A Review on Processing, and Applications of Nanocomposites

Asmaa El Hawary[1], Salma Hasan[1], Reem Abd El Sttar[1], Seif Mohamed[1] and M. Bassyouni[1,2,*]

[1]*University of Science and Technology, Materials Science Program, Zewail City of Science and Technology, October Gardens, 6th of October, Giza, 12578, Egypt*

[2]*Department of Chemical Engineering, Faculty of Engineering, Port Said University, Port Said, 42526, Egypt*

Abstract: In recent decades, nanocomposites have become one of the centers of interest in research and industrial fields because they provide electrical, mechanical and optical enhancements significantly superior to conventional microscale composites which makes them suitable for a wide range of applications in electronics industry, packaging industry, biomedical research and much more. This review thoroughly discusses three types of nanocomposites: ceramic-matrix nanocomposites (CMNCs), polymer-matrix nanocomposites (PMNCs), and metal-matrix nanocomposites (MMNCs) and provides an overview of the most common fillers, methods of preparation, challenges, properties and applications.

Keywords: Nanocomposite, CMNC, PMNC, MMNC.

1. INTRODUCTION

Composites are combinations of two or more materials in which one or more of them is called the reinforcing phase. The reinforcing phase has discontinuous structure, is in the form of fibers, sheets, or particles, and is embedded in another material of continuous structure known as the matrix phase. The matrix can be made of polymers, metals, inorganic materials or other types depending on the composite and its main purpose is to bind the reinforcement phases and distribute stresses among the reinforcement materials when a force is applied through modifying its structure [1]. The proper combination of both phases can produce properties different from that of the original constituent materials. These properties can vary significantly to fit a wide array of applications and that is why composites are highly desired in different research and industrial fields. Through the last decades, nanocomposites, which are defined as composites with at least one of the constituent phases' dimensions existing in the nanometer range (less than 100nm), have been widely reported to provide extraordinary enhancements superior to conventional microscale composites, even at low nanoparticles content [2-4]. The progress in nanocomposites covers many industries with applications varying from biomedical research to electronic devices, solar cells, aircraft components and even food packaging [5-7].

Through this review, different types of matrix-based nanocomposites will be thoroughly discussed emphasizing how can their substantial properties be achieved, and an overview of applications and technical advances will be presented.

2. CERAMIC MATRIX NANOCOMPOSITES (CMNC)

Ceramics have a wide range of advantages such as their good wear resistance and high thermal and chemical stability; however, their low toughness making them brittle and their sudden failures block them from being widely used in the industry [8]. During the last few years, Ceramic matrix nanocomposites have been receiving attention due to the significant enhancement in the ceramics' mechanical properties by the incorporation of metals or other types of ceramics into the matrix thus allowing the ceramics to be used in the engineering applications. The most commonly used structure for ceramic matrix nanocomposites is a micro-sized matrix with nano-sized particles embedded into it. Depending on the positions that the dispersed nanoparticles occupy within the matrix, the nanocomposites are classified into: a) intergranular nanocomposites at which the nanoparticles lie between the grain boundaries. b) intragranular nanocomposites at which the particles lie within the matrix grains and c) Inter/Intra-granular nanocomposites at which the nanoparticles can occupy both intergranular and intragranular positions thus leading to a combination of properties of the first two classes [9].

2.1. Improvements of the Mechanical Properties of Ceramics

The nano-sized reinforcements embedded within the matrix of ceramic materials highly affect their

---

*Address correspondence to this author at the University of Science and Technology, Materials Science Program, Zewail City of Science and Technology, October Gardens, 6th of October, Giza, 12578, Egypt;
Tel: 00201159675357;
E-mail: migb2000@hotmail.com; m.bassyouni@eng.psu.edu.eg

E-ISSN: 2312-5470/19

mechanical properties as for example the particles lying in intergranular positions of the matrix restrict the migration of grain boundaries and enhance the creep resistance while the particles lying in the intragranular positions enhance the overall strength and toughness of the nanocomposite [9]. An overview of the most common combination of materials used in the nanocomposites for the enhancement of their mechanical properties is given in this subsection.

a. SiC-based ceramic matrix nanocomposites:

Silicon carbide (SiC) is one of the widely studied structural materials due to its superior properties such as its high hardness, low density, low coefficient of thermal expansion, high chemical and thermal stability and its chemical inertness [10]. Also, it has high electron mobility and high thermal conductivity and its operating temperature can reach to 1200 K. Accordingly, many studies have investigated the effect of introducing SiC into the ceramic matrix nanocomposites on the mechanical and thermal properties of ceramics.

Zhao *et al*. studied the mechanical properties of SiC/AlON as AlON (aluminum oxynitride) is one of the most promising ceramic materials in structural applications as it has high corrosion and wear resistance, high rigidity and good chemical stability but has poor fracture toughness and strength [8]. For this, it was justified to introduce SiC into AlON matrix and study its effects. It was found that the hardness of the nanocomposite increased with the increase of the weight percentage of SiC up to 8 wt% and then decreased up to 12%. This behavior can be explained by the fact that SiC has hardness higher than that of AlON and by the mixture rule, the hardness of the mixture should increase by increasing the content of SiC. Also, Young's modulus of the composite increases with increasing the content of SiC up to 8wt% which can be justified by the decrease in the porosity of the structure as illustrated in the study [11].

Also, both the flexural strength and the fracture toughness of the nanocomposite increase with increasing the content of SiC up to 8wt% and then decrease up till 12 wt%. These trends can be explained by the decrease of porosity of the structure up to 8 wt% and then the increase of porosity until 12 wt% as the presence of pores have a negative effect on the mechanical properties as they act as stress concentrators leading to lower strength of the structure [11]. According to the trends of hardness, Young's modulus, flexural strength and fracture toughness exhibited by varying SiC content of the nanocomposite, the study concluded that the optimum weight percentage for the enhancement of mechanical properties of SiC-AlON nanocomposite is 8wt%.

For the unique properties offered by SiC reinforcements in the nanocomposites, they cover wide range of applications such as the use of AlON/SiC, Al_2O_3/SiC and Si_3N_4/SiC nanocomposites as structural materials, and the use of $BaTiO_3$/SiC nanocomposites in the electronic industry [11].

b. ZrO_2- based ceramic matrix nanocomposites:

Another material that is highly promising is ZrO_2 (Zirconia) as it is chemically inert and has high fracture toughness, and good thermal and ionic conductivity. And conventionally, Zirconia is associated with Alumina (Al_2O_3) in composites because their composites combine the high Young's modulus and hardness of the Alumina matrix with the high fracture toughness and chemical inertness of the zirconia leading to advanced ceramic composites structures with superior mechanical properties that can be used in a wide variety of applications [10, 12].

Recent studies have shown that the mechanical properties of the Al_2O_3-ZrO_2 can be further modified by reducing the grain size and the dispersion of the reinforcements inside of the matrix. It has been shown that the smaller the grain size for the Al_2O_3 matrix, the better the attained mechanical properties of the structure and that also that for the ZrO_2 reinforcements to improve the mechanical properties considerably, their particle size must be less than a critical value (0.7 um) to ensure the stability of the tetragonal phase of Zirconia [12].

However, it is difficult to achieve a highly dense ceramic nanocomposite structure with small grain size because during the sintering process, an inevitable growth of grains takes place. So, it was proposed to use microwave sintering to be able to attain the desired mechanical properties. Microwave sintering is a highly fast technique with very short sintering duration that leads to the inhibition of the grain growth [12].

Benavente *et al*, have reported a considerable increase in the fracture toughness of Al_2O_3- ZrO_2 composites with different ZrO_2.

Due to having high wear resistance, good electrical resistivity, low friction, excellent corrosion resistance, and good biocompatibility, Al_2O_3- ZrO_2 nanocomposites can be used in a variety of biomedical and technical applications.

For the applications that require reliable biomaterials with excellent mechanical properties, these nanocomposites are highly attractive like using them in dental implants and total joint prostheses [13].

Also, due to their relatively low cost associated with the highly improved performance, many companies have begun using the composites. For example, the CoorsTek Company developed Zirconia toughened alumina composites for many applications including bearing components, pump components, valve seats and Die and cutting tool inserts (to replace the carbide and metal tool inserts) [14].

c. CNT-based ceramic matrix nanocomposites:

Carbon nanotubes (CNTs) are considered the ideal candidates as reinforcement materials due to their superior mechanical, thermal and electrical properties and their one dimensionality thus leading to high aspect ratio. When CNTs are used as reinforcement for ceramic matrices, they can overcome the intrinsic brittleness of the ceramic materials [10]. However, there are two main challenges to successfully incorporate the carbon nanotubes into the matrix and achieve improvement in the desired properties: the first is to attain carbon nanotubes with intrinsic good characteristics and in sufficient quantity with moderate cost to be able to use it industrially, and the second is to disperse the CNT reinforcements homogeneously throughout the matrix [10].

Most of the CNT reinforcement research was directed to the nanocomposites based on the polymer matrices, however, the research on fabrication of CNTs with low cost is one of the driving forces for the ceramic-matrix nanocomposites research.

Estili and Kawasaki [15] have developed an approach to synthesize CNTs/alumina nanocomposites in large quantities and reported that the homogeneous dispersion of the CNTs require that their concentration must be in the range of 2.4-16 vol%.

They have also reported that the largest improvement in mechanical properties happened at 3.5 vol% of CNTs with an increase in their fracture toughness by 70%.

Due to the improvements in mechanical properties such as the fracture toughness along with the superior thermal and chemical ones, the ceramics reinforced with CNTs are promising for a variety of applications. For example, Al_2O_3- CNTs nanocomposites have the key properties of high wear resistance and high toughness which makes them suitable to be used as cutting tools, corrosion/erosion resistance pipes and armor plates [15]. The table below summarizes most of the promising CNTs reinforced nanocomposites with their applications.

d. Graphene-based Ceramic Nanocomposites

Due to the outstanding mechanical and electrical properties of graphene (a Young's modulus of 1 TPa, an intrinsic strength of 130 GPa and an electrical conductivity of 10^7 S/m [17, 18]), it is viewed as the ideal filler for ceramic materials. The incorporation of graphene nanoplatelets into the matrix of ceramic materials is very promising as it can produce tough materials suitable for structural applications, and thermally and chemically stable composites suitable for high-temperature operations such as in aircrafts [16].

Walker *et al*. have reported promising results regarding the mechanical properties with a measured ~235% increase in toughness compared to the monolith by only adding 1.5% volume graphene platelets into Si_3N_3 ceramic particles using aqueous colloidal processes to achieve homogeneous dispersion of the platelets [19]. Also, they have reported a novel toughening mechanism as the Graphene platelets appear to form a continuous wall along the grain boundaries thus hindering the propagation of cracks.

Table 1: Summary of the Most Promising CNTs Reinforced Ceramic Nanocomposites with their Proposed Applications [16]

Ceramic Nanocomposite	Key Characteristics	Its Applications
Si_3N_4/CNTs	Excellent mechanical and thermal properties	Can be used for gas turbines and aircraft engine components and bearings.
$BaTiO_3$/CNTs	Ferroelectric and piezoelectric properties	Can be used for electric generators, computer hard disks and sensors.
ZrO_2/CNTs	Good Mechanical properties, high fracture toughness, elevated temperature stability and high breakdown electric field.	Can be used for solid oxide fuel cells, oxygen sensors and ceramic membranes.

Using graphene for the reinforcement of the ceramic nanocomposites is expected to improve the wear resistance and the friction coefficient of the ceramic materials as graphene is a very good lubricant [20]. Hvizdoš *et al*. have reported a 60% improvement of the wear resistance of Si_3N_4 matrix with 3wt% graphene [21], and have made comparisons between Si_3N_4-graphene composites and Si_3N_4-CNT composites and found that the graphene-containing composite are more wear-resistant for the same filler loading.

3. POLYMER MATRIX NANOCOMPOSITES (PMNCS)

Polymer nanocomposites consist of a polymer matrix reinforced with nanosized particles (nanofillers) in the form of platelets, fibers, nanotubes, etc. [22] Polymer nanocomposites have shown enhanced optical, thermal, electrical and mechanical properties. This makes them suitable candidates for a wide range of applications in electronics industry, food industry, energy harvesting and storage field, etc.

3.1. 2D Nanofillers

The most common 2D nanofillers are clay and graphene nanoplatelet.

a. Clay nanoplatelets reinforced polymers:

Clay particles have at least one dimension in the nano-scale. Minerals as Montmorillonite, saponite and hectorite are commonly used in these composites. They consist of aluminum-containing octadedrical layers and tetrahedrical layers of silicon interchangeably. These layers are held together by Van der Waal's forces and weak electrostatic forces [23].

b. Graphite nanoplatelets reinforced composites:

Like clay platelets, Natural flake graphite consists of layers of nanosheets. The carbon atoms in the same layer are held together by covalent bonds while adjacent layers are held together by Van der Waal forces [23].

3.1.1. Processing and Structure

There are three common methods of preparation for the mentioned composites:

a. In Situ Polymerization:

In which the clay particles are dispersed in a solution containing the required monomers. The polymerization of the polymers is then initiated by providing the suitable conditions. This method enhances the uniformity of the clay particles' distribution in the matrix and the compatibility of the polymer matrix and the clay particles [23]. Organic modifiers could be added to the mixture to either enhance the dispersion of the monomers or their polymerization [24].

b. Solution Dispersion:

In which the clay is exfoliated into single layers by a solvent and the polymer is dissolved in the same solvent separately. Then, the two solutions are mixed, and the solvent is evaporated allowing the clay layers to reunite while filled by the polymer [23].

c. Melt Intercalation:

In which the clay particles are directly dispersed in the polymer matrix while the polymer is in a melted state. This method provides better homogeneity compared to the solution method [23].

As a result, the nanocomposite can have one of three structures:

a. Phase Separated:

Where the interaction between the clay particles and the polymer is very weak and the clay layers are not separated. This structure would be described as microcomposite rather than nanocomposite and would not have enhances properties [25].

b. Intercalated Structure:

Where the polymer is partially intercalated between the clay layers [25].

c. Exfoliated Structure:

Where the clay layers are completely exfoliated and are uniformly dispersed in the polymer matrix with a higher phase homogeneity than the intercalated structure and more enhanced properties [25].

3.2. 1D Nanofillers

The most common 1D nanofiller is nanotube. Single-walled nanotubes consist of a single layer of carbon atoms rolled into a tube with a diameter in the nanoscale. Multi-walled nanotubes consist of multiple layers of carbon atoms, in some models it is considered a single sheet that is rolled multiple complete rolls and in others it is considered as multiple coaxial tubes with the diameter of the innermost tube in the nanoscale [26].

3.2.1. Processing and Structure

There are three common methods of preparation:

a. In Situ Polymerization:

In which the nanotubes are dispersed in a solution containing the required monomers. The polymerization of the polymers is then initiated by providing the suitable conditions. This method is suitable for the formation of composites with high nanotubes concentration [27].

b. Solution Dispersion:

In which the nanotubes and the polymer are dispersed in a solvent. The composite is either precipitated or deposited as a film. This methods requires the nanotubes to be well de-aggregated and a surfactant could be used to prevent the aggregation of the nanotubes at higher concentrations [27]. Dispersion could be enhanced by Ultrasonic irradiation, magnetic stirring or elevated temperature [24].

c. Melt Blending:

In which the nanotubes are dispersed in the polymer matrix with a large shear force while the polymer is in a melted state. This method is low in cost, simple and suitable for industrial quantities [27].

3.3. Challenges in Processing and Manufacturing of Polymer Matrix Nanocomposites

3.3.1. Incompatibility of Polymers and Nanoparticles

This incompatibility of the polymers matrix and nanoparticle fillers results from the hydrophilic properties of the clay particle's surface and the hydrophobic properties of the polymer matrices. Multiple techniques are studied to improve the dispersion:

a. Particle Surface Modification:

Where the clay particles are mixed with a surfactant that contains at least one polar group and an aliphatic chain. The surface of the particle absorbs the polar group. Additional coupling agents like silane and titanite could be added to form covalent bond between the clay particles and the polymer [28].

b. Ultrasonic Oscillation:

As high energy ultrasonic treatment can enhance the dispersion of the nanoparticles in the polymer. The ultrasonic energy breaks the C-C bonds which results in the formation of long-chain radicals that can form covalent bond with the hydrophilic clay surface increasing its compatibility with the polymer [28].

3.3.2. Alignment of the Nanotubes in the Matrix

Nanotubes reinforced nanocomposites have enhanced electrical and thermal properties that can be utilized for a range of applications. However, matrices with randomly aligned nanotubes have lower electrical and thermal conductivities than expected. Hence, nanotube alignment should be obtained before, during or after forming the composite through mechanical stretching, melt fiber spinning, electrospinning or application of magnetic or electric field.

3.3.3. Dispersion

A homogeneous dispersion of nanoparticles in a polymer is very difficult due to the strong tendency of fine particles to agglomerate. At the same time if it is subjected to force, there is a possibility of splitting the agglomerate nanoparticles [29].

3.3.4. Degassing

Degassing is another critical problem while processing a nanocomposite. The air trapped while pouring the highly viscous material in the mold initiates crack and failure of specimen can take place under low strains [29].

3.4. Properties of Polymer-Based Nanocomposites

3.4.1. Optical Properties

Incorporating nanoparticles in a polymeric matrix provides can be utilized to tune the optical properties of the composite including its refractive index, coefficient of absorption, surface roughness, etc.

a. Optical clarity:

When single layers of clay are incorporated in polymeric matrices, the resulting nanocomposite is clear in the visible range because the size of the clay nanoparticles is smaller than the wavelengths of the visible light [27].

b. Photoluminescence:

It is the direct photo excitation of the material. Fluorescent polymers are unstable as they react with oxygen. This requires extra cost and complexity to add protective layers to prevent oxidation. Moreover, the fluorescent polymers have limited quantum efficiency. In nanocomposites, the polymer represents the host for the fluorescent material or filler rather than being the intrinsically fluorescent material. These polymeric matrices with photoactive fillers provide the stability, the improved thermo-mechanical properties and the aging resistance of the standard non-fluorescent polymers along with the photoluminescence of the fillers. However, distributing the fillers uniformly poses a challenge [27].

3.4.2. Barrier Properties in Flame Retardancy

2D and 1D nanoparticles dispersed in polymer matrices are impermeable to gases and hence, are shown to decrease flammability. The nano layers act as obstacles creating mazes and tortuous paths for the gaseous molecules, which delays their progress in the matrix.

Nanotubes in polymer matrices have shown flame retardancy properties as well for example, a small amount of multiwall nanotubes in polypropylene drastically reduces the heat release rate of polypropylene. It is possible that the nanotubes decrease the rate of heat release by conducting the heat away from the flame zone.

Moreover, the dispersed nanoparticles change the gases permeability of the surrounding area of the polymer matrix by making it less mobile. This immobility attenuates the propagation of the gas molecules in the areas that interacted with the nanoparticle [28].

The formation of barriers in the polymer matrix also leads to the increase of the melting and thermal decomposition temperatures of the polymer [30].

3.4.3. Mechanical Properties

Nanotubes reinforced polymers are shown to have improved tensile strength, higher indentation resistance and increased hardness. The improvement of the mechanical properties is a function of the load transfer between the matrix and the nanotubes. Better properties are obtained when the load is transferred between the matrix and the polymer over a short distance. The main three load transfer mechanisms are:

a. Micro-mechanical interlocking:

The defects in the nanotube surface mechanically interlocks with the surrounding polymer. The load transfer through this mechanism is weak because the surface of the nanotubes is mostly smooth, and the defects do not account for a significant portion of it [30].

b. Chemical bonding between the nanotubes and the polymer matrix:

Increasing the ionic or covalent bonds between the polymer and the nanotubes significantly improves the load transfer between them and hence the overall strength of the nanocomposite [30].

c. Van der Waals force between the nanotubes and the surrounding polymer matrix:

This mechanism is weak [30].

3.4.4. Electrical Properties

Nanofillers like carbon nanotubes, metal oxide nanowires and nanoscale gold dispersed in insulating polymers have conducting properties. These conducting nanocomposites have potential applications in transparent conducting coatings, electromechanical actuators and sensors [28].

3.5. Applications

Due to their enhanced electrical, mechanical, optical and thermal properties, polymer-based nanocomposites have been utilized in many applications.

3.5.1. Packaging

Due to their barrier properties, polymer nanocomposites provide a reliable seal against the diffusion of small molecules. As a result, they have been used in food packaging of processed meat, cheese, cereals, dairy products, etc. to increase the shelf life of the product. They are also used in the manufacture of seals and stoppers for medical containers like sample collection tubes and blood bags [31].

3.5.2. Energy Storage Systems

The enhanced electrical properties of polymer nanocomposites are utilized in various energy storage mechanisms like fuel cells and dielectric capacitors.

In fuel cells, proton exchange membrane’s role is to allow proton transport from the anode to the cathode, to be an electron nonconductive material and to act as a gas separating barrier. Using proton exchange membranes made of polymer nanocomposite utilized their enhanced chemical conductivity and their barrier properties to improve the efficiency of the fuel cell [31].

In dielectric capacitors, the dielectric layer is usually either ceramic or polymer. Ceramics provides high permittivity and excellent thermal stability but have a low breakdown point. This means under high electric fields the dielectric layer breaks down and avalanche conduction occurs. When ceramic fillers are incorporated in a polymer matrix the resulting dielectric has the high permittivity and thermal stability of the ceramics combined with the high breakdown strength of the polymers [32].

3.5.3. Optical Glass and Membranes

When clay platelets are incorporated into polymer matrices they enhance their mechanical strength and toughness while maintaining their optical clarity. This makes them a suitable candidate for contact lenses and optical glass industry [27].

3.5.4. Products with Low Flammability

The barrier properties of the polymer nanocomposites result in great resistance to flammability which makes the suitable for a wide range of applications including cable wire jacket, car seats, packaging films, textile cloths, surface coatings for many steel products, paints, rocket ablative materials [27].

3.5.5. Coatings

Nanoclay incorporated polymer nanocoatings exhibit superior properties such as superhydrophobicity, improved wettability, excellent resistance for chemicals, corrosion resistance, improved weather resistance, better abrasion resistance, improved barrier properties and resistance to impact, scratch, etc [27].

3.5.6. Tissue Engineering

Tissue engineering research requires growing skin, bone, cartilage and blood vessels cells on molds. These molds need to provide certain conditions to stimulate a specific cell response on the molecular level. As a result the materials used need to be biocompatible and have suitable mechanical properties. Polymer matrix nanocomposites provide enhanced mechanical and functional properties. Nanofibers reinforced polymers, for example, have fibrillar structures which allow the cells to attach strongly to their surface and grow along them. As another eample, a composite of inorganic/organic materials in a biodegradable polymer is suitable as a bone tissue mold because it resembles the natural human bone structure which consists of an organic/inorganic composite material of collagen and apatites [31, 33].

3.5.7. Sensors

The electrical and optical properties of the polymer nanocomposites is greatly affected by the concentration of the nanofillers in the polymer matrix. In addition, this effect is reversible by doping and dedoping processes. As a result, they can be used as chemical, optical or bio sensors [34].

4. METAL MATRIX NANOCOMPOSITES (MMNCS)

The second classification of nanocomposite materials is metal matrix nanocomposites (MMNCs) in which a metal matrix is being reinforced by a nanosized material [35]. The reinforcement material could be another metal, ceramic, or any other type. The most common nanosized reinforcement used is ceramics resulting metal/ceramic features. Those resulting materials exhibit toughness and ductility with high modulus and strength. Hence, with the production of materials with high temperature abilities, and high strength in compression/shear processes, having the potential for numerous applications. For instance, the applications in high development of structural materials, and in automotive and aerospace industries [35, 36]. Also, using MMNC with CNT nanocomposites is a promising ongoing research, but again comes with challenges for real-life application. Another set of applications of catalytic activity, modifying mechanical properties, and producing changes in refractive index or electromagnetism, depends on the feature size (nm) of numerous MMNCs, for example, Fe-Cr/Al_2O_3, Ni/Al_2O_3, Co/Cr, Fe/MgO, Al/CNT, and Mg/CNT [35].

4.1. Processing

Metals matrices used in MMNC are mainly Al, Mg, Pb, Sn, W and Fe. Those are the common ones due to their intercalation chemistry with very low particle sizes and availability. Almost all of these reinforcements are being employed by known techniques: mechanical (*e.g.* ball milling), chemical (*e.g.* sol gel), vapor deposition, etc. Besides, surface modifications can guarantee more homogeneous distribution with less agglomeration, and to improve interfacial bonding between the matrix and the nanosized reinforcements. Spray pyrolysis; Liquid metal infiltration; Rapid solidification; Vapor techniques (PVD, CVD); Electrodeposition and Chemical methods, which include colloidal and sol-gel processes are the used techniques for the processing of MMNCs. Table **2a** lists various systems prepared by these methods and Table **2b** shows their advantages and limitations [35, 37-43].

Table 2a: Processing Methods for Metal-Based Nanocomposite Systems

Process	System	Procedure
Spray Pyrolysis	Fe/MgO, W/Cu	Is a process in which precursors are atomized using an ultrasonic atomizer in a droplet-generating pre-heated chamber, evaporated and trapped with a filter in a heated reactor, and then decomposed into oxide materials. Finally, selective reduction of the metal oxides is employed to produce the respective metallic materials [35, 37, 38].
Liquid Infiltration	Pb/Cu, Pb/Fe, W/Cu/ Nb/Cu, Nb/Fe, Al-C	Is a mixing process of the reinforcements in a melted phase of the metal matrix surrounding it to promote their integration and to eliminate internal porosity of the dispersed phase inclusions [35, 37, 39].
Rapid Solidification Process (RSP)	Al/Pb, Al/X/Zr (X = Si, Cu, Ni), Fe alloy	Is a process in which the metal components are melted together, then going through rapid solidification [35, 40].
RSP with ultrasonics	Al/SiC	Ultrasonics is used for mixing [40].
High Energy Ball Milling	Cu-Al_2O_3	Nanosized component is obtained by milling the powder [35].
Chemical Vapor Deposition (CVD)/ Physical vapor deposition(PVD)	Al/Mo, Cu/W, Cu/Pb	CVD: Is the process of vaporizing the materials using chemical reactions, followed by consolidation [35]. PVD: Is an evaporation/Sputtering process of different elements, then, in an inert atmosphere, supersaturate and consolidate the nanocomposite using thermal treatment [35, 41].
Chemical Processes (Sol-gel, Colloidal)	Ag/Au, Fe/SiO_2, Au/Fe/Au	Colloidal Method: Is a chemical reduction to synthesize metal particles, then consolidate and dry the resulting solid with H_2 [35, 42]. Sol-Gel Process: Is a wet-chemical process in which solids is produced using solutions [35].

Table 2b: Advantages and Limitations of Processing Methods

Process	Advantages	Limitations
Spray Pyrolysis [35, 36]	Preparing homogeneous powders	High cost
Liquid Infiltration [37, 39]	Short contact time	High temperature effects
Rapid Solidification Process (RSP) [35, 40]	Effective, simple	Exclusive metal-metal NCs
RSP with ultrasonics [40]	Dispersion without agglomeration	
High Energy Ball Milling [35]	Uniform distribution	
CVD/PVD [35, 41]	High deposition rate	Relative complexity
Chemical Processes (Sol-gel, Colloidal) [35, 42]	High purity products, simple	Low porosity control

4.2. Structure and Properties

The MMNCs structure consists of the metal matrix containing the nanosized reinforcement components in the form of whiskers, particles, nanotubes, fibers, etc. Different characterization techniques have employed to investigate the structure and properties of the MMNCs. For instance, X ray photoelectron spectroscopy (XPS), scanning and transmission electron microscopy (SEM/TEM), atomic force microscopy (AFM), scanning tunneling microscopy (STM), Fourier transformed infrared spectroscopy (FTIR), X ray diffractometry (XRD), nuclear magnetic resonance (NMR), etc. [35] Table **2c** illustrates examples of some metal matrix nanocomposites and their properties.

Table 2c: Examples of metal Nanocomposites and their Properties

Matrix/Reinforcement	Properties
Ag/Au	Improvement in catalytic activity [35].
Al/AlN	Higher compression resistance and low strain rate [35].
CNT/Fe_3O_4	Improved electrical conductivity [43].
Ni/PSZ and Ni/YSZ	Improved hardness and strength [35, 44].

4.3. Applications

Per the ongoing research, it is apparent that nanocomposites provide many enhanced benefits such as improved manufacturing capability, reduction of solid wastes, and particularly for packaging applications. As observed, the use of the numerous promising applications of nanocomposite systems are not yet large, however, their massive shifting from abstract research to industry has already begun and is expected to be intense in the next couple of years [35]. Using nanomaterials as a reinforcing factor is also an ongoing field of research [45, 46]; nanoparticles enhance the mechanical strength and CNTs increase both the tensile strength and the wear resistance [47-49]. Table **2d** shows various potential applications for MMNCs.

Table 2d: Potential Applications of metal Nanocomposite Systems [35]

Nanocomposites	Applications
Au/Ag	Microelectronics, optical devices, light energy conversion.
Al/AlN	Microelectronic industry.
Nb/Cu	Structural materials for high temperature applications.
Ni/TiN, Ni/ZrN, Cu/ZrN	High speed machinery, tooling, optical and magnetic storage materials.
Al/SiC	Aerospace, naval and automotive structures.
Ni/TiO_2	Photo-electrochemical applications.

To conclude, nowadays technologies require more advanced properties and enhanced structure to withstand the novelty of our age. Nanocomposites are proper materials to meet the rising demands from the scientific and technological advancements. Processing methods for MMNCs are available, but some of them offers challenges hence giving a chance for research to overcome those nanosized problems.

Per view of their outstanding properties, such as high mechanical properties even at low loading of reinforcements, flame related properties, and gas barrier, numerous potential applications thus the industry for these materials have been proposed in different fields. Hence, MMNCs provide possibilities creating new global interest in these novel materials.

To summarize, this review article shed the light on the different kinds of matrix nanocomposites which are ceramic-matrix nanocomposites (CMNCs), polymer-matrix nanocomposites (PMNCs), and metal-matrix nanocomposites (MMNCs). Their processing, and numerous applications are also being elaborated along the review.

REFERENCES

[1] "Materials Science and Engineering introduction Chapter 16 Composites 7th ed", In.bgu.ac.il,2019. [Online]. Available:http://in.bgu.ac.il/engn/mater/Documents/LaboratoryBriefings/4/Materials%20Science%20and%20Engineering%20introduction%20Chapter%2015%20Composites%207th%20ed.pdf. [Accessed: 01- Dec- 2019].

[2] P. Ajayan, "Nanocomposite Science and Technology", 2003. Available: https://onlinelibrary.wiley.com/doi/book/10.1002/3527602127. [Accessed 1 December 2019].

[3] R. Gangopadhyay and A. De, "Conducting Polymer Nanocomposites: A Brief Overview", Chemistry of Materials, 2000; 12(3): 608-622. https://doi.org/10.1021/cm990537f

[4] A. Arora and G. Padua, "Review: Nanocomposites in Food Packaging", Journal of Food Science, 2010; 75(1): R43-R49. https://doi.org/10.1111/j.1750-3841.2009.01456.x

[5] M. Naito, T. Yokoyama, K. Hosokawa and K. Nogi, Nanoparticle Technology Handbook, 2nd ed. ELSEVIER, 2012.

[6] K. Müller *et al*., "Review on the Processing and Properties of Polymer Nanocomposites and Nanocoatings and Their Applications in the Packaging, Automotive and Solar Energy Fields", Nanomaterials 2017; 7(4): 74. https://doi.org/10.3390/nano7040074

[7] S. Masia, "Nanocomposite Review", Nanohub.org. [Online]. Available: https://nanohub.org/resources/5217/download/nanocompositescurrentscientificexamples.pdf. [Accessed: 25- Apr- 2019].

[8] P. Camargo, K. Satyanarayana and F. Wypych, "Nanocomposites: synthesis, structure, properties and new application opportunities", Materials Research 2009; 12(1): 1-39. https://doi.org/10.1590/S1516-14392009000100002

[9] A. Mukhopadhyay and B. Basu, "Bulk Nanoceramic Composites for Structural Applications: A Review," Proc. Indian Natl. Sci. Acad. 2006; 72(2): 47-61.

[10] J. Silvestre, N. Silvestre and J. de Brito, "An Overview on the Improvement of Mechanical Properties of Ceramics Nanocomposites", Journal of Nanomaterials 2015; 2015: 1-13. https://doi.org/10.1155/2015/106494

[11] X. Zhao *et al*., "Fabrication and mechanical properties of silicon carbide-aluminum oxynitride nanocomposites", Ceramics International 2014; 40(9): 14295-14303. https://doi.org/10.1016/j.ceramint.2014.06.020

[12] R. Benavente, M. Salvador, F. Penaranda-Foix, E. Pallone and A. Borrell, "Mechanical properties and microstructural evolution of alumina-zirconia nanocomposites by microwave sintering", Ceramics International 2014; 40(7): 11291-11297. https://doi.org/10.1016/j.ceramint.2014.03.153

[13] J. Chevalier and L. Gremillard, "Ceramics for medical applications: A picture for the next 20 years", Journal of the European Ceramic Society 2009; 29(7): 1245-1255. https://doi.org/10.1016/j.jeurceramsoc.2008.08.025

[14] "Zirconia Toughened Alumina - ZTA | Dynamic Ceramic", Dynacer.com, 2019. [Online]. Available: http://www.dynacer.com/materials/zirconia-toughened-alumina-zta/.

[15] M. Estili and A. Kawasaki, "An approach to mass-producing individually alumina-decorated multi-walled carbon nanotubes with optimized and controlled compositions", Scripta Materialia 2008; 58(10): 906-909. https://doi.org/10.1016/j.scriptamat.2008.01.016

[16] I. Ahmad, B. Yazdani and Y. Zhu, "Recent Advances on Carbon Nanotubes and Graphene Reinforced Ceramics Nanocomposites", Nanomaterials 2015; 5(1): 90-114. https://doi.org/10.3390/nano5010090

[17] V. Singh, D. Joung, L. Zhai, S. Das, S. Khondaker and S. Seal, "Graphene based materials: Past, present and future", Progress in Materials Science 2011; 56(8): 1178-1271. https://doi.org/10.1016/j.pmatsci.2011.03.003

[18] J. Keyte, K. Pancholi and J. Njuguna, "Recent Developments in Graphene Oxide/Epoxy Carbon Fiber-Reinforced Composites", Frontiers in Materials 2019; 6. https://doi.org/10.3389/fmats.2019.00224

[19] L. Walker, V. Marotto, M. Rafiee, N. Koratkar and E. Corral, "Toughening in Graphene Ceramic Composites", ACS Nano 2011; 5(4): 3182-3190. https://doi.org/10.1021/nn200319d

[20] K. Markandan, J. Chin and M. Tan, "Recent progress in graphene based ceramic composites: a review", Journal of Materials Research 2016; 32(1): 84-106. https://doi.org/10.1557/jmr.2016.390

[21] P. Hvizdoš, J. Dusza and C. Balázsi, "Tribological properties of Si3N4-graphene nanocomposites", Journal of the European Ceramic Society 2013; 33(12): 2359-2364. https://doi.org/10.1016/j.jeurceramsoc.2013.03.035

[22] RH. Cury Camargo, KG. Satyanarayana and F. Wypych, "Nanocomposites: Synthesis, Structure, Properties and New Application Opportunities", Materials Research 2009; 12(1): 1-39. https://doi.org/10.1590/S1516-14392009000100002

[23] F. Hussain and M. Hojjati, "Review article: Polymer-matrix Nanocomposites, Processing, Manufacturing, and Application: An Overview", Journal of Composite Materials 2006; 40(17). https://doi.org/10.1177/0021998306067321

[24] A. Dantas de Oliveira and C. Augusto Gonçalves Beatrice, "Polymer Nanocomposites with Different Types of Nanofiller" in Nanocomposites - Recent Evolutions. Intechopen, 2019, ch. 6. Available from: https://www.intechopen.com/books/nanocomposites-recent-evolutions/polymer-nanocomposites-with-different-types-of-nanofiller. https://doi.org/10.5772/intechopen.81329

[25] VC. Shunmugasamy and C. Xiang, "Clay/Polymer Nanocomposites: Processing, Properties, and Applications", Hybrid and Hierarchical Composite Materials, 2017.

[26] W. Wang and NS. Murthy, "Characterization of Nanotube-Reinforced Polymer Composites", Carbon Nanotubes - Polymer Nanocomposites, Dr. John Cuppoletti (Ed.), InTech, 2011. https://doi.org/10.5772/20267

[27] S. Anandhan and S. Bandyopadhyay, "Polymer Nanocomposites: From Synthesis to Applications", Nanocomposites and Polymers with Analytical Methods, J. Cuppoletti (Ed.), InTech, 2011. https://doi.org/10.5772/17039

[28] K. Müller, *et al.*, "Review on the Processing and Properties of Polymer Nanocomposites and Nanocoatings and Their Applications in the Packaging, Automotive and Solar Energy Fields", Nanomaterials 2017; 7(7). https://doi.org/10.3390/nano7040074

[29] D. Venkatesh, *et al.*, "Polymer-matrix nanocomposites, processing, manufacturing and application: an overview", world journal of pharmacy and pharmaceutical sciences 2016; 5(5): 288-301.

[30] V. Choudhary and A. Gupta, "Polymer/Carbon Nanotube Nanocomposites", Carbon Nanotubes- Polymer Nanocomposites, S. Yellampalli (Ed.), In Tech 2011. https://doi.org/10.5772/18423

[31] CG. Delides, "Everyday Life Applications of Polymer Nanocomposites" 2016.

[32] H. Zhang, *et al.*, "Polymer Matrix Nanocomposites with 1D Ceramic Nanofillers for Energy Storage Capacitor Applications-A Review", Applied materials and interfaces, 2019. https://doi.org/10.1021/acsami.9b15005

[33] I. Armentano, *et al.*, "Biodegradable polymer matrix nanocomposites for tissue engineering: A review", Polymer Degradation and Stability 2010; 95: 212-2146. https://doi.org/10.1016/j.polymdegradstab.2010.06.007

[34] S. Kumar, "Properties and Applications of Polymer Matrix Nano Composite Materials", in the 4th International Conference on Materials Processing and Characterization proceedings 2015; 2: 3704-3711. https://doi.org/10.1016/j.matpr.2015.07.148

[35] PHC. Camargo, KG. Satyanarayana, and F. Wypych, "Nanocomposites: synthesis, structure, properties and new application opportunities," Materials Research 2009; 12(1): 1-39. https://doi.org/10.1590/S1516-14392009000100002

[36] PM. Ajayan and PM. Ajayan, "Metal Matrix Nanocomposites," in Nanocomposite science and technology, Weinheim: Wiley-VCH, 2008; pp. 14-18.

[37] YH. Choa, JK. Yang, BH. Kim, YK. Jeong, JS. Lee, T. Nakayama, T. Sekino, and K. Niihara, "Preparation and characterization of metal/ceramic nanoporous nanocomposite powders," Journal of Magnetism and Magnetic Materials 2003; 266(1-2): 12-19. https://doi.org/10.1016/S0304-8853(03)00450-5

[38] DS. Jung, YN. Ko, YC. Kang, and SB. Park, "Recent progress in electrode materials produced by spray pyrolysis for next-generation lithium ion batteries," Advanced Powder Technology 2014; 25(1): 18-31. https://doi.org/10.1016/j.apt.2014.01.012

[39] KMS. Manu, LA. Raag, TPD. Rajan, M. Gupta, and BC. Pai, "Liquid Metal Infiltration Processing of Metallic Composites: A Critical Review," Metallurgical and Materials Transactions B 2016; 47(5): 2799-2819. https://doi.org/10.1007/s11663-016-0751-5

[40] X. Li, Y. Yang, and X. Cheng, "Ultrasonic-assisted fabrication of metal matrix nanocomposites," Journal of Materials Science 2004; 39(9): 3211-3212. https://doi.org/10.1023/B:JMSC.0000025862.23609.6f

[41] GM. Chow, RL. Holtz, A. Pattnaik, AS. Edelstein, TE. Schlesinger, and RC. Cammarata, "Alternative approach to nanocomposite synthesis by sputtering," Applied Physics Letters 1990; 56(19): 1853-1855. https://doi.org/10.1063/1.103067

[42] P. Kamat, M. Flumiani, and A. Dawson, "Metal-Metal and Metal-Semiconductor Composite Nanoclusters," Colloids and Surfaces A Physicochemical and Engineering Aspects 2002; 202(2): 269-279. https://doi.org/10.1016/S0927-7757(01)01071-8

[43] L. Jiang and L. Gao, "Carbon Nanotubes−Magnetite Nanocomposites from Solvothermal Processes: Formation, Characterization, and Enhanced Electrical Properties," Chemistry of Materials 2003; 15(14): 2848-2853. https://doi.org/10.1021/cm030007q

[44] O. Kamigaito, "What can be improved by nanometer composites?," Journal of the Japan Society of Powder and Powder Metallurgy 1991; 38(3): 315-321. https://doi.org/10.2497/jjspm.38.315

[45] A. Saboori, M. Dadkhah, P. Fino, and M. Pavese, "An Overview of Metal Matrix Nanocomposites Reinforced with Graphene Nanoplatelets; Mechanical, Electrical and Thermophysical Properties," Metals 2018; 8(6): 423. https://doi.org/10.3390/met8060423

[46] R. Casati and M. Vedani, "Metal Matrix Composites Reinforced by Nano-Particles-A Review," Metals 2014; 4(1): 65-83. https://doi.org/10.3390/met4010065

[47] AD. Moghadam, E. Omrani, PL. Menezes, and PK. Rohatgi, "Mechanical and tribological properties of self-lubricating metal matrix nanocomposites reinforced by carbon nanotubes (CNTs) and graphene - A review," Composites Part B: Engineering 2015; 77: 402-420. https://doi.org/10.1016/j.compositesb.2015.03.014

[48] SC. Tjong, "Recent progress in the development and properties of novel metal matrix nanocomposites reinforced with carbon nanotubes and graphene nanosheets," Materials Science and Engineering: R: Reports 2013; 74(10): 281-350. https://doi.org/10.1016/j.mser.2013.08.001

[49] SI. Cha, KT. Kim, SN. Arshad, CB. Mo, and SH. Hong, "Extraordinary Strengthening Effect of Carbon Nanotubes in Metal-Matrix Nanocomposites Processed by Molecular-Level Mixing," Advanced Materials 2005; 17(11): 1377-1381. https://doi.org/10.1002/adma.200401933

Received on 24-10-2019 Accepted on 14-11-2019 Published on 15-12-2019

DOI: https://doi.org/10.12974/2311-8717.2019.07.6