Microstructure Variation and Mechanical Behavior of Aged AZ61 Wrought Magnesium Alloy

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Abstract: The microstructural variation and mechanical behavior of aged AZ61 wrought magnesium alloy were investigated. The solid solution treatment was carried out at 410°C for 24hrs followed by water quenching. Subsequent aging treatments were carried out at 200°C with various aging time intervals from 0.2hr to184hrs. The changes in microstructure due to aging were studied by optical and scanning electron microscopy. Finally, the aged specimens were subjected to tensile testing and hardness measurements. The results showed that the solid solution and aging treatments of AZ61 alloy are essentially a microstructure transformation processes in which the discontinuous precipitate ($Mg_{17}Al_{12}$) at the grain boundaries in the as-received specimens was dissolved into the matrix after 24hrs solution treatment and then reprecipitates during the aging treatment. After prolonged aging time (up to 34hrs), a notable increase in the hardness was observed when aging treatment was implemented. Thereafter, with additional increases in the aging time (up to ~167hrs), the dependence of hardness values and the tensile properties on the aging time became more pronounced due to precipitation of β-phase. The formation of discontinuous precipitate $Mg_{17}Al_{12}$ was recognized as the major reason for the observed changes.
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1. Introduction

Magnesium alloys recently have become one of the widely used commercial alloys due to their high strength to weight ratio which makes these alloys popular with automotive and electronic manufacturers, whose main goal is to reduce the weight of products (Friedrich and Schumann, 2001). The majority of magnesium alloys used for structural applications, especially in automotive engineering, is based on the magnesium–aluminum–zinc series (AZ-series). This series of magnesium alloys could be age-hardened and the precipitation behavior has been widely studied in cast Mg alloys (Sinivasan et al., 2007; Zheng et al., 2008; Jin-feng et al., 2009; Buha, 2008; Oh-ishi et al., 2008). However, there have been very few studies on aging behavior in wrought Mg alloys (Zeng et al., 2009; Martínez et al., 2007).

In general, solution treatment and aging process are conducted to enhance the mechanical properties of magnesium alloys (Balasubramani et al., 2008). Solution treatment causes the precipitates dissolving into the Mg matrix and forms supersaturated solid solution during quenching. The aging process results in the transformation of supersaturated solid solution to fine precipitates. The aging time for magnesium alloys must be carefully chosen to allow sufficient precipitation of the β-phase (Chen et al., 2011). Depending upon ageing time and temperature, precipitation sequence in Mg–Al–Zn alloys has been reported to involve the formation of β-phase $Mg_{17}Al_{12}$ (Nie, 2003).

Zhan and Kelly (2003) stated that the $Mg_{17}Al_{12}$ precipitates are divided into two distinct categories according to how they are formed, being either discontinuous or continuous and both of them have lamellar form. It has been stated by Xu et al. (2009) that in order to obtain magnesium alloys with appropriate mechanical properties, it is necessary to fully use the precipitates to refine the grain size. Their studies showed that discontinuously precipitated $Mg_{17}Al_{12}$ phase could be effective in retarding the growth of the dynamic recrystallized grains, resulting in the refinement of dynamic recrystallization grains.

Consequently, this study was focused on the microstructural morphologies formed under different aging time and on the determination of the relationship between the $Mg_{17}Al_{12}$ precipitate morphologies and the associated aging time. The influence of aging time on the hardness and tensile properties was also investigated

2. Experimental Procedure

The experiments were conducted using AZ61 magnesium-alloy. The chemical composition of the used material is listed in Table 1. The as-received alloy was subjected to solid solution treatment at 410°C for 24hrs followed by water quenching to dissolve the eutectic α-phase precipitated at the grain boundaries during the casting into the matrix.

The specimens were subsequently aged at 200°C for different aging times ranging from 0.2 to 184hrs. In this work, the Mg-Al binary system was considered as the reference to determine the participation limit of AZ61 alloy at the given solution treatment temperature (Avedesian and Baker, 1999). From the binary system, it can be known that at the studied solution treatment temperature (410°C) the AZ61 alloy consists of α-Mg matrix without any existence of $Mg_{17}Al_{12}$ β-phase.

Table 1 Chemical composition of AZ61 alloy (wt.%)

Al	Cr	Mn	Si	Zn	Fe	Mg
6.7	0.012	0.25	0.047	1.11	0.001	Balance

The changes in microstructure due to aging process were studied by optical and scanning electron microscopy (SEM). The heat treated specimens for optical and SEM observations were prepared by the conventional metallographic techniques. Polished specimens were etched for 10 sec. in the etchant of Nital 3% i.e. 3% nitric acid and 97 Ethyl Alcohol. X-ray diffraction was utilized to identify the phases in the microstructures.

The Vickers hardness (HV) measurements were performed by Vickers hardness tester with 5kgf on the specimens aged under various duration of aging. Each reported value is the average of at least six measurements. The tensile properties of the aged alloy were measured by tensile testing at ambient temperature using a universal testing machine. Tensile specimens were machined along rolling direction based on the DIN Stander (50-125) specification.

3. Results and Discussions

Figure 1 shows the microstructure of AZ61 alloy on the cross-section perpendicular to the extrusion direction in the as-received condition. The structure of the as-received specimen (Figure 1a) was consisted of primary dendritic α-Mg matrix (dark contrast of α-Mg solid solution) with discontinuous $Mg_{17}Al_{12}$ and continuous $Mg_{17}Al_{12}$ at the grain boundaries (bright contrast of the second phase). Figure 1b shows the SEM image of the as-received specimen. From the SEM image, it can be observed that the eutectic is revealed to be a mixture of dark islands of β-$Mg_{17}Al_{12}$ phase and bright contrast narrow areas of lamellar mixture of depleted α-Mg solid solution and intermetallic $Al_{12}Mg_{17}$ compound (Wen et al., 2000).

The microstructure of the solution-treated AZ61 alloy is shown in Figure 2. It is revealed from the optical microstructure that the solid solution treatment at 410°C for 24hrs leads to a complete dissolution of the β-phase $Mg_{17}Al_{12}$ (in as-received microstructure) into the α-phase matrix. Chen et al. (2011) reported that during the solution treatment, the solutes are dissolved into the matrix resulting in the decomposition of the intermetallic compounds.

Figure 3 shows the optical microstructure of aged AZ61 alloy for various aging time intervals. From the figure, it is observed that upon ageing treatment at 200°C there was a reappearance of the discontinuous precipitate $Mg_{17}Al_{12}$ β-phase with homogeneous lamellae structure of α-Mg solid solution. Lai et al. (2009) stated that the lamellar structures appear mostly under 200°C, with the amount of discontinuous precipitate decreasing as the aging temperature increases and it is hard to see them above 250°C. Chen et al. (2011) observed that the continuous precipitation usually immerges in the matrix at high aging temperatures (approximately 350°C), whereas the formation of discontinuous precipitation dominates at lower temperatures.

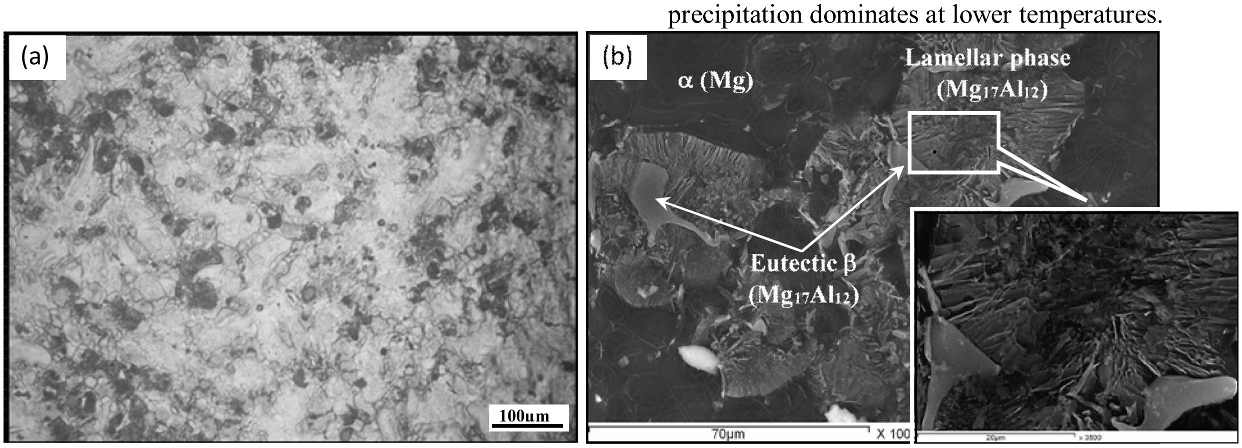


Figure 1. Microstructure of as- received AZ61 alloy (a) optical micrograph, (b) SEM image

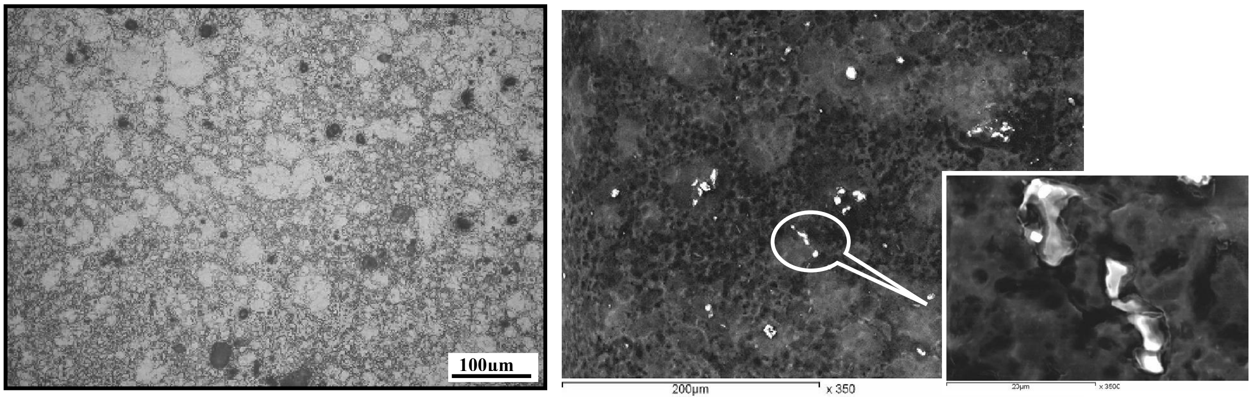
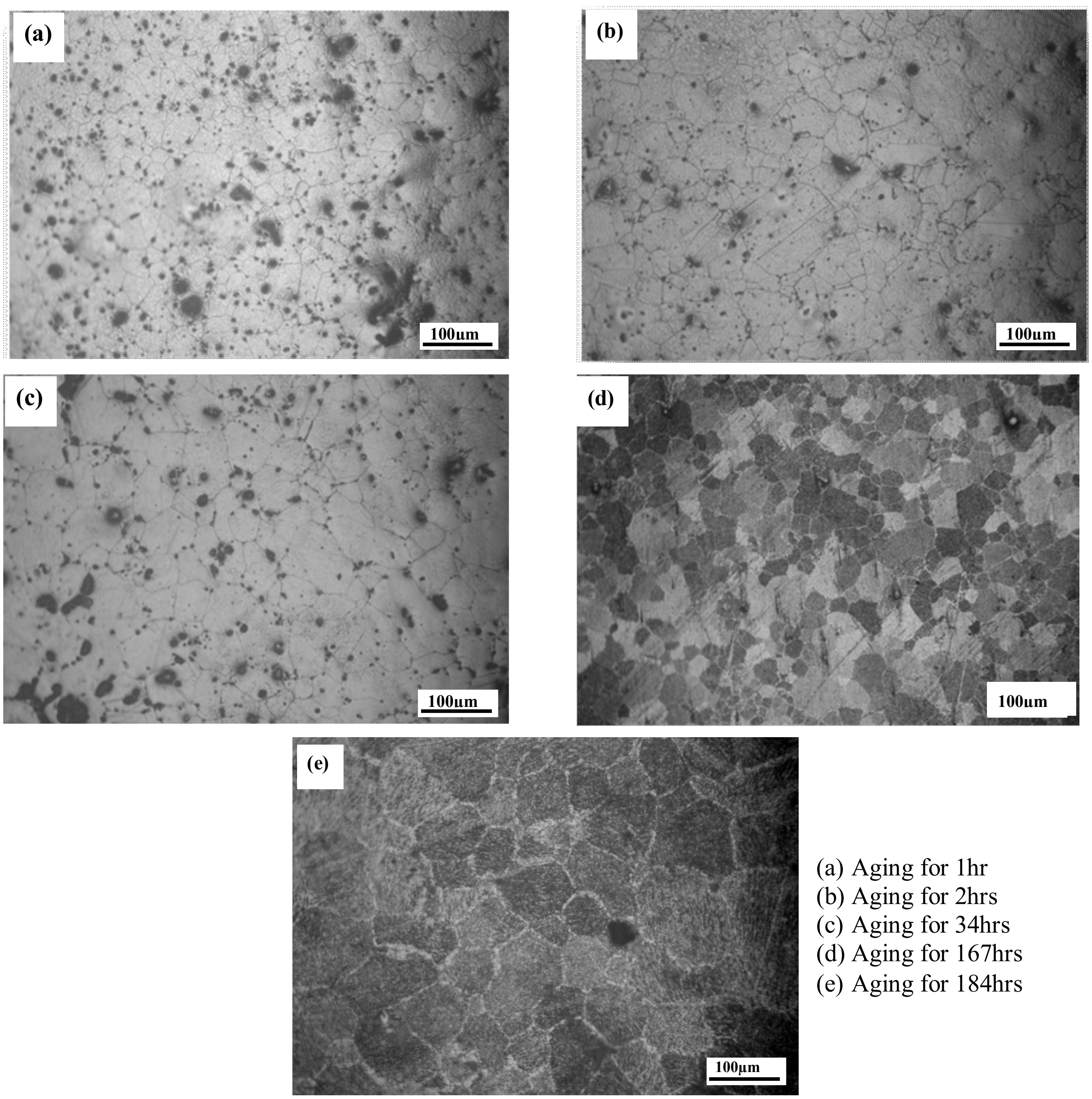


Figure 2 Microstructure of solid solution AZ61 alloy (a) optical micrograph, (b) SEM image



(a) Aging for 1hr
(b) Aging for 2hrs
(c) Aging for 34hrs
(d) Aging for 167hrs
(e) Aging for 184hrs

Figure 3 Optical micrographs of AZ61 alloy aged at 200°C for various time intervals

At the first stages during the ageing treatment (low aging time), the discontinuous precipitate $Mg_{17}Al_{12}$ β-phase didn't actually take place as shown in Figure 4a. However, after 2hrs aging time (Figure 4b), the precipitate β-phase and a few amounts of mechanical twins were observed at the interface of boundaries. With increasing the aging time, the discontinuous precipitation continued to grow towards the inside grains (Figure 4d) and the microstructure coincided with the transition from α-Mg matrix with discontinuous β-phase to lamellar structure. Figure 4e shows the optical micrograph of the aged alloy after 184hrs. The figure shows that coarsening of the grains occurred due to the over aged region

Figure 4 shows the SEM micrographs of AZ61 alloy aged at 200°C for various aging time intervals (1hr, 2hrs, 34hrs, and 167hrs). It is recognized that the $Mg_{17}Al_{12}$ β-phase precipitates on the grain boundary positions firstly, then grows towards the inside grains and composes lamellar structure mixtures with α-Mg phase (Figure 4d). The growth will stop if the grain is full of the precipitates or the continuous precipitates start to increase significantly and impede the growth of the discontinuous precipitates (Lai et al., 2009).

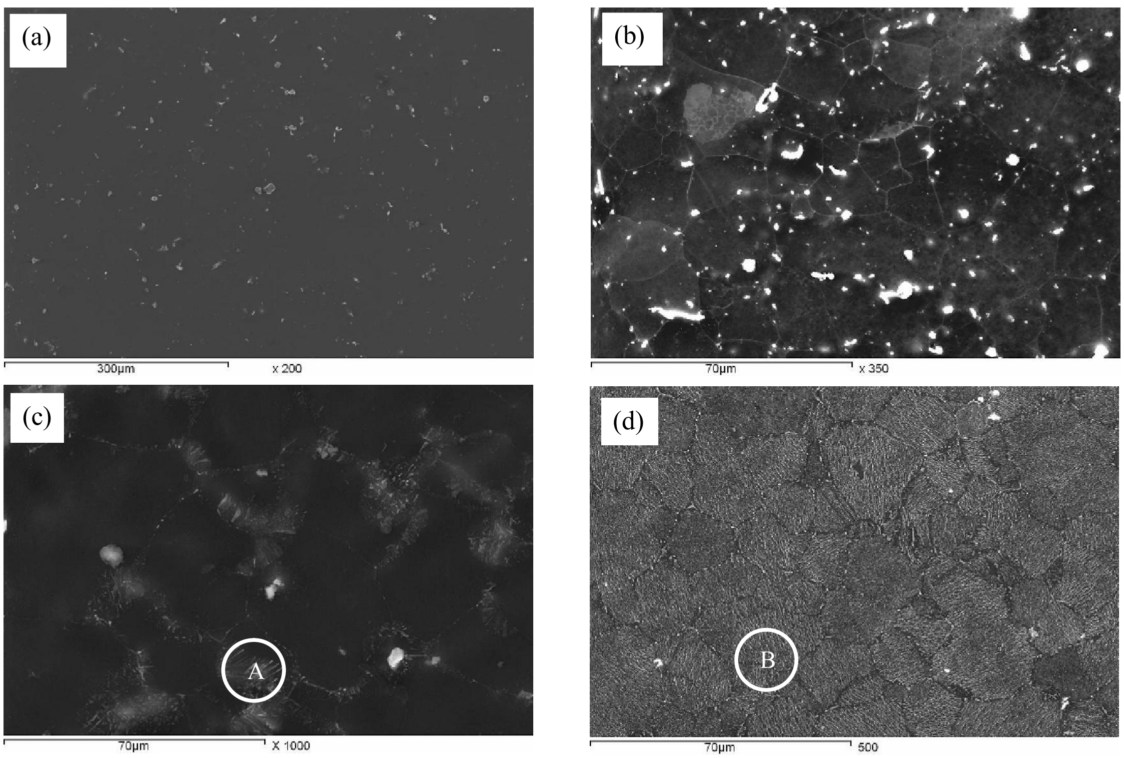


Figure 4 SEM of aged AZ61 for various aging time intervals: (a) 1hr, (b) 2hrs, (c) 34 hrs, and (d) 167 hrs.

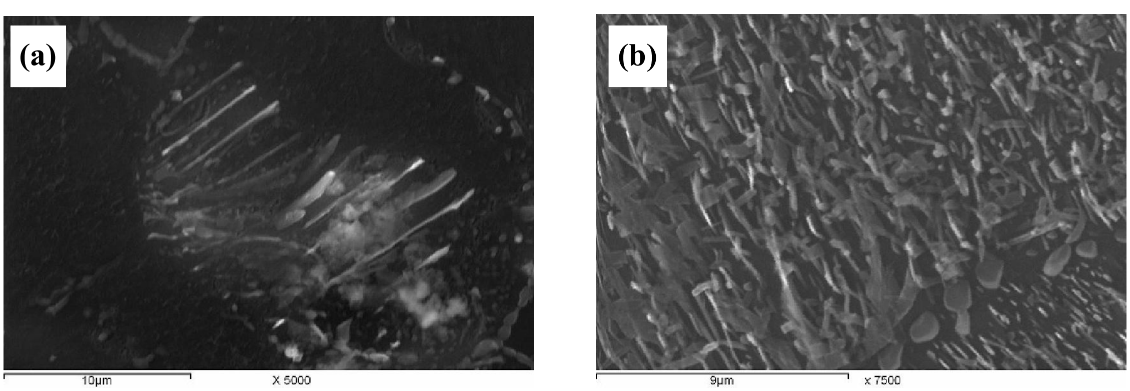


Figure 5 SEM magnified views of precipitates (a) after 34 hrs and (b) after 167 hrs aging.

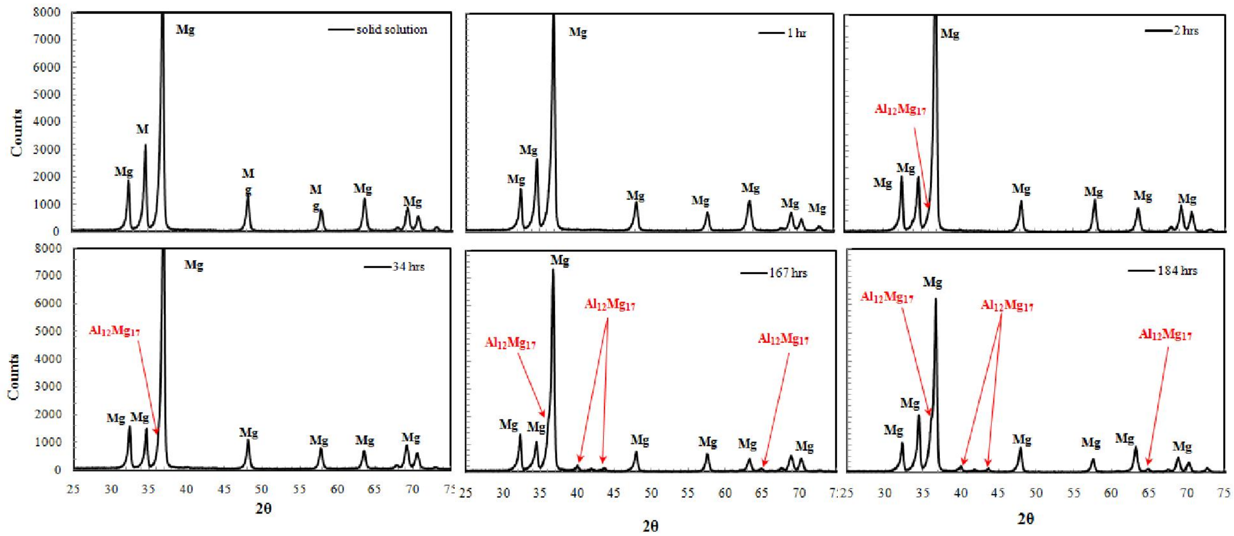


Figure 6 X-ray diffraction patterns for aged specimens at 200°C for various time intervals

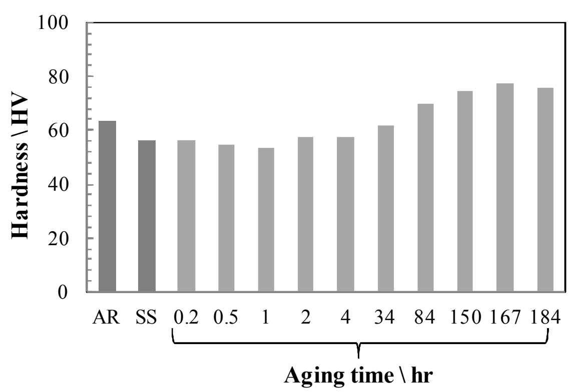


Figure 7 Hardness measurements as a function of aging time, compared with the as-received (AR) and solid solution specimens (SS).

Figure 5 shows the magnified views of the discontinuous $Mg_{17}Al_{12}$ precipitates for the marked area in Figure 4c and 4d. Lamellar-like precipitates were predicted within grains after 34hrs and 167hrs. Xu et al. (2009) stated that numerous numbers of discontinuous $Mg_{17}Al_{12}$ were observed distributing at the newly-formed dynamic recrystallized grain boundaries as shown in Figs. 3c, 3d and 3e. With increasing the aging time, $Mg_{17}Al_{12}$ precipitates continuously and the amount of lamellar structure mixtures increases gradually (Feng et al., 2010). On aging treatment for 167hrs, the microstructure was almost consists of lamellar structure, as shown in Figure 6b. Duly et al. (1995) reported that the discontinuous precipitations nucleate on the boundaries of the solid solution grains and when growing, they take the form resembling nodules. Figure 6 shows X-ray diffraction patterns obtained from the heat treated specimens. X-ray analysis revealed that the discontinuous precipitation reappear after 2hrs aging time.

Figure 7 illustrates hardness measurements (HV) of AZ61 alloy as a function of the aging time, compared with the as-received (AR) and the solid solution treated (SS) specimens. The as-received specimen has 64HV hardness value. After 24hrs solid solution treatment, the hardness value is slightly decreases to 57 HV as resulted from the dissolution of β-phase $Mg_{17}Al_{12}$. However, after aging treatment (up to ~2hrs), the hardness values are continuously decreased.

After prolonged aging treatment time (up to 34hrs), the alloy started to show slightly increase in the hardness. Thereafter, with additional increases in the aging time (up to ~167hrs), the dependence of hardness values on the aging time became more pronounced due to precipitation of β-phase. When the specimens aged for 167hrs, the alloy has the maximal hardness value. Further aging time excesses 167hrs, the hardness value decreases. The peak hardness drops to HV75 at 184hr for aging at 200°C. The statistical analysis of the hardness values of aged AZ61 magnesium alloy are listed in Table 2.

In general, the increase in hardness of the specimens is likely due to the precipitation of β - phase in the alloy matrix. By extending aging time, the grain growth effect becomes more dominant than hardening, so the hardness of the specimens starts to decrease as shown in Figure 7. It means that the coarsening of the β- $Mg_{17}Al_{12}$ precipitates (Figure 4e) occurs due to over-aging and consequently the hardness of the alloy decreases.

Figure 8 shows the variations in average ultimate tensile strength (UTS) and yield stress (YS) of the aged specimens obtained from the tensile tests.

At the beginning of ageing treatment, the tensile strength and yield stress generally were slightly decreased with increasing aging time. However, when aging time excesses 34hrs, the tensile strength and yield stress values were considerably increased. This phenomenon may be due to the development of $Mg_{17}Al_{12}$ precipitates.

Table 2. Hardness values statistical analysis of aged AZ61 magnesium alloy

Aging time hr	0.2	0.5	1	2	4	34	84	150	167	184
Mean	56.62	54.68	53.22	57.53	57.43	61.48	69.77	74.20	77.27	75.53
Standard Error	0.91	0.64	0.76	0.60	1.17	0.99	1.55	0.36	0.91	1.13
Standard Deviation	2.23	1.56	1.87	1.46	2.87	2.42	3.79	0.89	2.24	2.77
Minimum	53.7	52.3	51.2	55	52.4	57.1	62.8	73.3	74.3	70
Maximum	58.9	56.3	56.3	59.2	60.5	64.2	73.6	75.7	80.7	77.4
Count	6	6	6	6	6	6	6	6	6	6

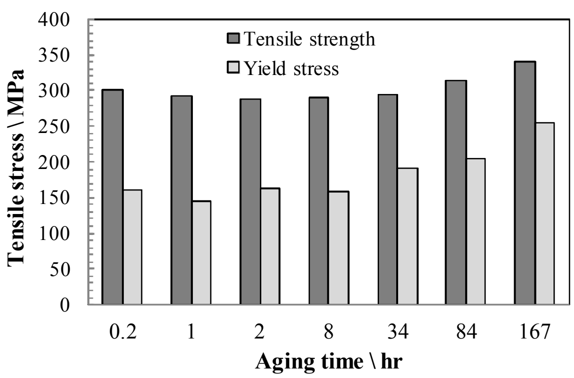


Figure 8 Tensile strength and yield stress as a function of the aging time for the AZ61 alloy.

Figure 9 shows the effect of the aging time on the elongation of AZ61 alloy. It is indicated that the elongation first increases and then decreases with the increasing of the aging time. The reason for the decrease in the elongation may be due to the increases of dislocation resistance gradually when the $Mg_{17}Al_{12}$ is precipitated with the increasing of the aging time.

4. Concluding Remarks

- The solid solution and aging treatment of AZ61 is essentially a microstructure transformation process in which the discontinuous β-phase (interdendritic $Mg_{17}Al_{12}$) is fully dissolved into the matrix after 24hrs solution treatment. However, by aging treatment the β-phase was reprecipitates at the interface after 2hrs aging time.
- Hardness of the aged AZ61 alloy diminishes considerably with the increase of aging time in the initial state of the treatment (low aging time). After prolonged aging time up to 167hrs, a notable increase in the hardness was observed due to the reappearance of β-phase at the grain boundaries. With further aging time excesses 167hrs, the specimens were over aged and the coarsening of the grains occurs consequently leads to a decrease in the hardness value.

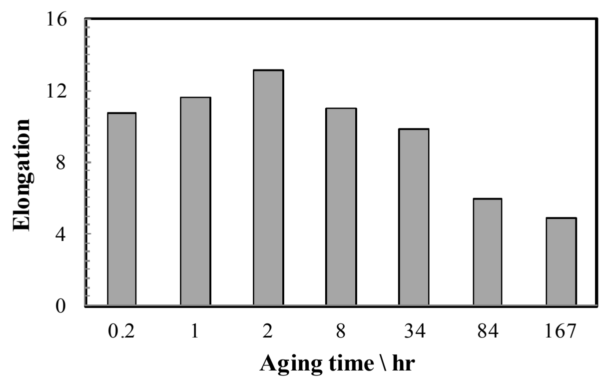


Figure 10 Effect of aging time on the elongation for the AZ61 aged at 200°C.

- The ageing process at 200°C following the solution treatment has a significant influence on the mechanical properties of AZ61 alloy. This is reflected in the tensile properties, specifically the yield stress and elongation of the alloy
- From the results, it is clear that the microstructure of AZ61 after 34hrs aging time coincided with the transition from α-Mg matrix with discontinuous β-phase to lamellar structure and also a significant change in mechanical properties occurred.

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References

1. Friedrich H, Schumann S. Research for a new age of magnesium in the automotive industry, J. Mater. Proc. Techno. 2001; 117: 276-281.
2. Sinivasan A, Pillai U, Pai B. Effect of Pb addition on ageing behavior of AZ91 magnesium alloy, Mater. Sci. Eng. A 2007; 452-453: 87–92.
3. Zheng K, Dong J, Zeng X, Ding W. Effect of pre-deformation on aging characteristics and mechanical properties of a Mg-Gd-Nd-Zr alloy, Mater. Sci. Eng. A 2008; 491: 103 -109.
4. Jin-feng H, Hong-yan Y, Yon-bingL, Hua C, Jian-ping H, Z. Ji-shan Z. Precipitation behaviors of spray formed AZ91 magnesium alloy during heat treatment and their strengthening effect. Materials and Design 2009; 30: 440–444.
5. Buha J. Reduced temperature (22-100°C) ageing of an Mg–Zn alloy, Mater. Sci. Eng. A 2008; 492:11–19.
6. Oh-ishi K, Hono K, Shin K. Effect of pre-aging and Al addition on age-hardening and microstructure in Mg-6 wt% Zn alloys, Mater. Sci. Eng. A 2008; 496: 425–433.
7. Zeng R, Ke W, Han E. Influence of load frequency and ageing heat treatment on fatigue crack propagation rate of as-extruded AZ61 alloy, J. Fatigue 2009; 31: 463–467.
8. Martínez R, Gäoken J, Letzig D, Steinhoff K, Kainer K. Influence of aging on damping of the magnesium–aluminum–zinc series, J. Alloys and Compounds 2007; 437: 127-132.
9. Balasubramani N, Pillai U, Pai B. Optimization of heat treatment parameters in ZA84 magnesium alloy. J. Alloys and Compounds 2008; 457: 118−123
10. Chen X, Huang X, Pan F, Tang A, Wang J, Zhang D. Effects of heat treatment on microstructure and mechanical properties of ZK60 Mg alloy, Trans. Nonferrous Met. Soc. China 2001; 21: 754-760.
11. Nie J. Preface to viewpoint set on: phase transformations and deformation in magnesium alloys, Scripta Mater. 2003; 48: 981–984.
12. Zhang M, Kelly P. Crystallography of $Mg_{17}Al_{12}$ precipitates in AZ91D alloy, Scripta Mater. 2003; 48: 647–652.
13. Xu S, Matsumoto N, Kamado S, Honma T, Kojima Y. Effect of pre-aging treatment on microstructure and mechanical properties of hot compressed Mg-9Al-1Zn alloy, Mater. Sci. Eng. A 2009; 517: 354-360.
14. Xu S, Matsumoto N, Kamado S, Honma T, Kojima Y., Dynamic microstructural changes in Mg-9Al-1Zn during hot compression, Scripta Mater. 2009; 61: 249-252.
15. Xu S, Matsumoto N, Kamado S, Honma T, Kojima Y. Effect of $Mg_{17}Al_{12}$ precipitates on the microstructural changes and mechanical properties of hot compressed AZ91 magnesium alloy, Mater. Sci. Eng. A 2009; 523: 47-52.
16. Avedesian M., Baker H (Eds.). Magnesium and Magnesium Alloys, ASM International, Ohio, 1999: 37.
17. Wen C, Yamada Y, Shimojima K, Mabuchi M, Nakamura M, Asahina T, Aizawa T, Higashi K. Microstructure Evolution and Mechanical Properties of AZ91 Mg Foams, Magnesium Alloys and their Applications, Edited by B. Mordike B, Kainer K. WILEY-VCH Verlag GmbH, Germany 2000; 571-576.
18. Lai W, Li Y, Hsu Y, Trong S, Wang W. Aging behavior and precipitate morphologies in Mg–7.7Al–0.5Zn–0.3Mn alloy, J. Alloys and Compounds 2009; 476: 118–124.
19. W. Lai, Y. Li, Y. Hsu, S. Trong, W. Wang, Aging behavior and precipitate morphologies in Mg–7.7Al–0.5Zn–0.3Mn (wt.%) alloy, J. Alloys Compounds 476, 2009, p.118–124.
20. Feng G, Pengfei L, Xia G, Juan X. Study on solid solution and aging process of AZ91D magnesium alloy with cerium, J. Rare Earths, 2010; 28(6): 948-951.
21. Duly D, Simon J, Brechet Y. On the competition between continuous and discontinuous precipitations in binary Mg-Al alloys. Acta Metall. Mater. 1995; 43: 101-106.

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