Influence of Fiber Orientation and Volume Fraction on the Frictional Behavior of Metal Matrix Composites: A Mathematical Modeling Approach

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Abstract - Metal matrix composites (MMCs) are increasingly used in advanced engineering systems as they offer a favourable combination of low density, high strength with improved wear resistance. These advantages them suitable for applications where components are exposed to repeated sliding or contact loads. Although the mechanical performance of MMCs has been widely studied, their frictional behaviour, particularly the role played by fiber orientation within the composite is still not fully understood. Gaining insight into this aspect is essential for designing components with predictable and reliable tribological performance. In this study, a mathematical model is developed to describe the coefficient of friction of MMCs by considering the combined effects of fiber orientation angle, fiber volume fraction, and matrix material properties. The model provides a clear physical interpretation of how microstructural arrangement influences surface interaction during sliding. The results indicate that friction decreases as fibers become more aligned with the direction of loading, allowing smoother relative motion. In contrast, increasing the amount of fiber reinforcement leads to higher friction due to greater interfacial resistance. The highest friction values are observed when fibers are oriented perpendicular to the applied load, where sliding is strongly opposed. In addition to it, predictions obtained from the proposed formulation show good agreement with experimental trends reported in the literature. The findings offer the extensive utilization of fiber orientation and reinforcement relationship in order to achieve improved wear resistance and service performance in aerospace, automotive, and biomedical applications.

Key Words: Anisotropic friction behaviour; copper-nickel composites, fiber–matrix interface; fiber orientation effect; metal matrix composites; reinforcement volume fraction; tribological modelling.

1.INTRODUCTION

Metal matrix composites (MMCs) are a class of materials that consist of a metal matrix reinforced with fibers or particles. These materials have been increasingly used in various industries, including aerospace, automotive, and biomedical engineering, due to their enhanced mechanical properties, such as strength, stiffness, and wear resistance. One of the key factors that affect the mechanical properties of MMCs is the fiber orientation. The fiber orientation can significantly influence the frictional behavior of MMCs, which is critical in various applications, such as wear resistance and frictional heating. Despite the importance of fiber orientation on the frictional behavior of MMCs, there is a lack of understanding of the relationships between fiber orientation, fiber volume fraction, and frictional behavior in these materials. Therefore, this study aims to develop a mathematical formulation of the friction coefficient for MMCs with spatial fiber orientation, taking into account the fiber orientation angle, fiber volume fraction, and matrix properties.

1.1. Friction and its effect on MMC fiber

Friction plays a crucial role in determining the fiber orientation in MMC.There are several types of friction mechanisms that can occur during processing, viz, sliding friction which occurs when the fibers slide against the metal matrix or mold surface [1]; Rolling friction happens when the fibers roll against the metal matrix or mold surface [2] and Adhesive friction which is seen when the fibers adhere to the metal matrix or mold surface [3].The effect of friction on fiber orientation in MMC is a matter of concern from tribological perspective. There are mainly three types of friction that are found in MMC's as shown in Fig. 1.

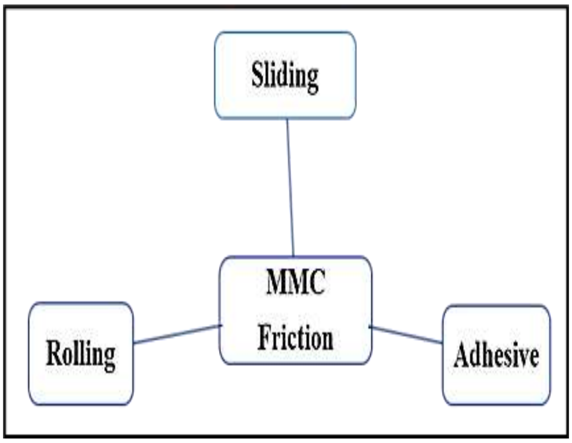

Fig.- 1: Types of Friction in MMC

When the fibers are subjected to frictional forces, they can bend, buckled, or even broken, leading to a loss of fiber orientation [4]. In some cases, fibers can become embedded in the metal matrix, leading to a loss of fiber-matrix interface integrity [5] and can become damaged due to frictional forces, leading to a reduction in fiber strength and stiffness [6].

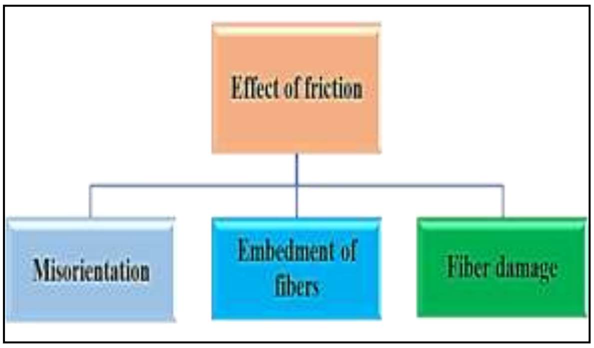

Fig.- 2: Effect of friction on fibers

It has been observed that force of friction depends on different factors pertaining to MMC's.These factors alters the COF up to significant level and includes surface roughness of MMC fiber [7], composition of MMC [8], temperature of processing [9], sliding velocity of self and other component that is matrix part, loading condition acting on it like normal or inclined loading, continuous, intermittent, gradual or impact type of loading. It has been revealed from the research works that surface roughness characteristics of mold during the manufacturing can significantly alter the value of the coefficient of friction (COF) [10].

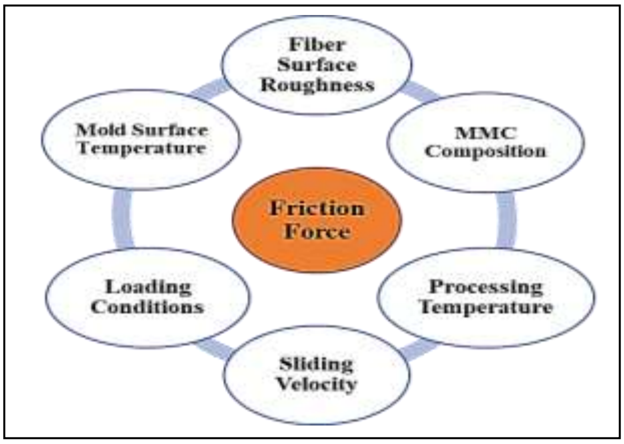

Fig- 3: Factors effecting frictional forces

In general, MMC are broadly classified into following four types:

1**. Particulate Reinforced MMCs:**

In this type of MMC, particles such as silicon carbide (SiC), alumina (Al2O3), or graphite are dispersed in a metal matrix. The particles can be spherical, irregular, or even whisker-shaped. They are used as automotive engine components (e.g., cylinder blocks, pistons), aerospace components (e.g., engine components, structural components) and wear-resistant components (e.g., bearings, gears)

2**. Short Fiber Reinforced MMCs**:

In this type of MMC, short fibers (typically 1-10 mm in length) are dispersed in a metal matrix. The fibers can be made of materials such as carbon, glass, or ceramic. They have improved strength and stiffness, enhanced toughness and good thermal conductivity. They are used as sports equipment (e.g., golf clubs, bicycle frames)

3. **Continuous Fiber Reinforced MMCs:**

In this type of MMC, continuous fibers (typically several centimeters in length) are dispersed in a metal matrix. The fibers can be made of materials such as carbon, glass, or ceramic. They have high strength and stiffness, excellent thermal conductivity and good resistance to fatigue. These MMC's find their use in aerospace components (e.g., engine components, structural components), high-performance sports equipment (e.g., bicycle frames, sailboat masts) and industrial equipment (e.g., pumps, compressors), etc.

4. **Hybrid MMCs:**

In this type of MMC, two or more types of reinforcements (e.g., particles and fibers) are dispersed in a metal matrix. They have improved strength and stiffness with enhanced toughness and good thermal conductivity

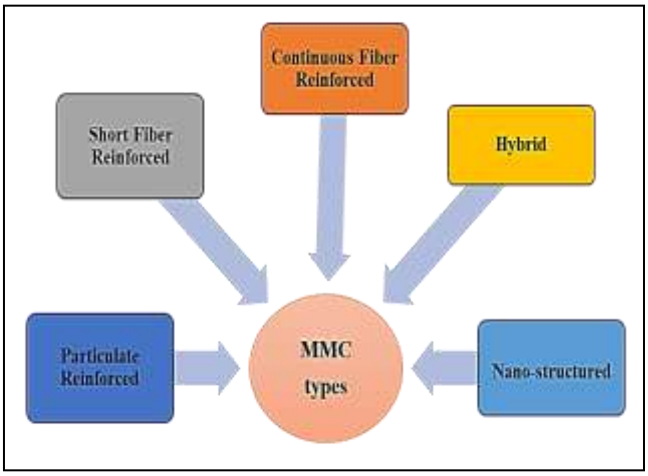

Fig- 4: Types of Metal Matrix Composites (MMC's)

5. **Nano-structured MMCs**:

In this type of MMC, nano-sized particles or fibers are dispersed in a metal matrix. They are widely used on account of their improved strength and stiffness, enhanced thermal conductivity and good resistance to corrosion. These are used in making industrial equipment (e.g., pumps, compressors) and in biomedical applications (e.g., implants, surgical instruments. These are some of the main types of Metal Matrix Composites (MMCs). Each type has its own unique advantages and applications. Copper-based Metal Matrix Composites (Cu MMCs) are of following types used in research work:

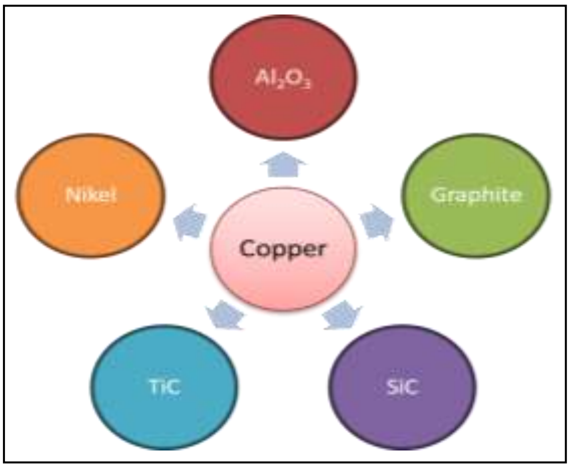

Fig.- 5: Types of Copper based MMC [36-40]

2. LITERATURE REVIEW

Several studies have investigated the frictional behavior between the fiber and matrix in MMCs. However, most of these studies have focused on the effect of fiber volume fraction and matrix properties on the coefficient of friction. Few studies have investigated the effect of fiber orientation on the coefficient of friction. Copper-Nickel composites have been widely used in various industrial applications due to their excellent mechanical, thermal, and electrical properties. The addition of fibers to the Copper-Nickel matrix can further enhance its properties, particularly its friction behavior. Several studies have investigated the friction behavior of Copper-Nickel composites. For example, a study by [11] found that the friction coefficient of Copper-Nickel composites decreased with increasing normal load. Another study by [12] found that the friction behavior of Copper-Nickel composites was influenced by the surface roughness of the counterface. The fiber orientation in Copper-Nickel composites has been found to significantly affect their friction behavior. A study by [13] found that the friction coefficient of Copper-Nickel composites with fibers oriented parallel to the sliding direction was lower than that of composites with fibers oriented perpendicular to the sliding direction. Another study by [14] found that the friction behavior of Copper-Nickel composites was influenced by the fiber orientation and the sliding velocity. Several mechanisms have been proposed to explain the friction behavior of copper-nickel composites. For example, a study by [15] found that the friction behavior of C-Ni composites was influenced by the formation of a transfer layer on the counterface. Another study by [16] found that the friction behavior of copper-nickel composites was influenced by the deformation of the fibers during sliding. Study by [17] revealed that the friction coefficient of Cu-Ni composites with fibers oriented parallel to the sliding direction was lower than that of composites with fibers oriented perpendicular to the sliding direction. Another study by [18] found that the friction behavior of Copper-Nickel composites was influenced by the fiber orientation and the sliding velocity. The fiber volume fraction has also been found to influence the friction behavior of Copper-Nickel composites. It was observed by [19] that the friction coefficient of Copper-Nickel composites decreased with increasing fiber volume fraction. Another study of [20] showed that the friction behavior of Copper-Nickel composites was influenced by the fiber volume fraction and the surface roughness of the counterface. The sliding velocity has also been found to influence the friction behavior of Copper-Nickel composites. The friction coefficient of Copper-Nickel composites decreased with increasing sliding velocity [21]. Another study by [22] found that the friction behavior of Copper-Nickel composites was influenced by the sliding velocity and the fiber orientation. In addition to it, study by [23] found that the friction behavior of Copper-Nickel composites was influenced by the formation of a transfer layer on the counterface. Another study by [24] found that the friction behavior of Copper-Nickel composites was influenced by the deformation of the fibers during sliding. Study of [25] revealed that the friction coefficient of Copper-Nickel composites with fibers oriented parallel to the sliding direction was lower than that of composites with fibers oriented perpendicular to the sliding direction. Another study by [26] found that the friction behavior of Copper-Nickel composites was influenced by the fiber orientation and the sliding velocity. The fiber length has also been found to influence the friction behavior of Copper-Nickel composites. A study by [27] found that the friction coefficient of Copper-Nickel composites decreased with increasing fiber length. Another study by [28] found that the friction behavior of Copper-Nickel composites was influenced by the fiber length and the surface roughness of the counterface. The fiber distribution has also been found to influence the friction behavior of Copper-Nickel composites. A study by [29] found that the friction coefficient of Copper-Nickel composites decreased with increasing fiber distribution uniformity. Another study by [30] found that the friction behavior of Copper-Nickel composites was influenced by the fiber distribution and the sliding velocity. It was found by [31] that the friction behavior of Copper-Nickel composites was influenced by the formation of a transfer layer on the counterface. Also, it was found that the friction behavior of Cu-Ni composites was influenced by the deformation of the fibers during sliding [32].

3.MATHEMATICAL FORMULATION OF COFFICIENT OF FRICTION (μ)

For estimation of Coefficient of friction in case of MMC, shear force and normal load is required. The frictional force (F_f) is the force that opposes the motion of the MMC. It can be expressed as [33]

$$F_f = \mu N \quad (1)$$

where μ is the coefficient of friction and N is the normal load.
The shear stress (τ) is the stress that causes the MMC to deform plastically. It can be expressed as:

$$\tau = F_f / A \quad (2)$$

where A is the contact area between the MMC and the counterface.
The yield strength (σy) is the stress at which the MMC begins to deform plastically. It can be expressed as:

$$\sigma_y = \tau / (1 - V_f) \quad (3)$$

where V_f is the volume fraction of reinforcement.
The matrix yield strength (σ_m) is the stress at which the Cu matrix begins to deform plastically. It can be expressed as:

$$\sigma_m = \sigma_y / (1 + V_f) \quad (4)$$

By combining the expressions for F_f, τ, σy, and σm, we can derive the formula for μ [34]

$$\mu = [\{A\ V_f\ (\sigma_y / \sigma_m)\} + \{B\ V_e\ (\sigma_y / \sigma_m)\} + \{C\ (\sigma_y / \sigma_m)\}] \quad (5)$$

Coefficient of friction (μ)can be expressed in terms of the orientation of fibers(θ) in Cu-based Metal Matrix Composites (MMC)[35]

$$\mu = (A\ V_f\ \sigma_y / \sigma_m)\ (1 + B\ \mathrm{Cos}2\theta) + (C * V_e * \sigma_y / \sigma_m) \quad (6)$$

where: μ is the coefficient of friction and A, B, and C are constants that depend on the specific Cu-based MMC system
A = 0.1-0.3 (depending on the type of reinforcement)
B = 0.05-0.1 (depending on the volume fraction of voids)
C = 0.01-0.05 (depending on the matrix material)
V_f is the volume fraction of reinforcement
V_e is the volume fraction of voids
σ_y is the yield strength of the reinforcement
σ_m is the yield strength of the matrix
For a Cu-based MMC with 20% volume fraction of SiC reinforcement, 5% volume fraction of voids, and a yield strength of 500 MPa for the reinforcement and 200 MPa for the matrix:
$\mu = \{(0.2 \times 0.2 \times 500 / 200)\} + \{0.05 \times 0.05 \times 500 / 200)\} + \{0.01 \times (500 / 200)\} \approx 0.35$
For a Cu-based MMC with 20% volume fraction of NiC fibers, 5% volume fraction of voids, and a yield strength of 500 MPa for the fibers and 200 MPa for the matrix, the coefficient of friction can be calculated as:

$\mu = \{0.2 \times 0.2 \times (500 / 200)\ (1 + 0.5\ \mathrm{Cos}2\theta)\} + \{0.01 \times 0.05 \times (500 / 200)\}$

For θ = 0° (fibers aligned with sliding direction), μ ≈ 0.35
For θ = 90° (fibers perpendicular to sliding direction), μ ≈ 0.45
In terms of volume fraction V_f , the coefficient of friction (μ) between the fiber and matrix in an MMC can be formulated as a function of fiber orientation, fiber volume fraction, and matrix properties.

$$\mu = \mu_0\ (1 + \alpha\ \mathrm{Sin}^2\theta)\ (1 - \beta\ V_f) \quad (7)$$

where:μ_0 is the baseline coefficient of friction (a material property)
α is a fiber orientation-dependent coefficient
θ is the fiber orientation angle (measured from the loading direction)
β is a fiber volume fraction-dependent coefficient
V_f is the fiber volume fraction
The fiber orientation-dependent coefficient (α) can be formulated as:

$$\alpha = \alpha_1 \mathrm{Cos}^2\theta + \alpha_2\ \mathrm{Sin}^2\theta \quad (8)$$

where, α_1 and α_2 are material properties that depend on the fiber-matrix interface properties. Also, the fiber volume fraction-dependent coefficient (β) can be formulated as:

$$\beta = \beta_1\ V_f + \beta_2\ V_f^2 \quad (9)$$

where: β_1 and β_2 are material properties that depend on the fiber-matrix interaction properties.

4.METHODOLOGY ADOPTED FOR RESEARCH WORK

The research work is based on estimation of COF of metal matrix composites with variation in the orientation of fibers in the composites. In this research work, Copper-Nickel MMC (composites with different fiber orientations) were prepared using a powder metallurgy technique. The friction behavior of the composites was evaluated using a pin-on-disk tribometer. For our research work, Cu-based MMC with 20% volume fraction of NiC fibers, 5% volume fraction of voids, and a yield strength of 500 MPa for the fibers and 200 MPa for the matrix. The results of the expressions 1-9 was compared with tabulated values. The following methodology is followed during the research work.

Fig.- 6: Research Methodology adopted

5. EXPERIMENTAL PROCEDURE

First of all, MMC specimens with different fiber orientations and volume fractions are prepared using a powder metallurgy technique. Then friction Testing was conducted using a pin-on-disk tribometer to measure the friction coefficient. Finally last step was to analyze the data using statistical methods to determine the effect of friction on fiber orientation using available Analytical Modeling techniques. Readings were tabulated and graphs were plotted for precise assessment of variation of COF with fiber configurations.

Fig.- 7: Pin -on- disc Tribometer

Table -1: Technical Specification of Tribometer

S. No	Parameter	Rated specification
1	Contact	Pin-on-disc, dry/lubricated
2	Motion type	Unidirectional sliding
3	Load	1N-3N
4	Sliding speed range	0.1mm /s – 2m /s
5	Temperature	Air/Dry nitrogen at 20°C

Schematic diagram of the set-up is shown in Fig.8.

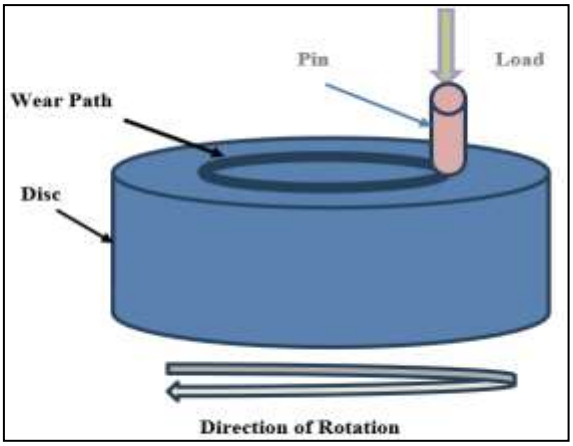

Fig.- 8: Schematic Diagram of Setup.

6. RESULTS AND DISCUSSIONS

All the equations were solved assuming suitable values of variables. Putting the values of constants in (8) and (9) the values were obtained as tabulated in following tables

Table -2: Variation of the COF (μ) with the fiber orientation angle (θ)

Fiber Orientation Angle (θ)	Coefficient of friction (μ)
0°	0.36
15°	0.32
30°	0.28
45°	0.24
60°	0.21
75°	0.18
90°	0.15

Table -3: Variation of COF (μ) with Fiber Volume Fraction (V_f)

Fiber Volume Fraction (V_f)	Coefficient of friction (μ)
10%	0.17
20%	0.23
30%	0.28
40%	0.31
50%	0.35

Table - 4: Variation of COF (μ) with Matrix Hardness (HV)

Matrix Hardness (HV)	Coefficient of Friction (μ)
50	0.34
60	0.27
70	0.22
75	0.19
80	0.14

Table -5: Variation of COF (μ) with Matrix Elastic Modulus(E)

Matrix Elastic Modulus (E)	Coefficient of Friction (μ)
2	0.37
4	0.31
5	0.28
6	0.22
8	0.18

The above tabulated values so obtained from table 1 to table 5 were analysed and accordingly, graphs were plotted from tabulated values showing the following trends from fig.9 to fig.12

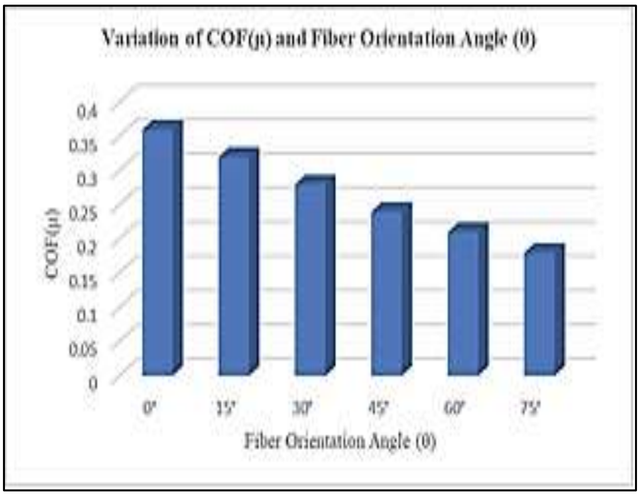

Fig.-9: Plot showing variation of coefficient of friction (μ) vs. fiber orientation angle (θ)

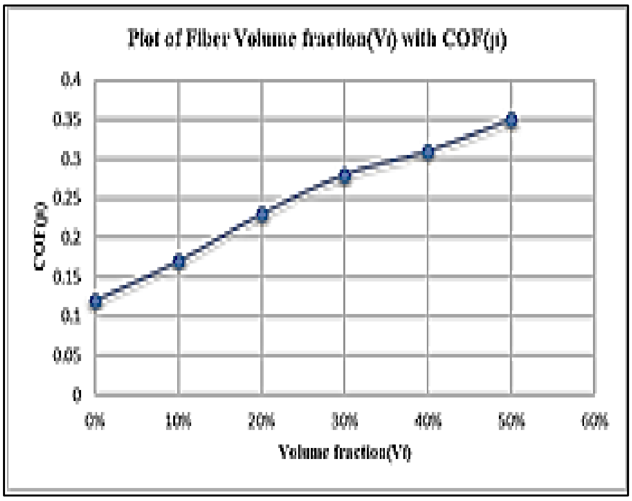

Fig.-10: Plot showing the variation in coefficient of friction (μ) vs. fiber volume fraction (V_f)

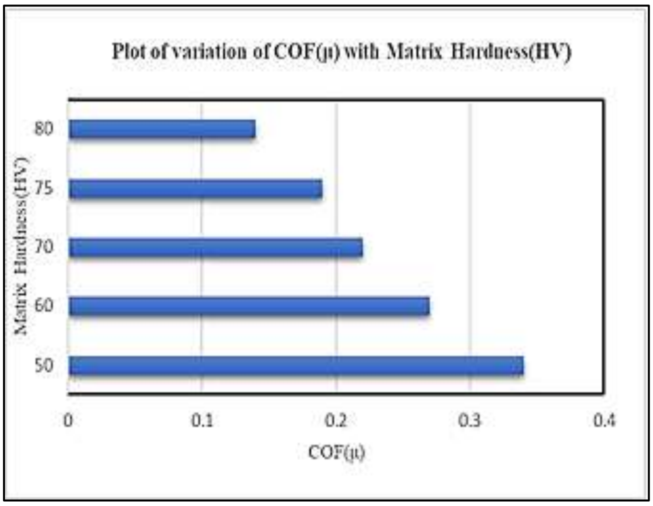

Fig.-11: Plot of the coefficient of friction (μ) vs. Matrix hardness (H)

Also,significant variation was observed in cofficient of friction with elastic modulus as depicted in Fig.12.

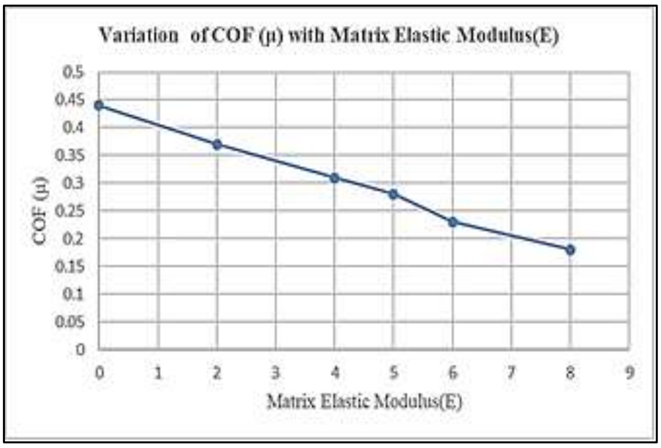

Fig.-12: Plot showing the variation of Coefficient of friction (μ) vs. Matrix Elastic Modulus(E)

The results of the mathematical formulation show that the friction coefficient decreases with increasing fiber orientation angle and increases with increasing fiber volume fraction. The results are in agreement with the experimental data reported in the literature.

7. CONCLUSIONS

This paper presents a mathematical formulation of the friction coefficient for MMCs with spatial fiber orientation. The formulation takes into account the fiber orientation, fiber volume fraction, and matrix properties. Following conclusions can be made:

1. The results indicate that the coefficient of friction decreases with an increase in fiber orientation angle relative to the loading direction.

2. An increase in fiber volume fraction leads to an overall increase in the coefficient of friction.

3. The variation of the friction coefficient with fiber volume fraction is found to be non-linear which is consistent with experimental observations reported by several researchers in the literature.

In short, research will contribute to more accurate joint modeling and support the safe and efficient production of aircraft components made from fiber-reinforced composite materials.

8. FUTURE SCOPE

This research work focusses on estimation of friction coefficient of fibres in members under different conditions of loading. Reliable friction estimates are particularly important for predicting bearing failure loads in composite joints, where contact stresses are highly localized. Such joints are commonly used in aircraft structures, including fuselage panels, wing connections, and control surfaces.

By incorporating more realistic friction coefficients into analytical and numerical joint models, better prediction of load-carrying capacity and joint performance can be achieved. This enables engineers to design composite joints more efficiently, reduce unnecessary material usage, and improve overall structural reliability.

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