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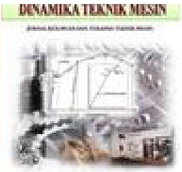

Characteristics of porosity properties and wear resistance of aluminum matrix composite (AMC) reinforced with silicon carbide (SiC) particles using stir casting method

A.H. Simangunsong[1], I.K.G. Sugita[*1], D.N.K.P Negara[1], I.M. Mara[2]
[1]Mechanical Engineering Department, Engineering Faculty, the University of Udayana, Jl. Raya Kampus UNUD, Bukit Jimbaran, Kuta Selatan, Badung, Bali 80361
[2]Mechanical Engineering Department, Engineering Faculty, the University of Mataram, Jl. Majapahit no. 62, Mataram, NTB, 83125, Indonesia. HP. 082111738971
*E-mail: tutdegita@unud.ac.id

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ABSTRACT

The use of composite materials with superior mechanical properties has become an important focus in addressing the challenges of continuously advancing technology, particularly for applications that require lightweight materials with high strength and good corrosion resistance. One material that has attracted considerable interest is aluminum due to its favorable physical, mechanical, and chemical properties. However, aluminum has limitations in terms of hardness and wear resistance, which still need to be improved. This study aims to evaluate the effect of adding silicon carbide particles (SiCp) on the porosity characteristics and wear resistance of aluminum matrix composites (AMC) produced using the stir casting method, which is a technique involving the mixing of molten metal and reinforcement particles through continuous stirring. The casting process was carried out at a temperature of 700 °C. The variations of SiC composition used were 0%, 1%, 2%, 3%, and 4%. Wear testing was conducted using the reciprocating ball-on-flat method in accordance with the ASTM G133-05 standard, while the porosity level was analyzed through immersion of the samples in a liquid fluid. The results show that an increase in the weight fraction of SiC leads to a reduction in the wear rate, with the lowest wear rate reaching 1.27×10^{-7} *g/cycle at a 4% SiC fraction and the highest at 0% SiC amounting to* 1.84×10^{-6} *g/cycle. In contrast, the porosity calculation shows an increasing trend from 1.85% at 0% SiC to 27.18% at a 4% SiC fraction.*

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1. INTRODUCTION

Astechnology advances and industrial demands increase, the development of materials with improved mechanical properties has become an important focus in addressing the challenges of continuous technological progress, particularly in the automotive and machinery sectors. Aluminum is one of the most widely favored

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metallic materials due to its abundant availability, ease of formability, and good corrosion resistance. In addition, aluminum is well known for its excellent thermal and electrical conductivity, making it a primary choice in various engineering applications.

Despite these advantages, aluminum also has limitations in terms of hardness and wear resistance. Its relatively low hardness makes the material prone to wear when used in components operating under frictional conditions, such as pistons, cylinders, camshafts, bushings, gears, and others (Wardhana, 2014). One approach to overcoming these limitations is the development of aluminum-based composite materials, known as Aluminum Matrix Composites (AMC), which are metal matrix composites where aluminum serves as the matrix combined with reinforcing materials such as silicon carbide (SiC) (Saefuloh, 2019). The fabrication of SiC-reinforced AMCs aims to enhance the mechanical properties of aluminum, particularly its hardness and toughness.

SiC has advantages over other ceramic materials because it is able to bond with aluminum and does not cause oxidation of the aluminum metal (Assidiq and Sulardjaka, 2014). One commonly used method for producing Aluminum Matrix Composites (AMC) is stir casting, which is a process of incorporating reinforcing particles into a molten metal matrix through mechanical stirring (Sarvani et al., 2024). The stir casting method has the capability to incorporate reinforcing particles that are naturally difficult to wet by molten metal, such as silicon carbide (SiC). The success of this incorporation is attributed to the stirring action generated during the process, which allows the reinforcing particles to be dispersed and entrapped within the molten metal matrix prior to solidification. In addition, this method is the simplest, relatively low-cost, suitable for high production rates, and does not require special equipment.

Severalinvestigations have demonstrated that the incorporation of silicon carbide (SiC) particles significantly enhances the mechanical properties of Aluminum Matrix Composites (AMC). In particular, a study utilizing the centrifugal casting method with SiC additions of 1.5%, 2.5%, and 3.5% indicated a progressive improvement in the composites' mechanical performance corresponding to the increase in SiC content. Microstructural examinations corroborated these findings, revealing a more uniform dispersion of SiC particles at the 3.5% fraction. The elevated SiC content facilitated more effective particle-matrix bonding, thereby contributing to the observed mechanical reinforcement (Fadel and Tugiman, 2015).

Another study conducted by Ashok and Krishnakumar (2018) investigated Al6063/SiC composites reinforced with 0, 4, 8, 12, and 16 wt% SiC powder using the stir casting technique. Their results demonstrated that the mechanical properties of the composites improved progressively with increasing SiC content. The maximum hardness of 93.15 HV was observed at 16 wt% SiC, surpassing that of the unreinforced aluminum (83 HV). Wear testing further revealed that the 12 wt% SiC composition exhibited the highest wear resistance, approximately 2.5 times greater than the base material, while the 16 wt% SiC composite displayed comparable wear performance. Moreover, Bharathi and Kumar (2023) reported that Al-MMC composites reinforced with SiC and B4C fabricated via powder metallurgy showed a 20.6% increase in hardness along with enhanced compressive strength and wear resistance, attributed to the uniform particle distribution. reported that Al-MMC composites reinforced with SiC and B4C produced through powder metallurgy exhibited a hardness increase of 20.6% and improved compressive strength and wear resistance due to the homogeneous distribution of particles. These observations align with Ranjitha et al. (2025), who found that Al6061 composites containing 6 wt% B4C and 3 wt% SiC achieved a hardness of 75.97 BHN and the lowest wear rate, indicating superior wear resistance relative to the pure aluminum matrix.

Basedon this background, this study focuses on the characteristics of porosity and wear resistance of Aluminum Matrix Composites (AMCs) reinforced with silicon carbide (SiC) particles, with reinforcement variations of 0%, 1%, 2%, 3%, and 4% added to pure aluminum using the stir casting method. The wear testing process was conducted using the reciprocating ball on flat method to evaluate the extent to which increasing SiC particle content influences the wear resistance and porosity level of the resulting composite.

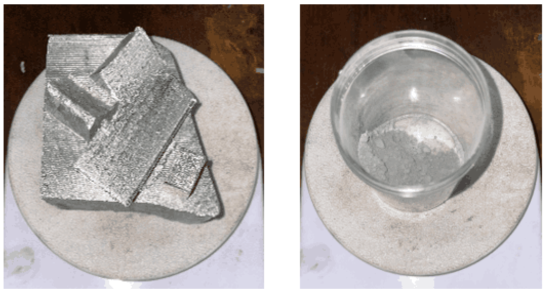
2. RESEARCH METHODS

2.1 Research procedure

This study employed a true experimental research method with the aim of analyzing the effect of adding silicon carbide (SiC) particles on the wear rate and porosity of Al/SiC composites. Figure1a shows the pure aluminum used in the casting process, and Figure 1b shows the silicon carbide (SiC) used as the reinforcing particles in mixing with the Al matrix. The independent variable in this study is the variation in silicon carbide (SiC) composition, namely 0%, 1%, 2%, 3%, and 4% SiC. The SiC particle size used was 320 mesh. The chemical composition of the pure aluminum is presented in Table 1 below.

The initial stage of this study involved designing the pattern and mold container using SolidWorks 2024 software, followed by the fabrication of the pattern and mold container from wood according to the predetermined design for producing a clay sand mold. After the mold was prepared, aluminum was melted in a crucible using a melting furnace until it reached a temperature of 700 °C. The slag on the surface of the molten aluminum was then removed or cleaned, and the melting temperature was reduced to a semi-solid condition at

650 °C to improve wettability. SiC particles that had been pre-heated at 200–300 °C were gradually added into the crucible and into the molten aluminum, then pressed into the melt using astainless steel spoon to ensure that the particles were coated by the aluminum matrix. Subsequently, the temperature was raised to 700 °C, and continuous stirring was carried out for 8 minutes at a rotational speed of 1000 rpm to achieve a uniform distribution of particles. The composite melt was then poured into a sand mold and allowed to solidify at room temperature. After solidification, the cast product was removed from the mold, cleaned, and machined to the dimensions required for testing

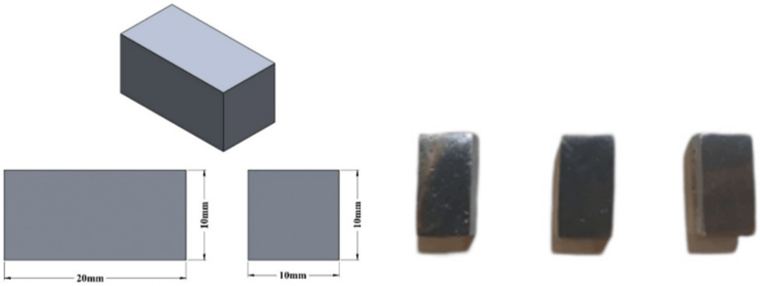


(a) (b)

Figure 1. Research materials: a) pure aluminium, b) silicon carbide

Table 1. Chemical composition of aluminium

Chemical composition (%)							
Al	Si	Fe	Ti	Mn	V	Ga	Mg
99.79	0.04	0.17	<0.01	<0.01	<0.01	<0.01	<0.01



(a) (b)

Figure 2. a) Specimen dimension design, b) As-Cast Al/SiC composite

2.1 Wear rate testing

Weartesting was conducted using the reciprocating ball-on-flat method in accordance with ASTM G133-05. In this test, the specimens were cut to dimensions of 20 x 10 x 10 mm, as shown in Figures 2a and 2b. Specimen wear refers to the amount of material lost due to contact and relative motion between two surfaces. The wear level can be expressed in terms of volume (m^3) or mass (g). The following is Equation 1 used to determine the wear rate:

$$Wear\ Rate = \frac{m_0 - m_1}{cycle} \tag{1}$$

where m_0 is the initial mass (g), m1 is the final mass (g), cycle is number of cycles during the test (5000 cycle).

2.2 Density and porosity testing

In the density test, the specimen dimensions were the same as those used for the wear rate test. The actual density was then measured using a digital densitometric balance. Density testing was based on Archimedes' principle. This method was carried out by comparing the weight of the sample in dry condition with its weight

when submerged in water. The calculation of actual density and theoretical density can be performed using the following equations:
The calculation of the actual density value was carried out using Equation 2.

$$\rho_m = \frac{m_s}{m_s - m_g} \times \rho_{air} \tag{2}$$

Whereρm is the actual density (g/cm^3), ms is the mass of the dry sample (g), mg is the mass of sample suspended in water (g),ρairis the density of water (g/cm^3).

The calculation of the theoretical density value was carried out using Equation 3.

$$\rho_{th} = \rho_{Al} \times V_{Al} + \rho_{SiC} \times V_{SiC} \tag{3}$$

Where ρth is the theoretical density (g/cm^3), ρAl is the density of Al (g/cm^3), ρSiC is the density of SiC (g/cm^3), VAl is volume fraction of Al, VSiC is volume fraction of SiC.

After that, the actual density value was compared with the theoretical density to determine the porosity value. The porosity calculation can be performed using Equation 4.

$$P = \left(1 - \frac{\rho_m}{\rho_{th}}\right) \times 100\% \tag{4}$$

Where P is the porosity (%), ρm is the actual density(g/cm^3), ρ is the theoretical density (g/cm^3).

3. RESULTS AND DISCUSSION

3.1 Wear rate test results

The results of the wear test on the Al/SiC specimens are presented in Table 2.

Table 2. Average calculated wear rate data

Composition	Cycle	Wear rate (g/cycle)
100% Al	5000	1.84 x 10^{-6}
99% Al + 1% SiC		1.05 x 10^{-6}
98% Al + 2% SiC		7.33 x 10^{-7}
97% Al + 3% SiC		3.20 x 10^{-7}
96% Al + 4% SiC		1.27 x 10^{-7}

Figure3 shows the relationship between the variation in silicon carbide (SiC) weight fraction and the wear rate of the specimens produced using the stir casting method. Based on the graph, a difference in wear rate can be observed between the pure aluminum specimen (without SiC addition) and the specimens reinforced with SiC. The graph indicates a gradual decrease in the wear rate as the SiC weight fraction increases.

At0% SiC fraction, the highest average wear rate was obtained, reaching 1.84 × 10-6 g/cycle. This indicates that the pure aluminum matrix without SiC reinforcement has relatively low wear resistance due to the softer nature of aluminum, which is more prone to plastic deformation during frictional contact. As the SiC fraction increases, the wear rate decreases. The lowest wear rate was observed at the 4% fraction, with an average value of 1.27 × 10-7 g/cycle. At this fraction, the higher presence of SiC particles provides greater wear resistance compared to pure aluminum. The hard nature of SiC contributes to increased surface hardness of the specimen, thereby reducing the wear that occurs.

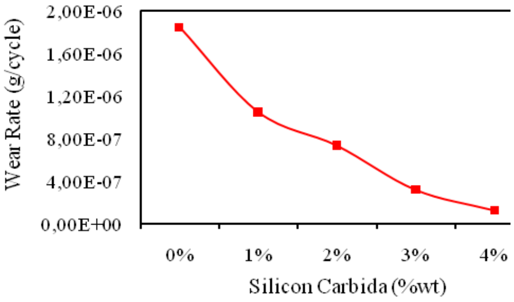


Figure 3. Effect of SiC fraction variation on wear rate

3.2 Porosity test results

The results of the porosity test for the Al/SiC specimens are presented in Table 3 below.

Table 3. Density and porosity test results

Composite	Actual density (g/cm^3)	Theoretical density (g/cm^3)	Porosity (%)
100% Al	2.65	2.70	1.85
99% Al + 1% SiC	2.38	2.70	11.85
98% Al + 2% SiC	2.06	2.70	23.70
97% Al + 3% SiC	2.00	2.71	26.19
96% Al + 4% SiC	1.97	2.71	27.18

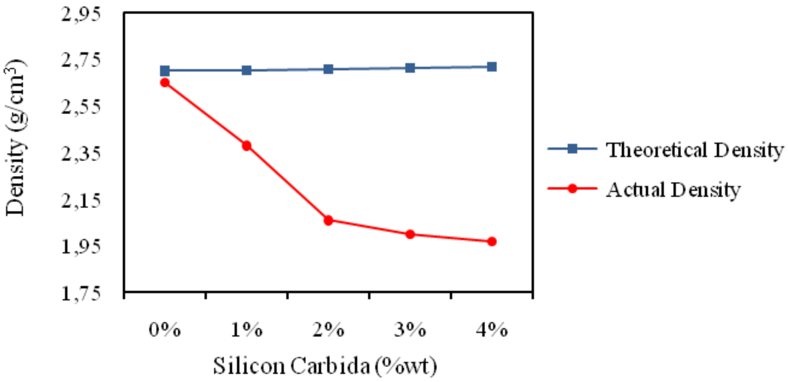


Figure 4. Effect of SiC fraction variation on theoretical and actual density

Based on Figure 4, the theoretical density shows a relatively constant trend, ranging from 2.70 to 2.71 g/cm3. This is because the theoretical density is calculated based on the density of each constituent and their fractional composition, and therefore is not affected by internal defects. In contrast, the actual density shows a decreasing trend with increasing SiC weight fraction. At 0% fraction, the actual density is closest to the theoretical density, at 2.65 g/cm3, then decreases to 2.38 g/cm3 at 1% fraction, 2.06 g/cm3 at 2% fraction, 2.00 g/cm3 at 3% fraction, and reaches the lowest value of 1.97 g/cm3 at 4% fraction. This decrease indicates an increase in the porosity formed during the casting process as the SiC weight fraction increases.

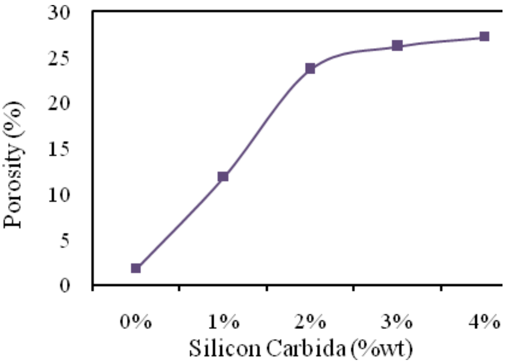


Figure 5. Effect of SiC fraction variation on theoretical and actual density

The porosity values shown in Figure 5 were obtained from the comparison between the theoretical density and the actual density at each variation of SiC fraction. Based on the graph, porosity shows an increasing trend as the SiC fraction increases. At 0% fraction, porosity has the lowest value, at 1.85%, indicating that the material structure of the specimen is relatively dense with only a small number of voids. This condition is also attributed to the more homogeneous flow of molten pure aluminum and the absence of reinforcing particles that could hinder mold filling and wettability during the casting process. In contrast, the highest porosity value occurs at the 4% fraction, reaching 27.18%. The high porosity at this fraction is caused by the increased formation of pores within the specimen. This is associated with the higher content of SiC reinforcing particles, which may lead to particle agglomeration, hinder the flow of molten metal into the mold, and trap air during the stir casting process. As a result, the material structure of the specimen becomes less dense and the porosity increases.

Based on the results shown in Figures 4 and 5, an inverse relationship between actual density and porosity can be observed. The decrease in actual density with increasing SiC fraction correlates with the increase in specimen porosity. The higher the porosity formed within the specimen, the lower the actual density due to the greater number of voids present in the material.

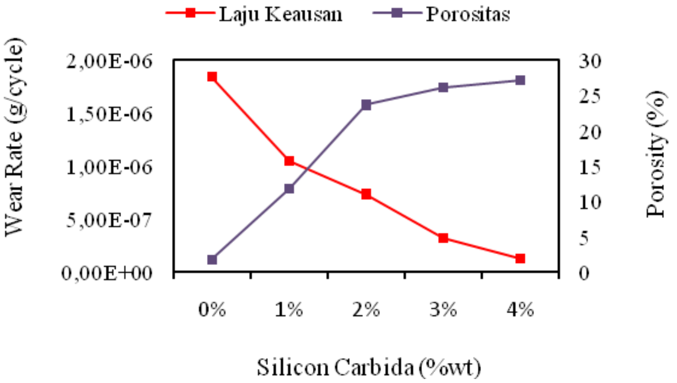


Figure 6. Effect of SiC fraction variation on theoretical and actual density

Based on Figure 6, the presence of porosity in Al/SiC composite materials does not necessarily lead to a higher wear rate, because in this study the effect of SiC reinforcing particles is more dominant than the negative influence of porosity on the mechanical strength of the material. As reported by Assidiq and Sulardjaka (2014) on the effect of physical and mechanical properties of Al/SiC composites with several SiC powder weight fraction variations of 0%, 5%, 7.5%, and 10%, the highest hardness value was obtained at the 10% fraction, reaching 72.3 HRB with a porosity of 3.7%, while the lowest hardness value was observed at the 0% fraction, reaching 55.15 HRB with a porosity of 0.37%. Another study by Chintada et al. (2022) on the mechanical behavior of Al/SiC composite materials produced using the microwave sintering method with SiC powder weight fractions of 5%, 10%, and 15% reported that porosity increased with increasing SiC weight fraction, with the highest porosity at the 15% fraction reaching 16.66% and the lowest at the 5% fraction reaching 6.28%. Despite the increase in porosity, the presence of harder SiC particles that were more strongly bonded within the Al matrix contributed to the improvement of the mechanical properties of the material. Test results showed that the hardness value at the 15% fraction increased to 121.5 VHN compared to pure aluminum at 93.5 VHN. Furthermore, Aigbodion and Hassan (2007) investigated the mechanical properties of Al–Si–Fe/SiC composites fabricated via the double stir casting method with SiC content ranging from 0 to 25%. Their results indicated that hardness and porosity increased by 75% and 39%, respectively, while the yield strength and ultimate tensile strength improved by 26.25% and 25%. This enhancement in strength and hardness was attributed to the uniform distribution of hard ceramic phases within the more ductile metal matrix. The incorporation of silicon carbide particles impedes dislocation motion and facilitates load transfer from the matrix to the reinforcing particles, thereby improving the composite's resistance to deformation.

4. CONCLUSION

This study investigated the effects of SiC reinforcement on the porosity and wear resistance of aluminum matrix composites (AMCs) produced via the stir casting method. The key conclusions are as follows:

1. In the wear rate test, increasing the silicon carbide (SiC) weight fraction resulted in a decrease in the wear rate of the Al/SiC composite. The highest wear rate was obtained at the 0% fraction (without SiC

addition), with a value of 1.84 × 10-6 g/cycle, while the lowest wear rate was obtained at the 4% fraction, with a value of 1.27 × 10-7 g/cycle. These results demonstrate that incorporating SiC particles through the stir casting method improves wear resistance, and that higher SiC fractions correspond to lower wear rates.

2. Increasing the SiC weight fraction led to an increase in porosity in the Al–SiC composite material. The lowest porosity value was obtained at the 0% fraction (without SiC addition), at 1.85%, while the highest porosity was obtained at the 4% fraction, at 27.18%. The porosity value obtained is inversely proportional to the actual density. The lower the actual density, the higher the porosity in the Al–SiC composite material. Furthermore, in this study, the presence of higher porosity in the Al/SiC composite material did not necessarily result in a higher wear rate, as the effect of SiC reinforcing particles was more dominant than the negative influence of porosity on the mechanical strength of the material.

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