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Advancements in Copper Metal Matrix Composites: A Review of Powder Metallurgy Processing Characterization and Properties

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Abstract

In recent times, Copper Metal Matrix Composites (Cu-MMCs) are gaining considerable interest among engineering applications as these find usage in electrical, thermal management and structural components used in automotive, aerospace and electronics industries. This is due to the excellent mechanical strength, corrosion resistance, electrical and thermal conductivity exhibited by the composite. The Powder Metallurgy (PM) method is widely adopted to produce the Cu-MMCs where parameters such as particle size, reinforcement distribution and microstructure can be well controlled and reduced defect incorporation is ensured. The reinforcements widely used are ceramic (SiC, Al_2O_3, TiC, B_4C) and carbon-based (Graphite, CNT, graphene). The Cu-MMCs are characterized by FESEM, EDX, XRD, FTIR and TGA/DSC and their Hardness, Compressive Strength, Electrical Conductivity, wear and Corrosion Resistance is assessed to understand the correlation of processing, microstructure and performance. Key challenges lie in uniform distribution of reinforcements, at interface bonding and a suitable combination between the mechanical and electrical performance while research is needed on optimizing processing and usage of hybrid reinforcements in future to develop high-performance composite.

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1. Introduction

Metal Matrix Composites (MMCs) are a group of engineered materials that synergize the properties of metallic matrix and reinforcement phase like ceramics or carbon-based particles. When ceramic particles are reinforced in metallic matrix, the developed composite possesses enhanced mechanical strength, stiffness, dimensional stability and wear resistance compared to that of monolithic metal [1]. Amongst metal matrix composites, the Cu-MMCs have been the subject of many research and industrial interests due to its inherent properties such as higher electrical and thermal conductivity, ductility and inherent resistance against corrosion [2]. Despite this, poor hardness, tribological performance and insufficient strength of pure copper restrict its use in stress induced and high temperature components. Therefore, to overcome this limitation, reinforcements were added into copper matrix which include silicon carbide (SiC), alumina (Al_2O_3,), titanium carbide (TiC) and boron carbide (B_4C)) and carbon-based particles such as graphite, carbon nanotubes (CNT) and graphene to impart higher hardness, chemical and thermal stability, self-lubricating property and improved wear performance [3]. Amongst the various methods developed to produce composites, powder metallurgy (PM) stands out as an effective and economical method for producing Cu-MMCs by yielding accurate control of particle size distribution and composition with minimal oxidation and segregation in the system. Also, this method can produce components to near net shapes with uniform microstructure at low sintering temperature when compared with the casting process [4]. This review mainly focuses on the recent progresses achieved in producing the powder metallurgy-based copper matrix composites and the effect of processing parameters, different type of reinforcements, microstructure development, mechanical, electrical and tribological properties on them. Novel aspects of Cu-MMCs were studied providing the composite manufacture methods, characterization techniques and the performance analysis in a comprehensive aspect. In contrast to most prior reviews that only separately consider either reinforcement effects or mechanical behavior, this paper establishes relationships between powder metallurgy process parameters, reinforcement selections, advanced characterization methods, and functional properties of copper-based composites. The paper also systematically correlates the 4 stages of powder metallurgy (powder preparation, blending, compaction and sintering), microstructure evolution as an outcome of those processes and the mechanical, thermal and electrical response of those final copper-based composites providing a clear processing-structure-property relationship. Reinforcement selections for Cu-MMCs as ceramic type (SiC, Al_2O_3, TiC, B_4C) or carbon type (graphite, carbon nanotubes or graphene) are both discussed with focus on the benefits of performing with both types of reinforcement synergistically to achieve balanced multifunctional performance. In detail, interfacial relationships and composite behaviors are described using a multi-technique characterization approach consisting of FESEM, EDX, XRD, FTIR, and TGA/DSC. An area of particular attention is placed on optimization methodologies that create a balance between the mechanical properties (hardness, tensile strength, etc) and thermal and electrical conductivities (i.e., how well heat/electric current travel through the composite material) which is the most significant long-term barrier in developing Cu-MMCs. Finally, this THE review identifies the future opportunities of that exist for developing new copper-based composites through the use of hybrid reinforcement systems and advanced sintering techniques. The novelty of this review lies on providing a comprehensive view of Cu-MMCs research as it relates to manufacture processes, characterization and composite performance. Figure 1 illustrates the overall framework of Copper Metal Matrix Composite (Cu-MMC) development, highlighting the relationship between powder metallurgy processing, reinforcement selection, characterization techniques, and engineering applications.

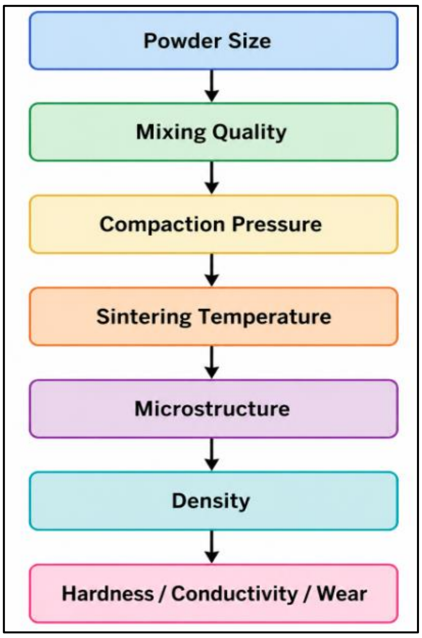

Figure 1. Overview of Copper Metal Matrix Composites (Cu-MMCs)

Figure 1 shows the general research framework adopted for Cu-MMC development. The fabrication process begins with the powder metallurgy processing, followed by the incorporation of ceramic and carbon-based reinforcements. Advanced characterization techniques are subsequently employed to evaluate the microstructure and phase composition, while the resulting mechanical, thermal, and electrical properties determine to the suitability of Cu-MMCs for industrial applications.

2. Fabrication of Copper Matrix Composites

The process of Powder metallurgy (PM) is used to produce Copper Metal Matrix Composite (Cu-MMC) involves series of precise steps to control microstructure, distribute the reinforcement uniformly and enhance mechanical property. Four steps are basically involved in PM route shown in Figure 2.

- Powder Preparation: Copper powder having high purity is chosen as the matrix and reinforcements like ceramics namely silicon carbide (SiC), alumina (Al_2O_3), titanium carbide (TiC), boron carbide (B_4C), or carbon-based particle such as graphite and CNT are prepared and selected based on precise particle size.
- Mixing or Blending: To ensure that reinforcements are uniformly distributed into the matrix material, thorough mixing is required. Various techniques like Ball milling, Mechanical Alloying or Ultrasonication are employed based on the type of the reinforcement and its volume fraction added into the matrix.
- Compaction: The blended powder mixture is compacted at higher pressures (300-600 MPa) to obtain a green compact. This provides sufficient density to handle easily and minimize the pores within the composite.
- Sintering: The green compact is further heated to a temperature below the melting point of copper (750-900°C) in inert or reducing atmosphere so as to prevent its oxidation, allowing metallurgically bonding among copper particles and reinforcements resulting in better structural integrity, enhanced mechanical property and uniform microstructure. Four main stages involved in PM route are shown in Figure 2.

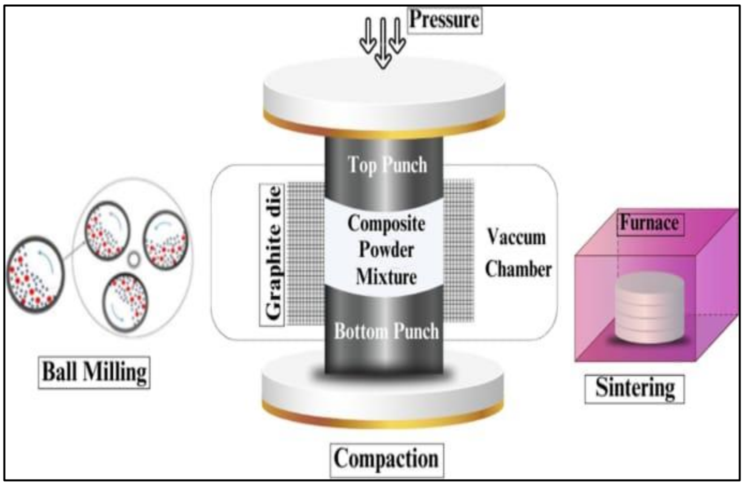

Figure 2. Powder Metallurgy Process

Figure 2 illustrates the four main stages involved in the Powder metallurgy processing namely powder preparation, blending, compaction and sintering. Each stage is responsible for uniform reinforcement distribution, porosity reduction, densification and interfacial bonding which directly contribute to the overall mechanical, electrical and tribological property of the Cu-MMC. Powders are pre-processed to select and use materials of high purity with optimal particle sizes to form composite. During the blending, the homogeneous dispersion of the reinforcements ensures uniform properties throughout the composite, the compaction leads to particle to particle contacts resulting in enhanced green density and then the sintering promotes diffusion to improve the structural integrity. The precise control over the above stages helps to improve the mechanical, wear and electrical properties of the Cu-MMCs.

The PM route offer sevaral advantages over the other fabrication techniques which include precise control over reinforcement distribution, refined grain structure, producing near net shaped components, and reduced wastage of materials [5]. The factors like sintering temperature, holding time, compaction pressure, and particle size of reinforcements play an important role in achieving superior property of Cu-MMC.

3. Reinforcements in Cu-MMCs

The properties of the Cu-MMCs is highly influenced by the type, size, and volume fraction of the reinforcement material incorporated into the copper matrix. Reinforcements are the primarily categorized into ceramic particles and carbon-based materials, each of its contributing uniquely to the composite's mechanical, thermal, and tribological behavior.

3.1 Ceramic Reinforcements

The presence of ceramics particles like silicon carbide (SiC), alumina (Al_2O_3), titanium carbide (TiC), and boron carbide (B_4C) enhances the hardness, stiffness and wear resistance of the Cu-MMCs [6]. Specifically, SiC offers excellent hardness, thermal stability and wear resistance which can effectively use in highly abrasive conditions. Alumina possesses excellent wear and corrosion resistance, along with fair conductivity; titanium carbide (TiC), and boron carbide (B_4C) provide excellent strength to weight ratio and hardness to the matrix. The uniform distribution of these ceramic particles throughout the copper matrix is essential for their optimal load bearing and stress induced behavior of the matrix, preventing localized stress concentration that may lead to premature failure (Figure 3).

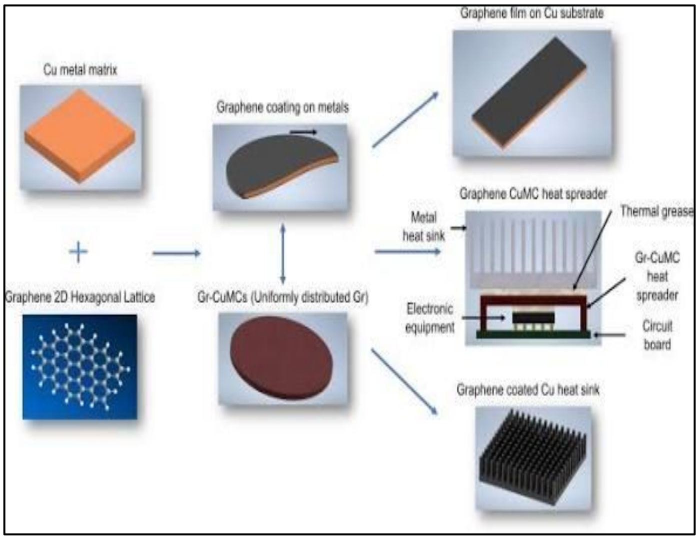

Figure 3. Ceramic Reinforcements Used in Copper Matrix Composites

The Figure 3 shows commonly used ceramic reinforcements namely SiC, Al_2O_3, TiC, and B_4C. These particles impart hardness, wear resistance and stiffness to the composite and enhance the mechanical load bearing capacity through mechanism of grain strengthening, load transfer and grain refinement within copper matrix. Addition of ceramics particles help the dislocation movement to be obstructed thereby improving the mechanical strength of the composite. They improve mechanical property of Cu-MMC with their higher mechanical hardness, stiffness, load bearing capacity and thermal resistance. Addition of SiC in Cu matrix was observed to exhibit significantly higher Hardness and Compressive strength when compared to the unreinforced Cu, because of enhanced particle strengthening, and reduced dislocation mobility due to dispersion strengthening and grain boundary strengthening [6]. The nature of ceramic reinforcement depends on the application where Cu-MMC is used.

3.2 Carbon-Based Reinforcements

Carbon-based reinforcements, including graphite, carbon nanotubes (CNTs), and graphene nanosheets is used to improve thermal conductivity, self-lubrication, and mechanical performance.

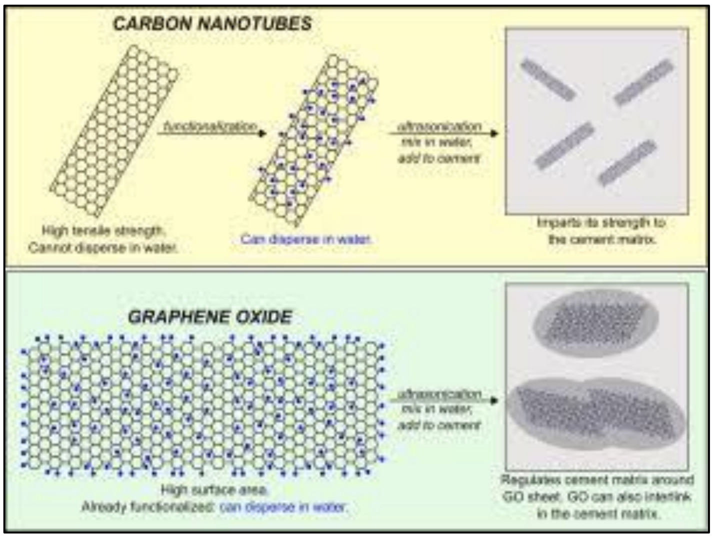

Figure 4. Carbon-Based Reinforcements for Copper Matrix Composites

Graphite, carbon nanotubes CNTs and graphene nanosheets, often utilized to improve thermal and electrical conductivity as well as tribological behavior, lead to self-lubricating and wear-resisting properties of Cu-MMCs [4] Figure 4. The good intrinsic electrical and thermal properties of these carbon-based reinforcements ensure the retention of their respective functionality as they serve to strengthen the Cu-MMCs matrix. The high aspect ratio and large surface area of C-reinforcements also contribute to effective load transfer and strengthened interfacial interactions. As a result, Cu-MMCs with C-based reinforcements are increasingly investigated for use in electrical contacts, heat sinks, electronic packaging and other engineering applications where good electrical and thermal conductivities along with durability are required. Their role is primarily to: Graphite addition renders self-lubricating and thereby low frictional coefficient during wear in a sliding motion. CNT addition improves tensile strength and compressive strength by 52% and 28% respectively, due to the high aspect ratio and excellent elastic modulus and tensile strength of the material [9]. The addition of graphene nanosheets with proper dispersion greatly improves mechanical properties of Cu-MMCs as well as electric and thermal conductivity [8]. The quantity and choice of reinforcement addition has to be carefully calculated; addition of too high quantity can cause particle agglomeration, thereby porosity in resultant MMC, which drastically affect the electrical and mechanical integrity of Cu-MMC. Conversely, less addition fails to increase the property significantly. The hybrid composites containing ceramic as well as carbon-based reinforcements offer a composite material suitable for industrial application, balanced for hard, wear resistant, thermally and electrically conductive properties.

4. Characterization Techniques

The performance and reliability of Cu-MMCs depend strongly on their microstructure, phase constituent and thermal properties. There are several advanced characterization techniques that are widely used to study the performance, the properties of Cu-MMCs and to provide various insights for it.

4.1 Microstructural and Morphological Analysis (FESEM & EDX)

The surface morphology, distribution of particles, and porosity of the Cu-MMCs were studied using FESEM at high magnifications. The FESEM also provides the microstructural study of distribution of the reinforcement particles and the interfacial bonding of the matrix and particles. EDX coupled with FESEM provided the elemental analysis and the elemental distribution pattern of the matrix and reinforcements. The EDX is especially important to study how efficiently the reinforcement is dispersed throughout the matrix.

4.2 Phase and Structural Analysis (XRD)

The XRD was used to determine the crystalline phases of the matrix and the reinforcements, thereby giving information on various phases present in the material after sintering.

4.3 Bonding and Chemical Interaction (FTIR)

FTIR study gives the information on the bonding of various elements, presence of functional groups and the reactions between the matrix and the reinforcements [5].

4.4 Thermal Stability Analysis (TGA/DSC)

Figure 5 explains various characterization techniques which are useful for study of the Cu-MMCs. FESEM and EDX techniques used for microstructural and elemental study. XRD for identifying crystalline phases. FTIR for chemical reaction identification. TGA and DSC are used for study of thermal stability and various phase changes. From the various characterization techniques used for study of the Cu-MMCs the distribution of reinforcing particles in Cu-matrix, interface bond between the reinforcing particles and the Cu-matrix as well as defects or undesired phases could be revealed.

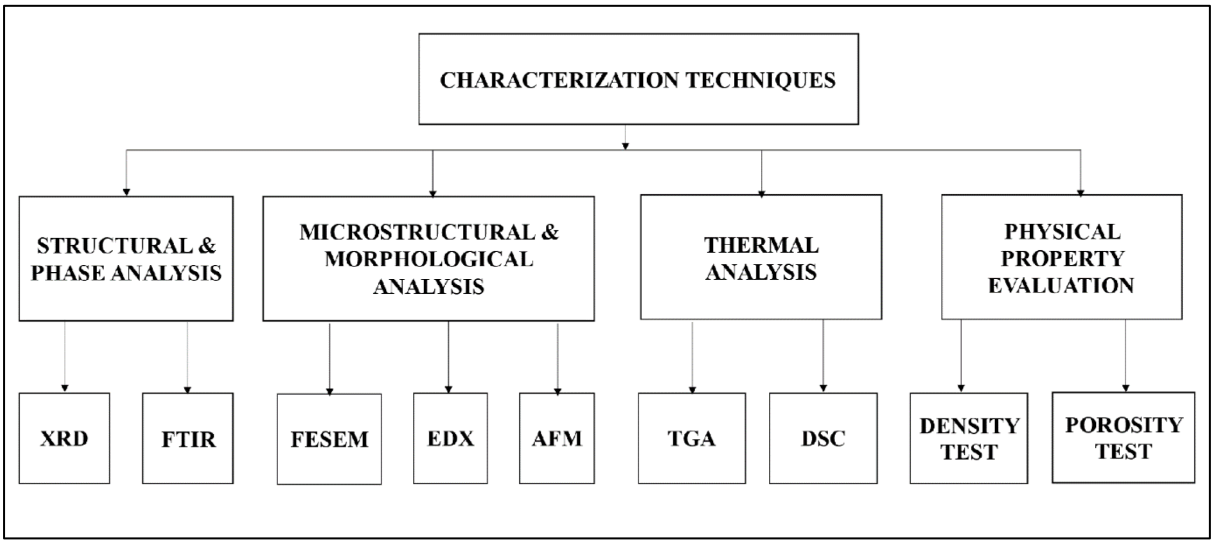

Figure 5. Characterization Techniques Employed for Cu-MMC Evaluation

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were used for the study of thermal stability and other thermal analysis like behavior under thermal loads, melting behavior etc. These techniques have been widely applied to Cu-MMCs research for various application related performance prediction. Together these characterization methods can establish a comprehensive view of microstructure, elemental composition and spatial distribution, phase information, chemical bonding and interactions, thermal stability, etc. For Cu-MMCs.

5. Mechanical and Physical Properties

The incorporation of reinforcements into the copper matrix substantially influences the mechanical and physical performance of Cu-MMCs. These enhancements are primarily attributed to load transfer, grain refinement, and improved interfacial bonding between the copper matrix and the reinforcement particles.

5.1 Hardness and Compressive Strength

According to empirical research, adding ceramic reinforcements to Cu-MMCs has greatly improved their hardness and compressive strength. To illustrate, powder metallurgy processed SiC-reinforced Cu composites had a hardness over 120 HV versus 60 HV for pure copper, with an increase in compressive strength of about 40%. Similarly, the addition of Al2O3 provides comparable increases in this property when optimized for the right amount of reinforcement where hardness values range from 110-130 HV. In addition, TiC and B4C also enhanced the load-carrying capability of the composite material by providing compressive strengths greater than 400MPa, given that the compaction and sintering processes are optimized. The improvements in the strength of Cu composites using ceramic reinforcements can be attributed to the efficient load transfer and grain refinements, whereas too much reinforcement will lead to an agglomeration and porosity issue which adversely affects mechanical integrity [10].

5.2 Electrical and Thermal Conductivity

The electrical conductivity measurements demonstrate a direct trade-off between reinforcement for strength and function. Due to their inherently insulating nature, ceramic reinforcements lead to an approximately 10–20% decrease in conductivity compared to pure Cu. However, carbon-based reinforcements are less intrusive. Graphite additions allowed conductivity levels to remain above 80% IACS while CNT-added Composites maintained electrical conductivity near 90% IACS along with superior electrical and thermal conductivities. Graphene nanosheets provided a dual benefit of increased mechanical strength and enhanced electrical conduction efficiency by the synergistic effects they impart. Optimization of the interface for reduction of electron scattering was found to be crucial to this process [11].

5.3 Wear Resistance and Friction Behavior

Sliding wear test conducted on the MMC confirmed the dramatic reduction in wear loss provided by the addition of ceramic reinforcements. The addition of SiC and B_4C lowered the wear volume loss by close to 50%. In addition, the addition of carbonaceous reinforcements has other beneficial effects: The addition of graphite rendered self-lubricating properties thus providing a low coefficient of friction 0.25, and that the addition of CNTs generated protective tribo-layer that levelled the sliding response over extended sliding cycles. Combination of both ceramic as well as carbon based reinforcing materials proved very effective. The wear performance was very high for such combinations of reinforcements due to improved tribological behavior [12].

Table 1. Comparative Mechanical, Electrical, and Thermal Properties of the Reinforced Cu-MMCs Reported in Literature

Ref.	Reinforcement	Hardness (HV)	Tensile Strength (MPa)	Electrical Conductivity (% IACS)	Thermal Conductivity (W/m·K)
[7]	MWCNT 0.7 wt%	86.1	227.5	87.8	350
[7]	MWCNT 4 wt%	92	210	78	152
[7]	MWCNT 8 wt%	110	245	68	145
[7]	MWCNT 12 wt%	131	275	58	138
[8]	CNT 0.1 wt%	216	216	81.8	350
[8]	CNT 0.3 wt%	240	245	78	330
[8]	CNT 0.5 wt%	260	270	73	310
[9]	ZrB_2 5 wt%	180	320	80	340
[9]	ZrB_2 10 wt%	220	360	75	310
[1]	TiB_2 3 wt%	165	320	79	335
[1]	TiB_2 6 wt%	190	350	74	315
[10]	Graphene 0.5 wt%	130	290	88	330
[10]	Graphene 1.0 wt%	145	320	82	310
[10]	Graphene 1.5 wt%	155	350	76	290
[11]	SnO_2-rGO 0.1 wt%	305	350	85	360
[11]	SnO_2-rGO 0.2 wt%	320	370	80	340
[12]	T15 HSS 2.5%	60	200	68	350
[12]	T15 HSS 10%	61	220	62	330
[13]	Fly ash 10 wt%	140	240	62	280
[13]	Fly ash 15 wt%	155	260	58	260
[13]	WO_3 5 wt%	165	290	65	300
[14]	WC 5%	248	280	75	320
[14]	WC 10%	490	295	70	300
[14]	B_4C 3 wt%	150	260	70	300
[14]	B_4C 5 wt%	170	290	65	280
[14]	TiC 2 wt%	175	310	82	340

[14]	TiC 5 wt%	210	340	78	320
[7]	MWCNT 1.5 wt% (microwave)	148	240	85	340
[1]	Hybrid (SiC nano + micro)	155–185	300–380	78–90	300–380
[12]	SS Chips 5 wt% (hybrid)	170	295	72	310

Table 1 clearly illustrates how the reinforcement type affects the performance characteristics of the composite materials. The superior electrical and thermal conductivities of CNT- and graphene-reinforced composites are largely due to the intrinsically high conductive characteristics of the reinforcements, while the TiB_2, ZrB_2, WC, and B_4C exhibit remarkable hardness, mechanical strength, and wear resistance properties. Other factors such as optimal sintering parameters are also critical for developing well densified Cu-MMC with strong interfaces. Hybrid reinforcements provide improved mechanical strength and electrical conductivity due to synergy between the properties of the two reinforcement types. These make the hybrid Cu-MMCs a strong candidate for various advanced applications requiring higher performance.

6. Applications of Cu-MMCs

The wide range of industrial applications of Cu-MMCs reflects their versatility. In the electrical and electronics industry, Cu-MMCs are extensively utilized in electrical contacts, commutators, and electrodes where both high conductivity and excellent durability are critical for repeated switching operations. Enhanced wear resistance provided by hard ceramic reinforcements ensures long component lifetimes. These components can function effectively under repeated cyclic electrical loads. In applications demanding significant heat dissipation, such as heat exchangers, heat sinks, and cooling plates, Cu-MMCs leverage copper's superior thermal conductivity while maintaining structural integrity. The mechanical strength of the reinforced composite ensures resistance to fatigue under thermal cyclic conditions and associated mechanical loading. In the automotive and aerospace industry, Cu-MMCs have found utility in brake pads, bearings, and bushings. Here, the components need to endure high friction and wear rates at elevated temperatures without compromise to mechanical performance. Self-lubricating behavior from graphitic carbon or CNTs extends the operational life in such demanding situations. The ability to tailor Cu-MMCs for different application needs by carefully selecting reinforcements, processing parameters, and composite designs will enable future innovation and advancement of Cu-MMCs to even more challenging and diverse applications [13].

Table 2. Performance Assessment of Common Reinforcements Used in Cu-MMCs

Reinforcement	Main Advantage	Main Limitation	Best Application
SiC	Hardness	Reduced conductivity	Wear parts
Al_2O_3	Corrosion resistance	Brittleness	Electrical contacts
CNT	Conductivity	Agglomeration	Thermal management
Graphene	Multifunctional	Cost	Electronics
B_4C	High hardness	Processing difficulty	Aerospace

As indicated by the qualitative comparison presented in Table 2 among a list of frequently used reinforcement materials within copper matrix composites, such as TiB_2, ZrB_2, WC, and B_4C into their effects upon various properties (hardenss, wear, electrical and thermal conductivity, composite performance etc.) is obtained. Primarily, ceramics are excellent in enhancing the hardness, strength and wear properties due to high rigidity and their ability to hinder dislocation movement in copper matrix. However, carbon-based reinforcements such as CNTs and graphene are effective in retain electrical and thermal conductivities apart from wear behaviour. In combination, they make a perfect Hybrid Reinforcement system; one is beneficial for mechanics and tribology and the other for electrical and thermal conduction properties which collectively provide an improved balance of mechanical, thermal and electrical performance of the Cu-MMCs depending on the requirement.

7. Challenges and Future Prospects

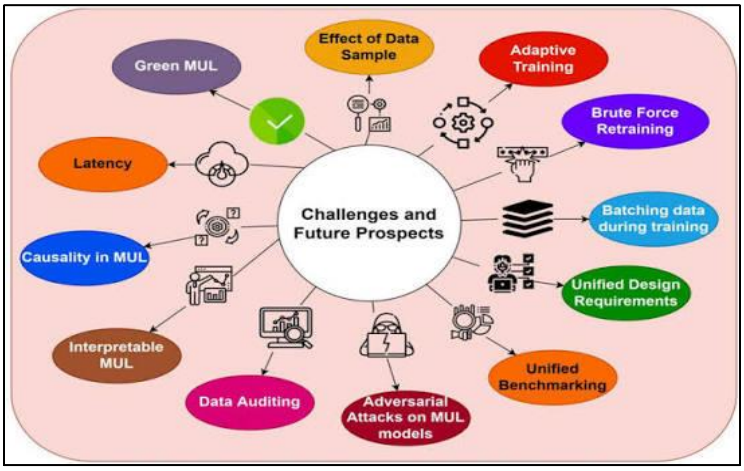

Figure 6. Challenges and Future Research Directions in Cu-MMC Development

The challenges are enlisted as pointed out in Figure 6 that hinders Cu-MMC's development i.e. Reinforcement agglomeration, residual porosity, decrease in electrical and thermal conductivity, poor interfacial bonding between copper matrix and particles etc. That leads to deteriorative effect on the performance, reliability and durability of the composite. Even distribution of reinforcements and reduction in process related defects remain main concerns researchers and manufacturers. Future scope includes improvement in those challenges in forms of using hybrid reinforcement systems, Spark plasma sintering and AM for achieving the desirable enhancement of densification, microstructural characteristics and multi-functionalities as shown in Fig. 6. Apart from that affordable processing routes, proper interfacial design and scalability is required for industrial application in electrical conductivity, thermal management and automotive and aerospace systems.

Despite of recent advancements, Cu-MMCs are plagued with several technical challenges, limiting their broader industrial implementation. Primarily among these is uniform dispersion of reinforcements in the Cu-MMCs matrix. Inhomogeneity can cause particle clumping and result in localized stress concentrations and mechanical inconsistencies. Porosity control during powder metallurgy processing is a major concern. Residual porosity not only degrades mechanical properties and wear resistance, but also affects electrical and thermal conductivities. A balance needs to be maintained between reinforcement content and matrix continuity to maintain structural integrity and functionality. Reduction in electrical conductivity caused by addition of insulators is also an issue in Cu-MMCs, the solution of which lies in improving matrix reinforcement interface bonding. Hybrid reinforcement systems that can balance conductivity and mechanical properties, alternative sintering techniques like spark plasma sintering (SPS), and integration with additive manufacturing are promising approaches for future work. Other beneficial factors include optimized interface design and cost-effective production. These developments can unlock widespread applications of Cu-MMCs in electric contacts, thermal management, aerospace and automotive components [14].

8. Conclusion

Evaluation of copper metal matrix composites (Cu-MMCs) produced by powder metallurgy through experimentation demonstrate tremendously that the type of composite reinforcement and processing parameters are crucial in determining the trade-off between mechanical strength and electrical conductivity and thermal stability. In general, ceramic materials including SiC, Al_20_3, TiC, B_4C showed the highest increase in hardness and compressive strength, with hardness measured above 120 HV and compressive strength above 400 MPa at optimised conditions. These improvements however resulted in only negligible decreases in electrical conductivity because of the non-conductive nature of ceramics. Reinforcements made from carbon including graphite, CNTs and graphene were able to overcome this limitation by reducing electrical conductivity to approximately 80-90% IACS, as well as providing increased thermal transport and improved tribological performance. Wearing testing of the composites produced with hybrid reinforcement systems showed the same benefits as keeping hardness of the ceramics but providing evidence of self-lubricating characteristics of the carbonaceous phase resulting in a decrease in wear loss volume by approximately 50% and friction reducing to around 0.25. Thermal analysis showed that the reinforced composites maintain strong stability at high temperatures, through very little degradation of the materials, even at 800 °C, confirming their ability to be applied to high-temperature applications. The processing structure property relationships of Cu-MMCs have been clearly demonstrated through these findings. The stages of Powder Metallurgy; powder preparation, blending, compaction and sintering directly influence all critical parameters namely reinforcement dispersion, porosity level, and interface bonding that affects mechanical strength, electrical conductivity and thermal stability. The ceramics enhance hardness, wear resistance, whereas the carbonaceous part offers conductivity and self-lubricity. Hence, Cu-MMCs fabricated using powder metallurgy show significant potential for applications in electrical contacts, thermal management and in tribologically demanding environments (automotive and aerospace) provided uniform distribution of reinforcements and strong interfacial bonding are maintained.

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