Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 4 (2024)

Enhancing Mechanical Performance of AA6061 Hybrid Metal Matrix Composites: A Stir Casting Investigation with MgO and SiC Reinforcements

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Abstract

The use of Aluminium Metal Matrix Composites (AMMCs) has gained considerable recognition in aerospace and structural applications due to its excellent corrosion resistance, good wear resistance, high strength, and lightweight properties. This paper presents an experimental study that investigates the influence of reinforcement particles, specifically Magnesium Oxide and Silicon Carbide, on various mechanical properties of Aluminium Alloy (Al 6061).The AMMCs were produced through the stir casting method, utilizing the ex-situ approach for its simplicity. Different weight percentages of reinforcing particles, namely 3%, 6%, and 9%, were incorporated to form the MMC specimens. After fabrication, the ingots were machined to create test samples, which underwent a series of mechanical tests, including tensile, compression, impact, and hardness tests. These tests aimed to assess the impact of varying weight percentages of reinforcements on the mechanical properties of the material.The results revealed a gradual increase in both tensile and compression strength with the addition of magnesium oxide and silicon carbide. The study demonstrates the potential for enhancing the mechanical properties of Aluminium Alloys through the incorporation of these reinforcing particles.

Keywords:Aluminiumalloy(Al6061),Magnesiumoxide, Siliconcarbide, stir casting, Hybrid Metal Matrix Composites (HMMC),Exsitu, Impact, Hardness, Tensileand Compressiontest.

Introduction

Composite materials are favored in engineering applications due to their exquisite mechanical properties. Composites involve the combination of distinct materials by mechanically or metallurgically binding them together to achieve desirable properties. A variety of composite materials and production categories exist, with new materials continuously being developed. Metal Matrix Composites (MMCs) use different engineering materials as a matrix to bind the composite. The most commonly used matrix materials in MMCs are Aluminium, magnesium, and their alloys due to their lightweight and ductile properties.MMCs typically consist of a single matrix and two or more reinforcements, creating what is known as Hybrid Composites. These composites reinforce different materials with varying properties within the matrix phase to improve stiffness, strength, and achieve a high strength-to-weight ratio, along with other desirable mechanical properties. Hybrid Composites are designed to enhance the mechanical properties of MMCs by combining multiple materials with the matrix phase [2].

Composites based on Aluminum are considered suitable choices in applications requiring factors such as lightweightness, enhanced strength, and high rigidity values [3]. Particulate-reinforced aluminum matrix composites not only significantly enhance the strength and hardness of aluminum and its alloys but also noticeably reduce plasticity and ductility properties. This reduction can affect the safety and dependability of components made from Aluminum matrix composites [4]. Commonly used reinforcement composite materials include Si-C, SiO2, Al2O3, and MgO. Among these, Aluminum Silicon carbide alloy composite materials are preferred for engineering structures, industrial and digital applications, sporting goods, etc. Aluminum matrix composite reinforcement with Silicon carbide particles provides excellent wear resistance, greater modulus, and better dimensional stability than traditional aluminum alloy [5].

Silicon carbide particles are continuously stirred with a wetting agent, Magnesium, to enhance wettability. Simultaneously, the metal matrix composites slurry is solidifying to increase wettability of Sic with Aluminum matrix alloy. Wettability can also be increased by reducing solidification time. However, increasing the volume fraction of existing Sic particles may have the opposite effect [6].Among the various manufacturing processes available for intermittent metal matrix composites, the most extensively used and acknowledged for a viable and practical approach is Stir Casting. This method is chosen for its ease, flexibility, applicability to bulk production, and cost-effectiveness in the production of metal matrix composites. Stirring is advanced for consistent dispersion of particulate metal matrix composites in an economical manner [7].

This article describes the investigation of mechanical properties and microstructural examination of an Aluminum Metal Matrix Composite produced using the stir casting method and reinforced with Silicon Carbide and Magnesium Oxide..

Experimentalprocedure

The stir casting technique was employed to prepare AA6061-MgO-SiC composites. The matrix material used was aluminum alloy 6061 with a chemical composition shown in Table 1. Magnesium Oxide and Silicon Carbide particles, each with a grain size of 50µm, were utilized as reinforcement materials. Their properties are listed in Table 2 and depicted in Figures 1 and 2. Before mixing with the matrix material, the MgO and SiC particles were preheated separately at 250°C for 20 minutes to improve their wettability. Composites with weight percentages of 0, 3, 6, and 9% reinforcement were prepared using the stir casting route illustrated in Figure 3. The AA6061 was melted in a crucible, and the preheated SiC and MgO particles were gradually added at a temperature of 800°C.

Dynamic stirring was conducted for 5 minutes at 700rpm to ensure the homogeneity of the molten metals. A stirrer was employed to evenly distribute the reinforcement throughout the entire matrix. The molten mixture was poured into a cast iron mold to obtain a rod-shaped composite.Mechanical properties of the composite were evaluated using a Brinell hardness tester, Charpy V-notch test, and Pin-on-disc machine, following ASTM standards. The tensile strength, hardness, impact strength, and wear rate were investigated through these experimental assessments.

Table-1:Al6061alloycompositionbyweight percentages (%)

Al	**Si**	**Mg**	**Cr**	**Cu**	**Fe**	**Mn**	**Ti**	**Zn**
95.50-98.60	0.42-0.82	0.8-1.2	0.04-0.35	0.15-0.40	0.0-0.7	1.0-0.15	0.0-0.25	0.0-0.25

Table-2:Properties of MgO &Si Cpowders

S.No	Properties	Values
MagnesiumOxide		
1.	Density	3.58g/cm^3
2.	Molarmass	40.30g/mol
3.	Meltingpoint	852°C
4.	Boilingpoint	3600°C
SiliconCarbide		
1.	Density	3.2g/cm3
2.	Molarmass	40.096g/mol
3.	Meltingpoint	2,730°C
4.	Boilingpoint	2700°C

Figure.1.Magnesiumoxidepowders

’**Figure.2.**Siliconcarbidepowders

Figure.3. Experimentalsetupofstircastingprocess

Al6061-SiC-MgO composites were prepared by varying the weight percentage of SiC and MgO at 3%, 6%, and 9% each as mentioned in the figure 3 and 4. The weight of the sample used was 600 grams, and the weight percentage varied accordingly.

Table-3:CompositionofSamples

SampleNo.	**Al6061 Alloy(Grams)**	**SiC(Grams)**	**MgO (Grams)**	**Weightpercentage (%)**
1	600	-	-	Al100%
2	564	18	18	Al94%,Sic3%,MgO3%
3	528	36	36	Al88%,Sic6%,MgO 6%
4	492	54	54	Al82%,Sic9%,MgO 9%

Figure.4.Specimenofcompositematerial

MechanicalTesting

HardnessTest

The Brinell hardness test was conducted with a 250 kg load and a 10mm steel ball indenter on Al 6061 composites with varying weight percentages of reinforcement particles (MgO and SiC). According to ASTM standards, the specimens were prepared. The test was conducted on each Al 6061 composite specimen, as depicted in Figure 5, with various surfaces to obtain an average hardness value.

Figure.5. HardnessTestSpecimen

Aluminum (Al) is a relatively soft metal, so having 94% aluminum in the composition will tend to lower the overall hardness of the material. Silicon Carbide (SiC) is a very hard and abrasive material, so its presence at 3% in the composition will contribute to an increase in hardness. Magnesium Oxide (MgO) is relatively hard as well, so its 3% presence will also contribute to increased hardness. The net effect on hardness will depend on the specific microstructure and bonding of these components.

Tensileand compression test

The tensile test was conducted using a Universal Testing Machine (UTM), and specimens were prepared according to ASTM standards. The UTM has a maximum capacity of 300 KN, and tests were carried out for all specimens, respectively. The presence of aluminum, while relatively soft compared to some other metals, can contribute to good tensile strength due to its ductility. The inclusion of SiC and MgO can increase the tensile strength due to their hardness and reinforcement properties, assuming they are well-bonded with the aluminum matrix.In the compression test, compression loads were steadily increased, and the corresponding strain was noted until the specimen failed. The Universal Testing Machine was used to conduct the compression test in accordance with ASTM standards. Compression strength is typically higher than tensile strength for most materials. The same principles as with tensile strength apply here, as mentioned in Figure 6..

Figure.6.CompressionTested specimen

Impact Test

A test conducted using the Charpy test is popularly known as the impact strength test or impact test. It measures the amount of energy absorbed by the material before actual fracture occurs. The evaluation procedures are performed in accordance with ASTM standards and are conducted prior to fracture. The nature of testing is usually of a high-strain type. The test specimens were machined according to the standard. Impact strength is often negatively affected by the presence of hard and brittle materials like SiC and MgO. These inclusions can make the material more susceptible to fracture upon impact.

WearrateTest

The Wear Rate Test was conducted on the pin and the disc, computed by evaluating the amount of wear for the pin and disk based on the volume of material removed during the testing process. It is usually expressed in weight percentages. During the testing process, variables such as time, contact pressure, and the speed of movement can be controlled. The wear rate is influenced by the hardness of the material. SiC and MgO can reduce the wear rate due to their hardness, which can resist abrasion and wear. However, wear resistance also depends on the bonding between these components and the microstructure of the material.

It's important to note that the actual mechanical properties of a material are influenced not only by its composition but also by factors such as the processing method, temperature, and the bonding between different components in the composite. To obtain precise values for these properties, it would be necessary to conduct material testing and analysis under specific conditions. Additionally, engineering design considerations, such as how the material is used and any required heat treatments, will also impact its properties and performance..

Results andDiscussion

ThecompositionofAluminium6061-Siliconcarbide-Magnesiumoxideas follows

Specimen1=100%0fAluminium6061

Specimen2=94% ofAl6061+3%ofSiC+3% ofMgO

Specimen3=88% ofAl6061+6%ofSiC+6% ofMgO

Specimen4=82% ofAl6061+9% ofSiC+9% ofMgO

HardnessTest

ThehardnessofAl6061withdifferentpercentageofreinforcement is tested using Brinell Hardness test and theexperimentalresults areanalyzedasshowninFigure 7.

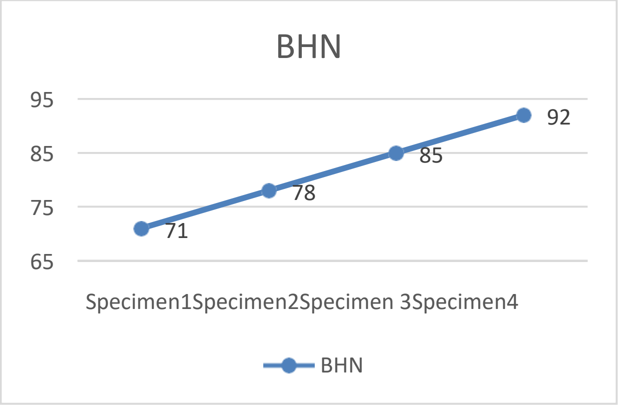

Figure.7.BHN vs. Reinforcement%

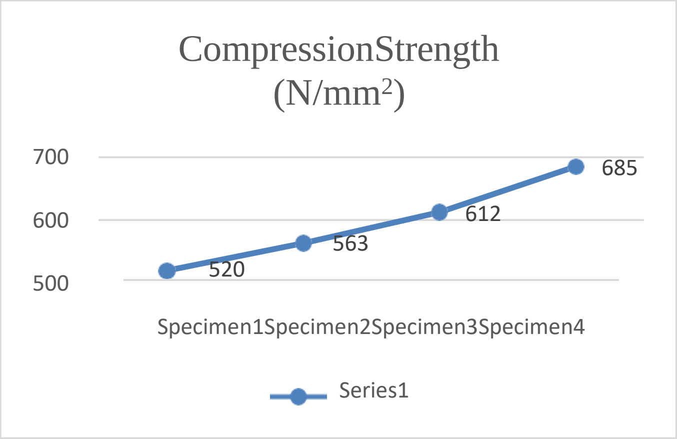

Figure.8. Compression Strength vs. Reinforcement %

Figure 7 reflects the hardness of the HMMC specified as BHN compared against the reinforcement percentage. From the results, it can be concluded that increasing the weight percentage tends to improve the robustness towards plastic deformation, which alternately defines an increase in the hardness of the specimen. The hardness of specimen Al 6061 is 71 BHN and reaches its maximum value of 92 BHN for the composition of 82% aluminum 6061 + 9% SiC + 9% MgO.

Tensile Test

The effect of weight percentage of Silicon Carbide and Magnesium Oxide on the tensile strength of Aluminum alloy Al 6061 is shown in Figure 7. The results indicate that increasing the weight percentage of reinforcement materials leads to an increase in the compressive strength of the Al6061 alloy. The compressive strength of the unreinforced Al6061 alloy is 520 N/mm². However, for the composite composition containing 82% Al6061 + 9% SiC + 9% MgO, the compressive strength increased to a maximum of 685 N/mm².

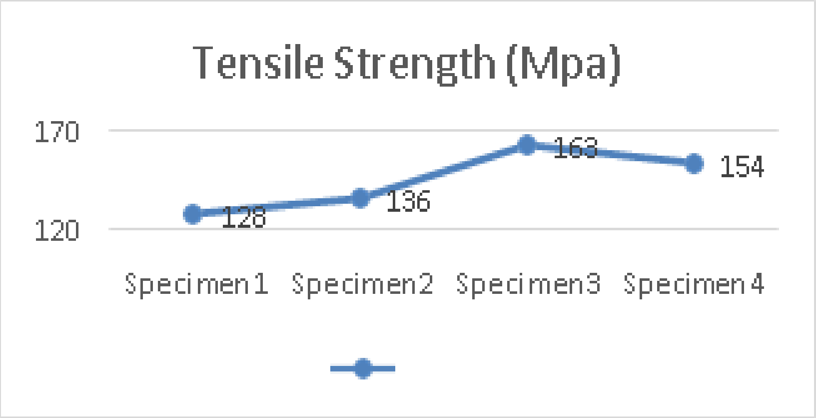

Figure.9. Tensile Strengthvs.Reinforcement%

Impact Test

The Charpy impact test was carried out for different specimens, and the outcomes were shown in Figure 9. The results show that there is an increase in the value of Ultimate Tensile Strength up to 6%. After that, a decrease in the values of tensile strength occurred due to poor wettability and poor bonding between the Al 6061 matrix and SiC-MgO reinforcement.

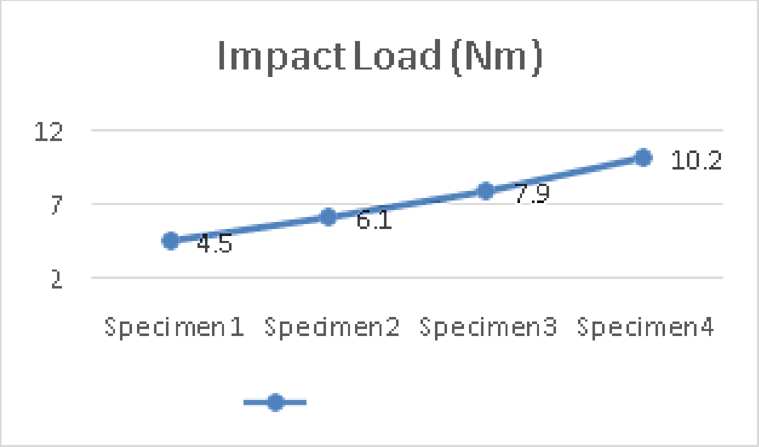

Figure.10.Impact strengthvs.Reinforcement%

CompressionTest

The effect of the compression test was shown in Figures 8 and 9. The graph above shows that with an increase in reinforcement, the impact strength of composites also improved. The impact attains a maximum value of 10.2 Nm for the composition of 82% aluminum 6061 + 9% SiC + 9% MgO composite.

WearrateTest

The findings of the wear rate test have been presented in Figure 11. The experimental plot shows the variation of wear rate as a function of increasing weight percentages. The wear rate is computed for AA6061 with differing weight percentages of SiC-MgO. The decrease in wear rate indicates a significant improvement in the weight percentage of reinforcing SiC-MgO compared to unreinforced AA6061 composites. Adequate lubrication and its associated features, coupled with the hardened nature of the reinforced particles, are the primary causes of the observed phenomena.

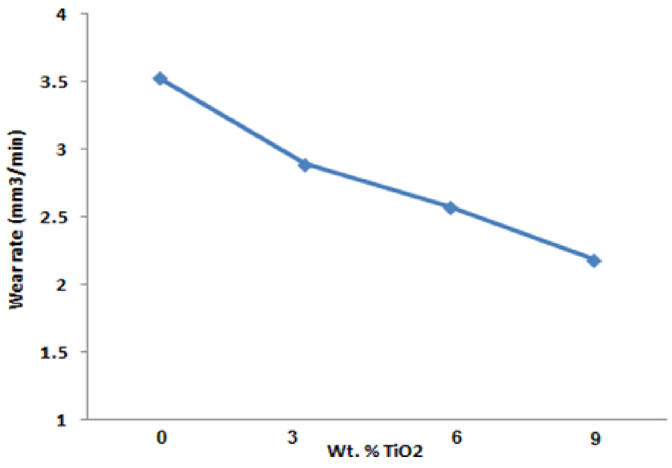

Figure.11.WearrateofAA6061-SiC- MgO composites

However, in the case of unreinforced AA6061, during the stages where the metal has not received the complete finishing (as-cast), an increase in wear condition is observed. The observed homogeneity in the unfinished structure is the primary cause of these phenomena. Simultaneously, the decrease in wear rate can be attributed to an increase in the fraction of SiC-MgO particles which possess high hardness with better interfacial bonding between the SiC-MgO particles and the AA6061 hybrid matrix formed during the stir casting process.At all levels of loads, the lowest wear rate is attained against 9 wt.% of SiC-MgO composites. Whenever the load increases, the wear rate goes on increasing correspondingly. After attaining sliding speed, the wear rate goes on decreasing and also concludes that over sliding speed is directly proportional to test time. The increasing test time of samples and disk causes a decrease in wear rate.

Another interesting observation is that the friction coefficient tends to decrease with increasing distances of sliding velocity. However, this friction coefficient is greatly reduced by the hard and thermally stable nature of SiC-MgO. The SiC-MgO was able to enhance the wear resistance of the composites at a temperature higher than room temperature. An oxide layer of the materials that acts as an effective insulation layer between the pin and the disc is formed due to high temperature. This is attributed to the observed high sliding velocity, which tends to increase the oxide layer formation on the materials, consequently improving wear resistance.

Interrelation of input and output responses

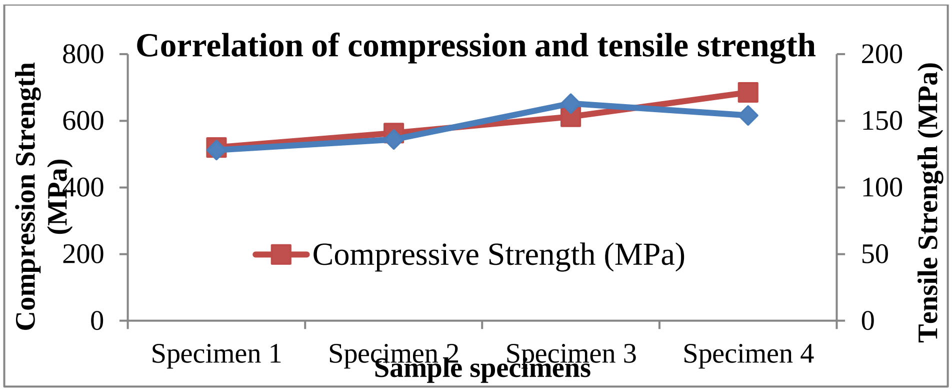

Figure.12. Correspondence of compression and tensile strength

Aluminum is ductile and may bend significantly before failing. It deforms and yields under compression before shattering. Due to its ability to bend and redistribute stress, aluminum can carry more strain before failing, increasing its compression strength. However, aluminum has decreased strength in tensile testing due to fracture initiation and propagation, which is more probable under tension.SiC ceramics are hard and brittle. Due to its hardness, SiC can endure significant compression forces but may fracture quickly without plastic deformation. SiC has lower tensile strength than compressive strength and is more brittle in tensile testing. Defects may concentrate stress and propagate fractures quickly, causing premature collapse.Another ceramic, MgO, is softer and more ductile than SiC. MgO can endure heavy compression stresses owing to its hardness, yet it may also bend plastically before failing.

Tensile testing may show lower MgO tensile strength than compressive strength due to ceramics' brittleness. Tensile tension may weaken strength by causing fractures. These materials have different mechanical characteristics; hence their compression and tensile strengths vary. Many materials vary according to their plastic deformation, fracture propagation resistance, and brittleness or ductility. Aluminum has better compression strength than tensile strength owing to plastic deformation; however, ceramics like SiC and MgO have lower tensile strength due to brittleness under tension. When comparing these qualities, material compositions, microstructures, and testing circumstances must be considered.

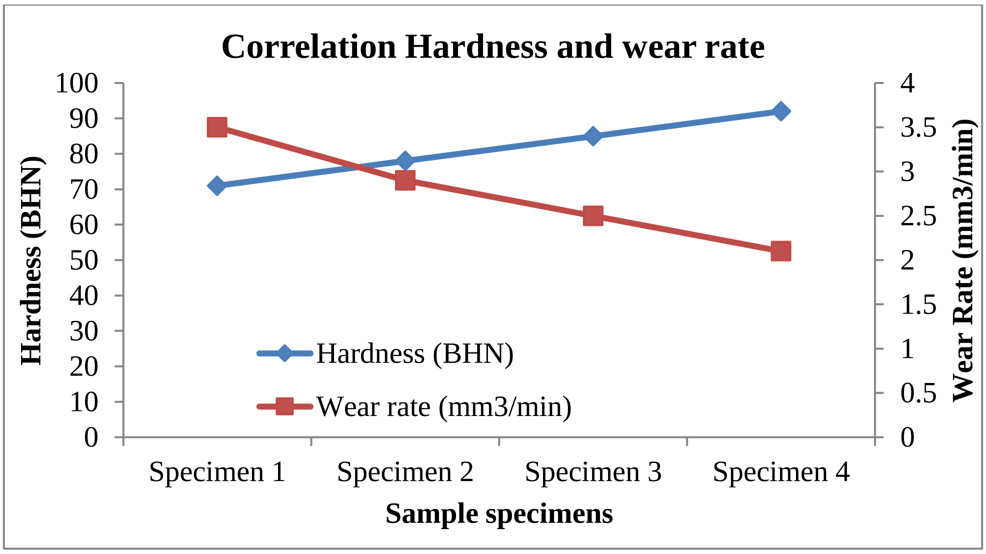

Figure.13. Relationship of hardness and wear rate

Hardness and wear rate of composite materials like Aluminum, SiC, and MgO are complicated and rely on many parameters. Hardness is frequently a key element in wear resistance, although other parameters including reinforcing phases (e.g., SiC and MgO), load, sliding conditions, and wear processes also matter. Hard reinforcing phases like SiC or MgO boost aluminum composite hardness, and as composite hardness improves, wear rate decreases because tougher materials resist abrasive wear and minimize material removal.The volume proportion of the reinforcement, particle dispersion, and composite manufacturing technique may also affect wear rate. SiC-reinforced composites are hard and wear-resistant, and their wear rate may rely on SiC volume percentage, particle dispersion, and wear processes. MgO, although less hard than SiC, improves aluminum composite wear resistance, and MgO-reinforced composites wear less than pure aluminum due to their hardness.Higher hardness generally improves wear resistance, but the relationship is not linear, and other factors like microstructure and wear conditions (e.g., sliding speed, load, and environmental factors) can affect wear rates. Different applications may use abrasive, adhesive, or erosive wear processes, hence the composite's characteristics must be adjusted to withstand the prevailing wear mechanism. Thus, to correctly forecast and optimize wear performance, one must understand the wear circumstances and composite microstructure.

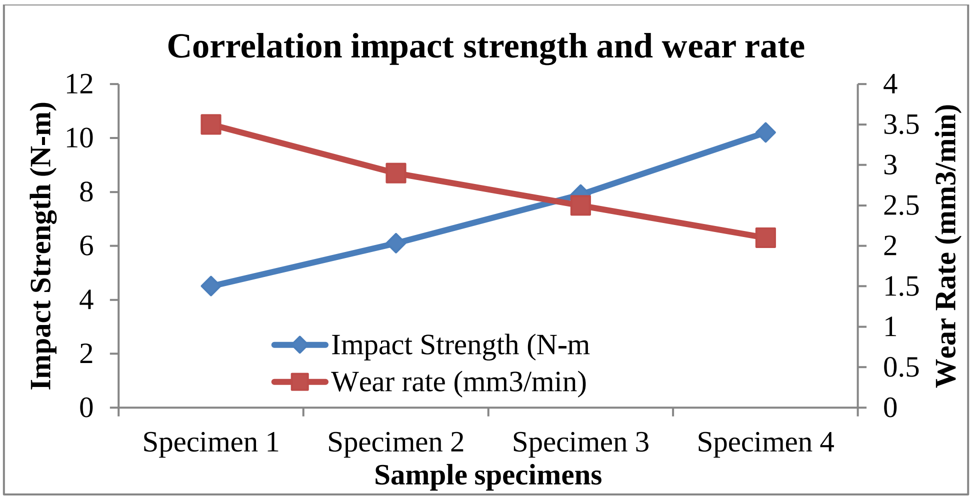

Figure.14.Connection of impact strength and wear rate

Composite materials, such as Al 6061 reinforced with SiC and MgO, have different compositions, production processes, and testing circumstances that affect their impact strength and wear rate. The mix and proportion of Aluminum 6061, SiC, and MgO are critical. SiC is robust and wear-resistant, whereas MgO may stabilize temperature. These components interact to determine impact strength and wear resistance. SiC and MgO particle size and distribution affect composite mechanical characteristics. Impact strength and wear resistance improve with homogeneous distribution and appropriate particle size.

Casting, powder metallurgy, and other composite manufacturing methods affect microstructure and characteristics. Proper processing improves matrix-reinforcing particle bonding and mechanical characteristics. Impact strength and wear resistance are affected by composite microstructure, including reinforcing particle dispersion and matrix material grain shape. Well-designed microstructures prevent fracture propagation and wear. Impact strength and wear rate testing are usually done under particular circumstances. Impact test type (Charpy, Izod) and wear testing technique (dry sliding wear, abrasive wear) might affect findings. The load, sliding distance, and testing environment matter. Matrix-reinforcing particle bond strength is critical.

Strong interfaces reduce particle pull-out and matrix fracture during impact, strengthening impacts. Particle detachment is reduced, improving wear resistance. Hardness and wear resistance of the composite depend on the matrix material (Al 6061) and reinforcing particles (SiC, MgO).A well-designed composite with a balanced mix of reinforcing components, processing, and interfacial bonding should have better impact strength and wear resistance. However, application needs must be considered and composite characteristics tailored. To verify composite material performance in real life, experimental testing and characterization are typically needed..

Conclusion

Aluminum-based Hybrid Metal Matrix Composites (HMMC) have been produced using the stir casting method. Silicon carbide and magnesium oxide particles were stirred for uniform spreading. The following conclusions were observed in this existing study:The Brinell Hardness Number (BHN) of Al 6061-SiC-MgO composite was found to be higher than the base aluminum alloy Al 6061, and the BHN increased with reinforcement percentage.The tensile strength value increased with the addition of reinforcement up to 6%, and upon further addition of reinforcement, the strength decreased subsequently. The optimum value of ultimate strength was achieved at 6% of SiC and 6% of MgO reinforcement.Comparing the monolithic Al 6061 alloy, the compression strength and impact strength increased gradually by adding reinforcements.The reinforced composite was compared against the unreinforced AA6063 composites. The decrease in wear rate was accomplished with an increase in the weight percentage of SiC-MgO reinforcing compared to unreinforced. This happened due to the lubricating properties and hardened nature of reinforced particles.

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