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To cite this article: R F Adiputra *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **285** 012030

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Effect of SiC addition to the characteristics of Al-11Zn-6.7Mg composite produced by squeeze casting for ballistic application

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Abstract. Aluminium composite material as an alternative to steel used in body of tactical vehicles has been studied. Addition of SiC was expected to have strengthening effect on the composite matrix therefore improving its ballistic performance. Composites of Al-11Zn-6.7Mg matrix and SiC strengthening particles with the fraction of 0, 10, and 15 vol. % were fabricated through squeeze casting process. Composite samples were then precipitation strengthened at 130 °C for 102 h to further improve their toughness. Final products were characterized by using chemical composition testing, optical microscopy, Scanning Electron Microscope – Energy Dispersive Spectroscopy (SEM-EDS) and quantitative metallography to calculate porosity, hardness test, impact test, and type III ballistic test in accordance with NIJ 0108.04 standard. The results showed that increase in SiC volume fraction from 0 to 10 and 15 vol. % managed to improve the hardness from 73 to 85 and 87 HRB, respectively, while on the other hand reduced the impact values from 12,278.69 to 11,290.35 and 9,924.54 J/m². SEM-EDS observation confirmed the presence of Mg₃Zn₃Al₂ intermetallic compound which formed during solidification and indicated the precipitation of MgZn₂ precipitates during ageing. The ballistic testing demonstrated a promising result of the potential of Al-11Zn-6.7Mg composite strengthened by 15 vol. % SiC to withstand penetration of type III bullet (7.62 mm).

1. Introduction

Aluminium 7xxx is a type of heat-treatable Al-alloys with superior strength compared to other series. It has been found that the alloys exhibited higher strength with addition of 9 wt. % Zn [1]. The high mechanical properties of these alloys are also influenced by the presence of MgZn₂ precipitates that form during heat treatment, be it either natural or artificial aging processes [2]. In a research conducted by Demir et al.[3] on comparison of ballistic impact resistance between Al 7075, Al 5083, and HSLA AISI 4040 steel, it was found that Al 7075 possessed the best ballistic resistance of all three materials. This shows that Al7xxx alloys are promising to be used as materials for tactical vehicles.

The mechanical properties of Al 7xxx alloys can be further enhanced by using it as the matrix (Metal Matrix Composites/MMC). These composites are engineered combination of the metal matrix and hard ceramic particle reinforcement in order to get tailored properties. Aluminium matrix composites are recently considered as alternatives to metals used in military applications due to their low density, high mechanical properties, and good resistance to corrosion. Common reinforcements for the Al-matrix composites are Al₂O₃, SiC, and MgO particles, which are utilized due to their high specific strength that remains steady at ambient temperatures [4]. Kheder et al. concluded that SiC acted as the most potential reinforcement in terms of increasing the strength and hardness of Al-MMC [5]. However, Zhou and Xu [6] found that SiC particles tended to float on the surface of molten metal during mixing due to their high surface tension and poor wetting mechanism. Nishchev et al. [7] also showed that SiC microstructure was chemically separated from the aluminium matrix which was well observed on the matrix-reinforcement interface. A research by Sigit and Sofyan [8] on solution treated and aged Al-7Si-Mg-5Zn composites with SiC reinforcement revealed that Mg acted as a wetting agent that lowered the surface tension between the matrix and the reinforcement, hence improving the matrix-reinforcement bond in the composites. Behera et al. [9] added that higher SiC content leads to



higher Al-MMC composites hardness. Addition of SiC also contributed in grain refining mechanism of the composite, as the reinforcement acted as nucleating agents during solidification.

Squeeze casting is a casting method in which an external pressure is applied to the molten metal during solidification [10]. The pressure will minimize the occurrence of porosities and shrinkage defects. Rahmalina et al. [11] performed an experiment on fabricating Al-7Si-6Mg-5Zn composite with SiC reinforcement through squeeze casting method which demonstrated a good distribution of SiC particles of 5, 10, and 20 vol.% in the fabricated composite. In addition, Rahmalina et al. [12] also found that precipitation strengthening mechanism was needed in order to improve the toughness of the composites matrix to withstand the ballistic impact. Therefore, this research focused on studying the Al-11Zn-6.7Mg composites with variation of SiC reinforcement of 10 and 15 vol. % for ballistic application. The samples were fabricated using squeeze casting. A plate of the corresponding Al-alloy without strengthening particles was also fabricated and viewed as the reference matrix.

2. Materials and Method

Experimental matrix material of Al-11Zn-6.7Mg alloy was prepared by commercial pure Al (99.99 wt. %), Zn (99.99 wt. %), and Mg (99.99 wt. %) ingots. Particulates of #400 SiC from Sigma-Aldrich were prepared as the reinforcement with the amount of 0, 10, and 15 vol. %. The SiC particles were preheated in a muffle furnace at 1000 °C for 1 h to increase their wettability with the aluminium molten.

Melting was inducted in a graphite crucible at 870 °C and degassed with argon gas for 1 minute. Preheated SiC particles were then added to the melt and stirred at 5000 rpm for 2 minutes. The melts were poured into a 170 x 170 x 15 mm³ preheated metal mould and then squeeze casted at 76 MPa for 10 minutes. To improve hardness and toughness, the composites were subsequently solution treated at 450 °C for 1 h, water-quenched, and aged at 130 °C for 102 h. The actual composition of the composites samples are shown in table 1.

The chemical composition of the composites was analyzed using ThermoARL Optical Emission Spectroscopy (OES). Hardness testing was conducted in accordance to ASTM E18 with 4 indentations using Rockwell B method, while impact testing was conducted by using Charpy method. Standard metallographic preparation was conducted with 0.5 % HF etchant. The microstructures were observed by Scanning Electron Microscope (SEM) – Energy Dispersive Spectroscopy (EDS) and Zeiss Primotech Optical Microscope (OM). Calculation of porosities was done using Image Pro-Plus Software. Type III ballistic testing was performed to three layers of 10 x 10 x 1.5 cm³ 15 vol. % SiC composite plates in accordance to NIJ 0108.01 (Ballistic Resistant Protective Material) standard using 7.62 mm caliber bullets, shot twice by an SPR-1 shotgun from the distance of 15 m.

Table 1. The actual composition of the samples.

Sample	Zn	Mg	Si	Cu	Fe	Mn	Ti	Cr	Ni	Al
A (0 vol.% SiC)	10.318	6.741	0.036	0.001	0.172	0.017	0.004	0.010	0.011	Rem
B (10 vol.% SiC)	11.546	7.052	1.039	0.001	0.209	0.001	0.001	0.012	0.011	Rem
C (15 vol.% SiC)	11.156	6.290	2.643	0.001	0.254	0.007	0.005	0.008	0.042	Rem

3. Results and discussion

3.1. Microstructural characterization

Figure 1 show the microstructures of the composites with different amounts of SiC particulates which were observed as gray particles. The microstructures revealed dendritic grain structure in which intermetallic phases Mg₃Zn₃Al₂ could be observed (*see arrows*). The intermetallic phases were found in a net shape with dark contrast. From Figure 1 (b-c), it is clear that SiC particles are uniformly distributed in the 10 and 15 vol. % SiC composites. This was proven by the hardness value examined of the top, middle, and bottom of the composite plate as shown in Figure 2. It can be seen that the hardness value are similar for each position in both composites.

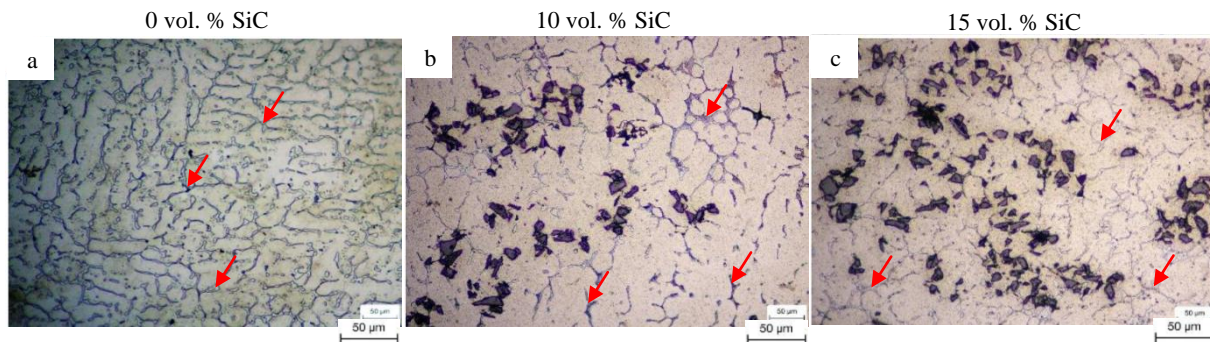


Figure 1. Microstructures of Al-11Zn-6.7Mg composites with additions of (a) 0, (b) 10, and (c) 15 vol.% SiC. Arrows showing intermetallic $Mg_3Zn_3Al_2$ phase

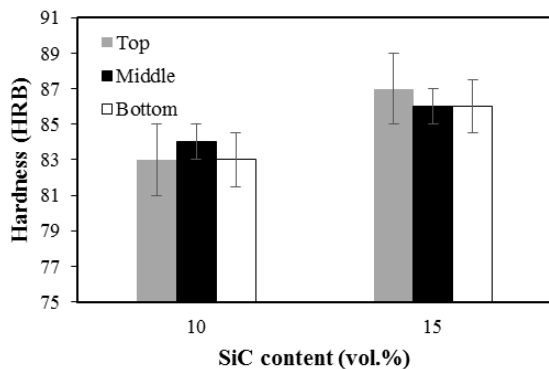


Figure 2. Amount of porosities in Al-11Zn-6.7Mg with different vol. % SiC addition

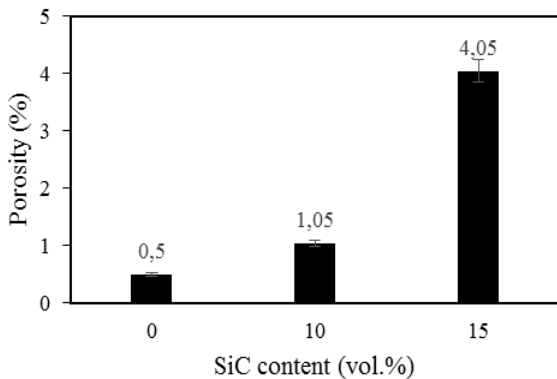


Figure 4. Hardness distribution of Al-11Zn-6.7Mg with 10 and 15 vol. % SiC composites

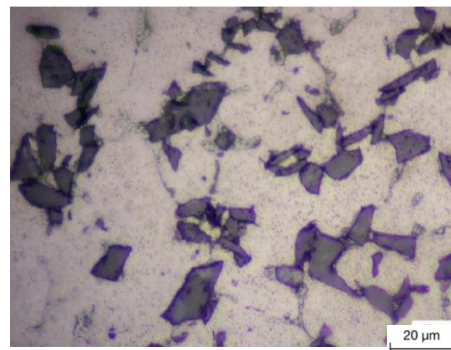


Figure 3. Microstructure of Al-11Zn-6.7Mg with 15 vol. % SiC as 130 °C for 102 h

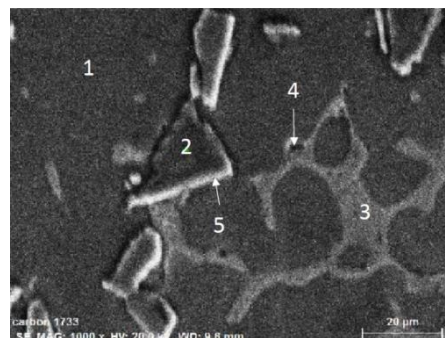


Figure 5. SEM micrograph of Al-11Zn-6.7Mg with 15 vol. % SiC as aged at 130 °C for 102 h

Addition of Mg is expected to reduce the contact angle between matrix and reinforcement, thus increasing the composite wettability. Mg has lower superficial stress than Al and SiC does, that it can support the infiltration process of Al – SiC and prevent the formation of Al_4C_3 interface which is hard and brittle [13]. However, in Figure 3, we remain see visible voids around the interface of 15 vol.% SiC composite due to the lack of wettability. The amount of porosities increased with more SiC content. Figure 4 shows that the porosities of samples with addition of 0, 10, and 15 vol.% SiC were 0.5 %, 1.05 %, and 4.05 % in average, respectively.

SEM-EDS micrograph of the composite with 15 vol. % SiC was presented in Figure 5. The results of EDS characterization at corresponding positions are presented in table 2. Furthermore, in Figure 5 α -Al was detected to be the matrix as pointed out by point 1. In addition, with Zn:Mg ratio at that point which is approaching 2:1, $MgZn_2$ is predicted to form [14]. At point 2, detected contents of Si and C atoms were 47.25 and 46.40 at. %, respectively, which was nearly 1:1 in ratio. This proved that SiC particles reinforcement did exist at this point. Meanwhile at point 3, it was noticed that the phases in the dendrites was mainly composed of $Mg_3Zn_3Al_2$. Point 4 indicated intermetallic phase as well as $Mg_3Zn_3Al_2$ due to the percentage of Mg:Zn are almost the same, 1:1. While point 5 in which the atomic percentage of Mg is higher than Zn and exists between SiC and the matrix, was identified as the interface area of the composite that consists of high Mg content. This indicates occurrence of segregation of Mg to the matrix-SiC interface that improves the overall wettability.

Table 2. EDS data of Al-11Zn-6.7 Mg with 15 vol. %SiC on as-aged condition at 130 °C for 102 h at positions as shown in Figure 5

Position	Element content (at.%)						Phase
	Zn	Mg	Si	C	O	Al	
1	4.59	1.96	-	18.77	2.62	72.06	\square -Al, $MgZn_2$
2	0,29	0.24	47.25	46.40	4.38	1.43	SiC
3	25.16	24.98	-	22.21	3.64	24.01	$Mg_3Zn_3Al_2$
4	12.73	11.53	-	3.95	19.36	52.43	$Mg_3Zn_3Al_2$
5	1.79	4.52	-	18.58	2.87	72.24	Interface, \square -Al

3.2. Mechanical Properties

Hardness of Al-11Zn-6.7Mg composites with 0, 10, and 15 vol. % SiC reinforcement is shown in Figure 6, which indicates an increase in overall composite hardness along with more SiC added into the matrix. Composite hardness increased from 73 to 85 and 87 HRB on addition of 10 and 15 vol. % SiC, respectively. This finding compromises results of the previous works [5, 9, 15].

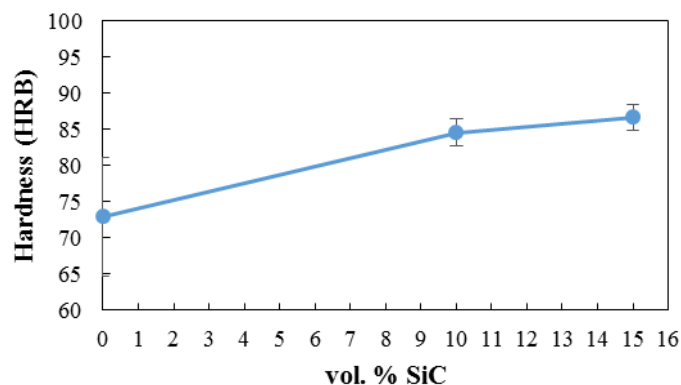


Figure 6. Effect of vol. % SiC on hardness of Al-11Zn-6.7Mg-SiC reinforced composites

Table 3. Calculated result of theoretical and actual composite hardness

SiC content (vol. %)	Theoretical Hardness (HRB)	Actual Hardness (HRB)
10	86	85
15	87	87

With help from image analysis, it was found that samples with targeted 10 and 15 vol. % SiC contained only 4.50 and 6.98 vol. % SiC. Using the rule of mixture theory [16], we can obtain the theoretical hardness of the composite plate as well as the amount of porosity and fraction of SiC contained within, that can be used further in comparison to the reference composite sample. Table 3 contains the calculated result of theoretical and actual composite hardness attained using the rule of mixture. Actual composite hardness was close to its theoretical hardness due to shortage in acquired final vol.% SiC inside the composite, which was lower than 10 and 15 vol.%. It is suspected that the mixing process was not done well that caused more material loss than presumed.

Figure 7 shows the effects of vol. % SiC addition on the toughness of Al-11Zn-6.7Mg composites. The figure has a decreasing trend of toughness with more SiC addition. This phenomenon might happen due to the increase of composite brittleness and the presence of porosities within the plate with the amount of 0.5, 1.05, and 4.05% on addition of 0, 10, and 15 vol. % SiC, respectively. It can be inferred from the fracture surface in Figure 8 that porosities exist around SiC reinforcement (marked with red arrows). These porosities may initiate crack propagation when composite is subjected to impact loading, making it more vulnerable to cracking, thus absorbing less energy before failure. Observed fracture area showed a brittle fracture due to the absence of plastic deformation and fibrous fracture morphology in the samples.

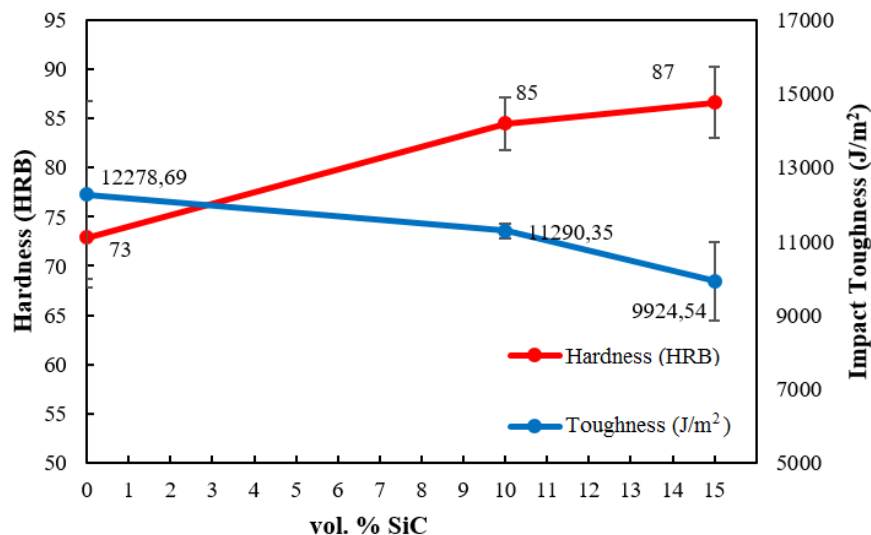


Figure 7. Effect of SiC reinforcement on impact toughness of the composite

3.3. Ballistic Properties

Ballistic testing was done on three composite plates with 15 vol. % SiC reinforcement. The surface of each plate was coated using High Velocity Oxygen Fuel method (HVOF) with 80 wt.% WC – 20 wt.% Co powders. The hardness of Plate 1, 2, and 3 are 87, 86, and 84 HRB, while toughness for each plate is 9,534.58, 10,387.76, and 9,851.29 J/m², respectively. Plate 3 with the lowest overall hardness was put up in front, followed by Plate 2 and 1 with higher hardness. Ballistic testing were done using SPR-1 shotgun with calibre 7.62 mm bullet. Shooting was done on 15 meter range which corresponded to the type III ballistic testing standard. Two shots were taken in the actual testing. Figure 9 showed the result of ballistic testing.

0 vol. % SiC

10 vol. % SiC

15 vol. % SiC

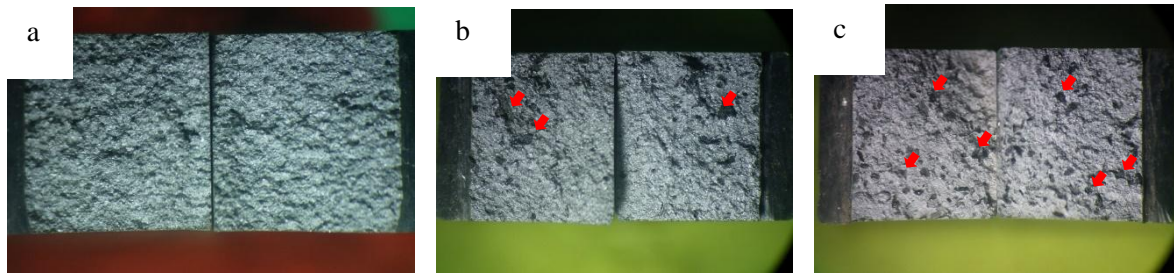


Figure 8. Fracture surface of Al-11Zn-6.7Mg-SiC reinforced composites with (a) 0, (b) 10, and (c) 15 vol. % SiC aged at 130 °C for 102 h

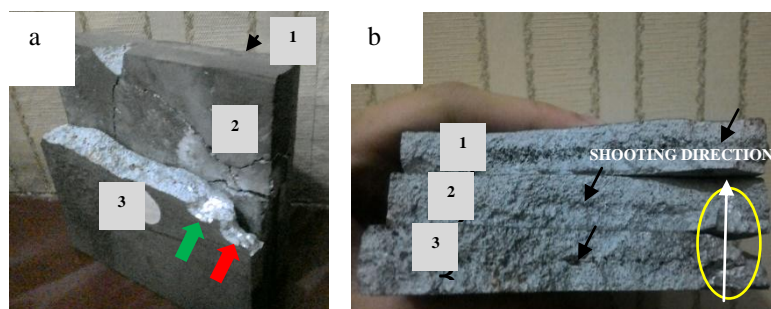


Figure 9. Result of ballistic testing: (a) propagation of crack (b) fracture surface morphology

Visual observation on macroscopic scale indicated a dominant brittle fracture mechanism due to the high hardness of each composite plate. It can also be concluded that porosities located around SiC reinforcement inside the composite were the source of crack propagation (Figure 9b, marked with black arrows). Plate 2, however, still showed traces of plastic deformation after the ballistic testing, which confirmed the occurrence of ductile fracture mechanism in the composite plate.

Experimental layer of three Al-10.6Zn-6.7Mg composite plates with 15 vol. % SiC reinforcement each shown an ability to resist bullet penetration in type III ballistic testing. With the occurrence of ductile fracture characteristic in Plate 2, it is safe to say that the fabricated composite plate is able to withstand and absorb the impact energy from the bullet shot. Previous ballistic testing on three Al-8Zn composite plates with 15 vol. % SiC reinforcement and variation of Mg addition by 3, 4, and 5 wt. % done by Septiani [17] showed that the produced composite could not withstand the ballistic penetration. Thus, this research has managed to improve the ballistic performance of composite plate fabricated using Al-11Zn-6.7Mg matrix with 15 vol. % SiC reinforcement.

4. Conclusion

Investigation on Al-11Zn-6.7Mg composite plates with variation of 0, 10, and 15 vol. % SiC reinforcement particles resulted in the following conclusions:

- (1) The addition of SiC reinforcement of 10 and 15 vol. % to Al-11Zn-6Mg alloys showed an increase in strength and lower the toughness of the composites. The strength of Al-11Zn-6.7Mg composites with variation of 0, 10, and 15 vol. % SiC are 73, 85, and 87 HRB, respectively, whereas the toughness are 12,278.69, 11,290.35, and 9,924.54 J/m².
- (2) Overall composite porosity increased from 0.5% to 1.05% and 4.05% with the addition of 10 and 15 vol. % SiC, respectively.
- (3) MgZn₂ precipitate and Mg₃Zn₃Al₂ intermetallic phase which formed and distributed in the matrix were found to influence the final mechanical properties of the composite matrix.
- (4) Layer constructed of three Al-11Zn-6.7Mg plates with 15 vol. % SiC reinforcement is potential to be used as materials for armor manufacturing due to its ability to withstand penetration of type III bullet despite of the cracking failure experienced.

Acknowledgements

The authors wish to acknowledge the financial support acquired from Ministry of Research Technology and Higher Education through Hibah Penelitian Unggulan Perguruan Tinggi (PUPT) 2016.

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