Effect of Nano Al_20_3 Addition and T6 Heat Treatment on Characteristics of AA 7075 / Al_20_3 Composite Fabricated by Squeeze Casting Method for Ballistic Application

Miqdad, Muhammad
Department of Metallurgical and Materials Engineering, Universitas Indonesia

Anne Zulfia Syahrial
Department of Metallurgical and Materials Engineering, Universitas Indonesia

https://doi.org/10.5109/4794184

出版情報：Evergreen. 9 (2), pp.531-537, 2022-06. 九州大学グリーンテクノロジー研究教育センター
バージョン：

Effect of Nano Al_2O_3 Addition and T6 Heat Treatment on Characteristics of AA 7075 / Al_2O_3 Composite Fabricated by Squeeze Casting Method for Ballistic Application

Muhammad Miqdad, Anne Zulfia Syahrial*
Department of Metallurgical and Materials Engineering, Universitas Indonesia

*E-mail: anne@metal.ui.ac.id

(Received February 11, 2022; Revised June 20, 2022; accepted June 20, 2022).

Abstract: Aluminum alloy AA 7075 majorly consists of Zinc and Magnesium, and it has been known as an alloy with high strength and ability to be heat treated. In regard to that, AA 7075 alloy was investigated to determine its application in military vehicles that require high protection and great mobility capabilities. The addition of Al_2O_3 can be done to improve the mechanical properties of the material such as hardness and impact toughness that is related to the protective ability of the material. This research was conducted to determine the effect of adding nano Al2O3 and heat treatment on the ballistic resistance of composite plates. The composites were fabricated by the squeeze casting method followed by heat treatment of T6 at 470 °C for two hours, water quench, and artificial aging at 120 °C for one hour. The reinforcement of nano Al_2O_3 is added to the melted aluminum alloy when the fabrication process takes place as much as 0.1, 0.2, 0.3 wt%. Furthermore, the composite plate was tested by ballistic testing Type II and III according to NIJ standard. Other characterizations were also carried out on the samples such as microstructural observations and hardness testing. The results of the characterization have found that all samples have protective ability in Type II ballistic testing but do not have protective ability in Type III ballistic testing. The addition of reinforcing particles affects the value of the hardness of composite material. Heat treatment increases the hardness value, impacts toughness value, and penetration trace in ballistic testing which has a direct relationship to microstructural changes that occur during the heat treatment process.

Keywords: aluminum composite, AA 7075, Al_2O_3 reinforcement, ballistics, heat treatment, aging

1. Introduction

Armor material or ballistic material is a material that has a high resistance to loading caused by gunfire or explosions of firearms.[1] Along with the development of firearms and bombs technology, this material is increasingly in demand to provide security functions for people whose work involves the use of firearms and bombs such as soldiers, Red Cross workers on the battlefield and also political figures.[2] Armor material can be applied to various fields, ranging from clothing used at work to military vehicles such as tanks or fighter aircraft. In order to achieve the ballistic resistance characteristic, the materials can be engineered to combine every mechanical strength each element has in a form of composite.[3–5]

Aluminum series 7 is a type of aluminum alloy containing 1-8% Zinc as the main alloying element. The addition of Zinc is intended to improve the strength of the alloy with a precipitation hardening method, besides Zinc can also improve the corrosion resistance of an alloy.[6,7] The density of this aluminum alloy is 2.81 g/cm³ (0.102 lb/in³), a relatively light density for metal alloys.[8] The strength of this aluminum alloy comes from a variety of alloying elements whose composition makes this alloy generally used as a structure for aircraft fuselages, military vehicles and various parts that have high stress applications. Reinforcement particle such as ceramic is commonly used to improve mechanical properties in materials. According to past research, the use of Al2O3 (alumina) as the reinforcement particle in composite fabrication has been shown to improve various aspects ranging from hardness, tensile strength, density, and tribological properties of aluminum composites.[9–11]

The fabrication methodology of the composite is an important factor that can determine the final characteristics of the material in addition to its selection of matrix and reinforcement.[12] There are various fabrication methodology that can be used to produced composite, such as (a) solid state processing, (b) liquid state processing, and (c) liquid-solid processing. The traditional method of fabrication including squeeze casting is considered as an attractive fabrication methodology due to its easiness on carrying the process.[13]

2. Materials and Experimental Procedure

2. 1. Materials

The ingot of AA 7075 as matrix and particle of alumina in form of nano powder as reinforcement is purchased commercially and used in the fabrication of the sample. The composition of the AA 7075 based on the mill certificate included during the purchase can be found in Table 1.

Table 1. AA 7075 composition in wt%.

Zn	Mg	Cr	Cu	Mn	Si	Fe	Ti	Al
5.1 – 6.1	2.1 – 2.9	0.18 – 2.8	1.2 – 2.0	0.15	0.4	0.20	0.07	Balance

2. 2. Squeeze Casting and Heat Treatment

The fabrication of the sample comprised of stir casting method followed by squeeze casting. The preparation of aluminum ingot was done by surface cleaning and cutting with a band saw. As the ingots are being melted, the alumina reinforcement was added to the melted aluminum after preheated at 900° C for 1 hour to increase its wettability. The mixture was then stirred for 2 minutes at 500 rpm and degassed with Argon gas for 1 minute before poured at a preheated mold and squeezed by 175 MPa pressure for 2 minutes. The mold has 20x15x1.5 cm in dimension and was preheated to 300 C to avoid thermal shock.

Two samples were prepared for each composition, one to be heat treated and one without any treatment. The heat treatment process began with solution treatment in 470° C for two hours, followed by water quench and artificial aging in 120 C for one hour. The heat-treated sample then cooled with air at room temperature. All of the samples are being kept in the freezer before the characterization process conducted to prevent natural aging. Table 2 shows the codification of samples used in this study.

Table 2. Samples used in this study

Sample	Heat Treatment	Reinforcement
N – As Cast	No	No reinforcement, as cast
N – 1	No	0.1 wt%
N – 2	No	0.2 wt%
N – 3	NO	0.3 wt%
HT – As Cast	Yes	No reinforcement, as cast
HT – 1	Yes	0.1 wt%
HT – 2	Yes	0.2 wt%
HT – 3	Yes	0.3 wt%

2. 3. Characterization of Samples

All samples undergo ballistic resistance tests according to NIJ 0108.01 Standard. The Type III test was carried out first with MU5-TJ (5.56 mm) bullet on air rifle (915 m/s) within 50 m range. The Type II test was carried with a 9 mm parabellum pistol (380 m/s) within 5 m range. The characterization was further done with microstructure observation with Optical Microscope (OM) and hardness test conducted in Hardness Rockwell B.

3. Result and Discussion

3. 1. Microstructure of Composite using OM

Figure 1. shows the results of observation of all samples with an optical microscope. In general, it can be seen that the increase in the weight variation of the reinforcement has an impact on the grain boundaries and the eutectic phase. The greater the variation in the weight of the reinforcement, the finer the grain boundaries and the larger the eutectic phase.[14)] In addition, in the heat-treated samples, it can be seen that the eutectic phase dissolves into the matrix and only a few insoluble phases are left behind. Figure 1. also shows the change in grain boundaries in the heat-treated sample. If the microstructure of the samples with heat treatment and without heat treatment are compared, it will be found that the eutectic phase in the heat-treated samples is dissolved with an aluminum matrix. In samples with codes HT – AS CAST and HT – 3, the picture shows the occurrence of micro segregation in $MgZn_2$ in the aluminum matrix while in samples with codes HT – 2 and HT – 1 shows very fine grain boundaries.

The variation of the weight of the Al2O3 reinforcement provides a significant change in the microstructure. The more variations in the reinforcing composition, the finer the grain boundaries and the larger the eutectic phase in the microstructure.[15)] This is caused by the pinning force phenomenon which limits grain growth. When a grain boundary interacts with reinforcing particles, part of the grain boundary will decay from the system if the grain boundary is to move. The decaying part of the grain boundary will cause a decrease in the grain boundary area so that over time the grain boundaries will become smoother.[16)] In addition, reinforcing particles in the composite microstructure can also inhibit the occurrence of dislocation movements in the matrix caused by the difference in the thermal coefficient between the matrix and the reinforcement.[17)]

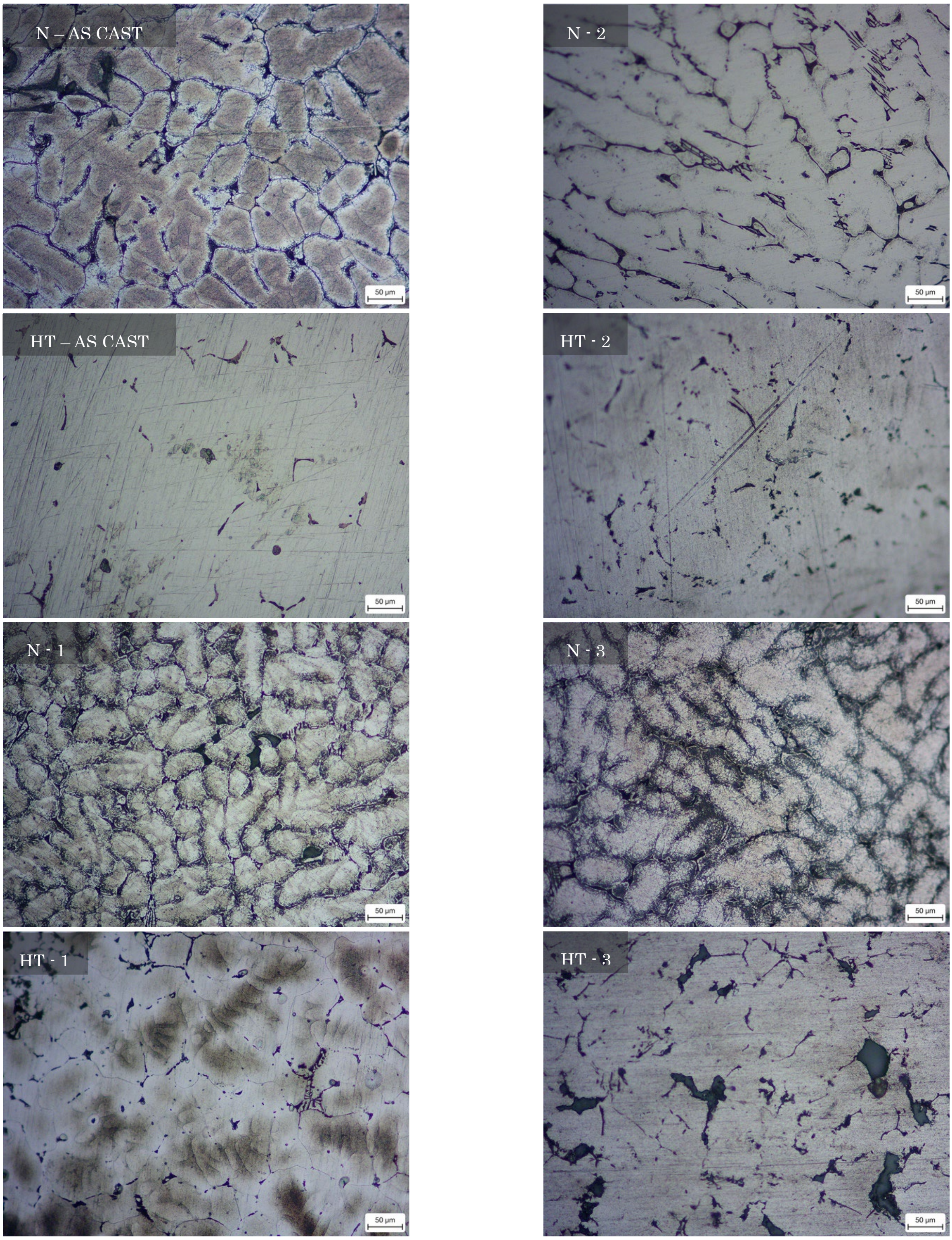


Fig 1. Microstructure observation with optical microscope

3. 2. Hardness Value

Figure 2. shows a comparison diagram of the hard test results on the Al 7075 – Al2O3 composite material sample in Hardness Rockwell B. In general, almost all samples with heat treatment have higher hardness test values than samples that do not undergo heat treatment. The highest

hardness value is obtained by the HT-3 sample with a value of 76.9 HRB which is a sample with reinforcement of 0.3% of the total weight of the sample and is subjected to heat treatment. Meanwhile, the lowest hardness value was obtained by the N – As cast sample of 52.6 HRB which was a sample without reinforcement and did not undergo heat treatment. Furthermore, there was a decrease in the value of hardness in the HT-2 sample which was a sample with a reinforcement of 0.2% of the total weight of the sample and underwent heat treatment.

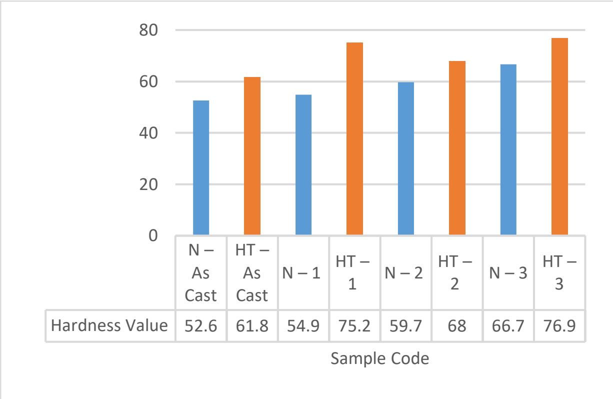


Fig 2. Comparison of the hardness values of composite materials in HRB.

It was found that the greater the variation in the weight of reinforcement, the greater the tendency for a material to increase in its hardness. The continuous increase in hardness values was experienced by samples that were not subjected to heat treatment. Meanwhile, in the heat-treated sample, there was a decrease in the hardness value in the sample with the code HT – 2. According to Zhang et al., the effect of variations in reinforcement weight on the composite hardness value was based on parameters such as reinforcement distribution, shape variations, and reinforcement size variations. The distributed Al2O3np particles also inhibited the grain growth tendency during the heat treatment process.[18] Heat treatment given to a material will also engineer the microstructure that is inside a material.[19] In AA 7075, microstructural evolution will occur when heating causes precipitation on the surface of the material. The presence of these precipitates is the main reason for the increase of hardness in the samples given heat treatment.[20,21] This theory was followed by evidence of an increase in the value of the relative hardness of the whole sample after undergoing heat treatment. The most significant increase in hardness based on the effect of heat treatment was experienced by sample N – 1 whose hardness value to sample HT – 1 increased by ~27%. Concurrently, in the sample N – 2, there was a decrease in the hardness of the HT – 2 sample with a percentage of ~ 4.6%. The improvement of material's hardness can also be affected by the hardness of the reinforcement particle, in which its right wettability result much on enhancing the interfacial reaction. The right amount of interfacial reaction can helped the material reduce its porosity hence the hardness of the material is increased.[22]

3. 3. Result and Analysis of Ballistic Testing

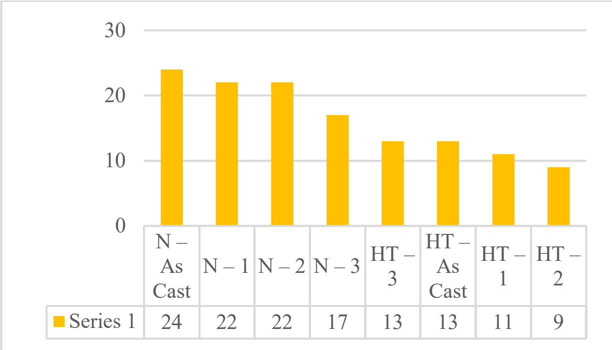
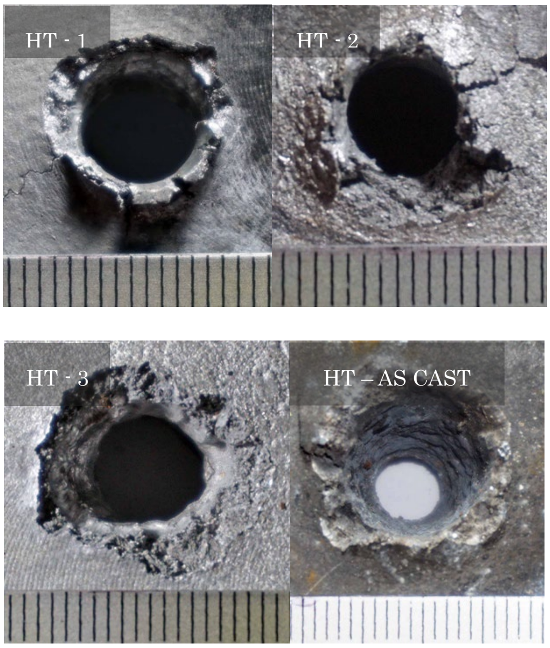


Fig 3. Comparison of diameter of perforation as the result of ballistic test Type III

The Type III ballistic tests give results that leave full penetration of the entire sample without completely deforming the sample. Figure 3 gives the test result along with the comparison of all samples while Figure 4. shows an image of the crater formed in the Type III ballistic tests in all samples. In the samples that were given heat treatment, it can be seen that the shape of the crater left behind tended to be smooth and there were borders like flower petals. Meanwhile, the samples that were not treated with heat showed a larger diameter of the penetration crater along with the deformation of the circumference around the crater. The depth of perforation from this type of test cannot be concluded, as the penetration of the projectile is fully penetrated.



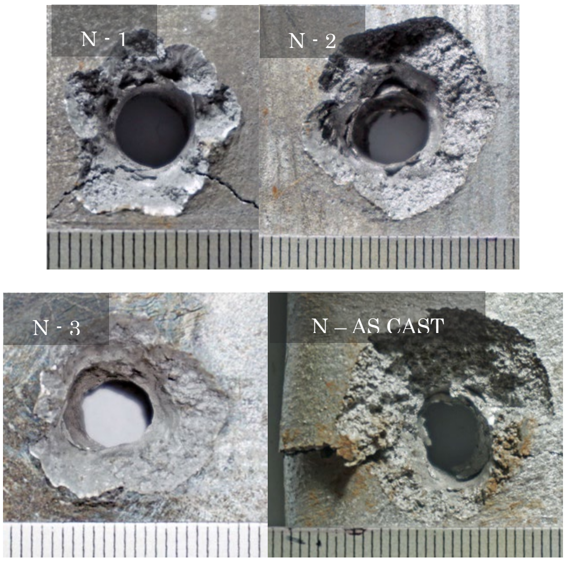


Fig 4. Craters cause by projectile penetration in Type III ballistic testing, presented according to treatment of the samples.

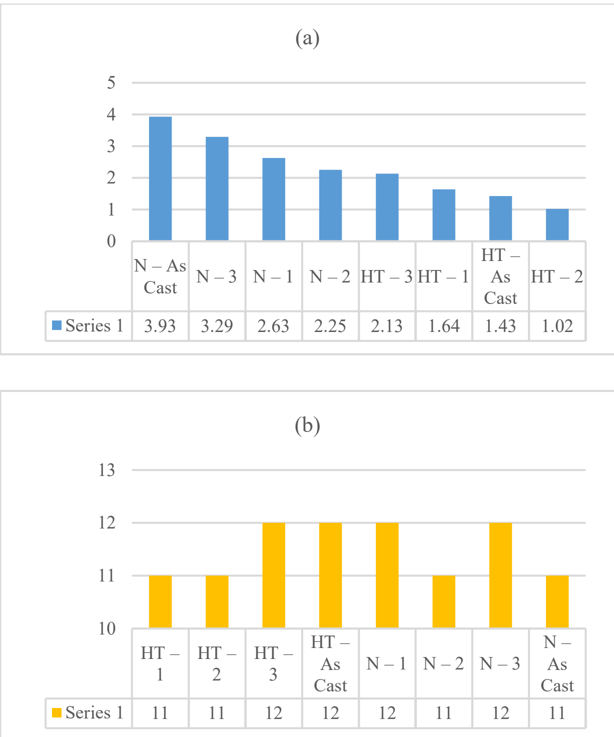


Fig 5. (a) Comparison of depth of penetration and (b) comparison of diameter of perforation from the ballistic test Type II.

Type II ballistic testing was carried out to provide supporting data for Type III ballistic testing. In this ballistic test, none of the samples experienced full penetration; the type of penetration that occurs leaves a crater shape similar to a well and the depth of penetration can be measured. Figure 5. shows the comparison of depth of penetration and diameter of perforation caused by the ballistic Type II. Figure 6. provides an image of the crater left by the penetration of the projectile on the Type II test in all samples. In the heat-treated samples, the penetration depths of the projectiles were not significantly formed. Meanwhile, in samples that were not subjected to heat treatment, the penetration depths of the projectiles were significantly formed. In the sample with the highest weight of reinforcement without undergoing heat treatment, macro cracks that occur cause full deformation so that the sample is divided into two large parts.

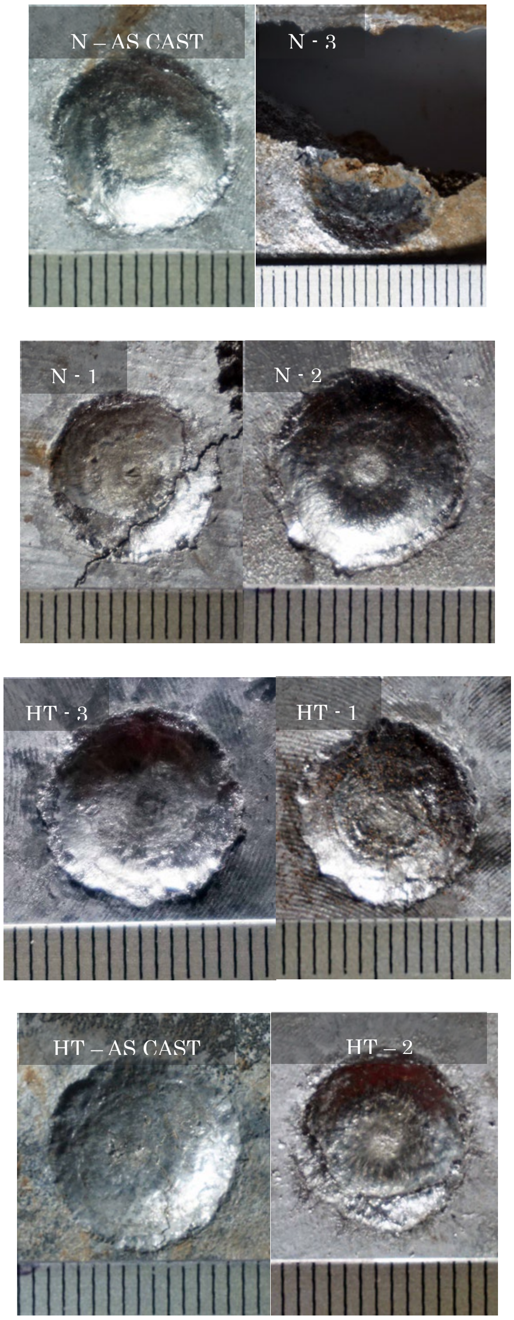


Fig 6. The evolution of the penetration depth of the Type II ballistic test on all samples from the highest to the lowest penetration depth.

The full penetration of the Type III ballistic test is due to the high projectile velocity and the sharp shape of the projectile. However, there is a difference in the shape of the crater from the penetration. When the projectile hits the surface of the sample at a certain speed, the projectile carries a very high impact force on the sample. In this case, a material that has good impact resistance and energy absorption can certainly withstand the force exerted by the velocity of the projectile. The rim around the crater left by projectile penetration is a material response to plastic deformation in a localized area.[23] From the differences in the types of craters, it can be concluded that samples subjected to heat treatment have higher ductility than samples that did not undergo heat treatment. Type II ballistic testing results in various sample penetration depths. This indicates that there are differences in the hardness of the sample. Samples that had not undergone heat treatment have much deeper and more ductile deformation. Furthermore, in samples that were not subjected to heat treatment, there were macro cracks caused by the force received by the sample when the projectile touched the sample surface at a certain speed.

Figure 7. shows the macro cracks on the sample with the highest reinforcing content without undergoing heat treatment. Macro cracks that occur cause full deformation so that the sample is divided into two large parts. The variation of reinforcement weight given at the time of sample fabrication did not have a significant effect on the ballistic resistance of this composite material, but heat treatment had a very significant effect in improving the material's characteristics. The characteristic of the sample found in this research after heat treatment is similar to what has been found in previous study. In the study of the effect of heat treatment T6 to aluminum type 2 composites by Ravanya, it is found that the ballistic resistance of the sample has been tremendously improved on the heat-treated sample.[24] Concurrently, according to Baskoro et al, the heating of the materials can develop the formation of new grain thus the more improved strength of the materials is produced. [25]

Fig 7. Full deformation on non heat-treated sample with 0.3 %wt reinforcement.

4. Conclusion

1. All samples were able to withstand bullet penetration in the NIJ Type II, but not in the NIJ Type III ballistic tests. The heat-treated sample had a shallower depth of penetration than the non-heat-treated sample. Samples that were not subjected to heat treatment experienced macro cracks in the area around the penetration trace. Samples with a weight variation of 0.3% and heat treated are the most optimum samples to withstand the bullet penetration from both tests.

2. Variations in reinforcement levels have an influence on the values of hardness although not significantly increased. Hardness values have a tendency to increase in samples that have not undergone heat treatment. The optimum hardness value is obtained by the sample with 0.3 wt% reinforcement and heat-treated.

3. Heat treatment given to the sample increases the value of hardness and ballistic toughness. In the NIJ Type III ballistic test, a penetration crater was left which tended to be smoother in the heat-treated sample compared to the rougher penetration crater in the non-heat-treated sample.

Acknowledgements

Authors would like to thank Directorate of Research and Community Services (DRPM), Universitas Indonesia for financial support through International Publications Index (PUTI) Q3, 2020 with contract number: NKB-2023/UN2.RST/HKP.05.00/20201.

References

1) I.G. Crouch, "Introduction to armour materials," Elsevier Ltd, 2017. doi:10.1016/b978-0-08-100704-4.00001-3.
2) P.J. Hazell, "ARMOUR: materials, theory, and design," *ARMOUR Mater. Theory, Des.*, (*July 2015*) 1–362 (2015). doi:10.1201/b18683.
3) A. Gupta, H. Kumar, L. Nagdeve, and P.K. Arora, "EDM parametric study of composite materials: a review," *Evergreen*, **7** (*4*) 519–529 (2020). doi:10.5109/4150471.
4) A.K. Srivastava, S.P. Dwivedi, N.K. Maurya, and M. Maurya, "3D visualization and topographical analysis in turning of hybrid mmc by cnc lathe sprint 16tc made of batliboi," *Evergreen*, **7** (*2*) 202–208 (2020). doi:10.5109/4055217.
5) E.A. Chernyshov, I.D. Romanov, and D. Romanov, "Development of ballistic protection from composition material on the basis of aluminum," *Mater. Sci. Forum*, **945 MSF** 350–355 (2018). doi:10.4028/www.scientific.net/MSF.945.350.
6) B. Khan, M.U. Rosli, H. Jahidi, M.I. Ishak, M.S. Zakaria, M.R. Jamalludin, C.Y. Khor, W.M. Faizal,

W.M. Rahim, and M.A.M. Nawi, “Effect of zinc addition on the performance of aluminium alloy sacrificial anode for marine application,” *AIP Conf. Proc.*, **1885** (2017). doi:10.1063/1.5002268.

7) L. Yan, Y. Zhang, X. Li, Z. Li, F. Wang, H. Liu, and B. Xiong, “Effect of zn addition on microstructure and mechanical properties of an al-mg-si alloy,” *Prog. Nat. Sci. Mater. Int.*, **24** (*2*) 97–100 (2014). doi:10.1016/j.pnsc.2014.03.003.
8) A.H. Commitee, “7075, Alclad 7075,” in: ASM Met. Handbook. Nonferrous Alloy. Spec. Purp. Mater., Materials Park, OH, 1992: pp. 450–462.
9) A. Baradeswaran, and A. Elaya Perumal, “Study on mechanical and wear properties of al 7075/al2o 3/graphite hybrid composites,” *Compos. Part B Eng.*, **56** 464–471 (2014). doi:10.1016/j.compositesb.2013.08.013.
10) G.B.V. Kumar, C.S.P. Rao, N. Selvaraj, and M.S. Bhagyashekar, “Studies on al6061-sic and al7075-al₂o₃ metal matrix composites,” *J. Miner. Mater. Charact. Eng.*, **09** (*01*) 43–55 (2010). doi:10.4236/jmmce.2010.91004.
11) R. N, and R. V S, “Tribological characterization of al7075/al203/sic reinforced hybrid particulate metal matrix composite developed by stir casting process,” *Int. J. Recent Adv. Mech. Eng.*, **4** (*3*) 113–127 (2015). doi:10.14810/ijmech.2015.4309.
12) R.R. Navagally, “Composite materials - history, types, fabrication techniques, advantages, and applications,” *Int. J. Mech. Prod. Eng.*, **5** (*9*) 82–87 (2017). http://linkinghub.elsevier.com/retrieve/pii/S0002939409008733.
13) M. Maurya, N.K. Maurya, and V. Bajpai, “Effect of sic reinforced particle parameters in the development of aluminium based metal matrix composite,” *Evergreen*, **6** (*3*) 200–206 (2019). doi:10.5109/2349295.
14) H.R. Ezatpour, M. Torabi Parizi, S.A. Sajjadi, G.R. Ebrahimi, and A. Chaichi, “Microstructure, mechanical analysis and optimal selection of 7075 aluminum alloy based composite reinforced with alumina nanoparticles,” *Mater. Chem. Phys.*, **178** 119–127 (2016). doi:10.1016/j.matchemphys.2016.04.078.
15) G. wei Zhao, C. Ding, X. sheng Gu, X.C. Ye, C. hua Huang, and M. chun Gu, “Solidification path calculations of al-zn-mg alloys in al-rich corner,” *China Foundry*, **14** (*5*) 443–448 (2017). doi:10.1007/s41230-017-7097-8.
16) P.R. Rios, and G.S. Fonseca, “Grain boundary pinning by particles,” *Mater. Sci. Forum*, **638–642** 3907–3912 (2010). doi:10.4028/www.scientific.net/MSF.638-642.3907.
17) H.R. Ezatpour, S.A. Sajjadi, M.H. Sabzevar, and Y. Huang, “Investigation of microstructure and mechanical properties of al6061-nanocomposite fabricated by stir casting,” *Mater. Des.*, **55** 921–928 (2014). doi:10.1016/j.matdes.2013.10.060.
18) P.X. Zhang, H. Yan, W. Liu, X.L. Zou, and B.B. Tang, “Effect of t6 heat treatment on microstructure and hardness of nanosized al2o3 reinforced 7075 aluminum matrix composites,” *Metals (Basel).*, **9** (*1*) (2019). doi:10.3390/met9010044.
19) C. Cho, S. Choi, O.M. Kwon, S. Lee, J. hwan Kim, and D. Kwon, “Evaluation of ballistic limit velocity using instrumented indentation test of 7xxx aluminum alloys after friction stir welding,” *Met. Mater. Int.*, (2020). doi:10.1007/s12540-020-00680-2.
20) G. OZER, and A. KARAASLAN, “Properties of aa7075 aluminum alloy in aging and retrogression and reaging process,” *Trans. Nonferrous Met. Soc. China (English Ed.*, **27** (*11*) 2357–2362 (2017). doi:10.1016/S1003-6326(17)60261-9.
21) S.A. Sajjadi, M. Torabi Parizi, H.R. Ezatpour, and A. Sedghi, “Fabrication of a356 composite reinforced with micro and nano al 2o3 particles by a developed compocasting method and study of its properties,” *J. Alloys Compd.*, **511** (*1*) 226–231 (2012). doi:10.1016/j.jallcom.2011.08.105.
22) S.P. Dwivedi, M. Maurya, and S.S. Chauhan, “Mechanical, physical and thermal behaviour of sic and mgo reinforced aluminium based composite material,” *Evergreen*, **8** (*2*) 318–327 (2021). doi:10.5109/4480709.
23) I. Sudhakar, G. Madhusudhan Reddy, and K. Srinivasa Rao, “Ballistic behavior of boron carbide reinforced aa7075 aluminium alloy using friction stir processing – an experimental study and analytical approach,” *Def. Technol.*, **12** (*1*) 25–31 (2016). doi:10.1016/j.dt.2015.04.005.
24) R.N.R. Parawansa, and A.Z. Syahrial, “ScienceDirect effect of nano sic addition and heat treatment on ballistic properties of al 2024 / nano sic composite produced by squeeze casting,” (2020).
25) A.S. Baskoro, M.A. Amat, R.D. Putra, A. Widyianto, and Y. Abrara, “Investigation of temperature history, porosity and fracture mode on aa1100 using the controlled intermittent wire feeder method,” *Evergreen*, **7** (*1*) 86–91 (2020). doi:10.5109/2740953.