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COMPARATIVE TRIBOLOGICAL PERFORMANCE OF HYBRID METAL MATRIX COMPOSITE MANUFACTURE USING DIFFERENT CASTING METHODS

KOMPARATIVNE TRIBOLOŠKE PERFORMANSE U PROIZVODNJI HIBRIDNIH KOMPOZITA SA METALNOM MATRICOM UPOTREBOM RAZLIČITIH METODA LIVENJA

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Keywords
- Hybrid Metal Matrix Composites (HMMCs)
- stir casting
- tribology
- wear
- friction
- worn surface morphology
- pin-on-disk

Ključne reči
- hibridni kompoziti sa metalnom matricom (HMMC)
- vrtložno livenje
- tribologija
- habanje
- trenje
- morfologija istrošene površine
- pin-on-disk tribometar

Abstract

The tribological characteristics of Hybrid Metal Matrix Composites (HMMCs) are examined in this work. The Al6061 alloy used in the research of hybrid metal matrix composites is reinforced with 4 % B_4C and 1 % MoS_2 using a variety of stir casting techniques, including vacuum casting, rotary casting and squeeze casting. The Pin-on-Disk test examines wear with an emphasis on adhesive wear, abrasive wear, and weight loss using several factors. Also, the friction force is measured in relation to the wear loss. The purpose of the study is to evaluate how various casting techniques affect the material's wear resistance, friction force and connect it to worn surface morphology characteristics.

Izvod

U radu se proučavaju tribološke karakteristike hibridnih kompozita sa metalnom matricom (HMMC). U istraživanju se koristi legura Al6061 ojačana sa 4 % B_4C i 1 % MoS_2 primenom raznih metoda livenja, uključujući livenje u vakuumu, rotaciono livenje i livenje utiskivanjem. Metodom Pin-on-Disk ispitivanja sa tribometrom se određuje habanje sa naglaskom na ponašanje pri habanju, nalepljivanju, i na gubitak težine korišćenjem nekoliko faktora. Sila trenja se takođe određuje s obzirom na trošenje materijala pri habanju. Cilj rada je procena u kojoj meri razne metode livenja utiču na otpornost materijala prema habanju, silu trenja i na povezanost sa karakteristikama morfologije istrošene površine.

INTRODUCTION

Hybrid metal matrix composites made of aluminium alloy are regarded as advanced materials because of their special qualities which include strength, wear resistance, and low weight. All of these characteristics are necessary for parts including engine blocks, brake discs, piston rings, brake rotors and neutron radiation absorbers, which in particular need strong corrosion resistance /1-5/. This is a requirement for an industrial material, and no material found in nature can meet it except in composites /6-7/. When two or more dissimilar elements are combined, a composite material is created that performs better than any of the original materials alone /8-9/. Two primary phases, a matrix phase and a reinforcing phase must exist in the material combination /10-11/. Pertaining to the matrix phase, there exist three fundamental categories of composites: metal matrix, ceramic matrix, and polymer matrix /12-13/. The mechanical and tribological properties of HMMCs are improved by the metal matrix and hard particles used for reinforcement.

Aluminium metal matrix composite, or Al-MMC, is a material that is reinforced with various materials, primarily ceramics like SiC, Al_2O_3, B_4C, and so on, using aluminium or aluminium alloy as the matrix material. Al-MMCs exceptional qualities, including their light weight, excellent ratio of strength to weight, resilience to wear and corrosion, elevated thermal conductivity, and others, have led to their employment in a variety of fields, including aerospace, land and water transportation /14/. Al-MMCs have been fabricated using a variety of manufacturing processes by different researchers. The hardest substance, boron carbide, is created when carbon and B_2O_3 combine in an electric furnace. It is then processed and refined for use in industry by eliminating impurities. B_4C has a high melting point of 2445 °C and a density of 2.52 g/cm^3.

As a black solid with a metallic sparkle, boron carbide (B_4C) is one of the toughest ceramic materials known to man /15/. It serves as an alluring reinforcement for superior chemical and thermal stability. Furthermore, its density is lower than that of SiC and Al_2O_3 /16-17/. Due to its relatively high chemical and thermal stability, poor resilience, and low elasticity, molybdenum disulfide is employed as a solid lubricant. Consequently, it is unaffected by oxygen and weak hydrochloric acid. They can produce a great deal of dry lubricant-up film.

The physical characteristics and catalytic activity of MoS_2 particles are good, and they have a low coefficient of friction. Additionally, large dynamic surface areas have extended adsorption limits and increased reactivity compared to mass materials. By inhibiting metal-to-metal contact owing to the stable MoS_2 rich mechanical mixed layer, the hybrid reinforcement of MoS_2 increases the wear resistance of the composite material /18/. We have used stir casting to HMMCs Al6061 alloy, 4 % B_4C, and 1 % MoS_2 of Al6061 alloy are combined with the total material to create the composite materials. All of these casting techniques are used, including squeeze, rotary, and vacuum casting.

LITERATURE REVIEW

The study /18/ looks at hybrid composites Al6061 reinforced with MoS_2 and Al_2O_3, exhibiting improved tribological and mechanical properties. It demonstrates increased hardness and decreased wear rates, which qualify these composites for use in the automotive and aerospace sectors. Further investigation into various reinforcements and performance circumstances is advised. Kevorkijan /1/ examines developments in aluminium metal-matrix composites (Al MMCs) for use in automotive applications, emphasising difficulties with production technology, economy, and quality enhancements. In an effort to provide competitive alternatives to conventional materials in the automobile industry, it highlights the necessity of finer ceramic reinforcements and optimal processing techniques to improve mechanical qualities. Shape Memory Materials (SMMs) and their shape memory affect such as one-, two- and three-way transformations are covered in this review study. It investigates several actuation techniques and shape changing technologies such as active origami. Furthermore, it provides a thorough tabular presentation of the uses and future prospects of 4D printing /12/. Thevenot /15/ in 1990 gave a thorough analysis of boron carbide, including its mechanical characteristics, uses, and industrial preparation techniques. It shows the material's hardness, wear resistance, and thermal conductivity while going over other synthesis processes, such as the reduction of boron anhydride with carbon. All of these points highlight the material's importance in advanced materials science. In /4/, the authors examine stir-cast aluminium matrix composites (AA6061/B_4C) and highlight their exceptional mechanical qualities that make them excellent for usage in aeronautical and automotive industries. It describes mechanical tests and microstructure characterisation, showing that higher B_4C content increases tensile strength and hardness, indicating the composites' potential for use in industrial applications. The impact of boron carbide (B_4C) reinforcement on the mechanical properties of aluminium matrix composites (AMCs) is reviewed in this study report. While addressing issues including particle distribution and bonding, it emphasizes increases in tensile strength, hardness, wear resistance, and fatigue. The results highlight B_4C ability to improve AMC performance /17/.

All the studies that discussed above look at a single casting because it looks at the effects of tribology and different casting methods.

In this paper, our research is unique as it examines the tribological impacts and various casting techniques which are missing in the previous literature. Research is conducted using stir casting while keeping the process characteristics in mind. This also takes into account the morphology in addition to the wear test and friction force. This sets our research apart from all others.

MANUFACTURING HYBRID METAL MATRIX COMPOSITES (HMMC)

We use the stir-casting process to produce different types of casting. The stir casting process produces three types of casting such as vacuum die casting, rotary die casting, and squeeze die casting. In the process, various parameters are used to make the hybrid metal matrix composite. In the manufacture of the hybrid metal matrix composite, we use metallic component Al and carbides and sulphides as ceramic reinforcement. We have used aluminium alloy 6061 as matrix material, with reinforcement of carbides as B_4C and sulphides as MoS_2. In the casting process we used 1200 gm of aluminium alloy (Al 6061 T6), 4 % B_4C (48 gm) and 1 % MoS_2 (12 gm). The melting point of aluminium is 750 °C; hence a furnace must be up to 800 degrees. After that, ultrasonic technology is used for five minutes at a power level of 12 kW (60 %) in the furnace.

The stir remains on for two minutes following the five-minute duration. After that, it is poured into the right mould. This procedure keeps the stirrer speed at 500 rpm. Typically, the reinforcement preheating temperature is kept at 150 °C, and the die at 300 °C, the preheating temperature is kept constant. Specifications vary throughout various moulds based on the type of container. Squeeze casting requires 30 MPa of pressure, while vacuum casting requires the vacuum to be turned on, whereas a motor running at 1000 rpm is required for rotary casting.

Figure 1. Stir casting machine.

In Fig. 1, the stir casting machine is shown which is used during the research work. There have been some noted modifications in their qualities as a result of these three traits shown in Fig. 2. Its mechanical properties change as different parameters change during the stir casting process. This parameter is determined using a variety of research investigations and experiments.

Figure 2 shows the HMMCs made during the various stir casting process. Vacuum casting, rotary casting and squeeze casting are made with the help of different parameters, as shown in Table 1.

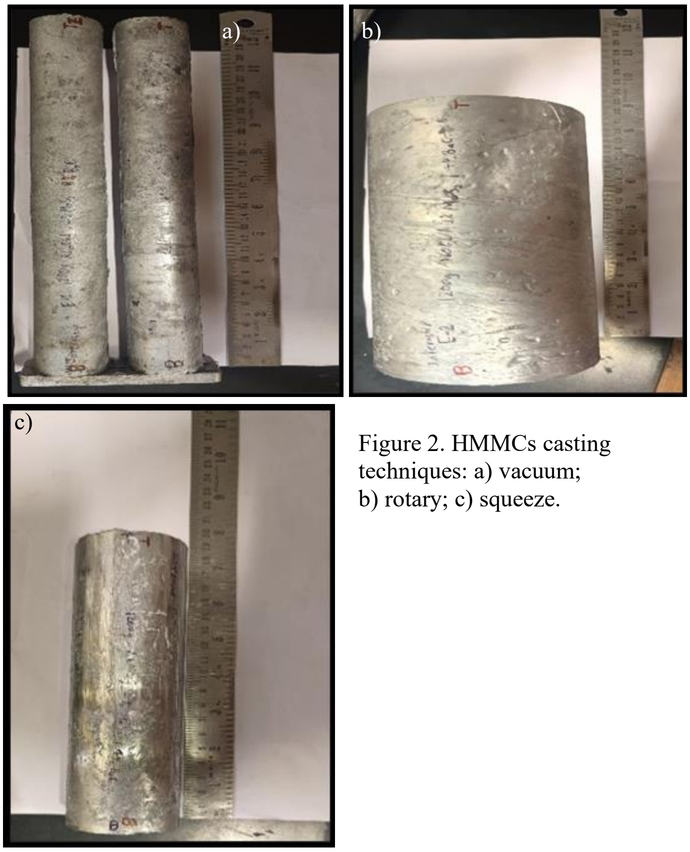


Figure 2. HMMCs casting techniques: a) vacuum; b) rotary; c) squeeze.

In Table 1, we describe the stir casting parameter for different processes during the work.

Table 1. Stir casting parameters.

Parameter	Process		
	Vacuum casting	Rotary casting	Squeeze casting
Melting temperature	750 °C	750 °C	750 °C
Die preheating temperature	300 °C	300 °C	300 °C
Ultrasonic power	12 kHz	12 kHz	12 kHz
Stirrer time	ultrasonic: before 8 min + after 2 min	ultrasonic: before 8 min + after 2 min	ultrasonic: before 8 min + after 2 min
Stirrer speed	500 rpm	500 rpm	500 rpm
Ultrasonic time	5 min	5 min	5 min
Vacuum	yes	no	no
Rotation speed	-	1000 rpm	-
Squeeze pressure	-	-	30 MPa

METHODOLOGY

In this section, we include experimental procedures with their parameters and the pin-on-disk tribometer with specimens.

Experimental procedure

A pin-on-disk has been carried out to evaluate the hybrid metal matrix composites. An EN31 steel disc with a hardness grade of 65 HRC has been used as the counter surface for rubbing in the wear experiments. The length and diameter of the wear specimens taken for the experiment is 6 mm. No lubrication and heat are used in this test. The wear test experiment is performed with normal load, 20 N, /19-21/, sliding speed V = 1 m/s /19-21/, track diameter 50 mm, sliding distance 2000 m, and rotational disk speed 383 rpm.

To calculate the rotational disk speed,

$$V = \frac{\pi DN}{60} \Rightarrow N = \frac{60V}{\pi D} ,$$

where: V is sliding velocity; D is disk track diameter; N is disk rotational speed.

Here, we have V = 1 m/s, D = 50 mm, and π = 3.14, so then, N = 383 rpm.

A total of three specimens from each casting are used for tribological testing.

Figure 3 shows the pin-on-disk tribometer machine used for testing. Figure 4 indicates the specimen's parameter of pin-on-disk in wear test having 6 mm diameter and 6 mm pin height in all various types of casting.

Figure 3. Pin-on-disk tribometer machine.

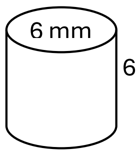


Figure 4 (left). Specimen for the tribometer test.

Table 2 lists the parameters used in the pin-on-disk wear test. The sliding speed between the pin-on-disk is kept at 1 m/s, and a standard load of 20 N is supplied to the pin.

The disk's track diameter, or the circumferential route the pin follows, is 50 mm. To assess the wear characteristics, the test was run over a 2000 m sliding distance. In order to obtain the required sliding speed and distance, the disk rotates at a speed of 383 rpm.

Table 2. Parameters of the pin-on-disk test.

Normal load	Sliding speed	Track diameter	Sliding distance	Rotational disk speed
20 N	1 m/s	50 mm	2000 m	383 rpm

RESULT AND ANALYSIS

This section includes the results and analysis of the stir casting methods through the tribology.

Results of tribology

This section provides the results on the mechanical behaviour of wear, friction force, and worn surface morphology.

Pin-on-disk results of wear and friction

Table 3 depicts the wear loss and friction force for several casting techniques, including vacuum, rotary, and squeeze casting. All wear loss is shown in milligrams (mg) and friction force is shown in Newton (N).

For each process, three specimens (A, B, and C) are used in the wear test to assess the performance in terms of material wear in tribology.

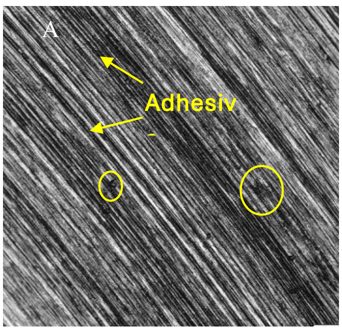
Table 3. Pin-on-disk results.

Process	Vacuum casting			Rotary casting			Squeeze casting		
Specimen	A	B	C	A	B	C	A	B	C
Wear loss (mg)	24.6	25.1	26.9	25.6	24.6	27.5	20.5	16.8	24.6
mean	25.53			25.9			20.73		
Friction force (N)	7.57	5.47	8.08	7.11	10.57	7.10	5.11	4.54	8.24
mean	7.04			8.26			5.96		

Worn surface morphology results

In this section, the worn surface morphology of the three castings specimens work is performed after using the pin-on-disk experiment. Worn Surface Morphology indicates the type of wear obeserved in the material such as adhesive wear and abrasive wear.

Optical microscope is used for worn surface morphology. The eyepiece lens is set at 10x magnification. The experiment is conducted by setting the object lens at two different types of 5x and 10x magnification. Figures 5, 6, and 7 represent the various types of casting specimens from the experiments of vacuum, rotary, and squeeze casting with their worn surface morphology in 5x on optical microscope.



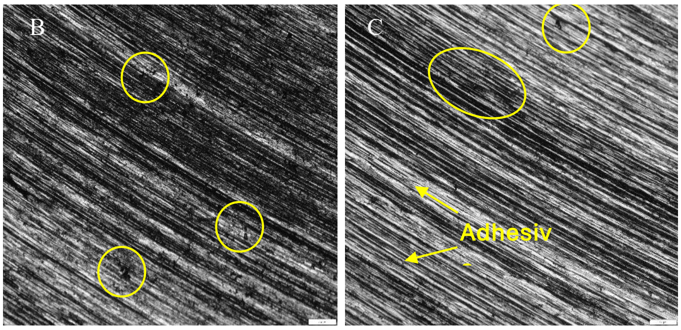


Figure 5. Vacuum casting, 200 μm, 5x, samples: A; B; and C.

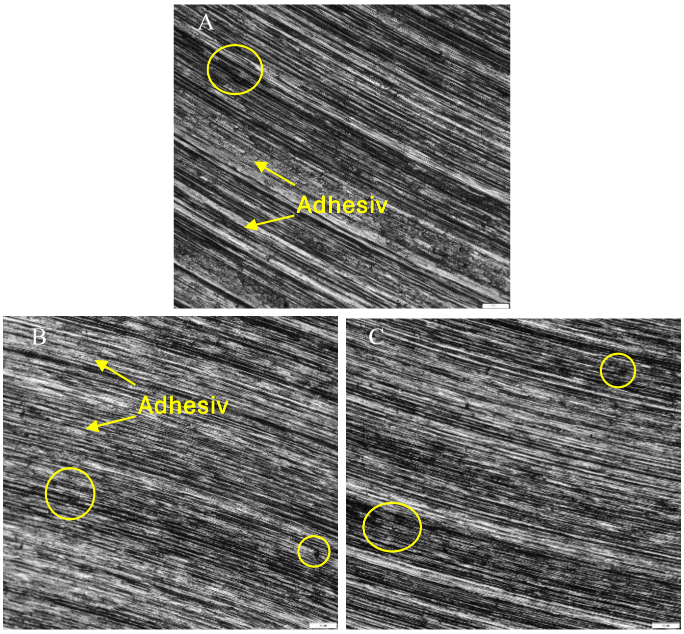


Figure 6. Rotary casting, 200 μm, 5x, samples: A; B; and C.

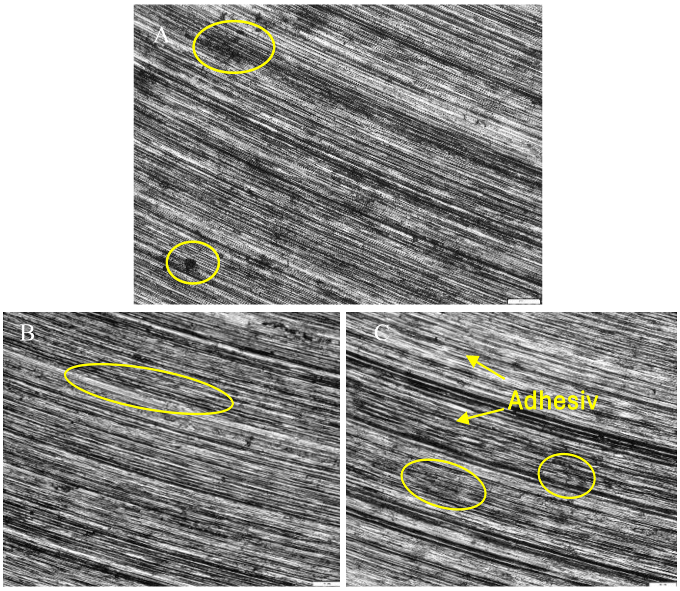


Figure 7. Squeeze casting, 200 μm, 5x, samples: A; B; and C.

Figures 8, 9, and 10 represent the various types of casting specimens with worn surface morphology in 10x on optical microscope. Here eyepiece lens power is 5x and object lens power is 10x used for testing morphology. All three specimens A, B, C, are shown in Figs 5-10.

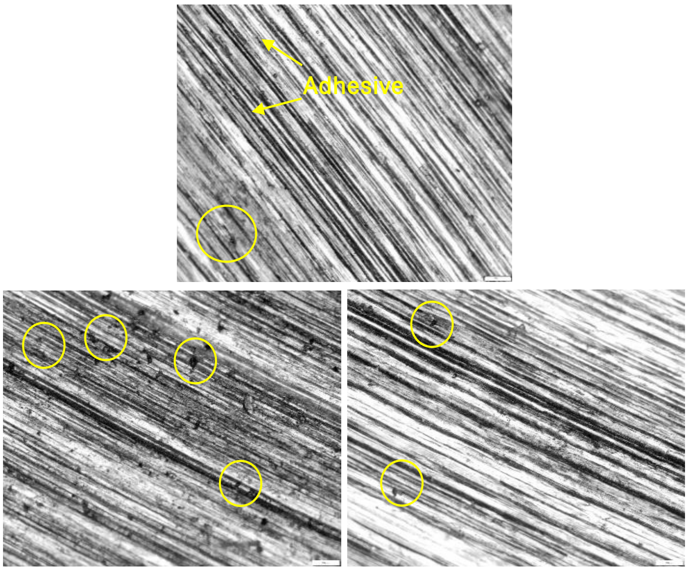


Figure 8. Vacuum casting, 100 µm, 10x, samples: A; B; and C.

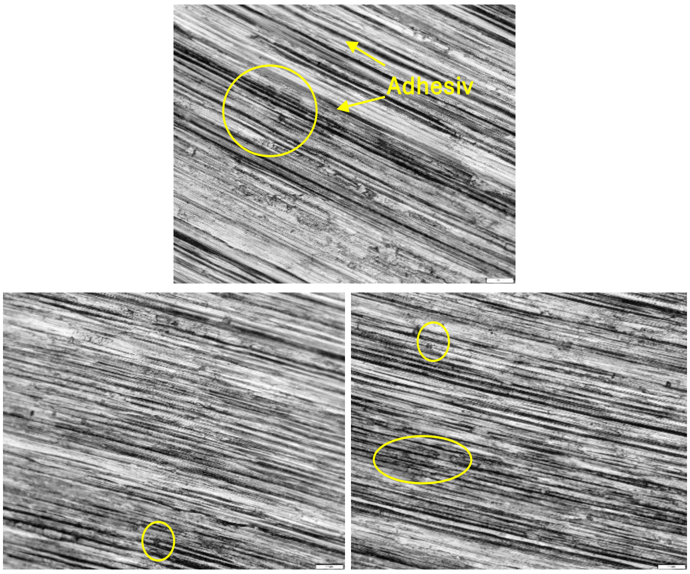


Figure 9. Rotary casting, 100 µm, 10x, samples: A; B; and C.

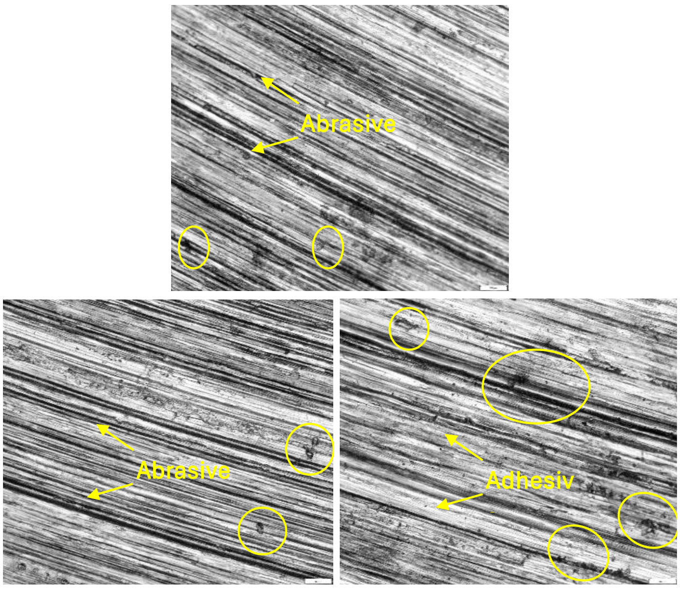


Figure 10. Squeeze casting, 100 µm, 1x, samples: A; B; and C.

Tested pin- on-disk specimens

In this section all castings specimens are included with tribology, for vacuum, rotary, and squeeze castings.

Various types of casting specimens (A, B, C) before the pin-on-disk wear test and after the pin-on-disk wear test are shown in Figs. 11, 12 and 13. All three figures show actual specimens prepared using the stir casting process in various moulds. The specimens are prepared using an EDM wire cut machine. Significant tribological and morphological results are observed in the previous sections.

The three castings from Figs. 11, 12, and 13 are shown here as specimens both before and after the experiment. We can determine these figures' true wear behavior with the use of an optical microscope.

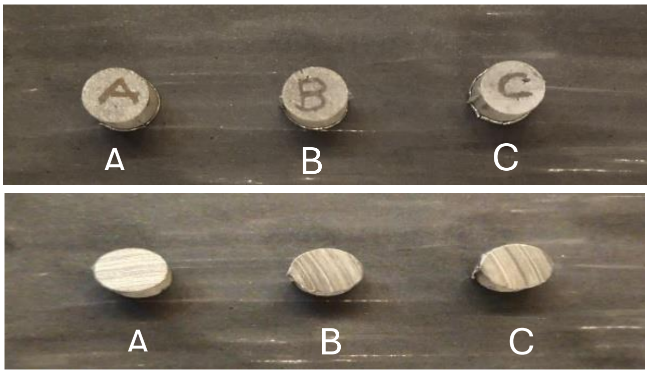


Figure 11. Vacuum casting specimens.

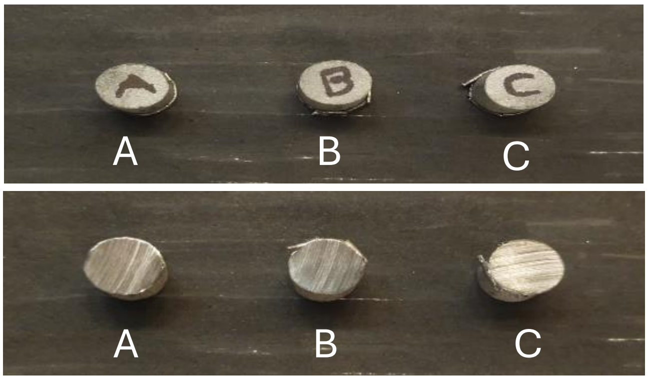


Figure 12. Rotary casting specimens.

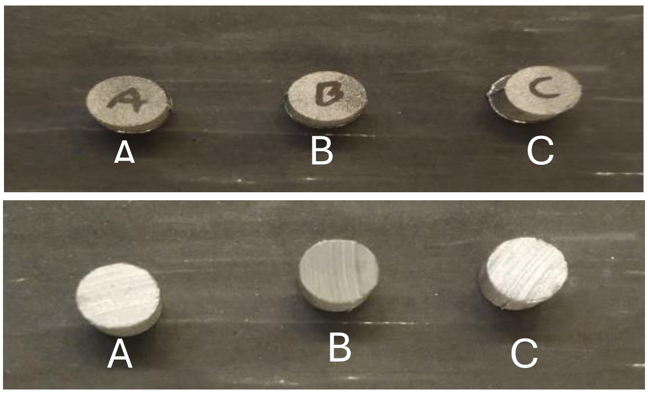


Figure 13. Squeeze casting specimens.

ANALYSIS

This section provides the analysis of the results obtained during the research.

Wear

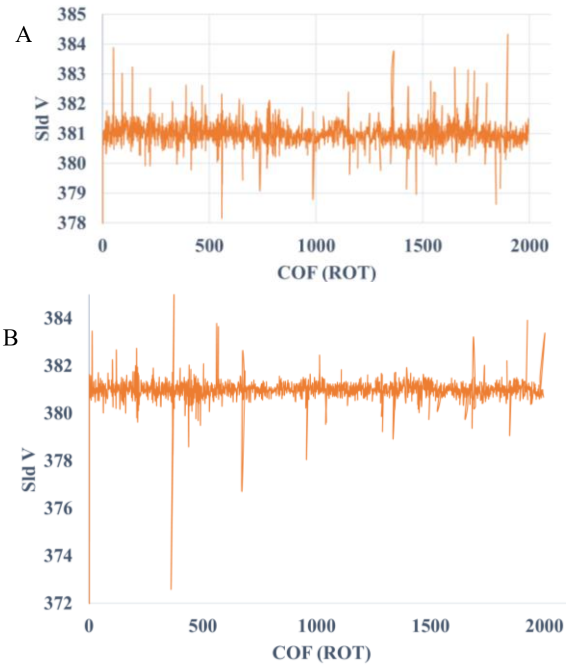
Various mould castings with different parameters are made during the stir process. Table 3 shows the results of 6 mm specimens with the wear coefficient. Every casting has a different parameter but HMMCs are the same. The pin-on-disk result with vacuum casting wear has a mean of 25.53 mg, squeeze casting wear has a mean of 20.73 mg and rotary casting wear has 25.9 mg. Squeeze casting has better resistance of all the three castings. Squeeze casting shows less wear loss compared with the other two castings which indicate a higher level of wear resistance. The qualities of HMMCs are substantially impacted by their methods and forms.

Friction force

Hybrid metal matrix composites are made by vacuum-, rotary-, or squeeze casting in a stir casting machine. The results of friction force are measured during pin-on-disk experiment with specimens made from these three processes. Excellent tribological qualities of the material or surface treatment are indicated by a low friction force. Materials with MoS_2 natural lubrication tend to have minimal friction. The mean of the results of friction force of vacuum-, rotary-, or squeeze casting are found to be 7.04 N, 8.26 N and 5.96 N, respectively. Among these, the highest friction force is found in rotary casting, and the lowest friction force is found in squeeze casting. Its means squeeze casting is better than the other castings with respect to friction force. Figures 14, 15 and 16 show that variation of coefficient of friction (COF ROT) rotational with the sliding speed (Sld V) of vacuum-, rotary-, and squeeze casting.

The spikes in Fig. 14 suggest sudden changes in friction, which may indicate surface regularities and irregularities or a more or less consistent material structure.

Figure 15 shows fewer extreme spikes, indicating a more uniform frictional response during sliding and suggests sudden changes in friction.



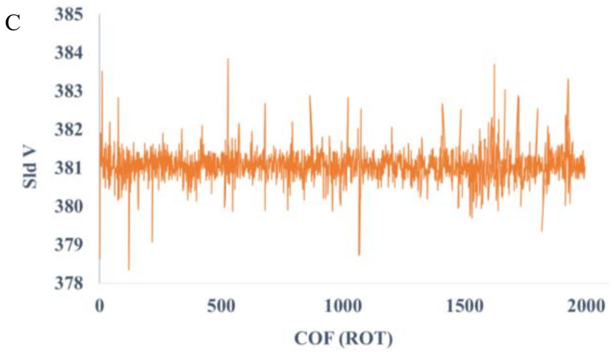


Figure 14. Variation of the COF(ROT) with the Sld V of vacuum casting HMMCs (specimens A, B, and C).

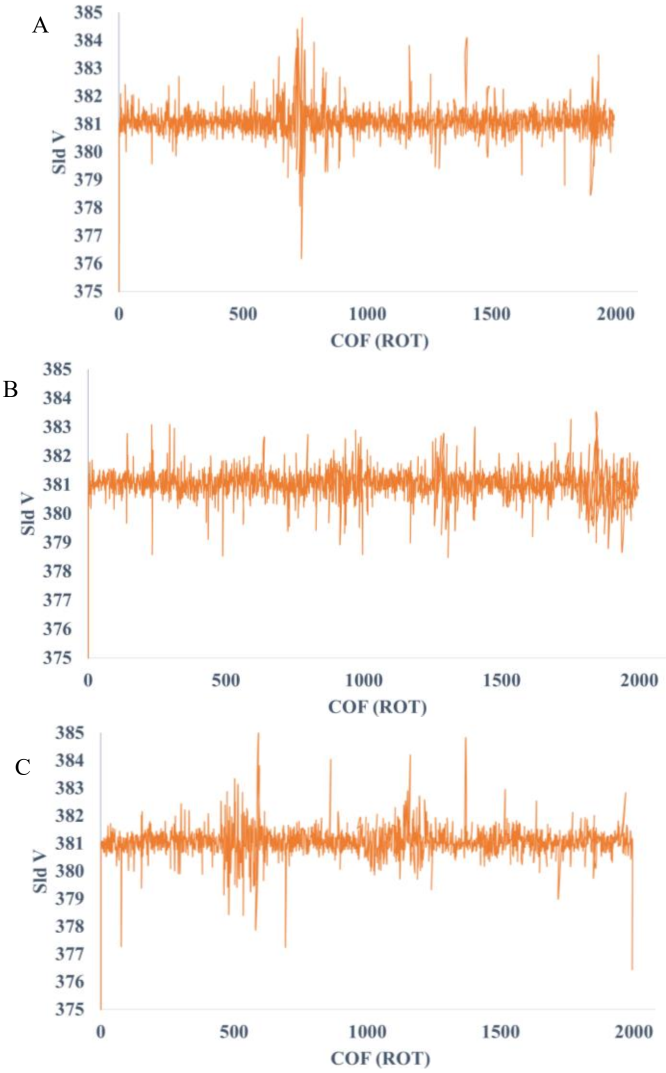
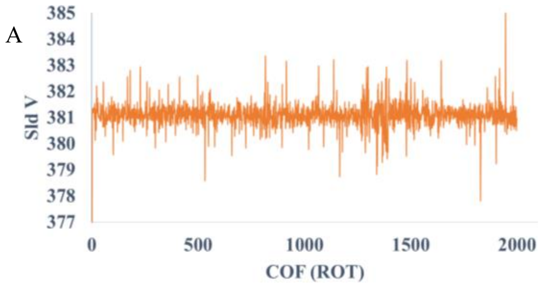


Figure 15. Variation of COF(ROT) with the Sld V of rotary casting HMMCs (specimens A, B, and C).



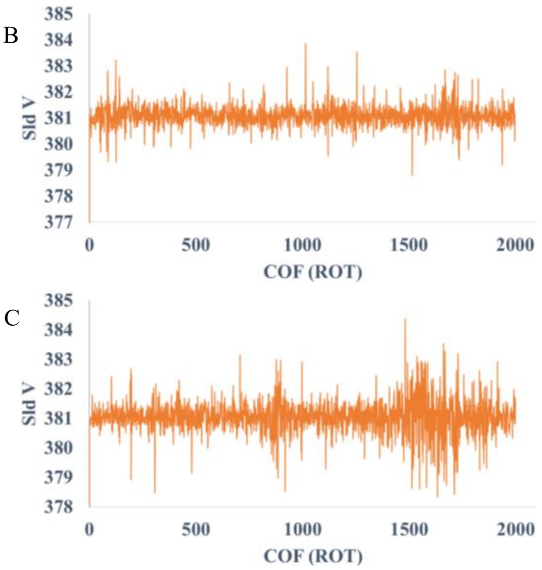


Figure 16. Variation of COF(ROT) with the Sld V of squeeze casting HMMCs (specimens A, B, and C).

Figure 16 shows higher noise levels and more spikes as COF increases, suggesting progressive wear or stability during the sliding process.

Some possible causes for discrepancies in friction performance are shown in Figs. 14, 15, and 16. These variations may result from changes in the casting parameters, such as vacuum, rotating speed, pressure, cooling rate, or alloy composition. Variations in material porosity, inclusion content, or grain structure may have an impact on the sliding behaviour. Disparities in frictional performance may result from variations in surface roughness.

Worn surface morphology

The casted HMMCs (stir casting products) are analysed for worn surface morphology under an optical microscope. Figures 5, 6, and 7 are viewed at 200 µm magnifiaction, whereas Figs. 8, 9, and 10 are viewed at 100 µm magnifiaction. Figures 5 to 10 depict the worn surface of Al6061 in which B_4C, and MoS_2 are visible. Fig. 5 shows particles from B_4C and enhanced adhesive wear. Similarly, Fig. 6 shows particles of B_4C and abrasive wear in addition to adhesive wear at specific locations. Figure 7 shows some cracks in some phases of MoS_2 particles so it can be said that both adhesive and abrasive wear are present in the specimen. In Fig. 8 adhesive wear and B_4C particles are observed. Figure 9 shows very few B_4C particles and numerous cracks and severe abrasive wear. Figure 10 shows B_4C particles and more visible cracks. Adhesive wear means the smearing or transfer of material and its effects on friction. High adhesion causes more friction, leading to energy losses. Abrasive wear is grooving or scratching by hard particles. It reduces surface smoothness and increases roughness. Abrasive and adhesive wear made by transfering B_4C particles on Al 6061 and grooving is observed due to some hard particles of B_4C and MoS_2.

CONCLUSIONS

In the present study, HMMCs Al6061 with 4 % B_4C and 1 % MoS_2 are successfully casted using different types of stir casting processes. The behaviour of three distinct castings made with the stir casting technique are examined based on tribological parameters.

The following outcome of the investigation could be drawn as conclusions:

- The tribological behaviour of all three castings is evaluated, i.e., the wear of the squeeze casting wear mean is 20.73 mg, which is better than the other two castings. The squeeze casting is highly wear resistant which indicates that the squeeze casting performs better than the vacuum and rotary casting.
- Squeeze casting has the lowest mean friction force of 5.96 N among the three castings. This result indicates the squeeze casting has a low friction force.
- The examination of the wear morphology of all three casting methods shows that the specimen squeeze casting method is better than the other two casting methods. In squeeze casting high adhesive and low abrasive wear means casting satisfies the mechanical properties.
- Squeeze casting, the best casting out of all, performs well in all of the criteria based on the qualities of Al6061 + B_4C + MoS_2.

In the future, the work can be extended to investigate the effect of varying reinforcement content and studying the impact of different loads, speed and temperature, with lubricant.

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