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Design and Optimization of Mg – B4C Formed Metal Matrix Composite

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Abstract: *The study focuses on developing new metal matrix composite (MMC) using magnesium as the base metal, boron carbide (B_4C) as the reinforcement particle, and vinyl ester resin as the binder. This MMC aims to achieve enhanced mechanical properties, including a higher strength-to-weight ratio, improved corrosion resistance, and increased hardness, making it suitable for automotive and aerospace applications. The fabrication process is simulated using advanced computer-aided design software, which allows for precise structural representation, as well as analysis of stress-strain, heat, and deformation. Analytical computations are used to validate the simulation results.*

Keywords: Magnesium, Boron Carbide (B_4C), Vinyl Ester Resin, Metal Matrix Composite (MMC), Mechanical Properties, Simulation Results

I. INTRODUCTION

Composites exist throughout nature [1]. Since ancient times, humans have utilized composites; early civilizations mixed mud and straw to build durable structures, and Mongols crafted powerful bows from wood, bone, and animal glue [1]. In order to create a material with improved qualities that are not possible with just the individual components, composite materials are created by mixing two or more constituent elements having radically different physical or chemical properties [2]. Composite materials, due to their high strength-to-weight ratio and exceptional environmental resistance, have become vital in aerospace, automotive, and construction sectors where performance and efficiency are critical [3]. Combining two or more distinct elements to produce a new material with superior overall qualities to the constituent parts is the straightforward goal of manufacturing composites. Polymer composite materials are widely used in shipbuilding, but their large-scale application is limited due to cost, fire safety, and classification society restrictions [4]. Composite materials are significant because they mix two or more materials to produce improved qualities such as durability, corrosion resistance, and a high strength-to-weight ratio. Metal matrix composite materials are made by combining a metal with a reinforcing material such as ceramic particles, fibers, or whiskers. Composites known as "metal matrix composites" have a combination of an alloy or metal matrix [5]. In educational applications, metal matrix composites (MMCs) are thought to be good substituents for traditional materials, including metals, polymers, and ceramics [6]. MMCs contribute to weight reduction in the automotive and aerospace industries, leading to better fuel efficiency and performance. Continuous reinforcement and discontinuous reinforcement are two different types of reinforcement [7]. The homogeneous characteristics in all directions are a feature of isotropic discontinuous metal matrix composites (MMCs), which may be manufactured efficiently using standard metalworking techniques including extrusion, forging, and rolling [7].

Magnesium-based MMCs can be synthesized using solid-phase methods like powder metallurgy or liquid-phase routes involving molten metal and solid reinforcements of varying characteristics [8]. The even distribution of thermally stable nanoscale ceramic particles throughout the grain matrix is a key component of the microstructural design of lightweight MMCs for creep-resistance applications [9]. Magnesium is a lightweight, silvery-white metal belonging to the alkaline earth metal group with an atomic number of 12. It is the third most abundant in seawater (0.13%) and the fifth most abundant metallic element in Earth's crust (2%) [10]. Magnesium is one of the lightest structural metals, making it an excellent choice for composite materials where weight reduction is essential. Due to its low density and high specific

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strength, magnesium serves as an ideal matrix material for improving the overall performance of composites. The addition of reinforcements into the magnesium matrix significantly enhances properties like wear resistance, hardness, and thermal stability, expanding its range of industrial applications. Excellent mechanical qualities, including high hardness, low density, and wear resistance, are possessed by boron carbide materials; as a result, they have been utilized for ceramic bearings and cutting and grinding tools [11]. Use of boron carbide increases the hardness of a new material. The nominal stoichiometric formula for boron carbide after cubic boron nitride and diamond, B_4C, is the third hardest single-phase material known to science [12]. When used in MMCs, B_4C improves tensile strength, hardness, and stiffness, making the composite suitable for applications requiring lightweight yet durable materials, such as in the aerospace, defense, and automotive industries. Additionally, B_4C contributes to thermal stability and neutron absorption, making it valuable in nuclear and high-temperature applications.

II. METHODOLOGY

A number of factors must be taken into account, including the size of the new material, the production process, the material qualities, and the choice of material. A novel material's size has a significant impact on how well it performs and if it is appropriate for a certain application. Furthermore, knowing how each parameter works together will help you make better design choices and maximize the finished product's overall efficacy. In addition to fulfilling the functional criteria, the finished product must also respect financial limitations and sustainability objectives. Designers can produce creative solutions that improve performance while reducing their negative effects on the environment by carefully weighing these variables.

Material Selection

TABLE I: Material and Particle Sizes for Composite Fabrication

Material	Importance	Mesh Size	Property
Magnesium	Magnesium is widely valued for its abundance, recyclability, and role in developing lightweight, energy-efficient materials, making it essential for automotive, aerospace, biomedical, and electronics industries.	200-350	Lightweight & good machinability.
Boron Carbide	Boron carbide is highly valued for its extreme hardness, low density, and excellent wear resistance, making it essential for armor, cutting tools, and advanced composite material.	60-120	High hardness.
Vinyl ester resin	Vinyl ester resin is preferred for its superior corrosion resistance, high mechanical strength, and excellent bonding properties.		Excellent bonding.

Software Selection

Autodesk's Fusion 360 tool, which integrates CAM, industrial design, structural design, and mechanical simulation, produces a design platform that allows for cross-platform and cloud collaboration and sharing. Its selection for this project is primarily prompted by its capacity to handle complicated geometries, integrate easily with computer-aided engineering (CAE) tools, and perform simulation-driven design. Engineers and designers can use Fusion 360 to construct objects with shapes and functionalities that are ready for manufacturing; this allows users to swiftly explore product concepts and achieve prototype results. Furthermore, cloud-based solutions allow designers to use Fusion 360 from any location, at any time.This flexibility allows for greater collaboration among team members and facilitates real-time updates, ensuring that all stakeholders can contribute to the design process efficiently. Ultimately, this enhances innovation and accelerates the development cycle.Teams can react to feedback and shifting market expectations more quickly because to this expedited development cycle, which also reduces time to market. Designers can push the limits of creativity and produce high-quality goods that satisfy their clients by utilizing these benefits.

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Material Properties

TABLE III: Properties of Material for CAD Integration

Property	Magnesium	Boron carbide	Vinyl ester resin
Density (g/cm³)	1.738	2.52	1.046
Young's Modulus (GPa)	45	460	3.3
Poisson's Ratio	0.29	0.17	0.38
Yield Strength (MPa)	65	261	58
Ultimate Tensile Strength (MPa)	90	350	80
Thermal conductivity (W/m-K)	156	36	0.2
Thermal Expansion Coefficient ($\times 10^{-6}$/K)	25.2	4.5	75
Specific Heat (J/g-K)	1.023	0.8	1.3
Melting Point (°C)	650	2763	-
Boiling Point (°C)	1090	3500	-

III. RULE OF MIXTURES

The application of the rule of mixtures enables a macroscopic understanding of lamina behavior by considering the contributions of individual component, both matrix and reinforcement. The idea of mixes can be used to materials with precipitates and matrix in addition to composites [13]. The rule of mixtures (ROM) provides an effective method for estimating the mechanical properties of composite materials by considering the volume fractions and individual properties of the matrix and fiber components [14]. ROM is a first-order model that ignores the shape and distribution of constituents and only includes their averages [15]. It assumes that the composite's behavior is a weighted average of its matrix, reinforcement, and any additional phases, such as binders or fillers.

The weighted average of the densities of the component materials—such as the reinforcement and matrix—while taking into consideration their individual volume percentages is the density of a composite material.

$$\rho c=Vm*\rho m+Vr*\rho r+Vb*\rho b \qquad (1)$$

Young's modulus, also known as modulus of elasticity, is an important property of materials that determines their stiffness or resistance to elastic deformation. It is the ratio of strain (proportional deformation) to stress (force per unit area) in the linear elastic zone of a material. A higher Young's modulus indicates that the material is stiffer and deforms less under a given load, which is important for material selection and engineering design.

$$Ec = Vm*Em + Vr*Er + Vb*Eb \qquad (2)$$

The Poisson's ratio measures a material's tendency to deform perpendicular to an applied force. The negative ratio of transverse strain (change in width/thickness) to axial strain (change in length). This dimensionless value specifies how much a material will narrow when stretched or widen when compressed, and it is important for forecasting material behavior under different loads.

$$\nu c=Vm*\nu m+Vr*\nu r+Vb*\nu b \qquad (3)$$

The maximum stress a material can withstand before experiencing irreversible plastic deformation is known as its yield strength. If the applied stress is removed beyond this point, the material will no longer regain its original shape, showing a change from elastic to plastic behavior.

$$\sigma yc=Vm*\sigma ym+Vr*\sigma yr+Vb*\sigma yb \qquad (4)$$

The highest stress a material can sustain before breaking or cracking under a tensile (pulling) load is known as its ultimate tensile strength (UTS). It shows the highest stress on the stress-strain curve of a material before to its ultimate failure.

$$\sigma UTS,c=Vm*\sigma UTS,m+Vr*\sigma UTS,r+Vb*\sigma UTS,b \qquad (5)$$

Thermal conductivity is a measurement of a material's capacity to transmit or convey heat. It is required for applications involving heat dissipation or insulation because it describes the rate at which heat travels through a medium when there is a temperature difference across it.

$$kc=Vm*km+Vr*kr+Vb*kb \qquad (6)$$

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The amount that a material changes size (expands or contracts) in reaction to temperature changes is known as the coefficient of thermal expansion, or CTE. For every degree of temperature change, it is the fractional change in dimension.

$$\alpha c = Vm*\alpha m + Vr*\alpha r + Vb*\alpha b \qquad (7)$$

The ability of a substance to store thermal energy is known as its specific heat capacity. It measures the amount of thermal energy required to raise a substance's temperature by one degree Celsius (or Kelvin) per unit mass. High specific heat capacity materials may absorb a lot of heat without causing a substantial temperature change.

$$Cc = Vm*Cm + Vr*Cr + Vb*Cb \qquad (8)$$

Fig. 1.List of properties for composite generation in CAD

Size, Shape & Volume Fraction

Size and Shape

In this study, a metal matrix composite (MMC) rod of dimensions 100mm length with diameter of 26mm was fabricated for experimental analysis. The selected dimensions ensure uniform distribution of reinforcement particles within the metallic matrix while maintaining structural stability. The diameter of 26mm was chosen to achieve an optimal balance between mechanical strength and material workability.The formation process aims to enhance the mechanical, thermal, and tribological properties of the composite material.

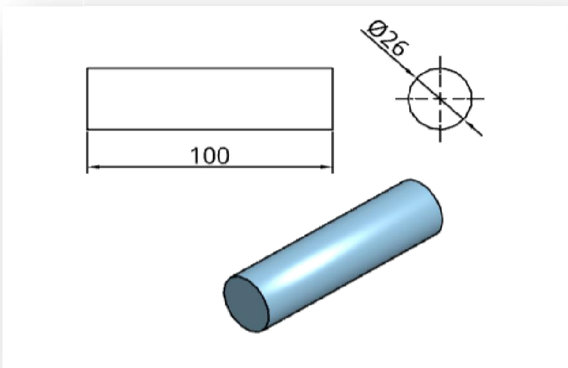

Fig. 2.Size & Shape of a model.

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Volume Fraction
Case 1: Mg: 80%; B_4C: 10%; VER: 10% (Low Hardness)
Case 2: Mg: 60%; B_4C: 20%; VER: 20% (Moderate Hardness)
Case 3: Mg: 40%; B_4C: 30%; VER: 30% (Higher Hardness)

TABLE IIIII: Properties of Material by ROM

Property	Case-1	Case-2	Case-3
Density (g/cm³)	1.747	1.756	1.765
Young's Modulus (GPa)	82.33	119.66	156.99
Poisson's Ratio	0.287	0.284	0.281
Yield Strength (MPa)	83.9	102.8	121.7
Ultimate Tensile Strength (MPa)	115	140	165
Thermal conductivity (W/m-K)	128.42	100.84	73.26
Thermal Expansion Coefficient ($\times 10^{-6}$/K)	28.11	31.02	33.93
Specific Heat (J/g-K)	1.0284	1.0338	1.0392

IV. FEA ANALYSIS

Static-Stress Analysis

TABLE IVV: Lateral Analysis

Load	FOS	Stress	Displacement	Reaction Force	Strain
5000	8.311	23.214	0.011	421.703	3.695E-04
10000	4.155	46.429	0.022	843.406	7.390E-04
15000	2.77	69.643	0.033	1265.109	0.001
20000	2.08	92.857	0.044	1686.813	0.001
25000	1.66	116.072	0.055	2108.516	0.002

TABLE V: Longitudinal Analysis

Load	FOS	Stress	Displacement	Reaction Force	Strain
10000	10.77	19.85	0.025	545.08	2.936E-04
20000	5.38	39.702	0.046	1090.188	5.872E-04
30000	3.59	59.553	0.069	1635.296	8.807E-04
40000	2.69	80.383	0.091	2204.379	0.001
50000	2.154	99.255	0.114	2725.513	0.001
60000	1.79	119.10	0.137	3270.43	0.002

TABLE VI: Transverse Analysis

Load	FOS	Stress	Displacement	Reaction Force	Strain
20000	8.99	16.126	0.019	124.262	3.359E-04
40000	4.50	32.253	0.037	248.524	6.718E-04
60000	3	48.379	0.057	372.786	0.001
80000	2.25	64.506	0.074	497.046	0.001
100000	1.80	80.632	0.093	621.31	0.002

From the above Static-Stress analysis tables, it is observed that increasing the applied load results in a progressive rise in Stress, Displacement, Strain and Reaction force, While factor of safety (FOS) decreases. This trend indicates the structure is experiencing higher deformation and stress levels, approaching its material limits, and becoming less safe under larger applied loads.

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Thermal-Stress Analysis

TABLE VII: Temperature Analysis

Temperature	FOS	Stress	Displacement	Reaction Force	Strain
40	1.133	127.994	0.001	2414.025	0.003

V. CONCLUSION

We have desired and improved a magnesium-based metal matrix composite (MMC) reinforced with boron carbide and bonded using vinyl ester resin. The composite is appropriate for demanding applications in the automotive and aerospace industries due to its improved thermal and mechanical qualities when compared to pure magnesium

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