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Influence of Anadara granosa Shell Particle Mesh on the Microstructure and Impact Toughness of Aluminium 6061 Alloy

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Abstract:
Even though Aluminium 6061 (Al6061) has low density and good corrosion resistance, its relatively low impact toughness increases the risk of failure under sudden dynamic loading. To overcome this, the addition of proper hard particle reinforcement can be applied to this alloy. Therefore, this study aims to investigate the effect of Anadara granosa shell (AGS) with different mesh sizes (50, 80, 100) on the microstructure, impact toughness, and hardness of the Al6061 alloy. The performance of each specimen was evaluated using the Charpy impact toughness and Vickers hardness tests. Meanwhile, the microstructure was observed using SEM-EDX, which provided insights into particle distribution and its correlation with mechanical properties. The results showed that the impact toughness increased from 5.6 J to 7.6 J, 8.1 J, and 9 J. Similarly, the hardness increased from 32.7 HV to 38.4 HV, 39.7 HV, and 42.7 J as the addition of AGS. The improvement continues to increase as the size of the reinforcement decreases. This trend is also reflected in the hardness results. In addition, SEM analysis showed that the finer mesh size promotes a more uniform particle distribution, indicating a factor of impact toughness and hardness improvement. These findings indicate that AGS is an effective natural reinforcement for improving the mechanical properties of Al6061, with a mesh size of 100 providing the greatest improvement.

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1. INTRODUCTION

Impact is the energy received by a material suddenly due to a collision or strike, which can cause deformation or even material failure [1]. In mechanical engineering, understanding how materials respond to impact loads is very important because many components work under dynamic load conditions. An example of its application can be found in vehicle bumpers, which are designed to absorb impact energy so that the vehicle structure and passenger safety are maintained [2]. Therefore, the material for these components should ideally be lightweight but capable of absorbing impact energy optimally to prevent failure during use. Aluminium is an attractive alternative to steel because it has low density, good corrosion resistance, and is easy to manufacture [3,4]. However, despite being lightweight and relatively strong, aluminium 6061 (Al6061) still has lower impact toughness than carbon steel, especially when subjected to sudden shock loads [5]. Therefore, efforts are needed to improve the impact toughness of Al6061 without sacrificing its light weight, one of which is through the development of Aluminium Matrix Composites (AMC) with the addition of reinforcing particles.

Several studies have been conducted on Aluminium Matrix Composites (AMCs) to improve the mechanical properties of aluminium alloys. It has been known that the addition of hard

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reinforcing particles can improve impact resistance, hardness, and wear resistance without significantly increasing mass [6,7]. Conventional ceramic particles, such as SiC and Al_2O_3, are widely used as reinforcement in materials. However, interest in biomineral reinforcing particles has recently grown due to their environmental friendliness and lower production costs. Previous studies have shown that AGS is among the most promising biomineral reinforcements due to its stable aragonite structure and high mechanical strength [8,9]. In addition, it is contributed by the abundant calcium content of hydroxyapatite (HAp) in the AGS [10]. Moreover, XRD/EDX data confirm the mineral stability of Ca, O, and C as the main elements after the conversion to HAp [11]. Further FT-IR and SEM observations confirmed that the shells are rich in calcium carbonate (approximate 98% $CaCO_3$) and have great potential for composite and biomaterial applications [12]. Therefore, it can be said that AGS has strong prospects as a composite reinforcement material.

Research on the effect of AGS on certain matrix materials has been initiated by previous scholars. It has been revealed that AGS with a mesh size of 170 and a weight fraction of 30 wt.% has been reported to increase the impact strength of the epoxy matrix by up to three times compared to without reinforcement [13]. Other scholars found that the hardness and tensile strength of aluminium composite fairly increase with 15 wt%.% addition of mollusk shell [14]. Meanwhile, other researchers have investigated the effect of SiC particle reinforcement on AMC with varying sizes. They stated that finer particle sizes resulted in significant improvements in tensile strength and wear resistance [15]. These findings indicate that particle size is one of the most important considerations in evaluating the mechanical response of composite materials.

In the context of aluminum alloys, recent studies on aluminum-based metal-matrix composites have further demonstrated that particle reinforcement can significantly improve mechanical and tribological properties. For example, aluminum alloy composites reinforced with hybrid particles have reported significant improvements in mechanical performance and wear due to the synergistic effects of ceramic reinforcement and solid lubrication [16]. Although their study focused on Al 7075 alloys, the results highlight the important role of reinforcement characteristics in controlling the performance of aluminium-matrix composites, a finding that is also relevant to Al 6061-based systems.

However, most existing research on Al 6061-based composites has focused on tensile and wear behaviour, whereas investigations of impact toughness under dynamic loading conditions remain limited. Furthermore, although *Anadara granosa* shell (AGS) has been widely used as a reinforcement material, the effect of AGS particle mesh size on the impact toughness of Al 6061 has not been systematically studied.

This trend is also reflected in the hardness results. In addition, SEM analysis shows that finer mesh sizes promote a more uniform particle distribution, which contributes to improvements in impact toughness and hardness. These findings indicate that AGS is an effective natural reinforcement for enhancing the mechanical properties of Al 6061, with a mesh size of 100 providing the optimal improvement.

2. MATERIALS AND METHODS

The methodology of this study was divided into several main stages, as shown in Fig. 1. The experimental work was conducted at the Material Engineering Laboratory, UPN Veteran Jakarta. First, the research started with material preparation, which included the provision of matrix materials Al6061 and reinforcing phases (AGS), as well as the necessary fabrication equipment such as digital scales, mortars, sieves, and sand molds. Test specimens were made using the sandcasting technique, with reinforcing particle sizes set at 50, 80, and 100 mesh. After the solidification process, the specimen surfaces were polished using a polishing machine, with P1000 silica sandpaper. Charpy impact tests were utilized to evaluate the impact toughness of each material. Meanwhile, a Vickers hardness machine test (Future Tech FV-300 instrument) was used with a load of 98.06 N. In addition, microstructural analysis was performed using a Scanning Electron Microscope (SEM) with EDS to visualize reinforcement distribution, assess the quality of the matrix-particle interface bonding, identify porosity, and examine the AGS spectral peak. The final stage of this study was data analysis and discussion, in which the experimental results were compared with the theoretical basis and relevant literature.

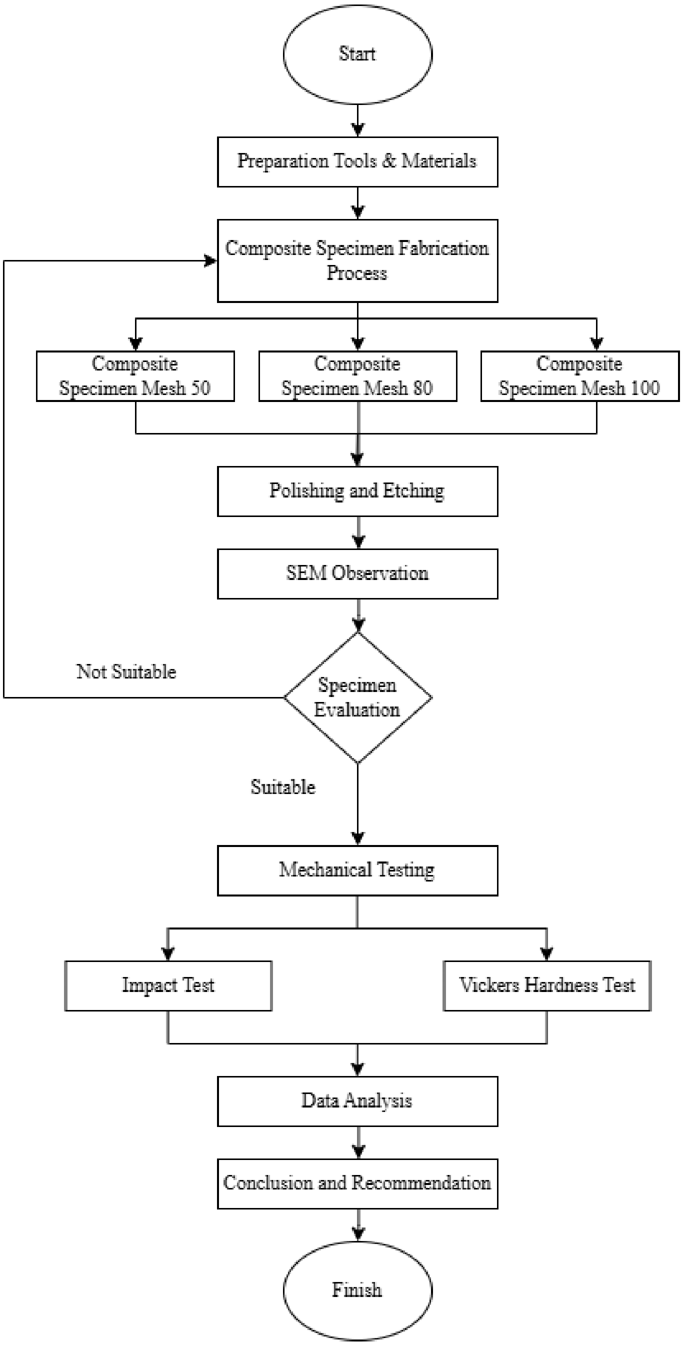

Fig. 1. Research Flowchart

2.1 Specimen Manufacturing and Preparation

A commercially available Al6061 was used as the matrix material in this study due to its combination of superior mechanical properties and high corrosion resistance, making it a popular material across a wide range of engineering applications. It has a density of approximately 2.7 kg/m³, about one-third that of steel. This property is particularly advantageous for applications that require lightweight yet strong materials, for instance, car wheels and bumpers [17]. The chemical composition of Al6061 was measured using an Olympus New Handheld XRF Analyzer before the remelting process. The data is compared with the previous study to ensure its validity. The result is given in Table 1.

Table 1. Chemical Composition Al 6061

Element (%)								Source
Mg	Si	Fe	Cu	Mn	Cr	Zn	Al	
0.85	0.68	0.7	0.22	0.32	0.06	0.07	Bal	[18]
0.84	0.822	0.322	0.178	0.0026	0.178	0.063	97.64	Current Study

This study utilizes blood clam shell waste (AGS) as a reinforcement particle in composite development. As is well known, the use of this biomaterial-based waste offers dual environmental benefits by reducing solid waste and improving the mechanical performance of the resulting composite. AGS consists of a significant amount of calcium carbonate ($CaCO_3$), approximately 98 wt.% [8], as summarized in Table 2. The $CaCO_3$ compound has been shown to significantly improve the mechanical properties of composites, particularly tensile strength and strength-to-weight ratio. Moreover, the combination of lightness and hardness of AGS makes it an ideal candidate for use as reinforcement in metal-matrix composites.

Previous studies have shown that the size of reinforcing particles greatly affects impact performance. Table 3 presents the impact strength of shell-reinforced composites with different mesh sizes; finer particles yield higher impact strength. This trend indicates that particle size refinement improves energy absorption capability.

Therefore, this study aims to analyse the effect of AGS mesh size variations on the impact toughness of Al6061 alloy. It will be compared with the situation without reinforcement, serving as the baseline for this research. In addition, the investigation of microstructure and hardness of materials is also involved to obtain the detailed information of the results.

Table 2. Chemical composition of AGS [8]

Element/compound	Concentration (%)
Ca + C ($CaCO_3$)	95.7 ± 1.5
Na	2.1 ± 0.2
Mg	0.13 ± 0.0
Fe	1.4 ± 0.1
Others (Cu, Ni, Pb, As, Cd, Si, Zn, Hg)	0.54 ± 0.0

Table 3. Chemical composition of AGS

Filler Fraction (%)	Impact Strength (J/mm^2)		
	Mesh 50	Mesh 110	Mesh 170
0	900	900	900
10	1700	2000	2200
20	2100	2400	2600
30	2400	2700	2900
40	2000	2200	2300
50	1500	1700	1800

The AGS utilized in this study was obtained from seafood waste. Thus, it was cleaned using a combination of disinfectants and detergents to remove organic and microbiological contaminants. After that, it was dried in the sun, then ground into a powder with a mortar and pestle. The powder is then sieved to ensure uniform particle size in accordance with 50, 80, and 100 mesh standards. The Al6061 composite was manufactured by sand casting, with an Al6061 alloy matrix containing 15 wt.% shell powder by total weight. The mass of matrix and reinforcement AGS was:

$$Mass = V \times w \times \rho \tag{1}$$

$$Mass\ AGS = 80{,}000 \times 0.15 \times 0.00128599 = 15.431\ gr \tag{2}$$

$$Mass\ \mathrm{Al} = 80.000 \times 0{,}85 \times 0{,}0027 = 183{,}6\ gr \tag{3}$$

After determining the masses of the matrix and reinforcement, the Al6061 alloy was melted at approximately 600°C. Then, the reinforcing powder was added while the aluminum was still molten, followed by manual stirring to promote uniform particle distribution. The liquid composite is poured into a sand mold, as shown in Fig. 2, and left to cool to room temperature. The hardened bar is then cut and machined to meet the required test dimensions. During fabrication, an interfacial reaction between the molten Al6061 matrix and the AGS particles may occur. Since AGS consists mainly of $CaCO_3$, partial thermal decomposition or interfacial reactions at high temperatures may contribute to the formation of reaction products or to increased interfacial bonding. However, no clear brittle reaction phase was observed in the SEM analysis, indicating that the reaction was limited to the processing conditions used in this study. For each composition, three replicate specimens were prepared and tested to ensure the reliability of the mechanical property measurements.

Fig. 2. Sand Casting Process

2.2. Impact Test

Impact resistance testing under impact loads was conducted in accordance with ASTM E23 to ensure consistent specimen dimensions and reliable data. Specimens were processed into a V-notch configuration in accordance with the standard, then tested using a Charpy impact resistance testing machine by applying a sudden impact load until fracture occurred. The energy absorbed during fracture was recorded as the material's impact resistance. The specimen design and detailed geometry are shown in Figs. 3 and 4.

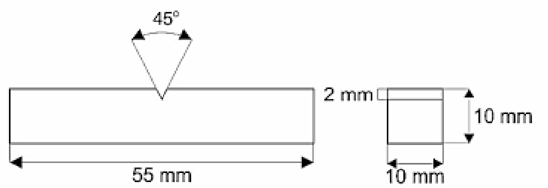

Fig. 3. Design ASTM E23

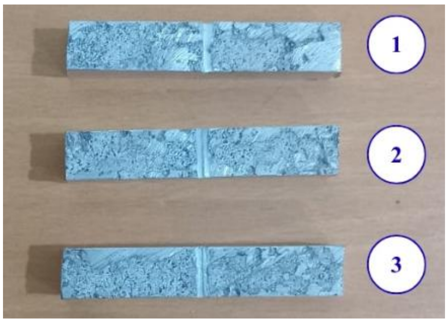

Fig. 4. ASTM E23 Specimen Geometry

2.3. Vickers Hardness Test

The Vickers hardness test was performed using a Vf-300 Vickers hardness machine. First, the test specimen was securely mounted on the test fixture. Then, a diamond-shaped indenter with two opposing sides at an angle of 136° was pressed into the specimen surface at a load of 98.07 N for 10 to 15 s to form a suitable indentation. To evaluate the consistency of hardness across the composite surface and obtain accurate hardness measurements, this test is performed 14 times at different locations on each test specimen.

2.4. Microstructural Analysis

Microstructural analysis plays an important role in understanding the internal phase distribution and the quality of interfaces between particles and the matrix. Observations were made using an optical microscope and a scanning electron microscope (SEM). The optical microscope was primarily used to evaluate specimens, focusing on particle dispersion effectiveness and bonding. Meanwhile, SEM produces high-resolution images to analyze the morphology of reinforcing particles, evaluate the interfacial bond between the matrix and the reinforcer, and identify porosity, all of which significantly affect the material's mechanical properties.

3. RESULTS AND DISCUSSION

3.1. Microstructure Analysis

The microstructure of each material was characterized using a scanning electron microscope (SEM) to visualize the microstructure constituents (matrix and reinforcement) and detect potential microdefects that could affect the mechanical behavior of the composite. SEM image of Al6061 alloy is shown in Fig. 5. The microstructure appears relatively homogeneous with a clear dendritic pattern and well-defined grain boundaries. However, micro-pores and interdendritic regions were observed. This dendritic pattern is a characteristic formation during the casting process for Al6061 alloys, where the microsegregation phenomenon of each element occurs during the cooling step of the solidification process. Consequently, the interdendritic regions tend to be more brittle than the dendritic core [19]. The presence of these micro-defects has important implications for the mechanical behavior of the material, which can act as a stress concentration area and be the starting point for crack propagation when the material is subjected to dynamic loading [20]. Microporosity has a detrimental effect on reducing the toughness of the material, which can accelerate crack propagation. In addition, the precipitation of intermetallic Mg2Si is observed in the white area, consistent with previous studies [3,4]. Since the microstructure of Al6061 has inherent limitations in absorbing impact energy, it should be modified by adding hard particle reinforcement [14].

AGS powder was selected as the reinforcement particle in this work. The chemical composition of AGS powder after the solidification process was detected using the EDX spectrum in SEM. The results in mass % and atom % are given in Table 4. It revealed that the area of reinforcement is mainly occupied by elements of Ca, O, and C, as shown in Fig. 6. These results are consistent with several previous studies that also encountered the dominance of $CaCO_3$ based on EDX and XRD characterization of AGS powder [10-12].

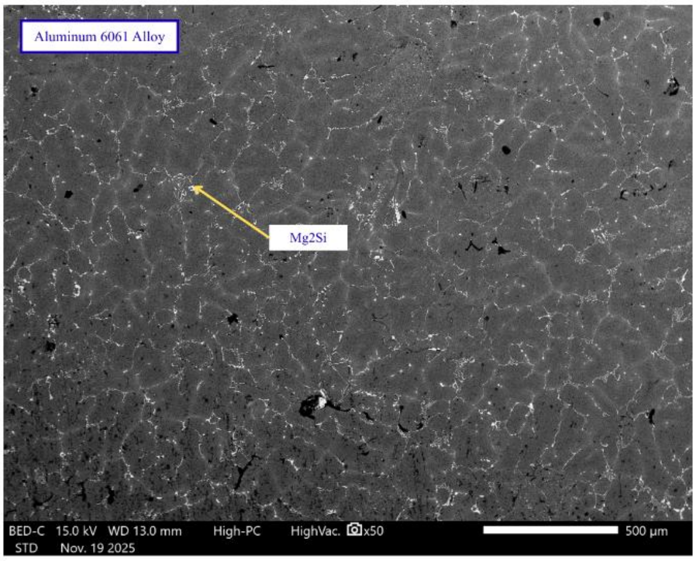

Fig. 5. Microstructural Observation of Al 6061

Table 4. The EDS of Elements in Anadara granosa Shell Powder

Element	Line	Mass%	Atoms%
C	K	21.08±0.23	33.52±0.37
O	K	39.65±0.70	47.33±0.83
Na	K	0.56±0.05	0.47±0.04
Al	K	0.73±0.04	0.52±0.03
Si	K	0.34±0.03	0.23±0.02
Ca	K	37.64±0.36	17.94±0.17
Total		100.00	100.00

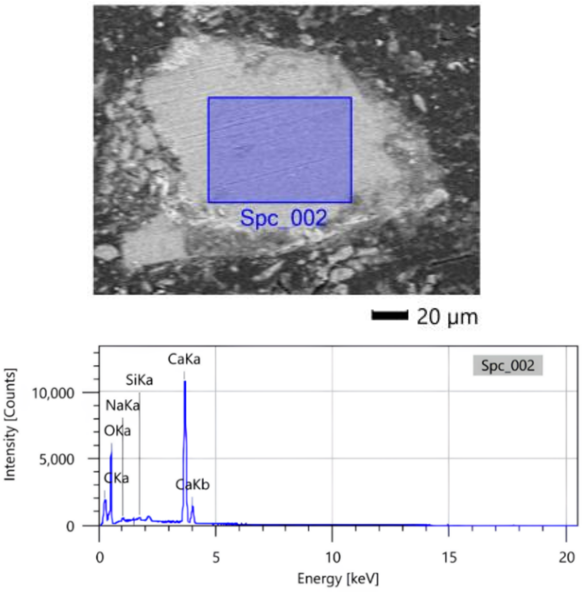

Fig. 6. EDS spectrum of Anadara granosa Shell with Mesh 80 as representative material.

The microstructure of Al 6061 with three mesh variations was characterized using SEM. The SEM morphology of each specimen microstructure is displayed in Fig. 7. All specimens show that AGS powder is well embedded in the matrix area, indicating that the reinforcement has good bonding properties with Al6061 alloy. In addition, the presence of porosity is difficult to observe, meaning the addition of AGS can effectively reduce the porosity during the cooling process. Due to the influence of reinforcement particles, it is important to evaluate, which was measured using the binarizing images technique using free engineering software ImageJ.

The size distribution of AGS particles is provided in a bar chart as shown in Fig. 8. It can be known that in the 50 mesh, the main size of the particle is 151-200 µm with approximate 43 %. It also contains bigger sizes 201-250 µm, 251-300 µm, and the coarsest is 301-350 µm with approximate 7 %. In the case of 80 mesh, the size distribution of AGS is dominated by the size 151-200 µm (approximate 31 %), with the lowest being 251–300 µm (6 %). It indicates that the 80-mesh filtration process still tends to maintain the domination of medium-sized particles. Conversely, in the case of 100 mesh, results in a more drastic shifting, which is characterized by the dominance of the 50–100 µm fraction (about 42%). Overall, the refinement of particle size toward a finer category is as expected. This refinement of AGS is highly relevant to the concept of enhanced biogenic reinforcement in a metal matrix. The reduction of the particle size increases the specific surface area and interparticle contact, which can directly improve the load transfer efficiency and accelerate the formation of strong interfacial bonds between the AGS and the Al6061 alloy [21,22]. Therefore, the finer the AGS particles, the more effective and uniform their distribution in the composite.

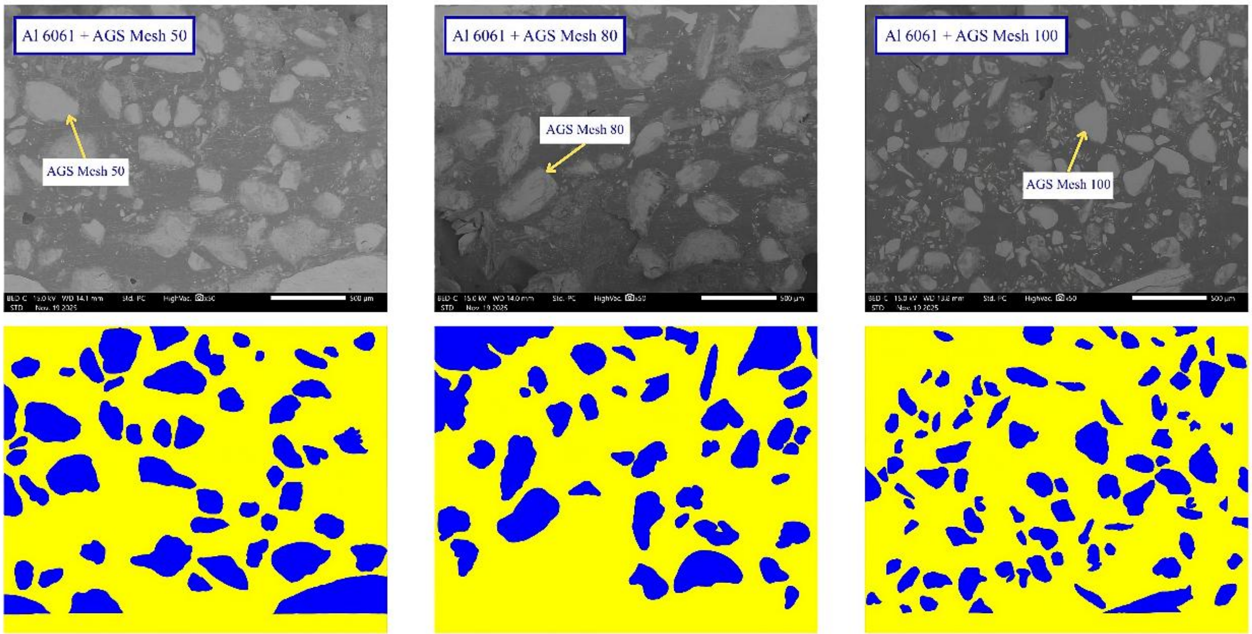

Fig. 7. Specimens Microstructure Observation using SEM

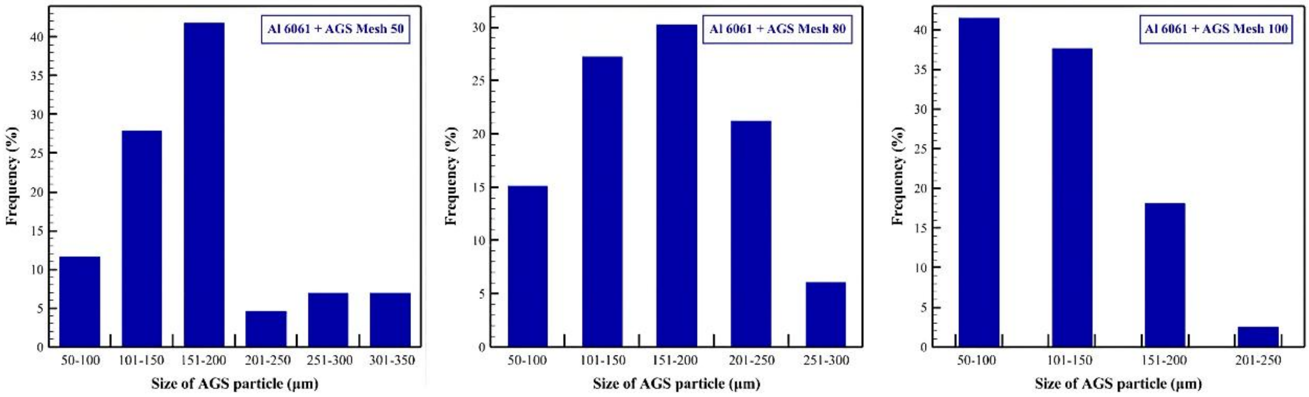

Fig. 8. The Distribution of AGS Particle Sizes of Mesh 50, 80, and 100 Specimens

The graphical and quantitative analysis reveals that the higher the degree of particle fineness can be achieved with the smaller the mesh size. Medium-sized AGS still dominates in mesh sizes 50 and 80. However, in mesh 100, there is a significant reduction in particle size with a more homogeneous distribution. This result is in good agreement with a previous study, which found that reducing the reinforcement size of shell powder can improve interfacial bond properties and effectively reduce porosity in aluminium composites, resulting in a denser microstructure [22,23]. In this study, porosity reduction was qualitatively assessed by comparing the number, size, and distribution of visible pores among specimens using SEM observations, while quantitative porosity values were estimated using ImageJ analysis. Therefore, reinforcement particle size is a crucial factor in controlling composite quality.

Besides that, the orientation of AGS was found to be not significantly different among all samples. It indicates that the influence of reinforcement orientation on impact toughness behaviour can be neglected in this study.

3.2. Impact Toughness Behavior of Each Material

Effect of AGS on Al6061 with different sizes is given in a bar chart Fig. 9. It can be known that Al6061 alloy has 5.6 J. By adding AGS reinforcement, the toughness gradually increased to 7.6 J at 50 mesh, 8.1 J at 80 mesh, and reached the highest value of 9 J at 100 mesh. This result trend clearly shows that the finer the particle size of the AGS reinforcement (100 mesh), the greater the impact energy capacity that the composite can absorb when subjected to dynamic loading.

In addition to chemical composition, the size of AGS reinforcement plays an important role in improving the impact performance of Al6061. It can be understood that finer AGS results in an enlarged contact area between the reinforcement and the aluminium matrix. Essentially, this allows for more efficient load transfer, minimizes void formation, and improves resistance to crack initiation and propagation. These findings are in line with previous work, which emphasizes that smaller particles contribute more effectively to composite reinforcement through superior particle strengthening mechanisms [13].

Overall, the observed increase in impact strength indicates the effectiveness of AGS particles as a natural reinforcing agent in Al6061 alloy. The highest strengthening effect can be achieved by adding the finer AGS reinforcement size because it promotes more uniform particle distribution and the formation of stronger interfacial bonds between the reinforcement and aluminium matrix.

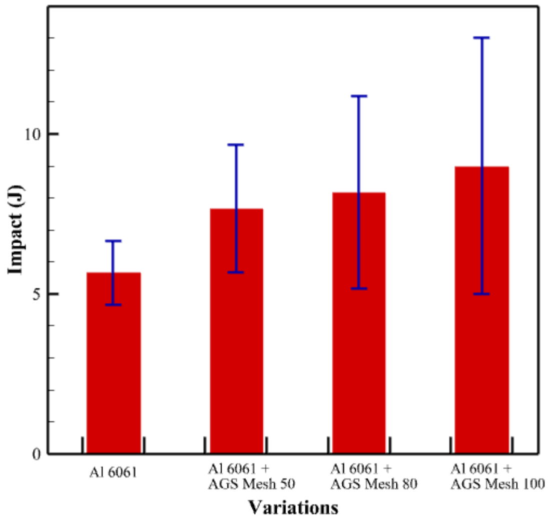

Fig. 9. Effect of AGS Particle Sizes on Composite Toughness

3.3. Hardness Characteristics of Each Specimen

The effect of AGS reinforcement on the hardness behaviour of Al6061 alloys is shown in Fig. 10. The result indicates that the hardness of Al6061 without the addition of AGS particles is about 32.7 HV. By adding AGS reinforcement, the hardness of the specimen increased gradually, reaching about 38.4 HV at a mesh size of 50, 39.7 HV at a mesh size of 80, and reaching a maximum value of 42.7 HV at a mesh size of 100.

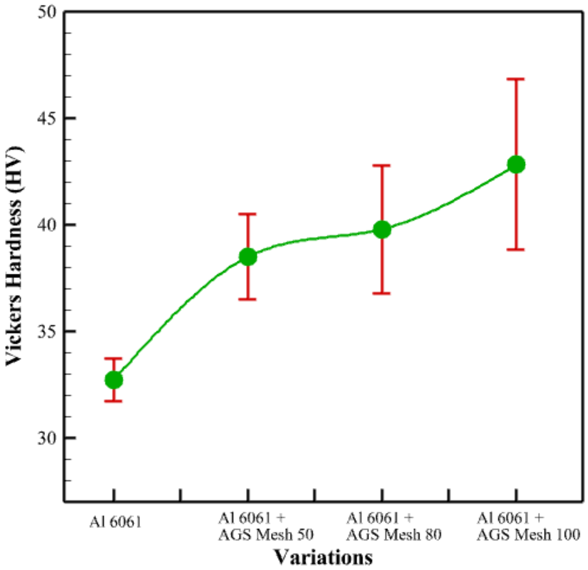

Fig. 10. Effect of AGS Particle Sizes on Composite Vickers

This improvement indicates that AGS functions as an effective reinforcing phase, increasing the resistance of the material experiencing the phenomenon of plastic deformation and crack initiation. A bigger mesh size corresponds to smaller particle dimensions, allowing for a more uniform distribution of the AGS reinforcement throughout the metal matrix. The homogeneous distribution directly increases the contact area between the AGS reinforcement and the aluminum matrix, thereby strengthening interparticle bonds while minimizing microdefects such as voids or porosity. These results are in good agreement with a previous study showing that the addition of mollusk shell can significantly increase hardness, due to the presence of Ca-rich particles that activate efficient strengthening of the matrix [14]. Therefore, it can be concluded that AGS is a highly promising natural reinforcement for improving the mechanical properties, particularly the hardness of Al6061 alloy.

4. CONCLUSION

Research about the effect of AGS mesh on the microstructure and mechanical properties of Al6061 has been evaluated in the present work. Based on the microstructure characterization and analysis of mechanical testing results, it can be concluded that the addition of AGS into the Al 6061 alloy as the matrix significantly improves the impact toughness and hardness of the material. The most considerable performance improvement was observed in specimens with the smallest reinforcement particle size (mesh 100). It is owing to the effectiveness of the load transfer mechanism, the quality of the interface bond, and the resistance to crack propagation that they increase in proportion. Therefore, it can be said that AGS waste is a very promising particle reinforcement material in Al6061.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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