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Precipitation Strengthening in Extruded AZ61 Magnesium Alloys During Heat Treatment Process

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Abstract: Magnesium alloys, in particular the commercial wrought alloy, AZ61 has been increasingly considered as an attractive material in the transportation industry. The objective of this paper is to determine the microstructure change and $Mg_{17}Al_{12}$ precipitation in the alloy and to evaluate its mechanical properties. After primary microstructure characterization and mechanical testing in the as-extruded condition the specimens are subjected to heat treatment to the temperature 400°C for one hour followed by quenching in the water. Specimens treated were found to have a coarse grain, homogeneous structure with a substantial increase in grain size. Optical observations also reveal $Mg_{17}Al_{12}$ precipitations grow in the form of needle shape within the grain after two hour aging. The mechanical properties and the Hardness Vickers (HV) of the AZ61 magnesium alloy are also found to increase owing to secondary hardening by precipitation strengthening. Therefore, the deformation mechanism improved the materials properties ex-specially in automotive industry. Future work should focus on the improvement of different mechanical properties such as fracture toughness and creep resistance by using precipitation strengthening.

Key words: AZ61 Magnesium Alloy %Heat Treatment %$Mg_{17}Al_{12}$ Precipitation %Aging

INTRODUCTION

The use of magnesium alloy in automotive industry highly promoted due to the increased emphasis on weight reduction. Magnesium is two-third less dense than aluminum and one-fourth less dense than iron [1,2]. Substantial progress has been made in the last few years in the development of wrought magnesium alloys produced by thermo mechanical forming. The extrusion process results in creation of large range of possible geometries, which are identified due to the effect of a combination of several shapes. This feature eliminates joints and reduces fabrication costs. The wrought forms of magnesium have advantages of higher strength and ductility, as well as better formability, in comparison with the cast form.

Despite of these advantages, magnesium alloys, normally exhibit limited mechanical properties because of their hexagonal close pack (h.c.p) structure which results in limited deformation mechanism, activated at room temperature [3]. Due to this fact, there is a necessity to improve materials properties parameter, which can be achieved by alloying or optimizing the process.

Therefore understanding the behaviors and properties of wrought magnesium alloys has been the central focus in several recent investigations [4,5]. In this study, the microstructures change of AZ61 magnesium alloy due to the heat treatment and the precipitation of $Mg_{17}Al_{12}$ during aging process are investigated. The effects of the process on the mechanical properties of the magnesium are also examined.

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MATERIALS AND METHODS

In this study, the commercial extruded AZ61 magnesium alloys with a diameter of 16 mm were cut into 2 mm thick using the diamonds cutter. The chemical compositions of the AZ61 magnesium alloys are as shown in Table 1. Before the heat treatments, specimens were wrapped with the anti rust aluminum foils to protect the specimens from oxidations. Every specimen was heat treated to 400°C for one hour until the transition of the phase occurred from (" +$) to " [6]. Figure 1 shows the equilibrium phase diagram of Mg-Al [7]. Then, the specimens were quenched in the water. After that, the specimens were put into aging at the temperature of 200°C for 30 minutes and another two hours to form intermetallic $ ($Mg_{17}Al_{12}$).

After the aging process, specimens were quenched in the water to maintain the internal microstructure. In the next process, the specimens were polished with the emery paper grid from No. 200 till No. 1500. The final polishing was done by using synthetic leather cloth with the diamond paste solution size of 0.5 µm. The final stage of metallographic preparation was completed by etching the mirror-like specimens using solutions of 6 gram of picric acid, 100 ml ethanol and 10 ml acetic acid. The etching time for each of the specimens varied from 5 to 15 seconds. Hardness test were conducted using Mitutoyo Vicker Hardness Machine and for every heat treatment process three samples have been prepared to validate the test data.

Tensile and fatigue tests were conducted on a pneumatic fatigue testing machine with a maximum capacity of 14 kN. All fatigue and fracture test were performed under a load control of sinusoidal waveform with a stress ratio R = 0.1 and at a frequency of 10 Hz. The test was stopped when the specimen did not fail up to 10^7 cycles. The fracture surfaces and specimen surfaces were then observed under a scanning electron microscope (SEM). The tests were conducted in laboratory environment at temperature of 25°C.

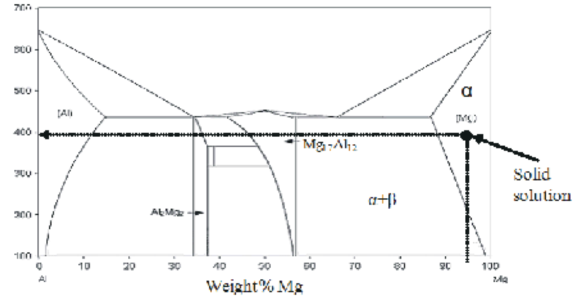


Fig 1: The equilibrium phase diagram of magnesium alloy

Table 1: The chemical composition of AZ61 magnesium alloy (wt %)

Al	Zn	Mn	Fe	Ni	Cu	Si	Be	Mg
5.890	0.7197	0.1565	0.009	0.0006	0.0022	0.0195	0.0006	Bal.

RESULTS AND DISCUSSION

Microstructure and Hardness of as-received and as-quenched AZ61 Magnesium Alloy: Figure 2 shows the microstructure of AZ61 magnesium alloy in the (a) as-received and (b) as-quenched AZ61 magnesium alloy. The as-quenched sample exhibits a typical stability homogeneous structure, i.e. coarse grain with a substantial increase in grain size. The size is increased from 12 ìm to 15 ìm. The quench reaction in magnesium is the second step in the precipitation-strengthening process. The structure of the alloy consists of a supersaturated solid solution of the á-magnesium phase [8].

The hardness values of as-received and as-quenched magnesium are shown in Figure 3. The as-quenched hardness of magnesium alloy increases mainly owing to the á-solid solution strengthening of Al and the hardness of magnesium containing solute the Al of 6.0wt% reached value of 71HV. The increase of the as-quenched sample's hardness is suggested to be due to the increase of the á solute content, as a result of the formation of the undissolved $Mg_{17}Al_{12}$.

Microstructure and Hardness of Aging AZ61 Magnesium Alloy: Figure 4 shows the microstructures of aging samples. The samples were aging at 200°C for (a) 1800s and (b) 7200s. The 1800s-sample still contained undissolved precipitation in its microstructure.

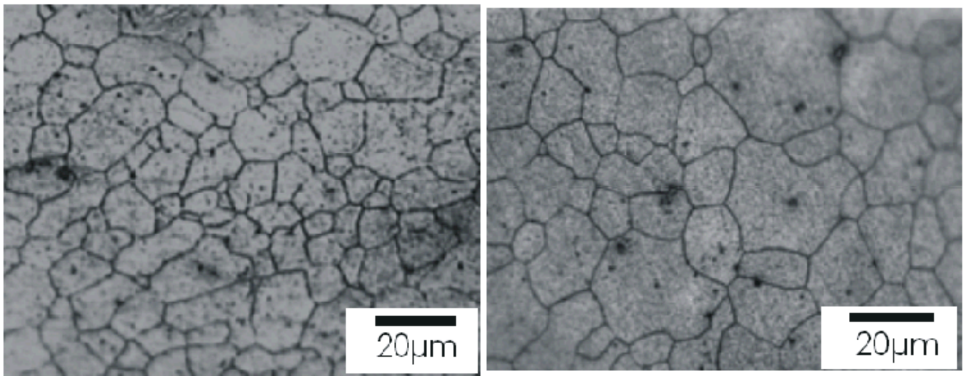
After 7200 seconds, the grain boundaries are completely covered by the precipitation of the intermetallic $ ($Mg_{17}Al_{12}$) [9]. The intermetallic ultimately grows into a needle-like shape within á.

Figure 5 shows the change in the hardness of the magnesium as a result of the holding time of the aging for 1800 seconds,; the hardness of the sample slightly decreased to 59HV. It is well-known that the aging is to relieve the stresses that are set up during the transformation of á to (á+$) and reduce the hardness [10]. The recovery of the dislocation and the decrease in contribution of solid solution strengthening to precipitate $Mg_{17}Al_{12}$ aging process may cause the decrease in hardness.

The hardness of the aging-sample for 7200 seconds increased to 69HV. Besides increasing the toughness of the sample through the aging process, the hardness can

Table 2: Mechanical properties of AZ61 magnesium alloy

Condition	F_y (MPa)	F_{max} (MPa)	E (GPa)	Hardness Vickess (HV)
As received	270	308	43	67
Solution treatment	308	381	45	71
Aging (1800 sec)	251	288	40	59
Aging (7200 sec)	289	362	44	69



(a) (b)

Fig 1: The equilibrium phase diagram of magnesium alloy

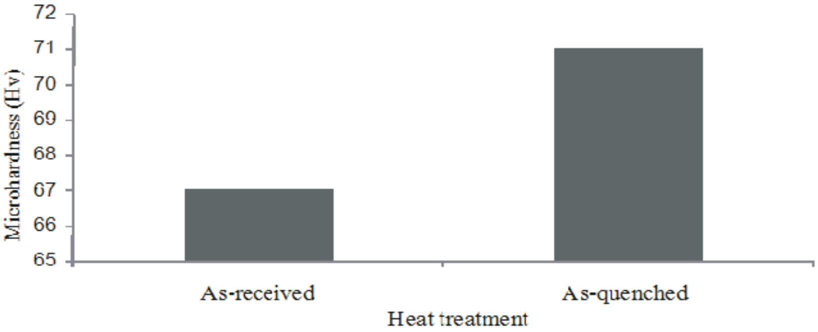
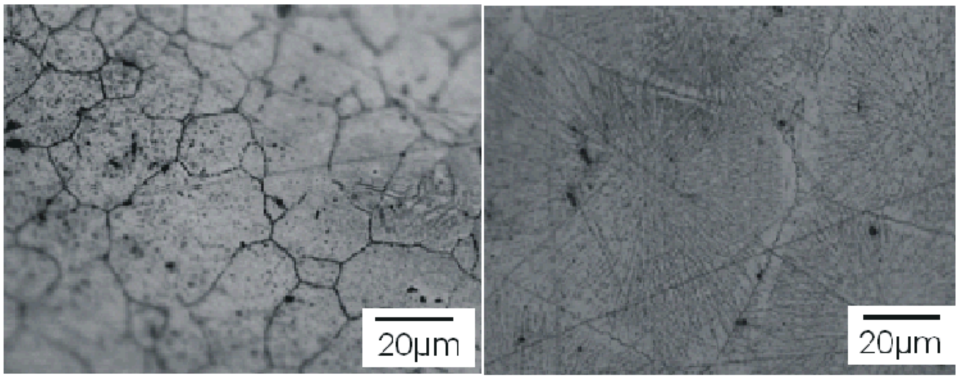


Fig 2: The optical micrograph of the specimens: (a) in as-received condition and (b) in as-quenched condition.



(a) (b)

Fig 3: The hardness values of Magnesium Alloy Fig 4: The optical micrograph of the aging samples at 200°C for (a) 1800s and (b) 7200s

also be increased similarly with the as-quenched sample. It is suggested that the formation of $Mg_{17}Al_{12}$ precipitation influences the increase in the hardness.

Tensile and Fatigue Strength of as-received and Heat Treated of AZ61 Magnesium Alloy: Table 2 shows the mechanical properties for AZ61 magnesium alloy after the

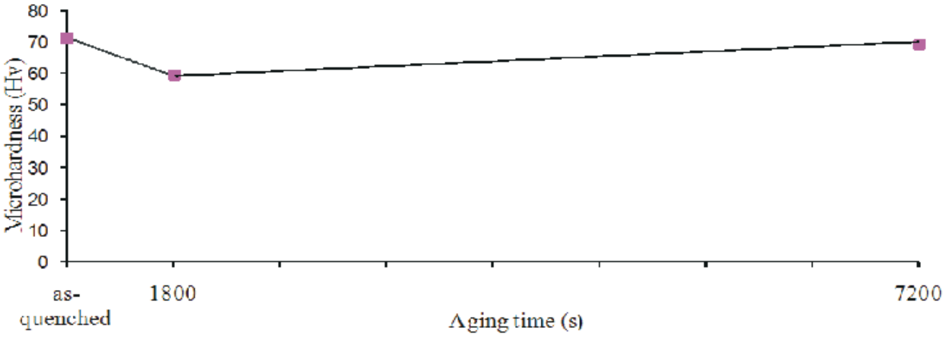


Fig 5: The hardness value of treated and aging magnesium alloy

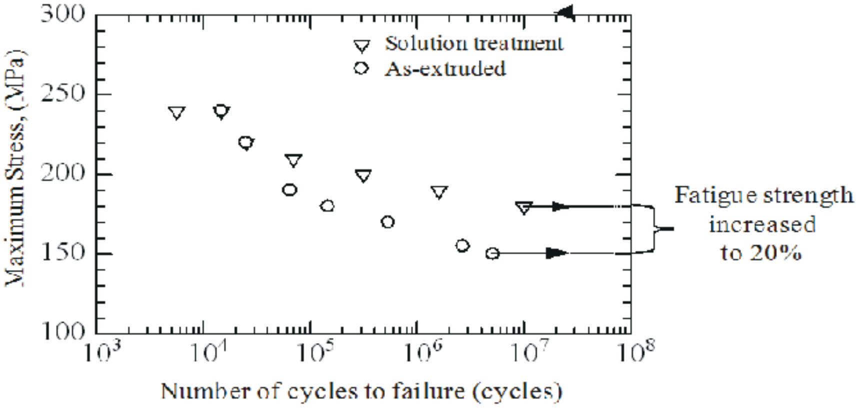


Fig 6: Fatigue strengths of solution treated and as-extruded samples

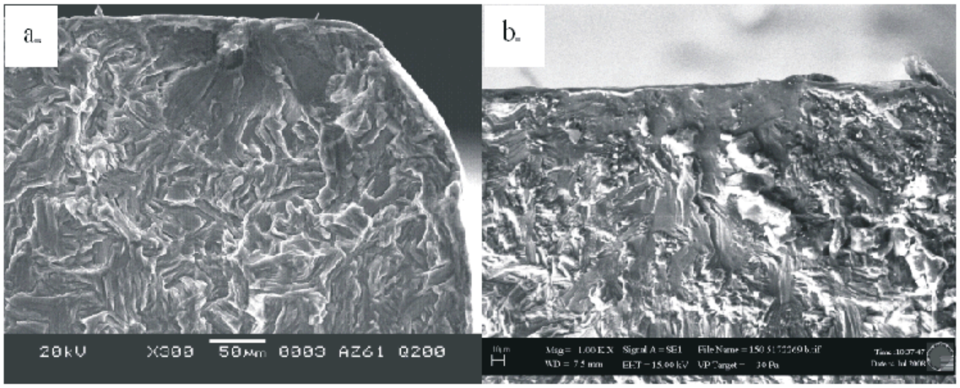
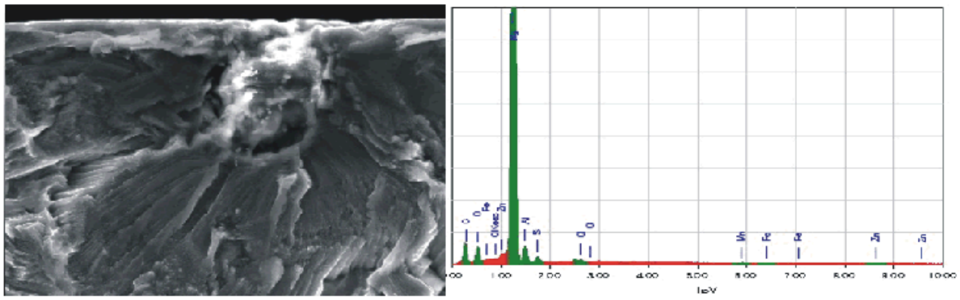


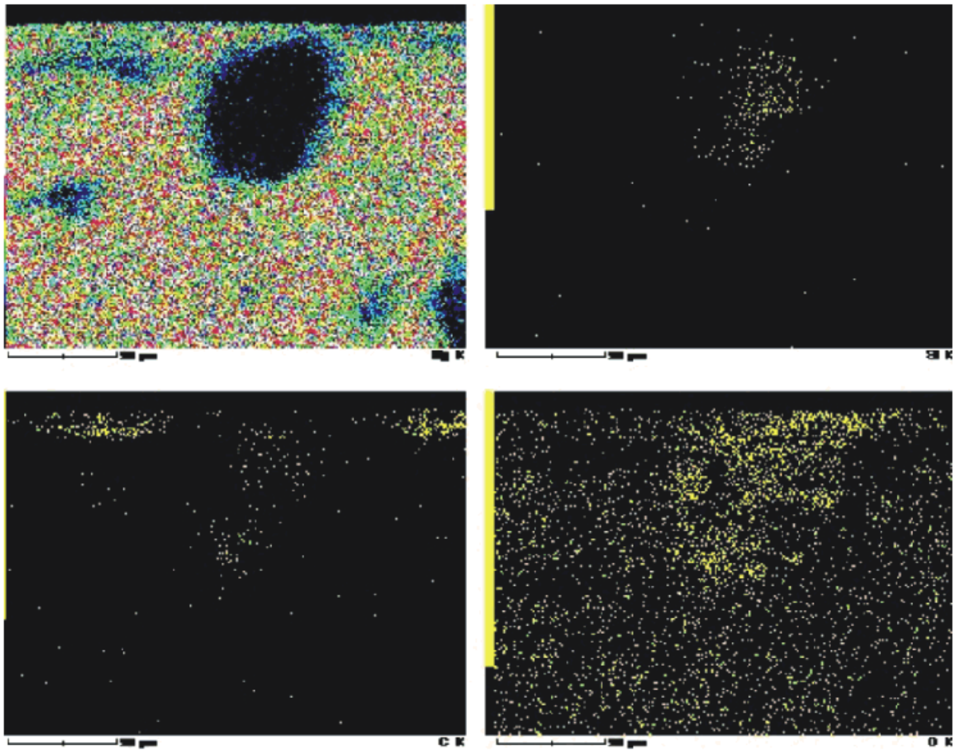
Fig 7: Observations were done using SEM equipped EDX. (a) Foreign particle (b) Flat surface

heat treatment process. The yield stress and ultimate tensile strength of the materials were significantly improved after the solution treatment and aging process. For as-extruded specimen, the yield stress and ultimate tensile strength obtained were 270 MPa and 308 MPa respectively. For the solution treated specimen, the yield stress and the ultimate tensile strength obtained were 308 MPa and 381 MPa, respectively. For the specimen aging at 1800 second, the yield stress and ultimate tensile strength obtained were 251 MPa and 288 MPa, respectively. For the solution treated specimen, the yield stress and the ultimate tensile strength obtained were 289 MPa and 362 MPa, respectively. The increment of yield stress and ultimate tensile values for solution treated and aging samples is believed to be due to the hardness properties and the $Mg_{17}Al_{12}$ precipitation hardening.

The comparison of fatigue strength of solution treated and extruded AZ61 magnesium alloy is shown in Figure 6. The figure shows that fatigue strength of the solution treated samples increased in comparison with the



(a) Point analysis



(b) Mapping analysis

Fig 8: EDX point and mapping analysis from the fracture surface of the foreign particle

fatigue strength of the as-extruded AZ61 samples. The fatigue limit for solution treated and as-extruded AZ61 were 180 MPa and 150 MPa, respectively. The higher fatigue strength observed for the solution treated sample is suggested to be caused by the higher tensile strength and also the higher hardness properties in comparison with the as-extruded sample.

Microstructures Observation from the Fatigue Fracture Surface of AZ61 Magnesium Alloy: Detailed fracture surface observations showed that foreign particle was found at the fatigue fracture origin of the solution treated samples especially for the samples which exhibited higher fatigue life more than 10^5 cycles as shown in Figure 7(a). The foreign particle size observed was about 20 to 30µm. The pile-up of the deformation around the foreign particle during the fatigue cycles contributed to the high stress concentration around the foreign particles and resulted in fatigue crack initiation. In contrast, SEM observation results on fracture surface of as-extruded samples showed that there was no evidence of foreign particle at the fatigue fracture origin. The fatigue crack initiation site was relatively flat as shown in Figure 7(b).

The foreign particles at the fatigue crack nucleation site were analyzed by using an energy dispersive X-ray spectroscopy (EDX) to identify constitutive elements. Figure 8 shows the result of EDS mapping and point analysis. From the figure it was found that the foreign particle mainly consists of carbon and silicon. It is suggested that the foreign particle was a SiC particle which probably exists in the AZ61 alloy powder as an impurity.

CONCLUSION

The change in the microstructure of AZ61 magnesium alloy and the $Mg_{17}Al_{12}$ precipitation during aging were observed to examine the effects on hardness and mechanical properties. The microstructure of the as-quenched sample consists of a supersaturated solid solution of the á-magnesium phase and retained as á during the aging process; however, the microstructure was completely covered by precipitation of the intermetallic $ ($Mg_{17}Al_{12}$). The increase in hardness and tensile strength of the aging sample are similar to the quenched sample. This is due to the formation of $Mg_{17}Al_{12}$ precipitation during aging process. The fatigue strength of the solution treated samples is higher compared to the as-extruded samples. It implies that the precipitation strengthening is capable to enhance the hardness, tensile strength and fatigue resistance. Future work should focus on improvement of different mechanical properties such as fracture toughness and creep resistance by using precipitation strengthening.

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