

EFFECT OF NANO PARTICLE Al_2O_3 ADDITION AND HEAT TREATMENT TO PROPERTIES OF SQUEEZE CASTED COMPOSITE AL2024/ Al_2O_3 FOR BALLISTIC APPLICATION

Tantiarini and Anne Zulfia Syahrial*

Received: February 10, 2021; Revised: April 03, 2021; Accepted: April 12, 2021

Abstract

The new lightweight material with high strength and adequate ballistic protection was needed in a ballistic application. Metal Matrix Composite (MMC) was produced to achieve those criteria to replace high-density steel. In this research, MMC with Al2024 as the matrix was produced. The Nano particle of Al_2O_3 was added as the reinforcement, and the composite was made with the squeeze casting method. One of every sample of Al2024/ Al_2O_3 composite with different compositions of Al_2O_3 was heat-treated before a ballistic test tested all the samples. The results showed that the sample with the best ballistic protection was the heat-treated sample with 0, 2% Al_2O_3 . The balance number of hardness, UTS, and impact energy resulted in this excellent ballistic protection. Al_2O_3 and heat treatment's addition increased the composite's hardness and UTS until the optimum point because of the strengthening effect of the reinforcement particle and precipitation. However, the impact of energy decreased with the addition of Al_2O_3 and heat treatment.

Keywords: Al_2O_3 ; ballistic protection; Metal Matrix Composite (MMC); squeeze casting

Introduction

The development of light armor material for ballistic-resistant vehicles leads to the development of composite technology as ballistic resistant material. Composite is a material that combines two or more kinds of materials with different characteristics to make a whole new better characteristic. One of the most common composites that used to be ballistic resistant material is composite with aluminum matrix. Aluminum is a light-weighted material that has excellent corrosion resistance and formability. Ceramic reinforcement is added to the matrix to increase the

mechanical properties of the composite. Ceramic is a complex and brittle material that has high compressive strength but relatively low tensile strength. Al_2O_3 is one of the most used ceramics to make ballistic resistant materials because of its excellent mechanical properties and affordable price compared to other reinforcement materials such as B_4C , SiC, and TiC (Zoran and Biljana, 2003).

Besides the composition, the composite production method is also an essential factor in defining the mechanical properties. Squeeze Casting is a casting method combining the benefits

Department of Metallurgy and Material Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI, Depok 16424, West Java, Indonesia. Tel.: +62-812-901-7857. E-mail: zulfiaanne@gmail.com; anne@metal.ui.ac.id

* Corresponding author

of High Pressure Die Casting and Forging (Stone, 1994). Heat Treatment is also applied in addition to Squeeze Casting. This Heat Treatment T6 consists of Solution Treatment, Quenching, and Aging to obtain better mechanical properties. A well-balanced combination of matrix, reinforcement, and the proper production process is applied to produce a composite with excellent ballistic resistance and high mechanical properties.

Materials and Method

Materials

The best aluminum used as a composite is aluminum with the 2XXX and 7XXX series because heat treatment can be done on this type of aluminum (Magno *et al.*, 2017). Aluminum-copper alloys or 2XXX series produce properties that are hard and strong but brittle. Generally, the alloy should not have a copper concentration above 5.6% for forging purposes because it will form a CuAl_2 compound throughout the metal that makes the metal brittle. The type of aluminum 2XXX series used is Aluminum 2024. Aluminum 2024 is aluminum that can be heat treated with the primary alloying element in the form of copper. Meanwhile, the complete composition of Aluminum 2024 can be seen in Table 1. This type of aluminum has a high strength-to-weight ratio and good fatigue strength.

Meanwhile, for the reinforcement, nano particle Alumina is used. Alumina, also known as aluminum oxide, is a white (nearly transparent) substance used as a starting material for smelting aluminum metal. Also, Al_2O_3 is widely used as a base for advanced ceramic products and active agents in chemical processes. Free Al_2O_3 in nature is obtained from bauxite seeds and naturally contains water in them. Al_2O_3 has excellent mechanical properties for use as a reinforcement material, with high hardness (Vickers 2000 GPa) and modulus of elasticity (380 GPa). With low density, the addition of Al_2O_3 will keep the material light.

Fabrication Method

As shown in the table above, the materials are prepared for each variation of samples before the casting process. Two samples of each variation were made; one of the samples will get heat treated when another one directs to the characterization. This process is started with the melting of Al2024

ingot at 850°C in Furnace. At the same time, the powder of Al_2O_3 is vibrated by Ultrasonic Stirrer to prevent agglomeration. After that, Al_2O_3 is pre-heating at 900°C in the Muffle Furnace. When both matrix and reinforcement are heated, the dies made by steel are also heat-treated until 350°C . After the material preparation, the pre-heated Al_2O_3 is poured into the molten Al2024. The stirring technique is used for mixing them at 500 rpm in 2 min. The process is then proceeded with degassing to eliminate the excess gas with 5atm Argon within 1 min. After mixing well, the molten composite is poured to $15 \times 15 \times 1,5$ cm dies before being pressed by the hydraulic press with 2 tons pressure in 2 min. The solid composite is taken out from the dies once it has cooled.

The finished samples are heated at a solid-solution temperature of 495°C with a holding time of 2 h in the Muffle Furnace. After that, the process continued with quenching using water for 2 min in a metal container. The process was continued after removing the sample from the quenching container by Aging at 100°C for 1 h in the Muffle Furnace. The heat treatment diagram can be seen in Figure 1.

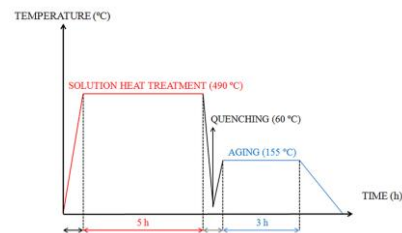


Figure 1. Diagram of T6 Heat Treatment (Pérez-Bustamante *et al.*, 2017)

Characterization

After all these stages of the process, the composite sample is then characterized by several tests. The tests include microstructural observations with light microscopy, OM, and TEM, Brinell hardness testing, tensile testing, impact testing, and type II ballistics testing.

Results and Discussion

Microstructure of Al2024/nano Al_2O_3 Reinforced Composites

The microstructure observation is conducted by optical microscope, SEM, and SEM-EDS.

Table 1. Composition of Al2024 used

Element	Cu	Mg	Mn	Fe	Mn	Si	Zn	Ti	Cr	Al
% weight	4.30	1.56	0.70	0.32	0.70	0.40	0.10	0.10	0.05	Equivalent

Figure 2 below shows the observance of samples with 0.1% and 0.3% Al_2O_3 without heat treatment. A sample with a larger amount of Al_2O_3 has a smaller grain size. The nucleation of the precipitate causes this reduction of grain size by Al_2O_3 in the matrix (Pérez-Bustamante *et al.*, 2017). Smaller grain sizes will affect the mechanical properties of the composite to have better strength. However, with the increase of Al_2O_3 , the possibility of agglomeration will increase.

The SEM-EDS observation in Figure 3 shows large, irregular eutectic phase and intermetallic particles in the grain boundary of non-heat-treated samples. The two different phases can also be seen in the grain boundary. The dark region shows similar stoichiometries with Al_2CuMg or S phase in Figures 4(a) and 4(b). Meanwhile, the light region in Figures 4(c) and 4(d) can be identified as Al_2Cu or Θ phase.

After the T6 Heat Treatment, more precipitations are formed in the grain boundary, as shown in Figure 4. In addition, there is no significant increase in grain size because the accumulation of particles of Al_2O_3 in the grain boundary will prevent grain growth. The combination of precipitation and small grain size gives a better result of mechanical properties. SEM-EDS was used to examine these samples. From all three different areas tested in Figure 5, all areas show a similar composition that can be identified as three different main phases: Al_2Cu , Al_2CuMg , and MgAl_2O_4 which shows that the intermetallic phases are formed more after heat treatment. Meanwhile, a small amount of Si found can be identified as the Mg_2Si phase.

Density of Al2024/nano Al_2O_3 Reinforced Composites

Figure 6 shows the results of density testing for all types of samples. It is possible to conclude that the addition of Al_2O_3 relatively decreases the composite density by a slight difference from the original weight of Al2024 (2.77 kg/m^3). This condition can occur because the vacancy might have developed around the Al_2O_3 particles that agglomerated. It also shows that Samples with HT have higher density and have more stable density even in different compositions of Al_2O_3 . However, the difference in Al_2O_3 component and treatment doesn't affect the density because all the samples' density is neither much nor less than 2.7 kg/m^3 . After all, the vacancies formed in the heat treatment process are lower than without the heat treatment.

Hardness of Al2024/nano Al_2O_3 Reinforced Composites

The result of hardness is shown in Figure 7, the hardness increase with higher of Al_2O_3 addition.

This increase in hardness can occur due to several things:

- The hardness of Al_2O_3 also increases the hardness of the composite. Where other studies found the hardness reached 1175 HB.
- The use of nano-sized Al_2O_3 the potential of porosity formation and increases the even distribution by increasing hardness.
- Al_2O_3 acts as a barrier when loads are applied to the composite (Thostenson *et al.*, 2005; Sajjadi *et al.*, 2011).

After T6 heat treatment, each stage will improve the hardness of the composite. In Solution

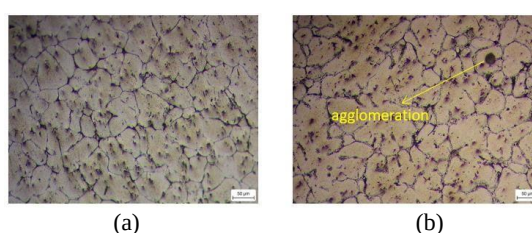


Figure 2. Microstructure of (a) 0.1% Al_2O_3 and (b) 0.3% Al_2O_3 Al2024/ Al_2O_3 composite

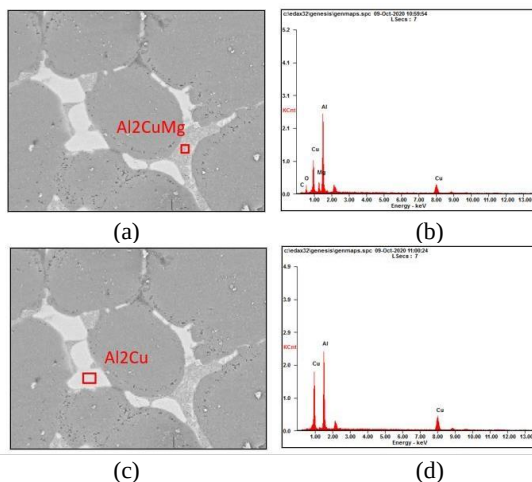


Figure 3. SEM-EDS of Al2024/ Al_2O_3 composite without heat treatment, (a) (b) 0.1 wt% Al_2O_3 and (c) (d) 0.3 wt% Al_2O_3

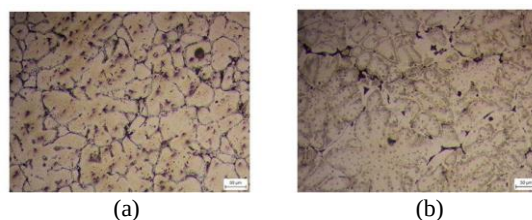


Figure 4. Microstructure of Composites with 0.3 wt% Al_2O_3 without HT (a) and with HT (b)

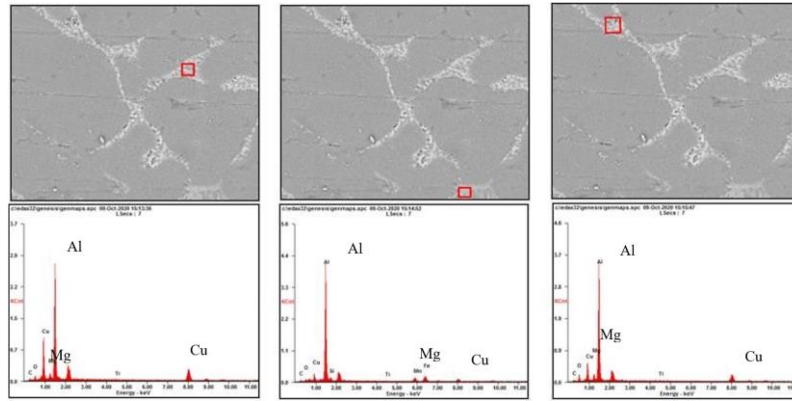


Figure 5. SEM-EDS of Al2024/Al₂O₃ composite without heat treatment in three different areas

Treatment, hardness increases due to Thermal Mismatch (Zhang *et al.*, 2019). Differences in thermal expansion coefficients are the primary cause of increasing hardness mismatch, where Al₂O₃ has a thermal expansion coefficient of 7.8 $\mu\text{m mK}^{-1}$ and an aluminum matrix of 2024 of 23.2 $\mu\text{m mK}^{-1}$. New dislocations are formed due to this Thermal Mis Al₂O₃ match and react with other dislocations that have previously existed, causing dislocation movement to be obstructed (Sankaranarayanan *et al.*, 2011; Zhibo *et al.*, 2014). Increasing the dislocation density also increases the hardness of the composite. A strong bond between the matrix and the reinforcement also contributes to the rise in dislocation density. In addition, grain boundary strengthening also contributes to the increase of hardness based on the Hall-Petch Formula (Equation 1) that said the smaller the grain size, the strength would increase. The phase of precipitation Al₂Cu and Al₂CuMg also affect the hardness, the coherent and semi-coherent phase that includes the GP Zone, θ'' , θ' , S'' , and S' phases give better hardness because these phases hold the movement of dislocations. On the other side, Super Saturated Solid Solution and incoherent phase show lower hardness.

$$\sigma_y = \sigma_0 + \frac{k_y}{\sqrt{d}} \quad (1)$$

Impact Energy of Al2024/nano Al₂O₃ Reinforced Composites

Figure 8 shows that the addition of Al₂O₃ does not provide a significant change in the impact strength of the composite. Even as the Al₂O₃ composition increases, the impact strength tends to decrease. This decrease caused by Al₂O₃ acts as an area of stress concentration when impact loads are applied. Also, the increasing amount of Al₂O₃ dispersion in the matrix can cause clusters

formation, which will decrease the strong bond between the reinforcement and the matrix. Same with aging temperature, the figure shows that

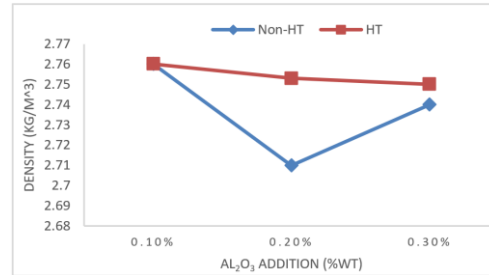


Figure 6. Density of Al2024/Al₂O₃ composite

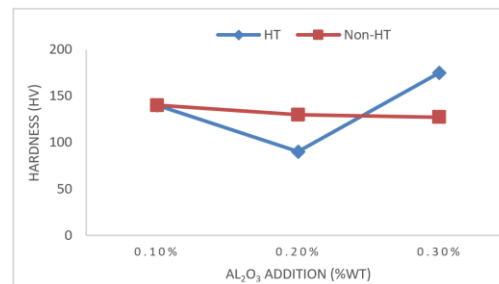


Figure 7. Hardness of Al2024/Al₂O₃ composite

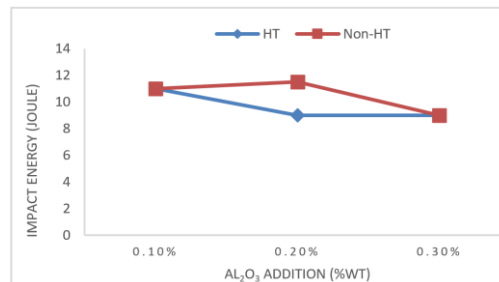


Figure 8. Impact Energy of Al2024/Al₂O₃ composite

composites without aging or with low aging temperatures have a better impact strength than composites with high aging times. This increase of impact strength is because, at lower temperatures, there is a more uniform distribution of the intermetallic phase, and the grain is finer during secondary precipitation (Shanmugam and Sahadevan, 2018). Whereas at higher temperatures, the grain of the intermetallic phase is coarser.

Ballistic Resistance

Ballistic testing is carried out with a 9 mm projectile at the distance of 20 m following the Level II Ballistic Test standards. The penetration and fracture of samples that have undergone ballistic testing are next analyzed. The surface of the shot can be seen in Figure 9 of unheated-treated samples and Figure 10 of heat-treated samples. The only resistant sample is the sample with 0.2% Al_2O_3 and heat treatment that only shows short indentation without crack or porosity.

The propagation of cracks at the ballistic testing results occurs at matrix material and interphase boundaries. The strength of the matrix can be described as the strength of the matrix atoms to remain bonded even when external loads are applied. The crack occurs when two atoms separate because the external load they receive is greater than the attractive force between them (Kvande, 2011). Also in some plates, the porosity those formed on the plate become where the crack initiation took place.

Conclusions

- The addition of Al_2O_3 and HT increased the hardness of the composite up to 125%. However, agglomeration and porosity in the higher composition of Al_2O_3 could decrease it. Sample of 0.3 wt% Al_2O_3 without HT had the highest hardness.
- The addition of Al_2O_3 and HT decreased the impact energy of composite up to 18%. Sample of 0.1 wt% Al_2O_3 with and without HT had the highest impact energy.
- Sample with 0.2 wt% Al_2O_3 and HT showed the best result in ballistic resistance due to its balance number of mechanical properties.

Acknowledgements

Authors would like to thank The Deputy for Research Strengthening and Development, Ministry of Research and Technology / National Research and Innovation Agency for financial support under

KRUPT Grant with contract number: NKB-5/UN2.RST/HKP.05.00/2020.

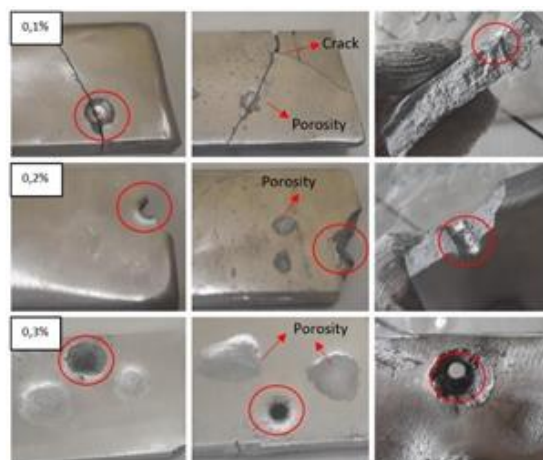


Figure 9. Macrostructure of $\text{Al2024}/\text{Al}_2\text{O}_3$ without heat treatment composite were ballistic tested with different of wt% of Al_2O_3 a) 0,1%, b) 0 ,2%, dan c) 0,3%

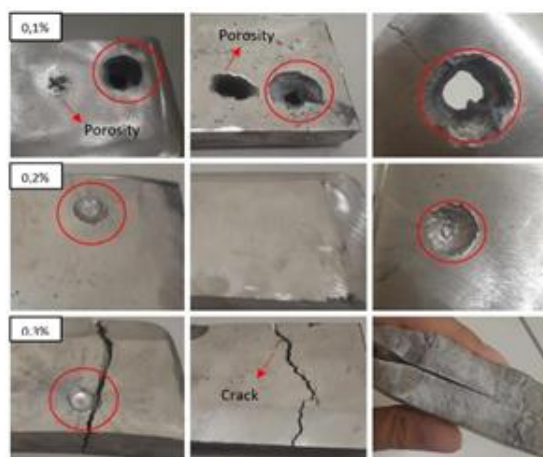


Figure 10. Macrostructure of $\text{Al2024}/\text{Al}_2\text{O}_3$ with heat treatment composite were ballistic tested with wt% of Al_2O_3 a) 0,1%, b) 0,2%, dan c) 0.3%

References

- Kvande, H. (2011). Production of primary aluminium. In: fundamentals of aluminium metallurgy (Production, Processing and Applications). Woodhead Publishing Series in Metals and Surface Engineering. p. 49.
- Magno, I., Souza, F., Barros, A., Costa, M., Nascimento, J., Costa, T., and Rocha, O. (2017). Effect of the T6 heat treatment on microhardness of a directionally solidified aluminum-based 319 alloy. *Mat. Res.*, 10.1590/1980-5373-mr-2016-0961.

- Pérez-Bustamante, R., Pérez-Bustamante, F., Maldonado-Orozco, M.C., and Martínez-Sánchez, R. (2017) The effect of heat treatment on microstructure evolution in artificially aged carbon nanotube/Al2024 composites synthesized by mechanical alloying. *Mat. Charact.*, 126:28-34. doi:10.1016/J.MATCHAR.2017.01.006.
- Sajjadi, S.A., Ezatpour, H.R., and Beygi, H. (2011). Microstructure and mechanical properties of Al-Al₂O₃ micro and nano composites fabricated by stircasting, *J. Mat. Sci. Engg. A.*, 528:8,765-8,771.
- Sankaranarayanan, S., Jayalakshmi, S., and Gupta, M. (2011). Effect of addition of mutually soluble and insoluble metallic elements on the microstructure, tensile and compressive properties of pure magnesium, *Materials Science and Engineering: A.*, 530:149-160, <https://doi.org/10.1016/j.msea.2011.09.066>.
- Shanmugam, K. and Sahadevan, R. (2018). Bioceramics-An introductory overview. 10.1016/B978-0-08-102203 0.00001-9.
- Stone, G. (1994). Projectile Penetration into Representative Targets. Sandia National Laboratories Sandia Report SAND94-1490. USA.
- Thostenson, E.T., Li, C., and Chou, T.W. (2005) Review nano composites in context, *J. Com. Sci. Tech.*, 65:491-516.
- Zhang, P.-X., Yan, H., Liu, W., Zou, X.-L., and Tang, B.-B. (2019). Effect of T6 heat treatment on microstructure and hardness of nanosized Al₂O₃ reinforced 7075 aluminum matrix composites. *Metals.*, 9(1):44. <https://doi.org/10.3390/met9010044>
- Zhibo, L., Ke, Z., Yiguang, W., and Linan, A. (2014). Thermal expansion of al matrix composites reinforced with hybrid micro-/nano-sized Al₂O₃ particles. *J. Mat. Sci. Technol.*, 30(1):61-64. <https://doi.org/10.1016/j.jmst.2013.04.022>.
- Zoran, O., and Biljan, B. (2003). Ballistic protection efficiency of composite ceramics/ metal armours. *Scientific-Technical Review*, LIII(3).