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Review

Recent Advances in Hybrid Nanocomposites for Aerospace Applications

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Abstract: Hybrid nanocomposites have emerged as a groundbreaking class of materials in the aerospace industry, offering exceptional mechanical, thermal, and functional properties. These materials, composed of a combination of metallic matrices (based on aluminum, magnesium, or titanium) reinforced with a mixture of nanoscale particles, such as carbon nanotubes (CNTs), graphene, and ceramic nanoparticles (SiC, Al_2O_3), provide a unique balance of high strength, low weight, and enhanced durability. Recent advances in developing these nanocomposites have focused on optimizing the dispersion and integration of nanoparticles within the matrix to achieve superior material performance. Innovative fabrication techniques have ensured uniform distribution and strong bonding between the matrix and the reinforcements, including advanced powder metallurgy, stir casting, in situ chemical vapor deposition (CVD), and additive manufacturing. These methods have enabled the production of hybrid nanocomposites with improved mechanical properties, such as increased tensile strength, fracture toughness, wear resistance, and enhanced thermal stability and electrical conductivity. Despite these advancements, challenges remain in preventing nanoparticle agglomeration due to the high surface energy and van der Walls forces and ensuring consistent quality and repeatability in large-scale production. Addressing these issues is critical for fully leveraging the potential of hybrid nanocomposites in aerospace applications, where materials are subjected to extreme conditions and rigorous performance standards. Ongoing research is focused on developing novel processing techniques and understanding the underlying mechanisms that govern the behavior of these materials under various operational conditions. This review highlights the recent progress in the design, fabrication, and application of hybrid nanocomposites for aerospace applications. It underscores their potential to revolutionize the industry by providing materials that meet the demanding requirements for lightweight, high-strength, and multifunctional components.

Keywords: hybrid nanocomposites; aerospace applications; nanoparticles; carbon nanotubes; thermal stability; mechanical properties; manufacturing techniques

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1. Introduction

Hybrid nanocomposites represent a rapidly advancing area of materials science characterized by combining two or more different types of micro- or nanoscale reinforcements within a single matrix. This hybridization allows for the tailoring of material properties to achieve a synergistic enhancement of mechanical, thermal, and functional characteristics unattainable with traditional composites. By integrating metallic, ceramic, and carbon-based nanoparticles, hybrid nanocomposites can offer improved strength, toughness, electrical conductivity, and thermal stability, making them highly versatile for various applications.

In recent years, the aerospace sector has been searching for materials that offer an exceptional combination of lightness, mechanical strength, thermal stability, and wear resistance. With increasing demands for energy efficiency, improved performance, and greater durability of aerospace structures, conventional materials have proved limited in meeting these increasingly stringent requirements. Hybrid nanocomposites provide distinct advantages over conventional metals in terms of mechanical and thermal performance, resistance to wear and corrosion, reduced weight, multifunctionality, and cost-effectiveness, making them ideal for next-generation aerospace applications. Figure 1 shows the percentage of materials used in different Boeing aircraft [1].

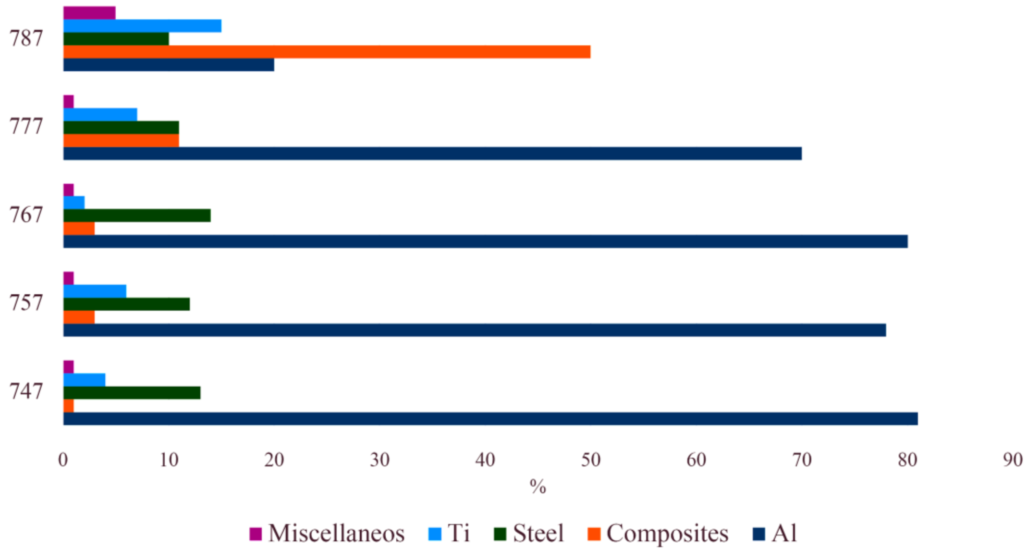


Figure 1. Percentage of the materials used in some Boeing aircraft. Adapted from [1].

Metal matrix hybrid composites, such as those with aluminum, magnesium, or titanium matrices combined with silicon carbide (SiC), boron carbide (B_4C), or carbon fibers, provide an ideal combination of properties that support the rigorous demands of advanced aircraft applications. These materials contribute to weight savings, enhanced structural integrity, and improved reliability in critical aircraft components, especially in areas exposed to high loads, temperatures, and wear conditions. Aluminum alloys play a key role in this application, but composites are also increasingly predominant. In this context, hybrid nanocomposites have emerged as a promising solution, offering superior properties by integrating multiple reinforcing phases into a matrix, such as nanoparticles, nanofibers, and nanotubes, to create multifunctional materials with optimized characteristics.

One of the primary materials used in metal matrix hybrid composites (MMHCs) is aluminum, specifically alloys such as 7075 and 6061. These alloys are favored for their high strength-to-weight ratio, making them ideal for aircraft applications. For instance, aluminum 7075 is known for its hardness and excellent wear resistance, crucial for high-stress and high-fatigue components such as aircraft wings and fuselage structures [2–4]. Incorporating reinforcements like silicon carbide (SiC) and titanium carbide (TiC) into aluminum matrices significantly enhances their mechanical properties, improving performance in demanding aerospace environments. Due to these superior properties, hybrid nanocomposites are increasingly explored in critical aerospace components like fuselage panels, engine parts, and structural reinforcements. Figure 2 shows the parts of the aircraft constructions that required composite materials. These materials help reduce aircraft weight and improve operational efficiency and longevity, leading to lower maintenance costs and enhanced performance under harsh environmental conditions. In addition, the ability to incorporate additional functionalities, such as self-repair and integrated sensing, further expands the application potential of these materials in the next generation of aircraft and spacecraft.

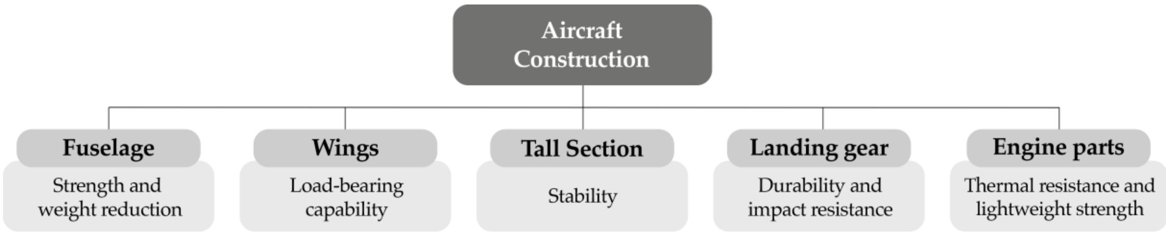


Figure 2. Representative diagram showing the parts of the aircraft constructions that required composite materials.

This review provides a comprehensive overview of recent advances in hybrid nanocomposites aimed at aerospace applications. It will discuss the main types of hybrid reinforcements used, such as ceramic nanoparticles, carbon nanotubes, and graphene, as well as the most common matrices and innovative processing methods. In addition, the review will address current challenges in the manufacture and characterization of these nanocomposites, including the uniform dispersion of nanomaterials, interfacility between matrix and reinforcements, and issues related to scalability and sustainability. Finally, future trends and prospects for applying these materials in aerospace structures will be explored, highlighting their potential to revolutionize the sector and develop more efficient, safe, and durable aerospace systems. Additionally, the review will explore the key challenges and limitations associated with producing and implementing these materials in aerospace applications. By examining current research trends and identifying potential future directions, this review highlights the significant potential of hybrid nanocomposites to revolutionize aerospace material design and provide a roadmap for future innovations in this field.

2. Hybrid Metal Matrix Nanocomposites

Hybrid metal matrix nanocomposites (HMMNCs) are advanced composite materials that combine multiple nanometer-scale reinforcing phases within a matrix to improve the resulting material's physical, chemical, and mechanical properties. By integrating different types of nanomaterials, such as nanoparticles, nanotubes, nanofibers, and nanoplatelets, it is possible to exploit synergistic effects that lead to superior performance compared to conventional nanocomposites that use a single type of reinforcement. This hybrid approach allows for greater customization of the material's properties for specific applications, making hybrid nanocomposites an attractive solution for high-demand applications, such as in the aerospace industry [2–4].

These nanoscale reinforcements can significantly alter the base matrix's physical, mechanical, and functional properties, resulting in materials that exhibit superior performance characteristics compared to their conventional counterparts. The unique properties of nanocomposites arise from the nanoparticles' high surface area to volume ratio and their ability to enhance interfacial interactions within the matrix.

These nanocomposites typically comprise a matrix into which different nanomaterials are incorporated as reinforcing phases. The matrix serves as a load transfer medium and distributes the reinforcements evenly, while the reinforcements act as strengthening agents, improving the material's mechanical, thermal, and functional properties. In hybrid nanocomposites, the combination of two or more types of nanomaterial, such as carbon nanotubes (CNTs) and ceramic nanoparticles (e.g., SiO_2, Al_2O_3), makes it possible to achieve a variety of properties, such as high tensile strength, thermal stability, and adjustable electrical conductivity. Figure 3 shows some reinforcements that can be combined to produce hybrid nanocomposites.

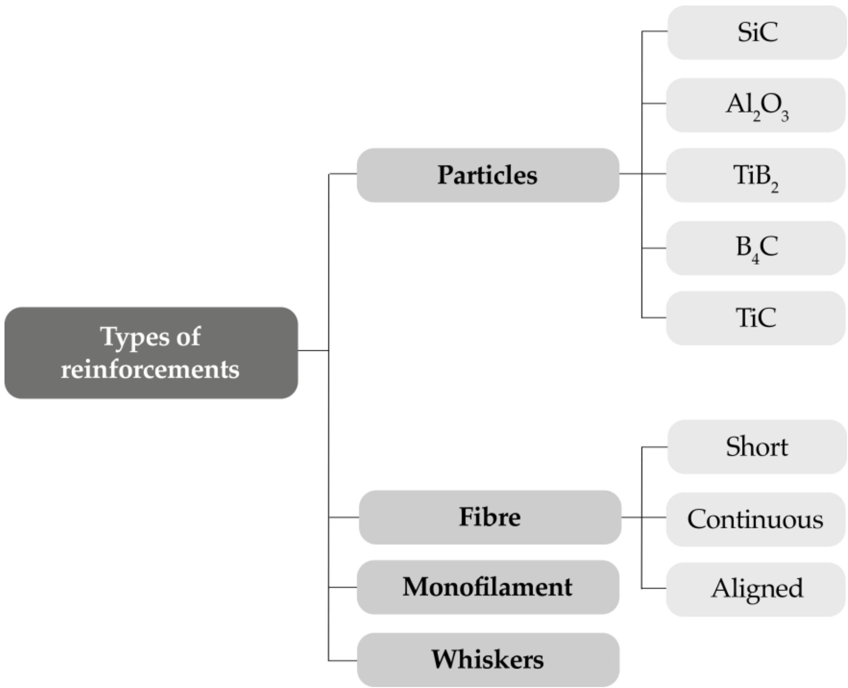


Figure 3. Representation of the reinforcements that can be combined to produce hybrid nanocomposites.

The aerospace industry increasingly focuses on reducing weight while maintaining or enhancing strength and durability. HMMNCs, often based on aluminum or magnesium matrices, exhibit a remarkable strength-to-weight ratio, which is crucial for aerospace applications [5]. The addition of nanoparticles, such as carbon nanotubes (CNTs) or boron carbide (B_4C), has been shown to significantly improve the wear resistance and mechanical properties of aluminum-based composites [6]. For example, studies have demonstrated that aluminum 5083 composites reinforced with CNTs and B_4C exhibit superior creep behavior and wear resistance compared to their non-hybrid composites [6]. This is particularly important in aerospace applications where components are subjected to high stresses (100 to 400 MPa) and temperatures (200 to 400 °C).

Moreover, the hybridization of reinforcements in metal matrix composites allows for the synergistic enhancement of properties. The combination of micro- and nanosized reinforcements can lead to improved mechanical performance due to the different mechanisms of strengthening they provide. The morphology of micro- and nanosized reinforcements in hybrid nanocomposites affects the balance of properties by providing complementary strengthening mechanisms: nanoscale particles contribute to hardness and thermal stability. In contrast, microscale reinforcements improve load-bearing capacity and wear resistance. Tailored morphology enhances the composite's adaptability to demanding environments such as high-stress and high-temperature applications. For instance, while microsized particles may enhance load-bearing capacity, nanosized reinforcements can improve toughness and ductility [7]. This dual reinforcement strategy enhances the mechanical properties and contributes to better thermal stability and resistance to fatigue, which are critical for aerospace applications [8].

The reinforcement mechanisms in hybrid nanocomposites are complex and depend on the interaction between the matrix and the different reinforcements and the interactions between the reinforcement phases. Generally, reinforcement is achieved through three main mechanisms: (a) Dislocation blocking: nanomaterials can hinder the movement of dislocations in the matrix, increasing mechanical strength; carbon nanotubes and ceramic nanoparticles are effective in this mechanism due to their high modulus of elasticity and strength. (b) Fiber bridges and nanoparticles: the combination of different reinforcements, such as nanofibers and nanoplatelets, can create a three-dimensional network within the matrix, which helps to improve impact resistance and toughness by preventing the propagation of cracks. (c) Effective load transfer: for hybrid nanocomposites to be effective, efficient load transfer between the matrix and the reinforcements is essential. Functionalizing the surface of nanomaterials can improve interfacial adhesion, resulting in a more uniform distribution of stresses and greater overall strength of the composite.

The hybridization of nanocomposites offers significant advantages, such as multifunctional properties, improved thermal stability, and property customization. Incorporating different nanomaterials makes it possible to obtain multifunctional properties, such as high mechanical strength combined with electrical and thermal conductivity. This is particularly useful in aerospace applications, where multifunctional materials can reduce structural weight and greater efficiency. Combining reinforcements, such as ceramic nanoparticles and carbon nanofibers, can increase the composite's thermal stability, a crucial characteristic for applications in extreme aerospace environments. By carefully selecting the matrix and nano-reinforcements, it is possible to design hybrid nanocomposites with customized properties to meet specific requirements, such as impact resistance, flexibility, or stiffness, resulting in a more uniform distribution of stresses and greater overall strength. The processing techniques employed in fabricating HMMNCs also play a vital role in determining their final properties. Methods such as powder metallurgy, stir casting, and spark plasma sintering have produced uniform reinforcements within the metal matrix [9,10]. These techniques allow for precise control over the microstructure, which is essential for optimizing the mechanical properties of the composites. For example, spark plasma sintering has been shown to produce HMMNCs with fine microstructures and enhanced mechanical properties due to the rapid heating and consolidation processes involved [11].

Despite the advantages, the manufacture of hybrid nanocomposites presents challenges. The homogeneous dispersion of the nanomaterials in the matrix is crucial to avoid agglomerations that can compromise the mechanical and thermal properties. In addition, interfacial compatibility between the matrix and the different types of reinforcement is a critical aspect since poor interfacial interaction can result in poor load transfer and, consequently, reduced performance of the composite. Surface functionalization methods and advanced processing techniques, such as additive manufacturing, have been explored to overcome these challenges and achieve greater overall strength of the composite.

In addition to mechanical properties, the thermal and electrical characteristics of HMMNCs are also of great importance in aerospace applications. The ability to tailor these properties by selecting appropriate reinforcements can lead to materials that not only withstand extreme conditions but also perform efficiently in terms of thermal management and electrical conductivity [10,11]. For instance, incorporating graphene or other carbon-based materials can significantly enhance the thermal conductivity of the matrix, making these composites suitable for applications where heat dissipation is critical [10]. Furthermore, the corrosion resistance of HMMNCs is a crucial factor in their application within the aerospace sector. Using ceramic reinforcements, such as alumina or silicon carbide, has improved the corrosion resistance of aluminum-based composites, thereby extending their service life in harsh environments [12]. This is particularly relevant in aerospace applications where components are often exposed to moisture, chemicals, and extreme temperatures. The ongoing research and development in composites are focused on optimizing processing techniques and understanding the fundamental mechanisms that govern their properties. Advances in computational modeling and simulation are also being employed to predict the behavior of these materials under various loading conditions, which can aid in the design of next-generation aerospace components [13–18].

One of the materials of greatest interest in the application of components in the aerospace industry is aluminum and its alloys. For this reason, the potential for producing hybrid aluminum nanocomposites has generated enormous scientific interest. The recent advancements in copper hybrid composites for aerospace applications underscore their potential to meet the industry's demands for lightweight, high-performance materials. Integrating nanostructured reinforcements, advanced manufacturing techniques, and multilayer designs pave the way for innovative solutions that enhance the functionality and reliability of aerospace components.

Table 1 summarizes some studies on the production of HMMCs, where adding different reinforcements improves nanocomposite properties.

Table 1. Summary of some studies on HMMCs.

Matrix	Reinforcement	Production	Improvement	Ref.
Al	TiB_2 Graphite	Electromagnetic stir casting	Mechanical properties	[19]
Al7075	TiC Graphene	Ultrasonic stir casting	Wear behavior	[20]
Al7085	TiC BN	Ultrasonic stir casting	Mechanical properties	[21]
Zinc and Al alloy	Al_2O_3 MoS_2	Stir casting	Mechanical properties	[22]
Al	SiC TiO_2	Powder metallurgy	Mechanical properties	[23]
Al	$Y_2W_3O_{12}$ AlN	Powder metallurgy	Mechanical properties	[24]
Al6061	SiC Graphite	In situ powder metallurgy	Mechanical properties	[25]
Al	Al_2O_3 MoS_2	Powder metallurgy	Tribological properties	[26]
Al	BN TiO_2	Powder metallurgy	Tribological properties	[27]
AA6082	TiC SiC	Stir casting	Tribological and mechanical properties	[28]
AA7075	B_4C ZrC	Powder metallurgy	Mechanical properties	[29]
Al	ZnO Y_2O_3	Powder metallurgy	Mechanical properties	[30]
Mg	TiC MoS_2	Powder metallurgy	Tribological and mechanical properties	[31]
Mg	SiC Al_2O_3	Powder metallurgy	Mechanical properties	[32]
AA5083	CNT MoS_2	Powder metallurgy	Mechanical properties	[33]
Cu	CNTs Graphene	Spark plasma sintering	Mechanical and electrical properties	[34]
Cu	TiC Graphite	Microwave sintering technique	Wear resistance	[35]
Ti_6Al_4V	TiB TiC	Arc melting	Physical properties	[36]

In conclusion, hybrid metal matrix nanocomposites significantly advance materials science, particularly aerospace applications. Their unique combination of lightweight, high strength, and enhanced performance characteristics make them ideal candidates for various aerospace components. As research continues to evolve, the potential for HMMNCs to revolutionize the aerospace industry remains substantial, paving the way for more efficient and sustainable aerospace technologies.

3. Production of Hybrid Metal Matrix Nanocomposites

The production of HMMNCs has emerged as a critical area of research and development, particularly for aerospace applications where the demand for lightweight, high-strength materials is predominant. HMMNCs combine the advantages of metal matrix composites (MMCs) with the superior properties of nanomaterials, such as carbon nanotubes, graphene, and ceramic nanoparticles. This combination enhances mechanical, thermal, and wear-resistant properties, making them suitable for the extreme conditions encountered in aerospace environments [37]. The fabrication methods for HMMNCs include techniques such as stir casting, powder metallurgy, and additive manufacturing, each offering unique benefits regarding material properties and processing efficiency [38]. For instance, stir casting is favored for its simplicity and cost-effectiveness, enabling the uniform distribution of reinforcements within the metal matrix [39].

Meanwhile, powder metallurgy techniques allow for precise control over microstructural characteristics, which is essential for optimizing the performance of the composites. Moreover, integrating hybrid reinforcements—combining different types of nanoparticles and microsized particles—enables the tailoring of composite properties to meet specific aerospace requirements, such as improved fatigue resistance and reduced weight [40]. As the aerospace industry continues to seek innovative materials that enhance performance while minimizing weight, the development of HMMNCs stands at the forefront of materials science, promising to revolutionize the design and manufacturing of aerospace components [41]. The next sub-sections describe the manufacturing processes with the most advantages in the production of HMMNCs, where the concepts of these processes are presented, and examples of successful work in their production.

3.1. Powder Metallurgy

Powder metallurgy (PM) is a technique widely used in producing metal matrix nanocomposites (MMNCs) due to its ability to process metals and ceramics at relatively low temperatures, avoiding the degradation of heat-sensitive nanomaterials. This method involves pressing and sintering metal powders and reinforcing nanomaterials to form a consolidated material with improved mechanical, thermal, and functional properties. In the case of hybrid nanocomposites, PM allows the incorporation of multiple nanoreinforcements, such as ceramic nanoparticles, carbon nanotubes (CNTs), and nanofibers, within a metallic matrix, making it possible to obtain materials with unique and customizable properties. The production of metal hybrid nanocomposites via powder metallurgy usually involves several sequential steps. The first stage consists of preparing the metal powders and reinforcing nanomaterials. The metal powders, such as aluminum, titanium, or magnesium, are combined with the reinforcing nanomaterials, such as ceramic nanoparticles (e.g., Al_2O_3, SiC) and carbon nanotubes, using mechanical or ultrasonic mixing methods. Homogeneous mixing of the powders is critical to ensure uniform distribution of the nanomaterials in the metal matrix, avoiding agglomeration of the reinforcements and promoting uniform dispersion. A standard mixing method involves high-energy milling, where the metal powders and reinforcements are subjected to repeated impacts in a high-energy ball mill. This process promotes particle size reduction and dispersion of the nanomaterials in the metal matrix. However, care must be taken to avoid introducing contamination and structural damage to the nanomaterials. After mixing, the powders are compacted to form a "preform" with adequate density. Compaction is carried out under high pressures in specific molds, which helps to align and orient the reinforcements within the matrix, directly influencing the nanocomposite's final properties. Sintering is a crucial stage in powder metallurgy, where the preform is heated to temperatures below the melting point of the metal matrix. Figure 4 shows a schematic representation of one possibility for producing these hybrid nanocomposites. During sintering, atomic diffusion occurs, leading to the bonding of the metal particles and the consolidation of the nanocomposite. The selection of sintering temperature and time is vital to optimizing the hybrid nanocomposite's densification, microstructure, and properties [39,42,43].

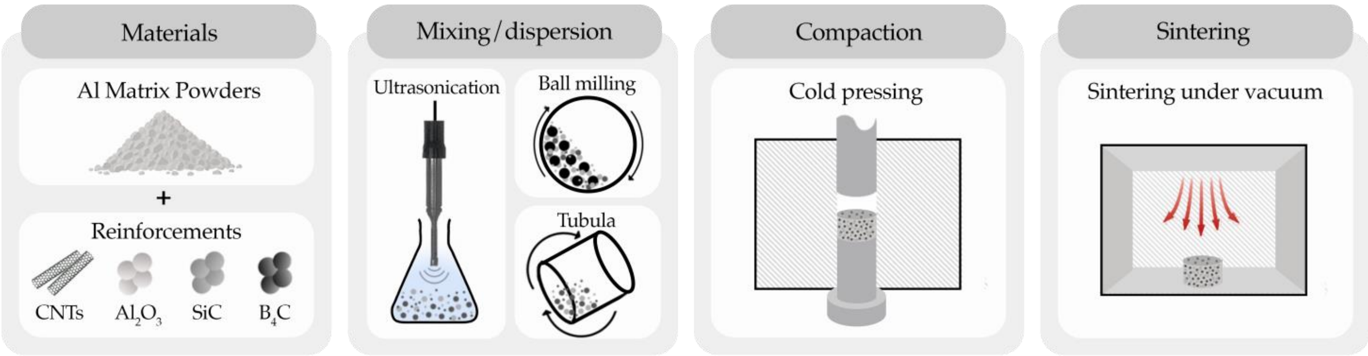


Figure 4. Schematic representation of the sequential steps of powder metallurgy route producing of Al hybrid nanocomposites.

It is possible to produce Al hybrid nanocomposites successfully using powder metallurgy. In producing aluminum hybrid nanocomposites using powder metallurgy, the particle size and morphology of the aluminum powder are critical factors that influence the final composite's mechanical properties, microstructure, and processability. For instance, spherical or near-spherical aluminum particles with sizes between 5 and 50 µm are ideal for producing Al hybrid nanocomposites via powder metallurgy. This morphology supports uniform reinforcement dispersion, good flowability, and efficient compaction, all necessary for high-quality composite production. Combining SiC and CNTs makes it possible to reinforce the Al6061 matrix and obtain an increase in mechanical properties. Figure 5 shows the electron backscatter diffraction (EBSD) results and mechanical properties of the matrix and hybrid nanocomposites produced by powder metallurgy. The microstructural evaluation showed a notable reduction in grain size and greater uniformity in the hybrid nanocomposites, which led to superior mechanical performance. Using EBSD results as unique color maps to represent the grains makes it easier to see the impact of the different reinforcements on reducing the grain size. The hybrid nanocomposites exhibit the most refined microstructure. This enhanced grain structure improves the mechanical performance of the nanocomposites, resulting in greater hardness, yield strength, and wear resistance. Another significant impact that reinforcements have on microstructural characteristics is an increase in the density of dislocations. The KAM maps show that the nanocomposites have increased dislocations, which will affect their properties. Tensile tests confirmed the microstructural observation and showed the highest tensile strength for the nanocomposite, reaching 104 MPa, compared to the 63 MPa obtained by the Al6061 matrix without reinforcement.

One of the primary benefits of using PM for the fabrication of MMNCs is the ability to incorporate nano-sized reinforcements, which significantly improve the mechanical properties of the composites. Incorporating nanoparticles, such as graphene or ceramic particles, has enhanced strength, hardness, and ductility while reducing porosity [44,45]. For instance, adding alumina nanoparticles to aluminum alloys has improved hardness and ultimate tensile strength, demonstrating the effectiveness of PM in producing high-performance materials [46]. Furthermore, the PM process allows the production of complex shapes and geometries that would be challenging to achieve with traditional casting methods [47,48].

The versatility of PM techniques extends to various processing routes, including quasi-static compaction and spark plasma sintering, which can be tailored to optimize the properties of the resulting MMNCs [49]. These methods facilitate the uniform dispersion of reinforcements, which is crucial for achieving the desired mechanical properties. Additionally, PM is economically advantageous as it often requires lower processing temperatures than other methods, thereby reducing energy consumption and production costs [50]. However, challenges remain in the PM process, particularly concerning the agglomeration of nanosized particles, which can adversely affect the mechanical properties of the composites [51]. Researchers are actively exploring solutions to these challenges, such as optimizing mixing parameters and utilizing secondary processing techniques to enhance the distribution of reinforcements [52]. Overall, the PM technique provides a reliable means of producing MMNCs and continues to evolve, addressing the complexities associated with the fabrication of advanced composite materials.

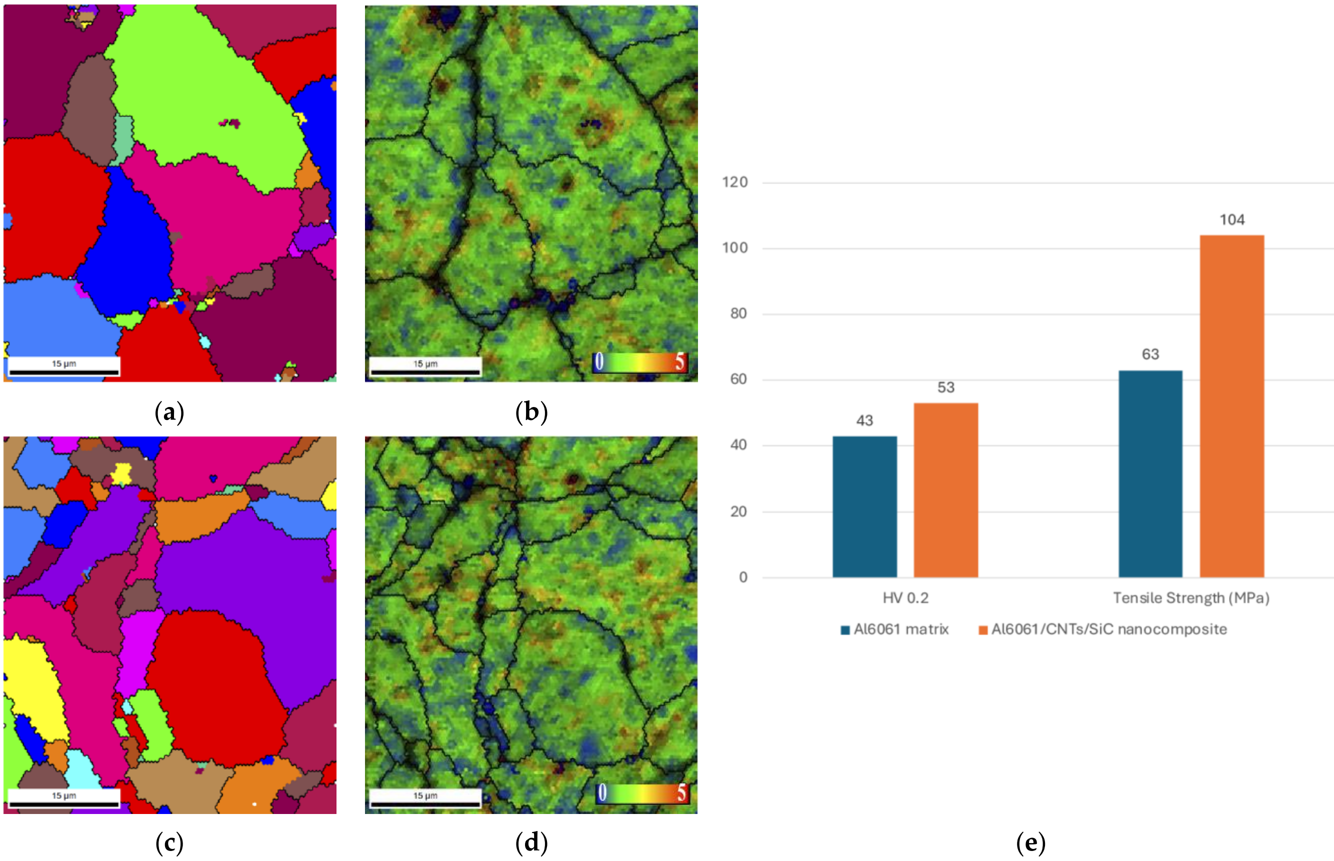


Figure 5. Unique color and Kernel average misorientation maps of (**a**,**b**) Al6061 matrix and (**c**,**d**) Al6061/CNTs/SiC hybrid nanocomposite produced by powder metallurgy and (**e**) hardness and tensile strength of the matrix and nanocomposite produced under the same conditions.

Manohar and Maity [26] investigated the production of hybrid nanocomposites using conventional and microwave sintering. The matrix used was AA7075, and the reinforcement was B_4C and ZrC. The microstructure characterization revealed that the B_4C particles were dispersed homogeneously while some agglomerates of ZrC were observed. Figure 6 shows the scanning electron microscopy (SEM) images of the nanocomposites produced by conventional sintering. Observing these images clearly shows the challenge in the dispersion of the ZrC particles. Nanocomposites produced by microwave sintering revealed better mechanical properties due to a strong bond interface. Implementing advanced techniques in producing these nanocomposites is crucial for nanocomposites with desired mechanical properties.

This method offers several advantages in producing hybrid nanocomposites because it allows precise control of the nanocomposite's microstructure, including the distribution, size, and morphology of the reinforcements in the metal matrix. This is essential for customizing the material's mechanical and functional properties. It is also a process conducted at lower temperatures than conventional melting methods, minimizing the reaction between the matrix and the nanoreinforcements and avoiding the degradation of heat-sensitive nanomaterials. The technique can be applied to a wide range of metals and alloys, as well as different types of nanoreinforcements, including nanoparticles, nanotubes, and nanofibers.

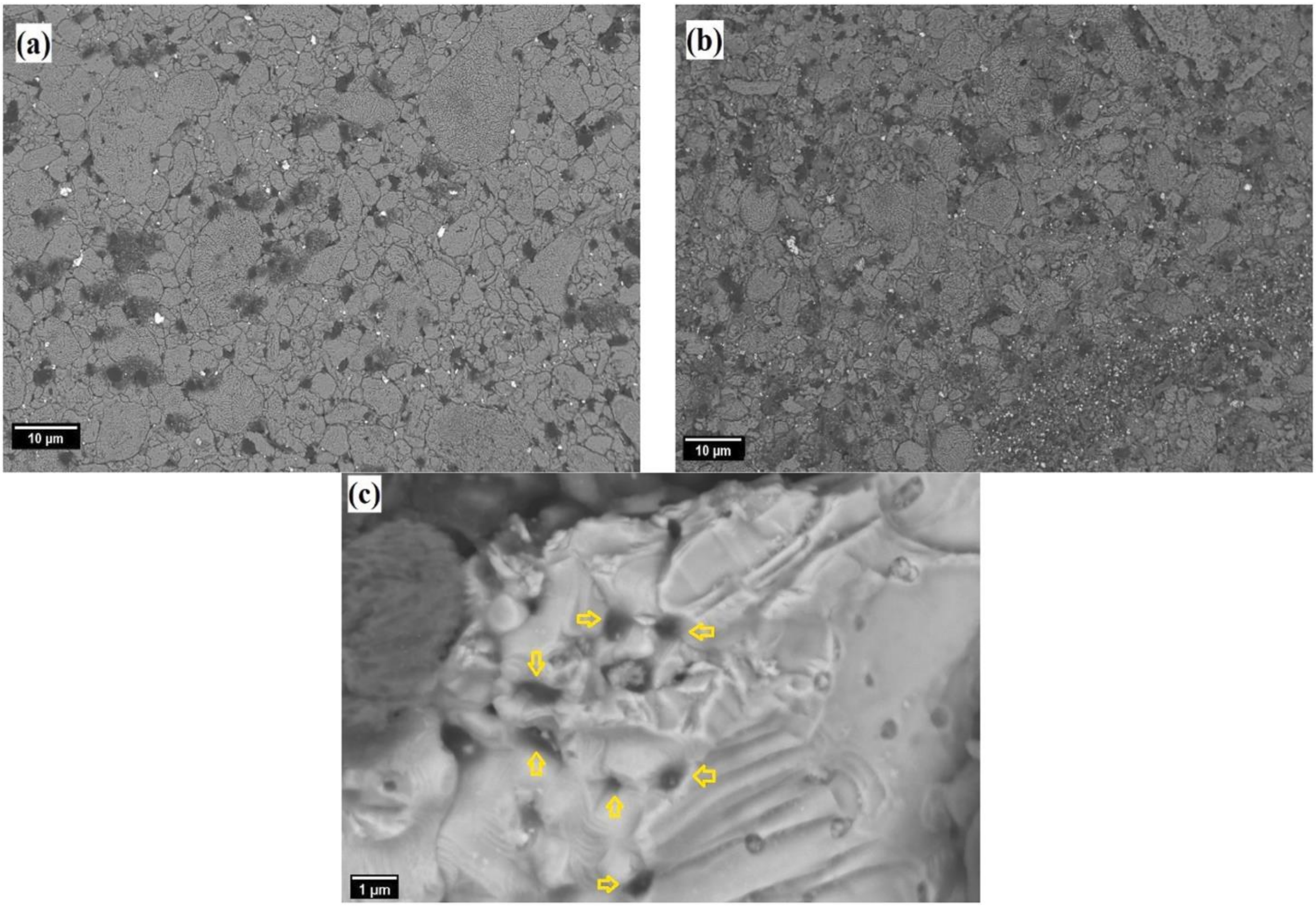


Figure 6. SEM image of the nanocomposites produced by (**a**,**b**) conventional sintering reinforced with ZrC and B_4C and (**c**) high magnification showing by arrows the ZrC agglomerates. Reprinted with permission from ref. [29]. 2021 Elsevier.

Chen et al. [34] investigated the strengthening behavior of carbon nanotube–reduced graphene oxide (CNT-RGO) hybrids in Cu matrix composites. It was observed that disordered areas and Cu_2O nanoparticles were formed in situ at the CNF-Cu interface in areas with low and high oxygen content, respectively, due to oxygen diffusion. The Cu_2O grew from the Cu matrix in a cube-on-cube fashion to minimize interfacial energy, causing equivalent planes and directions of Cu_2O and the Cu matrix to align at the Cu_2O-Cu interface. A possible mechanism for the formation/evolution of these disordered areas and Cu_2O, involving oxygen content and sintering temperature, was proposed. The maximum tensile strength of 412 Mpa was achieved in the 1.5 vol% CNT-RGO/Cu composite sintered at 1023 K, a value significantly higher than that of the CNT/Cu and RGO/Cu composites (231 and 263 Mpa, respectively). Transmission electron microscopy (TEM) observation revealed a well-bonded interface reinforcement/matrix.

The interface between the reinforcement and the matrix HMMNCs is pivotal in determining these advanced materials' mechanical, thermal, and functional properties. The bond strength and quality of the interface significantly impact the load transfer, stress distribution, and failure mechanisms within the composite structure. Pu et al. [53] investigated the interface of the hybrid aluminum matrix nanocomposites. The nanocomposites were produced by sintering and hot extrusion and reinforced by graphene with Cu nanoplatelets. Figure 7 shows the hybrid nanocomposites' scanning transmission electron microscopy

(STEM) and TEM images. The results reveal structural integrity, and a strong bonding interface are observed. A notable concentration of dislocations was observed near the reinforcement, consistent with the high local strain observed in the fine-grain zones of the microstructure of the composite. The results also demonstrate a second phase formation due to the reaction between the Cu and the matrix.

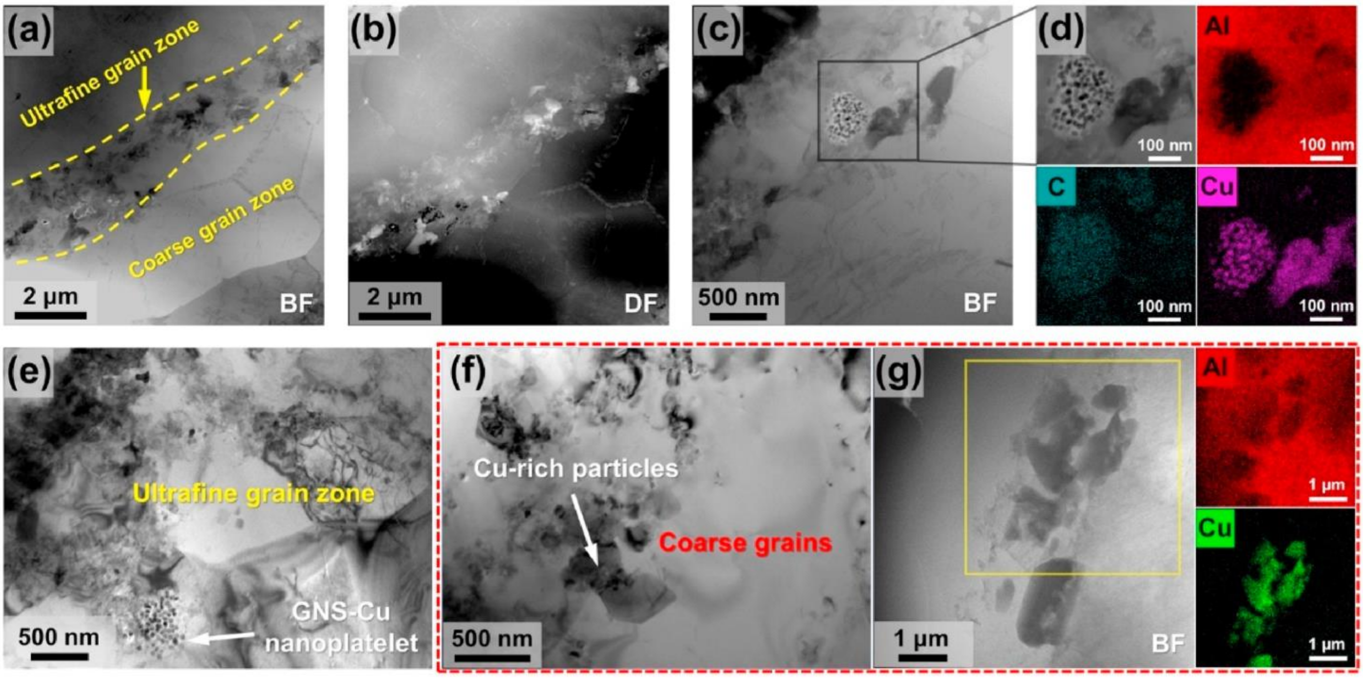


Figure 7. Scanning transmission electron microscopy (STEM) images of the Al hybrid nanocomposites: (**a**) bright-field, (**b**) dark-field images; (**c**,**d**) STEM images with the EDS regions marked; (**e**,**f**) TEM images showing regions with different grain size; and (**g**) STEM image with EDS mapping. Reprinted with permission from ref. [53]. 2022 Elsevier.

Despite the advantages, producing metal hybrid nanocomposites through powder metallurgy presents challenges, such as obtaining a homogeneous dispersion of the nanoreinforcements. Advanced mixing techniques, such as high-energy milling and the functionalization of nanomaterials, can help overcome this problem. Problems relating to contamination During milling and compaction, there is a risk of contamination of the powders, which can compromise the properties of the final nanocomposite. Using controlled environments and suitable grinding tools is crucial to minimize this risk. The sintering process must be carefully optimized to balance densification and preservation of the nanoreinforcements' properties, avoiding the formation of unwanted phases.

Metal hybrid nanocomposites produced via powder metallurgy have broad potential in applications requiring high mechanical strength, thermal stability, and lightweight, such as aircraft structural components, lightweight armor, and high-efficiency engine parts. The combination of multiple reinforcements allows multifunctional properties to be obtained, making them suitable for use in extreme environments and for extending the service life of aerospace components.

3.2. Chemical Vapor Deposition

The production of HMMCs using the chemical vapor deposition (CVD) technique represents a significant advancement in materials science, particularly for applications in aerospace and other high-performance sectors. CVD is a process that allows for the deposition of thin films and coatings on substrates through chemical reactions of gaseous precursors. The carrier gas ensures the continuous flow and even distribution of precursor gases over the substrate. This method is particularly advantageous for creating composites that require a high degree of control over the microstructure and properties of the materials involved [54]. Figure 8 shows the schematic drawing of the conventional CVD.

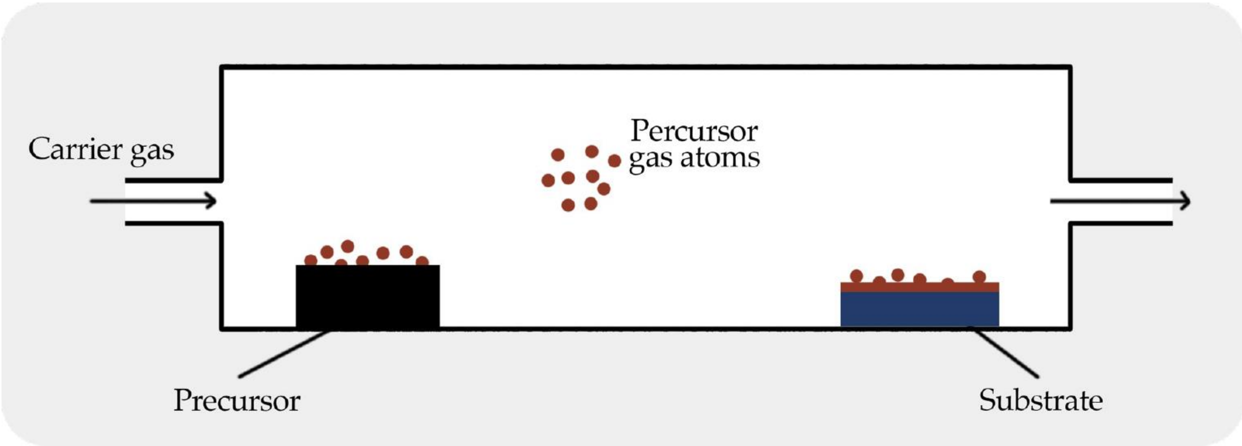


Figure 8. Schematic drawing of the conventional chemical vapor deposition (CVD).

CVD is utilized to produce continuous fibers, such as silicon carbide (SiC), which can be incorporated into metal matrices to enhance mechanical properties. The use of SiC fibers in metal matrix composites is auspicious due to their high tensile strength, stiffness, and oxidation resistance, making them suitable for high-temperature applications in aerospace vehicles [54].

The ability to grow these fibers directly onto the metal substrate via CVD ensures an interfacial solid bond, which is critical for the overall performance of the composite. This strong bond helps mitigate issues related to delamination and enhances the load transfer between the fiber and the matrix [55]. In addition to SiC fibers, CVD can also be employed to deposit carbon nanotubes (CNTs) directly onto metal substrates. This approach significantly improves the underlying metal's corrosion resistance while enhancing its mechanical properties [56]. Incorporating CNTs into aluminum or other metal matrices results in composites exhibiting superior strength-to-weight ratios, making them ideal candidates for aerospace applications where weight reduction is crucial [57]. The unique properties of CNTs, including their high aspect ratio and exceptional mechanical strength, contribute to the overall performance of the HMMCs produced via CVD.

The versatility of CVD allows for the production of hybrid composites that combine different reinforcements, such as fibers and nanoparticles. For instance, the simultaneous deposition of SiC fibers and CNTs can lead to a composite that benefits from the fibers' high strength and the nanotubes' lightweight nature [58]. This hybridization enhances mechanical properties and improves thermal stability and resistance to wear, which are essential for components subjected to extreme conditions in aerospace applications [59]. Moreover, the CVD process can be fine-tuned to control the microstructure of the deposited materials. Parameters such as temperature, pressure, and precursor composition can be adjusted to achieve the desired characteristics in the final composite [13]. This level of control is particularly beneficial when producing HMMCs, as it allows for the optimization of properties such as toughness, ductility, and thermal conductivity. For example, incorporating alumina or other ceramic reinforcements through CVD can enhance aluminum matrix composites' wear resistance and thermal stability, making them more suitable for high-performance applications [60,61].

The application of CVD in producing HMMCs also extends to the development of coatings that can improve the surface properties of metal components. Applying a thin layer of protective material through CVD can enhance the underlying metal's corrosion and wear resistance, extending its service life in harsh environments [62]. This is particularly relevant in aerospace applications where components are often exposed to corrosive atmospheres and high temperatures. Furthermore, the integration of advanced characterization techniques, such as high-resolution transmission electron microscopy (HRTEM), allows for a detailed analysis of the microstructural features of HMMCs produced via CVD, mainly the interface reinforcement/matrix. This enables researchers to understand the mechanisms governing these composites' mechanical properties and performance, leading to further improvements in their design and fabrication [57,63].

Despite the advantages, the production of metal hybrid nanocomposites via CVD faces some challenges, such as process complexity, as this technique requires precise processing conditions, such as temperature control, pressure, and flow of the gaseous precursors, which can increase the complexity and cost of the process. Scalability is a challenge because although CVD is suitable for producing thin films and coatings on a small scale, its scalability for the mass production of nanocomposites is still a challenge that requires optimization of processes and equipment. Unwanted chemical interactions are another challenge because during deposition, there may be unwanted reactions between the precursors and the metal matrix, potentially affecting the properties of the nanocomposite.

In conclusion, producing hybrid metal matrix composites through chemical vapor deposition offers a promising avenue for developing advanced materials tailored for aerospace applications. The ability to control the microstructure and properties of the composites, combined with the incorporation of high-performance reinforcements such as SiC fibers and CNTs, positions CVD as a key technique in the future of materials engineering. As research advances, the potential for HMMCs to revolutionize aerospace technologies remains significant, paving the way for lighter, stronger, and more durable components.

3.3. Additive Manufacturing

The production of HMMCs via additive manufacturing (AM) techniques has gained considerable attention in recent years due to its potential to create complex geometries and tailored material properties. Additive manufacturing allows for the layer-by-layer construction of materials, which is particularly advantageous for producing HMMCs that require precise control over the distribution of reinforcements within the metal matrix [64,65]. This capability not only enhances the mechanical performance of the composites but also enables the integration of multiple materials, leading to improved functionality and application versatility.

One of the most prominent additive manufacturing methods for HMMCs is selective laser melting (SLM), which utilizes a high-powered laser to fuse metallic powders layer by layer. Figure 9 shows a schematic drawing of the SLM process. This technique is particularly effective for producing complex shapes that would be difficult or impossible to achieve using traditional manufacturing methods [66]. The ability to control the microstructure during the AM process allows for optimizing mechanical properties, such as strength and ductility, which are critical for aerospace and automotive applications [67,68]. For instance, incorporating ceramic reinforcements, such as titanium diboride (TiB_2), into aluminum matrices through SLM has enhanced wear resistance and thermal stability, making these composites suitable for high-performance applications [69].

Another significant advantage of additive manufacturing in the production of HMMCs is the ability to tailor the composition and microstructure of the materials. By varying the type and amount of reinforcement added during the AM process, researchers can create composites with specific properties tailored to the demands of various applications [70]. For example, combining graphene and alumina as reinforcements in aluminum matrix composites has significantly improved mechanical properties, including tensile strength and hardness, while maintaining a lightweight structure [70]. This flexibility in design and composition is particularly beneficial in industries such as aerospace, where weight reduction and performance enhancement are paramount. Moreover, the integration of advanced characterization techniques, such as X-Ray computed tomography (CT) and scanning electron microscopy (SEM), allows for a detailed analysis of the microstructural features of HMMCs produced via additive manufacturing. These techniques enable researchers to investigate the distribution of reinforcements, porosity levels, and interfacial bonding between the matrix and reinforcements, which are critical factors influencing the overall performance of the composites [71,72]. Understanding these microstructural characteristics is essential for optimizing processing parameters and achieving the desired mechanical properties.

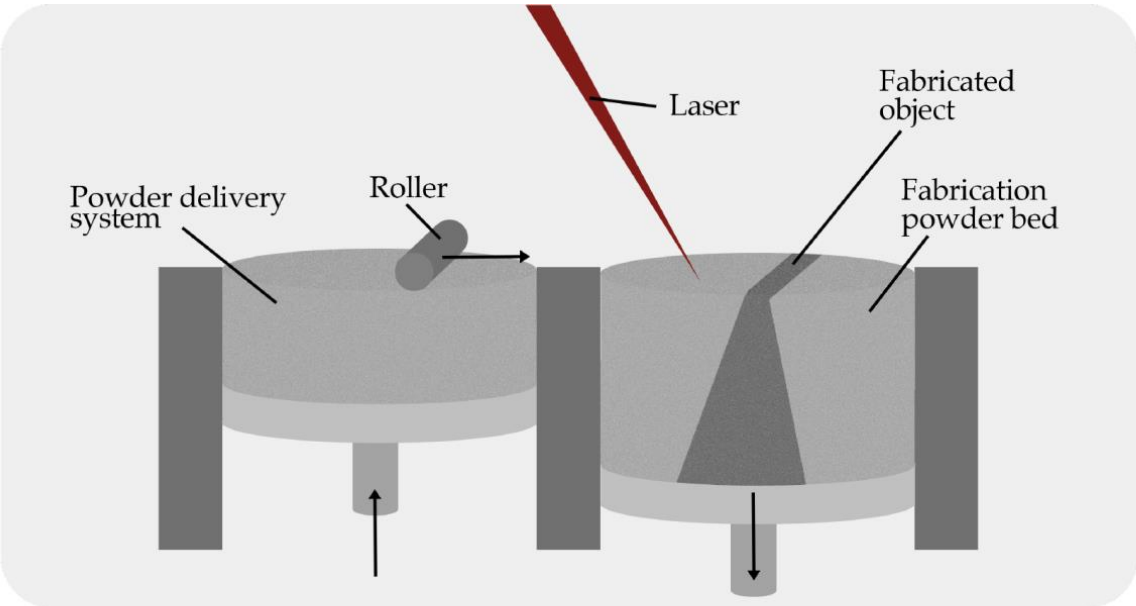


Figure 9. The schematic draw of the selective laser melting (SLM) process.

The use of hybrid reinforcements in additive manufacturing also presents unique opportunities for enhancing the performance of metal matrix composites. For instance, combining carbon nanotubes (CNTs) with traditional ceramic reinforcements can lead to synergistic effects that improve the mechanical and thermal properties of the composite [73]. Incorporating CNTs into aluminum matrices has enhanced strength and stiffness while reducing weight, making these composites particularly attractive for aerospace applications [73]. Furthermore, using hybrid reinforcements allows for the development of multifunctional materials exhibiting improved wear resistance, thermal conductivity, and corrosion resistance [74]. In addition to the mechanical advantages, the additive manufacturing process can contribute to the sustainability of HMMCs. Traditional manufacturing methods often involve significant material waste, whereas additive manufacturing allows for near-net-shape production, minimizing waste and reducing the environmental impact of manufacturing processes [75]. This aspect is increasingly important in industries striving for sustainability and reduced carbon footprints, such as the aerospace and automotive sectors.

The production of HMMCs by additive manufacturing can be promoted by friction stir additive manufacturing (FSAM). Sahraei and Misalehi [76] show that this process possibly successfully reinforces the AA6061 with TiC and graphene. The optimization of the process allows the improvement of the wear rate and friction coefficient of the nanocomposites. The nanocomposites were produced using different rotation speeds and a constant feeding speed of 25 mm/min. A fine-grain microstructure characterizes the nanocomposites, as seen in Figure 10.

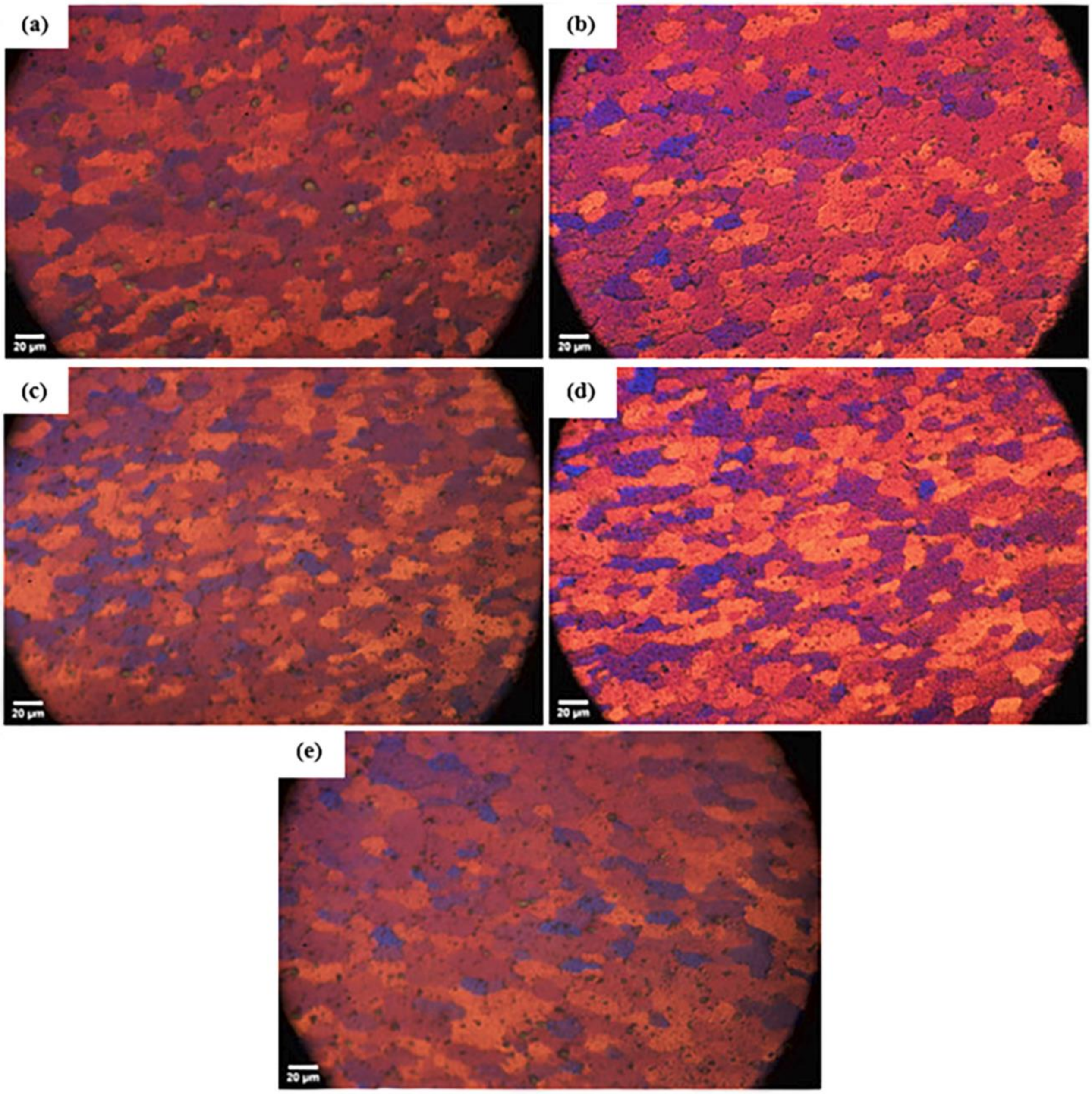


Figure 10. Polarized images of (**a**) nanocomposites produced at 1200 rpm, (**b**) nanocomposites produced at 1300 rpm, (**c**) nanocomposites produced at 1400 rpm, (**d**) nanocomposites produced at 1500 rpm, and (**e**) matrix produced at 1200 rpm. Reprinted from Ref. [76].

Abbasi-Nahr et al. [77] show that it is also possible to produce Al hybrid nanocomposites successfully with additive friction stir deposition. The authors used the AA5083 as a matrix and nano TiB and diamond. The nanocomposites were deposited using different rotation speeds and two different feed rates. Figure 11 presents the macrographs of the nanocomposites produced using different conditions. The microstructural characterization revealed that the nanocomposites improve properties for a rotation speed of 900 rpm and 12 mm/min feed rate.

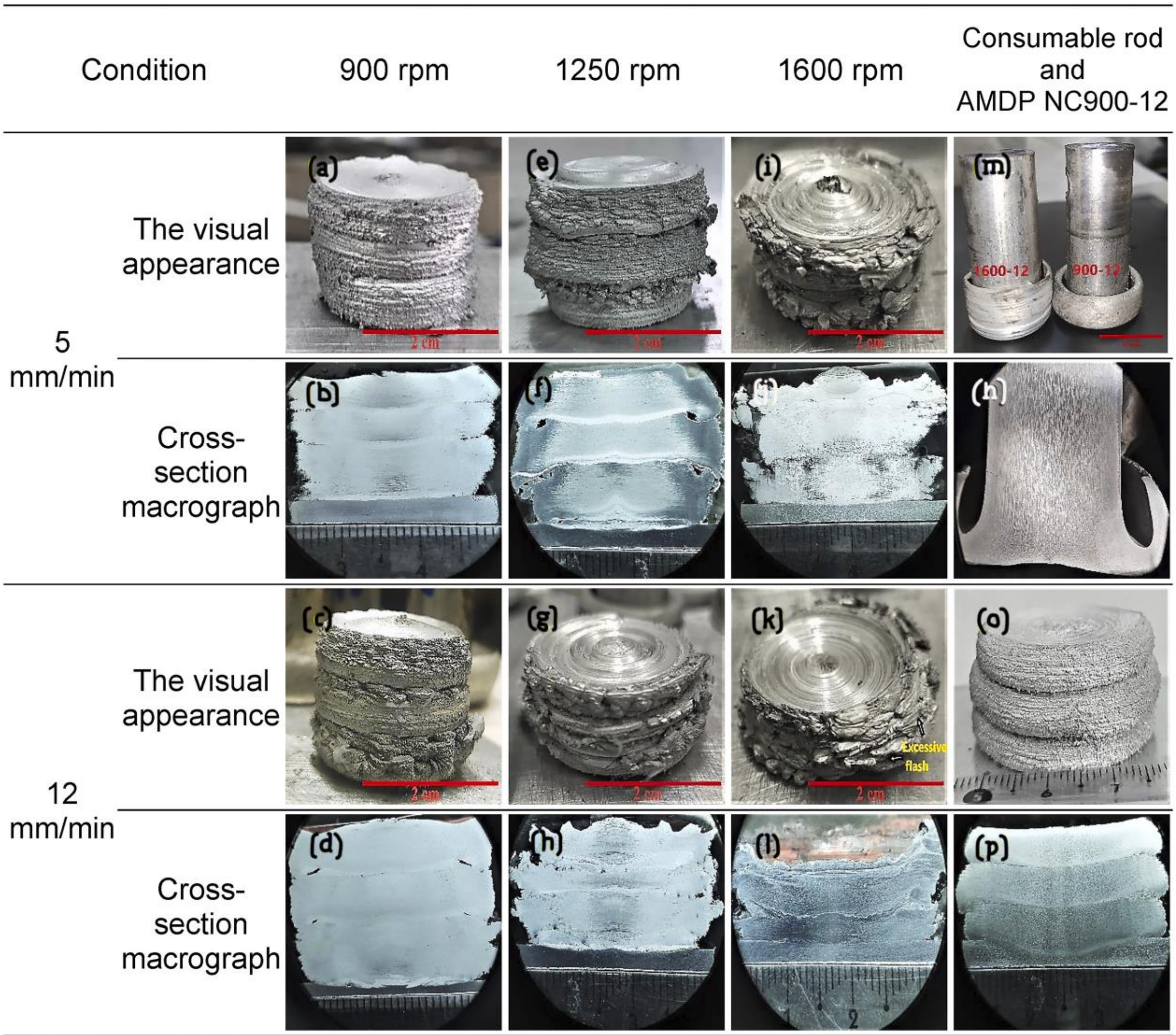


Figure 11. Images of the nanocomposites produced using different processing conditions (**a**–**d**) 900 rpm; (**e**–**h**) 1250 rpm; (**i**–**l**) 1600 rpm and (**m**–**p**) consumable rod and AMDO NC900-12. Reprinted from Ref. [77].

Figure 12 shows images of the microstructural characterization of the sample deposited at 1600 rpm with 12 mm/min. Based on the observation of the microstructure of the consumable tool, it is possible to observe that the plastic deformation induces the formation of recrystallized grains (Figure 12). Figure 12b shows a severe deformation between the substrate and deposited material. Larger grains are observed in the thermo-mechanically affected zone (TMAZ), as shown in Figure 12c. An increase in rotational velocity promotes a higher heat input in the composite parts that greatly influence the microstructure. This will affect the properties of the nanocomposites. Based on the microstructural and mechanical characterization, the authors found that the optimum parameters for fabricating a deposited high-performance part were found to be a rotation speed of 900 rpm and a deposition feeding rate of 12 mm/min, with homogeneous distributions and equiaxed fine grain size.

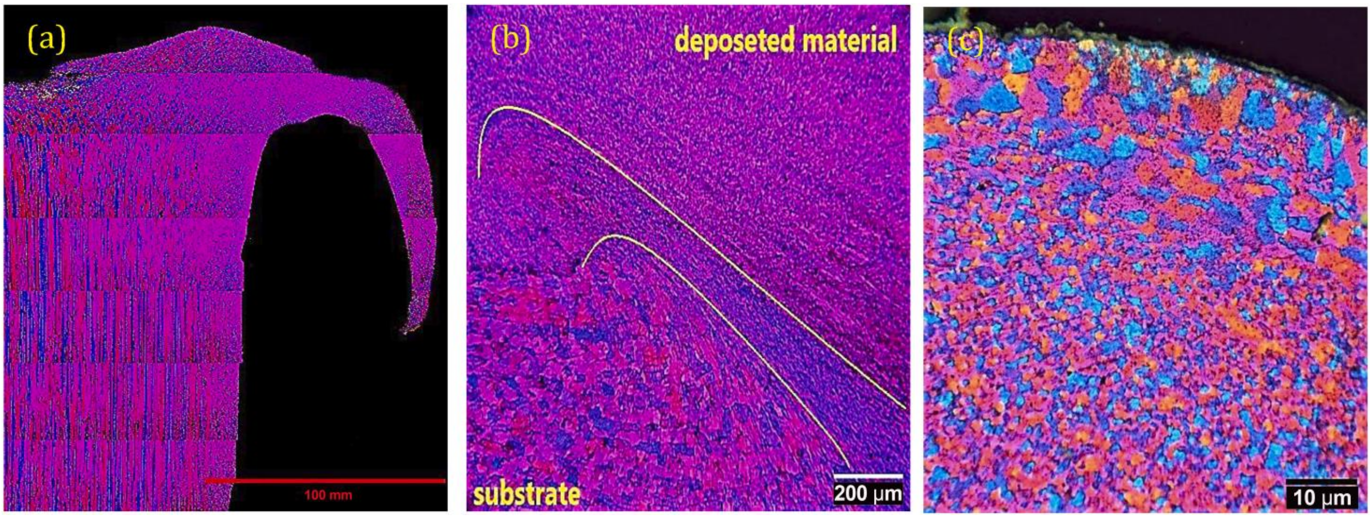


Figure 12. Optical microscopy images of (**a**) AA5083-H321 consumed rod, (**b**) interface region between the AA5083 rod/substrate, (**c**) TMAZ of the deposited sample using 1600 rpm with 12 mm/min Reprinted from Ref. [78].

Furthermore, rapidly prototyping and iterating designs using additive manufacturing facilitates innovation in developing HMMCs. Researchers can quickly test and evaluate new material combinations and geometries, accelerating the development cycle for advanced materials [78]. This rapid prototyping capability is particularly beneficial in the aerospace industry, where the demand for lightweight, high-performance materials constantly evolves. Challenges remain despite the numerous advantages of using additive manufacturing to produce HMMCs. Issues such as porosity, residual stresses, and the need for post-processing treatments can affect the mechanical properties of the final product. Ongoing research is focused on optimizing processing parameters and developing new techniques to mitigate these challenges, ensuring that HMMCs produced via additive manufacturing meet the stringent requirements of high-performance applications.

In conclusion, producing hybrid metal matrix composites through additive manufacturing presents a transformative approach to materials engineering. The ability to tailor material properties, optimize microstructures, and minimize waste positions additive manufacturing as a key technology in developing advanced composites for aerospace and other demanding applications. As research advances, the potential for HMMCs to revolutionize material design and manufacturing processes remains substantial, paving the way for innovative solutions in various industries.

3.4. Stir Casting

The production of aluminum hybrid nanocomposites through stir casting has garnered significant attention in materials science due to the enhanced mechanical, thermal, and tribological properties these materials exhibit. Stir casting is a widely adopted method for fabricating MMCs, particularly aluminum-based composites, owing to its simplicity, cost-effectiveness, and ability to achieve uniform dispersion of reinforcements within the matrix. Incorporating hybrid reinforcements, such as ceramic and carbon-based materials, has been shown to improve the performance characteristics of aluminum composites further, making them suitable for various engineering applications.

The stir casting process involves melting the alloy in a crucible and then introducing the reinforcement materials into the molten metal while stirring. Figure 13 shows a schematic of the conventional stir casting process. This method allows for better distribution of the reinforcements, which is crucial for achieving the desired mechanical properties. Studies have demonstrated that the mechanical and thermal properties of aluminum hybrid nanocomposites can be significantly enhanced by the addition of reinforcements like alumina (Al_2O_3), silicon carbide (SiC), and graphene oxide (GO) [73,79–81]. For instance, Mohammed et al. [80,81] reported that incorporating alumina and graphene oxide in aluminum composites improved hardness and wear resistance due to the complex nature of alumina and the lubricating properties of graphene oxide.

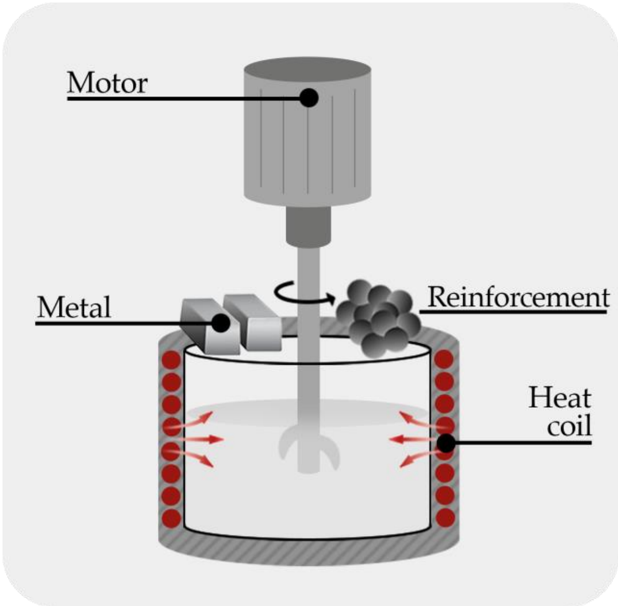


Figure 13. Schematic drawing of the conventional stir casting process.

Figure 14 shows the Al matrix and nanocomposites' hardness and specific wear rate reported by Mohammed et al. [80]. The hardness results of the different samples revealed that adding Al_2O_3 particles induces an increase in hardness. The best results for 0.25% of GO are observed for the hybrid nanocomposites. Regarding specific wear rates, the nanocomposites exhibit a reduction in wear rate.

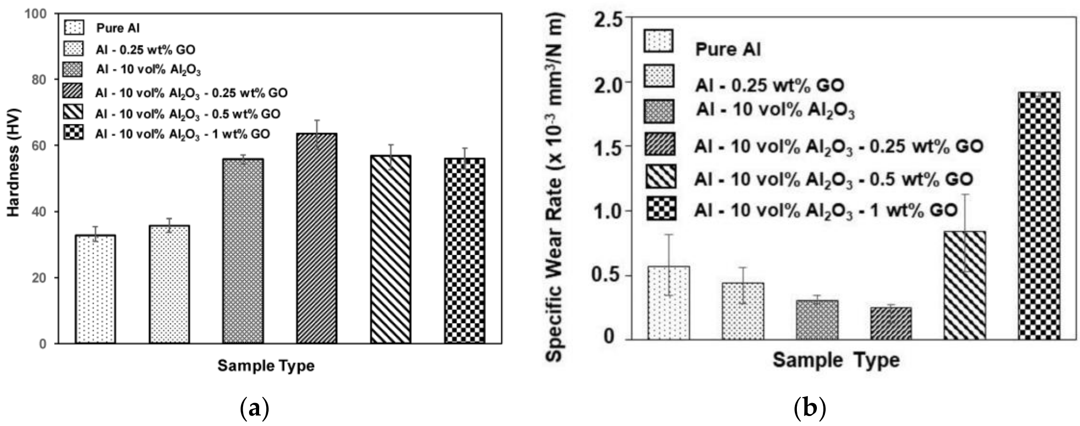


Figure 14. (**a**) Hardness and (**b**) wear rate of Al matrix and nanocomposites produced by stir casting. Reprinted from Ref. [80].

The effectiveness of stir casting in producing aluminum hybrid nanocomposites is also influenced by various processing parameters, such as stirring speed, temperature, and the type and amount of reinforcement used. Venkatesh et al. [82] highlighted that optimizing these parameters can significantly improve the mechanical properties of the resulting composites, achieving ultimate strengths of up to 156 MPa and hardness values reaching 431.4 Mpa. Furthermore, ultrasonic assistance during the stir casting process has been shown to enhance the dispersion of nanoparticles, leading to finer grain structures and improved mechanical properties [83].

The selection of reinforcements plays a critical role in determining the final properties of aluminum hybrid nanocomposites. The combination of different types of reinforcements can lead to synergistic effects that enhance the overall performance of the composite. For example, ceramic- and carbon-based reinforcements can improve the aluminum matrix's wear resistance and mechanical strength [84,85]. Abushanab et al. [84] explored the effects of varying fly ash and vanadium carbide contents in hypereutectic Al-Si alloy-based hybrid nanocomposites, demonstrating that the mechanical properties could be tailored by adjusting the reinforcement composition. Jiang and Yu [85] show that combining liquid-state blowing and ultrasonic-assisted casting is a good approach to producing Al hybrid nanocomposites. Figure 15 shows the mechanical properties obtained for the Al reinforced with Al_2O_3 and SiC. The best results are observed for the hybrid nanocomposites. The increase in yield strength corresponds to 45% in terms of the mechanical properties of the matrix.

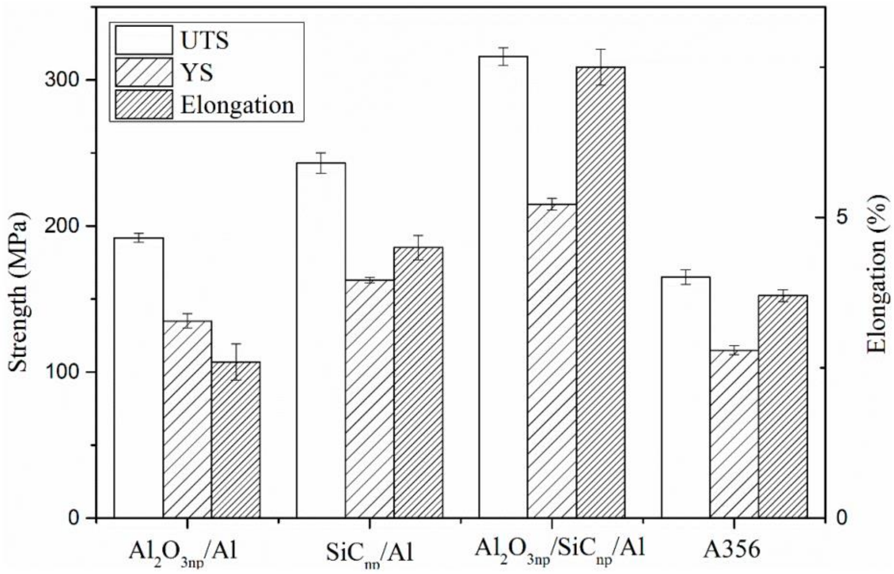


Figure 15. The yield strength (YS), elongation, and ultimate tensile strength (UTS) of the matrix of different nanocomposites. Reprinted from Ref. [85].

Moreover, the microstructural characteristics of aluminum hybrid nanocomposites produced by stir casting are crucial for their performance. The uniform distribution of reinforcements within the aluminum matrix is essential for achieving optimal mechanical properties. Sambathkumar et al. [86] utilized a two-step stir casting process to ensure a homogeneous distribution of B_4C reinforcements in Al7075 composites, improving wear resistance and tensile strength. This highlights the importance of processing techniques in achieving the desired microstructure and, consequently, the mechanical properties of the composites.

In addition to mechanical properties, the corrosion behavior of aluminum hybrid nanocomposites is also a significant consideration, especially for applications in harsh environments. The incorporation of reinforcements can influence the corrosion resistance of the aluminum matrix. For instance, studies have shown that adding alumina and SiC can enhance the corrosion resistance of aluminum composites, making them suitable for aerospace and automotive applications [87]. The corrosion behavior of these composites can be further optimized by controlling the microstructural features through processing techniques such as stir casting.

The tribological performance of aluminum hybrid nanocomposites is another critical aspect that has been extensively studied. The wear resistance of these materials can be significantly improved by adding hard reinforcements. For example, the specific wear rate of aluminum composites reinforced with alumina and graphene oxide decreased with the increasing reinforcement content, indicating enhanced wear resistance [88]. This improvement is attributed to the hard nature of the alumina particles and the lubricating effect of graphene oxide, which reduces friction during sliding contact. The versatility of stir casting allows for incorporating various reinforcements, including nanoparticles, which can further enhance the properties of aluminum hybrid nanocomposites. Using nanoparticles, such as carbon nanotubes (CNTs) and graphene, has significantly improved aluminum composites' mechanical and thermal properties [89,90]. The unique properties of these nanomaterials, such as their high strength-to-weight ratio and excellent thermal conductivity, make them ideal candidates for reinforcement in aluminum matrices.

The production of hybrid copper composites via stir casting is a promising approach combining various materials' benefits to enhance mechanical properties. The process parameters play a crucial role in determining the final characteristics of the composites, making careful optimization essential for achieving the desired performance in aerospace industries.

In conclusion, producing hybrid nanocomposites through stir casting presents a promising avenue for developing advanced materials with superior mechanical, thermal, and tribological properties. The ability to tailor the properties of these composites through the careful selection of reinforcements and optimization of processing parameters makes them suitable for a wide range of applications in industries such as aerospace, automotive, and construction. Ongoing research in this field continues to explore new reinforcement combinations and processing techniques to enhance hybrid nanocomposites' performance further.

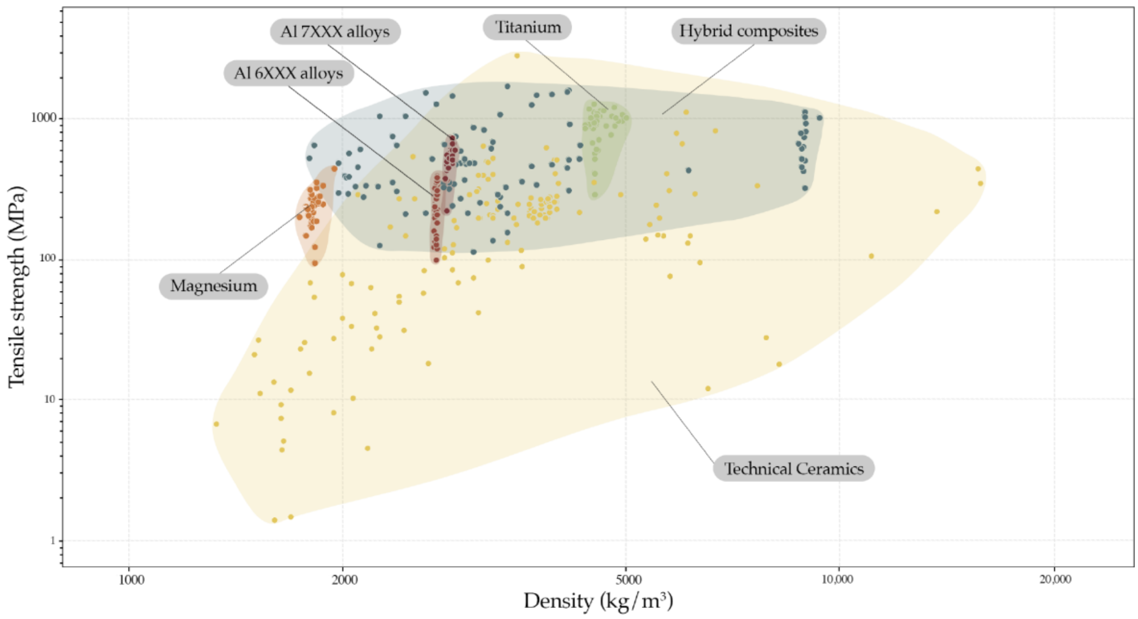
3.5. Mechanical Properties of the Hybrid Metal Matrix Nanocomposites

Analyzing strength properties in HMMNCs, particularly in aircraft applications, requires a comprehensive understanding of various mechanical properties, including hardness, yield strength, plasticity, toughness, and wear resistance. Integrating different reinforcements into a metal matrix, such as copper and aluminum, can significantly enhance these properties, making them suitable for demanding aerospace applications.

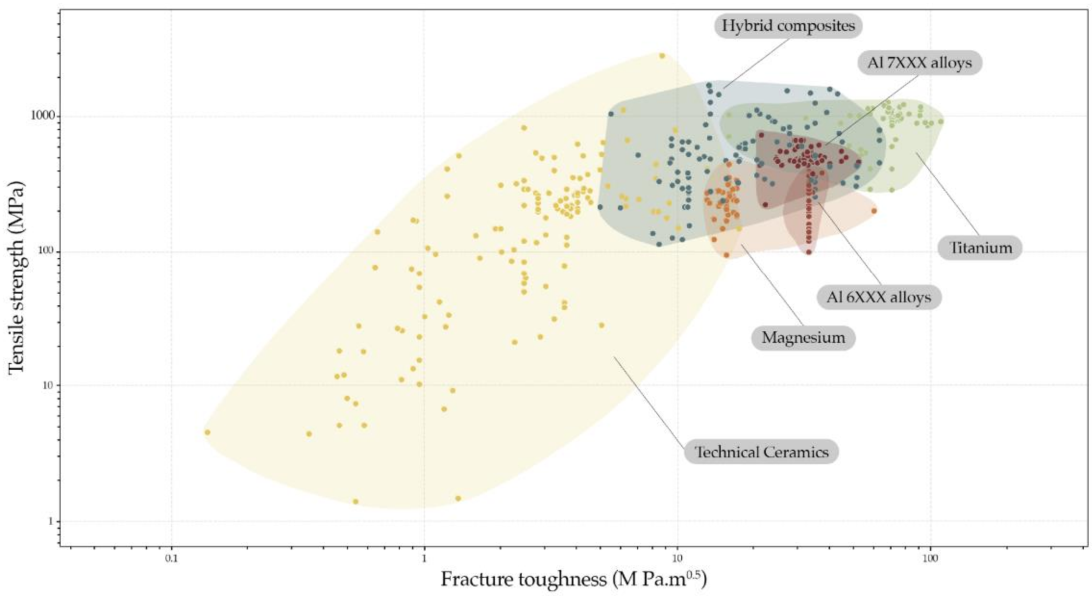
One of the primary advantages of hybrid composites is their ability to exhibit superior hardness and yield strength compared to traditional materials. For instance, incorporating graphene nanoplatelets (GNPs) into copper matrices has significantly enhanced mechanical properties. The intrinsic strength of GNPs, which can reach up to 125 Gpa, contributes to the overall strength of the composite. At the same time, the homogeneous dispersion of these nanoparticles within the copper matrix leads to refined grain structures, further improving strength through the Hall–Petch relationship [91]. This phenomenon illustrates the critical role of reinforcement distribution in achieving enhanced mechanical properties. In addition to hardness and yield strength, plasticity and toughness are crucial for materials used in aircraft applications, where the ability to withstand dynamic loads and fracture is dominant. Research has indicated that adding carbon nanotubes (CNTs) to copper matrices improves strength and enhances ductility, allowing for better plastic deformation under stress. The unique mechanical properties of CNTs, including their high tensile strength and stiffness, contribute to the improved toughness of the resulting composites, making them more resilient to impact and fatigue [92].

Figure 16 shows the comparison of mechanical properties and density between hybrid nanocomposites and metallic and ceramic materials

The type and proportion of reinforcements used can also influence the toughness of hybrid composites. For example, the combination of silicon carbide (SiC) and molybdenum disulfide (MoS_2) in aluminum hybrid composites has been shown to optimize mechanical properties, including toughness and wear resistance [93]. The self-lubricating properties of MoS_2, when combined with the hardness of SiC, create a composite that not only resists wear but also maintains structural integrity under high-stress conditions, which is essential for aerospace applications [93].



(**a**)



(**b**)

Figure 16. Comparison of mechanical properties and density between hybrid nanocomposites and metallic and ceramic materials: (**a**) relation between density and tensile strength and (**b**) relation between the fracture toughness with tensile strength. Graphs drawn based on data using Ansys Granta EduPack software R4.

Furthermore, the wear resistance of hybrid composites is a critical factor in their performance. Studies have demonstrated that the addition of hard ceramic reinforcements, such as alumina (Al_2O_3) and chromium carbide (Cr_3C_2) to copper or aluminum matrices, can significantly enhance wear resistance while maintaining other mechanical properties [94].

The uniform distribution of these reinforcements within the copper matrix leads to improved load-bearing capacity and reduced wear rates, which are vital for components subjected to friction and abrasion in aircraft systems [95].

The mechanical properties of hybrid composites can also be tailored through processing techniques. Stir casting, for example, allows for the effective mixing of different reinforcements, leading to a homogeneous composite structure that enhances mechanical performance [73]. The optimization of processing parameters, such as stirring speed and temperature, can further influence the microstructure and, consequently, the mechanical properties of the composites produced [95]. This adaptability makes stir casting a preferred method for fabricating hybrid metal matrix composites for aerospace applications.

The selection of nanoparticles for HMMNCs depends on their desired mechanical properties and application. Table 2 summarizes the main effect of the nanoparticles most commonly used in Al hybrid composites. When the goal is specific strength, CNTs and GO are ideal; for hardness and wear resistance, SiC and Alumina are beneficial; and for corrosion resistance with moderate toughness, TiO_2 is effective.

Table 2. Summary of the effect of the different nanoparticles on the Al hybrid composites.

Nanoparticle	Tensile Strength	Young's Modulus	Wear Resistance	Corrosion Resistance	Toughness
Carbon Nanotubes	×	×			
Graphene	×	×			
Silicon Carbide			×		
Alumina			×		
Titanium Dioxide				×	×

In conclusion, the strength properties of hybrid metal matrix composites, particularly in terms of hardness, yield strength, plasticity, toughness, and wear resistance, are significantly enhanced through the strategic selection and combination of reinforcements. Advanced materials, such as graphene and carbon nanotubes, alongside traditional reinforcements like silicon carbide, allow for the development of composites that meet the rigorous demands of aircraft applications. The ability to tailor these properties through processing techniques further underscores the potential of hybrid composites in advancing aerospace engineering.

3.6. Challenges in Fabrication and Scale-Up

Despite the promising potential of hybrid nanocomposites, several challenges must be addressed in their manufacture and scale-up for industrial applications. Achieving uniform dispersion of the nanoparticles in the matrix is essential to avoid agglomeration, which can lead to weak points and reduced material performance. Developing effective mixing techniques and nanoparticle surface treatments is crucial to overcoming this challenge. A strong interfacial bond between the matrix and the reinforcement is crucial for effective load transfer and increased mechanical properties. Poor bonding can result in delamination and reduce overall performance. Optimizing surface chemistry and processing conditions is necessary to improve bonding at the nanoscale. Many advanced manufacturing techniques, such as CVD and additive manufacturing, are currently limited by high costs and scalability issues. Developing cost-effective and scalable production methods is crucial for the widespread adoption of hybrid nanocomposites in industry. Each manufacturing technique has specific process parameters (temperature, pressure, time), which must be carefully controlled to obtain the desired microstructure and properties. The variability of these parameters can lead to inconsistencies in the material's performance. This is due to significant microstructural changes that will impact the final properties of the components. The use of nanoparticles raises environmental and health concerns due to their potential toxicity and the challenges associated with handling and disposing of nanomaterials. Developing safe and sustainable manufacturing processes is essential for the responsible use of nanocomposites. Solving these challenges is vital to realizing the full potential of hybrid nanocomposites, particularly in high-performance applications such as the aerospace industry, where the materials are subject to demanding conditions and must meet stringent safety and reliability standards. Ongoing research and development efforts aim to optimize manufacturing techniques and scale-up processes to meet these requirements effectively. Scaling up the production of aluminum-based nanocomposites, like Al6061 reinforced with SiC and graphite, involves several targeted strategies and methods to ensure that quality, consistency, and performance remain stable at larger volumes.

Powder metallurgy (PM) is commonly used in nanocomposite production because it controls particle size, distribution, and composition. Scaling up involves enhancing PM techniques to increase batch sizes while maintaining uniform dispersion of reinforcements like SiC and graphite throughout the aluminum matrix. Ensuring a consistent distribution of nanoparticles is crucial, as agglomeration is a significant challenge at larger scales. Scalable approaches, such as ultrasonic dispersion, ball milling, or high-shear mixing, are often optimized for larger batches. Newer techniques, like mechanical alloying and spark plasma sintering (SPS), help improve homogeneity in bulk production. Scaling up involves rigorous quality control methods like X-Ray diffraction (XRD), scanning electron microscopy (SEM), and in-line sensors to ensure that each batch meets consistent standards for particle dispersion, hardness, and mechanical properties. By refining these techniques and employing automation, manufacturers aim to scale up production while meeting the mechanical and wear-resistant properties required for high-stress applications, particularly in the aerospace and automotive industries.

4. Future Trends and Research Directions

As hybrid nanocomposites evolve, researchers focus on several key areas to further enhance their properties, expand their applications, and address existing challenges. Future and planned research trends include developing emerging materials and reinforcements, new manufacturing techniques, integrating innovative and adaptive features, and increasing emphasis on environmental and sustainability considerations.

One of the most exciting avenues for future research in hybrid nanocomposites is the exploration of emerging materials and novel reinforcements that offer unique or enhanced properties. High-entropy alloys (HEAs), which consist of several major elements, offer excellent mechanical properties and thermal stability. Research is exploring their use in hybrid nanocomposites to enhance strength, toughness, and resistance to extreme environments. Integrating nanoscale reinforcements into HEAs could lead to composites with unprecedented properties for aerospace applications.

Advancing the fabrication techniques for hybrid nanocomposites is crucial for optimizing their properties and scaling up production. The development of hybrid AM techniques that combine multiple printing methods (e.g., FDM with SLS or SLA) is a promising area of research. These techniques can enable the incorporation of different types of nanoparticles and create functionally graded materials with varying properties tailored to specific aerospace components. In situ synthesis techniques, where nanoparticles are formed directly within the matrix during fabrication, can achieve better dispersion and stronger bonding at the interface. Self-assembly methods, driven by specific chemical or physical interactions, can also be used to create ordered structures and hierarchical designs, improving the overall performance of nanocomposites. Plasma-assisted techniques, such as plasma-enhanced chemical vapor deposition (PECVD) and plasma spraying, are being explored for their ability to create nanocomposite coatings with unique properties. These methods can facilitate the uniform incorporation of nanoparticles and create surfaces with enhanced hardness, corrosion resistance, or catalytic activity.

Integrating innovative and adaptive features into hybrid nanocomposites is a burgeoning area of research that aims to create materials capable of responding to external stimuli or changing conditions. Developing nanocomposites with self-healing capabilities is a significant focus for enhancing the durability and lifespan of aerospace components. Incorporating microcapsules or nanocontainers filled with healing agents that release upon damage can automatically repair cracks and restore structural integrity, reducing maintenance and increasing safety. Embedding nanosensors and actuators within nanocomposites enables the creation of intelligent materials that can monitor their health or change properties in response to external stimuli. For example, incorporating piezoelectric nanoparticles (BT, PZT or ZnO) can allow a composite to generate an electrical signal when deformed, which is helpful for structural health monitoring in aerospace applications. Researchers are exploring materials that can adapt their thermal conductivity based on environmental conditions. These composites can regulate heat flow by integrating phase-change materials or thermally responsive nanoparticles, providing efficient thermal management for aircraft and spacecraft operating in extreme temperatures.

As the demand for greener technologies increases, future research in hybrid nanocomposites will also focus on environmental and sustainability considerations. There is a growing emphasis on using sustainable and eco-friendly raw materials, such as natural fibers or recycled nanoparticles, to reduce the environmental impact of nanocomposite production. Developing energy-efficient fabrication techniques that minimize waste and reduce carbon footprints is also becoming a priority. Ensuring that hybrid nanocomposites are recyclable and have a manageable end-of-life process is crucial for reducing environmental impact. Research is focused on developing composites that can be easily disassembled or repurposed after their service life, particularly in aerospace applications where materials are often replaced due to stringent safety requirements. Conducting comprehensive LCAs of hybrid nanocomposites is essential for understanding their overall environmental impact, from raw material extraction through production, usage, and disposal. This approach will guide the development of more sustainable composites and help identify areas for improvement in their design and manufacturing.

5. Conclusions

In conclusion, research into hybrid nanocomposites (based on aluminum or copper metallic matrices) for aerospace applications has made significant progress, opening new possibilities for designing and developing more efficient and multifunctional materials. Using nanostructures such as carbon nanotubes, graphene, metallic nanoparticles, and ceramic materials, combined with metallic matrices, has made it possible to obtain composites with improved mechanical, thermal, and electrical properties, overcoming many challenges conventional materials face. These hybrid nanocomposites stand out for their high mechanical strength, high energy dissipation capacity, better thermal stability, and excellent performance in extreme conditions. These are essential attributes for aerospace applications where safety and durability are critical.

In addition to superior structural properties, these new materials provide additional functionalities, which contribute to creating more intelligent and integrated components for aircraft and spacecraft. Such features are highly desirable in the aerospace sector, as they allow lighter and more fuel-efficient aircraft to be built without compromising safety and reliability. The integration of functionalities such as real-time monitoring of structural damage and adaptive responses to variable loads could, in the future, revolutionize the way aircraft and space structures are designed and operated.

However, despite promising advances, several challenges must be addressed before these materials can be fully adopted in practical applications. Issues related to the homogeneous dispersion of nanomaterials in the matrix (prevention of an agglomeration during synthesis), control of the interface between components, and the scalability of manufacturing processes still represent significant obstacles. Understanding the complexity of multiphase behavior and how different properties interact and complement each other within nanocomposites requires further investigation. In addition, evaluating these new materials' long-term performance and reliability under extreme environments and intensive load cycles is essential to ensure their suitability in the aerospace sector.

Although there is still a long way to go to overcome these challenges, the results obtained so far indicate that hybrid nanocomposites can redefine the standards of performance and functionality in the aerospace field. With continued investment in research and development, these materials are expected to advance to large-scale applications rapidly, playing a crucial role in developing more efficient, safer, and sustainable next-generation aircraft and space vehicles. Thus, the future of hybrid nanocomposites points to the consolidation of a new era of innovation and technological progress in the aerospace sector, with positive impacts not only in terms of structural performance but also in optimizing costs and reducing environmental impacts.

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