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Particle reinforcement of magnesium composites SiC_p/AZ80 and their mechanical properties after heat treatment

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Abstract

In this paper, the mechanical enhancement of SiC particles reinforced AZ80 Mg-based metal-matrix composites (MMCs) was investigated. The Mg MMCs were prepared by the melt-stirring technique with addition of 1 wt.% of 4.5 μm SiC particles. Mg MMCs were processed by various heat treatments to change their mechanical properties. The hardness, ultimate tensile strength and yield strength of Mg alloy (AZ80) can be improved by adding reinforcement particles (becomes AZ80 MMCs). The 10 h – T6 heat treated AZ80/1wt.%SiC has highest ultimate tensile strength of 256 MPa, which is much higher than 186 MPa of as-cast AZ80. By virtue of addition of only 1 wt.% SiC micro-particles, the strength of as-cast AZ80 increases tremendously (approx. 30 % increase) both for as-cast and T6 heat treated Mg MMCs.

Key words: metal matrix composites, magnesium alloy, micro-scaled silicon carbide, heat treatment

1. Introduction

Magnesium (Mg) alloys are gaining more recognition as the lightest structural material for light-weight applications, due to their low density and high stiffness-to-weight ratio. Even so, 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 various methods to obtain light-weight materials with excellent mechanical properties [1–9].

Regarding magnesium alloy AZ80, Zeng et al. [10] investigated the fatigue crack propagation behavior of the as-extruded magnesium alloy AZ80, which was made by means of the constant load amplitude fatigue test, SEM, TEM and Auger electron spectroscopy. They found that the coalescence of the micro-voids was proposed to be the mechanism of fatigue crack propagation of the extruded magnesium alloy AZ80. Zheng et al. [11] reported the mechanical behavior and microstructure of nanocrystalline (nc) Mg AZ80 alloy, synthesized via a cryomilling and spark plasma sintering (SPS) approach. The consolidated material consisted of a bimodal microstructure with nc fine and coarse grains formed in the SPS'ed Mg AZ80 microstructure. Inside of the coarse grains, nano-sized $Mg_{17}Al_{12}$ precipitates were observed. Zhang et al. [12] investigated the influence of shot peening (SP) on notched fatigue strength of the high-strength wrought magnesium alloy AZ80 using different SP media (including glass, Zirblast B30 and Ce-ZrO_2 (ZrO_2 stabilized by Ce shots)) and various Almen intensities. Their results showed that shot peening improved the notched fatigue strength of AZ80 more effectively than the un-notched fatigue strength.

There are not many researchers who investigated AZ80 Mg MMCs. Cai et al. [13] studied the interface of SiC_p/AZ80 Mg MMCs and determined the phase formed at the interface. They found the $Mg_{17}Al_{12}$ eutectic phase and Cu_5Zn_8 phase at the SiC_p/AZ80 interface. Chen and Li [14] studied the microstructure and orientation relationships of

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ZK60A MMCs reinforced with SiC whiskers and B_4C particles by means of transmission electron microscopy and high-resolution electron microscopy. MgO nanocrystalline particles were formed at SiC/Mg interfaces with a cube-on-cube orientation relationship with SiC whiskers. MgB_2 nanorods were formed near the B_4C particles. Amini et al. [15] reported the processing and microstructural characterization of 50 vol.% Ti2AlC/nanocrystalline (nc) Mg-MMCs fabricated by pressureless melt infiltration at 750 ℃ for 1 h, by X-ray diffraction and transmission electron microscopy. The Ti2AlC/nc-Mg composites are readily machinable, stiff (~ 70 GPa), strong, light (2.9 g cm^{-3}) and exhibit exceptional damping capabilities, that increases with the square of the applied stress to stress levels of the order of ~ 500 MPa. Until now, the interfacial phenomena in magnesium alloy matrix composites have not been fully understood because of their complexity and dependence on many variables.

Huang et al. [16] prepared AZ91 specimens with spray-forming and later with extrusion; then, three heat treatment processes, namely T4 heat treatment, T6 heat treatment, and specific heat treatment, were preceded individually. The findings showed that the specimen with T4 heat treatment reached the lowest hardness in the first hour, while the maximum hardness of the specimen with T6 heat treatment appeared at the aging of 12 h. At last, mechanical properties of the specimens with three heat treatment processes were also compared. The tensile strength and yield strength of the specimen with T6 heat treatment exhibited the highest value but the lowest elongation, while the values with T4 heat treatment and specific heat treatments were close but the yield strength of the former was far lower than the latter.

From previous studies [13–16] it has been found that the Mg MMCs using different kinds of particles and different heat treatment can improve the mechanical properties. But the research of AZ80 alloy Mg MMCs with added micro-scale SiC particle and treated with T4 and T6 is not adequate. In this study, a micro-scale SiC particle material was selected as the reinforcement particle and the melt stirring technique was used to integrate the reinforcement particles into AZ80 melt to form AZ80 MMCs. Finally, the properties of the Mg MMCs were improved by various heat treatment processes to obtain the best mechanical properties, such as hardness and tensile properties.

2. Experimental details

2.1. Materials preparation

The matrix used in this work is magnesium alloy AZ80 with ~ 8.0 % aluminum. Its chemical composition is shown in Table 1. SiC particles with the fraction of 1 wt.% within MMCs are used as the reinforcement phase. The commercially available SiC powder with a particle diameter about 4.5 μm and the purity ~ 99.0 % is added into AZ80 to form Mg-based metal-matrix composites.

Table 1. Chemical composition of AZ80

Elements	Al	Zn	Mn	Si	Fe	Cu	Ni	Be	Mg
wt.%	8.0	0.2	0.12	0.1	0.001	0.05	0.001	0.001	Balance

The melt-stirring technique is used to fabricate the present Mg MMCs. An experimental setup is shown in Fig. 1. The AZ80 and SiC particles were initially placed inside a graphite crucible and heated to 400 ℃ in a resistance-heated furnace for 15 min; then a stirring vane functioned; meanwhile, CO_2 and SF_6 gushed from gas tank into the crucible to help the mixture of melt. CO_2 and SF_6 also can prevent the melt from oxidation. After that, the melt was heated up to 600 ℃ lasting for 15 min. The crucible was continuously heated up to 750 ℃, then the molten alloy was stirred with a vane operated at 350 rev/min for 3 min. Then the composite melt was finally poured into a metallic mold. The Mg MMCs containing SiC with the fraction of 1 wt.% were prepared for further mechanical testing.

The T4 heat treatment was processed when the heat treatment furnace was heated to 260 ℃, the specimen was put into the furnace for 1 h to release the residual stress on the specimen, and then it was slowly (in about 2 h, 1.33 ℃ min^{-1}) warmed up to 420 ℃ for 6 h, and after that the specimen was cooled off with quenching by water. The T6 heat treatment was processed with air cooling at room temperature after the T4 heat treatment (260 ℃ for 1 h, then 420 ℃ for 6 h), then the specimen was put into the furnace with the duration of 2, 4, 6, 8, 10, and 12 h, aged at 170 ℃, and cooled off with air cooling afterwards.

2.2. Hardness tests and tension test

With a load of 196 N, Vickers macro-hardness measurements were carried out on the AZ80 and SiC_p/AZ80 MMCs with a Matsuzawa (Model MV-1) hardness tester. The average hardness of each as-cast AZ80 and AZ80 MMC specimen was obtained from 20 tests. The tension test of specimens was performed by Materials Test System of 49 kN. The specimens for tension test were prepared according to ASTM B 557M-02a, then tested with the strain rate of 5.5×10^{-4} s^{-1}.

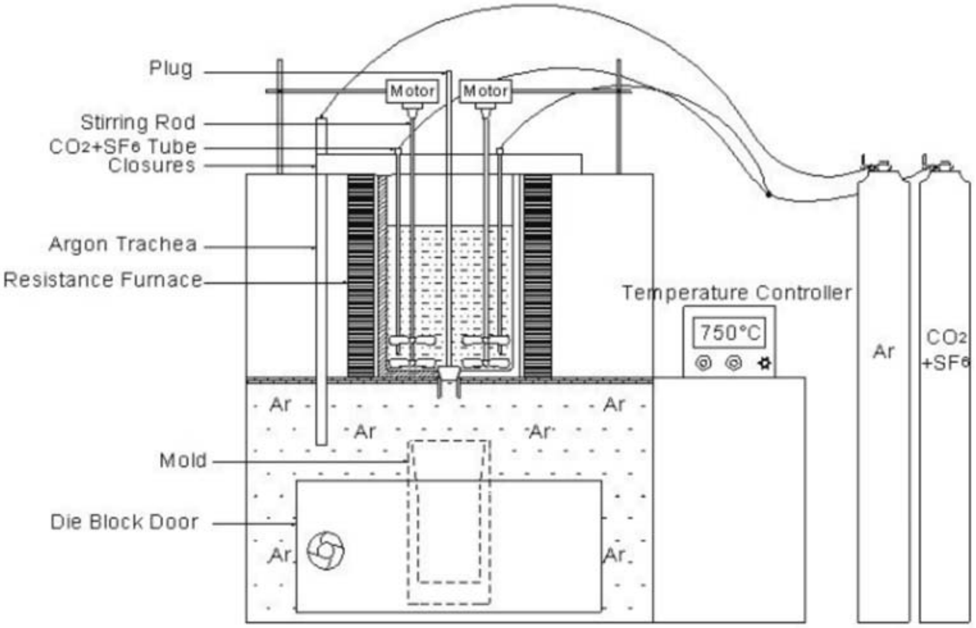

Fig. 1. Setup configuration.

3. Results and discussion

3.1. Hardness

The Vickers hardness of the matrix material (AZ80) is 61 HV. The hardness results for different heat treatment processes: without heat treatment, T6-treatment for 2, 4, 6, 8, 10 and 12 h, are presented in Fig. 2. It could be observed that the hardness of AZ80 MMCs was much higher than that of as-cast AZ80, except for T6 – 4 h and T6 – 6 h. In general, the hardness of as-cast AZ80 and AZ80/1wt.%SiC increased with increasing time of T6, except for the range between T6 – 4 h and T6 – 6 h, which will be discussed in sec. 3.3. The hardness of AZ80/1wt.%SiC with T6 – 12 h increased by 28.9 % more than that of as-cast AZ80. Hence, the hardness of Mg alloy can be improved both by adding reinforcement particles and T6 heat treatment.

3.2. Microstructure observation

The contribution of grain refinement to the strength levels could be discussed on the basis of the classical Hall-Petch equation [3]:

$$\Delta\sigma_{\text{Hall-Petch}} = K d_{\text{m}}^{-1/2}, \tag{1}$$

where K is the Hall-Petch coefficient and d_{m} is the matrix grain diameter. Parameter K was calculated from the slope of $\Delta\sigma_{\text{Hall-Petch}}/d_{\text{m}}^{-1/2}$ plot using different grain sizes of the Mg MMCs material before and after heat treatment and their corresponding yield stress values. In order to know the $\Delta\sigma_{\text{Hall-Petch}}$, the grain size calculation is needed. In this study, the mean grain size was determined using the linear intercept method.

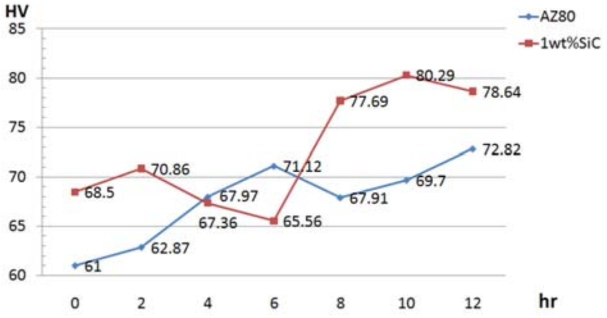

Fig. 2. Microhardness with time of T6.

Figure 3 shows microstructures of as-cast AZ80 and AZ80/1wt.%SiC with 0, 2, 6, 10 h heat treatments. Figure 4 shows the grain size of as-cast AZ80 varying with time of T6 treatment. It can be observed that the grain size of as-cast AZ80 decreases, when T6 treatment is conducted for 2, 4, 6, 10, and 12 h. Significant decrease of the grain size of AZ80 after 2 h T6 treatment is found, since T6 treatment can increase the yield strength accompanying smaller grain size than that of T4, i.e. 0 h – T6. Subsequent relatively stable grain sizes in further T6 treatment occur, because present aging time for as-cast AZ80 is not adequate to form significant larger grain size [17]. But the grain size with T6 treat-

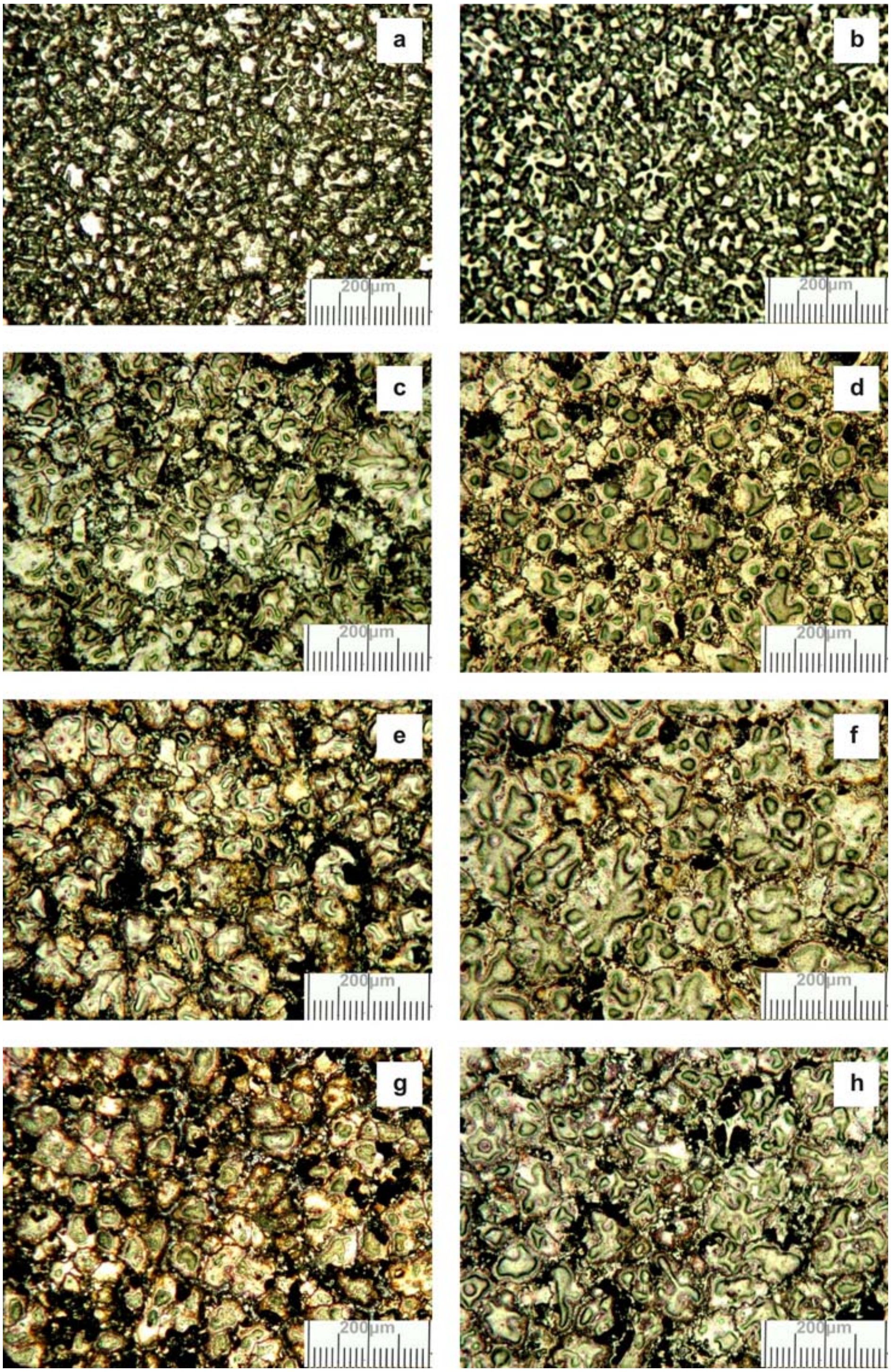

Fig. 3. Microstructure of (a) as-cast AZ80, (b) AZ80/1wt.%SiC, (c) as-cast AZ80 T6 – 2 h, (d) AZ80/1wt.%SiC T6 – 2 h, (e) as-cast AZ80 T6 – 6 h, (f) AZ80/1wt.%SiC T6 – 6 h, (g) as-cast AZ80 T6 – 10 h, (h) AZ80/1wt.%SiC T6 – 10 h; 100×.

ment for 6 h is smallest among T6 of 0 through 10 h.

Figure 5 indicates the grain size of AZ80/1wt.%SiC changing with time of T6 treatment. It can be discovered that the grain size of AZ80/1wt.%SiC decreased tremendously when T6 treatment was conducted for 2 h; later the grain size recovered during 4 and 6 h with T6 treatment; then it decreased during 8, 10 and 12 h with T6 treatment. However, the grain size with T6 treatment for 10 h was the smallest among all the T6 treatments. The reason of the grain size variation might be that the quantity of $Mg_{17}Al_{12}$ eutectic phase and Cu_5Zn_8 phase formed at the SiC_p/AZ80 interface (referring to [13]) caused the size change, which

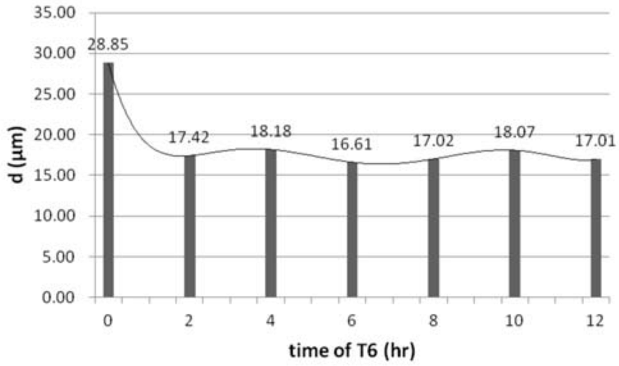

Fig. 4. Grain size of as-cast AZ80 with time of T6 treatment.

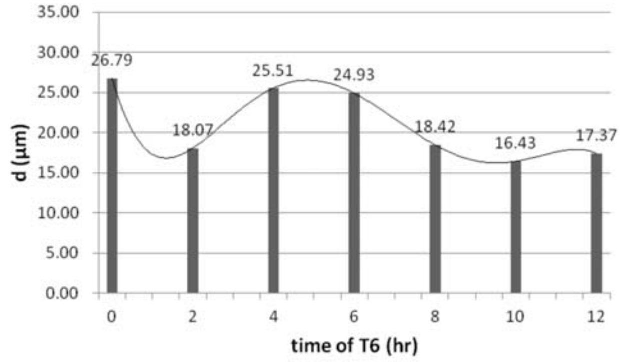

Fig. 5. Grain size of AZ80/1wt.%SiC with time of T6 treatment.

was not determined and might be verified by further EDS study in the future.

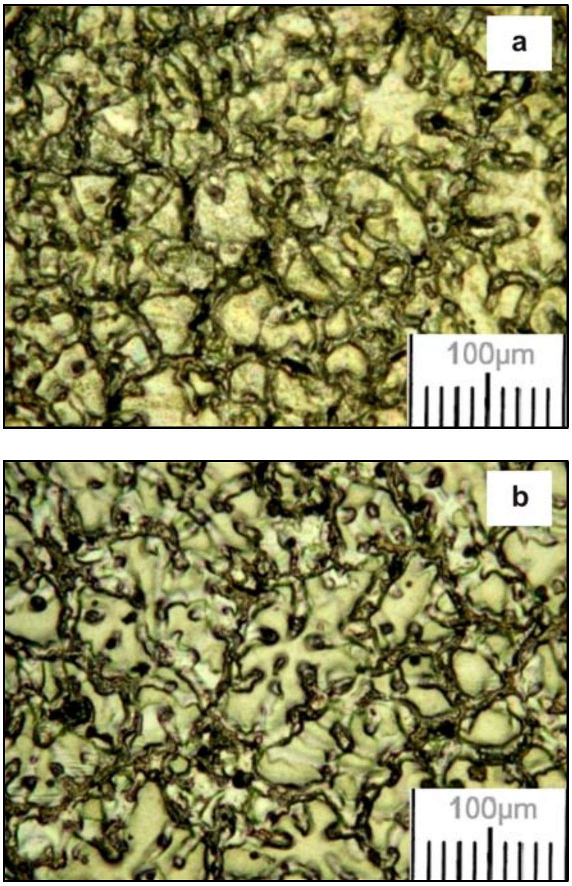

Fig. 6. Microstructure of (a) as-cast AZ80 without heat treatment, (b) AZ80/1wt.%SiC without heat treatment; 200×.

Microstructure of as-cast AZ80 and AZ80/1wt.% SiC without heat treatment is shown in Fig. 6. It is found that cast dendrites occur both in as-cast AZ80 and AZ80/1wt.%SiC. But the dendrites can be eliminated by T4 heat treatment, as indicated in Fig. 7. The homogenization (T4) can dissolve the β precipitates of the as-cast ingot of Mg MMCs into the grain.

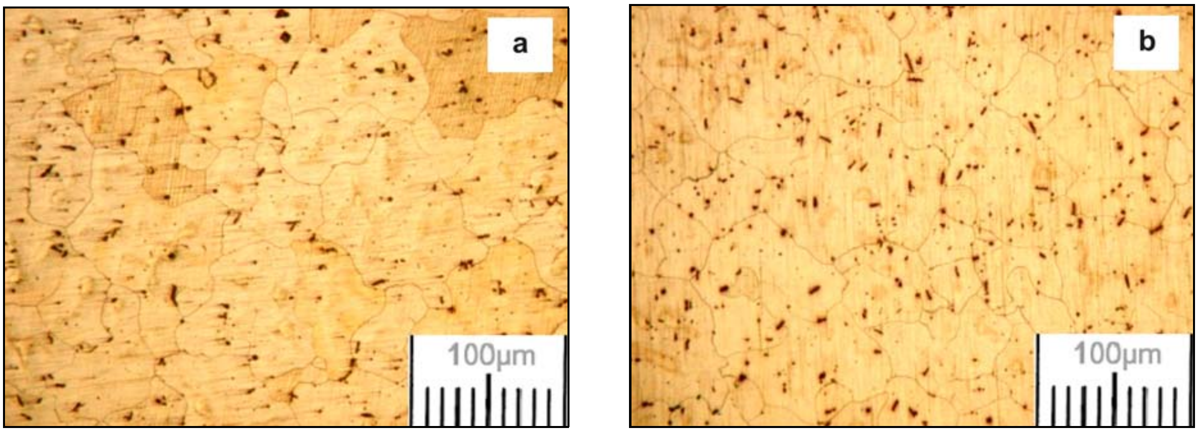

Fig. 7. Microstructure of T4 heat treated (a) as-cast AZ80 T4, (b) AZ80/1wt.%SiC T4; 200×.

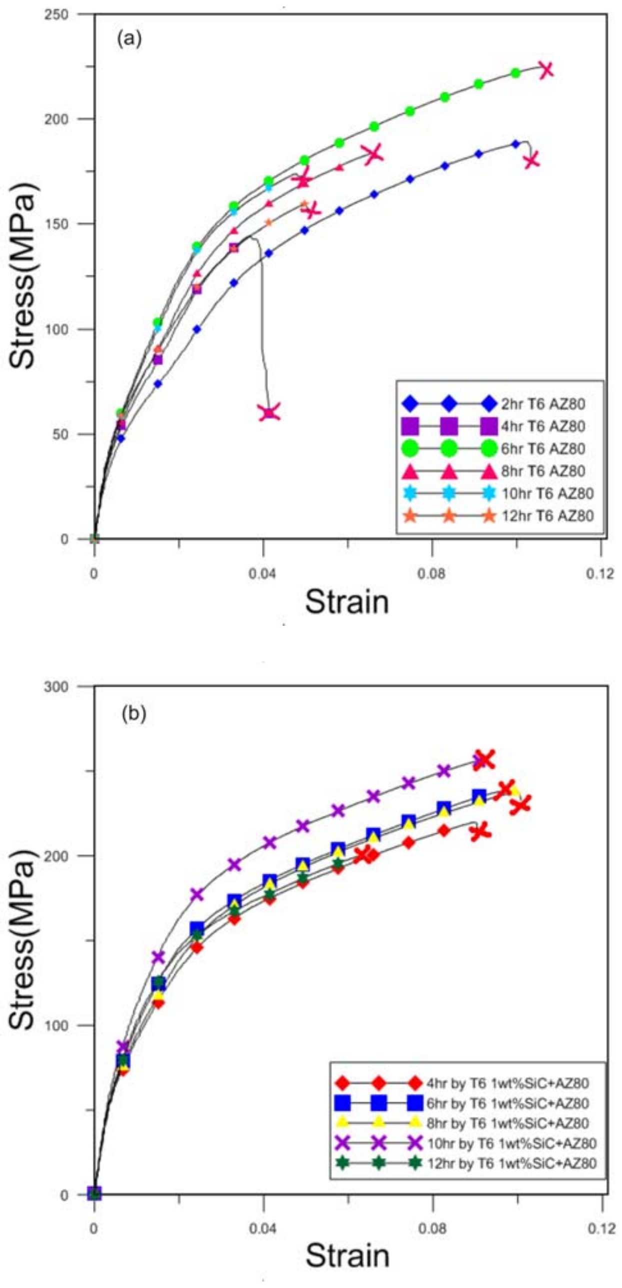

Fig. 8. Stress-strain curve of T6 heat treated (a) as-cast AZ80, (b) AZ80/1wt.%SiC.

3.3. Tensile strength and discussion

Figure 8 shows the stress-strain curve of T6 heat treated as-cast AZ80 and AZ80/1wt.%SiC. The ultimate tensile strength of the matrix material (AZ80) is 186 MPa. Comparing Fig. 8a,b, the ultimate tensile strength and yield strength of T6 heat treated AZ80/1wt.%SiC are greater than those of T6 heat treated as-cast AZ80.

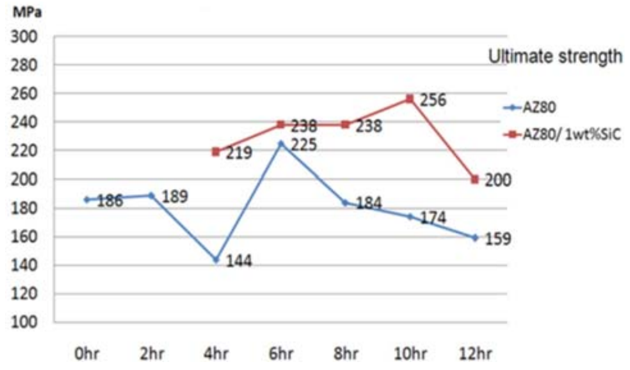

Fig. 9. Ultimate tensile strength of T6 heat treated as-cast AZ80 and AZ80/1wt.%SiC.

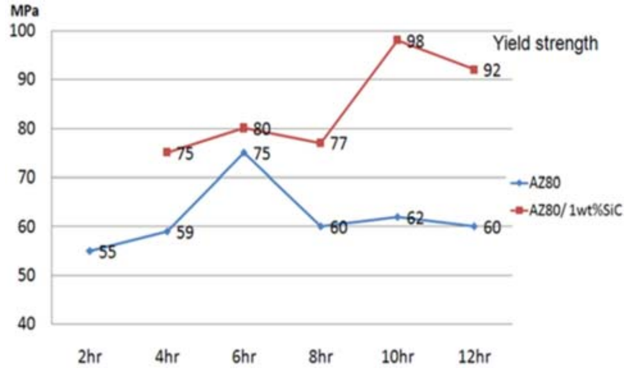

Fig. 10. Yield strength of T6 heat treated as-cast AZ80 and AZ80/1wt.%SiC.

Ultimate tensile strength and yield strength of T6 heat treated as-cast AZ80 and AZ80/1wt.%SiC are shown in Figs. 9 and 10, respectively. The average ultimate tensile strength of T6 heat treated AZ80/1wt.%SiC gets higher by 29.9 % than that of T6 heat treated as-cast AZ80. The 6 h – T6 heat treated as-cast AZ80 has largest ultimate tensile strength of 225 MPa, which is much higher than that of 186 MPa for AZ80. The 10 h – T6 heat treated AZ80/1wt.%SiC has highest ultimate tensile strength of 256 MPa, which is much higher than that of AZ80.

Regarding to the yield strength, the average yield strength of T6 heat treated AZ80/1wt.%SiC is by 33.5 % higher than that of T6 heat treated as-cast AZ80. By virtue of addition of just 1 wt.% SiC micro-particles, the strength of as-cast AZ80 increases tremendously (approx. 30 % increase) both for as-cast and T6 heat treated Mg MMCs. It can be observed in Fig. 10 that the 6 h – T6 heat treated as-cast AZ80 has highest yield strength of 75 MPa among all T6 treated AZ80 for different aging times; and the 10 h – T6 heat treated AZ80/1wt.%SiC has highest yield strength of 98 MPa among all T6 treated AZ80/1wt.%SiC with different aging times.

Figures 11, 12 show regression equation of Hall-

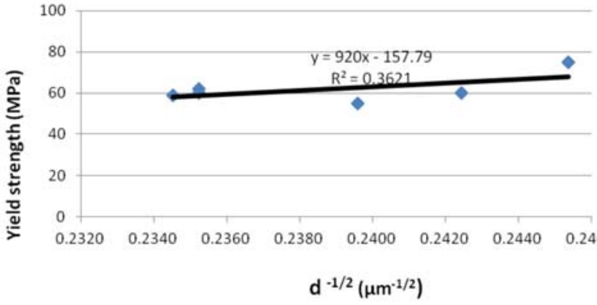

Fig. 11. Regression equation of Hall-Petch formula of as-cast AZ80.

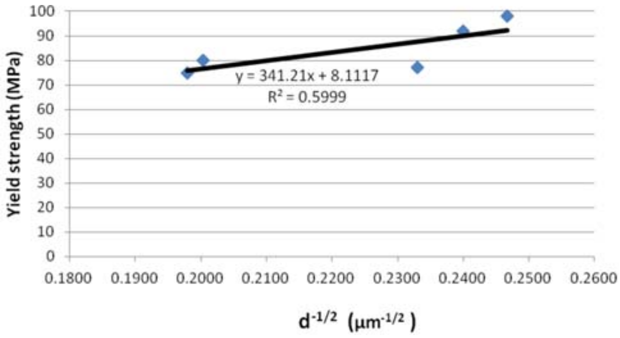

Fig. 12. Regression equation of Hall-Petch formula of AZ80/1wt.%SiC.

-Petch formula of as-cast AZ80 and AZ80/1wt.%SiC, respectively. They were obtained by substituting the yield strength and grain size into Eq. (1). Both regression equations show that the yield strength increases with increase of $d^{-1/2}$, which means the yield strength increases with decrease of the grain size.

Comparing Fig. 4 with Fig. 9, the 6 h – T6 heat treated as-cast AZ80 has smallest grain size among those with other heat treatment conditions, exhibiting highest yield strength, which is consistent with Hall-Petch equation. Comparing Fig. 5 with Fig. 9, the 10 h – T6 heat treated AZ80/1wt.%SiC has the smallest grain size among those with other heat treatment conditions, exhibiting the highest yield strength, which is also consistent with Hall-Petch equation.

The abnormal curves in Figs. 2, 9, and 10 can be explained by observing grain size changes in Figs. 4 and 5, i.e. grain size is inversely proportional both to the yield strength and hardness.

According to Hall-Petch equation, the smallest grain size of T6 – 10 h treated MMCs gets the best mechanical properties (Figs. 9, 10), including both the ultimate and yield strength.

For the purpose of strength enhancement, the 10 h – T6 heat treatment is the optimal treatment for AZ80/1wt.%SiC MMCs.

4. Conclusions

This study proposed and investigated the mechanical properties of SiC particles reinforced AZ80 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 can be drawn:

1. The mechanical properties of Mg alloy (AZ80) can be improved by adding reinforcement particles (becomes AZ80 MMCs), such as hardness, ultimate tensile strength and yield strength.
2. The homogenization (T4) can dissolve the β precipitates of the as-cast ingot of Mg MMCs into the grain.
3. The hardness of Mg alloy can be improved both by adding reinforcement particles and T6 heat treatment.
4. The yield strength can be increased by T6 heat treatment both for as-cast AZ80 alloy and AZ80/1wt.%SiC MMCs.
5. Accompanying optimal heat treatment 10 h – T6, AZ80/1wt.%SiC obtains the highest ultimate tensile strength of 256 MPa, which is much higher than 186 MPa of as-cast AZ80.
6. By adding only 1 wt.% SiC micro-particles, the yield and ultimate strengths of as-cast AZ80 increase tremendously with approx. 30 % increase (excluding 0 h or 2 h – T6 heat treated AZ80/1wt.%SiC, which were not tested) both for as-cast and T6 heat treated Mg MMCs.

References

[1] Lin, P.-C., Huang, S.-J., Huong, P.-S.: Acta Metallurgica Slovaca, *16*, 2010, p. 237.

[2] Huang, S.-J., Chen, Z.-W.: Acta Metallurgica Slovaca, *16*, 2010, p. 246.

[3] Huang, S.-J., Chen, Z.-W.: Kovove Mater., *49*, 2011, p. 259. doi:10.4149/km_2011_4_259

[4] Saravanan, R. A., Surappa, M. K.: Mater. Sci. Eng., A, *276*, 2000, p. 108. doi:10.1016/S0921-5093(99)00498-0

[5] Cai, Y., Tan, M. J., Shen, G. J., Su, H. Q.: Mater. Sci. Eng., A, *282*, 2000, p. 232. doi:10.1016/S0921-5093(99)00707-8

[6] Ho, K. F., Gupta, M., Srivatsan, T. S.: Mater. Sci. Eng., A, *369*, 2004, p. 302. doi:10.1016/j.msea.2003.11.011

[7] Lianxi, H., Erde, W.: Mater. Sci. Eng., A, *278*, 2000, p. 267. doi:10.1016/S0921-5093(99)00608-5

[8] Wang, A. H., Yue, T. M.: Compos. Sci. Technol., *61*, 2001, p. 1549. doi:10.1016/S0266-3538(01)00054-9

[9] Rogathi, P. K.: Cast Metal-Matrix Composites. ASM Handbook-Castings, *15*, 1992, p. 840.

[10] Zeng, R. C., Xu, Y. B., Ke, W., Han, E. H.: Mater. Sci. Eng., A, *509*, 2009, p. 1. doi:10.1016/j.msea.2009.01.013

[11] Zheng, B., Ertorer, O., Li, Y., Zhou, Y., Mathaudhu, S. N., Tsao, C. Y. A., Laverni, E. J.: Mater. Sci. Eng., A, *528*, 2011, p. 2180.

[12] Zhang, P., Lindemann, J., Leyens, C.: J. Alloys Compd., *497*, 2010, p. 380. doi:10.1016/j.jallcom.2010.03.079

[13] Cai, Y., Shen, G. J., Su, H. Q.: Scr. Mater., *37*, 1997, p. 737. doi:10.1016/S1359-6462(97)00172-3

[14] Chen, Y. X., Li, D. X.: Mater. Lett., *61*, 2007, p. 4884. doi:10.1016/j.matlet.2007.03.065

[15] Amini, S., Ni, C., Barsoum, M. W.: Compos. Sci. Technol., *69*, 2009, p. 414. doi:10.1016/j.compscitech.2008.11.007

[16] Huang, J.-F., Yu, H.-Y., Li, Y.-B., Cui, H., He, J.-P., Zhang, J.-S.: Mater. Des., *30*, 2009, p. 440. doi:10.1016/j.matdes.2008.06.001

[17] González-Martínez, R., Göken, J., Letzig, D., Steinhoff, K., Kainer, K. U.: J. Alloys Compd., *437*, 2007, p. 127.