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IMPROVEMENT OF WEAR-RESISTANT AND THERMAL CONDUCTIVITY OF ALUMINUM MATRIX COMPOSITE REINFORCED Al_2O_3/SiCw/Mg POWDER

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Technological progress demands the development of materials that have special characteristics such as high strength, stiffness, light weight, and good thermal conductivity at a low price. The development of hybrid metal matrix composites is the most important field in advanced materials science engineering.

This research determines about aluminum matrix composites (AMC) reinforced with alumina (Al_2O_3), Silicon carbide whisker (SiCw), and magnesium (Mg) addition. The matrix is made of 90 % pure aluminum powder, and commercially available reinforcing materials include Al_2O_3, SiCw, and Mg. Objectives include variation of reinforcement fraction and matrix, sintering holding temperature and time. The selection of the sample making process using powder technology followed by the sintering process at different temperatures namely 350, 450 and 550 °C with variations in holding time of 1, 2 and 3 hours. The purpose of this study was to determine the effect of variations in the fraction of reinforcement and sintering treatment on the properties of wear resistance, hardness and thermal conductivity of aluminum matrix composites.

The results showed that the composition ratio of reinforcement to aluminum in sintering treatment significantly affected the mechanical properties. The wear resistance of the material shows excellent performance, namely wear resistance of 0.000065 gr/s, hardness of 45.234 VHN and thermal conductivity of 184.855 Watt/m °C, at a reinforcement composition combination of 10 % Al_2O_3, 10 % SiCw and 20 % Mg and a sintering temperature of 550 °C. This indicates that the Aluminum matrix composite reinforced with Al_2O_3/(SiCw/Mg) is able to support the friction load due to its low wear rate, good hardness, and good thermal conductivity. This material is very suitable to be used as tribology material, brake element, especially brake drum

Keywords: aluminum hybrid composite, powder metallurgy hybrid Al_2O_3, SiCw/Mg, thermal conductivity, wear resistance

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1. Introduction

Composite is developed by combining two or more materials, each with chemical and physical properties, different from the final product [1]. Composite is formed from the combination of two or more constituent materials through an inhomogeneous mixture, resulting in product with different mechanical properties [2]. Composites offer many advantages when compared to metal alloys, especially those with high strength and stiffness and lightweight. The demand for high-strength, lightweight and low-cost materials is becoming an important requirement in the machinery industry [3].

Technological advances demand the development of new materials that have the properties of low density, light weight, high strength and stiffness. Aluminum matrix composite (AMC) is one material that has great potential to be developed to keep up with technological advances. Good mechanical and physical properties, low cost and relatively easy machining process. Many AMC applications are found in the automotive industry (such as pistons, cylinders, engine blocks, aerospace applications and the machining industry. Improvement of AMC properties is done by the addition of various reinforcements to the aluminum matrix. Several studies using non-metallic elements such as ceramic particles used as reinforcement in composites have received special attention because the resulting specific mechanical properties are superior compared to the base material. One of the advantages of specific mechanical properties such as strong material, toughness, durability and of course a lighter weight ratio.

Some commonly used ceramic particles/powders as reinforcement such as Al_2O_3, SiC, and B_4C are found in many MMC manufacturing applications [3].

The use of Alumina Al_2O_3 particles as composite reinforcement is particularly good because Alumina particles are capable of improving the overall mechanical properties of the composite.

In general, the process of adding reinforcement to composites uses the casting method, the reinforcement particles are added to the molten aluminum, then stirred. The stirring process sometimes generates bubbles that may be trapped in the composite material when solidification occurs. The trapped gas bubbles cause porous defects in the composite which results in a decrease in mechanical properties.

Studies on composite using aluminum powder added with SiCw and Mg showed that the thermal conductivity value increased with each additional pressure, while wear rate value decreased. Another study reported the significant effect of SiC reinforcing fiber [4] and Al_2O_3 particulates on composite characteristics.

The paper [5] examined the potential advantages of fabricating composites by powder metallurgy process, as a promising alternative as it is expected to grow rapidly compared to casting and other conventional methods. This research has explored the fabrication of aluminum hybrid composites using a mixture of fine aluminum powder as matrix with silica carbide (SiCw) and alumina (Al_2O_3) as reinforcement by powder metallurgy method.

The shape and size and type of powder as well as the distribution pattern of reinforcement particles are important considerations in the application of powder metallurgy. The finer the particles used, the more direct and homogeneous the distribution pattern will be which will form a stronger particle interfacial bond, which of course has an impact on strengthening the mechanical properties of the composite material. The technology is also well used to overcome the solubility of magnesium when using the stir casting method, because magnesium burns more easily when mixing in the aluminum melt.

Powder technology is very simple, requires lower temperatures and is also cost-effective. In the composite manufacturing process, only care is needed in determining the composition of the mixture, mold pressure and advanced heat treatment temperature, namely sintering temperature. Sintering treatment is very important to eliminate air bubbles due to the effect of oxidation due to pressure and process temperature.

Another study [6] reported the significant effect of sintering time and temperature on Al_2O_3/SiCw composite reinforcement. The results showed that the composite structure was more refined and homogeneous and evenly distributed.

In this context, the studies by determining the composition variation between aluminum matrix with Al_2O_3 reinforcement particles are scientific relevant. SiCw and Mg by powder metallurgy process method on the improvement of wear resistance properties and thermal conductivity of aluminum matrix composite. The application of powder technology is able to maintain the composition of Magnesium during the manufacturing process of composites because magnesium will not burn and evaporate. Aluminum Matrix composite reinforced with Al_2O_3 particles. SiCw and Mg are needed in the machining industry, automotive, tribology materials and lightweight materials that have good heat transfer.

2. Literature review and problem statement

Aluminum is a lightweight metal that has wide applications in the machining industry. Improvements in mechanical properties are made by adding other elements into new alloys. In the development of composite technology, aluminum is used as a matrix material and non-metallic elements such as ceramic elements as reinforcement [5]. Strong interface bonding forms new composite material properties such as better corrosion resistance, high wear, high thermal conductivity, aluminum metal matrix composites with high specific modulus are applied in various engineering fields. The changes in mechanical properties that occur in Aluminum matrix composites provide great potential in the development of advanced materials [3].

Aluminum Matrix Composite (AMC) has advantages in strength and resistance to friction. In addition, reinforcement using SiCw ceramic material is widely used as reinforcement due to its high hardness and wear resistance, [5]. Which exceeds the mechanical properties of the base material. Physical properties such as density and porosity of hybrid composites become better depending on the weight fraction ratio of reinforcement and composite matrix [6], The same research in the paper [6], also shows that the presence of SiC reinforcement particles in the Al matrix seems to have the ability to increase the hardness value of aluminum matrix composites.

In paper [7], examines the particle size characteristics of ceramics as reinforcement in Metal Composites of Aluminum. Manufacturing process uses stir casting. The weakness of the stir casting process is the presence of trapped air bubbles during solidification. The casting method is also not suitable for particles that are easily dispersible and volatile. The results showed the presence of lumps in the form of morphological defects due to weak bonding between reinforcements, Al_2O_3 and a combination of graphite (Gr) and ZrO_2. Especially the addition of MgO and SiC reinforcement has a positive impact on improving the mechanical properties of the composite. In this study, it was also found that the combination of MgO and SiC reinforcement particles clearly affected the microstructural properties of the alloy. The results of this study contribute to the selection of reinforcing materials in hybrid composites.

In work [8–13], showed the importance of Whisker alumina compound (Al_2O_3w) as reinforcement in aluminum matrix composites processed by powder metallurgy method. Alumina has a single crystal structure of AL_2O_3 and strong bonds are achieved between the crystals. The crystal structure of alumina remains physically stable up to temperatures around 1500–1700 °C. Variations in the composition and particle size of the Al_2O_3 reinforcement affect the hardness and wear resistance of the composite. Fabrication of composites using nanoscale Al_2O_3 reinforcement is very useful in specific applications in the aerospace field. Variations in composition and particle size of Al_2O_3 reinforcement affect the hardness and wear resistance of the composites. Some research results also show that adding hard reinforcements, such as $Al2O3$, increases the brittleness of the material, which is indicated by a decrease in the elongation percentage of the material during tensile testing.

In paper [8], the use of powder metallurgy in the manufacture of aluminum alloy-based metal matrix composites (MMC) is demonstrated. Composites containing a mixture of metal volume fractions and ceramic reinforcements such as SiC and Al_2O_3 that have been calculated are stirred evenly and then compressed according to the shape of the composite sample. The advantage of using powder technology is simple and efficient with a clean shape. Particle size selection is also very important in powder metallurgy. Particle size is an influential factor on the uniformity of reinforcement dispersion throughout the matrix. The smaller the particle size, the higher the agglomerate content in the composite structure. Particles also directly affect the porosity in the composite structure [7].

In work [9], authors investigate the same issue. and come to similar conclusion the study used a mixture of Al_2O_3, silicon carbide, fly ash, zircon, boron carbide reinforcement particles, the selected method stir casting, powder metallurgy. The results show that a mechanical and tribological properties of metal matrix composites depend on the distribution of reinforcement. The combination of stir casting and powder metallurgy can make the reinforcement distribution evenly distributed in MMC. The use of stir casting is more complex than the powder compacting method.

Based on previous studies, it is clear that the majority of researchers have conducted research to study the addition of reinforcement combinations on mechanical properties. However, little research has been seen in the determination of powder metallurgy effects on Al hybrid composites reinforced with Al_2O_3 (aluminum oxide), SiCw (silicon carbide whiskers) and Mg (Magnesium). A novel aspect of this research is the production of aluminum hybrid composites through the use of powder metallurgy process, process sintering treatment as well as variation of reinforcement addition with higher weight percentage fractions of SiCw and Mg particles into the composite simultaneously. Silicon carbide (SiCw) has properties such as high hardness and resistance to high temperatures and can be wetted quite well by Al, making it possible to incorporate these materials into new composites.

3. The aim and objectives of the study

The aim of the study is to determine composites using an Aluminum-based matrix reinforced with Silicon Carbide whiskers Al_2O_3/(SiCw/Mg) on the characteristics of mechanical and physical properties of composites. This contributes to new products that can be used for applications in machine elements that require materials with high hardness and thermal resistance.

To achieve this aim, the following objectives are set:

– determine the effect of temperature and holding time variable on wear resistance and Hardness of aluminum matrix composite;

– determine the effect of adding Al_2O_3, SiC and Mg reinforcement to the composite aluminum matrix on hardness properties of aluminum matrix composite;

– determining the effect of temperature and holding time sintering on the thermal conductivity of aluminum matrix composite reinforced with Al_2O_3, SiCw and Mg;

– determine the relationship of microstructure to wear resistance, hardness and thermal resistance properties.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this research focuses on the composite materials of aluminum matrix with the addition of a combination of Alumina (Al_2O_3), Silicon carbide whisker (SiC whisker) and Magnesium (Mg) reinforcement.

The research hypothesis shows the possibility of the influence of reinforcing particles in Aluminum matrix composites (AMC) on the improvement of hardness, wear resistance and thermal conductivity properties. The treatment of various fraction combinations between matrix and reinforcement is expected to produce composite materials that have high wear resistance and high thermal conductivity as well. The combination of various reinforcement treatments on Aluminum composites is expected to improve the wear resistance and thermal conductivity properties of composite materials that have a ratio of high strength and light weight.

The composite manufacturing process uses the powder metallurgy method with the assumption that the pressure process on the molding is even and uniform for the whole specimen.

4. 2. Materials

The matrix was made of 90 % pure aluminum powder, with a density of 2.7 g/cm^3, 95 HV hardness, 45 um grain size, dendritic average particle form, 72 GPa elastic modulus, and 6600 °C melting point. Commercially available reinforcement materials included Al_2O_3, SiCw, and Mg. The SiCw used had a diameter of 0.45 µm, length of 80 m, density (ρ) of 3.2 g/cm^3, hardness of 2400 Hv, free carbon of 0.30 %, and silica of 0.75 % by weight. Al_2O_3 particles had 3.8 gr/cm^3 density, 5 µm grain size, 1800 Hv hardness, 375 GPa elastic modulus, melting point of 1750 °C, 379MPa compressive strength, and 35 W/m°K thermal conductivity. Magnesium (Mg) had a density of 1.7 gr/cm^3, an elastic modulus of 410 GPa, a melting point of 651 °C, hardness of 260 VHN, a compressive strength of 3900 MPa, and a thermal conductivity of 156 W/m°K . This magnesium was used as a wetting agent, binding the matrix to the reinforcement, leading to a decrease in surface tension. A 96 % ethanol solution (CH_3COOH) was used as a mixing medium, while vaseline was applied to lubricate the mold walls, facilitating easy removal of specimens.

Initially, aluminum and Al_2O_3/(SiCw/Mg) were mixed using a magnetic stirrer. In this study, three compositions used, namely: A1 [Aluminum (80 %), Al_2O_3 (10 %)/SiCw (5 %)/Mg (5 %)], A2 [Aluminum (70 %), Al_2O_3 (10 %)/SiCw (10 %)/Mg (10 %)], and A3 [Aluminum (60 %), Al_2O_3 (10 %)/SiCw (10 %)/Mg (20 %)]. Sintering temperatures given to the matrix were 350 °C, 450 °C, and 550 °C, denoted as B1, B2, and B3, respectively. Holding times of 1.5 and 3 hours were used, denoted as C1 and C2, respectively. Subsequently, specimens were created in a cylindrical mold with a diameter of 30 mm and a height of 20 mm, as shown in Fig. 1.

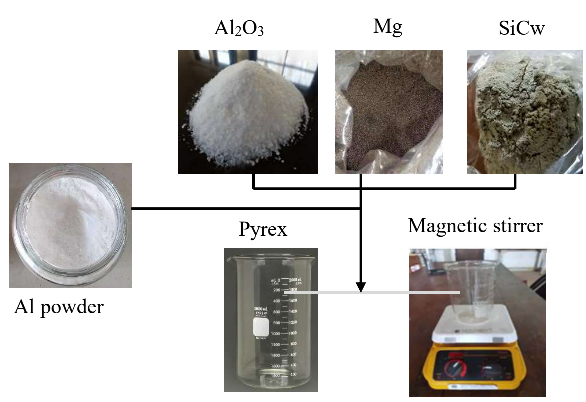


Fig. 1. Hybrid composite specimens manufacturing process

The specimens made are given symbols and names that correspond to the treatment codes. For example, specimen A1/B1/C1 composing aluminum (80 %), Al_2O_3 (10 %), SiCw (5 %), and Mg (5 %), was sintered at 350 °C for 1.5 hours. During this analysis, the characteristics examined included hardness, wear, and heat conductivity.

4. 3. Manufacturing of specimen

Manufacturing process of test material using powder metallurgy technology Fig. 2 shows the test material manufacturing process

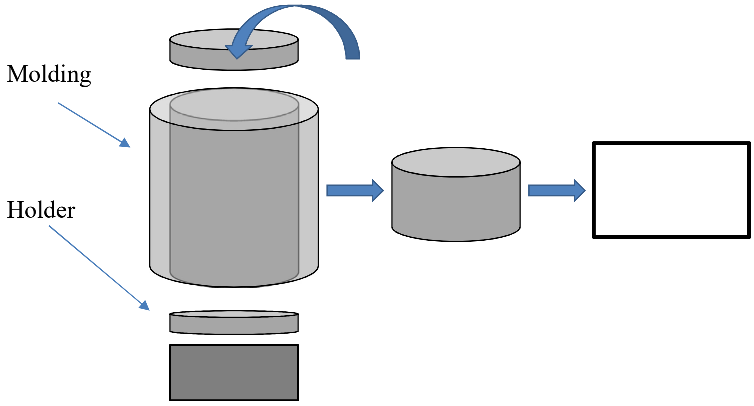


Fig. 2. Manufacturing process of hybrid composite spesimens

The powder material with the fraction of composite material composition that has been prepared (Fig. 1) is then inserted in a cylindrical molding. The pressure applied is 25 kN for each test sample. Specimens with a diameter of 30 mm and a thickness of 20 mm are sintered with temperature variations of 350 °C, 450 °C and 550 °C, respectively.

4. 4. Testing method

Wear resistance test. Wear is the loss of several surface layers of material due to friction between the solid surface and other objects. It has several mechanisms, namely abrasion, erosion, adhesion, fatigue, and corrosion. The wear testing process using the fin on disk method is as shown in Fig. 3. Wear rate is expressed by the amount of material loss or reduction (mass, volume, or thickness) per unit weight of the specimen with a unit time.

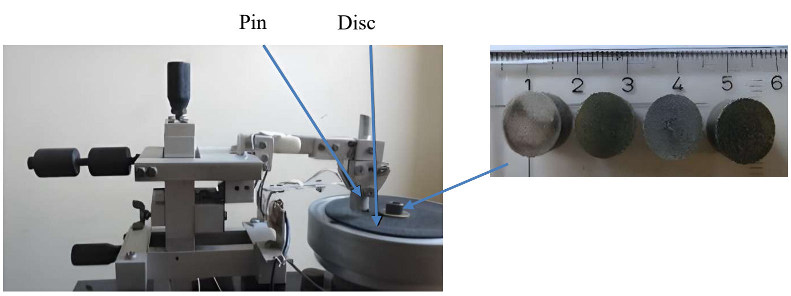


Fig. 3. Wear test tools and specimens

According to a previous study, [10] wear rate can be calculated by equation:

$$k' = \frac{w_0 - w_1}{l} = \frac{w}{l}, \tag{1}$$

where k' – wear rate (gr/cm), w_0 – initial weight of the specimen (gr), w_1 – final weight of specimen (gr), l – length of sliding distance (cm), and w – the difference in the weight of the missing scratches (gr).

Thermal conductivity test. Thermal conductivity is a measure of how heat is transferred by conduction through a unit cross-sectional area of material, when the temperature gradient exits perpendicular to that area. The value of thermal conductivity of material shows the rate of heat transfer flowing in a material. Specifically, thermal conductivity is a function of temperature and increases slightly as the temperature rises, although the variation is small and often negligible.

The thermal conductivity value is calculated using equation [11]:

$$q = -kA\frac{dT}{dX}, \tag{2}$$

$$k = -\frac{q \times dx}{AdT}, \tag{3}$$

where q – heat transfer rate (Watt), k – conduction heat transfer coefficient (Watt/m °C), A – cross-sectional area of the test object (m^2), dT – temperature difference (K), and dx – distance between test points ($T1$ and $T2$). In this test used $W=q=22$ Watt.

Fig. 4 shows thermal conductivity test equipment. This instrument is used to measure thermal conductivity capacity. The coefficient of thermal conductivity k is a constant that relates the heat flux Q to the temperature gradient $\partial T/\partial x$ and the unit is Watt/m °C or Watt/m.K.

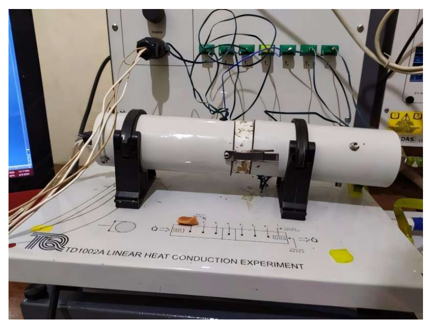


Fig. 4. Thermal conductivity testing set up

Thermal conductivity tests are carried out using the following thermal conductivity measuring instruments.

A test specimen measuring 30 mm in diameter and 20 mm thick, is inserted under load between two similar specimens of materials of known thermal properties. The test takes place, the ambient temperature is 19 °C and the heating power is 22 Watts.

At equilibrium conditions, the thermal conductivity is obtained from the average temperature gradient in each specimen and the thermal conductivity of the reference material. By using the one-dimensional conductivity equation, referring to equations (2) and (3), the thermal conductivity can be calculated.

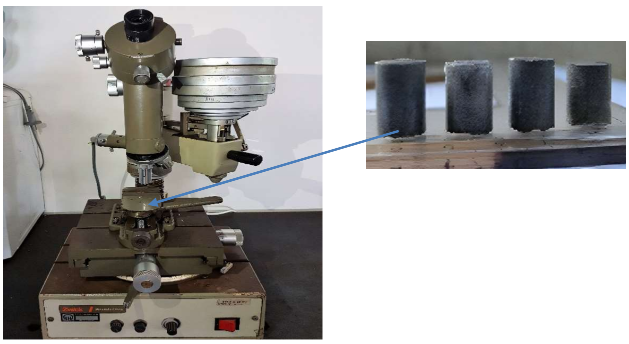
Hardness tests are performed on a Vickers hardness machine. The hardness instrument is shown in Fig. 5. For composite materials containing soft matrix and hard reinforcement phases. The selection of the test region in the sample to evaluate the hardness data is very important. Tests were carried out in each sample material with variations in matrix composition and composite reinforcement in each treatment.

Hardness Vickers test. The standard for Vickers hardness testing used ASTM E-92 macro range (1–100 kg). The test was repeated 3 times on each sample to determine hardness value, which was calculated using (4) [12]:

$$VHN = (1{,}854 \times P) / d^2, \quad (4)$$

where VHN – Vickers hardness number, P – given load (kgf), d^2 – diagonal mean square of indent (mm).

Fig. 5 shows the Vickers hardness testing equipment. Vickers hardness testing uses a diamond pyramid pounder whose base is square. The angle between the faces of the pyramid is 136°.



a *b*

Fig. 5. Materials and equipment for hardness: *a* – indenter tool and microscope; *b* – test specimen

4. 5. Scanning electron microscope (SEM) observations

Scanning Electron Microscope (SEM) used in this test was a JEOL JSM 5900 SEM type operating at 10 kV with magnifications of 20 µm, 100 µm, and 500 µm. SEM is an electron microscope used to analyze the microstructure of composite materials with the working principle including using two electron beams simultaneously. Specifically, one of the beams strikes specimen for testing and the other is directed to a Cathode Ray Tube (CRT) to provide the image. SEM uses X-rays that have a wavelength of 4×10^{-3} nm or approximately 100,000 times shorter than the wavelength of visible light, with a secondary electron serving as the detector.

5. Results of composition, sintering temperature, and holding time on hardness, wear resistance, and thermal conductivity and microstructure of aluminum composite matrix

5. 1. Effect of composition, sintering temperature, and holding time on wear resistance

The results showed the values of wear, thermal conductivity, and hardness for all composition treatment variables. The difference in the composition of matrix weight with each reinforcement is the composition (I, II, III), temperature (350 °C, 450 °C, 550 °C), holding time (1.5 and 3 hours), as shown in Table 1.

The results of wear test are shown in graphical form to facilitate discussion and present the relationship between composition, sintering temperature, and holding time. In this study, wear and tear test specimens were prepared following the ASTM G99-95 standard. Fig. 6 shows a graph of the relationship between the combined effect of sintering treatment and holding time on wear rate of material hybrid composite.

Table 1

Wear properties, thermal conductivity, and hardness of hybrid composite

Composition treatment variables	Wear (gr/s)	Thermal conductivity (W/m °C)	Harness VHN (kg/mm^2)
A1/B1/C1	0.0252	154.424	31.025
A1/B2/C1	0.0155	156.154	32.134
A1/B3/C1	0.00854	159.425	34.325
A2/B1/C1	0.021	158.895	35.554
A2/B2/C1	0.00995	159.556	36.654
A2/B3/C1	0.00375	161.275	38.865
A3/B1/C1	0.015	160.835	37.985
A3/B2/C1	0.00765	163.895	38.355
A3/B3/C1	0.003	167.455	40.012
A1/B1/C2	0.013	162.455	39.854
A1/B2/C2	0.0055	165.725	41.756
A1/B3/C2	0.00085	172.245	45.234
A2/B1/C2	0.0099	166.554	42.554
A2/B2/C2	0.0031	169.995	44.678
A2/B3/C2	0.00095	174.355	47.557
A3/B1/C2	0.00794	175.554	48.225
A3/B2/C2	0.00095	178.675	51.955
A3/B3/C2	0.00065	184.855	57.859

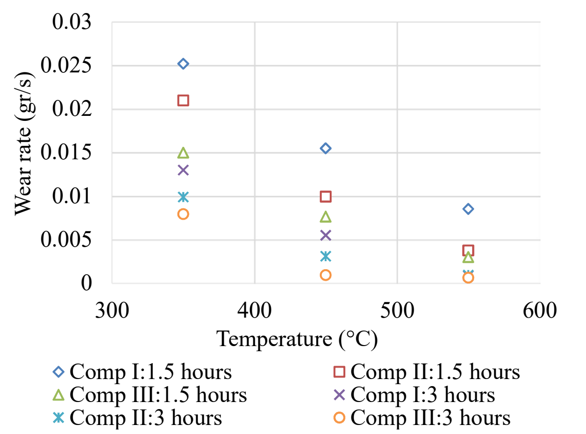


Fig. 6. Relationship between composite treatment and wear rate

The combination of reinforcing composition on aluminum matrix results in a decreasing wear rate value in the composition [A1, A2, A3], sintering temperature treatment [B1, B2, B3], and holding time [C1, C2]. Specifically, it was observed that a higher percentage of treatment combinations on the material led to a greater reduction in wear rate. This decrease was shown by combination of treatment A1/B1/C1, with wear rate of 0.0252 g/s, and A3/B3/C2 at 0.000065 g/s.

5. 2. Effect of composition, sintering temperature, and holding time hardness properties

The calculation of hardness value was carried out following (4) [12] and the results are presented in Fig. 8.

Fig. 7 shows the relationship between the combination of sintering temperature treatment, composition, and holding time to hardness value. The results showed that there was an increase in hardness in each treatment combination. The increase in hardness value in this hybrid composite study can be shown by the combination of treatment

A1/B1/C1 of 31.025 VHN to the combination of A3/B3/C2 of 57.859 VHN. At each sintering temperature, A2/B1/C1, A3/B1/C1, A1/B1/C2, A1/B2/C2, and A1/B3/C2 had values of 35.554 VHN, 37.985 VHN, 39.854 VHN, 41.756 VHN, and 45.234 VHN, respectively.

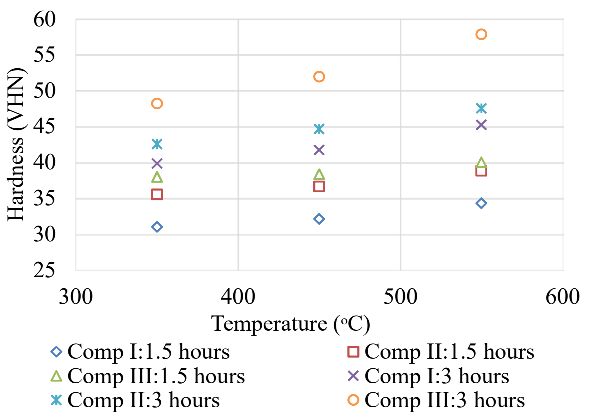


Fig. 7. Relationship between composite treatment and hardness

5. 3. Effect of composition, sintering temperature, and holding time on thermal conductivity

Fig. 8 shows the results of thermal conductivity test including the description of the material and thermocouple T1–T7, with the sensor reading distance from each thermocouple. Tests were carried out on each material with variations in different combinations of composite treatment and the result was calculated as the thermal conductivity value.

During testing, the room temperature was at 19 °C and the heating power was 66 Watt, according to the ability of the test machine. The results of the relationship between composite treatment and heat conductivity are shown in Fig. 7.

The results showed an increase in the thermal conductivity test on the combination of composition treatment, sintering temperature, and holding time, as presented in Fig. 7 Specifically, thermal conductivity increased from 154.425 W/m °C for A1/B1/C1 to 184.855 W/m °C for A3/B3/C2 of 184.855 W/m °C, at a holding time of 1.5 hours. In composition I, sintering temperature of 350 °C, 450 °C, and 550 °C resulted in thermal conductivity values of 154.425 W/m °C, 156.154 W/m °C, and 159.425 W/m °C, respectively at a holding time of 1.5 hours. In composition II, sintering temperature of 350 °C, 450 °C and 550 °C with a holding time of 1.5 hours, produced thermal conductivity values of 162.455 W/m °C, 165.725 W/m °C, and 172.245 W/m °C. In composition III, temperature of 350 °C, 450 °C, and 550 °C at a holding time of 3 hours resulted in thermal conductivity values of 175.554 W/m °C, 178.675 W/m °C, and 184.855 W/m °C.

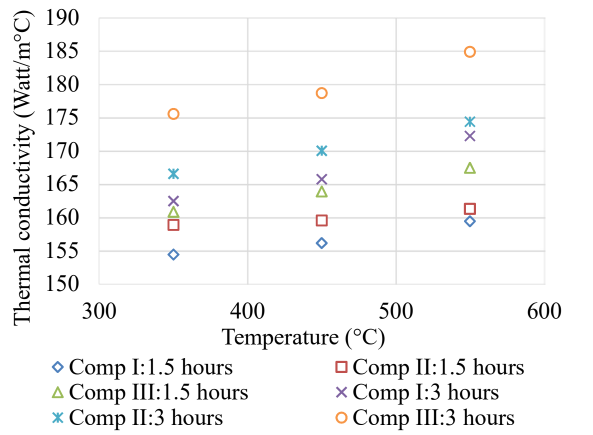
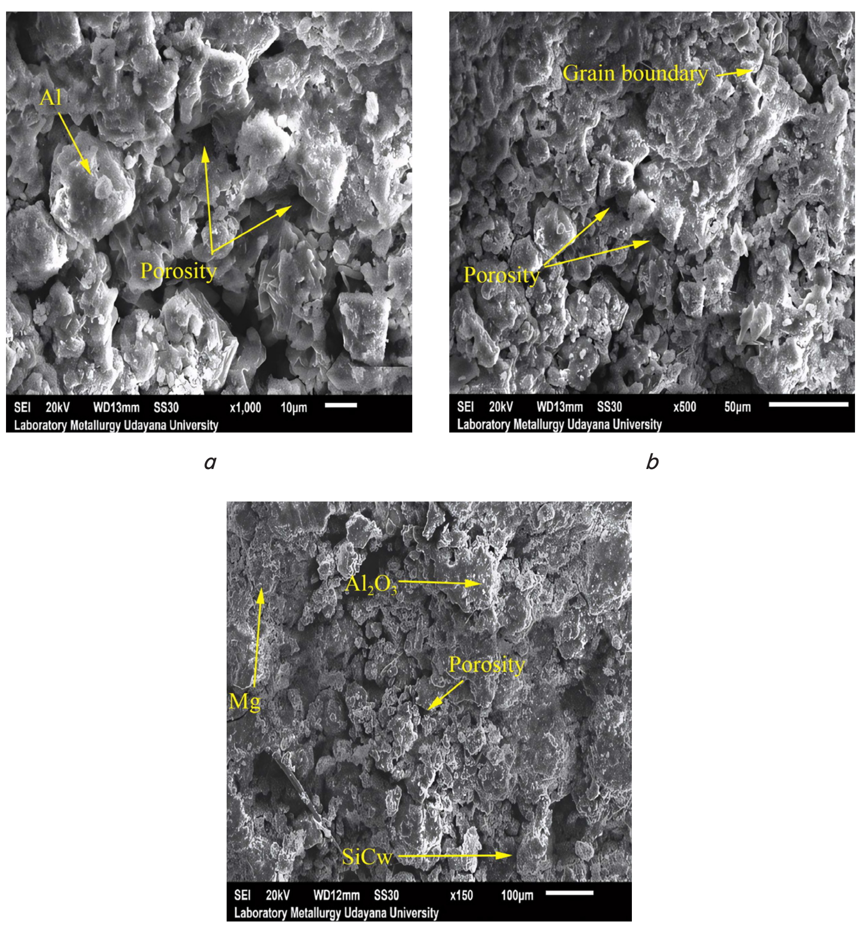


Fig. 8. Relationship between composite treatment and thermal conductivity

5. 4. Microstructure observation

Fig. 9–11 show microstructures of the composites by SEM, the results show the effect of the combination of material compositions at treatment sintering temperatures of 350 °C, 450 °C, and 550 °C with a holding time of 1.5 hours and 3 hours. The results showed denser microstructure, strong bond, and reduced pores due to variations in composition and sintering temperature treatment. This showed a visual and numerical correlation, indicating the effect of composition and sintering temperature treatment on composite.



a *b* *c*

Fig. 9. SEM photo of hybrid composite composition I at a holding time of 1.5 hours: *a* – sintering 350 °C; *b* – sintering 450 °C; *c* – sintering 550 °C

Based on the results of Fig. 9, *a–c* shows the internal condition of the material after wear testing of the composite composition of 80 % Al), 10 %Al_2O_3/5 %SiCw and 5 %Mg given different sintering temperatures. In the figure it appears that the higher the temperature the less porosity. As presented in Fig. 9, *a*, the composite result of 350 °C sintering temperature treatment has a higher wear rate than the composites treated with 450 °C and 550 °C sintering temperature. The porosity is more and the distribution of magnesium particles is not distributed evenly, which leads to low matrix strength. Fig. 9, *a-c* shows that the sintering temperature increases the strength and density of the composite, leading to a decrease in porosity, wear rate, and hardness, while the thermal conductivity increases.

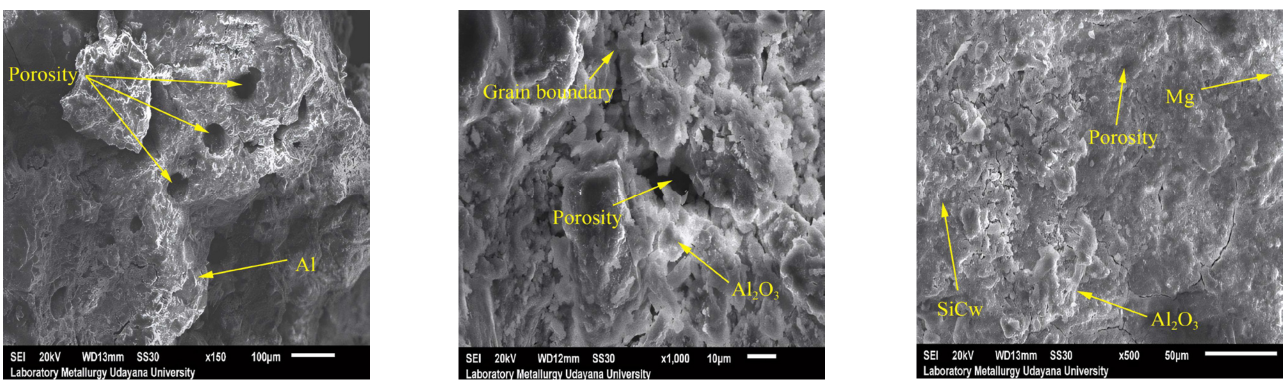
Fig. 10, *a–c* show the internal conditions of the hybrid composite of 70 % Al), 10 % Al_2O_3/10 % SiCw and 10 % Mg at different sintering temperatures. As presented in Fig. 10, *a*, the combined results of 350 °C sintering temperature treatment have a higher wear rate compared to the composites sintered at 450 °C and 550 °C.

Fig. 11, *a–c* show that as sintering temperature increased, the particles became closer, followed by a reduction in boundaries between grains. This phenomenon caused a reduction in porosity and wear rate, along with increased thermal conductivity and hardness values. Based on the results, it was concluded that a significant reduction in porosity of composite material led to improved hardness, thermal conductivity, and wear properties

6. Discussion of the results of the investigation of reinforcing particles in aluminum hybrid composites using the powder metallurgy

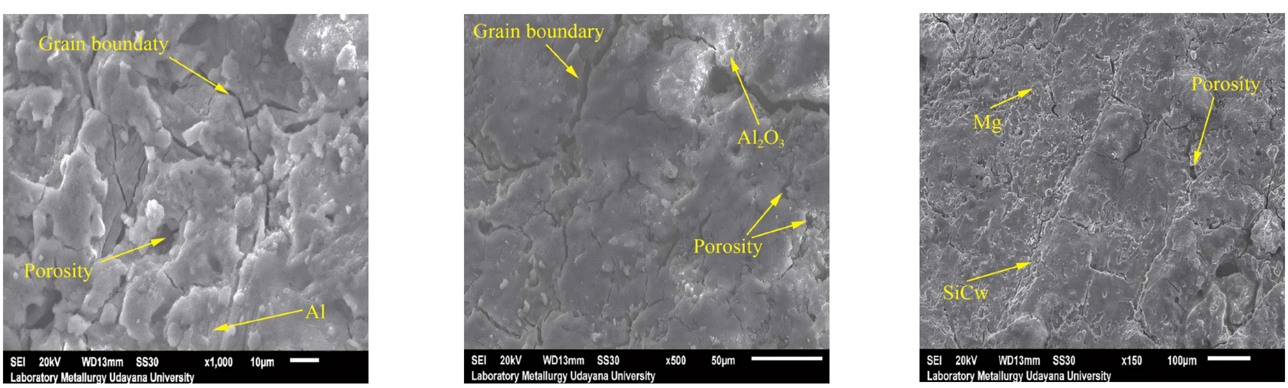
The significant result of this research is the improvement of wear resistance and thermal conductivity of aluminum matrix composite materials.

Fig. 7, 8 illustrate the graphical relationship of wear resistance and hardness at different reinforcement compositions and treatments. The trend of wear resistance and hardness graphs increases with the addition of reinforcing particles in the aluminum matrix composite. The effects of varying the content of reinforcement Al_2O_3 particles on the mechanical properties of the composites were investigated. The results showed that the addition of Al_2O_3 reinforcement led to a significant increase in hardness and wear resistance. Al_2O_3 was evenly distributed in each test sample. The alumina composition increased more evenly distributed which was shown by the increase in hardness in different test samples. The highest Vickers hardness values were observed for the composite samples with Al_2O_3. SiCw (10 %)/Mg (20 %), hardness increased by 44 % and wear resistance decreased by 387 % percent. The hardness of the specimens increases as the weight percentage of the reinforcement used increases and the particles are evenly distributed [13–21]. The increase in hardness value in the composite research is due to the high amount of magnesium (Mg), SiCw composition and sintering temperature. Harder SiC particles in the aluminum matrix, greatly impact the hardness of the composites [16, 22, 23]. This means that the addition of SiCw and Mg is highly recommended for use in the field of tribology.



a *b* *c*

Fig. 10. SEM photo of hybrid composite composition II at a holding time of 1.5 hours: *a* – sintering 350 °c; *b* – sintering 450 °c; *c* – sintering 550 °C



a *b* *c*

Fig. 11. SEM photo of hybrid composite composition III at a holding time of 1.5 hours: *a* – sintering 350 °c; *b* – sintering 450 °c; *c* – sintering 550 °C

Significant increase in strength and hardness of Al alloys reinforced with SiC and Alumina particles [7, 17]. The same trend of results was shown in paper [18] study, that the amount and distribution of nano-Al_2O_3 greatly affected the hardness of the composites due to the even distribution of the reinforcement and the refinement of the aluminum matrix grains. The 25 kN pressure compaction process, and the increase in sintering temperature on the composite sample can improve the mechanical bonding of Al and Al_2O_3. particles and contribute to a more even distribution. The characteristics of the flow of reinforcement particles during sample molding depend on the characteristics of the shape and size of the reinforcement particles, the finer the particles, the faster and more evenly distributed the particle flow. The difference in flow velocity is characterized by the difference in slip plane shear between particle grains. In the same paper also explained, there is an increase in hardness due to the inhibition of dislocation movement by Al_2O_3 particles.

Fig. 8 illustrates that the thermal conductivity increases with increasing reinforcement particles for all sample compositions. The thermal conductivity of Aluminum composites increases as the volume fraction of SiCw reinforcement in the aluminum matrix composite increases. Table 1 shows that there is a high increase in conductivity with increasing Al_2O_3, SiCw/Mg reinforcement at a sinter temperature of 550 °C, which is 184,855 W/m °C. The same thing is also shown in paper [19, 20, 24–26], that the high volume fraction of reinforcement produces a higher thermal conductivity value on the thermal conductivity value of the composite material. The porosity level decreases because the powder metallurgy process, followed by the sintering temperature treatment, is able to eliminate the porosity formed due to minor oxidation during the process. Fig. 9–11, a–c also clearly show that the higher the sintering temperature and holding time, the rarer the porosity.

The upward trend in the hardness of the composite illustrates that the particles present in the matrix have increased the overall hardness of the composite. Since the matrix is a soft material and the particles used as reinforcement are harder and contribute positively to the hardness of the composite. In addition, the effect of sintered holding time temperature has increased the hardness and wear resistance, due to the reduction in grain size of the composite. Comparison of Fig. 9–11 clearly shows the porosity of the aluminum composite material decreases. Small porosity forms a smooth surface during contact and tribology movements. The same research is shown in paper [6] that materials that have low porosity produce a low coefficient of friction, this is what causes inhibition of the erosion of SiC particles in the composite, because the friction force is less able to separate SiC particles. Materials that have good wear resistance characteristics are very suitable for use as brake component charts, especially brake drum.

One of the limitations of this research is that there has been no deep analysis of testing the movement of electrons and photon photons of reinforcing particles that make up the composite after mixing the matrix and reinforcement. This research also requires further development and analysis to predict mathematically the relationship of variations in composition, size and shape of the reinforcement to the thermal conductivity properties. Likewise, the analysis of the effect of contact stress between the surfaces of the grains that make up the composite material on mechanical properties is very important for a broader scientific contribution.

7. Conclusions

1. The highest aluminum matrix composite hardness is produced by composites with 10 % Al_2O_3, 10 % SiCw and 20 %Mg reinforcement with a sintering temperature of 550 °C, which is 45,234 VHN. Hardness increases with increasing weight fraction of reinforcement.

2. The variation of temperature and holding time affects the wear properties and hardness of the material. The wear resistance properties increased from 0.0252 gr/s to 0.000065 gr/s. The significant increase in wear resistance makes this aluminum composite material recommended for Tribological materials.

3. The thermal conductivity of the composite increased with the increase of temperature variation, holding time and reinforcement fraction (Al_2O_3·SiC/Mg). The highest thermal conductivity was 184.855 Watt/m °C in the Mg (20 %) reinforced composite.

4. The microstructure is more refined due to the treatment of temperature and holding time sintering increase. Aluminum matrix composite structure that is increasingly refined resulting in mechanical properties, especially hardness and wear resistance is getting better. The same thing also has an impact on the increase in thermal conductivity properties. The resulting hybrid composite material is very suitable for use as a drum brake because it has good wear resistance characteristics.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be made available upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the currrent work.

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