Effects of Magnesium Content on Ballistic Performance (R3)

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Effects of Magnesium Content on Ballistic Performance of Al-8Zn - SiC Composite after Heat Treatment Process

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Abstract. SiC – reinforced aluminium composite - have been developed to improve the ballistic performance and mobility of the armour material. Critical to obtaining ballistic resistance is that the materials must be sufficiently hard and strong, especially at the surface where a projectile will first make impact. To achieve this resistance, aluminium alloys can be strengthened by adding Zn, Mg and reinforced with silicon carbide. This research studied the ballistic properties of aluminium composites with varied Mg. The matrix used in this study was an Al-8Zn alloy with 3-5 wt. % Mg. Silicon carbide particulate with 15 % volume fraction was used as strengthening material, which was added to the liquid matrix by stirring at 5000 rpm. The liquid composite was then squeeze cast at a pressure of 72 MPa. Then composites were heat-treated and coated to improve the ballistic performance. Ballistic testing was performed in accordance with ASTM F1233 by using 7.62 calibre projectiles. Microstructural observation was conducted in samples, performed with optical microscope. The results showed that the as-cast hardness of the composite increased with addition of Mg content of 3, 4 and 5 wt. %. The peak hardness after ageing at 200 ^{o}C also increased with Mg addition. However, the composites were not able to withstand the 7.62 mm calibre projectile.

Introduction

Armour materials are designed to withstand the penetration of projectiles, at which they will rupture or trap the bullets with high impact loading. This requires high toughness at high velocity impact as well as high hardness. Steel has long been used as armour materials, because of its ability to meet the requirement. However, the high density of steel resulted in heavy weight that limits the mobility of the components, parts or vehicles [1-2]. Therefore, alternative materials were seek to substitute steel. High strength aluminium alloy is a very promising for armour application because of its low density and good ballistic impact properties.

Various aluminium armours has been developed; for instance, 5083-H116 via cryomilling technique [3-4], and aluminium laminates [5-7]. Sorensen et al. [8] studied high velocity impact characteristics of 2100 m/s using low-density projectiles on a 7039 aluminium plate. Some studies have improved the mechanical properties of aluminium alloy through manipulating the Zn and Mg content [9-10]. To further improve ballistic characteristics, aluminium is combined with other materials, such as alumina and silicon carbide to form high strength composite materials [11-17]. Karamis et.al [11] developed Al-Cu strengthened with Al_2O_3 in layered structures. The Al_2O_3 was found to slower the penetration of 7.62 mm bullet, although the bullet remained fully penetrating to the materials. In other study [12] they found that ballistic impact on Al 6061-T4 – 15 vol. % SiC composite resulted in ductile fracture of the matrix, followed by brittle fracure of the SiC particles. High speed projectile partly melted the the materials due to heat produced by the high friction. Previous results [18] showed that composite with Al-7Si-2.13-0.65Mg as the matrix and 2.8 vol. % of steel ropes were able to withstand projectile of type I and II. However, at type III threat, the material underwent petalling which indicated that it did not have sufficient hardness and toughness to fracture and stop the bullet.

To increase the hardness of the matrix, this research focused on the use of Al-Zn alloy which was added with 3 – 5 wt. % Mg and strengthened by 15 vol. % SiC particles. The composites were produced by squeeze casting process, which combining the advantages of pressure die-casting and forging technology [19-21].

Materials and Methods

The matrix used in this study was Al-8Zn alloy with varied Mg content of 3, 4 and 5 wt. %. silicon carbide particulate of 180 mesh from Sigma-Aldrich was used as the strengthening material with 15 % volume fraction. To increase wettability between silicon carbide surface and the aluminium matrix, the silicon carbide was preheated at 1000 ^{o}C for 1 hour. Pure aluminium, zinc and magnesium ingots were used as the starting materials. The ingots were melted in an electric furnace at 850-870 ^{o}C, followed by degassing process. The preheated SiC was then poured and stirred with the speed of 5000 rpm. The molten composite was squeeze cast at 72 MPa in a metal mould. The actual composition of the composite is presented in Table 1.

Table 1 Actual composition of the composites.

Element	Composition (wt. %)		
	Sample 1	Sample 2	Sample 3
Mg	**2.65**	**3.86**	**5.08**
Zn	**8.90**	**7.25**	**8.05**
Si	**11.70**	**12.86**	**13.72**
Fe	0.81	0.16	0.14
Mn	0.06	0.02	0.01
Ti	0.02	0.01	0.04
Al	*Rem*	*Rem*	*Rem*

The composite was subsequently solution treated at 500 °C for 1 hour, quenched in water and followed by ageing at 200 °C for 2 hour to increase hardness and toughness of the material. After that the composite was coated with 80 % W – 20 % Co by high velocity oxy-fuel (HVOF) thermal spraying technique. The hardness of coating was 68 HRC. The microstructures were observed through optical microscope and Scanning Electron Microscope (SEM). Mechanical properties were examined through hardness testing. Ballistic testing was performed in accordance with ASTM F1233 by using a projectile at a 90^{0} direction and an NIJ-0101.05 type of bullet with calibre of 7.62 mm. The results were investigated by microstructural examinations to observe perforated areas by measuring the diameter of the projectile perforations.

Results and Discussion

Fig. 1 shows the effect of Mg alloying on the ageing response of Al8Zn – 15 vol. % SiC composites at 200 ^{o}C. It is noted that the addition of Mg from 3 to 5 wt. % increases the as cast hardness of the composites by 15.33 %. After quenched, all the composites posessed almost the same hardness, only differed by 1.09 % with addition of Mg from 3-5 wt. %. It is thought to be due to complete solution of Mg in the Al-8Zn matrix and the entrapment of vacancies during quenching. Mg atom has the biggest atomic diameter (0.160 nm) compared to Al (0.143 nm) and Zn (0.133 nm). Therefore, Mg tends to trap more vacancies during quenching. Because of that, the solid solution strengthening contributed by Mg in the as-cast condition is reduced by the presence of more vacancies. Vacancy-rich clusters that formed during quenching will iniate the nucleation of precipitates during ageing. The Zn atoms will diffuse into the Mg-vacancy clusters and formed $MgZn_2$ precipitates. It is noticeable that within only 5 minutes of ageing, the hardness of the composites increased by 37.14 % compared to the as-quenched condition or contributed 50.16 % of the peak hardness. This phenomenon was called cluster hardening, in which sub-nanometer atomic co-clusters of Mg and Zn atoms forms in a massive amount that produced lattice distortion that increased the hardness of the material [19, 20]. These clusters will then grow as precipitates that contribute to the peak hardness of the composites.

The peak hardness of the composite was achieved after 2 hours for all composites. This is similar to the results of Sheu et al [21] that AA7075 – SiC composites obtained their peak hardness within 1-2 hours at 200 °C. The peak hardness of the composite increased with the increase of Mg content in the matrix. The average increase in peak hardness due to Mg addition is 3.29 %, higher than the increase in as-quenched hardness. This indicates that Mg contributes to the precipitation strengthening due to the formation of semi coherent $MgZn_2$ precipitates, as suggested by Sun et al [22] and Hsieh et al [23]. Aside from that, the Si from SiC may react with Mg to form Mg_2Si. Kumar et al. [24] found Mg_2Si precipitates at the interface of SiC and matrix in an Al-Zn-Mg composite strengthened with SiC and solution treated at 485 °C for 90 minutes and aged at 135 °C.

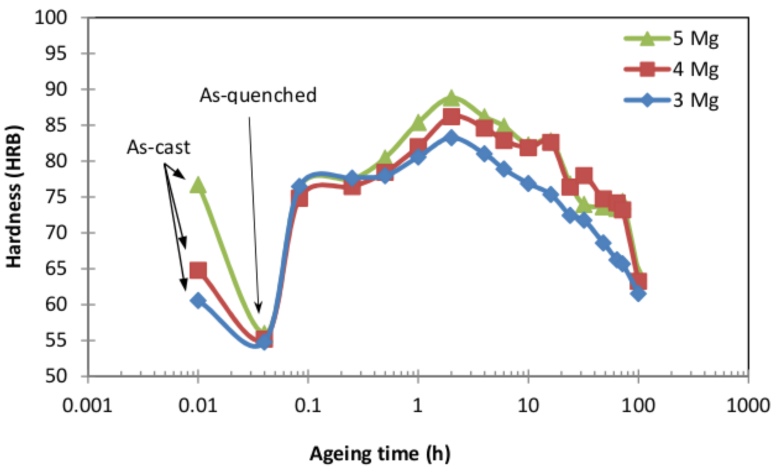

Fig. 1 The ageing curve of Al-8Zn – SiC composite varied with 3, 4 and 5 wt. % Mg content

To understand the strengthening mechanisms by addition of Mg, microstructures of the composite with variation of 3, 4, and 5 wt. % Mg in the peak ageing condition were observed and the results are shown in Fig. 2. In general, the SiC particles are not well distributed in the matrix. The grain size varied with no specific relationship to the Mg content. The addition of Mg seems to not affect the grain size. Second phases are dominant in the grain boundaries. The higher the Mg content, the more second phase particles were found in the grain boundary. It is thought that Mg promotes the formation of Mg_2Si or $MgZn_2$ second phases, which contribute to higher as-cast hardness. These second phase precipitates remained in the grain boundaries of the aged samples. By comparing Fig. 2 (c) to 2 (a), we can see that the ageing process seemed to form precipitates within the grains. Some contrast is visible inside the grains in all overaged samples (Fig. 2 (c), (e) and (i)). The contrast may come from the precipitates. The precipitates are possibly Mg_2Si and $MgZn_2$ [25]. The addition of Mg leads to more contrast, indicating formation of more precipitates within the grain. This correlates with the increased aged hardness by addition of Mg.

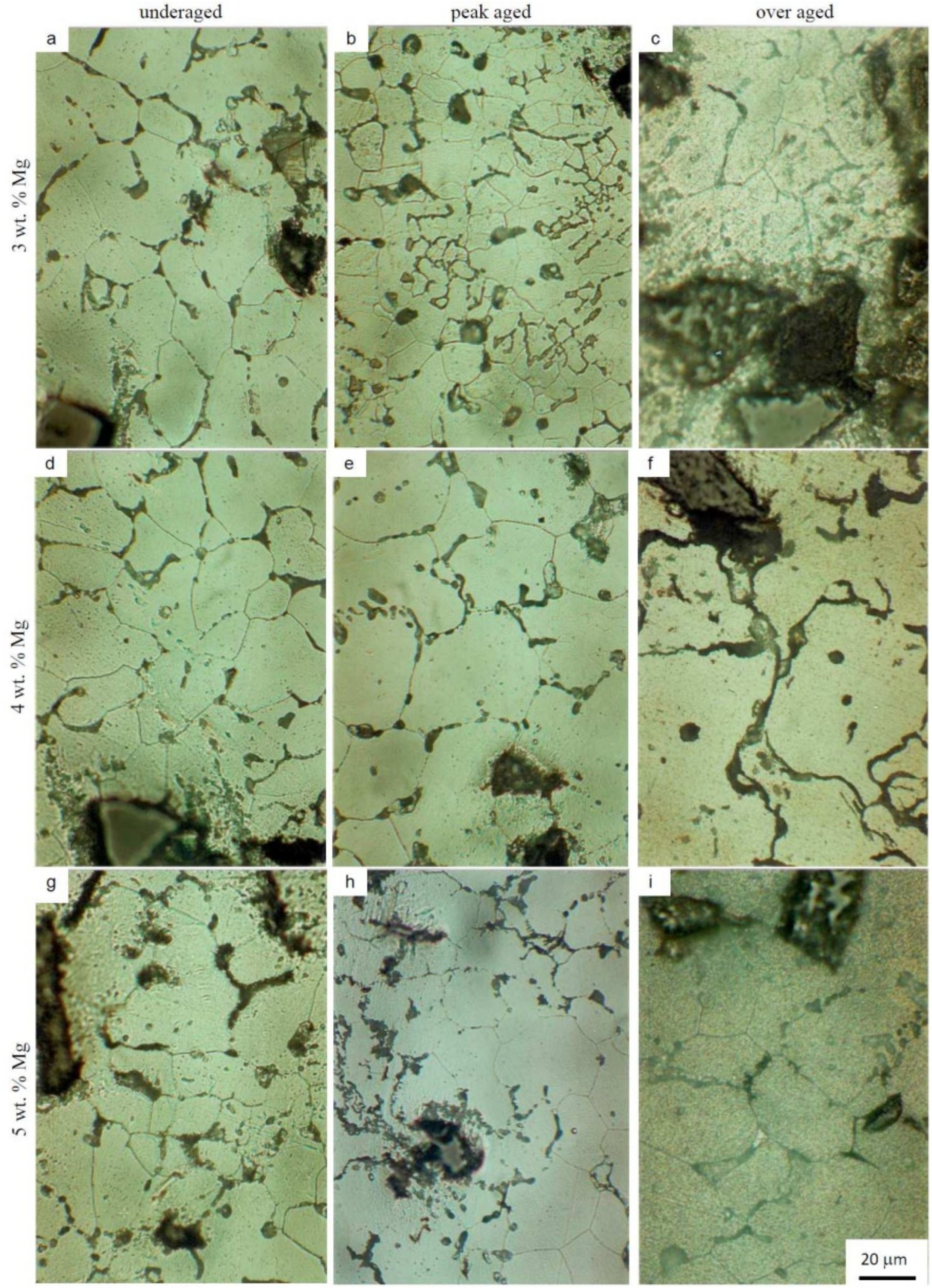

Fig. 2 The evolution of microstructure of Al-8Zn – 15 vol. % SiC composite with varied Mg content of (a - c) 3, (d-f) 4, and (g-i) 5 wt. % during ageing at 200 °C

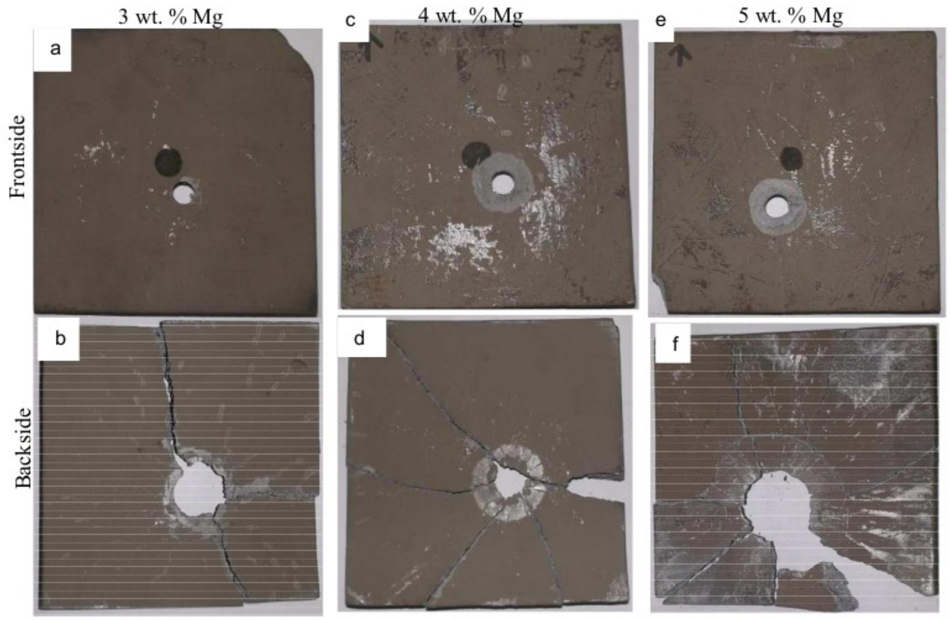

Fig. 3 Perforation area of a composite plate of Al-8Zn matrix varied with Mg content of: (a,b) 3, (c,d) 4, and (e,f) 5 wt.%, reinforced with 15 % SiC after 7.62 mm calibre of ballistic testing.

Ballistic impact is a high velocity impact using a small mass simulation with a very high strain rate. The ballistic resistance of an armour material is normally characterized in terms of the reciprocal of the areal density of the target material that is required to arrest a particular type of projectile striking with a specific velocity [1, 2]. Fig. 3 demonstrates the perforation area of the front side and backside of the three-layered composite as the result of 7.62 mm calibre projectile. It shows that the composites were not able to withstand the 7.62 mm bullet. The composite with 3 wt. % Mg has lower perforation area than that of higher Mg content. The backside plate of the 3 wt. % Mg containing composite shattered into three parts while other plates fully shattered into small peaces. This condition shows that the toughness of the composites need to be improved to be able to withstand the ballistic impact load.

Conclusions

- The higher the Mg content, the higher the as-cast hardness of the Al-8Zn composite with 15 % SiC.
- The composite underwent precipitation hardening which significantly increase the hardness. Higher Mg content led to higher peak hardness.
- The age hardening might be contributed by the precipitaion of Mg_2Si and $MgZn_2$ during ageing, therefore the higher Mg led to higher peak hardness.
- The developed SiC – reinforced Al-Zn-Mg composite cannot withstand a 7.62 mm calibre projectile of the ballistic testing.

Acknowledgement

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