# CHAPTER 2

# LITERATURE REVIEW

This chapter comprehensively summarizes the literature review on the development, microstructural analysis, mechanical properties, and tribological characteristics of copper-based composites and hybrid composites. Several researchers have created copper-based composites and hybrid composites using various approaches and revealed their findings. A growing focus has recently been on developing composites with improved mechanical and tribological qualities. This is driven by the need for higher efficiency, durability, and environmental friendliness, as demanded by new technologies. This chapter is structured into many subsections based on the available related work and literature.

## 2.1. Composite Materials and their several categories

A composite material is formed when two or more materials with distinct physical and chemical properties are mixed at a microscopic level, resulting in a combined material exhibiting different characteristics from its individual components. The production of composite materials is driven by its objective of creating materials that are stronger, lighter, or less expensive than traditional materials. The composites have been categorized based on three factors:

(i) The kind of matrix, which may consist of metal, polymer, or ceramic;

(ii) The type of reinforcing phase, which can be long or short fibers, whiskers, or particulates, and

(iii) The geometry of the reinforcement, which can be continuous fibers, discontinuous fibers.

### 2.2. Classification based on the matrix

Composite materials consist of a combination of two or more physically distinct and chemically separable components. The matrix is the main continuous phase, while the reinforcement is the minor, discontinuous phase. Composites are engineered to achieve specific properties for a particular use that cannot be provided by a single material. They are categorized based on the matrix (metal, polymer, ceramic), the reinforcing phase (long or short fiber, whiskers, particulate), and the geometry of reinforcement (continuous fiber, discontinuous fiber, wire). Figure 2.1 illustrates the typical classification of composites based on the matrix.

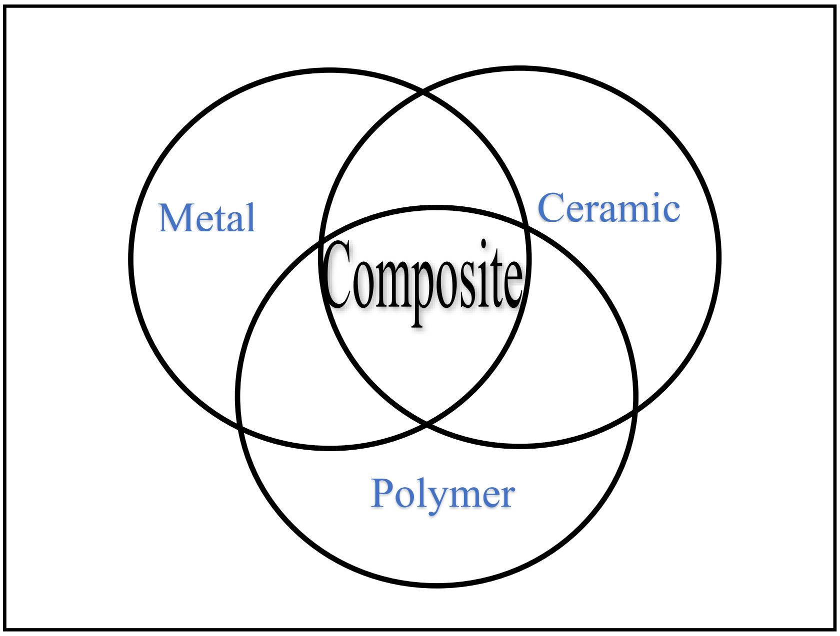

**Figure 2.1** Matrix based classification of Composites. (Rosso et al., 2006)

#### 2.2.1. Metal matrix composites (MMCs)

A Metal Matrix Composite (MMC) is a type of composite material that consists of at least two components, one of which must be a metal and the other can be a metal, ceramic, or organic substance. Reinforcement is incorporated into a metal matrix to create MMCs. On occasion, coating has been applied to the reinforcement surface to stop the reinforcement's chemical reaction with the metal matrix at high temperatures. Reinforcement is added to a monolithic material called a matrix, which is entirely continuous. Lightweight metals like titanium, magnesium, and aluminium are employed in structural applications, and hard reinforcement is applied to them based on the needs of the design. Materials that are added to a matrix are known as reinforcing materials.

### 2.2.2. Ceramic matrix composites (CMCs)

Ceramic materials act as the matrix phase, and other materials act as the reinforcing phases of a ceramic matrix composite (CMC). Composites made of ceramic materials are mainly produced to increase their fracture toughness. As such, it can be applied in stressful and extremely hot conditions. Particles, whiskers, and fibres can be used as the reinforcing phase in CMCs, which is crucial in preventing the propagation of cracks. Liquid phase sintering, hot pressing, hot isostatic pressing, cold pressing, sintering, and reaction bonding techniques, among others, can be used to create CMCs. Despite the composites' good characteristics, the widespread usage of CMCs is limited by several issues, including expensive production costs, high energy requirements, and challenging post-processing, such as machining [Galvalda et al., 2019].

### 2.2.3. Polymer matrix composites (PMCs)

A polymer matrix composite (PMC) is a composite material where polymers, such as epoxy, polyester, or phenolic resins, act as the matrix or binder that holds together reinforcing fibres or particles. These fibres or particles, often made of materials like glass, carbon, or aramid, provide strength and stiffness to the composite. PMCs are known for their lightweight, corrosion resistance, and versatility, making them widely used in aerospace, automotive, construction, and other industries. Carbon fibre-reinforced polymer (CFRP), glass fibre-reinforced polymer (GFRP), and aramid fibre-reinforced polymer composites are the three types of polymer matrix composites that are typically employed. Polyesters and vinyl esters are two popular polymers used as matrices.

### 2.3 Classification based on the reinforcement

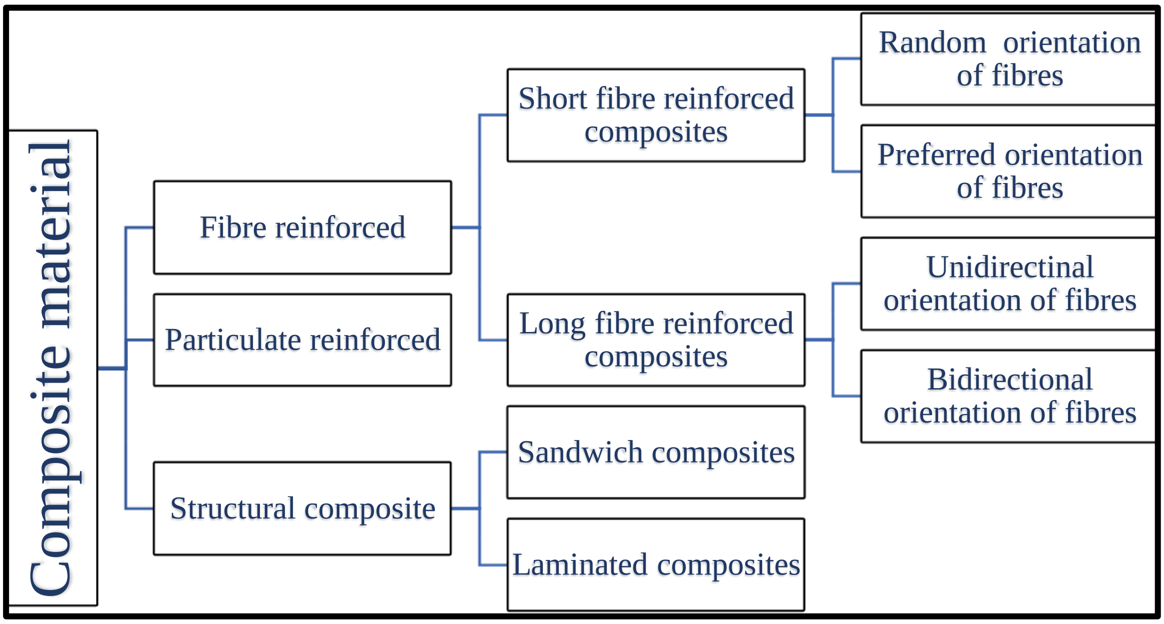

**Figure 2.2** Classification of composite materials based on the reinforcement used

[Schoutens et al. (1985)]

#### 2.3.1. Fibre reinforced

fibre-reinforced composites encompass a wide variety of fibres, whiskers, and filaments, both continuous and non-continuous, across the entire range of reinforcement concentrations.

#### 2.3.2. Particle reinforced

The particle-reinforced composites, akin to dispersion-strengthened composites, contain particles larger than 0.1 μm and can have volume percentages exceeding 25%.

#### 2.3.3 Structural composites

This type of composite material involves the uniform distribution of fine, hard particulates with a size ranging from 0.01 to 0.1 μm. These particulates are present in a volume percentage between 1% and 15%. They are strategically incorporated to improve the overall strength and hardness of the composite material.

**a) Sandwich composites**

Sandwich composites are formed by sandwiching two thin, stiff, and robust skins with a thick, light, and less strong core (Arboui et al., 2009). To facilitate the transfer of loads between the components, the core materials and the faces are bonded with an adhesive. These composites are employed to create structural elements that exhibit exceptional bending strength and stiffness-to-weight ratios.

**b) Laminated composites**

Laminated composites are developed using layers of different materials bonded together with adhesives to significantly enhance durability, strength, and other advantageous properties.

### 2.4 Type of reinforcements used in metal matrix composites

The four primary categories are as follows:

- Continuous fibres
- Discontinuous fibres
- Whiskers
- Particulates, etc.

The above-mentioned four principal categories of reinforcement materials are depicted in Figure 2.3. Beyond these metallic wires, ceramics serve as a prevalent choice for reinforcement purposes. These ceramics encompass metal nitrides, oxides, and carbides. Owing to their superior specific strength and stiffness across a spectrum of temperatures from ambient to elevated, these ceramic materials find frequent application as reinforcement agents. The interaction between each type of ceramic reinforcement and the base metal varies, influencing the composite material's properties in distinct ways.

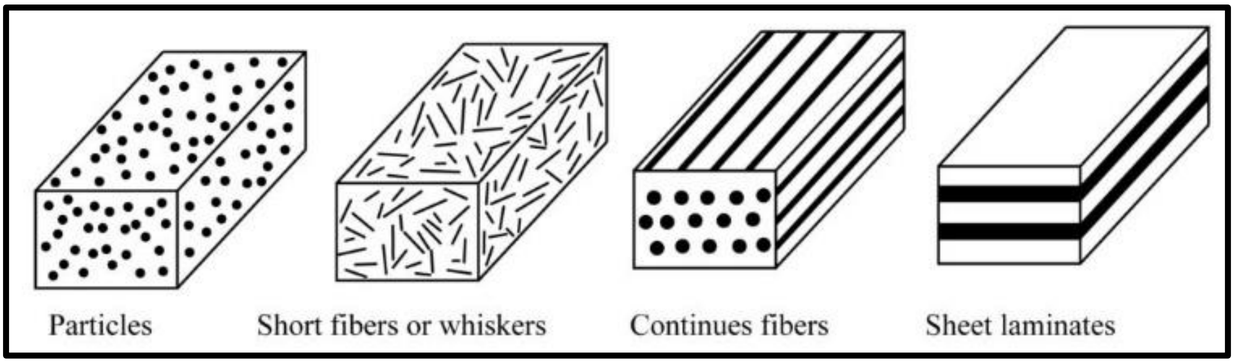

**Figure 2.3** Type of reinforcements used in metal matrix composites

### 2.5 Processing techniques for composites

The development of metal matrix composites involves various processing techniques, which largely depend on the state of the matrix material during processing. These techniques can be classified into five major categories, as shown in Figure 2.4

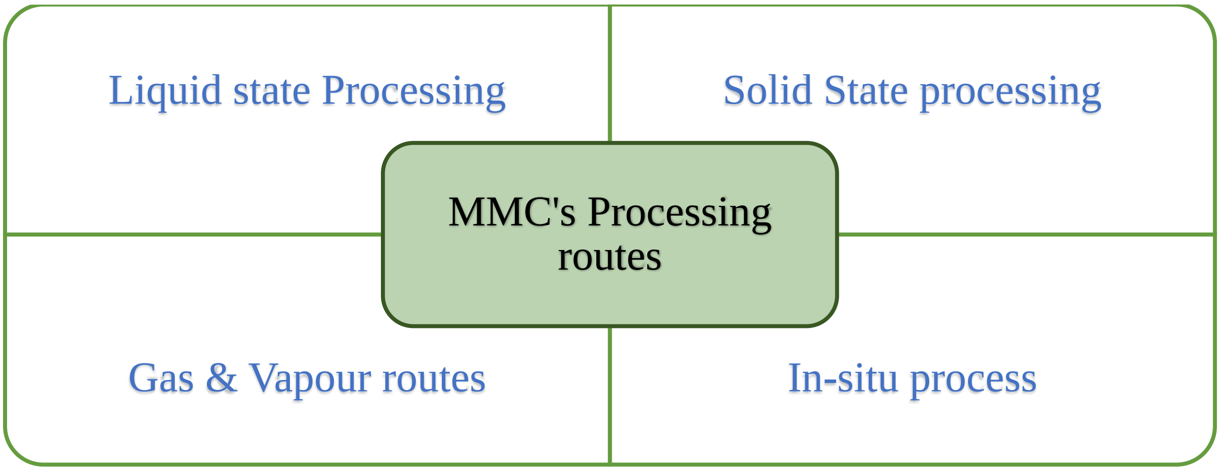

**Figure 2.4** Classification of the processing routes to develop MMCs

### 2.5.1 Liquid State Processing

In the liquid state processing method, the reinforcing phase particles are combined with the molten metal during the preparation of the composite material. This process includes mixing the components and then pouring the resulting mixture. Liquid phase processing can be categorized into three main methods: melt stirring, gas pressure infiltration, and squeeze casting.

**Melt stirring** involves adding the reinforcing phase to the molten metal and mixing them together using a stirrer before the mixture solidifies. While this method is straightforward, the high temperatures involved can potentially affect the quality of the reinforcement phase.

**Gas pressure infiltration** consists of infusing the molten metal into a ceramic preform using gas pressure, which results in a casting without any pores, offering a high-quality finished product.

**Squeeze casting**, on the other hand, is a liquid phase processing technique that entails pressurizing the molten metal to fill the preform by means of a ram displacement, with the preform held in the lower fixed part of the setup.

### 2.5.2 Solid State Processing

Metal reinforcement with particulates involves a process of using a mixture of blended elemental powders. Prior to the final consolidation, several specific steps are involved in this process. Powder metallurgy and diffusion bonding are two methods that fall under this category.

#### 2.5.2.1 Powder Metallurgy (P/M)

The process involves carefully blending of powdered matrix and reinforcements in specific proportions. This mixture is then compacted under pressure and sintered at a high temperature to facilitate diffusion. This method offers the flexibility to introduce various types of reinforcements, including whiskers, fibers, or particulates. It is a remarkably versatile process, enabling the combination of different materials that would be impossible with other techniques.

#### 2.5.2.1.1 Several effective methods for producing metal powder

The production of metal powder is a crucial initial step in the powder metallurgy (PM) process. As industrialization continues to advance, various innovative powder production techniques are being developed to meet the growing demand. These techniques play a key role in manufacturing metal powder from tough and high-strength materials, ensuring that the resulting products exhibit exceptional hardness and durability. there are different metal powder production techniques that are widely utilized in the industry (G.S. Upadhyaya, 2014).

##### a. Mechanical methods

This method, which dates back to ancient times, is utilized for the production of powder by effectively reducing the size of ceramic and brittle materials. It harnesses mechanical energy to break down the particles of the material. The process of powder preparation involves a detailed sequence of steps, including impact, pressure, and shear. Impact and pressure play a critical role in inducing crack formation and wear, leading to a reduction in dimension, while shear causes cleavage fracture, making it an intricate and multi-faceted process. (G.S. Upadhyaya, 2014).

##### b. Grinding

In the process of grinding, sintered sponge material, which is produced through a variety of powder production techniques such as sintering and compaction, is subjected to hammering and crushing in order to reduce its size. The sponge material is hammered between stationary and rotating jaws, effectively breaking down the coarse material into relatively small and finer particles. This hammering action of the jaws disintegrates the material, resulting in smaller sponge particles. Subsequently, these smaller sponge materials undergo milling in order to produce metal powder.

### c. Milling

During 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 milling duration, the speed of milling, the milling medium, and the ratio of balls to powder significantly impact the milling process. Figure 2.5 shows the schematic of the milling process. However, the powder being milled should exhibit ductile properties. For example, during mechanical alloying of Cu/graphite powder, the Cu particles are laminated over the soft graphite particles when a relatively hard phase is coated over the soft phase. (R.O. Thummler, 1993 and K. Skotnicova et al., 2014)

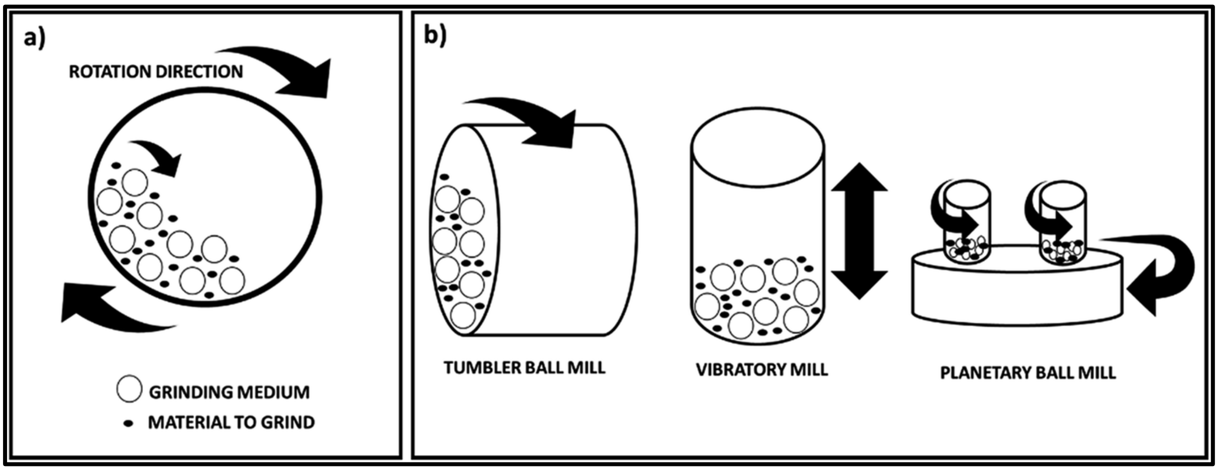

**Figure 2.5** Milling process schematic **(Carmen C. Piras et.al., 2019)**

### d. Electrolytic Method (Physical method)

The electrolytic powder preparation method is a widely utilized technique for obtaining the powder of copper (Cu), iron (Fe), and nickel (Ni). In this process, metal ions are deposited onto the cathode plate in flake form and then converted into powder form. The resulting metal powder boasts superior quality and is exceptionally well-suited for use in conventional powder metallurgy processes.

However, it is important to note that this method is relatively expensive and is characterized by a lower production rate when compared to alternative powder production methods. For instance, the production of electrolytic iron powder is significantly costlier compared to reduced or atomized iron powder. Despite these drawbacks, the high quality of the resulting metal powder makes the electrolytic powder preparation method a compelling choice for certain applications in the field of metallurgy.

#### e. Atomization

The manufacturing process of powder production involves atomization methods such as gas atomization and water atomization. In these processes, the raw material is first melted into a liquid state and then forced through a narrow opening. External sources, namely water or gas, are then employed to break down the liquid metal as it passes through the narrow opening, resulting in the formation of fine powder particles.

Atomization is known for yielding metal powder of exceptionally high purity. In this method, the molten material is carefully directed through a specially designed orifice, where a jet of water or gas is used to disintegrate it into fine powder particles. This process ensures the production of high-quality metal powders suitable for various industrial applications.

### 2.5.2.1.2 Synthesis of Metal matrix composite (MMC) by Powder Metallurgy

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

**Mixing and Blending:** Mixing is an essential process to achieve a consistent dispersion of all components. It involves blending elementary powders to form a well-integrated mixture of secondary powder with appropriately sized and uniformly distributed particulates, each possessing a distinct morphology. In addition to powders, lubricants are incorporated to reduce friction and wear on compaction dies, which can occur due to abrasive or hard particles during compaction. Various parameters, like milling time, milling vial and ball material, milling environment, ball-to-powder ratio, processing control agent, and ball size, have an impact on this process. However, mixing time stands out as a critical factor. Excessive mixing should be avoided, as it can lead to the hardening of particles.

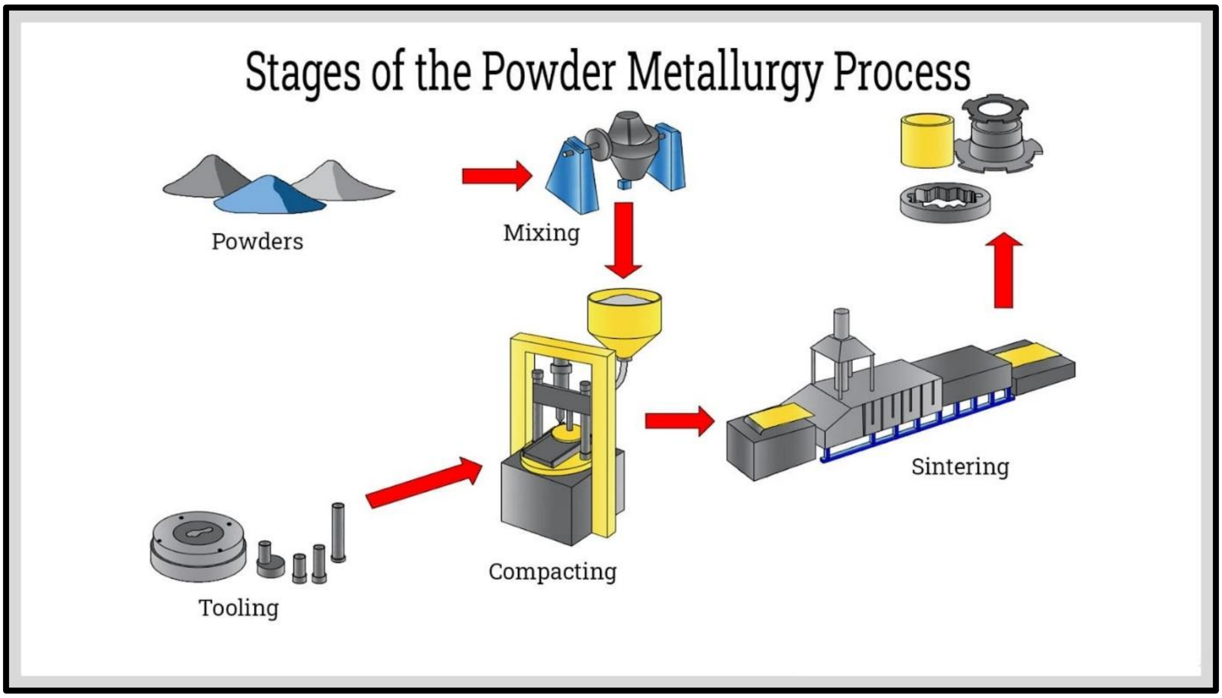

**Figure 2.6** Steps involved in powder Metallurgy process.

High energy ball milling is a widely favoured technique for mixing due to its exceptional efficiency and ability to uniformly disperse small reinforcement phase particles into the matrix phase. The planetary ball mill is particularly popular for this purpose as it not only mixes the materials but also reduces the size of the powder. This type of mill is comprised of a jar mounted on an eccentric sun wheel, both of which rotate in opposite directions and synchronize the centrifugal force alternately.

**Compaction:** During the compaction process, mixed powders are densely packed in a die by subjecting them to high pressure at room temperature, resulting in the formation of a green compact. This process imparts green strength to the compacts through mechanisms such as particle sliding, interlocking, and plastic deformation. As the compaction pressure increases, the density of the compact also increases while the porosity decreases (Garg, 2007).

**Sintering:** During sintering, compacts are heated to allow pores between particles to fuse, increasing density and strength. The process involves three stages:

1. Inter-particle welding occurs in the first stage as particles start fusing together, and the weld grows with sintering time (German, 2016).
2. In the second stage, the pore network becomes unstable and begins to shrink.
3. The third stage involves the disappearance of the pores. Figure 2.7 illustrates the different stages of sintering and the diffusion that takes place during the process.

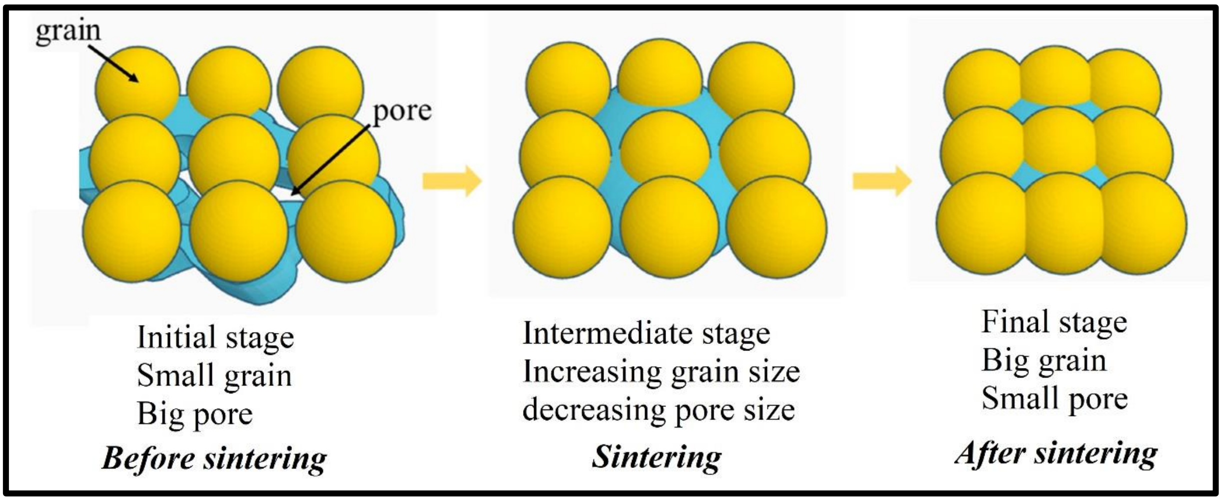

**Figure 2.7** A schematic diagram of sintering

There are various techniques of sintering like conventional sintering, **Microwave sintering** and **spark plasma sintering** are advanced techniques used in the production of composite materials. In the traditional sintering process, preformed powders are heated for diffusion at a temperature below the melting point, and this process can range from several minutes to hours. Microwave sintering is a process that involves using microwave irradiation to heat and sinter materials while taking advantage of the dielectric properties of the materials. These dielectric properties play a significant role when the material is exposed to microwave irradiation. On the other hand, hot isostatic pressing is a sintering technique in which high pressure and heat are simultaneously applied to achieve a high level of densification in the material. This technique is particularly effective for producing materials with uniform density and structure. During the spark plasma sintering process, joule heating occurs while a constant load is applied for the entire consolidation process. This sintering happens at a significantly lower temperature than the melting point and provides several advantages compared to other sintering techniques, such as shorter sintering time, prevention of grain coarsening, and the ability to sinter phases with a high difference in sintering tendency.

### 2.5.3 Vapour Phase Deposition

This manufacturing process involves the utilization of various methods, namely Electron Beam/Physical Vapour Deposition (EB/PVD), Physical Vapour Deposition (PVD), Chemical Vapour Deposition (CVD), and Plasma Assisted Chemical Vapour Deposition (PACVD). In EB/PVD, fibres are guided through a region with a high partial pressure of the melt deposit, leading to condensation and the production of a relatively thick coating on the substrate. Notably, this technique allows for the use of multiple evaporation sources and provides flexibility in varying the composition by controlling the evaporation rate of the sources. Vapour phase deposition presents several advantages, such as the capability to prepare a wide range of compositions, absence of mechanical disturbance to the interfacial region, achievement of uniform thickness, and control over thickness. It is important to note that there are two major vapour deposition techniques available: physical vapour deposition and chemical vapour deposition. Physical vapour deposition involves a vacuum deposition process where material transitions from the condensed phase to the vapour phase and then condenses as a film over the substrate. Conversely, chemical vapor deposition is a process through which solid materials are vaporized and deposited onto the substrate in the form of a thin film through a chemical reaction (Shi et al., 2011; Li et al., 2004; Guo et al., 2002).

### 2.5.4 In-Situ Processing

The in-situ processes can be divided into two main categories. The first category involves the controlled solidification of melts (Zhang et al., 2013; Hu et al., 2012; Gunjishima et al., 2002; Zhang et al., 2016), while the second category involves chemical reactions between two phases (Zhang et al., 2018; Yin et al., 2005; Sui et al., 2014; Peng et al., 2000; Singla et al., 2015).

One of the primary advantages of in-situ composite materials is the homogeneous distribution of the reinforcing phase. Additionally, the spacing or size of the reinforcement can be adjusted in some cases through controlling the solidification or reaction time. Furthermore, the interfaces between the phases are clean, mutually compatible, and coherent because the constituent phase crystallizes in situ rather than being combined from separate sources.

However, it's important to note that the selection of the system and the orientation of the reinforcement are limited, and the control of process kinetics (in the case of reactions) or the shape of the reinforcing phases can sometimes be challenging (Cuvas et al. 2018).

### 2.6 Copper based Metal Matrix Composites and their Properties

Copper and its alloys are highly valued in a variety of industries due to their outstanding properties. These properties include efficient heat and electrical conductivity, resistance to corrosion, non-magnetic nature, and stability at high temperatures. These qualities make copper essential in numerous industrial processes and applications. Copper possesses excellent thermal conductivity, a crucial attribute for components requiring effective heat dissipation.

Despite this, its high deformability and relatively low strength restrict its use in certain applications. Consequently, additional reinforcements are added to the copper matrix to enhance its strength, wear resistance, and frictional properties. As a result, copper-based composites are developed by integrating various reinforcement materials for electrical and thermal applications.

In a study conducted by Yuanyuan et al. (2012), the microstructural and thermal conductivity of copper metal matrix composites reinforced with silicon carbide (SiC) and diamond as hybrid particles was reported. The microstructure of the resulting diamond hybrid SiC/Cu composite demonstrated weaker interfacial strength between the reinforcement and matrix with a particle volume fraction of 65%, and a volume mixing ratio of diamond to SiC particles at 7:3. This was attributed to the poor wettability of SiC in the Cu matrix, leading to most of the particles settling away from the interface.

The addition of a coating of Titanium metal (Ti) can improve the way SiC particles bond with a Cu matrix. Theoretical estimates show that a diamond hybrid SiC/Cu composite can have a thermal conductivity of 500 W·m−1·K−1 when the particles make up more than 46% of the volume and the ratio of diamond to silicon carbide(SiC) particles is over 13:12. There are significant changes in the thermal conductivity of the hybrid composite when the particle size is over 200 μm. Experimental results show that the addition of Ti improves the way SiC bonds with the Cu matrix, resulting in the thermal conductivity of the diamond hybrid SiC-Ti/Cu being twice as high as the diamond hybrid SiC/Cu composite.

Liu et al. (2019) investigated how the physical characteristics of graphite fillers impact the thermal conductivity of composites. They found that graphite fiber/Cu composites exhibited thermal conductivity ranging from 287 W/mK to 321 W/mK. The study highlighted the low radial thermal conductivity and random two-dimensional distribution of the fibers as key factors in reducing thermal conductivity. Additionally, large graphite flakes were identified as promising fillers for heat dissipation in Cu matrix composites due to their high thermal conductivity and favorable orientation within the matrix.

Li et al. (2020) successfully synthesized graphene-reinforced copper-based composites (0.07 wt. % graphene) through a novel methodology involving the calcination of a polyethylene glycol and copper powder mixture under an argon and hydrogen atmosphere, subsequently consolidated by Spark Plasma Sintering (SPS) at 850 °C under a pressure of 50 MPa. The resultant composite material exhibited a superior ultimate tensile strength (UTS) of 254 MPa compared to pure copper's 208 MPa, albeit with a decrease in ductility. This enhancement in mechanical properties is attributed to several mechanistic contributions including efficient load transfer from the copper matrix to graphene, thermally induced mismatch stresses, grain boundary refinement, and Orowan strengthening mechanisms.

Haimin Dinga et al. (2024) studied how to make a special mixture of copper and titanium carbide. They found that when they heated copper, titanium, and carbon black powder to 1200 °C, the titanium combined with the carbon to form titanium carbide in the mixture. They also discovered that using more titanium compared to carbon led to a better spread of the titanium carbide in the mixture.

In another study, K M Shu et al. (2014) and M. Barmouz et al. (2011) looked at the heat properties of a mix of copper and silicon carbide made using a special process. They coated silicon carbide powder with copper using electricity, making the silicon carbide spread evenly in the copper. The tests done on how the mixture expanded when it was heated and then cooled down showed that the expansion decreased with more silicon carbide in the mix.

In a study conducted by Ravindran et al. (2013), the microstructural and density behaviors of aluminium-based hybrid nano-composites were investigated with the addition of solid lubricants. The analysis of the microstructure revealed the presence of graphite and silicon carbide (SiC) in all the hybrid nano-composites. It was observed that strong chemical bonding existed among the aluminium particles, resulting in the formation of a solid structure. The microstructure of the hybrid composite exhibited flake graphite and cube-like structures of SiC, with a uniform distribution of SiC particles in the Al 2024 matrix. The micrograph also indicated the absence of cracks. However, the density of the hybrid nano-composites, as determined using Archimedes' principle, was found to be lower compared to its matrix. It was further observed that the decrease in density of the hybrid nano-composites was attributed to an increase in graphite content, reinforcing the lower density of graphite.

In the study conducted by Luo et al. (2017), Cu-0.6 wt. % reduced graphene oxide (rGO) and Cu-0.6 wt. % Silver (Ag)- reduced graphene oxide (rGO) composites were created by sintering at 700°C in a vacuum hot press at 50 MPa for 45 minutes. These were then compared with pure copper prepared using the same method. The authors found that the addition of reduced graphene oxide (rGO) increased the Yield Strength (YS) and Ultimate Tensile Strength (UTS) by 93% and 98% respectively. This enhancement was attributed to dispersion strengthening by the rGO particulates. Furthermore, the Cu-Ag-rGO composite exhibited higher strength than the Cu-rGO composite due to strong interfacial bonding between Silver (Ag), graphene oxide (rGO), and the matrix, facilitated by the presence of silver.

In a study, A. Mazloum et. al. (2016) delved into the effects of varied graphite content on the thermal and electrical conductivity of Cu-graphite composite. They utilized the powder metallurgy approach to fabricate specimens with graphite volumes ranging from 0% to 50% in the Cu-graphite composite. The study uncovered a noteworthy trend of diminishing electrical conductivity, density, and thermal conductivity as the graphite content increased. This phenomenon was attributed to the subpar properties of graphite and the insufficient wettability between Cu and graphite, which led to a decrease in interfacial adhesion.

Samal et al. (2013) conducted a study comparing the mechanical properties of copper matrix composites reinforced with different percentages of graphite. They prepared composites with 1, 3, 5, and 10 vol.% graphite using a traditional powder metallurgy (P/M) method, and composites with 1 and 5 vol.% graphite using spark plasma sintering (SPS). The results showed that the composites fabricated through spark plasma sintering exhibited better properties such as hardness, density, and compressive strength due to their fine grain morphology compared to those prepared by the traditional method. However, the compressive strength and elastic modulus decreased with increasing graphite content, while hardness and flexural strength increased.

In their study, Ramesh et al. (2009) compared the properties of single-reinforced and hybrid composites. They found that hybrid composites have enhanced properties compared to single-reinforced composites because the advantages of constituent reinforcements are combined in hybrid composites. In another study, Rajkumar K. et al. () used 99.5% pure electrolytic copper powder with a size of 12µm as the metal matrix. They preheated the blended mixture at 150°C to evaporate the volatile matter present in the mixture. They utilized a 3.2 kW industrial microwave furnace operating at a frequency of 2.45 GHz with a multimode cavity. The researchers computed the coefficient of friction from the applied load strain gauge to obtain the tangential load. The ratio of volume loss to the sliding distance (6785m) was used to calculate the wear rate. An 'Rt' type thermocouple was used to measure the temperature rise of the pin during the wear test.

The study found that the Titanium carbide (TiC) reinforcement did not exhibit good wettability with the copper metal matrix. Additionally, by increasing the percentage of reinforcement in the copper metal matrix composite (MMC), the density of the sintered composite was reduced. The researchers also investigated the effect of increasing the percentage of graphite in the composite on porosity and found that as the percentage of graphite increased, the porosity also increased. They also researched the formation of clusters of graphite due to the improper mixing of the mixture, which affected the microwave absorption, thereby influencing the depth of penetration of microwave and the heating process.

They conducted experiments to study how the Copper composite wears. When the hard counter surface abraded the copper matrix, it exposed hard Titanium carbide (TiC) particles on the worn surface. These particles helped to bear the normal load, reducing the load on the copper metal matrix composite. However, increasing the sliding speed caused the hard reinforced particles to fracture and pull out, leading to an increase in the wear rate. They found that increasing the quantity of Titanium carbide (TiC) in copper metal matrix composites made the composite harder, while increasing the content of graphite made the Copper metal matrix composites less hard. Also, increasing the normal load led to a higher coefficient of friction and wear rate. Due to the combined effect of both reinforcements, the wear rate decreased with increasing the content of Titanium carbide (TiC) and graphite.

Zhu Xiao et al. (2020) compared the microstructure and mechanical properties of Cu-graphite composite and cuprous oxide-graphite ($Cu_2O$-Gr) composite. The microscopic images of the Cu2O-graphite composite showed superior interfacial adhesion and homogeneous dispersion compared to the Cu-graphite composite. They found that the $Cu_2O$-graphite composite exhibited 1.5-1.6 times increase in hardness and a 50-100 MPa increase in compressive strength compared to the Cu-graphite composite.

In a study by Hu et al. (2016), the mechanical behaviours of ($B_4C$+Al3Ti)/Al hybrid composites developed using the two-step stir-casting technique were investigated. The study found that the hybrid composites showed improvements in elongation, tensile strength, and hardness by 21.6%, 41.8%, and 13.6% respectively, compared to composites without Al3Ti particles. The results suggested that Al3Ti particles not only acted as reinforcement but also facilitated the continuous development of the Titanium diboride ($TiB_2$) layer at the interfaces of the matrix and reinforcements. This developed layer prevented further reaction of boron carbide ($B_4C$) with liquid Al and led to better bonding between the Aluminium matrix and boron carbide ($B_4C$) reinforcements.

In a comprehensive investigation conducted by Haimin Ding et al. (2019), the process of creating a Cu-TiC composite was explored by introducing titanium and carbon black powder into molten copper. It was observed that at a specific temperature of 1200 °C, titanium underwent a reaction with carbon black, resulting in the formation of titanium carbide (TiC) within the melt. Interestingly, the study revealed that increasing the Ti/C ratio resulted in a more effective dispersion of the TiC particles within the composite.

Furthermore, the thermal properties of Cu-SiC composites synthesized through a powder metallurgy route were meticulously examined by K M Shu et al. in 2014 and M. Barmouz et al. in 2011. These studies involved the application of a Cu coating on silicon carbide (SiC) powder particles using an electroless plating process, which notably enhanced interfacial bonding and the homogeneous dispersion of silicon carbide (SiC) within the Cu matrix. Thorough thermal expansion tests, conducted within a temperature range of 50 to 500 °C, revealed intriguing characteristics, including a positive hysteresis behavior during the cooling process, which was speculated to be attributed to residual stress and favorable interfacial adhesion. Additionally, it was observed that the coefficient of thermal expansion exhibited a decreasing trend with an increase in the SiC content.

Morvan et al. (2019) conducted a study on the powder processing methodology (PPM) for producing a metal matrix composite using Graphite flakes (Grf) to reinforce Copper (Cu). The manufacturing process involved three main steps: Firstly, a reductive treatment of Grf powder to purify and enhance its quality. Secondly, the mixing of Cu and Grf powders using a Resonant Acoustic (RA) mixer. Finally, the composite powders were cold and hot-pressed. This process yielded an excellent thermal conductivity of up to 630 $W \cdot m^{-1} \cdot K^{-1}$ for Cu/40 vol.% Grf, achieved via the new powder processing methodology (PPM) and densification through vacuum hot-pressing.

## 2.7 Friction and Wear

### 2.7.1 Friction

Friction is the resistance encountered by one body when moving over another. It occurs due to the interaction of tiny surface irregularities called asperities. The frictional force is the sum of the resistance offered by all the individual asperity contact sites. There are three basic laws of friction:

1. Friction is directly proportional to the normal load.
2. Friction force is independent of the apparent area of contact between the mating surfaces.
3. Kinetic friction force is independent of sliding velocity once the motion starts.

Additionally, there are several theories of friction:

**The Adhesion theory** states that strong junctions are formed between precisely clean surfaces due to cold welding and adhesion without inter-diffusion or recrystallization of metal atoms. A force is needed to break these junctions to move one body over the other.

**The Asperity interlocking theory** says that when two surfaces are placed in contact with each other, they touch at discrete points known as asperities. The applied load is born by these asperities, and when sliding occurs, soft asperities deform under the load, leading to frictional resistance.

**The Molecular attraction theory** states that friction is due to molecular attraction, which works over short distances and discriminates between real and apparent contact areas.

**The Stick-slip Theory** assumes that one surface rests over the other at junctions, and sliding occurs due to tearing apart of these welds.

### 2.7.2 Wear

Wear refers to the gradual loss of material from a solid surface due to the relative motion between the contacting surfaces. This can result from both mechanical and chemical interactions between a solid, liquid, or gaseous substance and the solid material surface (G.E. Dieter et al., 1978). When metal matrix composites are used in sliding contact applications, they experience gradual deterioration. The contact surface can be intentional, such as the sliding contact between the piston and cylinder surface of an automobile engine, or unintentional, such as fretting in joints (A. Fischer et al., 2011).

When two mating surfaces are in close contact, an external shear force is necessary for sliding motion to occur. Initially, the surfaces resist the applied force, and this resistance increases until it reaches its maximum value, known as static friction force. Once the applied force exceeds the static frictional force, sliding motion takes place between the surfaces. As sliding motion continues, the resistance force slightly decreases, transitioning into kinetic friction force (A. R. Lansdown, 2015). The ratio of friction force to the normal force is known as the coefficient of friction. Therefore, for sliding contact applications, it is essential to minimize the coefficient of friction, a goal that can be achieved by introducing solid lubricant into a metal matrix composite. A lower coefficient of friction in the material may result in a reduced wear rate. Consequently, metal matrix composites reinforced with a harder phase or solid lubricant are well-suited for sliding contact applications (A.M. Kovalchenko et al., 2012). However, for certain applications, enhancing the coefficient of friction is crucial, such as in the case of brakes and clutches in automobiles.

#### 2.7.2.1 Types of Wear

The classification of material wear is based on operative mechanisms.

abrasive,
adhesive,
erosive,
fatigue, and
corrosive wear.

Adhesive wear occurs when micro-junctions form due to welding between the rough surfaces of two objects rubbing against each other. In other words, material transfer happens when two bodies slide or press against each other. The load applied to a body is supported by the rough surface. Because of the small contact area, the load on the rough surfaces is high enough to deform and adhere to each other, forming micro-joints. The movement of the bodies causes the joints to break, and the breakage occurs in the non-deformed area. Material transfer occurs in this way from the other object.

Archard (1953) provided an expression for adhesive wear loss. According to this expression, wear loss is directly proportional to the applied load and inversely proportional to the hardness of the material. It can be expressed as:

$$W = \frac{k\,L}{H} \tag{2.1}$$

Where:

W = wear rate

L = applied load

H = hardness of the material

k = wear coefficient

**Abrasive wear** is a result of material loss caused by the action of hard protrusions forced against softer materials. The extent of wear depends on the type of contact and the contact environment. When two rubbing parts are involved in the friction process, it is termed as two-body wear. In this mode of abrasive wear, the asperities of the hard body cause material loss from the soft body during sliding. On the other hand, if material loss occurs due to the entrapment of hard particles between two mating surfaces, it is referred to as third-body abrasion.

**Erosive wear** occurs when material loss takes place from a solid body due to the impingement of fluid or solid particles. In this type of wear, particles exert mechanical action on the solid surface through repeated deformations and cutting, causing pits and subsurface deformation.

Particles may also detach from the surface due to cyclic crack growth that occurs from either superficial or subsurface microcracks. This type of material loss is known as **fatigue wear**. **Fretting wear**, on the other hand, is the result of material loss due to the cyclic rubbing of two surfaces at very low amplitudes. It can lead to the formation of cracks on the surface and eventually result in catastrophic failure.

Additionally, wear due to corrosion or oxidation during sliding in the presence of a corroding medium is known as **corrosive wear**. It can occur during dry sliding or in the presence of certain gases. Corrosive wear can also arise from the excessive use of anti-wear agents or other chemical interactions. Moreover, harsh environmental conditions such as high temperatures, exposure to seawater, and highly acidic or basic mediums can also contribute to this type of wear**.**

### 2.8 Tribological Potential of Copper (Cu)-Graphite (Gr) hybrid composite

Rajkumar et al. (2011) developed copper–titanium carbide (TiC) (5–15 vol%)–graphite (5–10 vol%) hybrid composites utilizing an innovative microwave processing technique. The evaluation of their tribological behaviour was conducted through a pin-on-disc apparatus under applied normal loads of 12–48 N and sliding velocities ranging from 1.25 m/s to 2.51 m/s. The investigations revealed an augmentation in wear resistance and a reduction in the friction coefficient, attributed primarily to the formation of a homogeneous, mixed-layer surface, particularly pronounced in composites with a higher volume of graphite. This improvement in tribological characteristics is further explored through detailed analyses of the wear surfaces and debris, aiming to elucidate the underlying wear mechanisms.

The study also observes a correlation between the graphite content and the mechanical properties of the composites, noting a decrement in hardness as the graphite volume increases. Additionally, both the hybrid composites and the monolithic copper specimens exhibited an increased wear rate and friction coefficient with an upward shift in the applied normal load.

However, the hybrid composites consistently outperformed the unreinforced copper in both aspects, implying the beneficial role of titanium carbide (TiC) and graphite reinforcements in wear resistance. Crucially, the frictional behavior of the hybrid composites was significantly influenced by the graphite content, with an increase in graphite percentage correlating with a reduced coefficient of friction. The presence of a mixed layer, especially prevalent in composites with higher graphite volumes, was determined to be a key factor in enhancing the tribological performance, suggesting that the microstructural features induced by specific reinforcement ratios play a pivotal role in the material's overall wear behavior.

M. Grandin et al. (2018) explored the tribological characteristics of copper-graphite composites, focusing on parameters such as friction, wear rate, and electrical contact resistance. The investigation revealed that incorporating graphite into the composite significantly reduces both the coefficient of friction and the wear rate. However, the influence of graphite content on the coefficient of friction was relatively minor. Conversely, the inclusion of graphite was found to result in an elevated contact resistance. Experimental conditions included scenarios both with and without electrical current. Noteworthy findings include an increase in the friction coefficient and a decrease in wear rate under conditions of current conduction. This research contributes to the understanding of the complex interplay between material composition and tribological performance in electrically conductive composites.

Behnamian et al. (2022) investigated the tribological performance of composites reinforced with multi-walled carbon nanotubes (MWCNTs) and boron carbide ($B_4C$). They found that samples with MWCNTs exhibited lower friction coefficients under low loading compared to those with varying $B_4C$ contents. Wear rates decreased with MWCNT additions up to 0.5 wt% but increased with higher $B_4C$ content, indicating a trade-off between hardness and toughness.

At 40 N, abrasion and plastic deformation were the dominant wear mechanisms, while delamination and oxidation prevailed at 80 N due to higher surface fatigue and oxidation. MWCNTs enhanced wear resistance by mitigating crack propagation and improving load transfer. The composite with 10 wt% $B_4C$ and 0.5 wt% MWCNTs demonstrated the best wear resistance, benefiting from the combined effects of $B_4C$'s hardness and MWCNTs' toughening ability.

Tasci et al. (2023) investigated the mechanical and tribological properties of nano $B_4C$-reinforced WE43 magnesium alloy composites produced through the hot-pressing method. Composite samples were prepared with varying nano $B_4C$ contents (0.25, 0.5, 1, and 2 wt%) by mixing powders at 300 rpm for 4 hours, followed by pressing under 350 MPa at 525°C for 90 minutes. X-ray diffraction (XRD), optical microscopy, and SEM-EDS were employed for microstructural characterization.

Mechanical properties, including microhardness, transverse rupture strength, and wear behavior, were evaluated. The results indicated that the WE43 composite with 2 wt% nano $B_4C$ exhibited the highest hardness, transverse rupture strength, and the lowest wear rate. The addition of nano $B_4C$ particles significantly improved wear resistance and reduced volume losses. The 2 wt% nano $B_4C$ composite had the lowest specific wear rate, while the highest wear rate was observed in the unreinforced WE43 alloy.

K. Rajkumar et.al., (2011) made tribological assessment of copper-coated carbon nanotube (CNT) composites. The research involved the integration of 5% to 20% volume fractions of copper-coated CNTs with copper metal powder, followed by consolidation using microwave sintering. The study revealed that enhancements in mechanical and wear resistance properties were optimal at a CNT volume fraction of up to 15%. Beyond this threshold, the benefits diminished due to the agglomeration of CNTs which impaired the composite's uniformity and, consequently, its mechanical integrity. The incorporation of CNTs into the copper matrix resulted in a notable reduction in both the coefficient of friction and wear rate, attributed primarily to the formation of a carbonaceous lubricating film at the interface. This self-lubricating mechanism facilitated by the dispersed CNTs was effective in minimizing frictional heating and wear. At lower CNT concentrations, wear was predominantly governed by plastic deformation mechanisms, whereas at higher concentrations, flake formation and spalling became prevalent. The study underscored the significance of optimizing the CNT volume fraction to leverage the tribological benefits while mitigating adverse agglomeration effects. This research contributes valuable insights into the tribological optimization of metal matrix composites augmented with carbon nanotubes, offering promising applications in enhancing the durability and performance of engineering materials.

Rajkumar et al. (2013) conducted a study on the impact of graphite particle size, normal load, sliding speed, and spatial distribution of graphite in the microwave-sintered metal matrix on the wear rate and coefficient of friction. They used a pin-on-disc tribometer to measure the wear rate and coefficient of friction. Their research revealed that the graphite particle size affects the wear resistance and coefficient of friction. The Copper-nongraphite composite exhibited a lower coefficient of friction and higher wear resistance than the Cu-graphite composite. Nano graphite present in the copper matrix has a higher surface area, resulting in the formation of a high adherent graphite tribo-layer at the point of contact. This leads to a lower coefficient of friction and higher wear resistance compared to graphite particles of micrometer size. The formation of a graphite layer reduces the sub-surface deformation of the metal matrix composite, thereby reducing the friction force. The study also found that Copper-nano graphite composites have superior physical and mechanical properties compared to the copper-graphite composite of the same volume percentage. However, when the volume content of Nano graphite in copper metal matrix composites reached 20%, the physical and mechanical properties deteriorated due to the formation of graphite nanoparticle clusters. The researchers observed that the maximum content of Nano graphite reinforcement in copper metal matrix composites is limited to 15% by volume. The Copper-Nano graphite composite forms a thick graphite layer at the point of contact, which enables it to withstand higher loads and exhibit lower coefficients of friction compared to the copper graphite composite. Additionally, the smaller size asperities of the Copper-Nano graphite composite, as compared to the copper-graphite composite, leave less space between the asperities, which is filled by Nano graphite particles during wear. This filled Nano graphite particle layer produces a more continuous graphite layer, leading to a reduction in the coefficient of friction.

Moustafa et al. (2002) experimentally investigate that three wear regimes are observed during testing pure copper compacts, Copper (Cu)-coated and uncoated graphite composites, namely, low, mild, and severe. The sintered copper compacts exhibit the highest wear rates and they withstand up to the lowest normal loads. The wear rates at each transition regime of either low/mild or mild/severe for both coated and uncoated graphite composites of the same graphite content are very close to each other. However, the transition loads of Cu-coated graphite composites are much higher than those of uncoated graphite composites, at each transition regime for the same graphite content.

The coefficient of frictions of Cu-coated graphite composites are the lowest, followed by uncoated graphite composites of the same graphite contents, whereas the copper compacts show the highest coefficient of friction. Generally, the higher graphite content in a composite of either Cu-coated or uncoated graphite composites, the lower is the coefficient of friction. The involved wear mechanisms of pure copper at low, mild and severe wear regimes could be oxidative-dominated, delamination, and seizure wear mechanisms, respectively. However, both Cu-coated and uncoated graphite composites exhibited the same wear mechanisms, namely, oxidation induced delamination, high strained delamination, and sub-surface delamination.

In a study conducted by Gautam et al. (2008), the tribological behavior of cast Cu-4 wt. % Cr4 wt. % SiC composites was investigated. This was done by performing dry sliding wear tests on a pin-on-disc setup against 4615 steels. The tests were carried out at loads ranging from 10 to 40 N, with a fixed sliding speed of 0.786 m/s over a total sliding distance of 1398 m. The study reported an increase in wear rate and a decrease in the coefficient of friction with increasing load. However, the composites exhibited a lower coefficient of friction and wear rate compared to pure copper. This was attributed to the presence of hard carbide particles, which improved the hardness of the composites and reduced the real area of contact. Bagheri et al., (2016) investigated the effects of altering the concentration of titanium carbide (TiC) particles within a copper matrix composite on its mechanical and electrical properties. The methodology employed involved ball milling of copper and titanium powders to the desired concentration for a duration of 60 hours under an inert gas atmosphere, followed by the addition of graphite powders, which were further milled for an additional 10 hours. Subsequent compaction and sintering processes were executed at a temperature of 900°C. The research findings indicated a notable enhancement in both hardness and wear resistance of the sintered composites proportional to the increase in titanium carbide (TiC) particle concentration, whilst concurrently observing a significant reduction in electrical conductivity.

The analysis extended to consider the aggregate influence of operational parameters on the wear rate of the composite material, underscoring the necessity of these parameters' evaluation for the minimization of wear rate. This is pivotal for augmenting the composites' durability, averting abrupt failures, realizing economic efficiencies, and ensuring optimal utilization of the fabricated composites. A combination of mathematical and statistical methodologies, inclusive of Response Surface Methodology (RSM), Taguchi methods, Artificial Neural Networks (ANN), Grey Rational Analysis, and the Design Expert software, have been applied by researchers to efficaciously optimize these wear parameters for maximal benefits. Notably, (RSM) emerges as a critical multivariate technique for the scrutiny and optimization of wear properties of composites, facilitating the fine-tuning of input operational parameters to achieve optimal material performance. This might encompass the dual objectives of wear minimization and the modulation of the coefficient of friction to meet specific criteria. Employing a polynomial equation to model the correlation between these parameters based on statistical data points, (RSM) provides a robust framework for this purpose, Ponugoti et al., (2018) advanced this line of inquiry by evaluating the wear performance of an Al-based hybrid composite through the application of (RSM) and multi-objective optimization techniques, aiming to refine the variables impacting wear properties.

Miranda-López et al. (2021) conducted a study on the wear behavior of three different composites containing graphite at volumes of 1%, 3%, and 5%. These composites accounted for 60% of the total volume of reinforcement. The composites were created by infiltrating liquid copper into porous titanium carbide (TiC)-graphite (Gr) preforms, resulting in materials with good bonding between the matrix and reinforcement, uniform distribution of the reinforcing particles, and no presence of second phases. The wear rate of the pure copper matrix was found to be up to four times higher than that of the composites under maximum wear conditions. In all materials, the wear rate increased with applied load and sliding velocity. A higher graphite content led to a lower wear rate, causing the wear mechanism of pure copper to change to abrasion and delamination with tribo chemical products forming a mechanically mixed layer on the surfaces of the Cu/TiC and Cu/TiC-Gr composites. This dynamic abrasion deforms the copper matrix, exposing micro-areas of contact to the oxidizing atmosphere, which intensifies the reaction processes of the exposed copper surfaces.

Ramesh et al. (2009), delved into the influence of different graphite contents on the tribological characteristics of the copper (Cu)-silicon carbide (SiC) composite. To perform this, they crafted specimens with varying volumes of graphite (3%, 7%, and 10%) in the Cu-10SiC composite.

The investigation unveiled that the Cu-10SiC composite displayed remarkable mechanical strength and wear resistance when the graphite content was low. As the graphite content increased, the mechanical properties of the Cu-10SiC-Gr composite diminished due to the soft nature of graphite. However, the addition of graphite had a substantial effect on reducing the coefficient of friction and enhancing the wear resistance of the Cu-10SiC-Gr composite. Furthermore, the study found that the coefficient of friction in the Cu-10SiC-Gr composite consistently decreased with increasing applied load until it reached equilibrium at a 30 N load. Beyond this point, the friction coefficient was found to remain unaffected by the graphite content for loads exceeding 30 N. Conversely, the wear rate of the composite increased under higher load conditions.

Haijun Zhao et. al., (2007) suggested that using the electroforming technique to synthesize Copper-graphite could overcome the drawbacks associated with hot pressing. They conducted tribological tests using a ring on a disc wear tester, and found that a higher graphite content significantly improves wear resistance. The primary wear mechanisms identified were adhesive and delaminated wear. The Copper (Cu)-graphite composite also shows promise for marine applications.

The study focused on evaluating the corrosion performance of the Cu-graphite composite. Corrosion tests were conducted using electrochemical impedance spectroscopy (EIS) in a 3electrode cell, and the specimens were immersed in a 3.5% NaCl solution for 24 hours and 120 hours. It is possible for Copper Oxide (CuO) to form, which increases the resistance to adsorption. Corrosion marks were observed at the grain boundaries and defects within the Cu oxide film, rather than at the Cu/graphite interface. The improved corrosion resistance can be attributed to the favorable interfacial adhesion and uniform distribution of components.

Qu et al. (2022) developed an innovative method to prevent the clumping of graphene in composites. This method involves using pulse electrodeposition to introduce copper into a 3D network of laser-induced graphene, followed by consolidating the matrix through spark plasma sintering. This process hardly disrupts the continuous 3D structure of graphene, ensuring that the graphene is evenly distributed in the copper matrix. As a result, the wear resistance of the composites was enhanced by more than three times compared to pure copper. It is also notable that the thermal and electrical conductivity of the composites are not compromised due to the pathways created by the intact graphene network.

### 2.9 Boron carbide ($B_4C$) and Silicon carbide (SiC) as reinforcement

Bommana et al. (2022) investigated the impact of different weight percentages of individual reinforcements (SiC and $B_4C$) on the mechanical properties of a specific composition (6 wt.%) of AA 6061 hybrid composite. The study aimed to understand how the hard particle reinforcements affect the strength and elongation behavior of the hybrid composite.

The hardness (BHN) value of the hybrid composite (AA6061 + 4% $B_4C$ + 2% SiC) showed a 60% improvement compared to the AA6061 base alloy. This increase in hardness is attributed to the presence of hard $B_4C$ particles within the matrix. Furthermore, the composite with an equal fraction of reinforcement (3% $B_4C$ and 3% SiC) exhibited the highest ultimate tensile strength (UTS) and yield strength (YS) values compared to other compositions and the base alloy.

Celik et al. (2017) conducted a study on the wear behaviors of aluminum matrix composites reinforced with different rates of $B_4C$ produced by the powder metallurgy method. They investigated the effects of using pure aluminum, as well as mixtures containing 4%, 8%, 12%, and 16% $B_4C$. The powders used had a purity of 99.9% and sizes ranging from 25–44 µm. After pressing the mixtures under 350 MPa, they were sintered for 90 minutes at 580°C in an atmospheric environment. The study found that as the $B_4C$ particle reinforcement ratio increased, there was also an increase in the hardness value. Additionally, the increasing reinforcement rate contributed to a reduction in weight loss. Furthermore, the coefficient of friction decreased as the reinforcement ratio increased.

Prajapati et al. (2019) conducted a study on copper (Cu)–$B_4C$ composites with different weight percentages of $B_4C$ (5%, 10%, and 15%). They manufactured these composites by cold powder compaction followed by conventional sintering at 900°C for 1 hour under an argon atmosphere. The research revealed that the $B_4C$ particles are uniformly dispersed in the copper matrix, and there is good compatibility between $B_4C$ and Cu. Analysis using FESEM showed a clean interface between the Cu matrix and $B_4C$, with no interfacial product formation. The study also examined the impact of $B_4C$ particles and their weight fraction on microstructure, mechanical properties, and electrical conductivity. The results demonstrated that the hardness value increases with the addition of $B_4C$ to pure Cu, and the compressive strength is improved with the addition of $B_4C$ powder to the Cu matrix.

Ramadoss et al. (2020) conducted a study on the synthesis of $B_4C$ and boron nitride (BN) reinforced Al7075 hybrid composites using the stir casting method. They varied the weight percentage of $B_4C$ (3%, 6%, and 9%) while keeping the percentage of boron nitride (BN) constant at 3%, with the aim of suitability for marine applications. They critically examined the morphology of the synthesized aluminum hybrid composite and the distribution of reinforced particles in detail using optical microscopy. The study found that the addition of $B_4C$ and BN reinforcements increased the strength of the hybrid composites by 22%. Additionally, the corrosion rate decreased by 18.5% when increasing the boron carbide content from 3% to 6%, and by 22.4% when increasing it from 6% to 9%. The presence of harder reinforcements in the matrix led to increased mechanical properties such as hardness, tensile strength, and compressive properties, compared to the monolithic Al7075 aluminium alloy.

Siddesh Kumar et al. (2020) conducted a study on the high-temperature wear behavior of metal matrix composites. They investigated Al2219 (base Alloy), Al2219+2%n- $B_4C$ (mono), and

Al2219+2%n- $B_4C$ +2%$MoS_2$ (hybrid) composites at different temperature conditions. The Al2219/2%n- $B_4C$ and Al2219/2%n- $B_4C$ /2%$MoS_2$ composites were prepared using a liquid metallurgical (stir casting) technique and high-temperature wear tests were performed on a pin-on-disc wear testing machine.

The study found that the wear rate of Al2219+2%n- $B_4C$ and Al2219+2%n- $B_4C$ +2%$MoS_2$ composites gradually decreases with increasing temperature (50 °C–100 °C) compared to the Al2219 matrix. This effect is primarily due to the development of glazing layers and oxide films on the sliding surface at higher temperatures. During sliding, the formation of these layers prevents direct metal-to-metal contact, reducing wear.

Uthayakumar et al. (2013) conducted a research study on the dry sliding wear behavior of aluminum reinforced with 5% SiC and 5% $B_4C$ hybrid composite using a pin-on-disc tribometer. They evaluated the wear performance of the hybrid composites under loads ranging from 20 to 100 N and sliding velocities from 1 to 5 m/s. The researchers carried out detailed metallurgical examination and energy dispersive analysis to assess the effect of SiC and $B_4C$ particles on the wear mechanisms. They used the Focused Ion Beam (FIB) technique to characterize the tribo layers formed at the worn surfaces of the composites.

The experimental results indicated that the hybrid composites retained their wear resistance properties up to 60 N and sliding speeds ranging from 1 to 4 m/s. The enhancement of wear resistance with a small amount of SiC and $B_4C$ was attributed to the cooperative effect of the reinforcement particles. Additionally, $B_4C$ particles were found to potentially produce a boron oxide-rich tribo layer, which reduced wear progression and the coefficient of friction.

In a study by Wu et al. (2023), a copper-based composite reinforced by dual ceramic particles ($B_4C$ –TiC) was prepared using a powder metallurgy route. They investigated the combined strengthening effect of $B_4C$ and TiC on the composite's tribological behavior and wear mechanisms. The results showed that a higher content of TiC (less than 5%) in $B_4C$ –TiC led to greater performance improvement. Specifically, a TiC/ $B_4C$ ratio of 5:3 resulted in exceptional mechanical and thermal performance for the copper-based composite. However, there were differences in tribological behavior: the copper-based composite with a TiC/ $B_4C$ 3:5 ratio achieved a more continuous tribo-film, higher friction stability coefficient, and lower wear rate. The study also found that the effects of the dual ceramic particles varied with changes in speed: at 3000 rpm, TiC and $B_4C$ similarly improved the friction performance, while at 4500 rpm, TiC was more effective than $B_4C$. At 6000 rpm, $B_4C$ played a major role in the tribological behavior due to the generation of $B_2O_3$ tribo-film.

Tian Yu-nan et al. (2019) conducted a study on the impact of varying amounts of $B_4C$ particles on composite properties. They used powder metallurgy to add graphite and boron carbide $B_4C$ particles to copper matrix composites, creating a new composite-reinforced and lubricated system. The addition of $B_4C$ particles effectively reduced composite porosity, improved hardness and compressive strength, and reduced wear rate. However, when the $B_4C$ particle content reached 3 wt %, the composite showed the lowest wear rate. As the amount of $B_4C$ particles increased, composite porosity also increased, disrupting matrix continuity and resulting in a significant increase in wear capacity.

Arabinda M. et. al., (2015), the researchers investigated the synergistic effects of incorporating graphite and silicon carbide (SiC) into a copper matrix during the fabrication of Cu–graphite–SiC hybrid metal matrix composites via the powder metallurgy method. The experimental procedure involved the cold compaction of a composite powder mixture followed by conventional sintering in a tubular furnace at 900°C for a duration of 1 hour under an argon atmosphere. This meticulous approach was chosen to unravel the examine the mechanical and electrical properties of the resultant composites.

The study yielded valuable insights into the mechanical behavior of the composites. It was revealed that the hardness of the composites displayed a discernible pattern, decreasing with an increase in graphite content, while exhibiting an augmented hardness with higher SiC content. Furthermore, the size of the SiC particles played a significant role, with composites containing fine SiC particles demonstrating superior hardness compared to those with coarse particles. The study highlighted the attainment of a maximum Vickers hardness value of 75 for a specific composite formulation comprising 1 volume percent (vol. %) graphite and 10 weight percent (wt. %) SiC.

Moreover, the investigation delved into the electrical conductivity of the composites, electrical conductivity decreased with an increase in both graphite and SiC content. Notably, composites containing coarse SiC particles exhibited markedly higher electrical conductivity compared to those incorporating fine SiC particles.

M. Melwin J. S. et al. (2021) synthesized copper-based composites using Cu and SiC powders through the Powder Metallurgy (PM) technique. They used a 400 kN hydraulic press to sinter the composites at 900 °C in a muffle furnace for 4 hours. Scanning Electron Microscope (SEM) analysis of the ball-milled powders and sintered samples showed uniform dispersal of SiC in the Cu. The addition of SiC improved the hardness and compressive strength (CS) of the composite. Salt spray corrosion testing revealed that the composite containing 10 wt.% of SiC exhibited improved corrosion resistance. The sample containing 10 wt.% of SiC had the highest CS, while the one containing 15 wt.% of SiC exhibited the highest hardness. As the wt.% of SiC in the Cu matrix increased, the density decreased and the % porosity increased.

Nalin S. et. al. (2018), a new composite of Cu–SiC was fabricated using powder metallurgy technique at a sintering temperature of 950°C. Different compositions of the composite were tested using a pin-on-disc tribometer to determine wear and coefficient of friction. The results showed that adding 20% of SiC increased the hardness and tensile strength of the samples by 48% and 24% respectively. The study also found that the addition of SiC reduced wear by 45% to 77% and friction by 25% to 44%, demonstrating that the SiC reinforcement enhances wear resistance and reduces the coefficient of friction in the Cu–SiC composite. The experimental results also indicated the presence of oxidative wear, abrasive wear, and a mechanically mixed layer when the composite was tested against a steel disc.

In a study by Yongzhong Z. et. al. (2003), researchers investigated the friction behavior and wear mechanisms of copper matrix composites reinforced with SiC and graphite particles. They found that hybrid composites demonstrated better tribological properties compared to SiC/Cu composites. The impact of graphite on wear behavior depended on the applied load. When tested at low loads, the wear rates of both the components in the hybrid composites were lower than that of the SiC/Cu composite. This was attributed to the formation of a graphite-rich mechanically mixed layer (MML) on the worn surface, which contributed to the good antifriction properties. However, at high normal loads, the incorporation of graphite particles led to a deterioration of mechanical properties, resulting in delamination wear becoming the predominant wear mechanism. This, in turn, increased the wear rate of the tribo-system and friction coefficient due to the large wear debris trapped by the contacting surfaces, thus leading to a three-body wear mechanism. Therefore, the researchers concluded that when the graphite content was high enough to induce delamination at any given load, the hybrid composites did not exhibit superiority in friction and wear. They also highlighted the importance of a continuous supply of graphite to the tribo-surface for the formation of the graphite-rich mechanical mixed layer (MML) and to exert its anti-friction properties.

## 2.10 The Impact of Different Parameters on Copper (Cu)-graphite (Gr) Composites

### 2.10.1 Impact of sintering techniques

Rajkumar et al. (2009) made a novel approach was taken to develop copper-graphite metal matrix composites, specially designed for use in electrical sliding contact applications. This development was achieved through the employment of microwave hybrid heating technology, operating at a frequency of 2.45 GHz and a power output of 3.2 kW. The process successfully sintered copper-graphite composites without the occurrence of any cracks, marking a significant achievement in material fabrication. Furthermore, the study proposed a theoretical model specifically tailored to understand the mechanisms of microwave sintering. This model highlights the unique benefits of microwave heating in achieving a microstructure characterized by finer details, including smaller and more uniformly rounded pores. Such a microstructural enhancement is directly attributed to the application of microwave energy, resulting in improved performance attributes of the metal matrix composite. This study, therefore, not only demonstrates a successful fabrication process for copper-graphite composites but also provides a fundamental insight into the potential impact of microwave sintering on material properties.

In a study conducted by Reddy et al. (2018), the researchers explored the impact of graphite and other reinforcement materials such as boron carbide ($B_4C$), alumina ($Al_2O_3$), and silicon carbide (SiC) on a copper (Cu) metal matrix, which was fabricated using the powder metallurgy method. The study focused on analyzing the mechanical and tribological properties at a compacting pressure of 700 MPa, while varying the sintering temperatures within the range of 900–950 °C. It was found that the incorporation of 5% SiC as reinforcement resulted in the lowest wear rate of 3.226 × 10−4 mm3/N-m when compared to $Al_2O_3$ and $B_4C$. The density was observed to be directly proportional to the sintering temperature. The study also revealed that the hardness of the hybrid composite increased with the rise in sintering temperature, with a consistent weight percentage of the reinforcing material. This increase in hardness was attributed to the grain refinement, which rendered the grains harder than their coarse counterparts. Notably, the hardness peaked by 89, recorded at 950 °C for Cu-1.5%Gr-5%SiC. Conversely, an increase in the weight percentage of graphite led to a decrease in the hardness of the hybrid composite due to the presence of graphite. Furthermore, a reduction in the graphite content was observed to enhance the compressive strength of the hybrid composite, as graphite functions as a soft reinforcement material. The study also demonstrated that higher sintering temperatures contributed to the improved compressive strength, primarily owing to the grain refinement. The coefficient of friction exhibited a decreasing trend, reaching its lowest value of 0.2 at 950 °C for 3.5% graphite reinforcement. This behavior was attributed to the nature of graphite, which exhibits soft and lubricating properties. Additionally, the coefficient of friction was found to decrease as the graphite content increased, mainly due to the softening of the hybrid composite at higher sintering temperatures. The microstructure analysis revealed a homogeneous distribution of reinforcement at the highest temperature.

K. Dash et al. (2012) produced a Cu-$Al_2O_3$ composite using both conventional sintering and spark plasma sintering methods. The research examined the impact of different sintering methods, such as sintering under different atmospheres ($N_2$, $H_2$, and Ar), as well as SPS sintering, on the adhesion and distribution of alumina particles in the Cu matrix. The study found that the highest hardness value (80 HV) was achieved for the Cu with 15 vol. % $Al_2O_3$ composites. The best mechanical properties were observed for the Cu-15$Al_2O_3$ composite when sintered in an $H_2$ atmosphere using conventional powder metallurgy. However, the Cu-5$Al_2O_3$ composite displayed the highest mechanical properties when fabricated using the spark plasma sintering technique. The study also emphasized that the SPS technique enhances interfacial adhesion and surface integrity, leading to significantly improved mechanical properties.

### 2.10.2 Impact of Milling

Dixit et al. (2019), developed flake composite particles using a process called controlled mechanical alloying (MA), followed by lamination of these particles over the surface of refined granules. This encapsulation process was shown to promote strong interfacial bonding among the composite constituents during sintering. The study's results revealed that the composite with 10% granules in Cu-10Gr demonstrated superior mechanical properties, while the composite with 15% granules in Cu-10Gr exhibited the highest electrical conductivity. As a result, the findings indicate that the composite with 10% granules in Cu-10Gr is more suitable for applications requiring robust mechanical properties, whereas the composition with 15% granules in Cu-10Gr is better suited for applications where high electrical conductivity is desired.

C. P. Samal et al. (2013), made an investigation was carried out to analyze the impact of milling and sintering temperatures on the mechanical properties of Cu-graphite composite. The study utilized both conventional and spark plasma sintering methods under different sintering atmospheres. The researchers observed that the composite initially exhibited a flake shape after 4 hours of milling, which then transformed into an irregular shape after 20 hours of milling. It was noted that mechanical properties, such as hardness, compressive strength, and flexural strength, showed an increasing trend with prolonged milling time.

The study further revealed that the maximum mechanical property values were achieved through conventional sintering at 900°C in an argon atmosphere. Interestingly, the researchers also found that spark plasma sintering at 700°C resulted in improved mechanical properties when compared to conventional sintering. This detailed analysis sheds light on the nuanced effects of milling and sintering parameters on the mechanical properties of the Cu-graphite composite, providing valuable insights for further research and industrial applications.

C. Suryanarayana (2001) conducted a comprehensive review of the mechanical alloying (MA) process and its various parameters for metal powders. Mechanical alloying is a technique that involves solid-state blending, where powder particles repeatedly undergo processes, such as flattening, fracture, cold welding, and re-welding. The study extensively discussed milling parameters, including processing time, temperature, processing control agent, ball to powder weight ratio, and ball diameter.

During mechanical alloying, powder particles experience plastic deformation due to high-energy collisions, leading to particle fracture and work hardening. Initially, this deformation causes an increase in powder particle size. However, continuous collisions can result in fatigue failure of powder particles, leading to the formation 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 lead to excessive work hardening of the composite powder particles.

### 2.11 Formulation of the Problem

Based on the review of the literature, it is evident that there is a lack of research on the friction and wear behavior of copper-based hybrid composites containing graphite (Gr) and boron carbide($B_4C$) despite their excellent lubricating properties and hardening capabilities. Many researchers have focused on incorporating graphite into the copper matrix to expand the application of copper material in tribological areas. Cu-graphite composites are widely used in sliding contact, bushing, and bearing applications. M. Grandin et al. (2018) studied the tribological characteristics of a Copper-graphite composite and found that the addition of graphite content notably decreased both the coefficient of friction and wear rate. Kumar et al. (2018) used a powder metallurgy approach to produce copper-graphite composites and found that the composite with 5% graphite exhibited the highest compressive strength, while wear resistance improved with increased graphite content. However, higher graphite content resulted in poor wettability of Cu and graphite, reducing mechanical properties. To address this, the addition of $B_4C$ particles as a reinforcement may enhance both the mechanical and tribological properties of the composite. Limited research is available on the mechanical and tribological performance of Copper-Graphite- $B_4C$ composites and no studies have been conducted on the tribological properties of these composites under lubrication conditions.

It is also observed that a combination of solid lubricants, such as Graphite, may synergistically reduce friction at the interface and provide effective lubrication over a range of working conditions like load, speed, and temperature. The composites containing a fixed amount of Gr and $B_4C$ can be synthesized at different sintering temperatures to determine the optimum temperature based on an examination of their mechanical properties and tribological performance. Copper-based composites with different contents of Gr and $B_4C$ can then be prepared at this optimized sintering temperature, and their friction and wear characteristics can be evaluated at different working conditions to explore the effect of reinforcement content on the coefficient of friction and wear rate. The study aims to establish the prevailing mechanisms of wear under the conditions used in the investigation for this new class of composites.

### 2.12 Objectives of the current study:

The objective of this study is to develop Copper-Graphite-boron carbide ($B_4C$) and Copper-Graphite-silicon carbide (SiC) composites with superior tribological performance for relevant applications. To achieve this objective, a comprehensive methodology has been established:

1) Synthesis of Copper-Gr-$B_4C$ and Copper-Gr-SiC composites incorporating varying weight percentages (wt.%) of Graphite (Gr), boron carbide($B_4C$) and silicon carbide (SiC) particulates via the powder metallurgy method.
2) Microstructural analysis of both the pure Copper and the composite materials to investigate phase morphology, particle size distribution, and the dispersion state of the reinforcing agents within the Copper metal matrix, and to elucidate their influence on the composite's tribological characteristics.
3) Evaluation of the effect of Gr, SiC, and $B_4C$ particulate reinforcement on the mechanical properties of the composites under standard atmospheric conditions.
4) Investigation into the role of various operational parameters, including sliding distance, sliding velocity, applied load, and the wt.% of Gr, SiC, and $B_4C$, on the tribological

behavior of the Copper-Gr-$B_4C$ and Copper-Gr-SiC composites under dry sliding conditions.

5) Characterization of the wear mechanisms through analysis of the worn surfaces, utilizing advanced analytical techniques such as Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and Atomic Force Microscopy (AFM), to derive insights into the prevalent wear processes.

This methodology is crucial for understanding the multifaceted interactions between the composite materials and their operational environments, thereby facilitating the optimization of their tribological performance.