Chapter 6

Nano Reinforced Metal Matrix Composites

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Abstract

Nano Reinforced Metal Matrix Composites (NRMMCs) combine the strength and stiffness of metals with the exceptional properties of nanoscale reinforcements, such as nanoparticles or nanofibers. This chapter will inquire into the world of nano reinforced MMCs, exploring their properties, manufacturing techniques, characterization methods, and potential applications. Furthermore, it will discuss the challenges and limitations associated with their development, providing valuable insights into the future prospects of these innovative materials.

INTRODUCTION

Nano Reinforced Metal Matrix Composites (NRMMCs) are a new class of materials that combine the high strength and stiffness of metals with the superior properties of nano-sized reinforcements. The development of NRMMCs can be traced back to the early 1990s when researchers started exploring ways to enhance the properties of metal matrices by incorporating nano-sized reinforcements. The groundbreaking discovery of carbon nanotubes in 1991 opened up new possibilities for strengthening and improving the performance of metals. Since then, significant progress has been made in the synthesis and manufacturing techniques, leading to the widespread application of NRMMCs in various sectors today **[1, 2]**. In recent years due to their superior properties and potential applications in various fields, these composites have attracted a lot of attention by researchers.

Some of the common matrix materials used in NRMMCs are Aluminum, Magnesium, Nickel, Titanium, and Copper **[3-6]**. These metals have high strength, toughness, ductility, thermal conductivity, and good corrosion

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resistance. However, they also have some limitations such as low wear resistance. In order to overcome these drawbacks, metal matrices can be reinforced with nano-particles or nano-fibers that have different physical and mechanical properties from the matrix.

The nano-sized reinforcements can be made of a variety of materials, including ceramics, metals, and polymers of various shapes and sizes, but their dimensions are generally less than 100 nm, which is about 1/100,000 the width of a human hair **[2].**

Nanomaterials can be broadly categorized into two main types based on the carbon content, i.e., organic and inorganic nanomaterials. Owing to the versatile applications and huge number of studies, carbon-based nanomaterials are considered as a separate class of nanomaterial with a broad range of spectroscopy [7]**.** The basic classification of nanomaterials is given in Fig. 1.

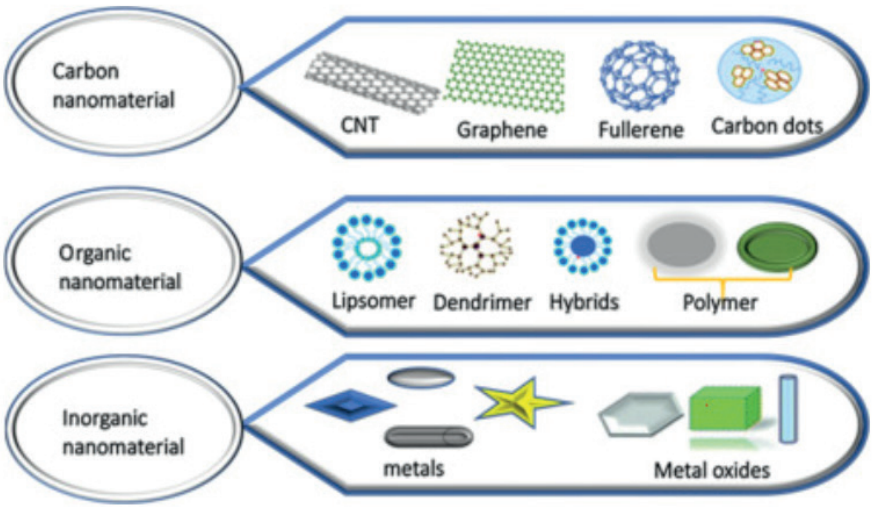

Fig.1. Basic classification of nanomaterial reinforcements [7].

As can be seen Fig. 1, the most recent nanomaterials can be classified into three material-based categories:

Carbon-based nanomaterials**:** Due to the unique property of catenation, carbon can form covalent bonds with other carbons in different hybridization states such as Sp, Sp2 and Sp3 to form a variety of structures of small molecules and longer chains. Carbon-based nanomaterials are found in morphological forms such as ellipsoids, hollow tubes, or spheres. Graphene (Gr), carbon nanotubes (CNTs), Fullerenes (C60), carbon nanofibers, carbon onions, and carbon black are the different categories of carbon-based nanomaterials.

Inorganic-based nanomaterials: These nanomaterials include metal-based nanoparticles, metal oxide/hydroxide nanoparticles, and transition metal chalcogenide (TMC) nanoparticles. These nanomaterials can be synthesized into metals like Ag, Au, Fe nanoparticles, and metal oxides such as ZnO, TiO_2, and Fe_3O_4, CeO_2.

Organic-based nanomaterials: These nanoscale materials are made mostly from organic matter, aside from inorganic-based or carbon-based nanomaterials. The use of noncovalent interactions for self-assembling and molecular designing helps to transform the organic nanomaterials into coveted structures such as micelles, dendrimers, ferritin, micelles, compact polymers, and liposomes nanoparticles. These types of nanomaterials are usually biodegradable and nontoxic, and, therefore, considered environmentally friendly materials.

The most common nano-reinforcements used in NRMMCs are various types of nano-particles, such as carbides, nitrides, oxides, and carbon nanostructures, such as carbon nanotubes (CNTs), graphene, and graphene oxide **[8, 9]**. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) images of the nano reinforcements using for NRMMCs are given Fig.2 **[2].**

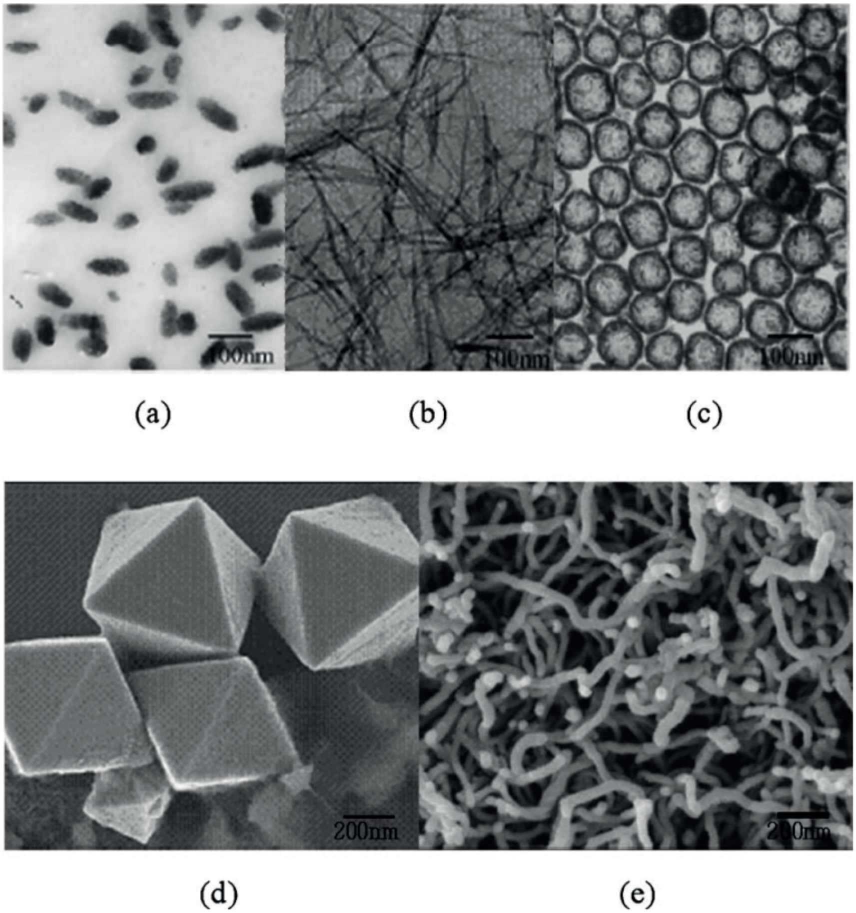

Fig. 2. TEM/SEM pictures of nanoparticles/nanotubes

a) Elliptical Nano particles, b) Nano fibers, c) Hollow nanoparticles, d) Octahedral nano particles and e) Carbon nanotubes. [2]

The nano-reinforcements have high surface area to volume ratio so they can improve the coefficient of thermal expansion (CTE) and mechanical properties of matrix material by grain refinement and by pinning dislocations. They can also improve the toughness of the matrix by deflecting cracks and promoting crack bridging, and improve the wear resistance and corrosion resistance of the matrix. These nano-particles have high hardness, high modulus, and high thermal stability. They can also interact with the dislocations in the metal matrix, resulting in additional strengthening effects **[3, 10, 11]**.

Fig. 3 shows carbon-based nanomaterials used as reinforcement for NRMMCs. Single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs) have a high aspect ratio and a large surface area [12]. Carbon nanotubes (CNTs) have also been intensively researched due to their excellent electrical, thermal and mechanical properties. These include an extremely high modulus of elasticity (0.9-2 TPa), a tensile strength of almost 63 GPa, extremely high thermal conductivity (3000 W/mK), high electrical conductivity of 106 S/m for SWCNTs and 105 S/m for MWCNTs [13] as well as non-corrosive properties towards acidic and alkaline media. [6]. These properties make them ideal candidates for the reinforcement of metal matrices [4].

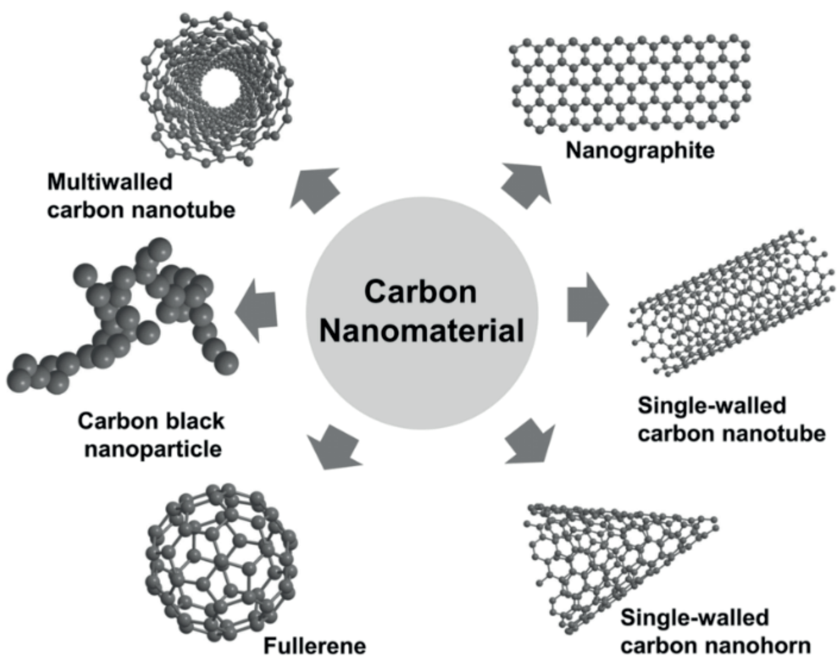

Fig. 3. Carbon nano materials used in NMMRCs [3]

For example, CNTs can increase the tensile strength of aluminum by more than 100% **[14],** graphene can improve the wear resistance of copper by more than 50% **[15]** , and graphene oxide can enhance the corrosion resistance of magnesium by more than 10 times **[16].**

ADVANTAGES of NRMMCs

NRMMCs offer a number of advantages over traditional metal matrix composites, which are reinforced with micro sized particles **[17, 18]:**

1. Nano reinforcements can provide greater strengthening and toughening effects.
2. Nano reinforcements can be dispersed more uniformly throughout the matrix, which can lead to improved properties.
3. Nano reinforced MMCs can be fabricated with lower reinforcement volume fractions, which can reduce weight and cost.

The properties of NRMMCs depend on the type and amount of reinforcement and the processing method used to produce the composite. In general, however, NRMMCs offer a number of advantages over conventional metal alloys, including:

- **Higher strength and stiffness:** Nanoparticles can significantly increase the strength and hardness of the metal matrix even in low volume fractions by forming grain refiners and dislocation barriers **[8].**

Grain refiners reduce the grains in the metal matrix, making the material stronger and more resistant to deformation. This is because the nanoparticles interact strongly with the metal matrix, creating a barrier to dislocation motion. Dislocation barriers prevent dislocations from passing through the metal matrix, making the material stronger.

For example, the tensile strength of aluminum can be increased more than 100% by carbon nanotubes **[14].**

- **Improved toughness:** Nanoparticles can also improve the toughness of MMCs by preventing crack propagation. This is because nanoparticles can deflect and pin cracks, making it more difficult for them to grow **[19].**
- **Improved wear resistance:** Nanoparticles can also improve the wear resistance of a metal matrix by forming a hard and protective layer on the surface of the material. This is because they are hard and abrasion-resistant **[13, 18].**
- **Increased corrosion resistance:** Nanoparticles can also increase the corrosion resistance of a metal matrix to oxidation and chemical attack than conventional metal alloys, which makes them suitable for applications that require high stability and longevity, such as marine structures **[1, 18].**

For example, graphene oxide can enhance the corrosion resistance of magnesium by more than 10 times . This is because they can form a protective layer on the surface of the metal matrix **[16].**

- **Reduced weight**: NRMMCs can be made lighter than traditional metal alloys by using nanoparticles with a low density. Nanoparticles can provide significant strengthening and stiffening effects at low volume fractions. This is important for applications where weight is a critical factor, such as aerospace and automotive applications **[20].**
- **Higher design flexibility:** NRMMCs can be tailored for specific applications by adjusting the type, amount, and distribution of nano-reinforcements in the metal matrix. This allows engineers to optimize the properties of NRMMCs for different needs and environments **[20].**

For example, an alloy can be designed to be strong and ductile or hard and brittle depending on the application.

APPLICATIONS of NRMMCs

NRMMCs are still at an early stage of development, but they have the potential to become one of the most important classes of engineering materials in the 21st century. NRMMCs have a wide range of potential applications in a variety of industries. Some of the specific applications of NRMMCs are **[4, 21, 22, 23]:**

- **Aerospace:** Nano-reinforced MMCs are being developed for use in aircraft and spacecraft components to reduce weight and improve performance. For example, NRMMCs are used in aircraft components, such as engine parts, landing gear, airframes and wings. This could lead to more fuel-efficient aircraft with longer ranges **[23].**
- **Military applications:** NRMMCs can be used to fabricate armor plating, ballistic missiles, and other defense-related components. The use of NRMMCs in military applications can lead to improved ballistic protection and performance **[23].**
- **Automotive:** NRMMCs are used in automotive applications to reduce weight and improve fuel efficiency. For example, NRMMCs are used in engine components, such as pistons, connecting rods, and cylinder heads. This could lead to more fuel-efficient and environmentally friendly cars **[13].**
- **Energy:** Nano-reinforced MMCs are being developed for use in energy components, such as fuel cells and solar cells. NRMMCs could

be used to make more efficient and durable energy components, such as turbine blades and heat exchangers. This could lead to lower energy costs and reduced emissions **[23, 36].**

- **Biomedical:** NRMMCs are used in medical applications to improve the strength and combination of biocompatibility and good wear resistance. For example, NRMMCs are used in dental implants and orthopedic implants such as artificial bones and joints **[2, 10, 18, 23, 25, 26, 27, 28]** .
- **Electronics:** Nano-reinforced MMCs are being developed for use in electronic components to improve heat dissipation and electrical conductivity. They can also offer good thermal conductivity and electrical insulation. For example, NRMMCs are used in heat sinks and circuit boards and electronic packaging materials **[23, 24]**.
- **Sporting goods:** NRMMCs are being developed for use in sporting goods such as golf clubs, tennis racquets, and bicycle frames. They offer the potential to improve performance and durability **[23]**.

FABRICATION of NRMMCs

Researchers fabricate NRMMCs using various methods, such as powder metallurgy, liquid metallurgy, solid-state processing, and some other novel techniques (Fig. 4) **[9].** Each method has its own advantages and disadvantages, depending on the type of metal matrix and nano-reinforcement, the desired properties, and the cost and complexity of the process. Here is a brief overview of some of the methods:

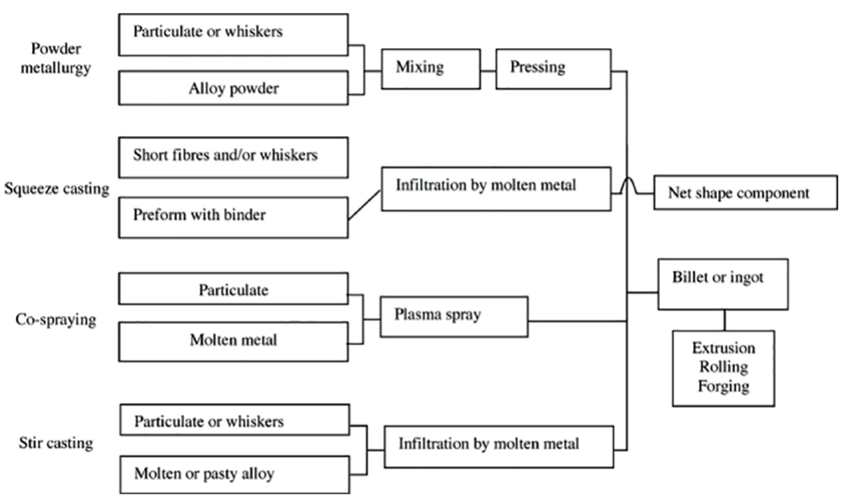

Fig. 4. Fabrication routes for NMMRCs [9]

Powder metallurgy: This method is the most employed technique to NRMMCs. The powder metallurgy method begins by an initial mixing of the raw material powders with a control agent through ball milling, ultrasonication, or both. Ball milling involves the use of small balls, usually steel or zirconia **[6].** The mixed powders are uniaxially compressed by using a wide range of forces for compacting. Afterwards, they need to be sintered at high temperature to form a solid composite (Fig. 5).

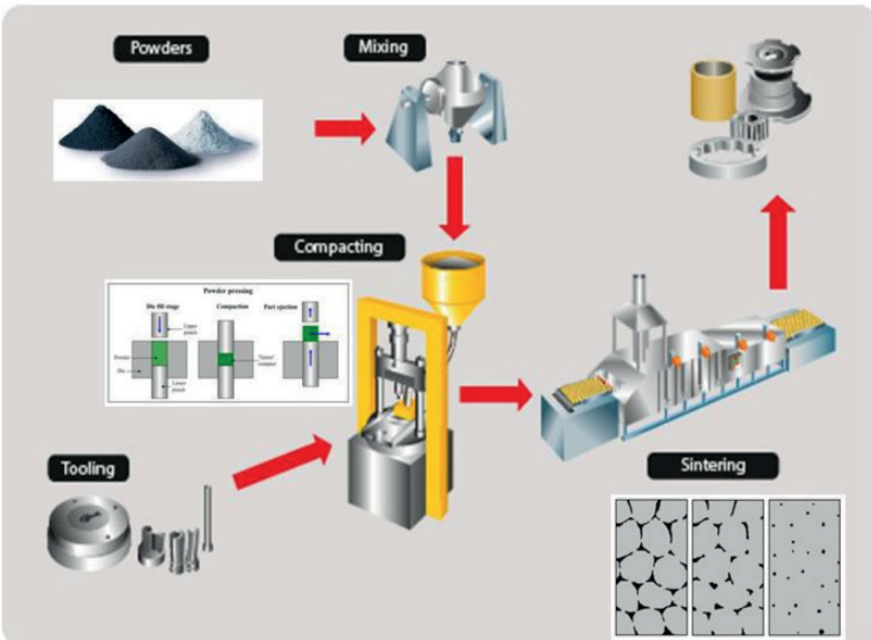

Fig. 5. Powder Metallurgy route for manufacturing NRMMCs [23, 27]

Compacting can be made at room and high temperatures. Room-temperature compression is followed by a sintering step up to 24 h **[29, 30].** Compacting at high temperatures includes hot pressing **[31]**, spark plasma sintering **[32]**, or deformation processing **[33].** Composites obtained by powder metallurgy are often subjected to post-treatment to improve their properties. Hot extrusion **[34]**, and hot rolling **[35]**, are some of the most common post-treatments for powder metallurgy-obtained NRMMCs **[36]**.

Powder metallurgy route can produce NRMMCs with uniform distribution of nano-reinforcements and good interfacial bonding. However, it also requires high temperature and pressure for sintering, which can cause oxidation and degradation of nano-reinforcements.

- **Liquid metallurgy:** This method involves melting metal matrix and adding nano-reinforcements into the melt and then casting or solidifying them to form a solid composite (Fig. 6).

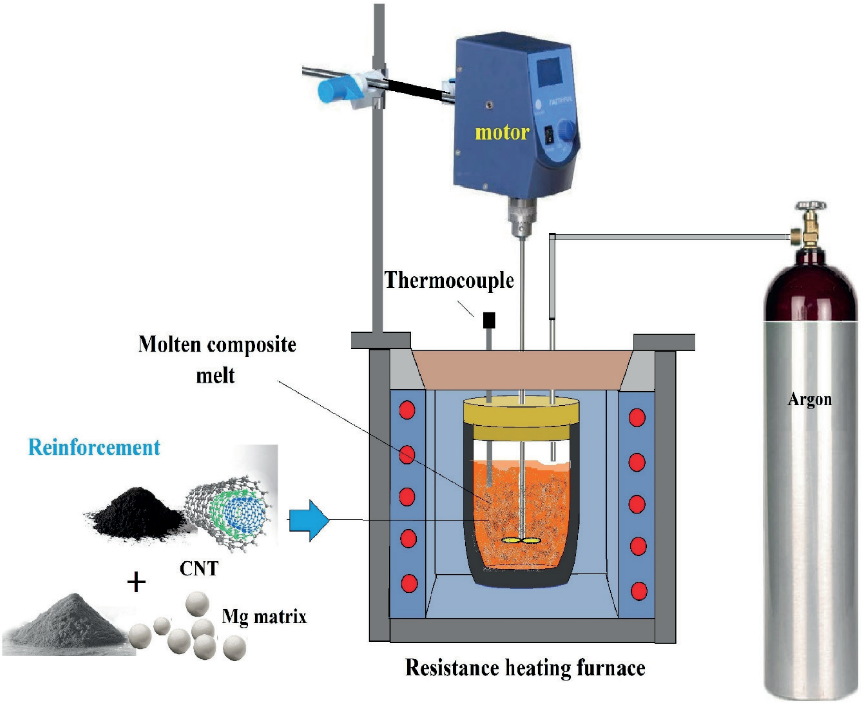

Fig. 6. Liquid Metallurgy route for manufacturing NRMMCs [1]

This method can produce NRMMCs with low cost and large scale. However, it also suffers from poor dispersion, the agglomeration and oxidation of nano-reinforcements during processing and low wettability of nano-reinforcements by molten metal, weak interfacial bonding of nano-reinforcements in metal matrix, and segregation of nano-reinforcements during solidification **[6].**

Several strategies have been implemented to increase the efficiency of this method, such as Centrifugal Casting **[17, 37],** Squeeze Casting **[38, 39, 40]**, and Pressure Infiltration **[41, 42].** In centrifugal casting, the molten material is transferred to a rotating mold, which is maintained at high pressure. In the squeeze casting process, the composite is poured into a die in which the material is then hydraulically pressed. In pressure infiltration, the molten matrix is injected at high pressure into a mold that contains the reinforcement.

Some novel methods have been proposed for fabricating NRMMCs, to improve the wettability, dispersion, interfacial bonding, and stability of nano-reinforcements in metal matrix by using physical or chemical means. Some of the novel methods for fabricating NRMMCs are:

- ❖ **Electro-deposition:** This method involves depositing metal matrix and nano-reinforcements on a substrate using an electric current **[43].** This method can improve the wettability, dispersion, interfacial bonding, and stability of nano-reinforcements in metal matrix by using physical or chemical means.
- ❖ **Laser cladding:** This method involves melting metal matrix and nano-reinforcements on a substrate using a laser beam **[44].** NRMMCs can be produced with high quality and precision by controlling the laser parameters (Fig.7a).
- ❖ **Friction-stir processing:** This method involves stirring the metal matrix and nano-sized particles are mixed together in a molten state and then cast into a mold **[45]**. This method (Fig. 7b) can produce NRMMCs with fine microstructure and enhanced properties by generating high temperature and plastic deformation **[8, 9].**

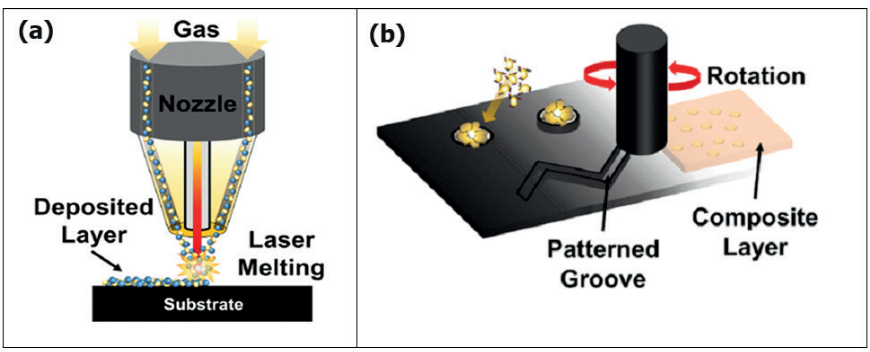

Fig. 7. Schematic illustration of Production Processes;

(a) Laser cladding, (b) Friction Stir Process [46]

Infiltration: A preform of the nanoscale reinforcement is infiltrated with a molten metal matrix. Pressure infiltration, pressureless infiltration and vacuum infiltration can be used to produce composites with high yield and approximate net shape **[47].** There are a variety of squeeze casting machines and systems that use an inert, pressurized gas to force the liquid metal into the preform **[28, 48].** Pressures of around 65–100 MPa are used for mechanical support, while lower pressures of 2–35 MPa are used for systems with inert pressurized gas. Pressureless infiltration, also known as capillary-controlled infiltration, is carried out by immersing the ceramic in a bath of molten aluminum alloy at atmospheric pressure **[49].** Vacuum infiltration, which is carried out just below atmospheric pressure, was investigated by Chung and Lin (1996). This study was conducted due to its simplicity, applicability and low pressure to minimize possible damage to the SiC foam **[50].**

In-situ processing is a process in which the reinforcement is created within the metal matrix during fabrication. In these techniques, the reinforcements are synthesized by exothermic reactions during the production of the composite itself **[51].**

In situ composites offer superior microstructural/mechanical characteristics as compared to their conventional counterparts where the reinforcement is made separately and introduced into the melt. In situ metal matrix composites have the advantage of the lower cost of fine-sized thermodynamically stable ceramic particles with clean and unoxidized ceramic-metal interfaces, since the reinforcement is formed within the melt.

Figure 8 illustrates the different in-situ processing methods for metal matrix composites, including reactive and non-reactive methods **[52].**

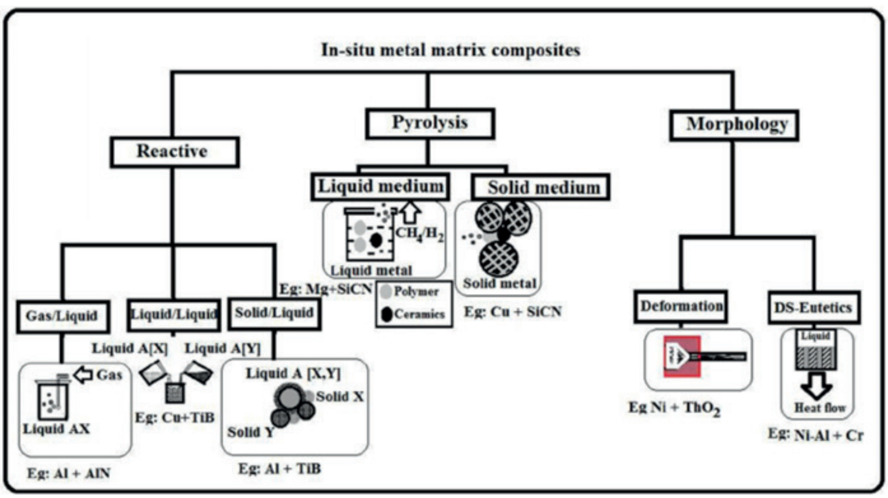

Fig. 8. Classification of in situ methods to fabricate NRMCs [52]

CHARACTERIZATIONS of NRMMCs

Researchers evaluate the quality of NRMMCs using various methods and criteria, depending on the type and purpose of the evaluation. Some of the common methods and criteria are:

- **Evaluating the quality of the fabrication process:** Researchers use different techniques to measure and analyze the physical and chemical properties of the NRMMCs, such as the Morphology, Distribution, Dispersion, Wettability, Interfacial Bonding, and Stability of the nano-reinforcements in the metal matrix. Some of the techniques include Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), X-Ray Diffraction (XRD), Energy Dispersive Spectroscopy (EDS), Atomic Force Microscopy (AFM), etc. **[21, 46, 53].**

These techniques can help researchers to identify and quantify the defects, impurities, and variations in the microstructure of NRMMCs that may affect their performance.

- **Evaluating the quality of the mechanical properties:** Researchers use different tests to measure and compare the mechanical properties of the NRMMCs, such as the Tensile Strength, Compressive Strength, Hardness, Modulus, Fracture Toughness, Fatigue Resistance, Creep Resistance, etc. **[54-56]**

These tests can help researchers to determine and optimize the optimal loading conditions and failure modes of the NRMMCs under different stress and strain scenarios.

- **Evaluating the quality of the functional properties:** Researchers use different experiments to measure and evaluate the functional properties of the NRMMCs, such as the Wear Resistance, Corrosion Resistance, Thermal Conductivity, Electrical Conductivity, Damping Capacity, etc. **[1, 2, 47, 51].**

These experiments can help researchers to assess and improve the performance and durability of the NRMMCs under different environmental and operational conditions.

FUTURE PROSPECTS of NRMMCs

NRMMCs are a promising new class of materials that have the potential to revolutionize a wide range of industries. While NRMMCs offer a number of advantages over traditional metal matrix composites, there are also some challenges associated with their fabrication and use **[56]**:

- *One of the biggest challenges is achieving a uniform distribution of the nano-sized reinforcement in the metal matrix.* This is important because it ensures that the composite has consistent properties throughout. This can be difficult due to the tendency of nanoparticles to agglomerate.
- *Another challenge is the cost of nano-sized reinforcements.* Nano-sized reinforcements are typically more expensive than traditional reinforcements, such as micro-sized reinforcements. NRMMCs are more expensive to manufacture than traditional metal alloys due to the cost of the nanoparticles and the complexity of the manufacturing process.
- *The developing fabrication methods that are scalable and cost-effective is another challenge.* There is significant research and development activity in the field of NRMMCs. For this reason, new fabrication methods are being developed, and new nanoparticle reinforcements are being discovered.
- *The lack of standardization for NRMMCs is another challenge.* There is currently no standard way to measure and test the properties of NRMMCs. This makes it difficult to compare different NRMMCs and to ensure that they meet the requirements of specific applications.

Consequently, further research is needed to optimize the processing parameters of NRMMCs, understand the reinforcement mechanisms, evaluate the performance under different conditions, and explore new types of nano reinforcements and metal matrices for NRMMCs. The specific research areas that are being pursued in the field of nano reinforced MMCs are given below **[36]:**

- Developing new fabrication methods that can produce nano reinforced MMCs with high reinforcement volume fractions and uniform particle distribution.
- Developing new nanoparticle reinforcements that have improved properties and are more compatible with metal matrices.
- Investigating the long-term performance of nano reinforced MMCs under various service conditions.
- Developing new applications for nano reinforced MMCs.

CONCLUSION

As a result, research and development investigations all over the world will contribute greatly to nano-reinforced MMCs becoming an important class of materials with a wide range of applications. As the manufacturing technology of NRMMCs continues to evolve and test and measurement standards are improved, the production cost of NRMMCs will decrease and the difficulties in their use will be overcome. Accordingly, NRMMCs are expected to play an increasingly important role in various applications such as aerospace and defense, automotive, biomedical, electronics and energy.

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