Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 4	Month	: August
p-ISSN	: 1693-5462	Volume	: 23	Year	: 2025

Processing dates: received on 2025-07-16, reviewed on 2025-08-22, accepted on 2025-08-24 and online availability on 2025-08-30

Improvement of mechanical properties of aluminium matrix composites through addition of alumina by stir casting method

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Abstract

Aluminum is a material widely used in various industries. Aluminum has superior properties, one of which is corrosion resistance and good formability. However, one of the disadvantages of aluminum is that it has relatively low strength compared to other materials. Therefore, this study aims to determine the effect of adding various alumina to aluminum metal casting using the stir casting method on physical and mechanical properties. In this research, aluminum waste was used as the main matrix, and alumina powder (Al_2O_3) was used as reinforcing particles with weight fractions of 15%, 20%, and 25%. The material was melted at a temperature of 800°C and a stirring speed of 500 rpm for 5 minutes. Macro and micro observations were conducted using an optical metallography instrument. Mechanical testing included hardness testing using a Rockwell Hardness scale B instrument and tensile testing using a Universal Testing Machine. The test results showed several defects, including porosity, shrinkage, air holes, misruns, flash, and rough surfaces. Porosity and air pockets are usually caused by gas (especially hydrogen in aluminum) that is trapped during cooling due to insufficiently dry moulds or poor ventilation. The microstructure results show that Al_2O_3 agglomeration is highest at a 25% addition, which occurs because the stirring speed of 500 rpm is not sufficient to evenly distribute the Al_2O_3 particles. The highest hardness value is still found in the raw material (without reinforcement) at 73.33 HRB, while the material with the highest Al_2O_3 reinforcement at 25% addition has a hardness of 43 HRB. The highest tensile strength value was observed at the 25% alumina reinforcement parameter, with a value of 135.35 HRB, and the lowest at the 15% reinforcement addition, with a value of 128.64. The decrease in both hardness and tensile strength values compared to the raw material is attributed to alumina agglomeration.

Keywords:
Aluminium, AMCs, stir casting, Al_2O_3, tensile strength.

1 Introduction

Aluminium is the most promising engineering material after steel for modern society because it is widely used for food packaging, transportation, construction, automotive, and more [3]. Sir Humphrey DavySir Humphrey Davy discovered aluminium discovered aluminium in 1809 as an element, and was first reduced as a metal by Paul Herolt in France and C.M. Hall in America separately have obtained Aluminium metal from alumina by electrolysis of its fused salts. Until now, the Heroult Hall process is still used to produce Aluminium [4]. The characteristics that make this material a widely utilized material include light weight, strength, good corrosion resistance, attractive appearance, reliable electrical conductor, good heat conductor, and several other advantages possessed by this material [5]. Materials that have hard and lightweight properties usually use composite-based materials, including: Aluminium Silicon Carbide (Al-SiC), Zirconium silicate ($ZrSiO_4$), Aluminium Oxide (Al_2O_3), Boron Carbide (B_4C), etc. [6].

Aluminium Oxide (Al_2O_3), better known as alumina, is a commonly used reinforcing material in the production of stir casting composites. Alumina powder has good mechanical properties and is resistant to corrosion, so it can improve the mechanical properties and durability of the resulting composite [1]. Aluminium Oxide (Al_2O_3) is used as a reinforcing particle in metal matrix composites because it has good thermal stability, hardness and high Young's modulus. Aluminium Oxide (Al_2O_3) plays an important role in the resistance of Aluminium metal to rusting in air. Alumina powder has good mechanical properties and is resistant to corrosion, so it can improve the mechanical properties and durability of the resulting composite [6]. One of the methods used in Aluminium Matrix Composites (AMC) casting with Copper (Cu), Magnesium (Mg), and Silicon Carbide (SiC). Reinforcement is the stir casting technique, the method used in this technique is a stirring process with variations in rotation at each stage of casting [4]. Casting using the stir casting method to make AMCs.

Composites with synthetic fibre reinforcement have been used in various aspects of life, both in terms of use and technology. Their use is not limited to the automotive field, but has now penetrated other fields such as household and industry [7]. However, industry players still experience several obstacles, including not all supporting industries, such as raw materials and components made in the country. One of the efforts that can be made is to use raw components that can be produced independently in the country [5]. In recent years, the development of materials has become an industrial conversation in the world, for example, Aluminium matrix composites or other alloys. The application of Aluminium in the manufacture of various construction materials and machining tools and other equipment in everyday life, but the selection of materials has not been in accordance with the required criteria, for example the need for one of the materials that have properties that are hard, strong, tough, resilient, lightweight, resistant to high temperatures and various other capabilities in their use. Therefore, many composite materials or other alloys have been developed to overcome this problem [8].

Composites are a combination of two or more materials that have different phases into a new material that has better properties than both. In other words, composites are formed from two or more different materials into one material with the aim of improving the mechanical properties of the material they belong to [9]. AMCs are materials that continue to be developed in the automotive and aircraft industries, because they have several advantages as composites, such as increased stiffness, reduced density, greater strength, and so on [10]. Aluminium matrix composites also have low density, corrosion resistance and better elasticity [11].

The process used is the stir casting process, which is a metal forming process by melting Aluminium to its melting point, then mixing with alumina, and then pouring it into a mould. This study was conducted to determine the hardness properties of Al-SiC composites through the stir casting process by varying the rotational speed [6]. Metal matrix composites with nano-sized alumina particle reinforcement can be made using the stir casting method with the addition of Mg as an alumina wetting agent. In his research, he mentioned that the use of Mg in the stir casting method has the potential to reduce the clustering effect and increase the wettability of the reinforcement particles [12].

In the stir casting process, many parameters are involved and play an important role in determining the physical and mechanical properties of the material. These parameters include differences in pouring temperature, stirring time and stirring speed [13]. To obtain the optimal temperature and ageing process time that can produce the highest hardness value in alumina (Al_2O_3) reinforced Aluminium matrix composite materials [14]. Al-Cu-Mg-SiC composite forming material is weighed by mass fraction, where the composition of Cu, Mg, and SiC powder as reinforcement is 5%, 12%, 15% and the rest is Aluminium matrix. The Aluminium matrix is put into the furnace and heated to a temperature of 700°C, 750°C and 800°C when the Aluminium has melted down, alumina (Al_2O_3) into the furnace and stirred as the temperature is raised to 700°C, 750°C and 800°C then poured into the mold [4]. The stir casting method is one of the most economical and simplest techniques for producing AMCs, as it allows the mixing of reinforcing particles into molten aluminum through mechanical stirring. However, previous research has shown considerable variation, with some reporting improved mechanical properties, while others have found a decline due to porosity, agglomeration, and suboptimal particle wettability. The novelty and urgency of this research lie in two aspects: the use of aluminum waste as the primary matrix. This approach supports sustainability, cost efficiency, and serves as a solution for industrial waste utilization. The findings contradict most of the existing literature. This study shows that the addition of Al_2O_3 under certain stir casting conditions actually reduces mechanical properties. This contradiction is important to investigate because it emphasizes that process parameters (stirring speed, pouring temperature, and holding time) play a crucial role in determining composite quality.

Thus, this study aims to determine the effect of adding 15%, 20%, and 25% alumina powder on the physical and mechanical properties of aluminum matrix composites processed using the stir casting method with fixed parameters (stirring speed of 500 rpm, pouring temperature of 800°C, and holding time of 5 minutes). The results of this study are expected to provide a clearer understanding of the relationship between particle distribution, casting defects, and the mechanical properties of AMCs, as well as serve as a basis for optimizing process parameters in the future.

2 Research methodology

In this study, Aluminium waste was used as the main matrix, as shown in Fig. 1, and the chemical composition of the material is shown in Table 1. Alumina (Al_2O_3) powder was used to reinforce particles at mass fractions of 15%, 20%, and 25%. Alumina (Al_2O_3) in this study is used as reinforcing particles; alumina powder in this study is 220 mesh or equivalent to 60 microns. Al_2O_3 was chosen for its ability to improve the mechanical strength and wear resistance of Aluminium composites [2]. The alumina powder reinforcement material is shown in Fig. 2.

Fig. 1. Aluminium material.

Table 1. Chemical composition

Element	Prosentase (%)	Element	Prosentase (%)
Si	3.128	V	0.045
Fe	0.974	Sr	0.061
Cu	7.752	Zr	0.064
Mn	0.137	Co	0.161
Mg	0.430	Bi	0.171
Cr	0.323	Ca	0.039
Ni	0.180	Li	0.978
Zn	6.349	Sn	0.460
Ti	0.068	Al	77.06

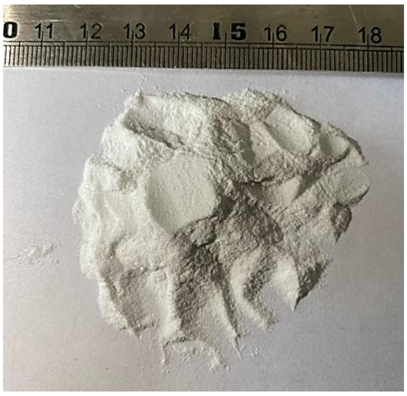

Fig. 2. Alumina powder.

The equipment used in this research includes a melting furnace (furnace) equipped with a stir casting system and electronic stirrer, metal moulds, optical microscopes, Rockwell Hardness scale B hardness tester and Universal Testing Machine (UTM), and scales and density measuring instruments are some other important tools. The main tools in the stir casting method are shown in Fig. 3.

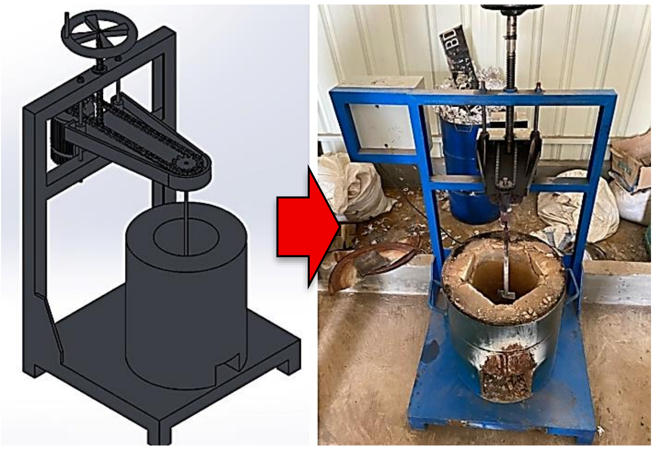

Fig. 3. Casting furnace and stir casting system.

The stages of the experiment began with preparing the materials. The Aluminium waste was cleaned and dried, and the Al_2O_3 particle reinforcement was weighed in stages according to the parameters of 15%, 20% and 25%. After that, Aluminium was melted in a casting furnace at 800°C. Furthermore, it is stirred with a mixer until it is well mixed at a speed of 500 rpm and held for 5 minutes. The results of the melting were poured into a mould that had been heated to a temperature of 300°C. Pouring of liquid metal using alligator pliers is done quickly to avoid a too drastic temperature drop. The fast pouring time is included so that the liquid metal can fill the entire mould cavity. After the cast product has cooled down, the mould can be opened. The schematic of the AMCs casting is illustrated in Fig. 4.

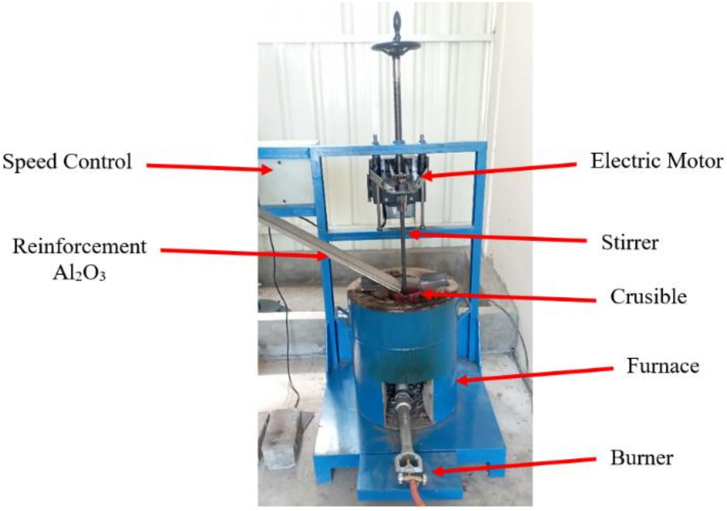

Fig. 4. Schematic of AMCs casting.

After the castings are cooled and removed from the mould, a series of tests is carried out, including observation of the results of casting defects. Observation of casting defects using photomacro. The next test is the observation of the microstructure of three specimens. The microstructure test specimens were then mounted using resin and smoothed using sandpaper with sizes 120, 220, 400, 800, 1000, 1500, 2000, as has been done by Kholis et al [15]. After smoothing the surface of the sample, followed by the etching process using chemicals including 2 ml HF, 5 ml HNO_3, 3 ml HCL and 190 ml Aquades, the use of these chemicals is in accordance with ASTM E407-07. 3 [16]. The next test is hardness testing using Rockwell Hardness Scale B. The next test is tensile testing; the specimens used in tensile testing are 3 samples/parameters. Tensile testing uses a UTM tool with a capacity of 10 tons of the GOTECH brand. Tensile test specimens according to ASTM E8M standard [17], as shown in Fig. 5. All tests of the research specimens were conducted at the Materials Engineering Laboratory of University of Wahid Hasyim.

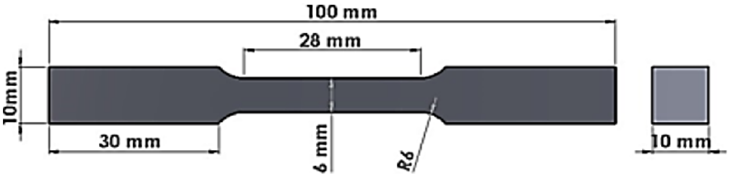

Fig. 5. ASTM E8M tensile test standard specimen [17].

3 Results and discussion

3.1 Casting defect

The observation results of casting defects in this study are shown in Fig. 6, which shows that casting defects can occur due to several factors, such as casting methods, material composition, and mould conditions. The casting results show several defects, including porosity, settlement, air holes, misrun, flash, and rough surface. Porosity and air holes are usually caused by gases (mainly hydrogen in Aluminium) trapped during cooling due to poorly dried moulds or poor ventilation. The absence of a liquid metal supply while cooling is a result of inefficient riser design. Misruns and cold caps occur due to too low casting temperature or low metal fluidity, so that the metal cannot fill the mould. Rough surfaces occur due to moulding sand that is too coarse or too high of a pouring temperature.

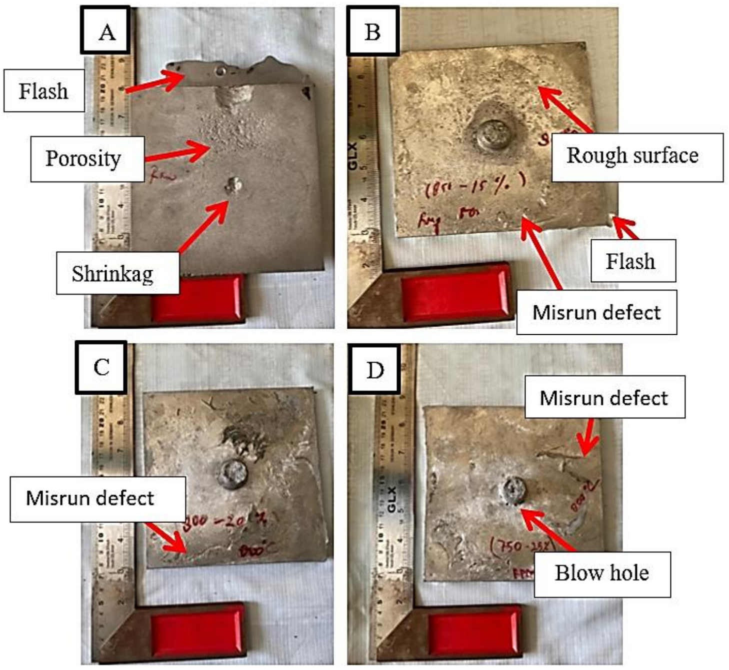

Fig. 6. Casting defects, (a) unreinforced material, (b) Al-Al_2O_3 15%, (c) Al-Al_2O_3 20%, and (d) Al-Al_2O_3 25%.

To avoid these defects, process controls such as mold drying, liquid removal, good gating and riser design, and the use of moulding sand with fine grain size are essential. These results are in line with previous research described by Mark Jolly in ScienceDirect on the relationship between process parameters and Aluminium casting defects [18].

3.2 Microstructure

Microstructure testing is conducted to observe the phase, grain morphology, and elemental distribution in the cast material. This examination uses an optical microscope after the sample has gone through the metallographic preparation stage, including polishing and etching. The microstructure test results can be shown in Fig. 7.

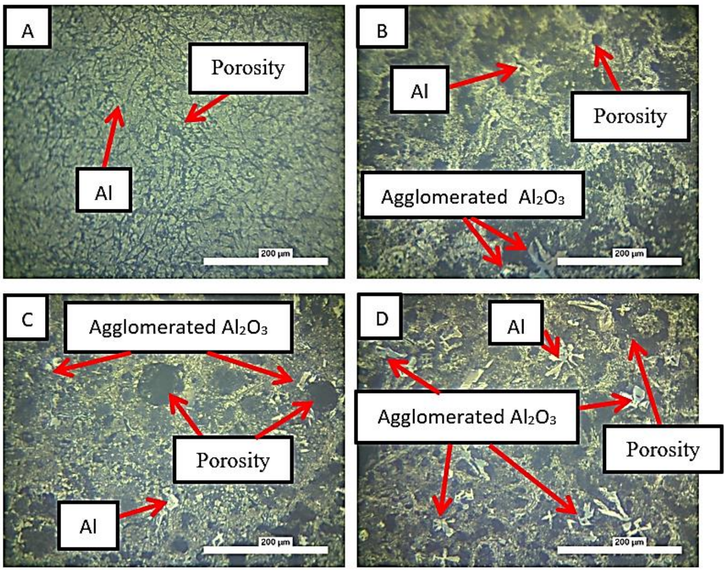

Fig. 7. Casting defects, (a) unreinforced material, (b) Al-Al_2O_3 15%, (c) Al- Al_2O_3 20%, and (d) Al- Al_2O_3 25%

Based on Fig. 7 of the microstructure, it can be seen that increasing the weight fraction of Al_2O_3 particles in Aluminium results in an increase in the amount of porosity and an increasingly even distribution of reinforcement particles, but also forms agglomerations at high levels. Fig. 7(a) raw material shows a pure Aluminium structure with minimal porosity. In Fig. 7(b)-Fig. 7(d), with the addition of 15%, 20%, and 25% Al_2O_3, there is an increase in the number of reinforcement particles and porosity. This occurs because the increase in ceramic particles increases the viscosity of the solution during stir casting, so the metal flow becomes less homogeneous and traps air, resulting in porosity. In addition, the dispersion of Al_2O_3 particles tends to be imperfect at high concentrations due to poor wetting between the Aluminium matrix and ceramic particles. This phenomenon is in accordance with the results of research by Thakur et al., who explained that increasing the volume fraction of reinforcement particles in metal composites can reduce the homogeneity of distribution and increase defects such as porosity due to turbulence and poor wettability during metal liquid mixing. [19].

3.3 Hardness test results

Hardness testing was carried out to determine the level of hardness of the material tested using the Rockwell Hardness B scale tool. Tests were carried out on several samples with variations of Alumina 0%, 15%, 20%, and 25%. The hardness test results can be shown in Table 2.

Table 2. Hardness test results

Prosentase %	HRB
0	73.33
15	40.33
20	41.66
25	43

The results of hardness testing values can be seen in Fig. 8, casting with a temperature of 800°C, where the highest hardness value is obtained at 25% alumina weight fraction, getting a value of 43 HRB. In contrast, the lowest hardness value is obtained at 15% alumina weight fraction, getting a value of 40.3 HRB. The raw material still exhibits the highest hardness value of 73.3 HRB, and the 20% alumina weight fraction achieves a value of 41.66 HRB. Tests were carried out at three points on the surface of the specimen. The tested points are on the left, center, and right sides of the specimen. In the hardness value, the more alumina, the higher the hardness value. The hardness value of the material decreased dramatically from 73.33 HRB (without the addition of Al_2O_3) to 40.33 HRB at 15%. After that, the value slightly increases to 41.66 HRB at 20% and 25% Al_2O_3 addition, respectively. As Table 2 shows, the hardness value of the material drops drastically. The Al_2O_3 reinforcing particles are unevenly distributed and form agglomerations, causing a decrease in hardness at the beginning of the addition. In addition, porosity increases due to ineffective mixing during the stir casting process. This porosity creates weak spots in the material's structure, significantly reducing its hardness. Higher amounts of reinforcing particles began to have a strengthening effect, which led to a gradual increase of between 20% and 25%. This is still not ideal as porosity is still high. Akash Deep et. al stated that agglomeration at high particle content can cause porosity to increase and the hardness of Aluminium-based composites to decrease [20].

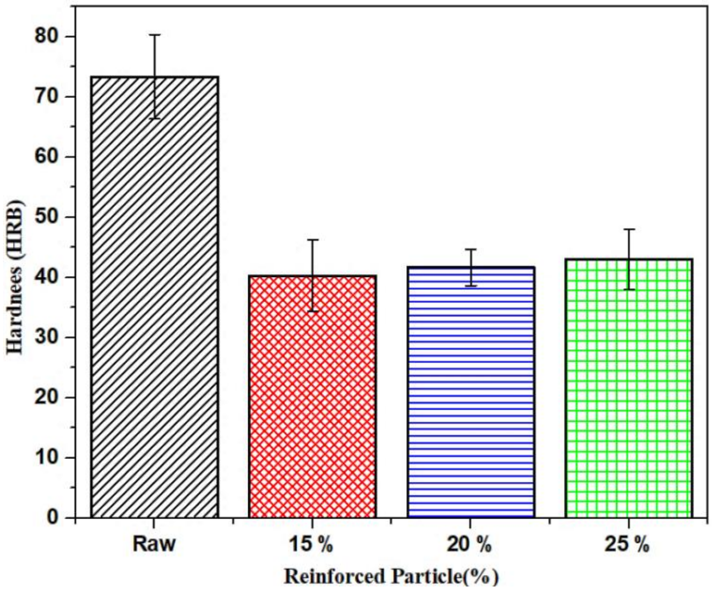

Fig. 8. Hardness value.

3.4 Tensile stress

The graph seen in Fig. 9 shows that the addition of Al_2O_3 particles to Aluminium shows a significant downward trend in Tensile Strength compared to the main material (without reinforcement). The yield stress value was 182.33 MPa, and the maximum stress was 208.21 MPa. A decrease in tensile strength was observed at 15% alumina reinforcement, the tensile strength value was 119.8 MPa, and the maximum tensile strength was 128.64 MPa. The tensile strength of the main material was still higher than that of the materials to which 15%, 20% and 25% alumina reinforcement was added. However, a gradual increase occurred with the addition of alumina reinforcement. Although Al_2O_3 theoretically strengthens the structure, this decrease is caused by porosity, which reduces the effective density and decreases strength and hardness. An increased agglomeration of Al_2O_3 particles in the aluminum matrix causes stress concentration and crack initiation. This agglomeration creates brittle areas that become crack initiators. However, suboptimal stir casting processes, such as stirring speed, temperature, and holding time, result in uneven particle distribution, which ultimately reduces mechanical properties.

When the particle distribution is not uniform, an increase in the reinforcement fraction can lead to porosity and a decrease in tensile strength, according to the research of Bharath et al. Therefore, in order to maximize the reinforcement effect of Al_2O_3 particles, it is very important to optimize the process parameters [21]. Stir casting at a stirring speed of 500 rpm may not be sufficient to ensure the homogeneous distribution of alumina particles at high concentrations. Stirring speeds that are not high enough may cause alumina particles to be unevenly dispersed in the Aluminium matrix.

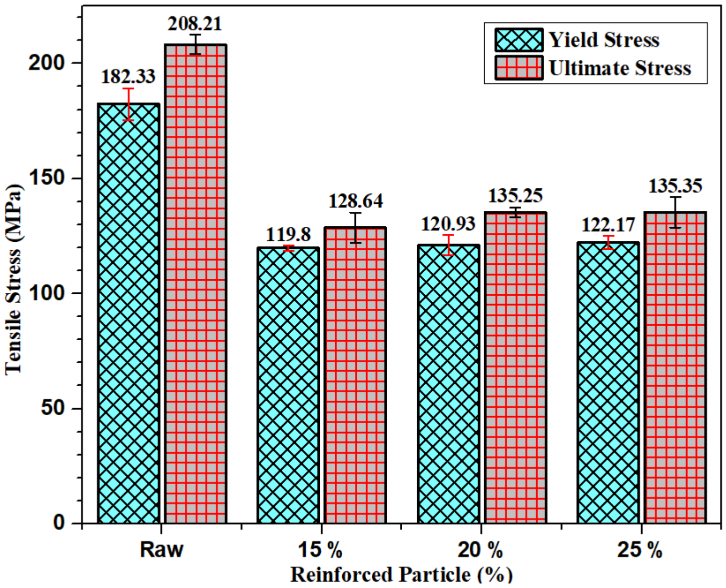

Fig. 9. Tensile stress.

3.5 Elongation

The decrease in elongation value in Aluminium composites reinforced with Al_2O_3 powder at a percentage of 15% to 25% is due to the addition of large amounts of Al_2O_3 powder, which tends to make the material more brittle as shown in Figure 10. The hard and brittle Al_2O_3 particles can inhibit the plastic deformation of the Aluminium matrix, thus reducing the ability of the material to stretch before fracture.

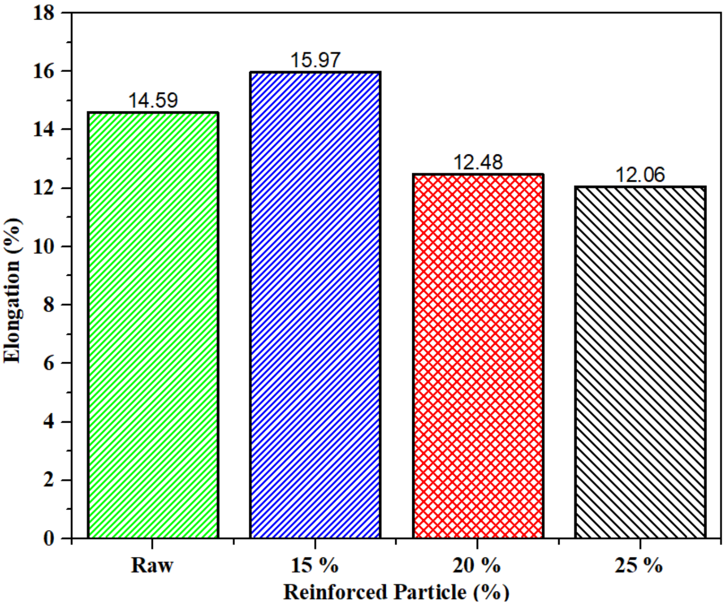

Fig. 10. Elongation.

At higher percentages, Al_2O_3 particles tend to gather into agglomerations or clumps. This agglomeration creates regions of high Al_2O_3 concentration and non-uniformity in particle distribution. The addition of large amounts of Al_2O_3 powder can increase porosity in the composite. Porosity is the presence of small cavities in the material that can act as crack initiation points. The hard and brittle Al_2O_3 particles can interfere with the plastic deformation of the Aluminium matrix. When the composite is deformed, these Al_2O_3 particles cannot conform to the plastic deformation of the matrix, thereby reducing the material's ability to stretch. The presence of pores leads to a decrease in the material's structural integrity and elongation properties. In addition, the nature of the Al_2O_3 particles not being able to follow the plastic deformation causes a deformation mismatch between the matrix and the reinforcement, which causes the microstructure damage to become more severe as the loading continues.

4 Conclusions

The results show that the addition of Al_2O_3 powder to the Aluminium casting process causes several defects, including porosity, misrun, blow hole, and shrinkage, which become more obvious at higher reinforcement compositions. The microstructure shows that the addition of Al_2O_3 causes uneven particle distribution and agglomeration at high concentrations, which also increases porosity. Hardness test results using the Rockwell B scale showed that the addition of 15% Al_2O_3 decreased the hardness significantly. A small increase occurred at 20% and 25%, respectively due to the particle reinforcement effect, which began to offset the internal defects. Tensile tests showed that the material without the addition of Al_2O_3 had the highest tensile stress with a yield stress of 182.33 MPa and ultimate stress of 208.21 MPa. The addition of 15% Al_2O_3 reduced the yield stress by 119.80 MPa and the ultimate stress by 128.64 MPa. The tensile stress values then increased at 20% with a yield stress value of 12.93 MPa and a maximum stress of 135.25 MPa, and 25% with a yield stress value of 122.17 MPa and a maximum stress of 135.35 MPa, but remained lower than the material without reinforcement. Overall, in order to reduce defects, improve microstructure homogeneity, and increase the mechanical capability of the material, increasing the Al_2O_3 particle content should be balanced with better process control.

Acknowledgements

With all humility, the author expresses his deepest gratitude to Lembaga Penelitian dan Pengabdian Masyarakat (LPPM) in University of Wahid Hasyim for the attention and support the Fiscal Year 2025 Fund has provided. Continued assistance from LPPM. We hope that this cooperation will continue in the future to advance education and research in Indonesia. We hope that this good cooperation can continue in the future to advance education and research in Indonesia.

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