INVESTIGATION ON MECHANICAL PROPERTIES OF AZ61 MAGNESIUM ALLOY METAL MATRIX COMPOSITES REINFORCED WITH BORON CARBIDE(B_4C) AND SILICON DIOXIDE(SiO_2) USING STIR CASTING

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ABSTRACT

This study investigates the mechanical behavior of AZ61 magnesium alloy composites reinforced with Boron Carbide (B_4C) and Silicon Dioxide (SiO_2)**.** Magnesium alloys, valued for their low density and excellent strength-to-weight ratio**,** are widely used in aerospace, automotive, and structural applications. They are the lightest structural metals available and are widely used in sectors where losing weight is crucial. This increases the need to produce composite materials with better qualities than alloys, like extreme hardness, low density, corrosion resistance, etc. To address these challenges, hybrid metal matrix composites were fabricated through the stir casting technique. Four compositions were prepared: (i) base AZ61 alloy, (ii) AZ61 + 2% B_4C, (iii) AZ61 + 2% B_4C + 2% SiO_2, and (iv) AZ61 + 4% B_4C + 4% SiO_2. This study investigates the mechanical properties of AZ61, The primary objective is to use composite materials to improve the mechanical properties of magnesium alloy. By adjusting the weight percentage of B_4C and SiO_2 nanoparticles and comparing the outcomes with Base Alloy AZ61 and the fabrication is finished using the Stir Casting process. reinforced B_4C and SiO_2 composites were assessed using the Tensile, Flexural, and Hardness tests using UTM and Rockwell hardness test. Results revealed that the inclusion of B_4C and SiO_2 significantly enhanced strength, hardness, and flexural performance compared to the unreinforced alloy. The optimal composition (AZ61 + 4% B_4C + 4% SiO_2) offered superior hardness and good overall mechanical properties, whereas higher reinforcement levels showed signs of particle clustering and reduced ductility. These findings highlight the potential of hybrid reinforcements in improving the performance of lightweight magnesium alloys, making them suitable for aerospace, automotive, and structural components.

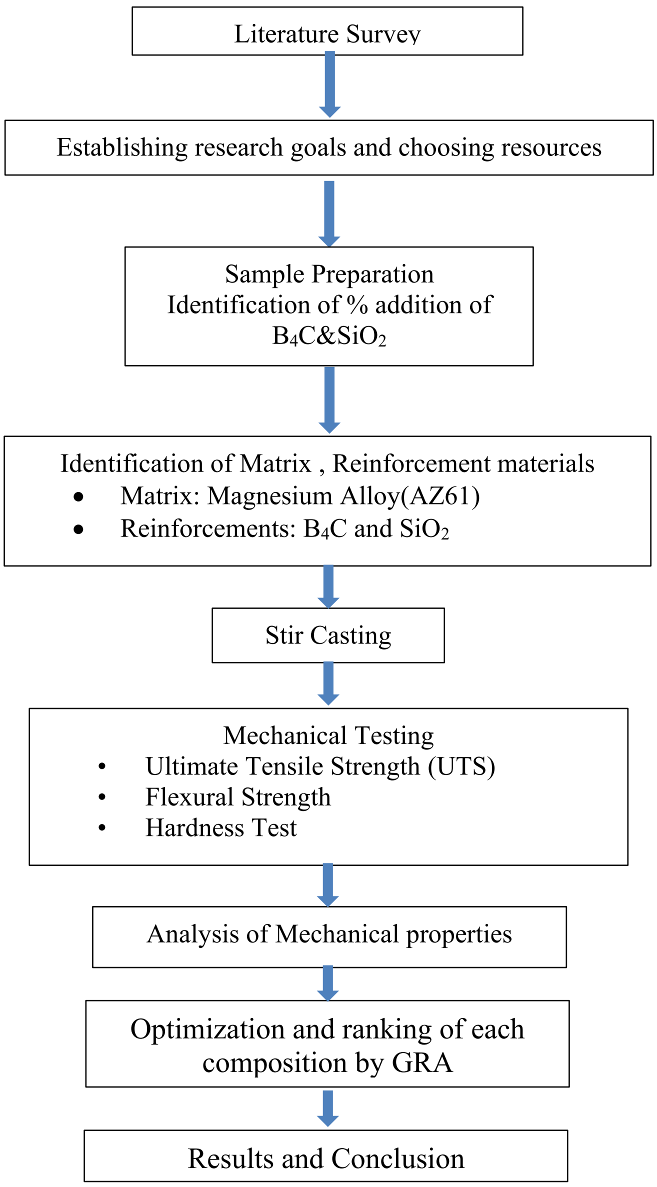
Keywords: Mechanical properties, AZ61, Silicon dioxide, Boron carbide, UTM (Universal Testing Machine), Rockwell Hardness test.

1. INTRODUCTION

Composite materials are made up of two or more components in which major constitution is called as matrix material and minor constitution is called reinforcement substance. Reinforcement material is a discontinuous phase, while matrix material is a continuous phase. In composites, the elements added in to the matrix will be chemically distinct. The eighth most prevalent element is magnesium. in the earth and its density (1.74 g/cm3) is 77% lesser than steel and 33% lesser than aluminum.

Mg alloys are reinforced with ceramic particles to enhance its Mechanical Properties like tensile strength, flexural strength and High strength to weight ratio to extend its application in field of marine, defense, pump impellers, biomedical applications, etc., and make the magnesium alloys fully functional material. Incorporating ceramic reinforcements such as Boron Carbide (B_4C) and Silicon Dioxide (SiO_2) has emerged as an effective way to overcome these drawbacks. The literature supports that hybrid reinforcement of AZ61 magnesium alloy with B_4C and SiO_2 can significantly improve its mechanical behavior when processed through stir casting. Combining B_4C and SiO_2 within magnesium alloys creates synergistic effects, leading to a better balance between strength, hardness, and ductility compared to single reinforcements. The main objective of this research is to evaluate how different reinforcement levels influence the tensile strength, yield strength, flexural strength, hardness, and elongation of AZ61 composites and to identify the optimum composition using Taguchi design, Grey Relational Analysis (GRA).

2. METHODOLOGY



MATERIALS

AZ61 Alloy

Due to its strength, stiffness, and light weight, magnesium (Mg) is the third most popular element used in constructed buildings, behind iron and aluminum. Although bulk mechanical qualities are heavily influenced by chemical composition and thermo-mechanical history, insofar as these factors impact microstructure, alloying with aluminum can further increase stiffness and strength. In this study, we employ nanoindentation to ascertain the characteristics of several phases in the well-known magnesium alloy AZ61. Commercially available magnesium alloy AZ61 contains trace amounts of zinc (about 1%), aluminum (around 6%), and other metals. AZ61 is a magnesium-based alloy with aluminum (Al) and zinc (Zn) as primary alloying elements.
Designation Breakdown: A-Aluminium, Z-Zinc, 6-6% Aluminium, & 1-1% Zinc. AZ61 Mg Alloy is a high-performance material from the aluminum-zinc (AZ) series of magnesium alloys. It's lightweight nature, high strength-to-weight ratio, and excellent corrosion resistance, making it as a favorite in aerospace, automotive, and defence industries. AZ series of wrought alloys of magnesium AZ31, AZ61 &AZ80. AZ61 is a wrought alloy containing twice the amount of aluminum compared to AZ31. The future of magnesium metal matrix composites (MMCs) in automotive applications looks promising, driven by the industry promote the use of lightweight, high-strength materials to enhance performance and fuel economy.

B_4C(Boron Carbide)

Boron carbide is a very hard substance that is less dense (2.51 g/cm3) and has outstanding thermal stability and chemical resistance. It is a good material for nuclear applications because of its high neutron absorption cross section. After cubic boron nitride and diamond, boron carbide is the hardest substance. Boron carbide also exhibits a very high elastic modulus and excellent resistance to abrasion, acids, and high temperatures, while maintaining stability up to around 2450 °C. and as a reinforcement in metal matrix composites. When incorporated into alloys such as AZ61 magnesium, B_4C enhances hardness, tensile strength, flexural strength, and wear resistance, making it an attractive reinforcement for structural, automotive, and aerospace applications where strength-to-weight ratio and durability are critical.

SiO_2(Silicon Dioxide)

Silicon Dioxide also known as silica, It is a naturally occurring compound made of silicon and oxygen. It's one of the most abundant materials on Earth and shows up in everything from beach sand to quartz crystals. Silicon Dioxide (SiO2) is increasingly used as a reinforcement in Metal Matrix Composites due to its excellent mechanical, thermal, and tribological properties. silicon dioxide serves as a lightweight reinforcement that improves hardness, flexural strength, and wear resistance, while also enhancing the material's thermal stability and corrosion resistance. When incorporated into magnesium alloys like AZ61, SiO_2 contributes to a uniform microstructure and supports load transfer between the matrix and reinforcement particles. Its abundance, low cost, and ability to enhance both mechanical and thermal properties make SiO_2 an effective additive for engineering materials used in automotive, aerospace, and structural applications.

3. STIR CASTING

Stir casting is one of the most widely used and economical techniques for producing metal matrix composites, and it was adopted in this study to fabricate AZ61-based hybrid composites reinforced with B_4C and SiO_2. In this process, ingots of the AZ61 magnesium alloy were first cut into small pieces, placed in a graphite crucible, and melted in an electric resistance furnace at a temperature above the alloy's melting point. The ceramic reinforcements were preheated to remove moisture and improve wettability, then slowly introduced into the vortex created by a mechanical stirrer. Stirring was carried out at a controlled speed (about 500 rpm) for a fixed duration (≈10 min) to achieve uniform particle dispersion within the molten matrix. The slurry was then poured into preheated steel dies and allowed to solidify. This method ensures good bonding between the matrix and the reinforcement particles, minimizes agglomeration, and provides a cost-effective route for producing magnesium composites with improved tensile strength, hardness, and flexural properties. In this technique, a mechanical stirrer creates a vortex in the molten metal, helping to uniformly distribute the reinforcement particles within the metal matrix. A standard stir casting system includes a furnace, a mechanical stirrer, and a feeder for the reinforcement material.

4. MECHANICAL TESTING

Mechanical testing under a Universal Testing Machine is conducted to evaluate the tensile and flexural properties of the developed composite materials. UTM is a versatile equipment that applies controlled force to a specimen to determine its mechanical behavior under various loading conditions. Standardized tests, including tensile strength, yield strength, percentage elongation, flexural strength and hardness are conducted to determine the composite's suitability for structural or functional applications. To guarantee accuracy, reproducibility, and comparability of results, these tests are carried out in compliance with pertinent ASTM standards.

TENSILE TEST

Composites were tested on a specimen shaped like a dog bone. The specimens used for the tensile test had a radius of 6 mm and a gauge length of 45 mm. The current study's test for determining the composite materials' tensile strength. With a cross-head speed of 5 mm per minute, the test specimen is positioned between the UTM's grips.

The sample is loaded incrementally until it fractures. The tensile strength of the composite specimens is then calculated using these test results

FLEXURAL TEST

One mechanical testing technique for figuring out the flexural strength and flexural modulus of composite materials is the 3-point flexural test. This test assesses a material's resistance to deformation when subjected to bending stresses. A flexural test was performed in accordance with ASTM D790 to determine the material's flexural strength. The three-point bend test was conducted using a computer-controlled UTM at a steady displacement rate of 0.5 mm/min.

HARDNESS TEST

The hardness values are typically reported on the Rockwell Hardness Scale 'E', denoted as HRE, which is appropriate for materials such as magnesium and aluminum alloys. In this test, a steel ball indenter is used along a 100 kgf major load. The testing apparatus features a red dial indicator, enabling direct reading of hardness values. This setup is suitable for evaluating the surface strength and wear resistance of softer metals and their composites

5. EXPERIMENTAL OBSERVATIONS

Sample	Wt% of Reinforcement [B_4C+SiO_2]	Ultimate Tensile strength [MPa]	Yield Strength [MPa]	Percentage of Elongation [%]	Flexural Strength [MPa]	Rockwell Hardness[RHN]
S1	0	60.12	25	4.9	12.5	80
S2	2(B_4C)	48.71	19.73	5	9.345	93
S3	2(SiO_2)	46.97	18.8	4.79	7.951	81.3
S4	2	41.91	17.03	5.13	13.02	78.6
S5	4	67.76	27.45	7.82	13.55	84
S6	5.5	73.5	31.5	3.5	14.1	74
S7	6	80.8	33	3	14.5	75.6
S8	6.5	83.2	35.2	2.4	14.2	73
S9	7	88	36.5	2	13.9	71

Tensile Strength

At 4%+4%, a substantial improvement in both tensile strength (67.76 MPa) and elongation (7.82%) is observed, suggesting optimal dispersion and bonding.

Yield Strength

From 5.5% to 7% Reinforcements, yield strength increases steadily, reaching a peak of 36.5 MPa at 7%+7%.

Hardness

Base Alloy has a hardness of 80 HRE, 2% B_4C and 2% SiO2 slightly improve hardness, due to the ceramic nature of reinforcements, Maximum Hardness is achieved at 4%+4% (93 HRE), indicating optimal dispersion and strong interfacial bonding of particles

Flexural Strength

Flexural strength continues increasing with more reinforcement, peaking at 6% total content (14.5 MPa), Beyond 6%, there is a slight decline in strength, suggesting particle agglomeration, microcracks, or brittleness due to overloading of ceramic phases.

6. GRA OPTIMIZATION

It is particularly useful in engineering and experimental optimization, especially when:
•The number of experiments is small,
•Information is insufficient for conventional statistical models,
•Multiple performance characteristics (outputs) need to be considered simultaneously.

GRA is a powerful & reliable technique used for solving complex multi-response optimization problems, especially in systems with incomplete, uncertain, or limited data. It has proven to be an effective decision-making tool across various fields including engineering, materials science, manufacturing. Works Effectively with Limited Data: Unlike RSM or regression-based models that require a large dataset, GRA works well with small sample sizes. In material testing or experimental work (e.g., Taguchi L9 design), GRA still provides reliable results without needing complex

Ranking of Specimens by using Grey Relational Analysis

1) Data Pre-processing
2) Normalization
3) Deviation Sequence Calculation
4) Grey Relational Coefficient Determination
5) Grey Relational grade

The process began with data pre-processing, where experimental results for tensile strength, yield strength, flexural strength, hardness, and percentage elongation were arranged in a decision matrix. Next, normalization was performed to convert the observed values into a dimensionless scale (0–1), ensuring comparability between "larger-the-better" characteristics (strength, hardness) and "smaller-the-better" characteristics (e.g., wear or elongation loss). Following this, the deviation sequence—the difference between the normalized value and the ideal reference (1)—was calculated for each property. The grey relational coefficient for every response was then determined to measure the closeness of each sample's performance to the ideal. Finally, the grey relational grade (GRG), obtained as the average of all coefficients, was used to rank the composites. A higher GRG indicated a better overall mechanical performance

7. GRA Optimization Table

Data Preprocessing

Sample	UTS(MPa)	YS(MPa)	Flexural Strength (MPa)	Hardness (RHN)	Elongation (%)
S1	60.12	25	12.5	80	4.9
S2	48.713	19.731	9.345	93	5.08
S3	46.978	18.802	7.951	81.3	4.79
S4	41.913	17.033	13.02	78.6	5.13
S5	67.765	27.455	13.55	84	7.82
S6	73.5	31.5	14.1	74	3.5
S7	80.8	33.2	14.5	75.6	3
S8	83.2	35.2	14.2	73	2.4
S9	88	36.5	13.9	71	2

Normalization

Sample	UTS	YS	Flexural Strength	Hardness	Elongation
S1	0.604943	0.590743	0.30539014	0.59090909	0.501718213
S2	0.852453	0.861406	0.78714308	0	0.470790378
S3	0.890099	0.909128	1	0.53181818	0.520618557
S4	1	1	0.2259887	0.65454545	0.462199313
S5	0.439061	0.464632	0.14506031	0.40909091	0
S6	0.314622	0.256845	0.06107803	0.86363636	0.742268041
S7	0.156226	0.169518	0	0.79090909	0.828178694
S8	0.104151	0.06678	0.04580852	0.90909091	0.931271478
S9	0	0	0.09161704	1	1

Deviation Sequence Calculation

The Deviation Sequence Calculation is an essential step that quantifies how far each experimental result is from the ideal reference value. After normalizing the mechanical property data of the AZ61–B_4C–SiO_2 composites, the ideal value for every response (such as tensile strength, yield strength, flexural strength, hardness, and elongation) is considered to be 1. For each sample and for every property, the deviation sequence is obtained by calculating the absolute difference between the normalized value and this reference point. A smaller deviation indicates that the corresponding sample is closer to the optimal performance for that property, whereas a larger deviation reflects a greater gap from the desired outcome.

Grey Relational Coefficient Determination

After calculating the deviation sequence for each mechanical property of the AZ61–B_4C–SiO_2 composites, the next step in Grey Relational Analysis is the Grey Relational Coefficient (GRC) determination. The GRC quantifies the closeness of each experimental result to the ideal reference value. A higher GRC indicates that the sample's performance for that property is closer to the ideal solution, while a lower coefficient reflects poorer performance. By calculating the GRC for each property (tensile strength, yield strength, flexural strength, hardness, and elongation), the relative performance of all composites can be assessed. This step is crucial for identifying how well each reinforcement level satisfies the desired mechanical requirements before combining them into the overall Grey Relational Grade.

Grey Relational grade

The Grey Relational Grade (GRG) represents the overall performance index of each composite and is the final step in Grey Relational Analysis. Once the Grey Relational Coefficients (GRCs) for all mechanical properties such as tensile strength, yield strength, flexural strength, hardness, and elongation have been determined, they are averaged (or, if required, weighted) to obtain a single value known as the GRG. This value reflects the degree of closeness of each composite to the ideal reference solution, considering all responses simultaneously. A higher GRG signifies that the sample has better overall mechanical behavior, balancing strength, hardness, ductility, and stiffness, while a lower GRG indicates inferior performance. By ranking the GRGs of all reinforcement combinations, it becomes possible to identify the optimum percentage of B_4C and SiO_2.

GRA Optimization table

The results of the Grey Relational Analysis (GRA) for all nine compositions are summarized through the Grey Relational Grade (GRG), which represents the overall performance of each sample based on tensile strength, yield strength, flexural strength, hardness, and percentage elongation.

Optimization table

Sample	Grey Relational Grade (GRG)	Rank
S1	0.662448384	7
S2	0.663302355	6
S3	**0.572663631**	**9**
S4	0.62079302	8
S5	**0.792131327**	**1**
S6	0.721861093	5
S7	0.76506082	4
S8	0.768175028	3
S9	0.783214436	2

8. RESULTS

Ultimate Strength (UTS): Specimen 9 (7%+7%) yields the maximum tensile strength (88 MPa) but at the cost of reduced elongation (2%), indicating brittleness.
Yield Strength: Achieved with Specimen 9 (7%+7%), offering maximum yield strength (36.5 MPa).
Flexural Strength: Achieved at Specimen 7 (6% B_4C + 6%SiO_2) with 14.5 MPa.
Hardness: Achieved with Specimen 5 (4%+4%) reinforcement, suggesting a well-bonded microstructure.
Based on the Grey Relational Analysis (GRA)
Sample 5 (Al_2O_3 + B_4C) achieved the highest overall performance, securing Rank 1. This indicates It suggests an ideal combination of mechanical qualities like tensile strength, hardness, flexural strength, and hardness because it has the shortest Grey Relational Distance from the ideal solution.
In contrast, Sample 4 (Al_2O_3 + B_4C) obtained Rank 9, signifying it is the least favorable among the tested samples in terms of proximity to the ideal mechanical behavior.

9. CONCLUSION

Stir casting was used to reinforce magnesium alloy AZ61 to create hybrid metal matrix composites. with varying proportions of boron carbide and silicon dioxide. First sample consisted solely of the base AZ61 alloy. In the second sample, 2% B_4C was added, while no SiO_2 was included. The third sample contained 2% B_4C and 2% SiO_2. The fourth sample included 4% B_4C and 4% SiO_2, with the remaining composition being AZ61 alloy in each case. The reinforcement percentages were varied among the samples to investigate their influence. Subsequent mechanical testing and analysis of these composites yielded the following results.

- Reinforcement Effect: Boron Carbide (B_4C) contributed significantly to strength and hardness, especially in higher wt.%, Silicon Dioxide (SiO_2) played a supportive role in flexural strength and hardness and combined Reinforcements (B_4C + SiO_2) led to synergistic improvement in overall mechanical properties, but at the cost of ductility.
- Optimal Composition: However, Specimen 5 (92% of Base Alloy + 4% of B_4C + 4% of SiO_2) is the best-balanced combination, offering good Tensile strength, highest hardness, and still retaining moderate ductility. Best-performing combination across all properties.
- Grey Relational Analysis confirmed that specimen 5 provides the most balanced mechanical performance, achieving the highest Grey Relational Grade (0.792).
- These composites are suitable for structural applications depending on the trade-off between strength and flexibility.

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