

EFFECT OF NANO SiC ADDITION AND HEAT TREATMENT ON BALLISTIC PROPERTIES OF AL 2024/NANO SiC COMPOSITE PRODUCED BY SQUEEZE CASTING

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Received: February 07, 2021; Revised: April 08, 2021; Accepted: April 10, 2021

Abstract

Combat vehicles usually consist of heavyweight high-strength steel that restricts the vehicle's mobility. To enhance its mobility, lightweight materials with good ballistic resistance are being developed, such as aluminum matrix composite. This research is to understand the effect of nano SiC content and heat treatment inside the Al 2024 matrix on its ballistic properties. Nano SiC reinforcement particles were added to Al 2024 matrix with a variety of 0.1, 0.2, and 0.3 wt%. The composite plates were fabricated by stir casting followed by squeeze casting, then heat-treated with solution treatment at 495°C for 2 h, water quench, and aging at 190°C for 1 h. The samples were then subjected to the ballistic impact test Type II and Type III NIJ standards. Other characterizations were conducted, such as microstructure observation, hardness, and impact. The results showed that all composite plates endured Type II ballistic properties, but not Type III. The addition of nano SiC content inside the matrix increases its hardness but lowers its impact endurance. Heat treatment increases hardness significantly but reduces its impact properties. Heat-treated composite plate with 0.3 wt% nano SiC reinforcement has the best ballistic properties.

Keywords: Aluminium matrix composite, Al 2024, Ballistic, Heat treatment, Nano SiC reinforcement

Introduction

The effectiveness of a combat vehicle relies on three main factors: firepower, protection, and mobility. Combat vehicles usually consist of RHA steel weighing 16-50 tons, restricting mobility, only moving at 60-70 km/h (TRADOC G-2 ACE-Threats Integration Fort Leavenworth, 2015). One of the solutions to increase the mobility of a combat vehicle is to change the material with lighter material, but have the same or even better ballistic

resistance properties than steel. Aluminum matrix composite is a good option (Karamis *et al.*, 2009). Aluminum has a relatively low density with good mechanical properties and will be strengthened even more by ceramic particle reinforcement.

Ceramic particles are commonly used as reinforcement due to their hardness and stability in high temperatures. Based on research conducted by (Kheder *et al.*, 2015), SiC is the reinforcement that

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has the most potential to improve the strength and hardness of aluminum matrix, compared to other ceramic reinforcement such as Al_2O_3 and MgO . Nanostructured reinforcement can strengthen the matrix without reducing the ductility of the material (Kim *et al.*, 2017). Copper (Cu) is the main element in Al 2024 alloy. They can make the alloy, with heat treatment, form precipitates and strengthens the material.

Therefore, this research will discuss the effect of nano SiC reinforcement content and heat treatment on the ballistic properties of Al 2024/nano SiC composite produced by squeeze casting.

Material and Experimental Procedure

Materials

This study used Al 2024 alloy matrix and nano SiC particles reinforcement for the composite plate fabrication. Both are purchased commercially. The nano SiC particles have 99.92% purity and ~20 nm in size. Table 1 below shows Al 2024 alloy composition analyzed by OES (Optical Emission Spectroscopy) compared to literature (Gregson, 2012).

The composition in this research matches with the literature, except for the other element which is dominated by Zn, Ti, and Cr. These elements generally increase the yield strength of aluminum after heat treatment, although not as much as Mn (Gregson, 2012).

Squeeze Casting and Heat Treatment

The composite plates were fabricated by stir casting followed by the squeeze casting method. The aluminum ingot was cut and melted. Then, nano SiC reinforcement was added to the melted aluminum after pre-heated at 900°C for 1 h to release SiO_2 coating and to prevent Al_4C_3 from forming. The mixture was then stirred for 2 min at 500 rpm and degassing with Ar gas for 1 min before poured at a pre-heated mold and squeezed by 175 MPa pressure for 2 min. The mold has 15×7.5×1.5 cm in dimension and was pre-heated to 300°C to avoid thermal shock.

The addition of SiC in the present work is small, mainly to preserve its ductility. The added ceramic particles such as SiC deteriorate the ductility of the aluminium matrix (Mazahery and

Shaban, 2012). In addition, the higher percentage of nano particles will risks agglomeration of the particles, as the method we choose is stir casting followed by squeeze casting. Moreover, if the particle size is much smaller, the reinforcements can cluster easily in the matrix and result in an inhomogeneous distribution of reinforcements (Wang *et al.*, 2011). In previous work with the same method of fabrication (Dhaneswara *et al.*, 2017), it is observed that small addition of nano-SiC addition has increased the mechanical properties significantly.

Samples Characteristics

The ballistic resistance of the samples was tested with NIJ 0108.01 standard. The heat-treated samples were tested with the Type III test and then Type II test, whereas the non-heat treated ones were only tested by the Type II test. The Type II test used a 9 mm parabellum pistol (380 m/s) within the 20 m range. The Type III test used MU5-TJ (5.56 mm) bullet on air rifle (915 m/s) within 20 m range. Other tests conducted are observation with OM and SEM, density test, microhardness test by Vickers method with 100 gf load, and Charpy test using 300 Joule pendulum by ASTM E23 standard.

Results and Discussion

Observation Results of Composite Microstructure Using OM & SEM EDS

Figures 1 and 2 show the result of the optic microscope (OM) of the composite plates. Samples with more SiC content have a larger eutectic phase, whereas the heat-treated samples have finer grains.

In theory, the pinning effect from nano SiC particles on the grain boundary hinders grains growth, forming finer grains and larger grain boundaries (Li *et al.*, 2018). This is observed in heat-treated samples, where the more nano SiC particles present, the finer the grains formed. However, it is not the case in the non-heat-treated samples. Figure 1 indicates samples 1 and 2 have a smaller grain size than sample 3 because of the presence of microporosity inside, where the microporosity hinders grain growth in the solidification process. This microporosity generates because nano particles are not distributed well inside the composite (Onat *et al.*, 2007).

Table 1. Al 2024 composition

Element	Cu	Mg	Mn	Si	Fe	Others, total
Composition on literature (wt%)	3.8-4.9	1.2-1.8	0.3-0.9	Max 0.5	Max 0.5	Max 0.15
Composition on the present work (wt%)	4.3	1.55	0.7	0.4	0.32	0.25

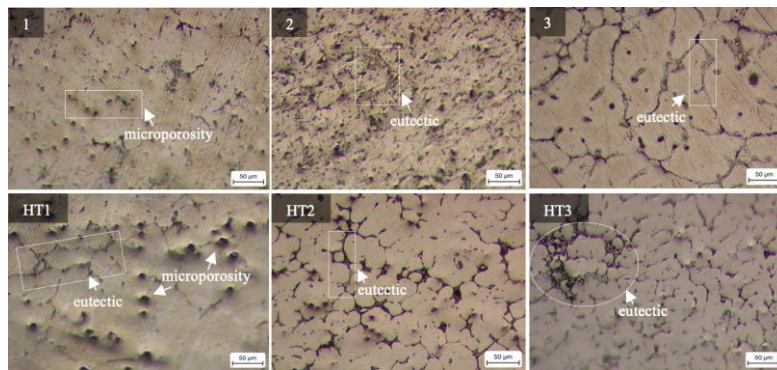


Figure 1. Microstructure of composite plate 1, 2, 3, HT1, HT2, and HT3 (50X magnification)

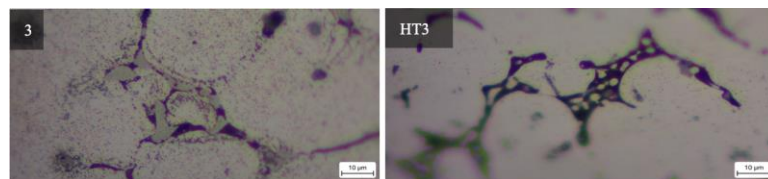


Figure 2. Comparison of eutectic phase from non-treated and heat-treated samples

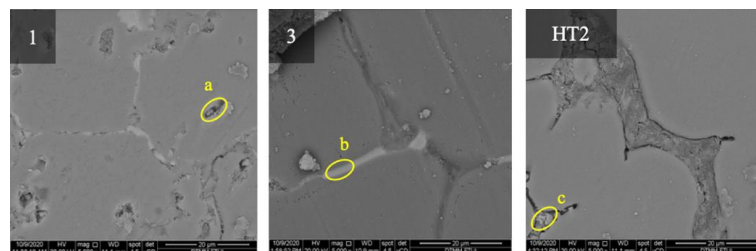


Figure 3. SEM of plate 1, 3, and HT2 (5000x magnification)

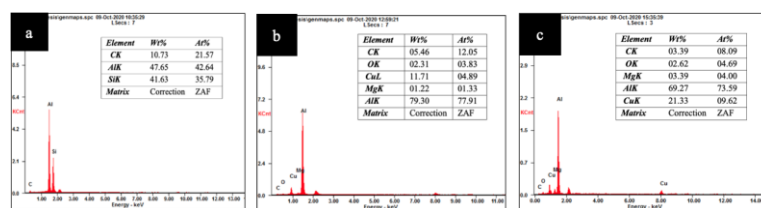


Figure 4. EDS in area a, b, and c

In squeeze casting, the smaller grains are the result of accelerating solidification. If the particles are not well distributed, a space will be created during solidification and later becomes microporosity (Onat *et al.*, 2007).

In retrospect, heat-treated samples with more SiC content have finer grains. The area around the reinforcement particles acts as a heterogeneous nucleation agent that helps the nucleation of precipitate and hinders grain growth (Pérez-

Bustamante *et al.*, 2017). In addition, the eutectic phase is dissolved in the solution treatment process and slowly grows when heated in artificial aging, making the eutectic phase finer. This finer eutectic phase is seen in Figure 2 above. The content of the eutectic phase and the microporosity of the samples is observed by SEM-EDS, as shown in Figures 3 and 4.

Figure 4 shows the EDS of areas a, b, and c in Figure 3. Based on Figure 4(a), the phases on

microporosity in plate 1 are Al_4C_3 , Al, Si, and SiC. The Al_4C_3 surrounding SiC particles will decrease the composite strength and increase the brittleness of the matrix (Bao *et al.*, 2011). If they contact water vapor, this phase will react with moisture (corrosion) to form $\text{Al}(\text{OH})_3$. The volume change caused by this phenomenon will invite segregation inside the composite and creates microporosity (Ortega-Celaya *et al.*, 2007). Figures 4(b) and 4(c) show Al, Cu, and Mg elements, which we can assume that the eutectic phase was formed by the Al_2Cu (θ) or Al_2CuMg (S) phase. Other elements, such as C and O, may be present from stir casting or impurities in the matrix.

The Mg content on the heat-treated sample is higher than the non-treated one. This is because of the artificial aging process that nucleates and grows precipitate. This precipitate is usually found around SiC particles because of the increase of strain energy in these areas (Wąsik *et al.*, 2020). Furthermore, there is a big difference in the coefficient of thermal expansion (CTE) between matrix ($24 \times 10^{-6}/\text{K}$ for Al) and reinforcement ($4.3 \times 10^{-6}/\text{K}$ for SiC). The temperature changes during the solution treatment process can generate thermal stresses in the aluminum matrix (Reddy *et al.*, 2017). These stresses can be partially released by producing dislocation in the interface, which acts as heterogeneous nucleation sites on the interface in the aging process (Wąsik *et al.*, 2020).

The density of the composite plates is shown in Figure 5. Overall, the density of the composite is lower than the density of the matrix Al 2024 (2.77 g/cm^3). The lower number is caused by the effect of

the lower-density alloying elements such as magnesium (1.74 gr/cm^3) (Wahyuningtyas *et al.*, 2019). In the non-heat-treated samples, the addition of SiC particles generally increases the density. The lower density is due to microporosity within the plate, as shown in Figure 1. However, in heat-treated samples, this is not the case. The free vacancies around the reinforcement particles that formed in the heat treatment process lowers the density of composite plates. The void on the matrix-reinforcement interface will eliminate dislocation and heterogeneous nucleation sites in that area, hence slowing the precipitate forming process.

Results and Analysis of Ballistic Testing

In this research, the non-treated samples were only tested with the Type II NIJ test, while heat-treated samples were tested with the Type III NIJ test before being tested with Type II NIJ. The macro deformation, penetration depth, as well as fractography from the ballistic impact, were observed. Table 2 shows the result of the ballistic test.

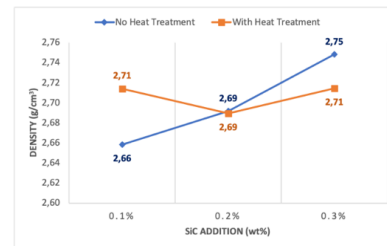


Figure 5. Density comparison of the composite plates

Table 2. Result of ballistic testing

Sample	Testing Bullet	Bullet Mass (g)	Speed (m/s)	Testing Results	Penetration Depth (mm)	Protection	Testing Standard
1	9 mm (Pistol Parabellum)	7,5	380	Bullet casing stuck inside; Deformation with perforation and crack on the exit	19.8; addition from initial thickness (16.3 mm)	Protective	Type II NIJ
2				Deformation with perforation	6.9		
3				Deformation with small perforation and crack on the side to the exit	3.75		
H1				Deformation with small perforation	4.6	Protective	
H2				Crater with smooth surface	1.2		
H3				Crater with rough surface	4.05		
H1	MU5-TJ (5.56 mm)	12,35	915	Deformation with perforation; Penetration complete	-	Non-Protective	Typel III NIJ
H2	PINDAD			Sample divided to more than two pieces; Penetration complete	-		
H3				Sample divided to two pieces; Penetration complete	-		

Note. Target range : 20 m.

Test angle (from horizontal line) : 90°.

Bullet speed is based on specification of testing gun and testing bullet.

In Table 2, deformation with perforation and crater is found at the entrance of the bullet. These deformations can show the hardness of the material in comparison to the hardness of the bullet (National Research Council, 2011). Deformation with perforation emerged when the plate is relatively softer. This deformation has a homogeneous plastic flow and little damage, which is observed in plates 1, 2, 3, and HT1. If the plate is relatively harder than the bullet, the plate will have shear banding and spallation deformation, which is observed in plates HT2 and HT3. The spallation is caused by a stress wave from the back of the plate as the bullet hits the plate. This stress wave can generate enough stress to nucleate, grow, and join voids as well as microcrack to create spallation. The deformation on the entrance of the bullet penetration and comparison of penetration depth can be seen in Figures 6 and 7.

Aside from the deformation on the entrance of the penetration, other macro deformations are observed. On the non-heated plates (plates 1 and 3), cracks were found on the back and side of the plate, as shown in Figure 8. Figure 8(a) shows crack propagating in all directions in the back of plate 1. This deformation is caused by the interaction of the plate with the bullet. Figures 8(b) and 8(c) show a crack propagating in only one direction. This suggests the deformation is caused by the impact stress and the microstructure of the composite, where voids and microcracks connected made a macro crack.

The heat-treated samples were shot twice, each with unique deformation. Figure 9 shows the macro deformation of the heat treatment samples, whereas Figure 10 shows the SEM observation of the fractography from each shooting.



Figure 6. Ballistic resistance mark, from the deepest penetration (upper left) to the most shallow penetration (bottom right)

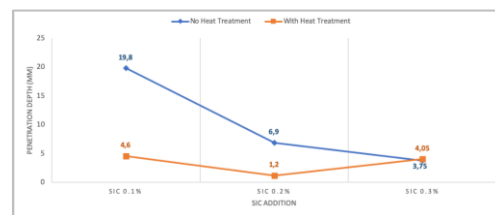


Figure 7. Comparison of ballistic penetration depth



Figure 8. Macro deformation of (a) the back of plate 1, (b) the back of plate 3, and (c) the side of plate 3

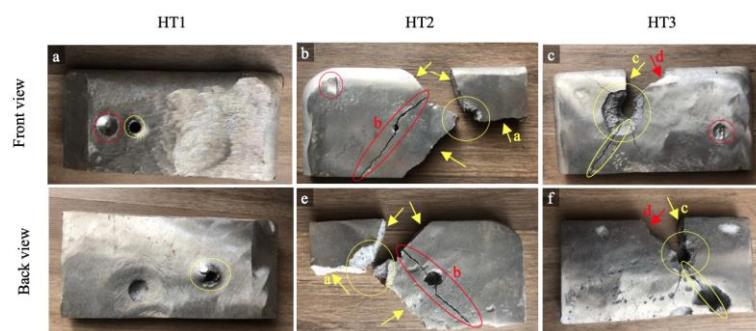


Figure 9. Macro deformation of heat-treated plate. Yellow circle marks the deformation of first shooting (Type III NIJ) and red circle marks the deformation from the second shooting (Type II NIJ)

Based on Figure 9, plate HT1 has perforation and minimum deformation on both of the shootings, indicating the plate is too soft for these ballistic threats. Plate HT2 and HT3 have deformations with the same characteristics on the first (Type III) shooting: crater on the penetration entrance and sample split into pieces. The crater indicates that the plate was relatively harder than the bullet, while the split indicates the plate cannot withstand the impact stress wave. Overall, plate HT2 had a bigger crater and more deformation than plate HT3, indicating plate HT3 had the best ballistic resistance performance.

On the second shooting (Type II NIJ), the plate split in a different region than the bullet penetration area: on the first shooting area, marked by red circles and arrows in Figure 9. The comparison of the fractography from the first and second shooting of plate HT2 and HT3 is shown in Figure 10. Figures 10(a) and 10(c) show the fracture from the first shooting, both with a more uneven surface than the second shooting. Figures 10(b) and 10(d) mostly consist of intergranular failure with voids and particle fallout. This suggests that the failure came from impact stress. Figure 10(b) shows traces of microvoids from matrix-reinforcement decohesion. Figure 10(c) shows traces of microvoids connected to one direction.

Results and Analysis of Hardness and Impact Testing

From this research, the resulting data are the microhardness of the eutectic phase and the impact value of the material.

Figure 11 showed the addition of SiC hardly increased the hardness, while heat treatment raised the hardness significantly. This corresponds to the

formation of high dislocation density area around the reinforcement particle (Pal *et al.*, 2008). The higher content of SiC on the heat-treated sample, the more dislocation density area and the precipitate formed, which increase its hardness. Both SiC addition and heat treatment lower the impact energy. The reduction of impact toughness is caused by SiC particles that act as a stress concentration point. This is due to the uneven distribution of the particles. Furthermore, the agglomeration of particles can be separated easily with impact loading. The SEM observation of impact samples fractography is shown in Figure 12.

The deformation shown on the Charpy test is similar to the deformation from the second shooting. Most of the failure is intergranular and

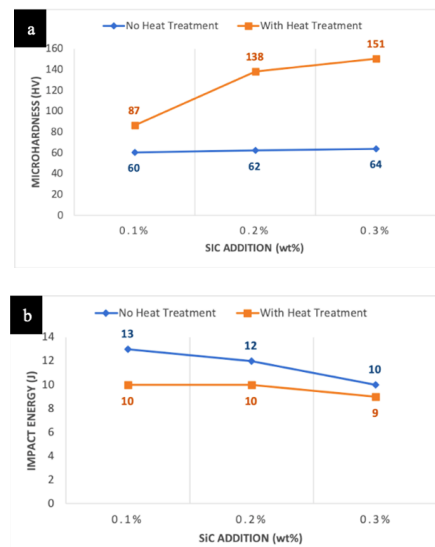


Figure 11. Comparison of (a) microhardness of grain boundary and (b) impact energy of the composite plates

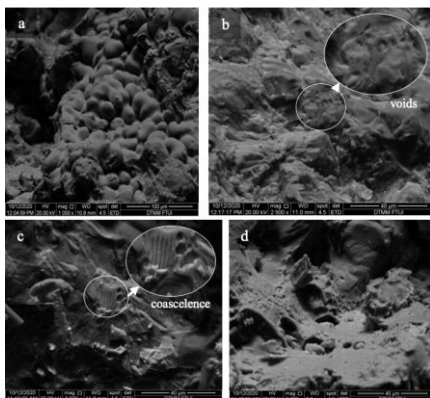


Figure 10. SEM observation of heat treated samples; deformation from ballistic test of the (a) HT2 first shooting, (b) HT2 second shooting, (c) HT3 first shooting, and (d) HT3 second shooting

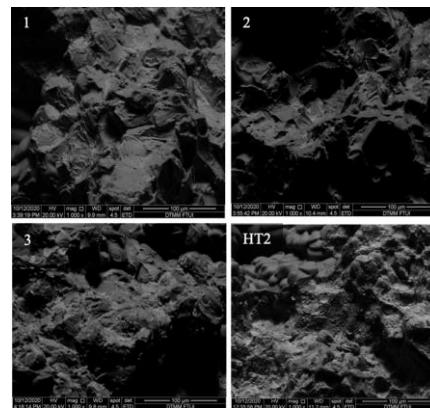


Figure 12. SEM images of charpy test fractography of plate 1, 2, 3, and HT2

there is void nucleation around the particles. The failure mechanism occurred in the areas with agglomeration particles and weak matrix-particles interface which was similar to the previous work (Ozden *et al.*, 2007). In these areas, the distance between particles is narrow enough to facilitate void or microcrack coalescence around the particles. Hence, the crack is formed in all directions.

Conclusions

- Composite plate HT3 has the best ballistic resistance. Plate HT3 has the highest hardness and the littlest deformation on Type II and Type III NIJ standards.
- The addition of reinforcement particles hardly affects its hardness and impact energy, as it only increases 3% hardness and lowers 12% of impact energy with the addition of 0.1 wt% SiC particles. With more particles, the plate have a more refined grain boundaries and a larger eutectic phase.
- Heat treatment increases the hardness but lowers the impact energy. On average, the hardness increased 101% and the impact energy lowers by 20% from plates with the same SiC content. The plate had a more homogenized and finer grain as well as a bigger yet finer eutectic phase.
- All samples can withstand the Type II NIJ Test, but not Type III NIJ. Plate 1, 2, 3, and HT1 show perforation while plate HT2 and HT3 show a crater on the entrance of the penetration.

Acknowledgements

Authors would like to thank Directorate of Research and Community Services (DRPM), Universitas Indonesia for financial support through International Publications Index (PUTI) Proceeding, 2020 with contract number: NKB-1084/UN2.RST/HKP.05.00/2020.

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