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Characteristic of AA 7075-Reinforced Nano-SiC Composites Produced by Stir-Squeeze Casting and Open Die Cold Forging as An Armor Material Candidate

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Abstract: This study presented the ballistic properties and impact strength of the aluminum alloy AA 7075-reinforced nano-SiC composites, which were produced by stir-squeeze casting and forging processes. Ballistic tests revealed that the samples met the National Institute of Justice (NIJ) Type II standard, except for samples that were not forged. The other characteristics examined were microstructural observations analyzed using optical and scanning electron microscopes. As a result of the pinning effect, the microstructure of the samples showed a decrease in grain size as the SiC content increased, except for samples with over 0.25 vf% of nano-SiC. This effect was observed in samples with and without forging. The forging process decreased grain size further, affecting ballistic and mechanical properties. The addition of 0.3 vf% nano-SiC improved the ballistic properties and impact strength, resulting in the highest impact value of 7.7 J, despite higher values of the average ballistic diameter of perforation (about 4.7 mm) and average indentation depth (about 17.22 mm) measured on this sample.

Keywords: Aluminium Alloy 7075, ballistic, nano-SiC, reinforcement, forging

1. Introduction

Armor is widely used in military applications since it provides protection that can save many soldiers' lives⁽¹⁾. Military vehicles use armor made of steel. However, steel armor adds weight to the vehicle significantly and may reduce the vehicle's mobility, causing a significant disadvantage as vehicle mobility is one of the key successes in combat. There are also other factors that affect the mobility of military vehicles, such as engine power, vehicle design, and overall weight.

Nowadays, military vehicles are generally made of high-strength steel. Tanks typically weigh more than 60 tons, which is considered too heavy for effective combat performance. In addition to affecting mobility, weight is also a critical factor affecting fuel consumption. Therefore, a lighter material is needed that can provide the same or greater mechanical strength and ballistic resistance as steel^(2,3).

Aluminum alloy (AA) 7075 is one of the alternative materials used in ballistic research due to its high potential in ballistic applications^(4,5). The alloy has a higher level of

strength and a lower density than steel. The aluminum alloy 7075 can also be used as a matrix in metal matrix composite materials, which can be incorporated with ceramic reinforcements such as silicon carbide (SiC)^(6,7).

SiC is a non-oxide ceramic material with superior mechanical properties, including its nano-sized dimensions, which makes it highly effective in improving the strength of composites. Compared to other ceramic reinforcements such as Al₂O₃ and MgO, SiC has been shown to provide superior results in enhancing composite strength^(8,9).

Aluminum matrix composites are generally produced using the stir casting method^(10,11). In this study, the composite materials were produced by the stir casting method to ensure even distribution of the reinforcing particles into the aluminum matrix, followed by the squeeze casting method to minimize the problems that often occur during casting, such as porosity⁽¹²⁾.

The AA 7075 matrix composite has ballistic properties that can be developed through the cold forging process to improve its mechanical properties⁽¹³⁾. To obtain superior ballistic and mechanical properties, AA 7075 with nano-

sized SiC reinforcement was produced through the stir-squeeze casting and forging process and studied as a lightweight armor material candidate.

2. Materials and Methods

This study aimed to analyze the effect of adding nano-sized SiC reinforcements on the ballistic and mechanical properties of an AA 7075 matrix composite produced

through a combination of stir-squeeze casting and forging process. The materials used were commercially purchased AA 7075 as the matrix and 50-nanometer-sized SiC as reinforcement. Table 1 shows the composition based on the mill certificate. The SiC nanoparticles were added to AA 7075 matrix with variations of 0 vf%, 0.1 vf%, 0.15 vf%, 0.2 vf%, 0.25 vf%, and 0.3 vf% (volume fraction percentage). In this study, small quantities of SiC were added to preserve ductility²⁾.

Table 1. Chemical composition of aluminum alloy (AA) 7075 (wt%)

Zn	Si	Fe	Ti	Cu	Mn	Mg	Cr	Balance
5.1-6.1	0.40	0.20	0.07	1.2-2.0	0.25	2.1-2.9	0.18-0.28	Al

The composite samples were made and produced using stir casting followed by the squeeze casting method at the Process Metallurgical Laboratory, Universitas Indonesia. The aluminum ingot was cut and melted at 850°C. At the same time, the nano-SiC reinforcing particles were prepared by exposing them to UV waves and stirring. These particles were subsequently heated in a muffle furnace at 900°C for an hour. After an hour of heating, the nano-SiC particles were added to the molten metal and stirred at 500 rpm for two minutes. Furthermore, the degassing process was applied by introducing argon gas to the furnace for one minute to remove hydrogen gas and other dissolved impurities before pouring the mixture into a preheated mold. The mold, which was made of stainless steel, was preheated to 300°C to avoid thermal shock. The process was followed by squeezing the composites at 20-ton pressure for two minutes.

Next, the forging process was conducted using an open die at the Research Center for Metallurgy and Materials-Indonesian Institute of Sciences (LIPI) facility. The forging was applied twice with the same load of 100 tons at room temperature. To increase formability, pre-annealing treatment at 415°C for 2 hours was applied prior to the first load. After the first load, the sample was heat-treated by full annealing at the same temperature with a holding time of 2.5 hours, cooled down to room temperature, and re-annealed at 250°C with an hour of holding time. The subsequent heat treatment was done to soften and eliminate residual stress which might occur during the first loading forging process¹⁴⁾. The samples were cast in a stainless-steel mold with a dimension of 20 cm x 15 cm x 1.5 cm.

After sample production and forging processes were completed, all samples were subjected to ballistic testing using the ballistic resistance protection material standard of the National Institute of Justice (NIJ) 0108.01 at an Indonesian army base, KOPASSUS, in Cijantung, Indonesia. The ballistic tests were conducted with two shots for each type of the NIJ test for accuracy. Metallographic characterization as standardized in ASTM (American Standard Testing and Materials) E3-11 was

done at the Metallographic Laboratory, Universitas Indonesia, with a Zeiss Primotech Optical Microscope. The scanning electron microscopy-electron dispersive spectroscopy (SEM-EDS) observation of the non-forged sample was done at Universitas Indonesia with a JEOL JSM-6510LA, while the forged samples were examined at the Indonesian Police Forensic Laboratory with a Themoscientific Quanta 650. The impact test was conducted at the Physical Metallurgy Laboratory, Universitas Indonesia. The impact test was done using the Charpy method adhering to the ASTM E23 standard.

3. Results and Discussion

3.1 Forging Process

The forging process carried out on the samples resulted in a thickness reduction, which affected the microstructure and mechanical properties of the material. Table 2 shows that the reduction in thickness decreases the grain size in the microstructure, and this condition is further explained in 3.3¹⁵⁾. Figure 1 shows the form of a sample before and after forging. As shown in Figure 1(b), a crack defect was detected on the sample after the forging process, which occurred due to the presence of residual stress¹⁶⁾.

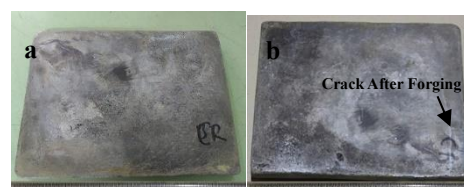


Fig. 1 An example of sample (a) before and (b) after forging.

Table 2. Thickness and surface area measurement

No	vf% SiC	P	Plate Initial		Plate Final		(%)
			Size (mm)		Size (mm)		Thickne
			T ₀	A ₀	T ₁	A ₁	ss Reducti on (T ₀ – T ₁)/T ₀
1	0	10 0 to n	15.1 6	2965 1	14.0 1	3035 1	7.59%
2	0.10		14.5	2980 0	13.3 9	3055 2	7.66%
3	0.15		15.2 4	2980 0	14.3 6	3020 0	5.77%
4	0.20		15.4 5	2965 1	14.7 1	3015 0	4.79%
5	0.25		14.5 6	2965 1	13.9 2	3035 1	4.40%
6	0.30		15.7 9	2980 0	14.4 9	3055 2	8.23%

Notes: T₀ = Initial Thickness, T₁ = Final Thickness, A₀ = Initial Surface Area, and A₁ = Final Surface Area

3.2 Ballistic Test

The ballistic test in this study was done in accordance with the NIJ Type III and II for both non-forged and forged samples. After undergoing the NIJ Type III test with MU5-TJ 5.56 mm bullets fired at a velocity of 900 m/s from a distance of 50 meters, all samples experienced complete penetration and developed holes. The test results indicated that spalling deformations occurred on the side of the bullet inlet for both non-forged and forged samples (Figure 2)¹⁷.

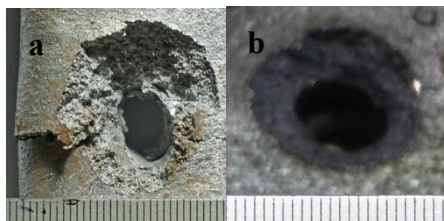


Fig. 2 Spalling deformation of the sample after ballistic test for (a) non-forged and (b) forged samples.

The NIJ Type III test results for the non-forged samples with 0-0.01 vf% nano-SiC and 0.2 vf% nano-SiC reinforcing compositions showed a homogeneous plastic flow on the side of the bullet exit hole, as illustrated in Figure 3. These results suggested the samples were softer than the bullet, as they experienced penetration through homogeneous plastic flow¹⁸. The sample with a reinforcing composition of 0.15 vf% nano-SiC had radial cracks (Figure 3), while the sample with a reinforcing composition of 0.25-0.3 vf% nano-SiC exhibited a petaling penetration mode on the side of the bullet exit hole (Figure 2)¹⁷. Petaling is a radial crack phenomenon that causes the formation of "petals" on the deformed metal around the bullet exit hole¹⁹.

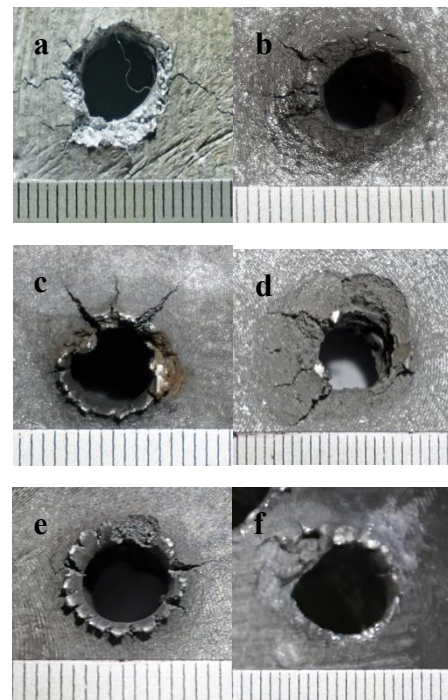


Fig. 3 The results of ballistic test of non-forged AA 7075 with reinforcing compositions of (a) 0 vf%, (b) 0.1 vf%, (c) 0.15 vf%, (d) 0.2 vf%, (e) 0.25 vf%, and (f) 0.3 vf% nano-SiC.

All samples tested on NIJ Type II with 9 mm bullets at a velocity of 380 m/s and a shooting distance of 5 meters did not show full penetration and resulted in a crater with a shallow perforation. Specifically, the result of the NIJ Type II test on a non-forged sample with a reinforcing composition of 0.1 vf% nano-SiC (Figure 4a) indicated that a crater was formed before it was fully deformed or broken, and this condition also occurred in the non-forged sample with a reinforcing composition 0.15 vf% nano-SiC⁵. This condition may be caused by the agglomeration of reinforcing particles, which resulted in an uneven distribution of reinforcement, leading to a decrease in the material toughness (related to mechanical properties)²⁰. Figure 4b illustrates the sample with a reinforcing composition of 0.2 vf% nano-SiC without a broken condition after the ballistic test, and this condition also

happens in all samples except 0.1-0.15 vf% nano-SiC.

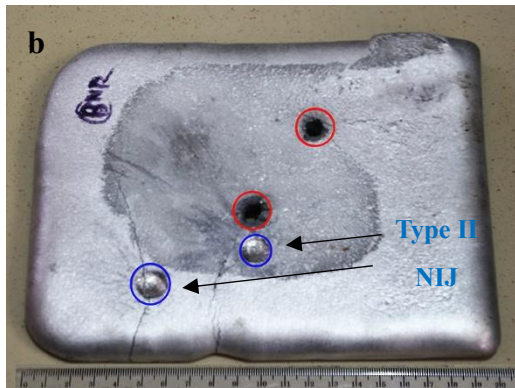
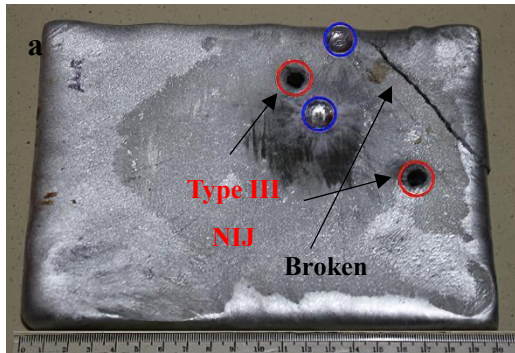


Fig. 4 The results of ballistic test of the non-forged AA 7075 with reinforcing compositions of (a) 0.1 vf% and (b) 0.2 vf% nano-SiC.

The NIJ type III test results on forging samples revealed that the samples with reinforcing compositions of 0 vf% and 0.2 vf% nano-SiC possessed homogeneous plastic flow on the side of the bullet exit, as shown in Figure 5¹⁸⁾. Figure 5 demonstrates a petaling penetration mode on the side of the bullet exit hole in samples with reinforcing compositions of 0.1-0.15 vf% and 0.25-0.3 vf% nano-SiC. Specifically, for the sample with a 0.3% nano-SiC reinforcement composition, two Type II NIJ bullets were shot into the hole of the NIJ Type III test (Figure 5e).

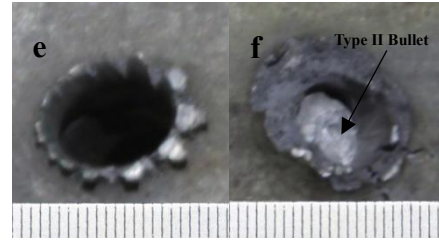
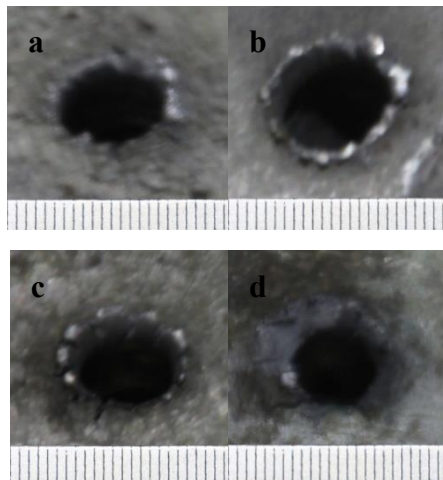


Fig. 5 The results of ballistic test of the forged AA 7075 with reinforcing compositions of (a) 0 vf%, (b) 0.1 vf%, (c) 0.15 vf%, (d) 0.2 vf%, (e) 0.25 vf%, and (f) 0.3 vf% nano-SiC.

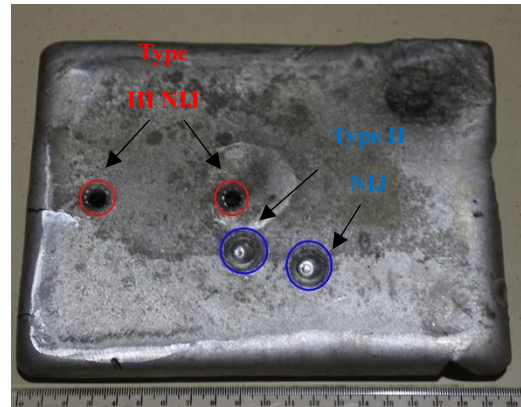


Fig. 6 The results of ballistic test of the forged AA 7075-reinforced nano-SiC composite plate.

The NIJ Type II test results on forged samples showcased that all samples formed craters⁵⁾. These results were different from samples that were not forged since there was no full deformation or breaking in all samples (Figure 6). The forging process can improve the toughness of the samples¹³⁾, thereby increasing their ballistic properties. This phenomenon is further explained in 3.3 and 3.4.

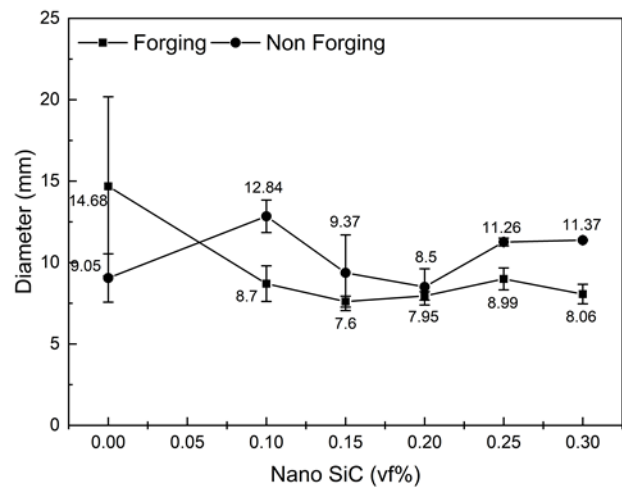


Fig. 7 Average perforation diameter of tested samples following NIJ Type III test.

Figure 7 reveals the result of the NIJ Type III test,

highlighting the bigger bullet hole diameter of non-forged samples compared to that of forged samples. In this study, the result of Type III indentation could not be measured as all tested samples experienced full perforation, leading to hole formation. Meanwhile, Figure 8 illustrates the NIJ Type II test results, where the average bullet hole diameters and indentations of forged samples were bigger than those of non-forged samples. These conditions occurred due to the annealing treatment prior to the forging process, causing the samples to soften²¹⁾. The Type II indentation could be measured due to the crater formation after testing, with the lowest indentation of 1.23 mm for the 0.2 vf% nano-SiC non-forged sample.

The lower ballistic indentation does not necessarily indicate better ballistic properties. Instead, mechanical testing results, particularly the impact properties, are better indicators for ballistic properties. In line with this, a study done by Ravanya et al.²⁾ proved that the ballistic indentation values of AA 2024-reinforced nano-SiC did not match its impact values on all percentage reinforcement variants.

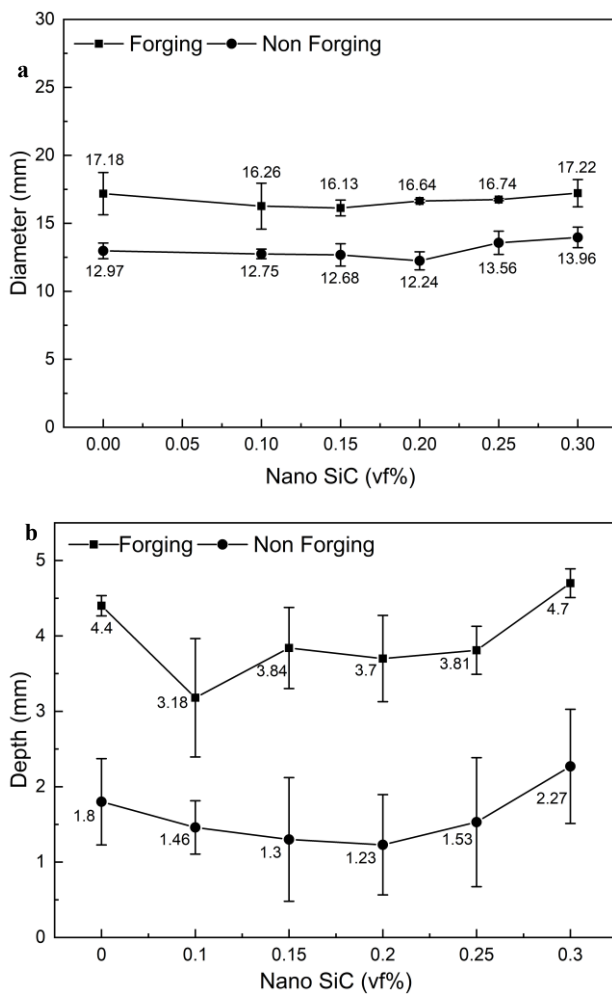


Fig. 8 Results of the NIJ type II showing the (a) average perforation diameter and (b) indentation depth of forged and non-forged samples.

3.3 Microstructure Observation

The microstructure observed with a 100x magnification using optical microscope on all samples (Figures 9 & 10) revealed an α -dendrite (matrix AA 7075) and a eutectic phase²²⁾. Adding nanoparticle reinforcement made the grain finer and smaller because the pinning effect from SiC nanoparticles in the grain boundary can prevent grain growth. This phenomenon occurred in samples with a reinforcing composition of 0.1 vf% to 0.2 vf% nano-SiC. On the other hand, the samples with SiC reinforcement above 0.25 vf% did not have a smaller grain size as expected, most likely due to SiC agglomeration. It is known that the addition of more SiC nanoparticles can lead to an increased likelihood of agglomeration²³⁾.

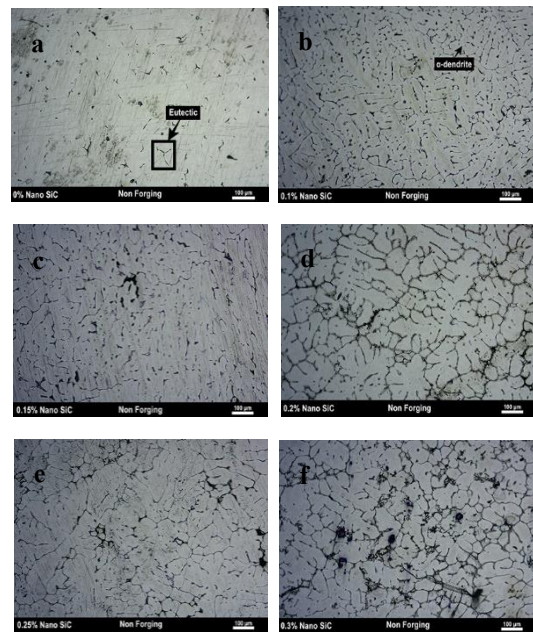


Fig. 9 100X magnification of AA 7075-reinforced nano-SiC composites microstructure before forging with composition of 0 vf%, (b) 0.1 vf%, (c) 0.15 vf%, (d) 0.2 vf%, (e) 0.25 vf%, and (f) 0.3 vf%.

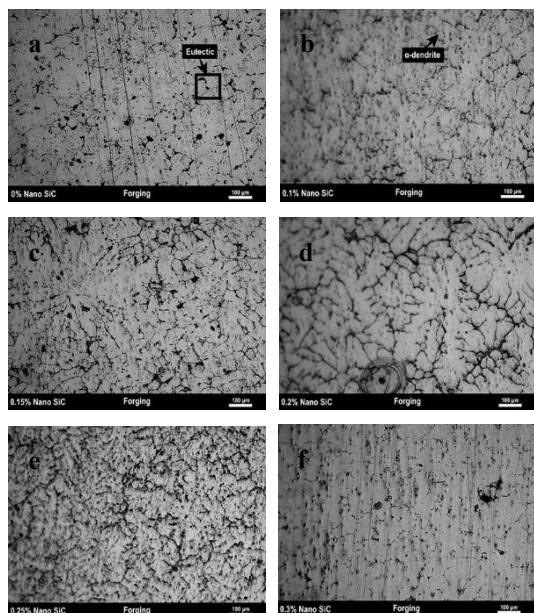


Fig. 10 100X magnification of AA 7075-reinforced nano-SiC composites microstructure after forging with composition 0 vf%, (b) 0.1 vf%, (c) 0.15 vf%, (d) 0.2 vf%, (e) 0.25 vf%, and (f) 0.3 vf%.

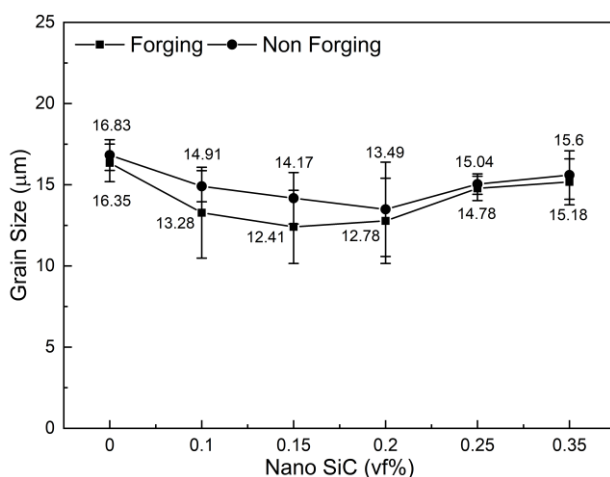


Fig. 11 Average grain size of the forged and non-forged samples.

The grain size was measured using the intercept method. Figure 11 displays a graph of the average grain size with a magnification of 100x on a 100 μm scale. This graph illustrates a slight decrease in grain size for the reinforcing compositions of 0 vf% to 0.2 vf% nano-SiC. There was also an increase in grain size for reinforcing composition of 0.25 vf% to 0.3 vf% nano-SiC, which might arise due to SiC agglomeration. The average grain size of forged samples was smaller than that of non-forged samples because the forging process can decrease the grain size, which in turn affects the mechanical properties of the sample^{15,24}.

Hanamantraygouda M. B. et al.¹³) conducted a study that demonstrated the grain size reduction through forging

could increase the mechanical properties of the sample, including impact toughness. This finding is supported by a study by Sandeep Kumar et al.²⁵), which also showed that the forging process could result in finer grain size and further enhance the mechanical properties of the sample.

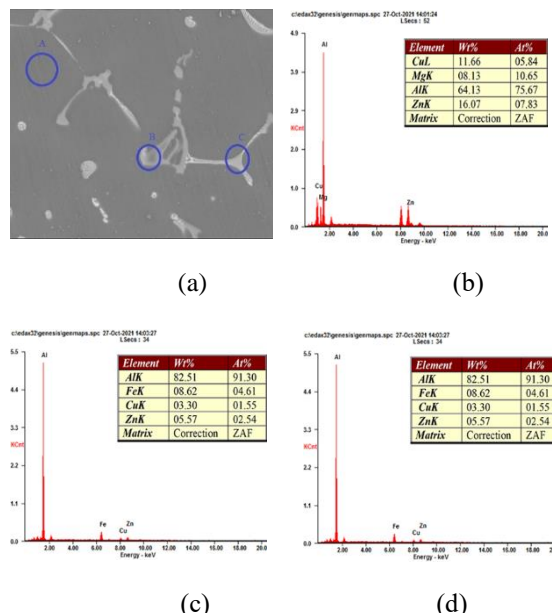


Fig. 12 (a) SEM of 0.2 vf% nano-SiC non-forged sample with detailed element compositions of (b) EDS area a, (c) b, and (d) c.

SEM-EDS observations were conducted for microstructure analysis to detect the phase, and these observations were taken from each sample, both non-forged and forged. The SEM-EDS observation for a non-forged sample was taken from the AA 7075 with 0.2 vf% of nano-SiC due to the good result (Figure 12a). The formed phase is marked with a blue circle, and the element compositions are shown in Figure 12b–12d. MgZn_2 – AlCuMg (M) phase was formed in the area a because that phase would be formed after the casting process. Al_3Fe Phase in area b was formed possibly due to impurities from the casting process where the stir casting tool was made from stainless steel containing Fe. Phase $\text{Al} + \text{MgZn}_2$ (η) area c was the eutectic phase, which was the primary phase^{26,27}.

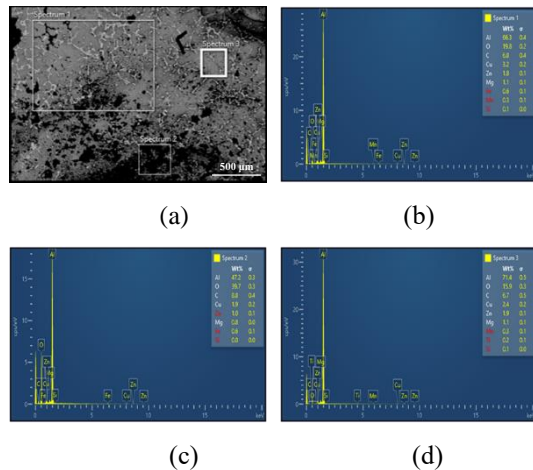


Fig. 13 (a) SEM of 0.15 vf% nano-SiC forged sample with (b) EDS spectrum 1, (c) 2, and (d) 3.

The SEM-EDS observation for forged samples was taken from the 0.15 vf% nano-SiC due to the good result (Figure 13a). The formed phase is marked with the spectrum, and the element compositions are shown in Figure 13b-d. Due to the annealing treatment prior to the forging process, the phase formed from spectrum 1 was Al_2CuMg (Phase S), and the phase formed from spectrum 2 was $\text{Al}_2\text{Mg}_3(\text{Cu}, \text{Zn})_3$ (Phase T). Phases S and T may cause the sample to soften and affect the average diameter and indentation of the forged samples, as explained in 3.2^{21,28}). Phase $\text{Al} + \text{MgZn}_2$ was a eutectic phase in spectrum 3. Furthermore, nano-SiC particles are usually detected in grain or grain boundary²⁹), but these particles were not detected in this sample.

3.4 The Impact Strength of AA 7075-Reinforced Nano-SiC

The mechanical properties in this study were evaluated using the impact test. Figure 14 showcases the results of the impact test of the composite. The addition of nano-reinforcement up to 0.15 vf% nano-SiC decreased the impact toughness. However, the addition of higher concentrations of nano-SiC resulted in an increased impact toughness. The forging process can increase impact toughness value, so several forged samples exhibited higher impact toughness than non-forged samples, with a maximum value of 5 J and 7.7 J for non-forged and forged samples, respectively^{13,30}).

The higher impact value of the forged samples may be attributed to the increased average grain size following the forging process (Figure 11), which increases the mechanical properties that can affect the ballistic properties. Furthermore, the impact strength is also a better indicator of ballistic properties since all forged samples, except for the 0.15-0.25 vf% nano-SiC samples, exhibited almost higher impact values than non-forged samples and were able to withstand Type II NIJ bullets.

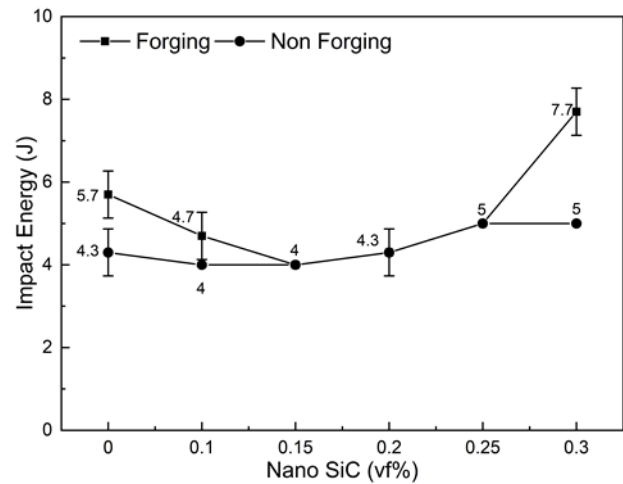


Fig. 14 Results of the impact test of the forged and non-forged samples.

The 0.15-0.25 vf% nano-SiC forged samples possessed the same impact value as the non-forged samples. However, the forging process can lead to a more uniform distribution of SiC reinforcement¹³), enabling the sample to withstand NIJ Type II test. The lowest impact value observed was 4 J for the non-forged samples containing 0.1-0.15 vf% nano-SiC, indicating that the ballistic performance was not resistant to NIJ Type II test as both samples were fully deformed or broken. These problems most likely occur because of the agglomeration of reinforcing particles, stemming from the uneven distribution of the particles during the production process. According to Guangyu Liu et al.³¹), agglomeration can occur during the casting process and decrease the toughness of the material.

4. Conclusions

This study focussed on analyzing the effect of adding nano-SiC reinforcements on the ballistic and mechanical properties of an AA 7075 matrix composite produced through a combination of stir-squeeze casting and forging processes. It was found that the forged and non-forged samples could not withstand the NIJ Type III test following the ballistic test. Albeit, they could withstand the NIJ Type II test, except for the non-forged samples with a reinforcing composition of 0.1 vf% and 0.15 vf% nano-SiC.

Additionally, microstructure observation of all samples revealed a decrease in grain size for samples with SiC content of up to 0.2 vf% as a result of the pinning effect. This effect was observed in both non-forged and forged samples. Furthermore, SEM-EDS observation of the forged samples indicated the presence of phases S and T. Our findings also suggested that the impact strength increased after the forging process, with the highest impact strength value of 7.7 J for the 0.3 vf% nano-SiC forged sample. The impact strength is a better measure of ballistic properties than the average diameter perforation and ballistic indentation depth.

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