CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1. INTRODUCTION

The swift progress in industrial technologies has paved the way for the production of cost-effective, high-strength materials to fulfil the evolving demands of various industries. Among these innovations, metal matrix composites stand out as a relatively recent breakthrough in technology. These composites allow the customization of properties by incorporating a durable reinforcement in the matrix phase, aligning with specific application requirements. Consequently, metal matrix composites exhibit superior mechanical and tribological properties when compared to their solid, unalloyed counterparts. Though fiber reinforced MMC have equivalent specific strength and stiffness but economic factors motivated the researcher to explore the particulate reinforced metal matrix composite. It may utilize several reinforcements including Al_2O_3, SiC, TiO_2, TiC, and B_4C to improve the properties of the composite. However, a lot of development has been made in the processing of MMC but still, it still has lot of future scope to explore [P.D. Srivyas et al. 2018, Rohtagi, 1993, K.K. Chawla et al., 1986].

Copper stands out as a highly suitable material for numerous engineering applications, including the production of current-conducting wires, automotive components, electric appliances, heat sinks, electronic devices, and various power transmission devices. Hence, copper-based composites are used in many technological areas because this as a matrix material provides excellent thermal and electrical conductivity, good corrosion resistance, and high ductility. These properties make copper an ideal material for various industrial applications, especially those requiring efficient heat transfer or electrical conductivity. Copper based metal matrix composites can be fabricated by use of different reinforcements such as laminated fibres, hard ceramic particles or lubricating materials like graphite, graphene, MoS_2, CNT etc. Graphite particles are used as reinforcing phase in the copper composite for past many decades. Graphite is a form of carbon that imparts several qualities to the composite, such as low friction, good self-lubricating properties, and high thermal stability. The combination of copper and graphite in the composite results in a material that possesses enhanced mechanical, thermal, and tribological (friction and wear) properties. Copper graphite composites find applications in various industries, including electrical engineering, where their excellent conductivity is beneficial, and in applications requiring good lubrication properties, such as sliding electrical contacts or bearings. The tailored combination of copper and graphite in these composites provides a balance of properties suitable for specific engineering needs.

Further, adding secondary phase particles to copper-graphite composites has been noted by researchers as a means to enhance both the mechanical strength and wear resistance of the materials. Several studies propose that reinforcing the base matrix with hard particles not only improves thermal stability but also increases the load-bearing capacity during sliding wear tests [Z.Q. et al., 2001, Murphy et al., 1992]. Numerous research has been done to see the influence of secondary reinforcements such as SiC, fly ash in copper-graphite composites. However, it was observed that the hybrid reinforcements steadily improve both the mechanical and tribological characteristics of the composites when compared to traditional copper-graphite counterparts.

To explore the full potential of composites, it is important to understand the various types of composites and their fabrication methods. The upcoming sections will discuss the different types of composites, their fabrications techniques and effect of varying parameters of fabrication on the different properties of composites.

1.2. METAL MATRIX COMPOSITE: AN OVERVIEW

1.2.1. Definition of Composite

‘Composite is a combination of two or more physically distinct phases that are tightly bonded to develop a material with properties that arise from the synergistic integration of its components. [Chawla et al., 1986, A. Evans et al., 2003]. It comprises two phases; (1) Matrix phase, and (2) Reinforcement phase.

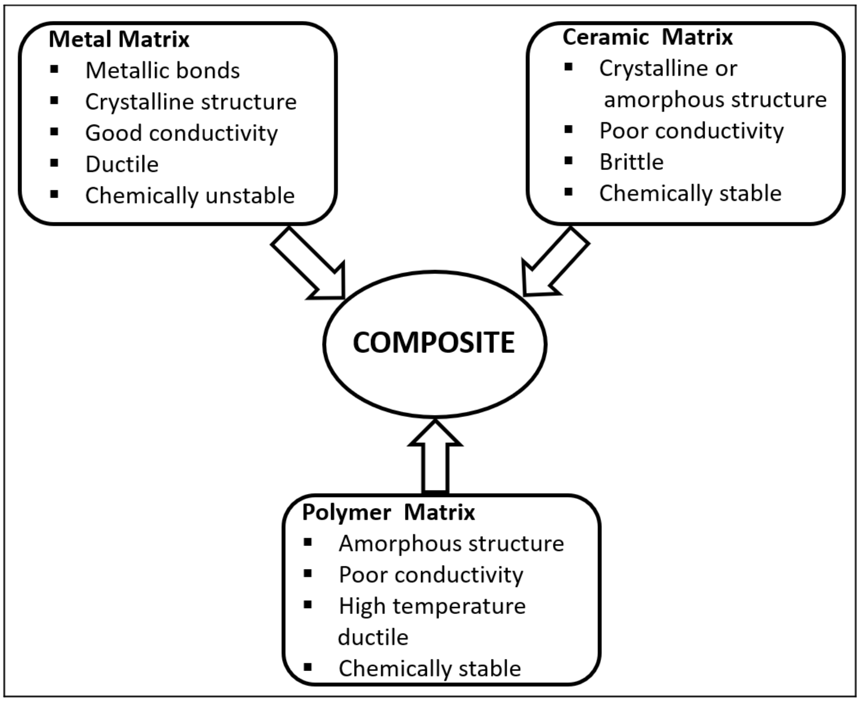

Fig. 1.1 Showing matrices used in composites

The matrix is the primary and continuous phase of a composite having significant volume. Conversely, the harder phase embedded within the matrix is referred to as the secondary or reinforcement phase. This reinforcement phase can take the form of particulates, continuous or discontinuous fibers, varying in size and shape. The matrix phase encompasses materials such as polymers, ceramics, and metals. The choice of both matrix and reinforcement is mostly influenced by the specific requirements of the application and the techniques used for synthesis, as illustrated in Figure 1.1. Composites are generally categorized based on their matrix composition.

(1) Polymer matrix composite

(2) Ceramic matrix composite

(3) Metal matrix composite

1.2.2 Polymer matrix composite

Polymer matrix composites (PMCs), or fiber-reinforced polymer (FRP) composites, are crafted by combining a polymer resin—essentially a high molecular weight reinforced plastic—as the foundational matrix, with fibers acting as the strengthening component. This manufacturing approach allows for the creation of diverse composites on a large scale. PMCs exhibit commendable properties even at room temperature, offering an economical and easily fabricated option. Various reinforcing materials, such as glass fibers, carbon fibers, and aramid fibers, can be integrated into PMCs. PMCs are manufactured using distinct techniques categorized into Thermoset-based and Thermoplastic-based composites. For Thermoset matrix composites, methods like Hand lay-up spray, Filament winding, Pultrusion, Resin transfer molding, and Autoclave-based procedures find frequent application. In the case of Thermoplastic-based composites, techniques like Injection moulding, Film stacking, Diaphragm forming, and Thermoplastic Tape laying are commonly employed [Rajak et al., 2019; Majidi, 2000]. However, the widespread use of PMCs raises environmental concerns as they cause the production of solid wastes, hazardous waste (HW), and hazardous air pollution (HAPs) [Sands et al., 2001].

1.2.3. Ceramic matrix composite

The monolithic ceramics generally have impressive strength and stiffness even at elevated temperatures. But their disadvantage is poor toughness which leads to the development of ceramics matrix composites (CMCs) so as to enhance the toughness and make them useful for high temperature applications. In CMCs, the ceramics are utilized as a matrix and short fibers or whiskers of SiC, BN, and ZrB_2 etc are used as reinforcements. CMCs can be fabricated by liquid phase sintering, hot pressing or hot iso-static pressing, cold pressing, sintering and reaction bonding processes etc. Despite showing excellent properties, high fabrication cost, high energy requirements and difficult post processing such as machining these types of composites are major concerns which restrict the widespread use of CMCs [Gavalda et al., 2019].

1.2.4. Metal matrix composite

The metal matrix composite also comprises of two or more physically distinct phases intimately bonded with the continuous metallic phase matrix with a certain volume % of reinforced phase. The MMCs have high toughness, elasticity, impact resistance, damping properties, and low thermal expansion coefficient. Therefore, MMCs exhibit superior mechanical properties, good thermal resistance, and wear resistance which makes them the suitable candidate material in the automobile and aerospace industries.

1.2.4.1 Matrix selection

The matrix is the continuous and high-volume phase of the composite which holds the uniformly dispersed reinforcement phase. It is generally softer and ductile phase as compared to reinforcement which exhibits good tensile properties, high shear modulus, and low coefficient of thermal expansion. In metal matrix composite, Al, Cu, Ni, Mg, Ag, Zn, and Ti, metals are frequently used as a matrix phase [Chawla et al., 1986].

Amongst the above metals, Cu and Al are extensively used as matrices because of their high corrosion resistance, high thermal conductivity, low melting temperature, lightweight, and low cost [C. Mitchell et al., 2002].

1.2.4.2 Reinforcement selection

The purpose of introducing the reinforcement is to enhance the mechanical, tribological, and thermal strength of the composite. It may be of fiber or particulates of different sizes (micro to nano level) and shapes. The short fibers and particulates reinforcement are manufactured by cost-effective techniques and exhibit isotropic properties. The reinforcement may enhance the modulus, stiffness, strength, wear, and thermal resistance of the composite [T.W.C. and P.J. Withers, 2016]. The selection of reinforcement may be subjected to the dispersion of reinforcement, interface adhesion between matrix and reinforcement phases, and application of composite. However, based on the form of reinforcement, MMCs are broadly classified into four major categories. (1) Particulate reinforced MMC (2) Short fiber or whisker reinforced MMC (3) Continuous fiber-reinforced MMC (4) Monofilament reinforced MMC.

Over the past decades, a new class of metal-matrix composites has emerged, known as hybrid composites. These materials are distinctive because they incorporate two or more types of reinforcements within a single matrix. Hybrid composites obtain wide array of properties across each aspect when compared to the single reinforced conventional composites. The most attractive trait of hybrid composites is that when under tensile stress condition, the failure is usually non catastrophic [Prabhuram et al., 2010]. It is understood from the above discussions that MMCs are versatile in their applications due to the broad variation in properties, easy availability of raw materials and simple fabrication techniques. Following section briefly discuses different preparation techniques and reinforcements and their effect on MMCs. The subsequent section will provide a concise exploration of diverse preparation techniques, various types of reinforcements, and their impact on the properties of metal-matrix composites (MMCs).

1.3. FABRICATION TECHNIQUES OF MMCS

There are majorly two ways to fabricate MMCs, either through exsitu or insitu techniques. In exsitu method the reinforcing second phase is added to solid or liquid state matrix separately. Whereas in the insitu method, second phase to be reinforced is generated by a chemical reaction between suitable inorganic salts and the matrix material [Zhang et al., 2017].

The fabrication routes of MMCs involves considering factors like the cost of the fabrication, simplicity of the process, and the impact on composite properties. Different fabrication methods have their positives and negatives, the choice depends on the specific needs. The most popular methods for MMCs preparation are liquid state and solid-state fabrication. The liquid state method is fairly easy and less costly as compared to solid-state. However, solid state involves powder metallurgy technique that has benefit of using nano particles and the grain boundary strengthening capability which makes it preferrable when high precise and complex products are needed.

1.3.1 Liquid state techniques

Liquid-state methods are very popular due to their simplicity, cost-effectiveness, and potential scalability for large-scale production. Techniques such as stir casting, centrifugal casting, infiltration methods, ultrasonic-assisted casting, and disintegrating melt deposition (DMD) are examples of these approaches.

1.3.1.1 Stir casting

It is one of the most commercially used technique to fabricate MMCs. In this method reinforcements are introduced into the molten metal/alloy matrix, followed by casting. It is important to have proper wetting between the matrix and reinforcements for better properties. The characteristics of the composite fabricated by stir casting technique can be altered by varying process variables like stirring speed, stirring duration, processing temperature, pouring temperature. Nageswaran et al. (2018) employed stir casting setup to fabricate copper metal matrices reinforced with TiO_2 and Graphite (Gr). They found that stir casting ensures homogeneous reinforcement with improved dispersion over conventional casting technique and being more economical. Enhanced wettability between the second phase particles and matrix leads to improved homogeneity. Haimin Dinga et al. (2019) fabricated the Cu- TiC composite by incorporating Ti and carbon black powder in the Cu melt. They observed that Ti reacts with carbon black and forms TiC in the melt at 1200 ºC temperature. However, it was shown that increasing the Ti/C ratio leads to better distribution of the TiC particles in the composite.

1.3.1.1 Compocasting

Improving the interaction between reinforcement particles and the matrix material is key for enhancing material properties, Compocasting is used to achieve optimal wettability between reinforcements and the matrix material [Rosso, 2006]. In the compocasting process, the alloy is melted initially and then gradually cooled to a semisolid state. During this phase the particle reinforcements are incorporated and thus, preventing the negative effects of gravity separation and minimizing the undesirable agglomeration of particles [Ejiofor et al. in 1997]. Sevik et al. (2006) prepared composite by combining Al-Si alloy with Al_2O_3 reinforcement. Their findings indicated that porosity in Compocasting can be effectively minimized by employing the die casting method.

1.3.1.3 Liquid infiltration

The liquid infiltration method involves injecting molten metal into a porous preform with the assistance of pressure. This technique has been widely employed for manufacturing composites that incorporate various reinforcements, such as SiC particles, foams, TiC, glass fiber, Al_2O_3, AlN, and Al_4C_3. The pressure-assisted infiltration method can be applied in two approaches: gas infiltration and pressure infiltration. The primary benefits of this process include increased wettability owing to higher reinforcement activity in vacuum environments, lower porosity, and near net shaped production of components. Zenga et al. (2014) have prepared carbon/carbon (C/C)–Zr–Ti–C composites using liquid infiltration technique and stated that increase in the reaction temperatures, leads to lessening in the terminal density of samples. They also reported that prolonged initial holding time led to higher final density.

1.3.2 Solid state techniques

1.3.2.1 Diffusion bonding

Diffusion bonding is the most used solid-state techniques for the fabrication of similar or dissimilar metals. In this technique, composites are produced by inter diffusion of atoms between the metallic surfaces. Diffusion bonding offers versatility in the use of diverse materials and also provides control over fiber direction and volume fraction. However, there are drawbacks such as long processing times, elevated temperature and pressure making this technique relatively expensive. It is mostly used to fabricate complex shape products [Attar et al., 2015]. Diffusion bonding technique is also employed to produce mono-filament reinforced metal-matrix composites [Kandpal et al., 2014].

1.3.2.2 Powder metallurgy

Numerous researchers have reported the manufacturing of Metal Matrix Composites (MMCs) through the powder metallurgy technique. This method offers a range of distinctive properties through the sintering of powders, representing one of the most notable advantages of Powder Metallurgy (PM). Refining the particle size contributes to enhancements in properties, ultimately resulting in the development of a more uniform microstructure [Sluzalec, 2015].

1.4 POWDER METALLURGY, PROCESSING, AND DEVELOPMENT

Powder metallurgy serves as an important technique for synthesizing both metal and non-metal powders, facilitating the entire process from powder production to the creation of finished parts. This oldest metal processing method involves a sequence of three fundamental steps: (1) the production and mixing of metal powders, (2) the compaction of these powders under specified pressures to form green composites within a compaction die, and (3) the sintering of the green composite at an elevated temperature (typically 0.75-0.85% of the melting temperature of the matrix material). The schematic representation of these synthesis steps is illustrated in Figure 1.2.

Several compelling factors contribute to the widespread adoption of powder metallurgy in industrial applications. These include its (1) cost-effectiveness in processing, (2) capacity for dry mixing, allowing for the selection of a diverse range of materials, and (3) minimal wastage, leading to development closely aligned with the final product. Powder metallurgy techniques find extensive use in synthesizing composite materials based on ferrous metals, steel, copper, aluminium, and titanium powders. Furthermore, it is a versatile method employed in the fabrication of various alloys, ranging from amorphous to crystalline and high-performance alloys. In contemporary industrial settings, powder metallurgy techniques play a vital role in the production of diverse engineering components. These applications encompass abrasive wheels, carbon brushes, automotive friction materials, soft magnetic components, high-energy magnets, gears, assembly parts, and more. The technique's adaptability and efficiency contribute to its continued relevance and utilization across a range of manufacturing processes.

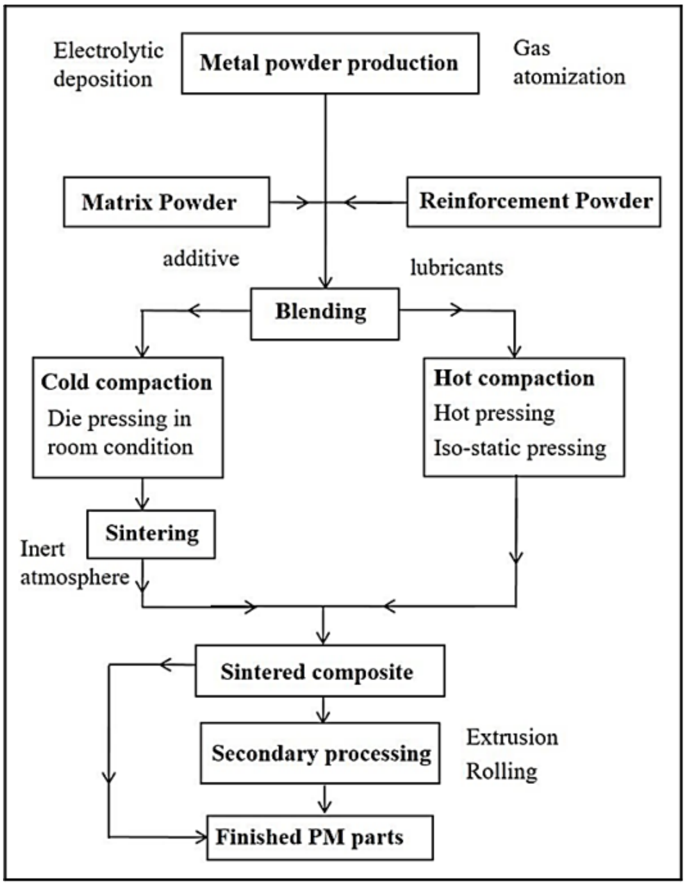

Fig. 1.2 Synthesis steps of Powder Metallurgy route

1.4.1 Different powder production techniques

The production of metal powder production is the first step of powder metallurgy (PM) processing. As industrialisation grows, different powder production techniques are developing to fulfil the requirement. It can aid in the manufacturing of metal powder from tough and high-strength materials, ensuring their hardness and durability. The different metal powder production techniques are as follows [G.S. Upadhyaya, 2014]

1.4.1.1 Mechanical methods

It is the earliest method for producing powder, widely employed to reduce the size of ceramic and brittle materials. This method employs mechanical energy to break down the particles of the material. In the mechanical approach, the powder preparation involves a series of processes: impact, pressure and shear. Impact and pressure may induce the crack formation and wear leads to the reduction in dimension whereas the shear causes cleavage fracture [G.S. Upadhyaya, 2014].

1.4.1.1.1 Grinding

In the grinding process, sintered sponge material derived from various powder production techniques is subjected to hammering and crushing for size reduction. The sponge material undergoes hammering between stationary and rotating jaws. The coarse material is disintegrated into relatively small and finer particles by the hammering action of jaws. The small size sponge materials are afterwards milled to obtain metal powder.

1.4.1.1.2 Milling

In the milling procedure, powder milling occurs through high-energy collisions facilitated by the rotary motion of a drum. Hardened balls, rollers, and rods serve as the grinding media in the milling process. The duration of milling, the speed of milling, the milling medium, and the ratio of balls to powder significantly impact the milling process. Figure 1.3 shows the schematic of the milling process. However, milling powder should exhibit ductile properties. In milling relativity hard phase-coated over the soft phase e.g., during mechanical alloying of Cu/graphite powder, the Cu particles are laminated over the soft graphite particles [R.O. Thummler, 1993 and K. Skotnicova et al., 2014]

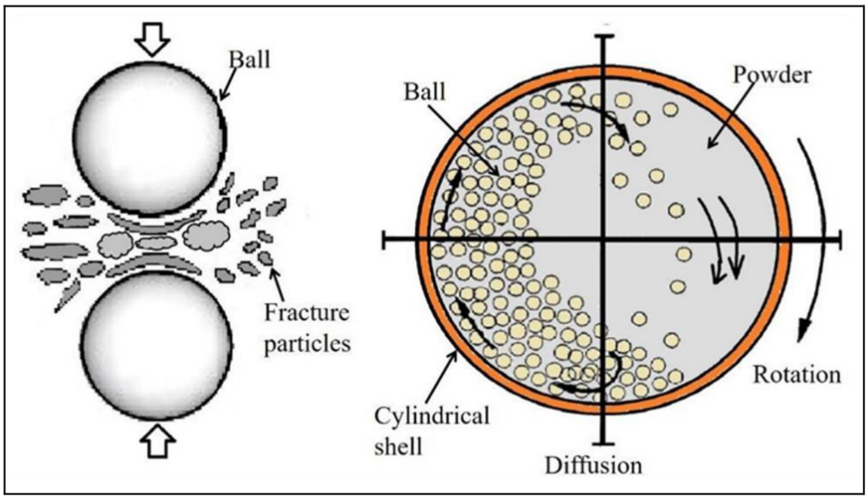

Fig. 1.3 Milling process schematic

1.4.1.2 Electrolytic method (Physical method)

The electrolytic powder preparation method is widely used to obtain the powder of Cu, Fe, and Ni. In this metal ions get deposited on the cathode plate in flake form and converted to powder form. The metal powder produced through this method boasts superior quality and is exceptionally well-suited for conventional powder metallurgy processes. Although, it is worth noting that this technique is relatively expensive and characterized by a lower production rate when compared to alternative powder production methods. e.g., production of electrolytic iron powder is much expensive compare to reduced or atomized iron powder.

1.4.1.3 Atomization

The various atomization methods for powder production include gas atomization and water atomization. In these processes, the material is melted to a liquid state and then forced through a narrow opening. External sources such as water or gas are utilized to break down the liquid metal passing through the narrow opening into powder particles.

The metal powder of very high purity is obtained in atomization. In this method, the molten material is directed through a specifically designed orifice, where a jet of water or gas is introduced into the melt. This induces turbulence in the melt, leading to its atomization and disintegration. Additionally, the impact of the water or gas jet may further reduce the particle size.

1.4.2 Synthesis of MMC by Powder Metallurgy

Powder metallurgy is a process of synthesizing the desired specimen by processing the respective powder. It involves three fundamental stages.: (1) Blending; (2) Compaction; and (3) Sintering.

1.4.2.1 Blending of composite powders

Blending is the method of mixing the matrix and reinforced powder of the desired size and morphology. On the other hand, milling is a process that combines mixing with particle size reduction. This widely adopted technique for size reduction induces particle fracture, welding, and re-welding through high-energy impact. Milling of two or more different material powders is referred to as mechanical alloying. In the milling process, a confined rotating shell is used, within which hardened balls and composite powder are introduced. The balls cause powerful impact, transferring high energy to the composite powders. The high energy impact rises the temperature of composite powder which may induce some chemical reactions to develop an interface and a new phase. [K. Skotnicova et al., 2014].

1.4.2.2 Compaction of blended powders

Compaction is the consolidation process that transforms composite powder into a green compact. In this method, the milled composite powders are placed within a confined space, such as a die, and external pressure is applied to achieve consolidation. Green compact formed through the compaction process, is characterized by relatively weak mechanical bonds. [G.S. Upadhyaya, 2014]. Therefore, it has poor strength just adequate for handling. The compaction process comprises several steps. Initially, the die cavity is filled with the desired amount of blended powder. As the punch moves, the compaction pressure on the composite powder progressively rises. This process can develop mechanical bonds among the powder particles, bringing them together to form a cohesive metal plug called ‘green compact’. The term "green" signifies the continuance of the synthesis process. A green compact exhibit poor mechanical properties owing to the poor mechanical bonds therefore, to enhance the mechanical properties compaction process is subsequently followed by the sintering process. The compaction of the milled powders can be achieved through various methods. Below are a few commonly employed compaction techniques. [G.E. Dieter et al., 1978]:

(a) Single action unidirectional pressing

(b) Double action unidirectional pressing

(c) Isostatic pressing

(d) Stepwise pressing

(e) Powder extrusion

1.4.2.3 Sintering of green compact

In the sintering process, green composites undergo heating within the range of 75-85% of the melting temperature of the matrix material. [K.K. Chawla et al.,1986]. The green composite has poor mechanical bonds owing to poor particle-to-particle contact and, it consists of large pores. Sintering at high temperatures has the potential to create metallic bonds at contact points. As the sintering time is raised, there is the development of necks at these contact points, leading to the initiation of nucleation at various locations.

Extended sintering at elevated temperatures may develop the nucleation front. These nucleation front propagate at high temperatures and closes the pores. This can lead to an enlargement of the contact area, resulting in decrease in pore size. The mismatch in the orientation of the nucleation front may give rise to the development of grain boundaries. In the sintering process, consolidation occurs through the diffusion of particles. The poor mechanical bonds are transformed into stronger metallic bonds that results in densification and significantly improves the strength of composite. Since the diffusion of particles takes place below the melting temperature, therefore the powder metallurgy technique is regarded as the solid-state processing. The essential factors for ensuring effective particle diffusion include the temperature and duration of the sintering process. [T.W. Clyne, 2017].

1.5 COPPER (Cu) BASED METAL MATRIX COMPOSITES

Copper and its alloys find extensive applications across various industries owing to their remarkable properties such as efficient heat and electrical conductivity, corrosion resistance, non-magnetic nature, and elevated temperature stability. These properties make them indispensable materials in various industrial processes and applications. Copper possesses excellent thermal conductivity, a crucial attribute for components needing effective heat dissipation. However, its high deformability and relatively low strength limits, its suitability for certain applications. It becomes necessary to introduce additional reinforcements into the copper matrix to enhance strength, wear resistance, and frictional properties. Therefore, Copper-based composites are fabricated by incorporating various reinforcement materials for electrical and thermal based applications.

The strength of copper-based Metal Matrix Composites (MMC) is significantly impacted by the morphology of the reinforced material. However, the reinforcement based on particulates and short fibers exhibits better mechanical properties and have low cost. The particulate reinforced composites can accommodate particles of sizes ranging from micro to nanoscale. These smaller size reinforcements enhance the ductility, the fracture toughness, and machinability of the composites. In order to incorporate reinforcing particles, particulate-reinforced composites can employ both in-situ and ex-situ processes for improving the features of Cu-Al_2O_3 nanocomposite. However, Cu- Al_2O_3 composite produced through ex-situ method depicted inadequate interfacial strength and poor uniform dispersion [R. Casati et al., 2014].

D.W. Lee et al. (2001) also explored the thermal properties of Cu-Al_2O_3 composite. From their findings, they showed that the thermal conductivity and coefficient of thermal expansion (CTE) decreased with the incorporation of 0 to 12.5 wt. % Al_2O_3 in the Cu-Al_2O_3 composite. This is may be due to the robust interfacial adhesion of Cu and alumina. Also, the thermal performance of Cu-12.5 Al_2O_3 composite displayed good compatibility with the semiconductor materials commonly employed in electronic packaging applications.

The Cu- Al_2O_3 composite was prepared using powder metallurgy by Fathy et al. (2013) and they examined influence of Al_2O_3 on thermal behavior of composite. Cu- Al_2O_3 composite is widely utilized in electrodes, spot-welding electrodes, lead wires, relay blades, and electrical contact sockets. The incorporation of alumina significantly enhances strength of the Cu- Al_2O_3 composite with a slight reduction in electrical properties. Akbarpour et al. (2013) developed a copper-based composite reinforced by (2, 4 and 6 vol. %) SiC nanoparticles by vacuum hot pressing process to investigate the effect of SiC content on mechanical properties and reported an increase in strength with addition of SiC particles due to grain refinement. Mostafa Amirjan et al. (2013) made the Cu-Al_2O_3 composite by powder metallurgy route and did comparative analysis with artificial neural network model. They examined the variation of hardness and electrical conductivity with the Al_2O_3 content and sintering temperature. The outcomes revealed a strong agreement between the theoretical model and the actual sintered composite, with an average error of 3% for hardness and 5% for electrical conductivity. Poulami Maji et al. (2009) studied the effect of different wt.% of tungsten addition in Cu-W composite through powder metallurgy technique to increase the fretting wear for electrical contact applications. The coefficient of friction decreases with increasing the load and obtained its minimum value of 0.5 for 10 N load irrespective of W content. It depicts that at higher load, effect of W content became irrelevant. However, at lower load, and with 5% of W addition wear resistance increases significantly. The dominating wear mechanism is the adhesive wear and abrasive wear.

Avijit Mondal et al. (2013) fabricated the Cu-W alloy in a microwave sintering furnace with 30% Cu content. They studied the sintering behavior of Cu-W alloy and perform a comparative study of microwave sintering and conventional sintering. The microwave sintering shows better densification, homogeneous dispersion with fine grain structure. It also depicts superior hardness and electrical conductivity corresponding to conventional sintering.

Haimin Ding et al. (2019) investigated the creation of a Cu-TiC composite by introducing titanium and carbon black powder into the molten copper. It was observed that at a temperature of 1200 ºC, titanium reacts with carbon black, leading to the formation of titanium carbide (TiC) in the melt. However, it is seen that increasing the Ti/C ratio leads to better dispersion of the TiC particles in the composite. K M Shu et al. (2014) and M. Barmouz et al. (2011) reported the thermal properties of Cu-SiC_p composite synthesized by powder metallurgy route. They performed the Cu coating of SiC_p powder particles by an electroless plating process. It enhanced interfacial bonding and homogeneous dispersion of SiC_p in the Cu matrix. The thermal expansion tests were done in temperature range of 50 to 500 ºC. They showed the positive hysteresis behavior during cooling. It may be due to the residual stress and good interfacial adhesion. The coefficient of thermal expansion decreases with increasing the SiC_p content.

1.6 MOTIVATION FOR THE THESIS

Copper, renowned for its versatility, finds extensive application in various engineering domains due to its remarkable ability to conduct heat and electricity, resist corrosion, and maintain high ductility. However, when combined with graphite as a reinforcement, copper-based composites exhibit enhanced mechanical, thermal, and tribological properties. Copper-graphite composites having exceptional thermal and favourable tribological properties are employed for tribological engineering components such as bushing and bearing materials in industrial machinery. For bushing material, the study of tribological properties is essential. Moreover, investigations into wear behaviour and mechanical properties of Cu-graphite composites have highlighted the importance of wear coefficient and on the potential of using hybrid reinforcements to enhance composite’s performance. This improved performance can be achieved by incorporating TiC particles as a reinforcement. The resulting titanium carbide-reinforced Cu-graphite composite has the potential to enhance both mechanical strength and tribological properties for the bushing application in the various industries. The upcoming sections will discuss about the Cu- graphite composites in detail.

1.7 COPPER – GRAPHITE (Cu-Gr) COMPOSITES

Copper-graphite composites depict remarkable characteristics, including outstanding thermal and electrical conductivity, favourable tribological properties, and cost-effectiveness. These attributes make them a preferred option for the development of components in the field of tribological engineering. Researchers have been extensively exploring the influence of graphite on copper for many decades

D. D. L. Chung (2002) carried out a detailed examination of the physical and chemical characteristics of graphite. Graphite exhibits repeated hexagonal crystalline lamellar structure characterized by sp^3 hybridization. Carbon atoms that are positioned at the hexagon's edges exhibit robust covalent bonding, whereas the layers are connected by weaker Vander Waals forces. This arrangement is evident in the polycrystalline structure of graphite, as denoted by its JCPDS number 41-1487. Graphite has a very high melting temperature of 3550^{o}C. However, it undergoes oxidation at a relatively low temperature of 700^{o}C and form CO_2 and carbon mono oxide. Therefore, oxidation protection is required at high temperatures.

A. Mazloum et al. (2016) conducted a study to investigate how the thermal and electrical conductivity of Cu-graphite composite is influenced by varying graphite content, employing the powder metallurgy approach. Specimens were fabricated with graphite volumes ranging from 0% to 50% in the Cu-graphite composite. The findings reveal a reduction in electrical conductivity, density, and thermal conductivity as the graphite content increases. This trend is attributed to the poor properties of graphite and the inadequate wettability between Cu and graphite, leading to decreased interfacial adhesion.

Kumar et al. (2018) employed powder metallurgy route to fabricate copper- graphite composites by varying the graphite content (5-15 wt.%). They found that composite reinforced with 5 wt.% graphite had maximum compressive strength. Further, wear resistance gets enhanced with the increasing graphite content.

H. Kato et al. (2003) pointed out the poor mechanical properties of Cu-graphite and Cu-MoS_2 composite which may be because of poor interfacial adhesion between metallic Cu and non-metallic solid lubricant material. However, it may be enhanced by Cu coating of graphite and MoS_2 powder particles and by introducing the 10 vol. % tin to Cu-graphite/MoS_2 composite. It substantially increases the mechanical and tribological properties of Cu- graphite/MoS_2 composite. Further the value of the coefficient of friction gets reduced with rise in graphite content and the minimum value of 0.15 is for 40 vol. % of graphite. The specimen prepared with Cu coated graphite and MoS_2 powder displays a low wear rate as compare to uncoated specimen. They also reported that the wear rate of the Cu- MoS_2 composite increase with an increase in the MoS_2 content. It may attribute to the formation of brittle $CuMo_2S_3$ at elevated temperatures during the wear test.

Zhu Xiao et al. (2020) did a comparison of the microstructure and mechanical properties of Cu-graphite composite and cuprous oxide-graphite (Cu_2O-Gr) composite. The microscopic images of Cu_2O-graphite composite revealed that it had superior interfacial adhesion and homogeneous dispersion as compared to Cu-graphite composite. They found that Cu_2O-graphite composite had 1.5-1.6 times increase in hardness and 50-100 MPa increase in the compressive strength with its corresponding component of Cu-graphite composite.

S.K. Khatkar et al. (2018) studied the mechanical and wear properties of the Cu- graphite reinforced hybrid composite. They mentioned that Cu reinforced with Al_2O_3, and SiC exhibited good mechanical properties whereas they have poor electrical and tribological properties. To address these limitations, the addition of graphite in Cu-Al_2O_3 and Cu-SiC composites is found to be effective. The lamellar structure of graphite contributes in improving lubricating properties. Consequently, the Cu-graphite composite reinforced with Al_2O_3 and SiC has superior mechanical strength and improved tribological properties. These hybrid composite have broad application on sliding contact parts like bearing surfaces, brakes, rocker, liner, and piston.

Venkatesh R et. al. (2018) reported the effect of alumina in Cu graphite composite for marine applications including bearings, bushes, and blocks. The study depicts the increase in the hardness of the hybrid composite with an increase in the alumina content. It also stated improvement in the wear and corrosion resistance of Cu-graphite-alumina composite.

1.7.1 EFFECT OF VARIOUS PARAMETERS ON Cu-Gr COMPOSITES

1.7.1.1 Effect of milling

C. Suryanarayana (2001) had studied a detailed review of the mechanical alloying (MA) mechanism and its different parameters for metal powder. Mechanical alloying (MA) is a solid-state blending technique where powder particles undergo a repetitive process of flattening, fracture, cold welding, and re-welding. The study involved a detailed discussion of milling parameters including processing time, temperature, processing control agent, the ball to powder weight ratio, and ball diameter. During Mechanical Alloying (MA), powder particles undergo plastic deformation due to high-energy collisions, leading to particle fracture and work hardening. Initially, this deformation results in an increase in powder particle size. However, sustained collisions may lead to fatigue failure of powder particles, giving rise to the development of delicate flake-shaped particles. Throughout the milling process, ductile particles undergo fragmentation and cold-welding onto the softer phase. The literature suggests that mechanical alloying can achieve a high level of dispersion uniformity and develop strong interfacial adhesion. However, an extended milling process may result in excessive work hardening of the composite powder particles.

C. P. Samal et al. (2013) investigated the effect of milling and sintering temperature on mechanical properties of Cu-graphite composite by conventional and spark plasma sintering methods at different sintering atmospheres. They demonstrated that the composite exhibited a flake shape after 4 hours of milling. Accordingly, this flake shape transformed into an irregular shape after 20 hours of milling. They observed that mechanical properties including hardness, compressive strength, and flexural strength increase with milling time. The maximum valve of mechanical properties was achieved by conventional sintering 900^{o}C in argon atmosphere. However, spark plasma sintering at 700^{o}C had better mechanical properties.

1.7.1.2 Effect of sintering techniques

K. Rajkumar et al. (2009) reported the influence of microwave sintering on Cu- graphite composite. In microwave sintering, energy is transferred to the composite through direct molecular interaction, leading to internal heat generation. This causes the composite to function as its heat source, enabling rapid heating and reducing both sintering temperature and time. Microwave sintering may increase the densification and interfacial addition of Cu and graphite. It reduces the average grain size and porosity content of the composite. It may substantially enhance the properties of the Cu-graphite composite.

C Padmavathi et. al (2011) and G Sethi (2003) explored the impact of microwave sintering on Cu-Sn composite, aiming to address the issue of negative densification that is observed in conventional sintering. Negative densification can lead to composite material's expansion. However, the study revealed that the quicker and more uniform heating achieved through microwave sintering may induce shrinkage, indicating positive densification of the composite. Tungwai L. Ngai et al. (2013) studied the influence of sintering temperature(750-1070^{o}C) and atmosphere on diffusion and mechanical properties of Cu-Ti_3SiC_2 composites. They depicted highest value of green density, sintered density, and hardness for 950^{o}C by spark plasma sintering. However, sintering temperature had a very limited effect on the electrical resistivity of the composite.

K. Dash et al. (2011) fabricated the Cu-Al_2O_3 composite by conventional sintering and spark plasma sintering route. The study illustrated the effect of different sintering route including; sintering at different atmosphere (N_2, H_2, and Ar) and SPS sintering on the interfacial adhesion and dispersion of alumina particle in Cu matrix. The highest value of hardness 80 HV was found for the Cu with 15 vol. % Al_2O_3 composites. The maximum values of mechanical properties have been obtained for Cu-15Al_2O_3 composite when sintered in the H_2 atmosphere with a conventional powder metallurgy route. However, the maximum value of mechanical properties is achieved for Cu-5Al_2O_3 composite by spark plasma sintering technique. The paper highlights the SPS technique gives superior interfacial adhesion and surface integrity which remarkably enhances the mechanical properties.

1.8 WEAR

Wear is the progressive loss of material from a solid surface caused by the relative motion between the contacting surfaces. Wear is the result of either mechanical or chemical interactions between a solid, liquid, or gaseous substance and the solid material surface. [G.E. Dieter et al., 1978]. Metal matrix composites employed in sliding contact applications experience gradual deterioration. The contact surface can be either deliberate or unintentional, depending on the nature of surface interactions. For instance, intentional motion is observed in the sliding contact between the piston and cylinder surface of an automobile engine or between the wire and strip of a railway pantograph. On the other hand, unintentional motion, like fretting in joints, is also recognized. [A. Fischer et al., 2011].

When two mating surfaces are in intimate contact then an external shear force is required for sliding motion. Initially, a surface develops resistance against the applied force, the value of resistance increases with applied force and achieved its maximum value known as static friction force. As applied force exceeded the static frictional force, sliding motion occurs between the contact surfaces. During sliding motion, the value of resistance force slightly decreases and it is known as the kinetic friction force [A. R. Lansdown, 2015]. The ratio of friction force to the normal force is known as the coefficient friction. Therefore, for sliding contact application coefficient of friction should be minimum. This can be achieved by minimizing the friction force by introducing the solid lubricant in metal matrix composite. The lower coefficient of friction in the material may lead to a low wear rate. Therefore, metal matrix composite reinforced with a harder phase or solid lubricant is a candidate material for sliding contact application [A. M. Kovalchenko et al., 2012]. However, for some applications, it is desired to enhance the coefficient of friction that includes brake and clutch in automobiles [K. Kondoh et al., 2012].

1.8.1 Type of Wear

The wear phenomenon is classified it into four major categories; sliding, fretting, erosion, and cavitation wear [Bharat Bhushan et al., 2008]. Most of the engineering parts are subjected to the sliding motion therefore sliding wear is described in detail with a brief introduction of the remaining three. In sliding wear contact solid surfaces are in direct contact and exhibit relative motion. To reduce the coefficient of friction lubrication is provided between the mating surfaces.

Adhesive wear occurs when two sliding surfaces are in close contact and fragment from one surface get adhered to the counter surface and detached the surface atom from its position. These atoms of the sliding surfaces form intimate contact which develops the strong adhesive bonding between the high contact points. The high applied force has broken adhere contact between the asperities of the surface which detaches the material from the relatively softer surface. In this, the material is pulled out because of the adhesion of atoms therefore it is known as adhesive wear.

Abrasive wear takes place during sliding motion, when relatively harder asperities cause micro ploughing and remove the material in the form of wear debris. The interaction of these asperities or particles induces plastic deformation, leading to the formation of cracks and grooves in the softer surface as motion occurs. Material removal can take various modes as plowing, cutting, or the wedge formation.

Corrosive wear exists when the sliding motion of the mating surface occurs in a corrosive atmosphere. As the sliding motion discontinue, corrosion is initiated between the newly develop worn surfaces and form oxide film. However, further sliding motion between the mating surfaces removes the oxide film and exposes the nascent surface to the corrosive atmosphere. This process continuously removes the corroded material from the mating surfaces.

1.8.2 Friction and its laws

Friction is defined as the force that opposes or resists the relative sliding or rolling motion of two surfaces. Physical, chemical, and mechanical characteristics of the materials affect the basic mechanism of friction. At the microscopic level, the mechanism involves adhesive forces between contacting surfaces, asperity interaction, ploughing of one surface by the other harder surface, debris caused by surface fragmentation or fracture of the oxide film, and the surroundings. The fundamental laws of friction are as follows:

Maximum tangential force is proportional to applied load in static conditions.

- Tangential friction force is proportional to applied load during sliding motion.
- Friction force is independent of sliding speed or area of contact.

1.8.2.1 Various stages of friction

Initially, continuous welding and surface fracture was considered to be the key mechanisms for sliding friction, but subsequent investigations revealed that plastic deformation is the main mechanism that takes place owing to adhesion of surface asperities. During sliding motion, coefficient of friction (COF) is influenced by number of factors such as adhesion, ploughing, deformation, and third body particle. The friction force does not change much in the initial stage and remains nearly constant. In this region, the ploughing component of friction (plough) is dominant. Because of surface contamination, the adhesive component is of little importance. The friction force increases in second stage because adhesive forces become more significant with time; nevertheless, the friction force increases dramatically in third stage. The higher COF is caused by an increase in the amount of wear particles as well as increased adhesion caused by oxide removal from the contacting surface. Furthermore, surface irregularities may contribute to friction force. The friction force does not change in fourth stage because the amount of wear particles and adhesion stay nearly constant. Friction force reduces in the fifth stage due to reduced ploughing and asperity deformation. This type of state is created as a result of asperity elimination, which results in a mirror smooth surface. Finally, since both surfaces have the same surface finish, the friction force remains constant in the sixth stage. However, because wear particles are always present, mirror smooth surfaces are impossible to produce. The wear particles are entrapped at the interface during sliding motion between hard and soft surfaces, and there is little change after the fourth stage, and the friction force remains constant.

1.8.3 Operating conditions affecting wear

There are different conditions which affect the wear of materials. They are environmental conditions such as humidity, temperature, surrounding air or medium. The operating parameters affecting wear are: material composition, applied load, sliding velocity, sliding distance, counter surface against which the material motion occurs. The applied load and sliding distance majorly result in more wear of a material. At higher load there are more chances of plastic deformation of material, grooves and crack formation causing rise in wear. As the duration of contact is more at larger distances more loss of material occurs. However, sliding velocity may have positive or negative influence on the wear. The sliding velocity of the material leads to temperature rise enabling an oxide layer formation that hinders the wear deterioration. However, due to higher velocity after sometime this formed layer may break resulting in direct contact among the mating parts leading to sharp rise in wear of the material.

When evaluating the wear characteristics of test specimens, weight loss and wear rate are commonly assessed. However, it has been determined that the wear coefficient is a more comprehensive parameter for understanding material wear. This is because the wear coefficient not only considers the wear rate (V/S) and applied load but also accounts for the hardness of the wear pin or counterface, a crucial factor influencing the wear rate [J. Kumar et al, 2018, H. Bai, 2018]. The wear coefficient holds significant importance across various industrial applications, influencing decisions related to material selection, product design, maintenance planning, energy efficiency, safety, and quality assurance. Consequently, the ability to predict and quantify the wear rate empowers engineers to enhance the durability and reliability of mechanical components.

The following Archard's wear equation (Eqn. 1.1) can be used to determine the wear coefficient [J. Jang et al., 2020]:

$$Wear\ Coefficient\ (K) = \frac{\Delta W * H}{\rho * L * S} \quad \text{…………… (Eqn. 1.1)}$$

where, ΔW-weight loss, H-hardness, ρ-density, L-applied load and S-sliding distance.

1.8.4 Tribological Properties of Cu-Gr and of Cu-Gr hybrid composite

M. Grandin et al. (2018) studied the tribological properties including friction, wear rate, and contact resistance of Cu-graphite composite. The coefficient of friction and wear rate significantly decreases with introducing the graphite content. However, graphite content had less influence on the friction coefficient. The contact resistance had increased with increasing the graphite content. The investigation had been performed for both with and without current. The friction coefficient increase and the wear rate decrease when tribological tests were performed with current conduction.

Kestursatya et al. (2003) focused on evaluating the tribological characteristics of a composite formed by synthesizing copper alloy (C90300) with graphite (CG) using the centrifugal casting method. They did a comparative study of the wear performance of CG composite with the Cu-(18-22%) Pb alloys, as they harm the atmosphere. The wear test of samples of CG composite is performed at different load (27-110 N) conditions. At, a lower load of 27 N the CG composite depicted a coefficient of the friction as 0.37 which is similar to the leaded Cu alloys. However, at higher load condition CG composite exhibit higher coefficient of the friction.

S. F. Moustafa et al. (2002) studied the tribological properties of Cu-graphite composite synthesized with Cu coated and without Cu coated graphite powder. Wear tests of both sample sets was done by pin-on-ring tribometer under the applied load (50-500 N). Metallographic observation confirms the three-wear regime named as low, mild, and severe. Transition regimes of the Cu-Gr composite for corresponding content Cu coated and uncoated graphite are much similar. However, Cu coated graphite composite may withstand much higher load conditions as compared to uncoated graphite composite. The friction coefficient of the Cu-Gr composite has decreased with increasing the graphite content for both Cu-coated and uncoated graphite particles. Both composite sets are governed by the same wear mechanism such as oxidation induced and high strain delamination.

Haijun Zhao et al. (2006) suggested that synthesis of Cu-graphite using the electroforming technique could address the drawbacks associated with hot pressing. Tribological tests were carried out using a ring on a disc wear tester, revealing that higher graphite content substantially enhances wear resistance. The dominant wear mechanisms identified were adhesive and delaminated wear. The Cu-graphite composite also has potential applications in marine. The investigation focused on examining the corrosion performance of the Cu-graphite composite. Corrosion tests were carried out using electrochemical impedance spectroscopy (EIS) in a 3-electrode cell and the specimens were kept in a 3.5% NaCl solution for 24 h and 120 h. It may form Cu_2O which develops the adsorption resistance. Corrosion traces were noted at the grain boundaries and defects within the Cu oxide film, rather than at the Cu/graphite interface. The enhanced corrosion resistance can be attributed to the favorable interfacial adhesion and uniform distribution of components.

Y. Zhan et al. (2003) illustrated the impact of 10 vol. % SiC on the tribological characteristics of Cu-graphite composite. They observed a decrease in flexural stress of the composite when graphite content is raised because of the inherent softness of graphite and a surge in porosity as the graphite content rises. The dry sliding wear test was performed by block-on-ring wear machine with applied load of 20, 50 and 110 N and sliding velocity of 0.42 m/s. The wear rate was found to decreases with a rise in graphite content at low loading condition. However, the wear rate increases with higher graphite content for a higher load of 110 N. The particles of graphite are separated from the composite material during the wear test, and a graphite layer is continuously forming between the mating surfaces. The hexagonal layered structure of the graphite layer formed considerably lowers the wear rate and coefficient of friction.

Ambesh Jamwal et al. (2020) examined the incorporation of SiC particles on the mechanical and tribological characteristics of the Cu-graphite composite. It was reported that a tribo-layer is formed between the mating surfaces. The layer comprises of the constituents of composite and the counter surface. Thus, this tribo-layer is termed as a ‘‘mechanically mixed layer’’ (MML). The subsurface cavities experience deformation from their subsurface matrix. It may refer to the presence of lamellar and soft nature graphite particles in the subsurface cavities. In this way, graphite particles are squeeze out to the wear surface and smeared onto it in layered form. These layers combine with debris generated from both the composite and worn surfaces, resulting in the formation of a graphite-rich mechanically mixed layer (MML) between the mating surfaces.

M. L. Ted Guo et al. (2000) fabricated the SiC and graphite-reinforced in Al6061 matrix composite by semisolid consolidation technique. Here, the composite powder undergoes dry mixing and consolidation below the liquidus point of Al6061. The research found that an escalation in graphite content correlates with a decrease in fracture toughness and coefficient of thermal expansion (CTE). Although, an increase in graphite content brings about a reduction in the coefficient of friction. It was noted that the wear rate experiences an initial rise up to 5% graphite; however, further increases in graphite content result in a decline in wear rate. Optimal wear resistance is achieved with an 8% graphite content. The study suggests that the reduced fracture toughness at higher graphite content may contribute to an increased fractures on the composite surface.

S.F. Moustafa et al. (2002) investigated the impact of Ni-coated Al_2O_3 and SiC powders in Cu-Al_2O_3 and Cu-SiC composites. The Cu coating of Al_2O_3 and SiC was achieved through an electroless plating technique. Specimens were prepared for Cu-20Al_2O_3 and Cu-20SiC composites, both with and without Ni-coated Al_2O_3 and SiC powder, respectively. The primary focus of the study was on enhancing the interfacial adhesion between the matrix and the reinforcement phase. The nickel-coated specimens exhibited 2.5 times higher densification compared to their respective uncoated composites. The mechanical properties of the Ni-coated Cu-Al_2O_3 and Cu-SiC composites were found to be superior to their uncoated counterparts.

Ramesh et al. (2009) explored the impact of different graphite contents on tribological characteristics of the Cu-SiC composite. They prepared the specimen for different vol. %

(3, 7, and 10%) of graphite in Cu-10SiC composite. For lower graphite content, Cu-10SiC composite exhibits superior mechanical strength and wear resistance. The mechanical properties of the Cu-10SiC-Gr composite declined as the graphite content increased because of the soft nature of graphite. However, graphite addition may considerably lessen the coefficient of friction and enhance the wear resistance of Cu-10SiC-Gr composite. As the applied load increased, the coefficient of friction in the Cu-10SiC-Gr composite consistently decreased until reaching equilibrium state at 30 N load. Beyond this point, the friction coefficient remained independent of the graphite content for loads exceeding 30 N. Conversely, the wear rate of the composite increased with higher load conditions.

Liu Ru-Tie et al. (2011) accomplished the fabrication of tin-lead bronze-steel bimetal composites through the powder metallurgy route. The study revealed that the tribological properties of the composite exhibit improvement with the incorporation of graphite. Optimal tribological performance was achieved with a graphite content of 3 wt.%, showing superior characteristics. However, a decline in tribological performance was observed with additional graphite, suggesting diminished interfacial adhesion at higher graphite content.

1.9 TIC AS A REINFORCEMENT

TiC is widely recognized as a reinforcing agent in metal composites owing to its exceptional attributes, including a high melting point, elastic modulus, Vickers hardness, low density, substantial flexure strength, excellent thermal conductivity, resistance to corrosion and oxidation, and remarkable thermal shock resistance. Titanium carbide (TiC) is an important ultra-high temperature ceramic (UHTC) material well known for many years. It possesses excellent hardness (25.1GPa) with high melting temperature

(3067ºC), relatively low density (4.93g/cm^3), high flexural strength (490-595 MPa), high modulus, great thermal conductivity (21W/mK) and significant wear and chemical resistance [Lipatnikov et al., 2000, T. Ali et al., 2022]. TiC crystallizes in a fcc- cubic lattice structure like NaCl. The Ti atoms are at the corner of cube and at face of each side with C atoms occupying the octahedral sites. It is a promising candidate as reinforcement in the fabrication of MMCs due to the above defined properties in aerospace, automotive, structural applications.

Huabing Yang et. al (2018) studied the effect of in-situ formed TiC nanoparticles in the Al-4.5Cu alloy. Firstly, an Al/14TiC master alloy was formed using pure A, Ti and graphite using direct melt reaction process. Then this master alloy was introduced in Al-4.5Cu melt to fabricate the composites. Grain refinement of Al-4.5Cu happened due to TiC nanoparticles addition. The composite with 1.5 wt.% TiC depicted maximum UTS value of 340 MPa owing to grain refinement, load bearing ability and Orowan strengthening.

G.H.A. Bagheri (2016) investigated the effect of varying percentage of TiC particles in copper matrix composites. The copper and titanium powders with desired content were milled for 60h under inert atmosphere. Following which the graphite powders were added and further milled for 10 h and then compaction and sintering was carried out at 900ºC. The sintered composites showed enhancement in hardness and wear resistance with increase of TiC percentage and sharp decrease in electrical conductivity.

The operating parameters during the wear of a material may have a combined influence on the wear rate of the composite material. It is necessary to analyse these parameters for prediction of minimum wear rate to increase the durability of the composites. The optimization of wear rate of the composite with respect to the operating parameters leads to increase in life of the composites and to hinder sudden failure of the material in addition to save in economy. It also leads to efficient utilisation of the composite so produced. There are different mathematical and statistical tools for effective optimization of parameters for maximum gain. The researchers have used various modelling techniques such as RSM, Taguchi, ANN, Grey rational analysis, Design expert to optimize the operating wear parameters. Response surface methodology (RSM) is an important multivariate method to study and optimize the wear properties of a composite. It is used for the input operating parameters and optimizing them for the best performance of the material. It may refer to minimizing the wear and minimizing or maximizing the coefficient of friction as per specific needs. RSM approach is postulated by the fit of a polynomial equation to the statistical data points. Ponugoti et al. (2018) studied the wear performance of an Al-based hybrid composite using RSM and a multi-objective optimisation in order to optimise the factors that affect the wear properties.

Renjin J Bright et al. (2022) prepared the Al 6082/China clay particles composites by stir casting and determined the sliding wear behaviour using RSM. The reinforcement percent, sliding spend and load were taken as the independent wear parameters. Minimum wear and coefficient of friction occurred at 7.1769% of reinforcement, 500 rpm speed and 38.838 N applied load. More wear loss was revealed at higher load and sling speed. The morphology of the worn surfaces showed delamination and abrasive as the important wear modes.

Mandava et al. (2022) prepared Al 7075 based hybrid composites with fly ash and SiC as reinforcements using stir casting setup. The varied the weight percentages from 2.5% to10% equally for both the reinforcements. They also examined the wear behaviour of composites using RSM approach with MINITAB software and optimised the wear parameters. The hardness and UTS was maximum for Al-10%fly ash-10% SiC composite. The results of RSM suggested that load is the dominant factor for wear rate. Now, the Table 1.1 illustrates the comparison of different literatures of copper graphite composites.

Table 1.1 Comparison of literature of copper graphite composite

Literature	**Material**	**Route**	**Focus**	**Key Findings**
Zhu Xiao et al. (2020)	Cu-graphite composite	In-situ Hot pressing	Microstructure and mechanical properties	Cu_2O-graphite had 1.5-1.6 times higher hardness and 50-100 MPa higher compressive strength than Cu-graphite
K. Rajkumar et al. (2009)	Cu-graphite composite	Microwave sintering	Microwave sintering effects	Microwave sintering reduced sintering temperature and time, increased densification and reduced grain size and porosity
S.K. Khatkar et al. (2018)	Cu-Al_2O_3, Cu-SiC reinforced with graphite	Powder metallurgy	Mechanical and wear properties	Graphite addition to Cu-Al_2O_3 and Cu-SiC composites improved their mechanical strength and tribological properties
Kestursatya et al. (2003)	Copper alloy (C90300) with graphite	Centrifugal casting method	Tribological characteristics	Copper alloy with graphite exhibited similar friction coefficient as

				leaded Cu alloys at low loads but higher friction at higher loads.
Haijun Zhao et al. (2006)	Cu-graphite composite	Electroforming technique	Electroforming technique for Cu-graphite	Cu-graphite made using electroforming showed improved wear resistance with higher graphite content
S. F. Moustafa et al. (2002)	Cu-graphite composite	Powder metallurgy	Tribological properties with Cu-coated graphite	Cu-coated graphite composite had higher wear resistance under higher loads compared to uncoated graphite
Y. Zhan et al. (2003)	Cu-graphite composite with 10 vol. % SiC	Powder metallurgy	Tribological characteristics	Wear rate decreased at low loads but increased at higher loads with higher graphite content
Ambesh Jamwal et al. (2020	Cu-graphite composite reinforced with SiC particles	Stir casting	Tribological characteristics	Synergetic influence of graphite and SiC reduced wear rate and friction

1.10 RESEARCH GAP IN THE LITERATURE

The literature review suggests that copper-based composites are favoured in various technological fields because it offers superb thermal and electrical conductivity, strong resistance to corrosion, and impressive ductility, making it an ideal matrix material. Fathy et al. (2013) prepared Cu- Al_2O_3 composites by powder metallurgy and found that alumina significantly enhances the strength of the composites. Akbarpour et al. (2013) developed copper-based composite by integrating varying volumes (2%, 4%, and 6%) of SiC nanoparticles as reinforcement. Many researchers have worked on incorporating graphite into the copper matrix so to widen the application of copper material in tribological areas. The Cu-graphite composites are extensively used in sliding contact, bushing and bearing applications. M. Grandin et al. (2018) investigated the tribological characteristics of a Cu-graphite composite, analysing factors such as friction, wear rate, and contact resistance. They observed a notable decrease in both the coefficient of friction and wear rate with the addition of graphite content. Kumar et al. (2018) utilized powder metallurgy approach to produce copper-graphite composites, varying the graphite content from 5% to 15% by weight. Their findings indicated that the composite containing 5% graphite exhibited the highest compressive strength. Additionally, they observed that wear resistance improved as the graphite content increased. However, at higher content of graphite the poor wettability of Cu and graphite reduces its mechanical properties. Therefore, there is a need to develop a cost-effective method to improve properties of Cu- graphite composite. It may be achieved by addition of TiC particles as a reinforcement. The titanium carbide reinforced Cu- graphite composite may enhance both the mechanical and tribological properties of the composite. There exists limited amount of research available on the mechanical and tribological performance of Copper-Graphite-TiC composites. However, no work has yet been done for studying tribological properties of these composites under lubrication condition. Further, the tribological parameters can be optimised using response surface methodology that may help in predicting and improving the life of the composite. Therefore, the current study involves a comprehensive investigation to explore the above aspects in detail.

1.11 OBJECTIVES OF PRESENT STUDY

The objective of the current study is to fabricate Copper-Graphite-TiC composites having enhanced tribological performance under dry and lubricating sliding conditions for the tribological applications and to attain the objective, the following methodology has been adopted:

- Fabrication of Copper-Graphite-TiC composites with different wt.% of TiC particles using powder metallurgy route.
- Microstructural characterization of pure Cu and composites to study the phase morphology, particle size and dispersion of the reinforcements in synthesized Copper-Graphite-TiC composite to understand their role on tribological properties.
- Study the influence of TiC particle reinforcement on mechanical properties of composites at atmospheric conditions.
- Study the influence of different parameters such as sliding distance, sliding velocity, applied load and wt.% of TiC on tribological properties of Copper-Graphite-TiC composites in dry sliding condition and lubricating sliding condition.
- Study of the worn surfaces using diverse tools such as SEM, EDS, and AFM to gain insights about the different wear mechanisms operating during the wear process.

- Utilisation of Response Surface Methodology statistical technique to optimize/predict the wear parameters of composites for both dry sliding and lubricating sliding condition.