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APPLICATION OF METAL MATRIX NANOCOMPOSITES IN ENGINEERING

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Abstract:
Nanocomposites nowadays, have the tendency to replace conventional composite materials in many commercial products. These composites find application in a diverse range of fields, including computer components, data storage systems, various membranes and filters, as well as advanced materials in the automotive and aerospace industries. They are available in different forms and from various manufacturers, providing a wide selection. Although they may be more expensive, compared to conventional materials, the ability to customize the properties of nanocomposites to the specific needs of end-users makes them highly attractive and innovative. International scientific bodies, including International Standards Organization (ISO), are actively working on formulating standards to regulate the safe use, disposal and recycling of nanowaste. The importance of standardization will grow with the expansion of the market for metal matrix nanocomposites. The aim of this paper is to review the existing research on metal matrix nanocomposites and their application to achieve significant improvements in the chemical, aerospace, automotive and other industries.

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1. INTRODUCTION

Metal Matrix Composites (MMCs) are widely used today in various industrial applications, as they represent materials whose characteristics can be fully adapted to the industry's needs through different production methods. The composite structure consists of a "matrix" or "base," providing the structural framework for integrating the reinforcement. Reinforcements are components inserted into the composite base to achieve structural strengthening, which can lead to changes in various material properties. This change in properties may include wear resistance, thermal conductivity and other significant properties. The basic idea is to create a composite material with improved properties by combining the appropriate characteristics of different components [1]. The modification of composites characteristics includes changing the type of matrix, type, shape, size or concentration of the reinforcement [1,2].

The basic classification of composites is according to the type of matrix material. It includes composites with a polymer matrix, Polymer Matrix Composites (PMC), composites with a ceramic matrix, Ceramic Matrix Composites (CMC) and composites with a metal matrix Metal Matrix Composites (MMC). According to the shape of the reinforcement, composites can be divided into particle-reinforced composite materials, fiber-reinforced composite materials (where the fibers can be long or short), as well as structural composites (which include laminar composites and composites with a sandwich structure). According to

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the dimensions of the reinforcements, composite materials can be divided into macrocomposite (with constituents visible to the human eye), microcomposite (with constituents visible under a microscope) and nanocomposite (where the constituents are of nano size) [3].

The aim of this paper is to review the previous research on metal matrix nanocomposites with examples of their application in order to achieve significant improvements in the chemical, aerospace, automotive and other industries.

2. METAL MATRIX NANOCOMPOSITES

The matrix material in these composites is usually lighter metals, such as aluminum (Al), magnesium (Mg), titanium (Ti), copper (Cu) and their alloys, that serve as a support for the secondary phase or reinforcement. Carbides, ceramics or borides are often used as reinforcement material [3,4]. Using nano reinforcements, whose smallest dimension is less than 100 nanometers, can significantly reduce the number of disadvantages of conventional metal-based composites, such as poor machinability, low ductility and low fracture toughness. Such materials, known as Metal Matrix Nanocomposites (MMNCs), open new perspectives for specific applications (for example in the automotive and aerospace industries). The main difference between nanocomposites and conventional metal matrix composites is that nanocomposites have an extremely high aspect ratio, which enables them to have special properties. MMNCs can thus be ideal for use in the automotive or aerospace industries, where advanced technical characteristics and performance are required [5–7]. In the chemical industry, nanotechnology can be used to develop new catalysts, sensors and materials with specific properties. In the electronic industry it leads to the development of components and devices of nano dimensions, such as nanotransistors and nanomemories. Nanotechnology in medicine has applications in various fields, including diagnostics, therapy and nanomedical technologies, such as nanosensors for rapid and accurate disease diagnosis. One of the challenges in the development of nanotechnology is to understand the connection between nanomaterials and the environment. This includes investigating potential toxicological and environmental effects. There is a need to develop standards and regulations to ensure the safe and responsible use of nanomaterials. The integration of nanotechnology into industrial processes also depends on the development of new manufacturing technologies and devices. Research in the field will be the key in shaping the future of the industry [7–9].

2.1 Production of Metal Matrix Nanocomposites

There are different reinforcement phases of nanocomposites, which can be zero-dimensional (core-shell structures), one-dimensional (such as nanotubes) and two-dimensional (laminar). Based on these characteristics, nanocomposites can be divided into various subcategories, such as nanoparticle, nanofiber and nanosheet reinforced composites. This diversity allows engineers and scientists to design materials with specific properties for various applications. The properties of nanocomposites, such as mechanical, thermal, catalytic, electrochemical and optical properties, depend on the materials used in their production [7,10]. The production processes for MMNCs can be divided into ex situ and in situ methods. Ex situ processes involve the production of reinforcement nanoparticles prior to their addition to the matrix, while in situ processes refer to generating the reinforcements during the production process itself, often through controlled reactions. Within ex situ processes, the production of MMNCs can be carried out in liquid, solid and semi-solid states. Liquid state processes are attractive due to their simplicity and low cost. However, they may face challenges with the dispersion of nanoparticles, which can negatively impact the mechanical properties of the nanocomposite. Examples of ex situ processes include stir casting, ultrasonic-assisted casting, infiltration process, the deposition of disintegrated and high pressure die casting. Solid-state processes include different powder metallurgy techniques with modifications in the processing steps, such as high-energy ball milling, hot pressing, hot isostatic pressing, and cold pressing followed by sintering treatment and extrusion. Semi-solid processes include thixotropic and rheological techniques with its variants such as compo casting or in combination with squeeze casting. A description of the production methods mentioned for MMNCs is presented in the study by Ceschini et al. [11]. It is also possible to combine different manufacturing processes to obtain MMNCs. This diversity in production methods allows engineers to select the most suitable methodology to achieve the desired properties of nanocomposites according to specific requirements and applications. Various fabrication methods for MMNCs have been explored by researchers such as Wang and Moneta, as well as Saxena et al., and others [12–16].

3. APPLICATION OF METAL MATRIX NANOCOMPOSITES

In modern engineering and automotive manufacturing, advanced materials are increasingly used to achieve better performance and efficiency. Due to their sound characteristics in terms of wear resistance and good thermal conductivity in combination with satisfactory specific strength, MMNCs are a suitable choice for the production of aircraft brakes [17]. Also, due to their sound characteristics in terms of modulus of elasticity and specific strength, they can be used in the sports industry to produce sports props and equipment (racquets, bicycle frames, etc.). Due to good thermal conductivity, electrical devices are used in the production of heat exchangers, the role of which is to remove heat from electronic components. In addition to the mentioned applications, these materials can be used in the automotive, aviation and space industries to develop and manufacture aircraft stabilizers, heat exchangers, cylinder liners, disc brakes and brake calipers. In addition to the previously mentioned applications, metal nanofiber composites are used in the production of pipes for Selective Catalytic Reduction (SCR), heating cables for automotive seats, and AdBlue reservoirs. In the aviation and space industry, they are used when making jet engines, and they can also be used as a protective coating due to their resistance to heat, corrosion and UV radiation [18–21].

3.1 Aluminum Based Metal Matrix Nanocomposites

Aluminum Metal Matrix Nanocomposites (AMMNCs) represent a material with superior mechanical and tribological properties compared to other metal matrix composites. In the production of AMMNCs, as reinforcements, mainly used are particles of MgO, SiC, B_4C, TiC, AlN, ZrO_2, Si_3N_4, Al2O3, and TiO_2. AMMNCs materials can be produced in any complex shape depending on the production method [22,23]. Due to the uniform distribution of nanoparticles in the matrix, these nanocomposites possess improved properties, including higher specific stiffness, higher strength and ductility compared to unreinforced aluminum, better creep resistance, thermal stability and wear. It is particularly important to note that AMMNCs reinforced with SiC are exceptionally significant due to their excellent mechanical properties and wear resistance. For instance, SiC has a high melting temperature of 2730°C, making it especially suitable for high-temperature conditions. It can be concluded that AMMNCs represent an advanced material with a wide range of applications in the aerospace and automotive industries, offering lightweight, durability and wear resistance [24]. Singh et al. [25] dealt with the method of manufacturing Al-CNTs (carbon nanotubes) by combining ball milling and spark plasma sintering. Based on the experimental results, they concluded that the mechanical properties of aluminum, in terms of tensile strength, increased from 105 MPa to 217 MPa, by adding CNTs at a value of 0.5%. Also, with the increase in strength, there was a decrease in ductility, from 41.9% to 4.7%. AMNCs have a broad range of applications, including in the automotive and aerospace industries. In the automotive industry, AMNCs are successfully used for manufacturing various components, such as clutches, brakes and mechanical seals. Potential applications of aluminum nanocomposites in the automotive industry include components such as pistons, cylinder blocks/liners, brake discs and connecting rods [26,27]. These components require materials with exceptional mechanical properties and wear resistance, which AMNCs provide [23]. In the context of aerospace applications, the Hubble Space Telescope, managed by the National Aeronautics and Space Administration (NASA), is another example of AMNC usage. The antenna booms on the Hubble Telescope (Fig. 1) are made of aluminum and are reinforced with graphite fibers.

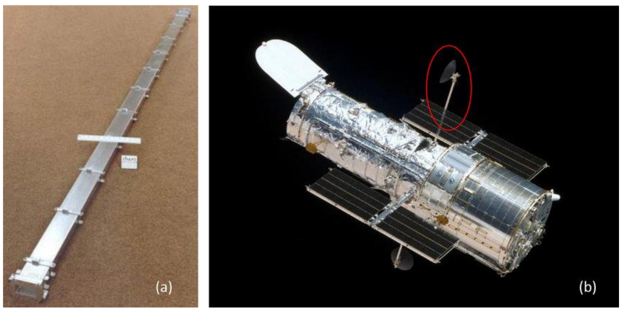

Fig. 1. Hubble telescope high gain antenna [28]

This design helps create lightweight and highly durable components, which is crucial for the demanding conditions of space. These examples illustrate the broad range of applications for AMMNCs and their importance across various industries where lightweight, strength, and durability are critical factors [28].

3.2 Nickel Based Metal Matrix Nanocomposites

Nickel (Ni) is a metal with a high sintering temperature and mechanical strength higher than aluminum. Due to its unique properties, such as corrosion resistance, reduced friction, and wear resistance, nickel has become an increasingly common subject of research [29]. Significant improvements in the mechanical properties of nickel metal matrix nanocomposites have been achieved when carbon nanotubes are used as reinforcements. This is possible because nickel has a low tendency to form carbides at the interface with carbon, which would typically have a negative impact on the mechanical performance of these composites. Such research opens new possibilities for the application of nickel matrix nanocomposites in industries where mechanical strength and wear resistance are critical [30].

Research has also demonstrated significant improvements in both mechanical and electrochemical properties of nickel metal matrix nanocomposites reinforced with SiC particles. As a result of this process, a nanocomposite known as "Nikasil" has been produced; this is widely used in the manufacturing of piston rings and cylinders (Fig. 2) [31].

Fig. 2. Nikasil coated cylinders [31]

The main advantage of Nikasil is its durability under high temperatures and high pressure, making it ideal for use in racing engines. Due to its excellent properties, Nikasil and similar coatings are still widely used in racing engines, including those in Formula 1 [32,33].

Research conducted by Wasekar et al. [33] focused on the tribological performance of heat-treated Ni-W/SiC nanocomposite coatings, emphasizing the effect of SiC particle content on mechanical and wear properties. Heat treatment improved hardness due to grain boundary relaxation and grain growth. At the same time, the wear rate and frictional behavior were found to depend on inter-particle spacing, following the inverse rule of mixtures. Additionally, the study revealed that the wear rate primarily depended on the volume fraction of SiC particles. This research highlighted the importance of heat treatment as a method for enhancing the mechanical properties and stability of nanocomposite coatings [33].

Due to their exceptional mechanical properties and superior corrosion resistance, nickel metal matrix composite coatings are mostly used in the aviation and automotive industries. These coatings are particularly useful in applications requiring high durability and wear resistance. In addition, they are used in various engineering applications where the functional properties of coating materials are of key importance, such as electrochemical protection and increased resistance to erosion [34].

This composite material similarly offers a combination of exceptional resistance to wear, heat dissipation, thermal shock, strength, durability, metallurgical integrity, workability, and weldability. Additionally, its ability to perform under various operating conditions, including high temperatures, makes it comparable to creep-resistant materials. Nickel and nickel alloys of world-class use are widely used in steel, marine, aero industry, watches, cars, PCs, etc. [35].

In the review paper [35], the mechanical and tribological properties of nickel-based composite materials were investigated, with a focus on enhancing their properties by incorporating reinforcing particles such as SiO_2, Gr, Ag and hBN. The papers analyzes the impact of these additions on hardness, durability and wear resistance, providing insight into the potential of particle-reinforced composites for advanced applications in industries requiring high mechanical and tribological performance.

3.3. Cooper Based Metal Matrix Nanocomposites

The development of copper-based composites originated from the need to enhance the strength of pure copper. By adding various nanoreinforcements, strength can be increased; however, this often results in a reduction in conductivity, which is practically undesirable. Graphene is considered the most effective reinforcement for copper metal matrix composites, as it simultaneously improves the material's strength and conductivity. However, the interface between copper and graphene is weak, leading to very poor bonding between these materials. Addressing this issue involves methods similar to those used for AMMNC, such as improving preparation processes and employing new technological methods like molecular-level mixing. These advanced methods aim to enhance the interaction between copper and graphene, achieving better integration and improved performance of the nanocomposite material [36].

Chen et al. [36] utilized molecular dynamics simulations in their research of copper metal matrix nanocomposites reinforced with graphene. The results suggest that graphene can significantly enhance the modulus of elasticity and yield strength of the nanocomposites. Additionally, plastic deformation in the nanocomposites was primarily observed as sliding along the graphene surfaces. This indicates the significant impact of the interfacial properties between graphene and copper on the performance of the nanocomposites. Research investigating the tribological properties of lubricating oils containing nanoparticles of CuO, TiO_2 and diamond has shown that CuO nanocomposites exhibit exceptional anti-friction and anti-wear properties. This finding has significant implications for the application of CuO nanocomposites in areas where tribological properties are crucial, such as in the lubrication of various machines and mechanisms. Additionally, nickel and copper nanoparticles are materials that can be directly applied or combined with noble metals to facilitate hydrogenation in biofuel production [36–38].

3.4 Titanium Based Metal Matrix Nanocomposites

Titanium alloys are highly desirable structural materials widely used across various industrial sectors due to their high strength, low density and exceptional corrosion resistance. However, their application is limited in parts subjected to frequent friction and wear because of their relatively low hardness and inadequate tribological properties. This includes a high and unstable coefficient of friction and low wear resistance [39].

Experimental studies have shown that the properties of motor oils are significantly improved by the addition of TiO_2 nanoparticles. This enhancement includes a reduction in the friction and wear rate, as well as an increase in the efficiency and longevity of the oil. This opens up possibilities for improving the tribological properties of titanium alloys and applying them in areas where maintaining low friction and preventing wear are of utmost importance [36–40].

Researchers have explored ways to enhance the tribological properties of titanium alloys, with a focus on the Ti–6Al–4V alloy. The goal was to provide adequate mechanical support through thin, hard nanocomposite coatings. The studies found that applying nanocomposite coatings to softer materials, such as pure titanium or Ti–6Al–4V alloy, could actually degrade their properties. Consequently, it was concluded that hard nanocomposite coatings should be applied to hard substrates, such as ceramics or hardened steel, to improve tribological characteristics. These findings have a significant impact on the potential application of nanocomposite coatings in components exposed to wear and sliding in the automotive and aerospace industries. Enhanced tribological characteristics on hard substrates can contribute to increased durability and efficiency of these components [39–41]. Titanium metal matrix nanocomposites have the potential to replace steel in engine shafts. A key factor for the successful application of Ti metal matrix nanocomposites in engines is the establishment of high-quality processing with adequate process control.

3.5 Magnesium Based Metal Matrix Nanocomposites

Metal matrix nanocomposites based on magnesium are significant materials in the automotive and aerospace industries due to their optimized properties. Successful metallurgical processes for producing these nanocomposites, which use ultrasonic methods to disperse nanoparticles during melting, have proven to be highly effective. Adding small amounts of nanoparticles has achieved exceptional effects on the mechanical properties of the base alloy, whether it is pure magnesium or magnesium alloys [42].

Magnesium, being the lightest structural material, offers numerous opportunities for reducing the weight of components, which is particularly important for the aerospace and automotive industries. Automotive manufacturers are expected to use 400–100 kg of magnesium alloys in the future, which is in line with Corporate Average Fuel Economy (CAFÉ) standards and other environmental regulations [43].

Research has shown that the wear of magnesium metal matrix nanocomposites with graphene addition is significantly lower compared to magnesium alloys without graphene, which is due to the self-lubricating effect of graphene. Over the past thirty years, magnesium alloys have become widely used in the automotive industry, communications, consumer electronics and computing due to their favorable characteristics, including good mechanical properties and low density. Specifically, in the automotive industry, using magnesium alloys for manufacturing engine blocks could significantly reduce vehicle weight, leading to decreased fuel consumption and improved efficiency [11,44,45].

The use of 72 kg of magnesium-based nanocomposites can replace 48.5 kg of steel and 19.5 kg of aluminum alloys [43]. In 2004, BMW began the production of the N52 engine (Fig. 3), which was the first water-cooled engine to utilize a composite construction of magnesium and aluminum in the engine block. This engine ensured a reduction in weight without compromising durability [46].

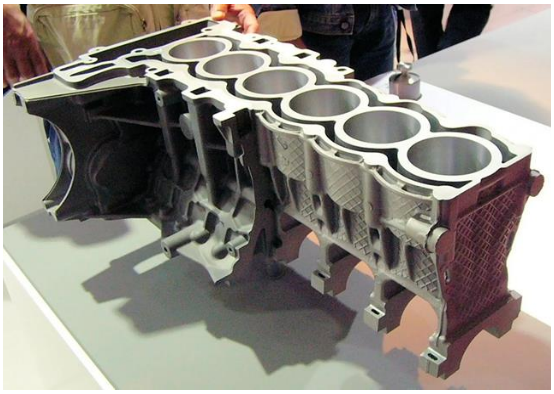

Fig. 3. BMW engine [46]

Currently, magnesium-based nanocomposites are not widely available. However, due to their low weight, exceptional dimensional stability and good mechanical properties, magnesium-based nanocomposites can potentially replace magnesium alloys in various sectors, in addition to the previously mentioned applications, including electronics and biomedicine [47].

3.6 Silver Based Metal Matrix Nanocomposites

Pure silver (Ag) has a high thermoelectric conductivity, so it is usually used with reinforcements such as copper, zinc, manganese or aluminum alloys to obtain suitable characteristics for various industrial applications. The results of tribological tests of silver-based nanocomposites showed that the increased concentration of aluminum oxide directly affects its surface, which leads to a decrease in the coefficient of friction and the wear rate. These improvements make the silver-based material highly suitable for various industrial applications [48]. Research by Paturi et al. [49] involved adding silver nanoparticles to an emulsifier oil, polysorbate 80, to provide a cooling, lubricating and friction-reducing fluid during machining. This fluid is adaptable for use with a minimum amount of lubricant, making it environmentally friendly.

Future applications of silver-based nanocomposites could include aerospace motors, electrical contacts and friction bearings. These materials have the advantage of a good lubrication effect and the ability to withstand high thermal stress during high frictional forces. Although there are few studies on the application of silver-based nanocomposites in the automotive industry, research and development in this direction could bring new opportunities for improvements in the field of tribology and materials [48,49].

4. STANDARDIZATION AND THE MARKET

The European Commission's Regulatory Committee and other bodies have concluded that certain nanomaterials used in specific applications are toxic, underscoring the need for health and environmental risk assessments throughout their lifecycle. While standards exist through ISO and ASTM, current tests often focus on physical and chemical properties, neglecting toxicity. Developing new disposal procedures is crucial to ensure safety and prevent environmental harm.

ISO and other international organizations are working on standards for safe nanowaste disposal and recycling. A proposal suggests allocating 10% of nanotechnology R&D budgets to safety and sustainability. Research shows nanoparticles in emissions during municipal waste incineration, highlighting the need to study nanomaterials in waste treatment. Although green synthesis techniques show promise, challenges remain in scaling them to industrial levels, requiring further research [50].

The importance of standardization will increase with the growth of the MMCs market. The MMCs market is estimated to be worth around US$460 million in 2024 and is expected to reach around US$630 million by 2029. North America holds the largest market share, but the Asia Pacific region is predicted to take the lead in the next few years. Demand growth in countries such as China, India, Japan, and South Korea will contribute to the development of the MMCs market in that region (Fig. 4).

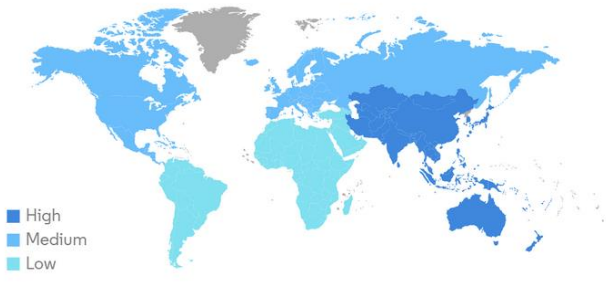

Fig. 4. MMCs market [51]

Also, the demand for electronic components, which are used in the production of mobile phones, laptops, and other personal devices, will contribute to the growth of the MMCs materials market [51].

New nano-based coatings (coatings) are widely used for surface functionalization and protection, which will also influence the increase in demand for nanomaterials in the coming period [52]. For example, the Inframat company introduced a series of nanocomposite coatings in 2020. These coatings, enriched with high concentrations of nanoparticles, offer improved wear and corrosion resistance, matching the needs of high-performance components in the aerospace industry [53]. Inframat's nanocoating powders include Al_2O_3/TiO_2, WC/Co, Cr_2O_3/TiO_2 and YSZ [54].

Nanocomposites have a smaller environmental impact than traditional composite materials, as their production requires less energy, and resources and they have better durability and recyclability. In addition, the use of nanocomposites in various industries can help reduce the weight of the final product, leading to a reduction in fuel consumption and emissions in the transportation sector.

Additionally, significant growth is expected in the metal nanocomposite segment during the forecast period. This growth can be attributed to the increase in demand for lightweight and high-strength materials in the automotive and aerospace industries. MMNCs stand out for their exceptional mechanical properties, including increased strength and toughness, improved wear and corrosion resistance and reduced thermal expansion. These characteristics make them ideal for a variety of applications, such as engine components, structural parts and aircraft interiors. Fig. 5 shows the MMC market forecasts for 2027 related to end users.

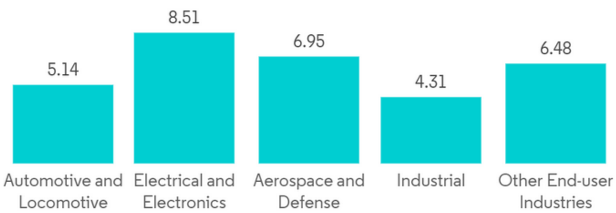

Fig. 5. MMCs Market by end-user industry [51]

In terms of revenue distribution in 2021, the automotive segment has emerged as dominant, but it is expected that by 2027, the electrical sector will take over that place. Given the continuous growth of the MMC market, the application of MMNC will also increase significantly in the coming period. This trend is logical, as technological advancements and the growing demand for materials with enhanced mechanical, thermal and other properties facilitate the broader use of nanocomposites, which offer additional advantages over traditional composites.

5. CHALLENGES IN RECYCLING MMNCs

Recycling is a critical factor in the commercialization of MMNCs, driven by the need to protect the environment, conserve energy and minimize waste. Stricter environmental regulations, particularly in industries such as automotive, have made recyclability increasingly important. Recycling requires significantly less energy compared to producing new materials and differs from reclamation, which involves separating reinforcement particles from the matrix when the material is no longer reusable. The primary challenge in recycling MMNCs lies in restoring their original microstructure and properties, as high temperatures and prolonged interaction between the matrix and reinforcement during the recycling process can lead to undesirable reactions and material degradation. Further research is essential to develop efficient, cost-effective and reliable recycling methods for MMNCs.

Paramsothy et al. [55] studied the influence of microparticle concentrations and their size on the mechanical properties of $AZ31/Al_2O_3$ nanocomposites and the possibility of their reuse after remelting. For the purposes of the experiment, they prepared samples of $AZ31/Al_2O_3$. During the preparation, Al_2O_3 particles with sizes of 50 nm, 300 nm and 1000 nm were used, with different concentrations of reinforcements in the range of 1.5%, 5% and 10%. After remelting the mentioned materials, the results showed no change in the tested samples' microstructure or mechanical properties. Pasha et al. [56] investigated the possibility of recycling magnesium nanocomposites containing Fe_3O_4 nanoparticles, with the aim of improving mechanical and tribological characteristics, for potential application in the automotive industry. The test was performed on a tribometer, under conditions without lubrication, under different loads, and at sliding speeds. The experiment results showed that the recycled nanocomposites have better wear resistance and a lower coefficient of friction than pure magnesium samples. Based on a comprehensive case study, it can be concluded that the application of recycled magnesium nanocomposites is environmentally justified and suitable for use in the automotive industry.

6. CONCLUSION

Nanocomposites are a new type of material that, in recent decades, has attracted the attention of researchers globally. For the purposes of various research projects, MMNCs have been reinforced with different types of materials, such as Al_2O_3, SiC, TiC, graphene, ZrB_2, TiO_2, AlN, and carbon nanotubes. These studies have investigated their influence on the characteristics of nanocomposites and explored the possibilities for exploiting these newly acquired properties. The mechanical characteristics of MMNCs largely depend on the properties of the reinforcement and matrix, as well as on interphase bonding, particle dispersion in the matrix, shape and size of particles, percentage of particle content and processing methods.

The integration of MMNCs into automotive, aerospace and other industrial sectors demonstrates their capability to enhance performance, efficiency, and sustainability. These materials offer lightweight, durable and customizable solutions for applications ranging from structural components and heat exchangers to aerospace coatings and electronic devices. Although they may be more expensive compared to traditional materials, their ability to be tailored to specific end-user requirements makes them highly innovative and attractive.

Future advancements in nanotechnology, coupled with the development of standardized recycling methods, are expected to further expand the applicability of MMNCs. The increasing emphasis on sustainability underscores the importance of responsible production and disposal of these materials. Moreover, the unique properties of MMNCs position them as key candidates for addressing challenges in space exploration, renewable energy, and advanced manufacturing.

In order to use the full potential of MMNCs, ongoing research should focus on optimizing their production processes, improving recyclability, and developing new applications. By bridging the gap between laboratory-scale innovations and practical industrial applications, MMNCs have the potential to significantly influence the future of materials science and engineering.

Conflicts of Interest

The authors declare no conflict of interest.

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