



A comparative analysis was conducted by applying casting law of mixture on three distinct composites having same matrix metal, LM-25, but reinforced material is having three different ceramics in equal by volume fraction for mechanical properties of the composites. The different ceramics—Boron Nitride (BN), Boron Carbide (B₄C), and Silicon Nitride (Si₃N₄)—at varying reinforcement levels of 3%, 6%, and 9%.

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Abstract

This study focuses on the comparison of the effect of three different ceramics (BN, Si₃N₄, B₄C) together in equal volume fraction as reinforcement with Aluminum Alloy LM25 matrix on mechanical properties of composites. Composites fabricated by using law of mixture for casting process. The reinforcement content varied from 3% to 9% in steps of different percentages (3%, 6%, 9%), for a set of three composites. The number of different elements present in the reinforcement, matrix and the three sets of composites is demonstrated using elemental mapping. The result of this investigation based on the theoretical results, the properties of the composites (Poisson ratio, density, tensile strength, Young's modulus, and hardness) are significantly influenced by the type and percentage of reinforcement and with percentage variations. Increasing the reinforcement percentage generally leads to a decrease in Poisson ratio and Tensile Strength, increase in Young's Modulus and Hardness, variation in Density, indicating complex interactions. Further work is to verify the results with composites of same matrix and reinforcement material synthesized in laboratory by using casting process.

Keywords: Composites, Casting Law of Mixture, Reannouncement, Parallel & Perpendicular Law of Mixture.

1. Introduction

1.1. Composite

Humans have employed composites for millennia. The Mesopotamians in Iraq developed the first artificial composites in 3400 B.C. Ancient societies constructed plywood by adhering wood strips at various angles in layers. Subsequently, the Egyptians commenced the production of death masks using plaster-impregnated linen or papyrus in 2181 B.C. Subsequently, each of these tribes started utilizing straw to augment

their products, including mud bricks, pottery, and boats. The Mongols commenced the construction of composite bows around 1200 A.D., which were quite effective during that period. These were fabricated from pine resin, wood, bamboo, bone, cattle tendons, horn, and silk. Polymerization is the reason manufactured resins to start to harden after the industrial revolution. In the 1900s, people learned about chemicals and used that information to make polymers like polyester, phenolic, and vinyl. Chemist Leo Baekeland created Bakelite, the first man-made material. Because it does not carry electricity and it can stand up to high temperature before melting, it could be used in many areas. The 1930s were a very important time in the history of composites. Owens Corning created glass fiber and was the leader in the fiber reinforced polymer (FRP) business. Resins made during this time are still used today, and in 1936, unsaturated polyester resins were trademarked. Enhanced performance resin solutions were introduced two years subsequently. Carbon fiber was initially patented in 1961 and subsequently became commercially accessible. In the mid-1990s, composites gained prevalence in industrial operations and construction owing to their reduced cost relative to previously utilized materials. The composites utilized in the Boeing 787 Dreamliner throughout the mid-2000s exhibited their appropriateness for high-strength applications. A composite material consists of two or more distinct phases, including a reinforcing phase and a matrix phase, with bulk properties that markedly differ from those of the individual components of the matrix material. Due to the similar qualities of several common materials to those of their base constituents, despite the presence of modest scattered phases in their structures, they are not categorized as composite materials. Composite materials possess favorable features such as high tensile strength, stiffness, low density, and high-temperature stability. In certain applications, electrical and thermal conductivity properties are considered, whereas characteristics such as the coefficient of thermal expansion and corrosion resistance should be minimized with enhanced wear resistance. All these attributes are considered in the production of metal matrix composites. Metal Matrix Composites readily incorporate enhanced mechanical properties. The rationale for the heightened interest in Metal Matrix Composite (MMC) materials in recent years is outlined below. Composites consist of two primary components: Matrix and Reinforcement [1][2].

1.2. Matrix

Usually integrated and requiring equal distribution of the reinforcement, the matrix acts as a single material. Among other materials, matrix ones include aluminum, magnesium, nickel, titanium, and cobalt. This work uses an aluminum LM25 alloy matrix. LM25's chemical makeup is described here. Cast in either permanent or sand molds, LM25 alloy shows exceptional machining and welding qualities, great corrosion resistance, remarkable castability, and great wear resistance. Optimal qualities of the metal matrix composite depend on uniform distribution of the second phase within the matrix alloy and optimal wettability, or bonding between these components. Particulate reinforced MMCs have attracted a lot of interest since their particular stiffness and strength at both room and increased temperatures. Because of their low density, good mechanical properties, cost-effectiveness, and simplicity of manufacture, aluminum metal matrix composites show great potential for wear and structural uses.

➤ LM-25

LM25 The low density, outstanding corrosion resistance, processing flexibility, high electrical and thermal conductivity, improved elastic modulus, strength, and significant damping capability of Al alloys render them exceptionally appealing. The unique property of liquid metal to stay in a liquid state at room temperature or lower has attracted considerable interest as an innovative functional metal material. Moreover, fluidity, elevated thermal conductivity, and significant phase change latent heat per unit volume of LM have led to crucial modifications in advanced heat dissipation technology. LM25 is primarily employed in castings that require an alloy with outstanding castability to achieve the desired level of soundness, particularly in applications where strong mechanical properties are essential. The alloy finds application in scenarios where it is essential to have corrosion resistance, particularly in conjunction with the requirement for high strength. The wettability is favorable. The density of LM25 is measured at 2.68 g/cm³ [3][4][5]

Table-1

Cu	Mg	Si	Fe	Mn	Ni	Zn	Sn	Ti	Al
0.1	0.2-0.6	6.5-7.5	0.5Max	0.3	0.1	0.1	0.1	0.05	Rest

1.3. Reinforcement

In the context of composites, the term "reinforcement" refers to the process of incorporating a material, typically fibers, into a matrix in order to improve the mechanical properties of the composite, including its strength, stiffness, and durability. The reinforcing material is responsible for providing structural support, while the matrix, which can be made of a polymer, metal, or ceramic, is responsible for binding the reinforcement together, distributing stresses, and protecting it from harmful effects of the environment [6]. Reinforcements bear the load, while the matrix facilitates load transfer among fibers and maintains their alignment. Fibers inhibit the spread of cracks within the matrix. Reinforced composites exhibit a greater capacity to absorb energy prior to fracturing, thereby improving toughness [7]. Different types of reinforcements are

➤ Fibers

- **Glass Fibers (GFRP):** Glass fiber reinforced polymers are the most common type of reinforcement. They are relatively inexpensive and offer a good balance of strength and weight.
- **Carbon Fibers (CFRP):** Known for their high strength-to-weight ratio and stiffness. Carbon fiber composites are used in aerospace, automotive, and sporting equipment due to their superior mechanical properties.
- **Aramid Fibers (Kevlar):** These fibers are highly resistant to impact and wear, often used in bulletproof vests and protective gear.

- **Natural Fibers:** These include jute, flax, and hemp. While less strong than synthetic fibers, they are biodegradable and sustainable.
- **Particulate Reinforcements:**
 - **Metal or Ceramic Particulates:** Tiny particles are added to improve wear resistance, toughness, and other mechanical properties. These are typically used in ceramic-matrix composites or metal-matrix composites.
 - **Whiskers or Short Fibers:**

In some applications, short fibers or whiskers are used to reinforce the matrix, improving properties like crack resistance and toughness.

1.3.1. Particulate Reinforcements:

Metal or ceramic particulates serve as reinforcements in particulate-reinforced composites. The incorporation of these composites improves attributes like strength, wear resistance, and thermal stability through the dispersion of fine particles within a matrix material, which may consist of metal, polymer, or ceramic. Here is a comprehensive examination of each

➤ **Metal Particulate Reinforcement**

The incorporation of metal particles, such as aluminum, copper, or titanium, into a matrix enhances mechanical properties, including toughness and conductivity.

➤ **Ceramic Particulate Reinforcement**

Reinforcing a matrix with ceramic particles improves its mechanical qualities including hardness, wear resistance, and thermal stability. Common ceramic particles include silicon carbide (SiC), aluminum oxide (Al₂O₃), silicon nitride (Si₃N₄), boron nitride ((BN), boron carbide ((B₄C), and zirconia (ZrO₂) etc.

• **Boron Nitride (BN)**

Boron nitride Boron nitride ceramics are sophisticated materials predominantly composed of hexagonal boron nitride (h-BN). Hexagonal boron nitride exhibits very poor tensile strength, particularly in relation to metals or other ceramics. The elastic modulus is roughly 14–45 GPa, indicating a relatively low value that reflects its soft, layered structure. It has a relatively low hardness, akin to graphite, measuring approximately 0.5–1 on the Mohs scale. It possesses exceptional thermal shock resistance, enabling it to endure abrupt temperature fluctuations without fracturing. Owing to its stratified, graphite-like configuration, h-BN exhibits brittleness and readily fractures under mechanical stress; however, boron nitride ceramics are chemically inert and withstand assault from most molten metals, acids, and alkalis, in addition to being resistant to oxidation, thereby extending their longevity in adverse environments. Boron nitride ceramics exhibit stability up to 2000°C in inert or vacuum environments and up to 1000°C in oxidizing conditions. Their strong heat resistance allows for application in elevated temperature environments. BN ceramics exhibit stability and resistance to thermal shock due to their minimal thermal expansion rate. This renders them advantageous for applications involving rapid temperature fluctuations. Although BN ceramics are electrically insulating, they transport heat effectively, rendering them suitable for applications requiring heat dissipation without electrical conduction. BN ceramic has low density (1.85 g/cm³), rendering them lightweight in comparison to numerous other ceramics, hence enhancing their attractiveness for applications necessitating little weight and strong strength [8][9][10][11][12].

• **Boron carbide (B₄C)**

A ceramic substance made of boron and carbon is called boron carbide, it is a very hard type of ceramics material after diamond and cubic boron nitride (c-BN), it is considered one of the hardest materials. Boron carbide is perfect for uses requiring resistance to abrasion and wear because of its extraordinarily high hardness (about 9.5 on the Mohs scale). It is categorized a light weighted ceramics material due to its low density of approximately 2.52 g/cm³, in comparison to other ceramics. It can take a lot of heat since boron carbide has a high melting point of about 2450°C. It can withstand hostile settings for an extended period of time because it is resistant to oxidation and most chemicals. Because of its high production cost, boron carbide is not often used in situations where every dollar counts.

• **Si₃N₄ (Silicon Nitride)**

Silicon Nitride (Si₃N₄) is a man-made ceramic material that has taken significant attention of researcher across the world due to its exceptional mechanical, thermal, and electrical properties. First synthesized in 1857, but only developed for industrial use in the 1960s and used in the production of advanced ceramic balls for bearings. higher the value of strength, toughness, and corrosion resistance, make it a primary material for various demanding applications. Furthermore, it has the ability to be processed into various forms, including powders, fibers, and films, expands its potential uses. Since silicon nitride may take on many various forms, each of which has unique properties, it is regarded as an extremely significant engineering ceramic. Silicon nitride at high temperatures shows good mechanical properties, like low density, high bending strength, high elastic modulus, fracture toughness, high abrasion wear, and resistance to solid particle erosion. Stated differently, this material possesses extraordinary strength and toughness. Additionally, as far as thermal properties are concerned the ceramic has outstanding thermal properties, including the capacity to tolerate thermal shock and little temperature-related expansion and contraction. The density of Si₃N₄ is 3.17 g/cm³. It can be used in harsh and critical environments because it has high hardness value hardness (8-9 on the Mohs scale), electrical insulation, and low thermal expansion coefficient. Si₃N₄ is valued for its exceptional mechanical properties, thermal stability, and corrosion resistance, making it suitable for demanding composites [12][13][14].

2. Methodology

Aluminum metal matrix composites are produced by using several processing methods. The techniques comprise hot pressing, cold pressing, powder extrusion, powder forging, diffusion bonding, squeezed casting infiltration, stir-casting, spontaneous infiltration, gas pressure infiltration, vacuum, and centrifugal infiltration. Among these several approaches Stir casting allows a high rate of production by

being a cheap and effective method of manufacturing composites. It also improves particle distribution while lowering flaws such porosity and insufficient bonding between the matrix and the reinforcement [15].

2.1. Stir Casting

For the aim of incorporating reinforcement, casting uses a mechanical stirrer to create a vortex in the matrix material. Because of its cost-effectiveness, application in mass production, simplicity, near-net shaping capabilities, and simplicity of composite structure management, technology is fit for the manufacturing of metal matrix composites. Comprising a furnace, a reinforcement feeder, and a motorized stirrer, the stir casting equipment One uses the furnace to raise temperatures and liquefy materials. Stir casting is better suited for the bottom pouring furnace since fast pouring following the agitation of the mixed slurry is necessary to avoid solid particles from settling at the base of the crucible. The mechanical stirrer creates a vortex that helps the reinforcing materials included into the melt to mix together. The stirrer comprises the impeller blade and the stirring rod. The impeller blade could show different geometries and blade count. Because flat blades with three digits consume less energy and create an axial flow pattern in the crucible, they are chosen. Linked to variable speed motors, the stirrer rotational speed is under control by a controller attached to the motor. Attached to the furnace, the feeder helps to get the reinforcing powder into the melt. One could pour the mixed slurry using lost-wax mold, sand mold, or a permanent mold. The several stages of the stir casting process are shown here. For melting during this process, the matrix material is kept in the bottom pouring furnace. Reinforcements are also preheated in a separate furnace at a certain temperature to remove moisture, contaminants, and other pollutants concurrently. Mechanical stirring starts the development of a vortex for a given period once the matrix material melts at a specified temperature. After the whole addition of the reinforcement particles, the stirring process starts at a consistent feed rate through the feeder positioned at the center of the vortex. After that, the molten material is poured into a prepared mold and let to naturally cool and harden. Subsequent operations like machining, heat treatment, testing, and inspection could also be carried out as advised [16][17][18].

2.2. Mixture Law for Composite Materials Made Through Casting Process.

The Law of Mixtures is a principle employed to forecast the characteristics of a composite material composed of two or more distinct constituents (fibers and a matrix). It evaluates composite characteristics such as density, modulus of elasticity, or thermal conductivity by analyzing the attributes and volume fractions of the constituent components. For a two-component composite, the attribute P_c (such as modulus, density, etc.) can be approximated using the formula below [19][20][21].

$$P_c = V_f P_f + V_m P_m$$

Where,

P_c = property of the composite

P_f = property of the fiber (reinforcement)

P_m = property of the matrix

V_f = volume fraction of the fiber

V_m = volume fraction of the matrix ($V_m = 1 - V_f$)

Depending on whether we are interested in the composite properties along the direction of the fibers (longitudinal) or perpendicular (transverse), there are two different versions of the Law of Mixtures.

➤ Longitudinal Law of Mixture for Composites (P_{c-II})

This equation is applicable when the load is exerted in the same direction as the fibers in the composite (parallel to the fibers). It posits that both the fiber and the matrix bear the load in accordance to their property (density, moduli etc) and volume percentages. The combination of fiber and matrix is termed as a composite material.

$$P_{c-II} = V_f P_f + V_m P_m$$

The properties of the composite (density, moduli, etc.) are directly proportional to the volume fractions of the fiber and matrix. The longitudinal properties (density, moduli, etc.) of the composite are a straightforward weighted average of the properties (density, moduli, etc.) of the fiber and matrix, indicating that the contributions of the fibers and matrix are exactly proportional to their volume and respective properties (density, moduli, etc.) [22][23].

➤ Transverse Law of Mixture for Composites ($P_{c\perp}$)

This law is applicable when the load is exerted perpendicular to the orientation of the fibers. The matrix governs the load transmission because the fibers are misaligned with the load direction and cannot effectively disperse the load.

$$1/P_{c\perp} = V_f/P_f + V_m/P_m$$

In this case, the volume fractions define the inverse of the attributes (density, moduli, etc.). This formula provides uniform stress distribution in the composite together with an estimate and presumptions of optimal adhesion between the fiber and matrix. Because the fibers, the stiffer component, are less effective in load resistance, the transverse properties—density, moduli, etc.—are inferior to longitudinal qualities. The matrix qualities mostly affect the transverse properties (density, moduli, etc.; the relationship is defined as an inverse weighted sum generating a reduced total material response) [19][20][21].

➤ Key Differences Between Longitudinal and Transverse Law of Mixture for Composites

✓ The transverse law is applicable when the load is perpendicular to the fibers, whereas the longitudinal law is useful when the load is parallel to the direction in which the fibers are oriented.

- ✓ In the longitudinal direction, the fibers bear a substantial percentage of the load owing to their rigidity. In the transverse direction, the matrix significantly contributes to load resistance, whereas the fibers have a reduced impact.
 - ✓ Because the fibers align with the load direction, the composite properties along the longitudinal direction are typically higher. On the other hand, the transverse modulus is lower because the fibers are less effective in the perpendicular direction.
- The differences result from the anisotropic qualities of composite materials, which suggest that their features change with the direction of applied forces. Usually, the casting technique for a composite is to embed fibers within a matrix material—such as metal or polymer—then for the matrix to set. For transverse and longitudinal properties, the computation method is essentially consistent. Still, some further factors related to the manufacturing process have to be considered, especially with relation to fiber alignment and the adhesion between fibers and the matrix.

➤ Consideration of Composites Made Through Casting

In casting, fiber orientation might not always be exactly controlled. Should the fibers be distributed randomly, the composite will show isotropic characteristics, therefore reducing the relevance of the difference between longitudinal and transverse elements. Should fibers be aligned, the composite will show anisotropy and requires different computations for both longitudinal and transverse characteristics. Mechanical characteristics of the link between the fiber and matrix affect their integrity. In the transverse direction especially, suboptimal bonding can lead to reduced effective stiffness. Voids or porosity may develop during casting, therefore reducing the composite's general stiffness. This can be ascribed to declining matrix or fiber effective volume percent. As such, the composite properties must be averaged over all possible orientations when casting composites with randomly orientated fibers. An efficient method is using a semi-empirical model for randomly oriented composites, such the Halpin-Tsai equations or a weighted average of longitudinal and transverse properties. The computation of an average attribute for a cast composite consisting of randomly orientated fibers follows.

$$P_{avg} = 1/5 P_{c-II} + 4/5 P_{c\perp}$$

This equation presupposes that fibers are uniformly probable to be orientated in any orientation. In the casting process, if the fibers are oriented, the longitudinal and transverse properties (density, moduli, etc.) can still be determined using the conventional rule of mixing. Nonetheless, if the fibers are spread randomly, the composite is often regarded as isotropic, allowing for the calculation of an average properties (density, moduli, etc.). Consideration must be given to the quality of fiber alignment, bonding, and any manufacturing faults such as porosity when forecasting the attributes of cast composites [24][25].

2.3. Procedure

First, we calculated mechanical properties of composites by applying longitudinal law of mixture then again, all values were calculated through transverse law of mixture method. After finding all mechanical properties through longitudinal and transverse law of mixture, we used the law of mixture for casting materials. This final determined value of mechanical properties is taken as the final value of respective properties which are mentioned in the results section.

3. Measurement

3.1. Density Measurements

The density of a material plays a vital role in Al MMCs (Metal Matrix Composites). It was estimated theoretically to find its approximate density value. The rule of mixture is a method of approach to find out theoretical estimation of composite material, based on the assumption that a composite property is the volume weighted average of the matrix and reinforcement phase properties. Then, the density of fabricated LM25 (2.68 g/cm³) metal alloy matrix with ceramics (BN – 2.1 g/cm³, B₄C – 2.52 g/cm³, Si₃N₄ - 3.17 g/cm³) reinforced composite was measured. The results derived are tabulated in the table below.

Table - 2

	Density of Composite With 0% reinforcements (LM25+0%BN+0%B ₄ C+0%Si ₃ N ₄) g/cm ³	Density of Composite With 3% reinforcements (LM25+1%BN+1%B ₄ C+1%Si ₃ N ₄) g/cm ³	Density of Composite With 6% reinforcements (LM25+2%BN+2%B ₄ C+2%Si ₃ N ₄) g/cm ³	Density of Composite With 9% reinforcements (LM25+3%BN+3%B ₄ C+3%Si ₃ N ₄) g/cm ³
Longitudinal Law	2.68	2.6775	2.675	2.6725
Transverse Law	2.68	2.675048	2.670115	2.665199
Law for Casting	2.68	2.675539	2.671092	2.66666

3.2. Hardness measurements

The hardness values of different weight % of the processed composites are determined for different weight fraction % of (BN ~ (50–70 GPa), B₄C ~ (30–42 GPa), Si₃N₄ ~ (17–21 GPa)), containing aluminum alloy LM25 ~(0.7–0.9 GPa), matrix.

Table - 3

	V. Hardness of composite with 0% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa	V. Hardness of composite with 3% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa	V. Hardness of composite with 6% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa	V. Hardness of composite with 9% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa
Longitudinal Law	0.8	1.926	3.052	4.178
Transverse Law	0.8	0.824082	0.84966	0.876876
Law for Casting	0.8	1.044466	1.290128	1.537101

3.3. Young Modulus measurements

To estimate the Young Modulus value of the composites, the rule of mixtures was employed, which assumes that the composite property is a volume-weighted average of the matrix and reinforcement phase properties. The theoretical Young Modulus values were then evaluated for LM25 ~ (70–72 GPa) metal alloy matrix composites reinforced with ceramics (BN ~ (900–1000 GPa), B₄C ~ (450–470 GPa), Si₃N₄ ~ (300–320 GPa)). The results are summarized in the table below.

Table - 4

	Young Mod. Of composite with 0% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa	Young Mod. Of composite with 3% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa	Young Mod. Of composite with 6% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa	Young Mod. Of composite with 9% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa
Longitudinal Law	71	86.07	101.14	116.21
Transverse Law	71	72.85181	74.8028	76.86116
Law for Casting	71	75.49545	80.07024	84.73093

3.4. Tensile Strength measurements

Al-MMCs (Metal Matrix Composites), material tensile strength is very important. It was calculated theoretically to obtain an approximate tensile strength value. The rule of mixture is a method for theoretically estimating composite materials that is based on the idea that a composite attribute is the volume weighted average of the matrix and reinforcement phases. The tensile strength for composites of LM25 ~ (0.23–0.31 GPa) metal alloy matrix with ceramic reinforced composite (BN ~ (2–5 GPa), B₄C ~ (0.2–0.4 GPa), Si₃N₄ ~ (0.4–1 GPa)) with different weight percentages was calculated. The resulting results are presented in the table below.

Table - 5

	Tensile Str. Of composite with 0% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa	Tensile Str. Of composite with 3% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa	Tensile Str. Of composite with 6% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa	Tensile Str. Of composite with 9% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄) GPa
Longitudinal Law	0.27	0.3069	0.3438	0.3807
Transverse Law	0.27	0.274494	0.27914	0.283946
Law for Casting	0.27	0.280975	0.292072	0.303297

3.5. Poisson Ratio measurements

A material's Poisson Ratio is necessary to know to evaluate the composites. To determine its approximate value, an approximation was made theoretically. The rule of mixture is a theoretical estimating technique for composite materials. It is predicated on the idea that a composite property is the volume-weighted average of the properties of the matrix and reinforcement phases. Next, Poisson ratio measurement was conducted for the theoretical composites of LM25 ~ (0.31 – 0.34 metal alloy matrix augmented with ceramics (BN ~ (0.1 – 0.15), B₄C ~ (0.17–0.21), Si₃N₄ ~ (0.24 – 0.28)) having varying value of percentages. The table below tabulates the derived results.

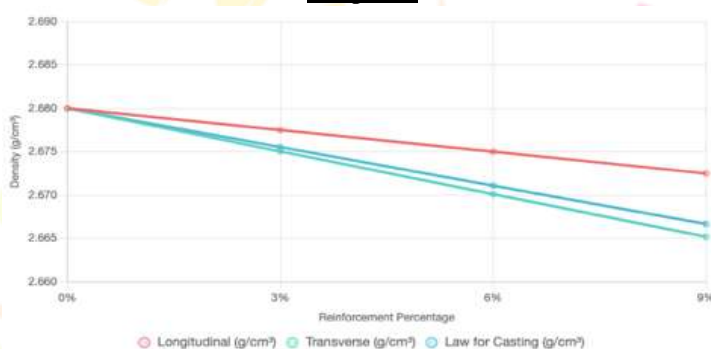
Table - 6

	Poisson Ratio Of composite with 0% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄)	Poisson Ratio Of composite with 3% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄)	Poisson Ratio Of composite with 6% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄)	Poisson Ratio Of composite with 9% reinforcement (LM25+BN+B ₄ C +Si ₃ N ₄)
Longitudinal Law	0.325	0.321	0.317	0.313
Transverse Law	0.325	0.316886	0.309167	0.301816
Law for Casting	0.325	0.317709	0.310734	0.304053

4. Results and discussion

4.1. Density Analysis

- 0% Reinforcement: 2.68 g/cm³ (all directions).
- 3% Reinforcement: Decreases to 2.6775 g/cm³ (Longitudinal), 2.675048 g/cm³ (Transverse), 2.675539 g/cm³ (Casting).
- 6% Reinforcement: Further decreases to 2.675 g/cm³ (Longitudinal), 2.670115 g/cm³ (Transverse), 2.671092 g/cm³ (Casting).
- 9% Reinforcement: Decreases to 2.6725 g/cm³ (Longitudinal), 2.665199 g/cm³ (Transverse), 2.666666 g/cm³ (Casting).

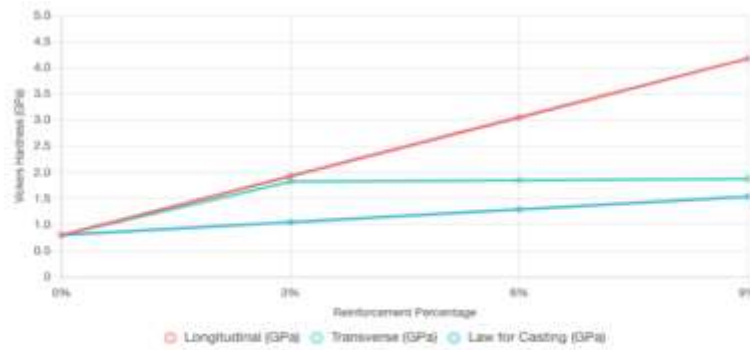
Graph - 1**Density Across Directions vs. Reinforcement Percentages**

Observations:

- ✓ Density slightly decreases with increasing reinforcement percentage, from 2.68 g/cm³ at 0% to around 2.665–2.6725 g/cm³ at 9%.
- ✓ This trend aligns with the lower densities of the reinforcement materials: c-BN (3.48 g/cm³), B₄C (2.52 g/cm³), and Si₃N₄ (3.17 g/cm³) relative to LM25 (2.68 g/cm³). The slight reduction suggests B₄C (the lightest reinforcement) may have a more dominant effect in the composite's overall density.
- ✓ The differences across directions are minimal, indicating isotropic behavior in density.

4.2. Vickers Hardness Analysis

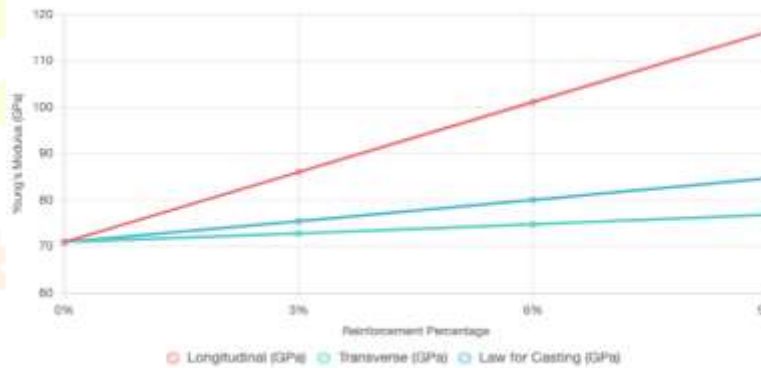
- 0% Reinforcement: 0.8 GPa (all directions).
- 3% Reinforcement: Increases to 1.926 GPa (Longitudinal), 1.824086 GPa (Transverse), 1.044466 GPa (Casting).
- 6% Reinforcement: Further increases to 3.052 GPa (Longitudinal), 1.84966 GPa (Transverse), 1.290128 GPa (Casting).
- 9% Reinforcement: Peaks at 4.178 GPa (Longitudinal), 1.876876 GPa (Transverse), 1.537101 GPa (Casting).

Graph - 2**Vickers Hardness Across Directions vs. Reinforcement Percentages****Observations:**

- ✓ Hardness increases significantly with reinforcement percentage, especially in the Longitudinal direction (from 0.8 GPa to 4.178 GPa at 9% reinforcement).
- ✓ The increase is less pronounced in the Transverse and Casting directions, indicating anisotropic behavior. For example, at 9% reinforcement, Longitudinal hardness (4.178 GPa) is much higher than Transverse (1.876876 GPa) and Casting (1.537101 GPa).
- ✓ This aligns with the high hardness of c-BN (45–50 GPa) and B₄C (30–35 GPa), which significantly enhance the composite's surface hardness, especially in the direction of reinforcement alignment (Longitudinal).

4.3. Young's Modulus Analysis

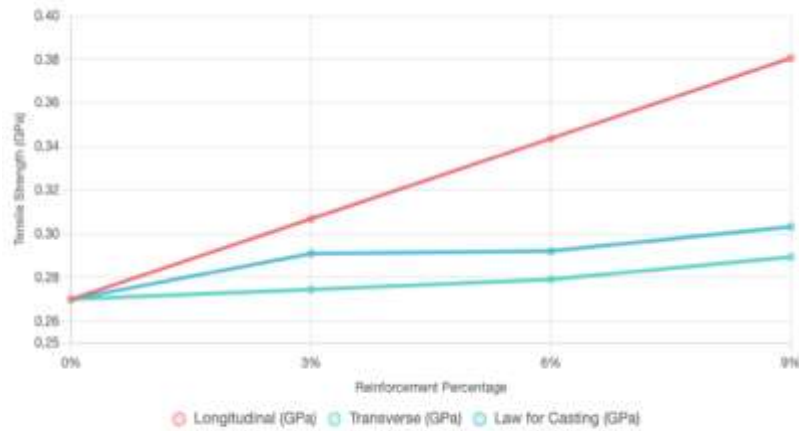
- 0% Reinforcement: 71 GPa (all directions).
- 3% Reinforcement: Increases to 86.07 GPa (Longitudinal), 72.85181 GPa (Transverse), 75.49545 GPa (Casting).
- 6% Reinforcement: Further increases to 101.14 GPa (Longitudinal), 74.8028 GPa (Transverse), 80.07024 GPa (Casting).
- 9% Reinforcement: Peaks at 116.21 GPa (Longitudinal), 76.86116 GPa (Transverse), 84.73093 GPa (Casting).

Graph - 3**Young's Modulus Across Directions vs. Reinforcement Percentages****Observations:**

- ✓ Young's modulus increases with reinforcement percentage in all directions, with the most significant improvement in the Longitudinal direction (from 71 GPa to 116.21 GPa at 9% reinforcement).
- ✓ The increase is less pronounced in the Transverse and Casting directions, again showing anisotropic behavior. For example, at 9% reinforcement, Longitudinal modulus (116.21 GPa) is much higher than Transverse (76.86116 GPa) and Casting (84.73093 GPa).
- ✓ This trend reflects the high stiffness of c-BN (900–1000 GPa), B₄C (450–470 GPa), and Si₃N₄ (300–320 GPa), which enhance the overall stiffness of the LM25 matrix, particularly in the direction of reinforcement alignment.

4.4. Tensile Strength Analysis

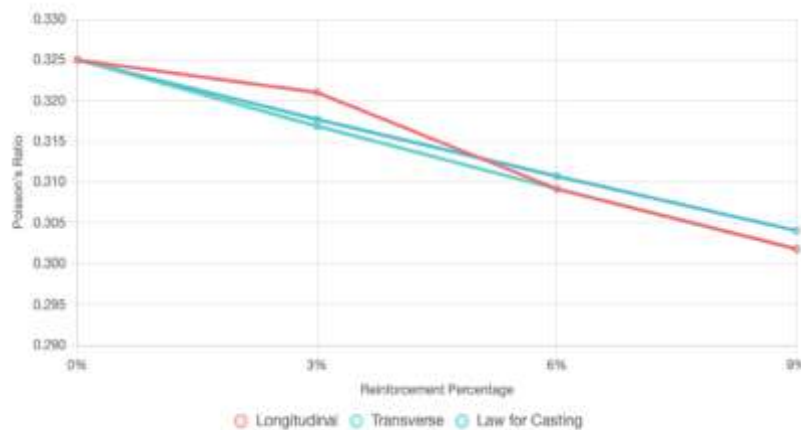
- 0% Reinforcement: 0.27 GPa (all directions).
- 3% Reinforcement: Increases to 0.3069 GPa (Longitudinal), 0.274494 GPa (Transverse), 0.290975 GPa (Casting).
- 6% Reinforcement: Further increases to 0.3438 GPa (Longitudinal), 0.27914 GPa (Transverse), 0.292072 GPa (Casting).
- 9% Reinforcement: Peaks at 0.3807 GPa (Longitudinal), 0.289346 GPa (Transverse), 0.303297 GPa (Casting).

Graph - 4***Tensile Strength Across Directions vs. Reinforcement Percentages*****Observations:**

- ✓ Tensile strength increases with reinforcement percentage, with the most significant improvement in the Longitudinal direction (from 0.27 GPa to 0.3807 GPa at 9% reinforcement).
- ✓ The increase is less pronounced in the Transverse and Casting directions, showing anisotropic behavior. For example, at 9% reinforcement, Longitudinal strength (0.3807 GPa) is higher than Transverse (0.289346 GPa) and Casting (0.303297 GPa).
- ✓ The improvement aligns with the high tensile strength of Si_3N_4 (400–1000 MPa) and the reinforcing effect of c-BN and B_4C , though their brittleness may limit the overall tensile strength gain in non-Longitudinal directions.

4.5. Poisson's Ratio Analysis

- 0% Reinforcement: 0.325 (all directions).
- 3% Reinforcement: Decreases to 0.321 GPa (Longitudinal), 0.316886 GPa (Transverse), 0.317709 GPa (Casting).
- 6% Reinforcement: Further decreases to 0.309167 GPa (Longitudinal), 0.309167 GPa (Transverse), 0.310734 GPa (Casting).
- 9% Reinforcement: Decreases to 0.301816 GPa (Longitudinal), 0.301816 GPa (Transverse), 0.304053 GPa (Casting).

Graph - 5***Poisson's Ratio Across Directions vs. Reinforcement Percentages*****Observations:**

- ✓ Poisson's ratio decreases with increasing reinforcement percentage, from 0.325 at 0% to around 0.301816–0.304053 at 9% reinforcement.
- ✓ The decrease is relatively uniform across all directions, suggesting isotropic behavior in this property.
- ✓ This trend aligns with the lower Poisson's ratios of the reinforcements: c-BN (0.1–0.15), B_4C (0.17–0.21), and Si_3N_4 (0.24–0.28), compared to LM25 (0.31–0.34). The reduction indicates that the composite becomes less prone to lateral deformation under stress as reinforcement increases.

4.6. General Trends and Insights**1) Effect of Reinforcement Percentage:**

- Density: Slightly decreases with increasing reinforcement (from 2.68 g/cm^3 to ~2.665–2.6725 g/cm^3), likely due to the lower density of B_4C (2.52 g/cm^3).

- Hardness: Increases significantly (from 0.8 GPa to 4.178 GPa in Longitudinal at 9%), driven by the high hardness of c-BN and B₄C.
- Young's Modulus: Increases substantially (from 71 GPa to 116.21 GPa in Longitudinal at 9%), reflecting the high stiffness of the reinforcements.
- Tensile Strength: Increases (from 0.27 GPa to 0.3807 GPa in Longitudinal at 9%), though the improvement is modest compared to hardness and modulus, due to the brittleness of the reinforcements.
- Poisson's Ratio: Decreases (from 0.325 to ~0.301816–0.304053), indicating reduced lateral deformation with increased reinforcement.

2) Anisotropy:

- Hardness, Young's modulus, and tensile strength exhibit significant anisotropy, with the Longitudinal direction showing the highest values. This suggests that the reinforcement particles are aligned or more effective in the Longitudinal direction, likely due to the composite processing method (e.g., directional casting or extrusion).
- Density and Poisson's ratio are more isotropic, showing minimal variation across directions.

3) Comparison with Base Materials:

- **LM25 (0% reinforcement):** Density (2.68 g/cm³), Hardness (0.8 GPa), Young's Modulus (71 GPa), Tensile Strength (0.27 GPa), Poisson's Ratio (0.325).
- Adding c-BN, B₄C, and Si₃N₄ significantly improves hardness, stiffness, and tensile strength, while slightly reducing density and Poisson's ratio.
- The improvements align with the properties of the reinforcements: c-BN (hardness 45–50 GPa, modulus 900–1000 GPa), B₄C (hardness 30–35 GPa, modulus 450–470 GPa), Si₃N₄ (modulus 300–320 GPa, tensile strength 400–1000 MPa).

4) Application Implications:

- **Hardness and Stiffness:** The significant increase in hardness (up to 4.178 GPa) and Young's modulus (up to 116.21 GPa) makes these composites ideal for wear-resistant and high-stiffness applications, such as cutting tools, abrasives, or structural components in aerospace.
- **Tensile Strength:** The moderate increase in tensile strength (up to 0.3807 GPa) suggests improved load-bearing capacity, but the brittleness of the reinforcements may limit toughness, requiring careful design to avoid brittle failure.
- **Density:** The slight reduction in density is beneficial for lightweight applications, such as in automotive or aerospace industries.
- **Anisotropy:** The anisotropic behaviour suggests that the composite's performance will depend on the direction of applied stress. For optimal performance, components should be designed to align the Longitudinal direction with the primary stress axis.

5. Conclusion

Mechanical properties (density, Vickers hardness, Young's modulus, tensile strength, and Poisson's ratio) of LM25 composites reinforced with varying percentages (0%, 3%, 6%, and 9%) of cubic boron nitride (c-BN), boron carbide (B₄C), and silicon nitride (Si₃N₄) are highly anisotropic based on the analysis we have performed above. Particularly in terms of hardness and stiffness, the inclusion of several reinforcements (c-BN, B₄C, and Si₃N₄) to the matrix material LM-25 considerably improves the mechanical performance of composites. Driven by the remarkable hardness of c-BN (45–50 GPa) and B₄C (30–35 GPa), Vickers hardness in the Longitudinal direction rises drastically from 0.8 GPa to 4.178 GPa at 9% reinforcement. Reflecting the great rigidity of the reinforcements (c-BN: 900–1000 GPa, B₄C: 450–470 GPa, Si₃N₄: 300–320 GPa), Young's modulus also rises from 71 GPa to 116.21 GPa in the Longitudinal direction. With Si₃N₄ (400–1000 MPa), tensile strength similarly increases—though more modestly—from 0.27 GPa to 0.3807 GPa in the Longitudinal direction. But the composite shows strong anisotropic behavior: the Longitudinal direction routinely beats the Transverse and Law for Casting directions, where hardness, modulus, and strength show smaller improvements (e.g., hardness of 1.876876 GPa and 1.537101 GPa, respectively, at 9% reinforcement). This anisotropy implies, perhaps from the processing technique, that reinforcement particles are aligned preferentially in the Longitudinal direction. Attributed to the decreased density of B₄C (2.52 g/cm³), density somewhat drops from 2.68 g/cm³ to approximately 2.665–2.6725 g/cm³ across all directions, a minor but useful adjustment for lightweight applications. Consistent with the decreased Poisson's ratios of the reinforcements (c-BN: 0.1–0.15, B₄C: 0.17–0.304053, Poisson's ratio also reduces from 0.325 to approx. 0.301816–0.304053, showing reduced lateral deformation. More isotropic behavior of density and Poisson's ratio than of other characteristics reveals. Ultimately, the 9% reinforcement level provides the best overall mechanical performance, thus the composite is quite appropriate for uses needing great hardness and stiffness, such as abrasives, cutting tools, or aerospace components. To maximize performance, meanwhile, the material's anisotropic character requires careful design attention to align the Longitudinal direction with main stress axes. Furthermore, the low tensile strength increases, and natural brittleness of the reinforcements imply that more optimization—such as enhancing reinforcement distribution or including toughening mechanisms—may be required to balance strength and toughness for more general uses.

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