Su et al. [8] studied the effect of rolling temperature on microstructure and mechanical properties of $Mg_{97}Y_2Zn$ sheet. They found that the network of I-phase breaks down into chain of particles in the rolling direction with increasing rolling temperature. Further, hot rolled $Mg_{97}Y_2Zn$ sheet exhibits good mechanical properties; $\sigma_Y \approx 310$ MPa and $\sigma_{UTS} \approx 320$ MPa. Jain et al. [9] and Aljarrah et al. [10] studied the effects of alloying elements (Mn and Ce) on the microstructure and mechanical properties of Mg–Zn–Y sheets, A (Mg–1.7Y–0.53Al–1.2Zn–0.27Mn–0.013Ce) and alloy B (Mg–2.2Y–0.49Al–1.1Zn–0.3Mn–0.23Ce), processed by hot rolling and friction stir processing. They observed that anisotropy in the mechanical properties in the as-rolled sheet was reduced after aging. In friction stir processing, grains were refined and the mechanical properties varied with test direction.

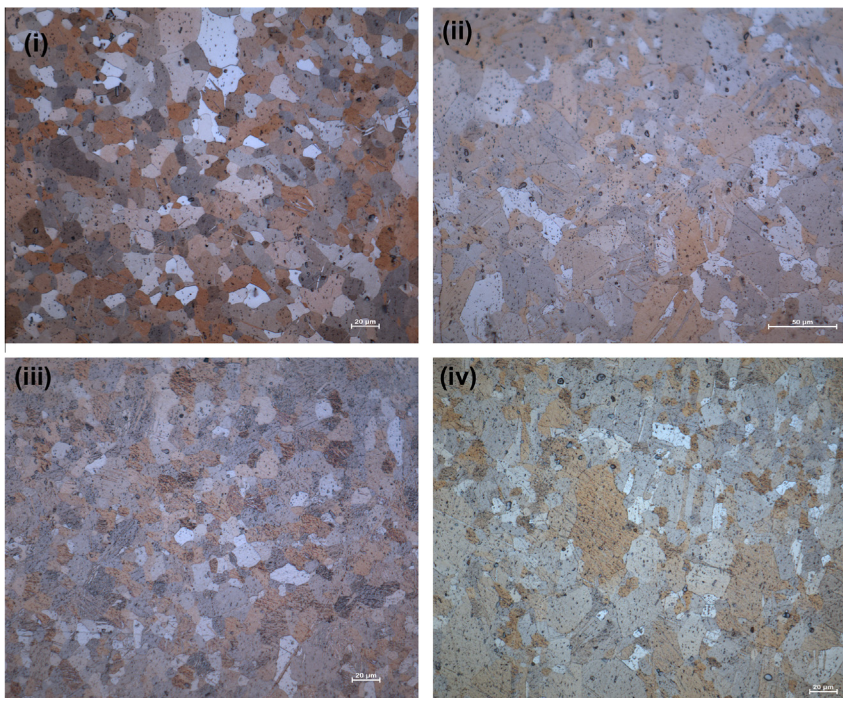

Figure 1 Optical micrograph of hot rolled and annealed of C alloy in: (i) transverse and (ii) rolling directions and D alloy in: (iii) transverse and (iv) rolling directions.

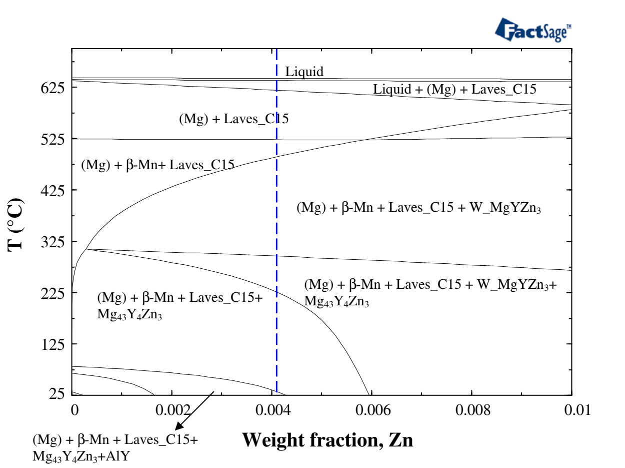

Figure 2 Vertical section of Mg–Y-based alloys with low Zn (alloy C).

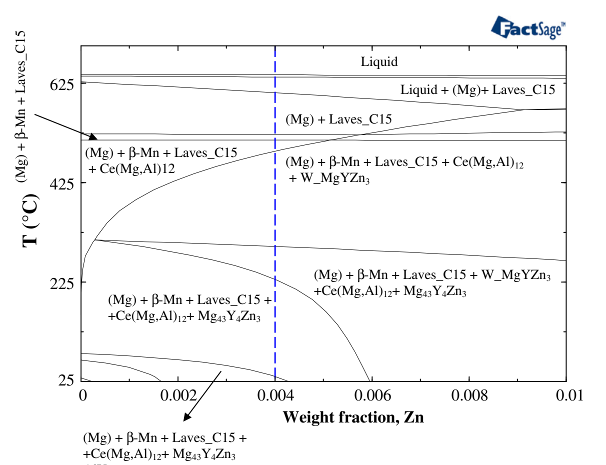

Figure 3 Vertical section of Mg–Y-based alloys with low Zn (alloy D).

In the current study, two new magnesium sheets, alloy C (Mg–2.05Y–0.57Al–0.4Zn–0.29Mn) and alloy D (Mg–2.04Y–0.58Al–0.41Zn–0.29Mn–0.17Ce), all in wt.% (Ce was added as Mishmetal), were produced through conventional multi-pass hot rolling process. C and D alloys were cast and rolled to 1.8 mm thick sheets. The mechanical properties of these hot rolled and annealed sheets were determined and related to the sheet microstructure. Microstructure of the hot rolled and annealed C and D sheets were investigated using optical and SEM. Precipitates evolution during the thermo-mechanical process were calculated using FactSage and the calculated results were compared with the experimental ones.

2. Experiment

The alloy compositions C and D were cast into $14 \times 30 \times 1.3\ cm^3$ plates. The compositions of the as-cast plates are listed in Table 1. Samples were cut from plates C and D and annealed for 10 h at 500 °C. These plates were hot rolled at ~500 °C to a final thickness of 1.8 mm in 9 passes with a total reduction of 88%. Following each pass, the samples were reheated to ~500 °C in sand bath furnace. After rolling, the samples were annealed at 500 °C for 10 min. The rolled and annealed sheets were machined into ASTM E8 tensile samples with a 3 mm gauge width and 12 mm gauge length using

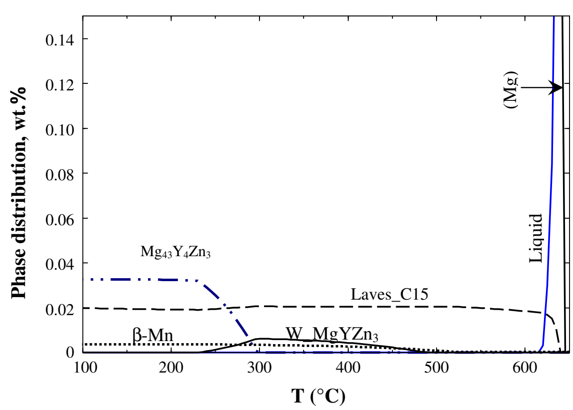

Figure 4 Phase distribution of Mg–Y-based alloys with low Zn (alloy C).

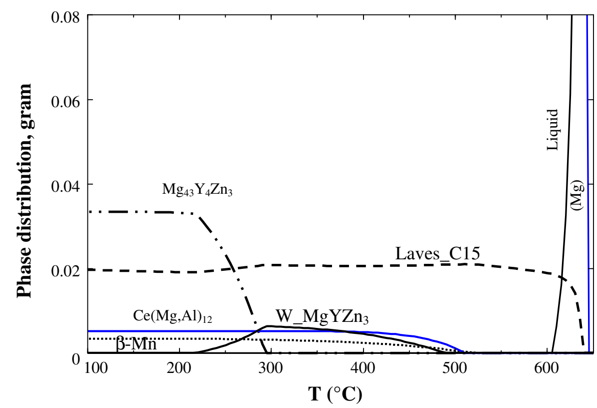

Figure 5 Phase distribution of Mg–Y-based alloys with low Zn (alloy D).

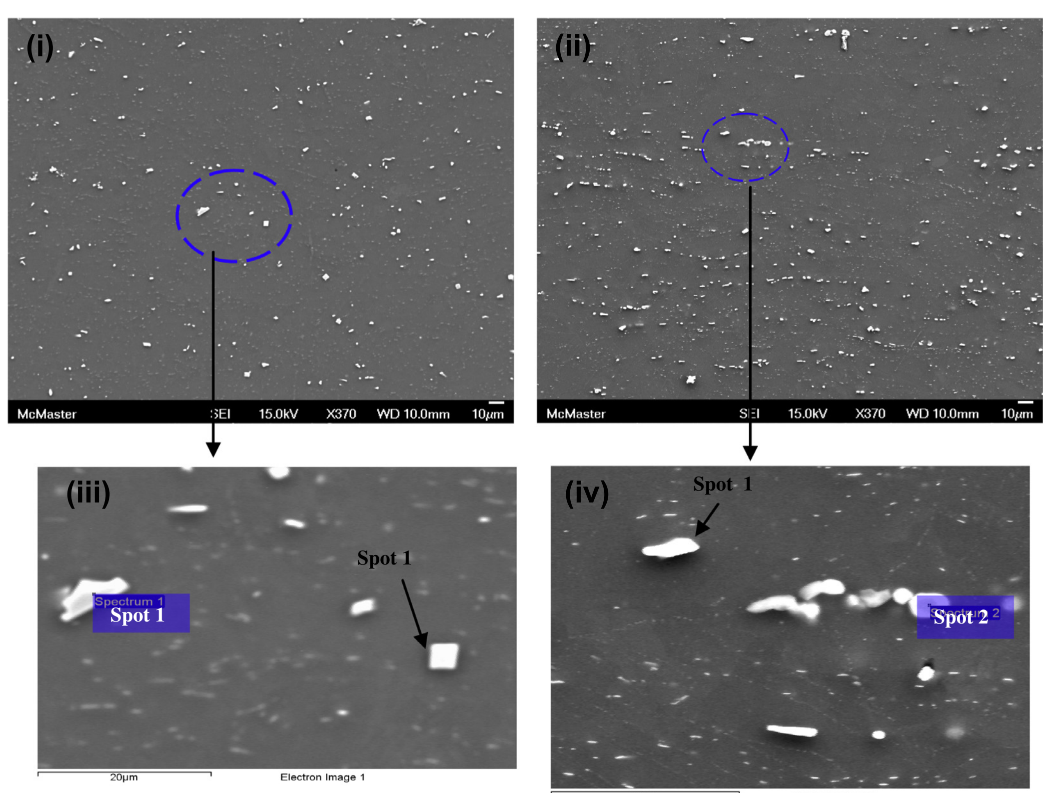

Figure 6 SEM image of (i) and (iii) C, and (ii) and (iv) D magnesium alloys.

Electrical Discharge Machining (EDM). The tensile test was conducted using and Instron 4206 universal testing machine. Metallographic examinations were conducted on hot rolled and annealed condition. To reveal the grains, the specimens were etched with 10 ml of distilled water, 70 ml of ethanol, 4.5 g of picric acid and 10 ml acetic acid.

3. Results and discussions

Microstructures of C and D alloys after hot rolling and annealing at a temperature of 500 °C for 10 min were shown in Fig. 1. Average grain size of C alloy was 14 μm compared to 14.8 μm in D alloy. These alloys were characterized by fine precipitates in the grain and coarse precipitates in the grain boundaries. Traces of twin bands could be observed in C alloy compared to numerous twin bands in D alloys. Figs. 2 and 3 displayed thermal histories of C and D alloys during cooling using FactSage. The C and D alloys were indicted by vertical discontinuous lines in Figs. 2 and 3, respectively. Thermodynamic calculations predict the existence of the following phases in the final stage of solidification of C alloy; (Mg), β-Mn, Laves_C15 (Mg_2Y), AlY and $Mg_{43}Y_4Zn_3$. Whereas (Mg), β-Mn, Laves_C15, AlY, $Ce(Mg,Al)_{12}$ and $Mg_{43}Y_4Zn_3$ were predicted for alloy D. Scheil phase distribution diagram of C and D alloys were shown in Figs. 4 and 5. During Scheil cooling of C and D alloys (Mg) appears at the beginning of solidification. The liquid fraction decreases significantly when Laves_C15 phase start to form. $Ce(Mg, Al)_{12}$ phase exists in D alloy has not in C alloy.

SEM image of hot rolled and annealed C and D alloys were presented in Fig. 6. The morphology of the precipitates in C and D alloys was varied from square to plate-like shape. The size of these precipitates with the order of nano to micrometers were formed as can be seen in Fig. 6. In C alloy, these secondary particles include small Laves_C15 (Mg_2Y) precipitate with the size of 2–5 μm (spot 1) and β-Mn and W_$MgYZn_3$ could be observed in spot 2 in Fig. 6iii. Yuttrium is the only element could be detected in Mg matrix. Magnesium matrix dissolves small amount of Y (∼1.3 wt.%) compared to 7.5 wt.% at 450 °C in the Mg–Y system. Significant amount of particles have been observed in D alloy (Fig. 6ii compared to that of C alloy (Fig. 6i)). Phases were identified using SEM-EDX and EMPA analysis as shown in Fig. 7.

The non-uniform distributed particles were coarser than that observed in C alloy. Mg, Al and Y were detected in spot 1 in Fig. 6iv. This particle appears to be a non-equilibrium phase of Mg–Al–Y. Spot 2 successfully detected $Ce(Mg,Al)_{12}$ phase in D alloy. Further, less than 1.3 wt.% of Y was dissolved in magnesium matrix.

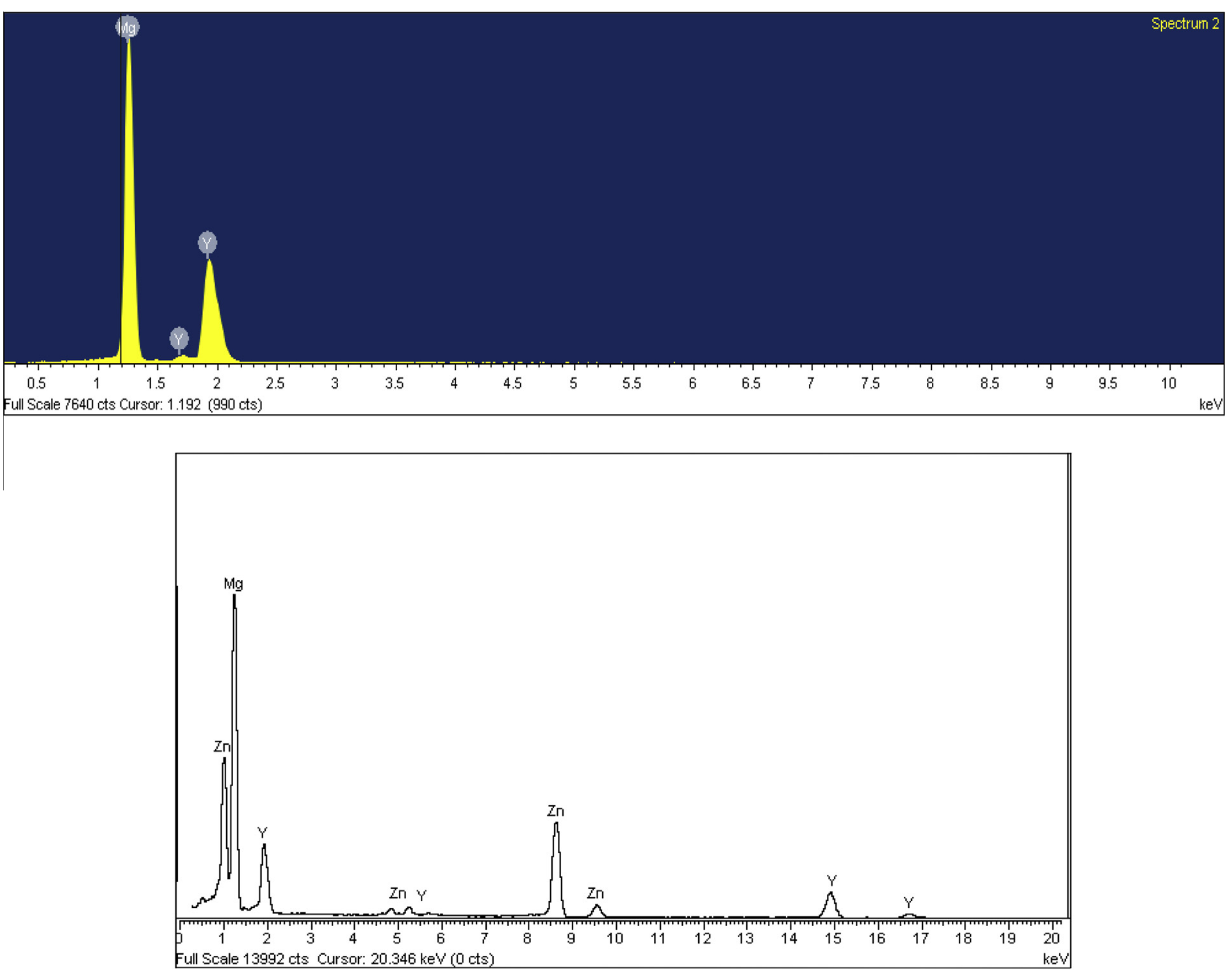

Figure 7 (i) SEM-EDX spectra of spot 1 and (ii) EPMA spectra of spot 2 in Fig. 6.

Table 2 Mechanical properties of C and D sheets compared with A, B, AZ31and ZKA1261 sheets.

Alloy	Yield stress (MPa)	Ultimate tensile stress (MPa)	Elongation (%)
C-HR&AN	129	209	20.7
D-HR&AN	201	244	11.4
A-HR&AN [10]	146	228	30.5
B-HR&AN [10]	146	230	23.9
ZKA1261 [11]	106	203	4.9
AZ31 [12]	220	290	15

A comparison between the mechanical properties of sheet C and D with AZ31 magnesium commercial alloy is presented in Table 2. Yield and tensile strength of as-hot rolled C and D alloys were slightly lower than that of AZ31 alloy. The rolled sheet exhibits a similar mechanical anisotropy to other conventional magnesium alloys. The elongation is lower in D than that in A alloy. However, thermodynamic calculations of precipitates indicate the possibility of heat treatment optimization of C and D alloys in further study.

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