Agitation Depth and Reinforcement Treatment on Tribology Characteristics of Aluminium particulated Composite under the Stir Casting Method

Fahmi Imanullah
Department of Mechanical Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Indonesia
imanullah147@gmail.com

Hammar Ilham Akbar
Department of Mechanical Engineering, Vocational School, Universitas Sebelas Maret, Surakarta, Indonesia
hammar_ilham@staff.uns.ac.id (corresponding author)

Eko Surojo
Department of Mechanical Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Indonesia
ekosurojo@staff.uns.ac.id

Dody Ariawan
Department of Mechanical Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Indonesia
dodyariawan@staff.uns.ac.id

Ganjar Pramudi
Department of Mechanical Engineering, Vocational School, Universitas Sebelas Maret, Surakarta, Indonesia
ganjar.pramudi@staff.uns.ac.id

Received: 9 January 2025 | Revised: 7 February 2025 | Accepted: 22 February 2025

DOI: https://doi.org/10.48084/etasr.10171

ABSTRACT

The stir casting process involves several key parameters, including agitation speed, agitation time, holding time, stirrer size and dimension, stirring position, and particle treatment. This study evaluates the effect of stirring depth and surface particle modification on the hardness and tribological properties of Al6061-Al_2O_3 composites. These composites were manufactured using the current method at a temperature of 720 ^oC, with an agitation speed of 600 rpm for 10 minutes. The reinforcement consisted of 6%wt Al_2O_3 particle, while 2.5%wt Mg was added as a wetting agent. The results indicate that the optimum stirrer depth was 30% of the molten metal height, leading to enhanced hardness (66.5 HBN) and reduced specific wear rate ($1.17x10^{-4}$ mm^3/Nm). Additionally, the electroless coating treatment at a stirrer depth of 30% improved wettability, further increasing hardness, and lowered the specific wear rate (70.2 HBN and $1.10x10^{-4}$ mm^3/Nm). These findings highlight the importance of stirrer depth optimization and surface modification techniques in enhancing the mechanical and tribological performance of Al6061-Al_2O_3 composites.

Keywords-stir casting; composite; aluminium; tribology properties; agitation

I. INTRODUCTION

In recent years, the demand for products that exhibit superior properties is increasing more and more. One such innovation is composite materials, which are composed of two or more different materials, to create a final product with enhanced characteristics. These materials offer advantages, including lightweight construction, corrosion-resistant, durability, low maintenance costs, and a long lifespan [1]. Composite materials are generally used in various industries, such as shipbuilding, aerospace, railways, and automotive manufacturing. In the automotive industry, Metal Matrix Composites (MMCs) are gradually utilized in pistons, cylinder heads and connecting rods [2]. One common MMC is Al6061 matrix which is reinforced with Al_2O_3, often called alumina. It offers high hardness, resistance to oxidation, and good chemical stability to the material [3]. The characteristics of MMCs are generally influenced by the properties of the matrix and reinforcing materials. Many researchers have focused on their development, having combined them with ceramic reinforcements, including Al_2O_3, SiC, B_4C, SiO_2, and others. This procedure provides several benefits, such as improved mechanical properties, better wear resistance, and better electrical and thermal properties, playing a crucial role in the overall performance of the material [4, 5].

The manufacturing of Al6061-Al_2O_3 composites is typically carried out using the stir casting process. Several parameters affect this process, including stirring speed, stirring time, holding time, casting temperature, stirrer size, and stirring position [6-8]. Hardness, thermal conductivity, corrosion resistance, and dimensional stability are some of the properties that are highly influenced. However, stir casting lacks in achieving uniform particle distribution and the existence of porosity in the final product [9]. Various researches have been conducted to optimize the mechanical and physical properties of AMC. Authors in [10] investigated the effect of stir casting parameters on the AMC parameters, revealing that the stirrer depth exerts an influence on achieving uniform particle distribution. Specifically, a stirring depth of 40% of the crucible height creates a well-formed vortex, preventing air bubbles from being trapped in the Al matrix, which is able to remove clusters of reinforcing particles. Thus, lower stirrer positions lead to high porosity and particle agglomeration. In [11], four shaped stirrer blade pitch turbines were examined with stirrer diameter ratios of 1/2 and 1/3, relative to the crucibles width. The stirrer depth was varied at 1/3, 1/2, 2/3, and 3/4 of the fluid height. The results indicated that positioning the stirring too close to the fluid surface does not achieve an optimal mixing . Another study conducted a stir casting simulation using a stirrer position of 20 mm from the bottom of the molten metal crucibles and a height of 65 mm. The experiment used both three-bladed stirrer and four-bladed, showing that effective mixing is essential for achieving uniform particle distribution [12]. To enhance the wettability between molten metal and reinforcement particles, some techniques have been proposed. One approach is adding wetting agents, such as Mg, to reduce the surface tension of molten aluminum, further mitigating aluminum oxidation, resulting in enhanced wettability [13]. Another method involves preheating the reinforcement particles before mixing them with molten metal to reduce moisture. In addition, coating reinforcement particles is also an effective strategy, which acts as a catalyst for subsequent coatings and continues until the reactant is depleted [14]. Specifically, electroless coating offers the advantages of relatively low cost, low processing temperature, and is independent of reinforcing geometry [15, 16]. Previous research investigated the effect of electroless coating on Al_2O_3 reinforcement particles [17]. Coating was developed by mixing the components into an electrolyte solution of HNO_3, Mg powder, and Al powder to form a thin spinel layer of $MgAl_2O_4$. During the manufacturing of Aluminum Matrix Composite (AMC), this layer plays an important role in bonding the interface, allowing the molten metal to effectively access the reinforcement particles by lowering the interfacial energy. A higher magnesium concentration in the electrolyte solution leads to an increased concentration of magnesium on the surface, further improving wettability.

Studies on the effect of stirring position using a three-blade impeller are limited, with some of them focusing on simulation methods rather that experimental performance. In this study, Al_2O_3 reinforcing particles were used, examining the agitation position in the stir casting process, using a three-blade impeller on aluminum composite performance to improve production efficiency.

II. MATERIALS AND METHODS

The manufacturing process of the Al6061- Al_2O_3 composite using the stir casting method, is illustrated in Figure 1. The setup includes a 3.5 kW stir casting furnace, controlled by an Autonics TX4s series temperature controller, and a ¼ HP motor to rotate the impeller. A TiO_2-coated three-blade impeller is used for agitation, including a 50 mm diameter and a 45° blade angel. The molten composite is thrown into a permanent steel mold. Al6061 is supplied from PT. Sutindo Surya Sejahtera, Surabaya, Indonesia is used as a matrix, as shown in Table I, while Al_2O_3 powder, obtained from PT Justus Kimiaraya, Surabaya, Indonesia is utilized as reinforcement, as evidenced in Table II.

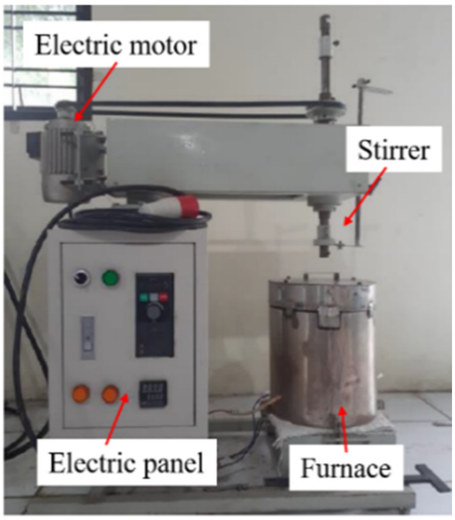

Fig. 1. Stir casting apparatus.

TABLE I. CHEMICAL COMPOSITION OF AL6061

Element	Wt%
Mg	0.8-1.2
Si	0.4-0.8
Fe	Max 0.7
Cu	0.15-0.4
Ti	Max 0.15
Zn	Max 0.25
Mn	Max 0.15
Cr	0.04-0.35
Al	Balance
Others	Max 0.15

TABLE II. SPECIFICATIONS OF AL2O3

Chemical composition				
Element	Al_2O_3	Na_2O	SiO_2	Fe_2O_3
(wt%)	99.6	0.30	0.02	0.02
Average Grain Size			**Specific Gravity**	
50 μm			3.92	

The electroless coating process begins with the Al_2O_3 powder cleaning using 96% alcohol, followed by drying in an oven at 100 °C for 10 minutes. Next, 40 ml of 68% HNO_3, 20 grams of Al_2O_3, 0.5 grams of fine Al powder, and 0.1 grams of Mg powder are mixed in a measuring cup, stirred with a magnetic stirrer, and heated at 70 °C for 45 minutes. The electroless Al_2O_3 is then dried in a furnace initially at 200 °C for 60 minutes, and afterwards at 400°C for 120 minutes.

The Al_2O_3 powder is tested with electroless coating treatment and without treatment. The stirrer depth varied at 30%, 45%, and 60% of the molten metal height. The composite characteristics are evaluated through density and porosity tests, microstructure observation, hardness testing, coefficient of friction testing, and specific wear rate testing. The manufacturing parameters of Al6061-Al_2O_3 composite are presented in Table III, and the specimen details are provided in Table IV.

TABLE III. MANUFACTURING PARAMETERS OF COMPOSITE

Parameters	
Casting temperature	720 °C
Stirring speed	600 rpm
Stirring time	10 min

TABLE IV. TABULATION OF AL6061-AL_2O_3 COMPOSITE SPECIMENS

Depth stirrer	Treatment	Specimen code
30%	Non-Electroless coating	NC-30
	Electroless coating	EC-30
40%	Non-Electroless coating	NC-45
	Electroless coating	EC-45
50%	Non-Electroless coating	NC-60
	Electroless coating	EC-60

For microstructure observation, Keller's reagent was used as an etching solution, consisting of 2ml HF, 3 ml of HCl, 5 ml HNO_3, and 190 ml of distilled water. Specimens were immersed in this solution for 20-25 seconds and then washed. Brinell hardness testing was performed following ASTM E-10 standards using a Contorlab Dia Testor 2RC (Controlab, Paris, France). Hardness measurements were taken at three points on each specimen using a 2.5 mm diameter steel ball indenter, with a load of 62.5 kg and a holding time of 30 seconds. The coefficient of friction testing was carried out by the tribometer type of pin-on-disc, with a speed of 2 m/s under a 20 N load. Each test was performed 3 times, and the results were averaged. Specific wear testing was conducted using the same pin-on-disc tribometer with a sliding speed of 2 m/s and a load of 20 N over a total distance of 2000 m. Each specimen was tested three times, and the average values were recorded. Density and porosity were calculated according to Archimedes principle, using (1)-(3) and a Vibra AJ-620E Precision Balance Analytical Scales (Shinko Denshi Co. Ltd., Tokyo, Japan):

$$\rho_{th} = \rho_m V_m + \rho_p V_p \tag{1}$$

$$\rho_{ac} = \frac{m_a}{m_a - m_w} \times \rho_{H_2O} \tag{2}$$

$$P = \left(1 - \frac{\rho_{ac}}{\rho_{th}}\right) \times 100\% \tag{3}$$

III. RESULTS AND DISCUSSION

A. Density and Porosity

Figure 2 illustrates the density calculation of the composite. The highest density was obtained at 30% stirring depth in the electroless coating treatment, and as depth increased, the density consistently lowered. The maximum density initiated the occurrence of vortex flow in the liquid metal. This flow encouraged the dispersion of reinforcing particles and resulted in interfacial bonding increasing the mechanical properties of composite [18].

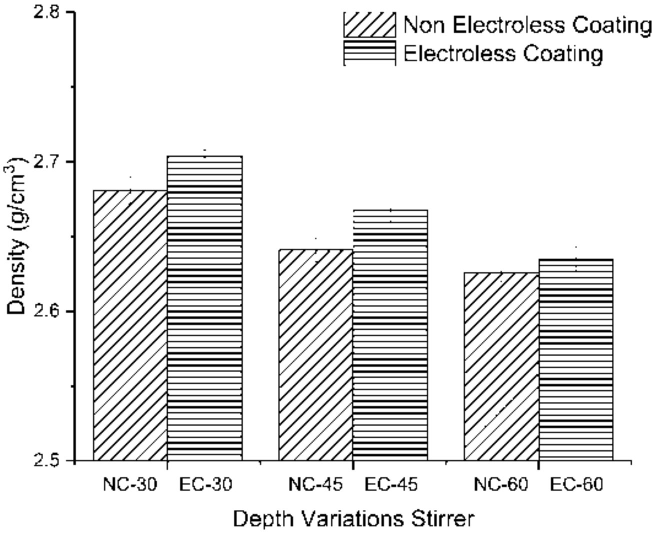

Fig. 2. Average density of the stirrer depth.

The influence of stirrer depth and the electroless coating treatment in porosity is presented in Figure 3. Porosity is inversely proportional to the density of the composite. The higher the density of a specimen is, the lower is its porosity. Additionally, the electroless coating treatment has an important impact on lower porosity, as an $MgAl_2O_4$ layer is formed on the surface of Al_2O_3, which is capable of lowering the surface tension of Al_2O_3 and Al matrix, while improving their bonding

[17, 19]. The lowest value is detected at a 30% depth with electroless coating treatment. Previous research demonstrated that the average porosity in aluminum composites ranges from 10 to 15% [20].

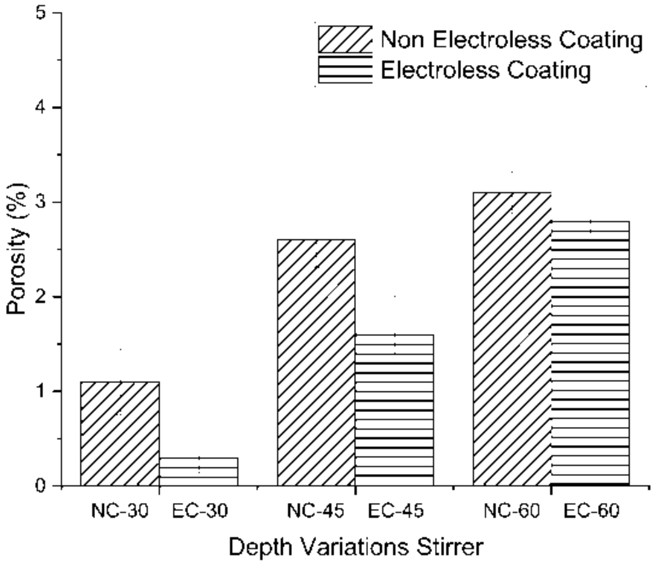

Fig. 3. Porosity of the stirrer depth.

B. Metallography Observation

Metallographic observations in Figure 4 display the influence of the stirrer depth against Al_2O_3 distribution as well as the percentage of the existing porosity. Position stirring close to the surface of the liquid fluid exhibited an increase in porosity. This increase is caused by the growth of the air trapped in the liquid metal, further trapped inside the molten metal [2, 21]. This observation is consistent with the data porosity, where the lowest porosity is presented in the stirrer depth variation 30% from the height of the fluid. Figure 5 compares the microstructure of specimen reinforcement Al_2O_3 without and with electroless coating at 30% stirrer depth. The treatment of $MgAl_2O_4$ electroless coating forms a layer that can reduce the surface tension between Al_2O_3 and the Al matrix to increase the bonding interface [18].

C. Hardness Test

Figure 6 depicts the effect of stirrer depth and electroless coating treatment on Brinell hardness values. The hardness of NC-30 was recorded at 66.5 HBN, while EC-30 exhibited a higher value of 70.2 HBN. Similarly, NC-45 showed a hardness of 54.5 HBN value, whereas EC-45 was measured 56.7 HBN. For NC-60, the hardness was 51.7 HBN, while EC-60 reached 53.4 HBN. It is obvious that the highest hardness value was observed at 30% of the stirrer height, indicating that an optimal stirrer position allows uniform Al_2O_3 distribution, enhancing hardness. When the stirrer is positioned too close to the molten metal surface, Al_2O_3 particles will settle at the bottom of the crucible [21], reducing the composite density, as portrayed in Figure 2. Density is inversely proportional to the porosity, meaning that higher porosity leads to lower mechanical properties [22]. The application of electroless coating improved hardness across all stirrer depth variations. Furthermore, electroless coating treatment enhances wettability and reduces particle agglomeration. Reduced agglomeration ensures better particle distribution, leading to more uniform mechanical properties. Improved wettability also strengthens the interfacial bonds between the matrix and reinforcement particles, significantly enhancing the overall composite performance [23].

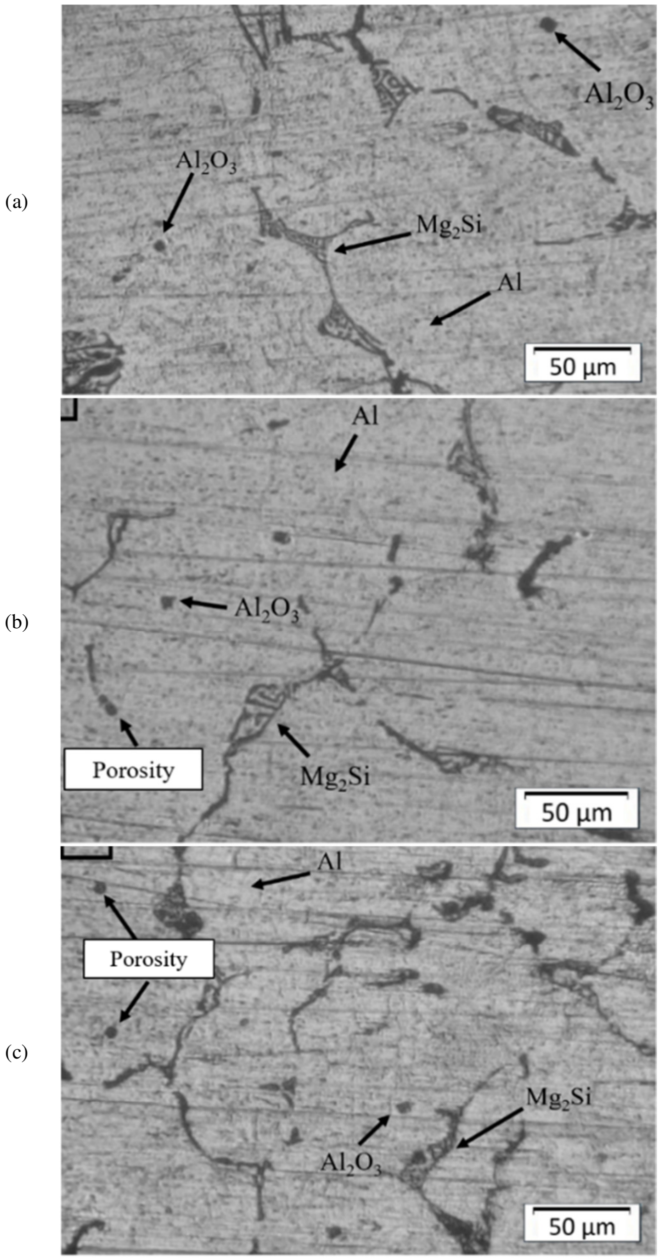

Fig. 4. Observation of metallographic specimens with electroless coating treatment with variation depth of stirrer: (a) 30%, (b) 45%, and (c) 60% from the height of molten metal.

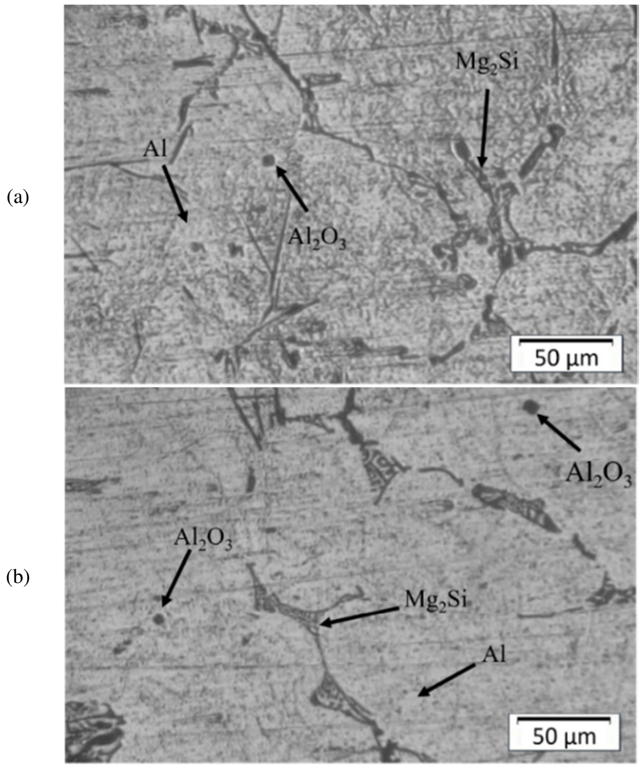

Fig. 5. Observation of metallographic specimens with a depth of 30% of the fluid stirrer (a) untreated and (b) with electroless coating treatment.

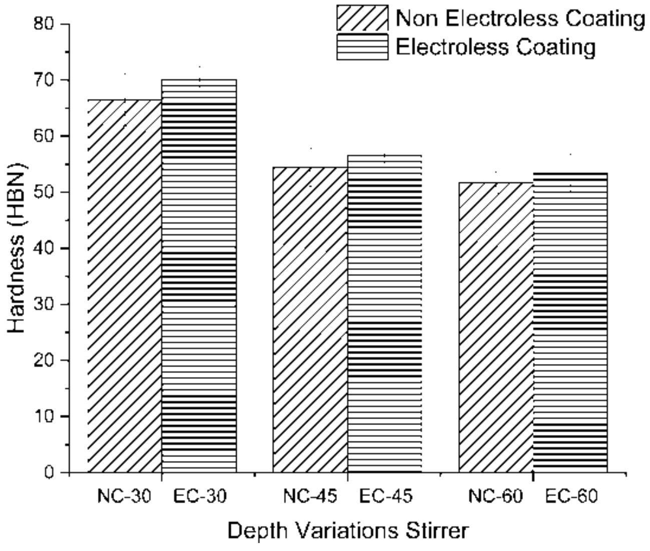

Fig. 6. Brinell hardness against the depth of the stirrer.

D. Coefficient of Friction

The highest coefficient of friction for untreated composites was observed at a stirrer position of 30% of the height fluid, with a value of 0.517. At this position, Al_2O_3 particles are distributed within the matrix, enhancing elastic modulus and hardness [24]. An increase in material hardness will further increase the coefficient of friction [25], due to the abrasive nature of Al_2O_3. Abrasive material serves to trap other components with lower hardness, thus increasing the coefficient of friction [26-27]. So, the more Al_2O_3 is bonded, the more increase occurs in the coefficient of friction [28].

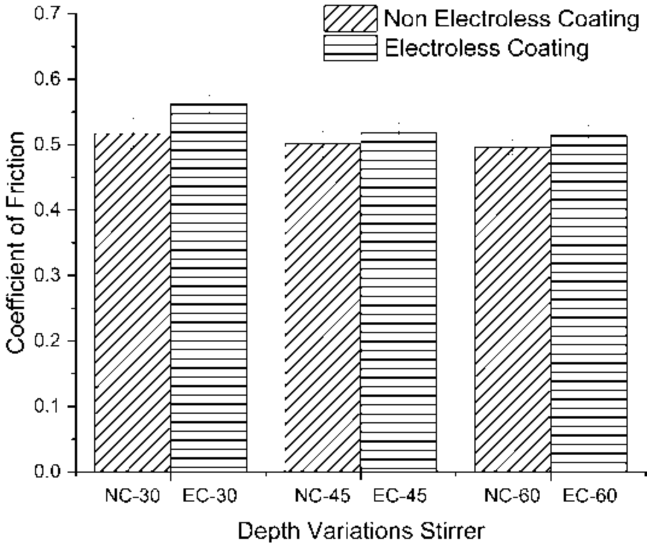

Fig. 7. The effect of stirrer depth on the coefficient of friction.

E. Specific Wear Rate

The term wear refers to a material's resistance to surface degradation due to its friction with other materials. The specific wear rate of the specimens was evaluated using a pin on disk tribometer. The results, as illustrated in Figure 8, revealed the influence of both stirrer depth and electroless coating treatment on the behavior of composites.

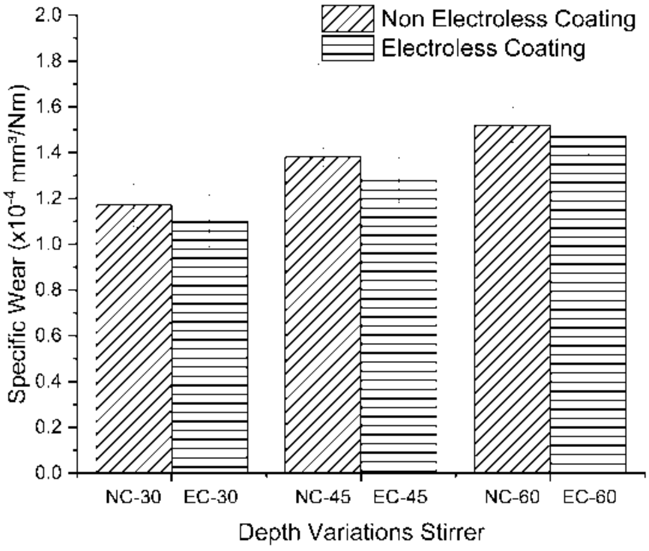

Fig. 8. The relationship between specific wear rate and stirrer depth.

The untreated composite (NC-30) with Al_2O_3 at a stirrer depth of 30% exhibited the lowest rate value of 1.17×10^{-4} mm^3/Nm. A lower value indicates higher wear resistance, which can be attributed to an increase in the material's hardness. So, the addition of Al_2O_3 particles not only increases the elastic modulus and hardness, but also improves wear resistance [23]. Additionally, electroless coating treatment at all stirrer positions further reduced the specific wear rate, maybe due to an improved bonding between Al_2O_3 and the Al matrix. These enhanced bonds help reduce porosity, leading to a decrease in specific wear and an increase in wear resistance [24]. Additionally, the specific wear rate of the composite correlates with its hardness, resulting in a higher friction coefficient, which in turn reduces specific wear [29].

IV. CONCLUSION

This study evaluates the effect of stirring depth and surface particle modification on the hardness and tribological properties of Al6061-Al_2O_3 composites. Based on the results, several conclusions were drawn:

- A 30% stirrer depth of the molten metal height resulted in the highest hardness (66.5 HBN) and lowest specific wear (1.17×10^{-4} mm^3/Nm), indicating better particle dispersion and reduced porosity.
- The electroless coating treatment of Al_2O_3 particles using Mg Al_2O_4 spinel formation improved wettability and interfacial bonding between the particles and Al matrix.
- The coated particles exhibited higher hardness (70.2 HBN) and improved wear resistance ($1.17x10^{-4}$ mm^3/Nm) compared to the untreated ones.
- The coefficient of friction was the highest at 30% stirrer depth, corresponding to the highest hardness.

From the above, it is evident that 30% stirring depth and the electroless coating treatment significantly enhance the mechanical properties of the composite.

ACKNOWLEDGMENT

This research was supported by RKAT PTNBH Universitas Sebelas Maret Fiscal Year 2024 through the FUNDAMENTAL RESEARCH scheme (PF-UNS) with Research Agreement Number: 194.2/UN27.22/PT.01.03/2024.

REFERENCES

[1] B. Chandra Kandpal, J. Kumar, and H. Singh, "Manufacturing and technological challenges in Stir casting of metal matrix composites– A Review," in *International Conference on Processing of Materials, Minerals and Energy*, Ongole, Andhra Pradesh, India, Jan. 2018, vol. 5, pp. 5–10, https://doi.org/10.1016/j.matpr.2017.11.046.

[2] V. Bharath, M. Nagaral, V. Auradi, and S. A. Kori, "Preparation of 6061Al-Al2O3 MMC's by Stir Casting and Evaluation of Mechanical and Wear Properties," in *3rd International Conference on Materials Processing and Characterisation (ICMPC 2014)*, Hyderabad, India, Jan. 2014, vol. 6, pp. 1658–1667, https://doi.org/10.1016/j.mspro.2014.07.151.

[3] M. D. Kiran, H. K. Govindaraju, and T. Jayaraju, "Evaluation of Mechanical Properties of Glass Fiber Reinforced Epoxy Polymer Composites with Alumina, Titanium dioxide and Silicon Carbide Fillers," in *International Conference on Advances in Science & Engineering ICASE -2017*, Lisbon, Portugal, Jan. 2018, vol. 5, pp. 22355–22361, https://doi.org/10.1016/j.matpr.2018.06.602.

[4] Md. T. Alam and A. H. Ansari, "Ceramic Materials and Stir Cast Aluminium Matrix Composites: A Literature Review," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 6, no. 7, pp. 14148–14160, Jul. 2017.

[5] M. O. Bodunrin, K. K. Alaneme, and L. H. Chown, "Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics," *Journal of Materials Research and Technology*, vol. 4, no. 4, pp. 434–445, Oct. 2015, https://doi.org/10.1016/j.jmrt.2015.05.003.

[6] L. Singh, S. Sehgal, and K. S. Kuldeep, "Behaviour of Al2O3 in aluminium matrix composites: An overview," in *3rd International Conference on Design and Manufacturing Aspects for Sustainable Energy (ICMED-ICMPC 2021)*, 2021, vol. 309, Art. no. 01028, https://doi.org/10.1051/e3sconf/202130901028.

[7] B. C. Kandpal, J. kumar, and H. Singh, "Fabrication and characterisation of Al2O3/aluminium alloy 6061 composites fabricated by Stir casting," in *5th International Conference of Materials Processing and Characterization (ICMPC 2016)*, Hyderabad, India, Jan. 2017, vol. 4, pp. 2783–2792, https://doi.org/10.1016/j.matpr.2017.02.157.

[8] K. Wang, W. Li, J. Du, P. Tang, and J. Chen, "Preparation, thermal analysis and mechanical properties of in-situ Al2O3/SiO2(p)/Al composites fabricated by using zircon tailing sand," *Materials & Design*, vol. 99, pp. 303–313, Jun. 2016, https://doi.org/10.1016/j.matdes.2016.03.064.

[9] A. Arifin and J. Junaidi, "Pengaruh Parameter Stir Casting Terhadap Sifat Mekanik Alumunium Matrix Composite (AMC)," *Flywheel: Jurnal Teknik Mesin Untirta*, vol. 1, no. 1, pp. 21–31, Apr. 2017, https://doi.org/10.36055/fwl.v1i1.1459.

[10] M. Saravana Kumar, S. R. Begum, and M. Vasumathi, "Influence of stir casting parameters on particle distribution in metal matrix composites using stir casting process," *Materials Research Express*, vol. 6, no. 10, Jun. 2019, Art. no. 1065d4, https://doi.org/10.1088/2053-1591/ab4045.

[11] G. Özcan-Taşkin and H. Wei, "The effect of impeller-to-tank diameter ratio on draw down of solids," *Chemical Engineering Science*, vol. 58, no. 10, pp. 2011–2022, May 2003, https://doi.org/10.1016/S0009-2509(03)00024-1.

[12] K. Vishnu Prasad and K. R. Jayadevan, "Simulation of Stirring in Stir Casting," in *International Conference on Emerging Trends in Engineering, Science and Technology (ICETEST - 2015)*, Trissur, India, Jan. 2016, vol. 24, pp. 356–363, https://doi.org/10.1016/j.protcy.2016.05.048.

[13] A. Sankhla and K. M. and Patel, "Metal Matrix Composites Fabricated by Stir Casting Process–A Review," *Advances in Materials and Processing Technologies*, vol. 8, no. 2, pp. 1270–1291, Apr. 2022, https://doi.org/10.1080/2374068X.2020.1855404.

[14] Y. Kim, J.-H. Jeong, and J.-C. Lee, "The Interfacial Reaction Products and Mechanical Properties with Oxidized Layer Thickness of SiC Particle in 2014Al/SiC Composites," *MRS Online Proceedings Library (OPL)*, vol. 654, Jan. 2000, Art. no. AA3.16.1, https://doi.org/10.1557/PROC-654-AA3.16.1.

[15] F. Kretz, Z. Gácsi, J. Kovács, and T. Pieczonka, "The electroless deposition of nickel on SiC particles for aluminum matrix composites," *Surface and Coatings Technology*, vol. 180–181, pp. 575–579, Mar. 2004, https://doi.org/10.1016/j.surfcoat.2003.10.150.

[16] H. Q. Gao, L. D. Wang, and W. D. Fei, "Electroless plating copper coating of Al18B4O33 whisker for interface improvement of whisker reinforced aluminium matrix composite," *Materials Science and Technology*, vol. 23, no. 12, Dec. 2007, https://doi.org/10.1179/174328407X239091.

[17] A. Zulfia and A. I. Adyatma, "Electroless Plating of Al2O3 Particles Reinforced Composites," *Advanced Materials Research*, vol. 789, pp. 66–71, Sep. 2013, https://doi.org/10.4028/www.scientific.net/AMR.789.66.

[18] B. Bihari and A. K. Singh, "An Overview on Different Processing Parameters in Particulate Reinforced Metal Matrix Composite Fabricated by Stir Casting Process," *International Journal of Engineering Research and Applications*, vol. 7, no. 1, pp. 42–48, Jan. 2017.

[19] A. Zulfia, D. Ramdaniawati, and D. Dhaneswara, "The Role of Al2O3 Nanoparticles Addition on Characteristic of Al6061 Composite Produced by Stir Casting Process," *International Journal of Materials*

Science and Engineering, vol. 6, no. 2, pp. 39–47, Jun. 2018, https://doi.org/10.17706/ijmse.2018.6.2.39-47.

[20] G. Tosun and M. Kurt, "The porosity, microstructure, and hardness of Al-Mg composites reinforced with micro particle SiC/Al2O3 produced using powder metallurgy," *Composites Part B: Engineering*, vol. 174, Oct. 2019, Art. no. 106965, https://doi.org/10.1016/j.compositesb.2019.106965.

[21] J. Hashim, L. Looney, and M. S. J. Hashmi, "Metal matrix composites: production by the stir casting method," *Journal of Materials Processing Technology*, vol. 92–93, pp. 1–7, Aug. 1999, https://doi.org/10.1016/S0924-0136(99)00118-1.

[22] K. Hemalatha, V. S. K. Venkatachalapathy, and N. Alagumurthy, "Processing and Synthesis of Metal Matrix Al 6063/Al2o3 Metal Matrix Composite by Stir Casting Process," *International Journal of Engineering Research and Applications*, vol. 3, no. 6, pp. 1390–1394, 2013.

[23] B. R. Mithun, M. Nagaral, V. Auradi, and V. Bharath, "Microstructure and Mechanical Properties of Cu-Coated Al2O3 Particulate Reinforced 6061 Al Metal Matrix Composite," *Materials Today: Proceedings*, vol. 4, no. 10, pp. 11015–11022, Jan. 2017, https://doi.org/10.1016/j.matpr.2017.08.060.

[24] J. R. Gomes, A. Ramalho, M. C. Gaspar, and S. F. Carvalho, "Reciprocating wear tests of Al–Si/SiCp composites: A study of the effect of stroke length," *Wear*, vol. 259, no. 1, pp. 545–552, Jul. 2005, https://doi.org/10.1016/j.wear.2005.02.088.

[25] G. B. Veeresh Kumar, C. S. P. Rao, and N. Selvaraj, "Studies on mechanical and dry sliding wear of Al6061–SiC composites," *Composites Part B: Engineering*, vol. 43, no. 3, pp. 1185–1191, Apr. 2012, https://doi.org/10.1016/j.compositesb.2011.08.046.

[26] M. Eriksson and S. Jacobson, "Tribological surfaces of organic brake pads," *Tribology International*, vol. 33, no. 12, pp. 817–827, Dec. 2000, https://doi.org/10.1016/S0301-679X(00)00127-4.

[27] A. Ugur, H. Gokkaya, G. Sur, and N. Eltugral, "Friction Coefficient and Compression Behavior of Particle Reinforced Aluminium Matrix Composites," *Engineering, Technology & Applied Science Research*, vol. 9, no. 1, pp. 3782–3785, Feb. 2019, https://doi.org/10.48084/etasr.2507.

[28] A. Mandal, M. Chakraborty, and B. S. Murty, "Effect of TiB2 particles on sliding wear behaviour of Al–4Cu alloy," *Wear*, vol. 262, no. 1, pp. 160–166, Jan. 2007, https://doi.org/10.1016/j.wear.2006.04.003.

[29] J. Singh and A. Chauhan, "Overview of wear performance of aluminium matrix composites reinforced with ceramic materials under the influence of controllable variables," *Ceramics International*, vol. 42, no. 1, Part A, pp. 56–81, Jan. 2016, https://doi.org/10.1016/j.ceramint.2015.08.150.