Chapter 1
Metal Matrix Nanocomposites: An Overview

Abstract In this chapter, an overview on both Al and Mg based nanocomposites is given, emphasizing particularly on the importance of using reinforcements at nano length scale. The strengthening mechanisms at the basis of the reinforcing action exerted by nanoparticles (Orowan mechanism, enhanced dislocation density, grain refinement and load bearing effect) is described and their contribution discussed; modelling of the above mentioned mechanisms is also presented.

1.1 Metal Matrix Nanocomposites

The pressing need in reducing fuel consumption and emissions in ground and aerospace transportation has led in recent years to an increasing trend in employing light alloys for the production of structural components. Furthermore, high-performance and low-weight structural materials are increasingly required in a wide range of industrial applications, including thermal management and automatic precision devices. Some of these materials, such as aluminium and magnesium alloys, combine good mechanical properties, excellent castability and high thermal conductivity, being therefore very attractive for the production of complex shaped components. These alloys, however, present a noticeable decrease of mechanical properties at relatively low temperatures, less than about 200 °C [1, 2], which strongly limits their application for critical components, e.g. in the automotive and aerospace sectors. One of the most promising ways to enhance mechanical properties of light alloys, both at room and at high temperature, is the addition of a hard reinforcing phase, typically ceramic or carbon based, obtaining the so-called metal matrix composites (MMCs) [3–5], developed to combine the good ductility and toughness of the metal matrix and the high strength and stiffness of the reinforcement [3]. Among possible reinforcement shapes, i.e. fibers, whiskers or particles, the latter gained major interest as they enable obtaining a strong enhancement of mechanical properties while maintaining an isotropic behaviour, with relatively simple production routes [6–8] and possibility to apply secondary processes (machining [9], welding [10, 11], forming [3, 12]). Although traditional MMCs

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may offer many advantages with respect to the unreinforced alloys, they present noticeable limitations, due to the micron length scale of the reinforcement, such as low ductility and toughness as compared to the unreinforced matrix [13], excessive wear damage of the counter-material in tribological application [14] and extremely high tool wear during machining [6, 15].

Aiming to solve these major issues and to obtain materials with enhanced tensile strength, hardness, and dimensional stability, coupled with good ductility and fracture toughness both at room and high temperatures, the length scale of reinforcing phase has been decreased to the nanometric levels (<100 nm) to produce metal matrix nano composites (MMNCs). One necessary condition to obtain sound nanocomposites with enhanced mechanical properties is to obtain a good dispersion of the reinforcement phase within the matrix, through a proper production route. MMNCs manufacturing processes are classified in ex situ routes, when the reinforcing phase is formerly produced then added to the matrix, or in situ routes, if the reinforcement is generated during the composite production, typically through controlled reactions [4, 5, 16, 17]. Ex situ processing techniques can be further classified between solid and liquid state routes. Liquid state processes are particularly attractive due to their relative simplicity and to the possibility to obtain near net shape components on an industrial scale, although they pose bigger challenges in terms of nanoparticles dispersion with respect to powder metallurgy based processes. In particular, due to the tendency to agglomerate and low wettability within the molten matrix, nano-sized particles present the tendency to generate clusters, with a detrimental effect on mechanical properties [4, 18–22].

This chapter aims at reviewing the most recent advances in ex situ production routes and properties of Al and Mg based MMNCs, focusing on liquid and semi-solid processes. A comprehensive list of references, mostly published in the last 10 years, is critically analysed. Mechanical properties of composites with different matrices and reinforcing phases are compared, in relation to the production method employed.

1.2 Strengthening Mechanisms

Yield strength (YS) of metallic materials is the stress required to move dislocations and to activate dislocation sources. It is therefore influenced by the additive and/or synergistic action of the obstacles that restrict their motion. Several approaches have been proposed for the modelling of constitutive relationships to predict the bulk mechanical properties of MMNCs as a function of the reinforcement, matrix, and processing routes. They take into account some or all of the following strengthening mechanisms.

Orowan strengthening. Orowan strengthening is due to the obstacle posed by closely spaced hard particles to the movement of dislocations. In conventional micro sized particulate-reinforced MMCs, Orowan strengthening is known to have limited significance since the reinforcement particles are coarse and the interparticles spacing is large [23]. In particular, it has been demonstrated that in cast MMCs with particles of 5 µm or larger, Orowan strengthening has a secondary effect on material strengthening [24]. On the other hand, the Orowan mechanism is more favourable when highly dispersed fine particles are present [25, 26]. In particular, the presence of a dispersion of fine insoluble particles in a metal can considerably raise the creep resistance, even for only a small volume percent (<1 %) [23]. This is due to the Orowan bowing mechanism, wherein owing to the presence of the dispersed nano-sized particles in the matrix, dislocation loops form as dislocation lines bypass the particles.

Enhanced dislocation density. Since matrix and reinforcement are generally characterized by different CTE, thermal stresses arise around particles, e.g. during cooling from processing temperature. The stress level is often large enough to cause plastic deformation, especially at the matrix/reinforcement interface region [27], thus inducing an increase in the dislocation density [28], as also experimentally observed in refs. [29, 30].

Other possible sources of residual plastic strain and consequently of dislocation density increase are the matrix/reinforcement elastic modulus (EM) mismatch and work hardening during deformation processes (e.g. extrusion or forging) [31].

Load bearing effect. The shear transfer of load from the soft matrix to the hard ceramic particles is called the load bearing effect. This reinforcing mechanism is effective only if a strong cohesion between matrix and reinforcement can be achieved [32].

Grain refinement. When introduced in a molten matrix, nanoparticles can act as heterogeneous nucleation sites during solidification, thus giving rise to more refined and possibly equiaxed microstructure, as shown in Fig. 1.1 [33]. Moreover, in

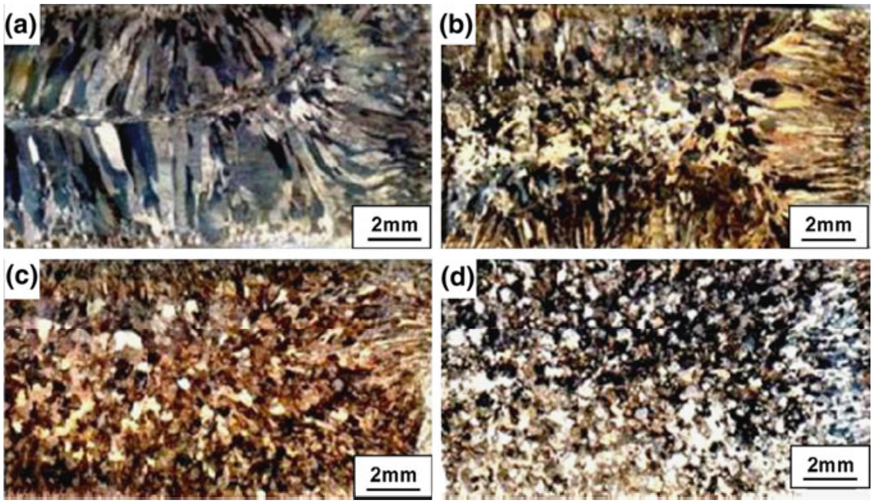

Fig. 1.1 Grain refinement effect in as cast Mg based nanocomposites: (**a**) Mg, (**b**) Mg–0.5 wt% Al_2O_3, (**c**) Mg–1 wt%Al_2O_3 and (**d**) Mg–2 wt%Al_2O_3 [33]

wrought alloys, during high temperature plastic deformation the nano-particles hinder grain growth. Habibnejad-Korayem et al. [33] inferred that nanoparticles restrict the migration of thermally excited grain boundaries during the recrystallization process. Davies et al. [34] proposed that the nanoparticles pinning effect is the dominant contribution in the refinement of the matrix microstructure during dynamic recrystallization. However, it should be noted that when a dendritic structure is present in cast alloys, the strengthening effect is mainly dependent by SDAS (secondary dendrite arm spacing) rather than by grain size [35].

1.2.1 Modelling

Several approaches have been developed starting from the 1980s to model the yield strength of MMCs and more recently of MMNCs. Three main models have been hitherto proposed: arithmetic summation, quadratic summation, and compounding methods [36]. Summation methods are based on dislocation theory applied to single crystals, where quadratic and arithmetic summation are adopted to account for obstacles to dislocation motion respectively on the same structural scale and at significantly different scales [37]. On the other hand, the compounding method, based on the modified shear lag mechanism originally proposed by Nardone and Prewo for MMCs [38], treats all strengthening mechanisms as load-transferring mechanisms from the matrix to the reinforcement and it is represented mathematically by a series of improvement factors (fi).

In order to take into account that multiple strengthening effects are simultaneously present, the rules of addition of strengthening contributions (arithmetic summation) was first developed [39]. However, the summing methods, in some cases, may over-predict the yield strengths of the composites [40]. An analytical compounding model to compute the YS of MMC, taking into account both additive and synergistic effects, was developed by Ramakrishnan [41] by integrating a modified shear lag model (accounting for the load bearing effect with a continuum mechanics approach) and an enhanced dislocation density model. The model can be expressed as follows:

$$\sigma_{yc} = \sigma_{ym}(1 + f_l)(1 + f_d) \tag{1.1}$$

where σ_{yc} is the YS of the MMCs, σ_{ym} is the yield strength of the unreinforced matrix, f_l is the improvement factor associated with the load-bearing effect of the reinforcement, f_d is the improvement factor related to the dislocation density in the matrix, caused by the thermal mismatch between the matrix and the reinforcement particles. Zhang et al. [23] integrated the Ramakrishnan model [41] as to take into account the Orowan strengthening, considered to be particularly important in the case of MMNCs, as follows:

$$\sigma_{yc} = \sigma_{ym}(1+f_l)(1+f_d)(1+f_{Orowan}) \tag{1.2}$$

where f_{Orowan} is the improvement factor related to Orowan strengthening. The predicted yield strength was found to be in good agreement with the experimental data, reported in the literature, although the grain refinement is not directly considered.

Several authors inferred that the contributions to the increase in the YS of the composites could be computed as the root of the sum of squares of the different mechanisms contribution [40, 42], as originally proposed by Clyne for MMCs [3], while a combination of the quadrature and additive methods was proposed in [33]. The improvement in yield strength with the quadrature method can be expressed as follows [36]:

$$\Delta\sigma = \sqrt{(\Delta\sigma_{load})^2 + (\Delta\sigma_{CTE})^2 + (\Delta\sigma_{EM})^2 + (\Delta\sigma_{Orowan})^2 + (\Delta\sigma_{Hall-Petch})^2} \tag{1.3}$$

Some of the strengthening factors can be omitted depending on the processing routes and assumptions. In the equation, the incremental contribution to YS by the load bearing effect can be expressed as [41]:

$$\Delta\sigma_{load} = 0.5\, V_p \sigma_{ym} \tag{1.4}$$

where V_p represents the particle volume fraction and σ_{ym} the matrix yield strength. The incremental contribution of grain refinement to the strength levels can be estimated on the basis of the classical Hall-Petch equation [43, 44]:

$$\Delta\sigma_{Hall-Petch} = K d_m^{-1/2} \tag{1.5}$$

where K is the Hall-Petch coefficient and d_m is the matrix grain diameter. The effect of mismatch strain due to the difference between the CTE values of particles and that of the matrix is given by the Taylor equation as [40]:

$$\Delta\sigma_{CTE} = \sqrt{3}\beta G_m b \sqrt{\rho_{CTE}} \tag{1.6}$$

which, expressing the increase in geometrically necessary dislocations as detailed in [45], becomes:

$$\Delta\sigma_{CTE} = \sqrt{3}\beta G_m b \sqrt{\frac{12\, V_p \Delta\alpha \Delta T}{b d_p}} \tag{1.7}$$

where the strengthening coefficient β is considered to be 1.25, $\Delta\alpha$ is the difference between CTE of matrix and particles, and ΔT is the difference between the processing and the tensile test temperatures, V_p and d_p are the volume fraction and diameter of the reinforcement particles.

The strength improvement by the modulus mismatch is approximated by [36]:

$$\Delta\sigma_{EM} = \sqrt{3}\alpha G_m b\sqrt{\rho_{EM}} \tag{1.8}$$

where α is the material-specific coefficient and

$$\rho_{EM} = \frac{6\,V_p}{bd_p}\varepsilon \tag{1.9}$$

where ε is the bulk strain of the composite.

Starting from the Orowan equation, the increase in the material yield stress due to the Orowan mechanism can be expressed as [33]:

$$\Delta\sigma_{Orowan} = \frac{0.13\,G_m b}{\lambda}\ln\frac{d_p}{2b} \tag{1.10}$$

where G_m is the shear modulus of the matrix, b is the Burgers vector, d_p is the average diameter of nanoparticles and λ is the inter-particle spacing, expressed as:

$$\lambda = d_p\left[\left(\frac{1}{2\,V_p}\right)^{1/3} - 1\right] \tag{1.11}$$

It is however clear that in case particles are aggregated in clusters, the Orowan dispersion strengthening is significantly reduced with respect to the computed values. Therefore in addition to the size, volume fraction (V_f) of nanoparticles, CTE difference and processing condition, the yield strength of MMNCs is also governed by particle distribution. It is worth noticing that no agglomeration factor has been hitherto taken into account in these models.

Although several studies have stated that the quadratic method exhibit the best match with experimental data [31, 40, 45], it should be noted that there is no general agreement as concerning which physical model best represents the real MMNC behaviour [36].

As regarding the contribution of each single mechanism to the improvement in the yield strength on MMNCs, the load bearing contribution was found to be low [40] or even negligible [33], also due to the fact that relatively low V_p (<5 %) are usually employed. The grain refinement effect was reported to be limited in some studies [40], and it is even neglected by others [23, 46], although Habibnejad-Korayem et al. [33] found a contribution of more than 15 % to the total YS increase in Mg/Al_2O_3 system. Conversely, the CTE mismatch between the matrix and the particles was deemed to be the most effective strengthening contribution, followed by Orowan strengthening [40]. In fact, Zhang et al. [46] inferred that the relative contribution of the Orowan strengthening effect increases as the size of nanoparticles decreases, up to critical particle size (5.44 times the Burger vector for Mg/Al_2O_3 and Ti/Y_2O_3 nanocomposites), below which the breakdown of Orowan strengthening effect occurs; in [23], it was more generally shown that

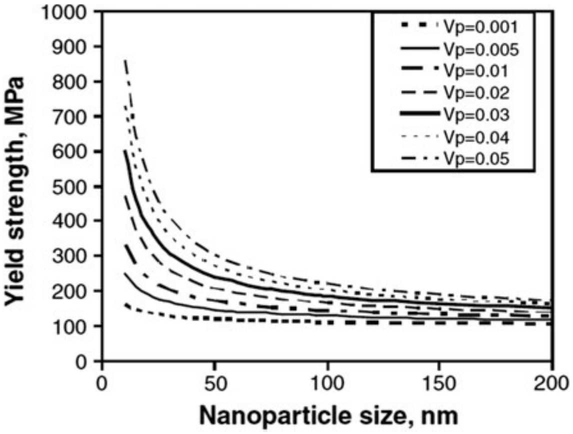

Fig. 1.2 Yield strength as a function of nanoparticle size for different volume fractions in nano-Al_2O_3 particulate-reinforced magnesium nanocomposites, predicted by model for 20 °C testing [23]

100 nm is a critical particle size, below which the Orowan mechanism is particularly effective and the yield strength increases remarkably with decreasing particle size [23], as also shown in Fig. 1.2.

The effect of grain refinement was recently revaluated by Kim et al. [36] in a review on the prediction models and reinforcing mechanisms concerning the yield strength of particle reinforced MMNCs. It should be noted that the review was focused on Mg-MMNCs due to higher availability of data. Grain refinement was shown to be the predominant factor determining the overall yield strength of most Mg-MMNCs developed to date. Furthermore, it was inferred that yield strength is generally overestimated by all of the arithmetic, quadratic, and compounding methods when considering grain refinement, Orowan, CTE, and modulus mismatch strengthening mechanisms. In fact, the full activation of CTE mismatch strengthening mechanism in MMNCs is unclear as the absence of CTE effects on the strength improvement was reported e.g. for nanostructured [47] and traditional MMCs [48]; similar considerations were reported for modulus mismatch strengthening [36]. On the other hand, the three conventional summation methods using only grain refinement and Orowan mechanisms generally predict YS values lower than the experimental ones [36]. Therefore, by considering that CTE and modulus mismatch mechanisms are unlikely to be fully activated and the yield strength prediction based only on grain refinement and Orowan mechanism generally showed underestimation, it was concluded that the increase of dislocation density caused by work-hardening during post-processing of MMNCs applied by many studies is in part responsible for improvement to the yield strength of these materials [36].

It was computed that the theoretical strength of pure Mg-MMNCs could reach 380 MPa with a submicron matrix grain size and 7.5 vol.% particle addition, in case the Orowan strengthening fully activates, i.e. particles are perfectly distributed [36]. Such theoretical strength pose a challenge for MMNC production routes and technologies to be able to obtain a uniform particle distributions while preventing excessive generation of dislocations in effectively reducing matrix grain size.

1.3 Al-Based Nanocomposites

Aluminium alloys are widely used in the transportation industry due to their high strength-to-weight ratio, good castability and formability, high electric and thermal conductivity and good corrosion resistance. Further improvement in the mechanical properties can be achieved by precipitation heat treatment, where a coherent precipitation of very small intermetallic compounds efficiently hinders dislocation movement and therefore increases strength (peak-aged condition). Unfortunately, the coherency between the precipitate and matrix lattice disappears with excessive aging temperature (overaged condition), due to the growth of the reinforcing phases that lose the hardening effect. As a consequence, at temperatures in the range from 200 to 300 °C, the tensile strength of age-hardened Al alloys reduces very quickly. As an example, Al–Si-Mg-(Cu) alloys are largely used in the transport field to produce engine heads or pistons and they are generally put into operation in the peak-aged condition. However, local temperatures up to 290 °C can be reached under most severe operating conditions, leading to a relevant softening of the Al alloys.

The need for high specific strength, to be maintained even at high temperature, has led to the development of MMCs, where the synergistic combination of a tough metallic matrix with a hard reinforcement phase (often ceramic in nature) permits to significantly enhance stiffness, strength and wear resistance, even at high temperature. Al-based composites reinforced by carbides, borates, nitrides and oxides have been successfully fabricated by either powder metallurgy (PM) techniques or casting methods [49–51]. The development of MMCs was particularly in vogue in the 1980s and early 1990s among all major aluminium producers. MMCs have found applications in a wide spectrum of markets, such as automotive, electronic packaging, industrial products and recreational goods, with products including, in a non-conclusive list [52]: pick-up truck drive shafts, brake rotors and drums, diesel engine pistons, aeronautic engine fan exit guide vanes, aircraft ventral fins and fuel access covers, bicycle components, golf clubs and electronic packaging applications. In the automotive sector, the attention has been mainly devoted to discontinuously reinforced aluminium composites (DRA), which have been commercially used in this market for nearly 20 years. Properties of interest include increased specific stiffness, wear resistance, and improved high-cycle fatigue resistance and superplastic behaviour [11, 51, 53–57]. Although weight saving is very important in automotive applications, low-cost premiums are tolerated in this sector, thus requiring cost effective processes. On the other hand, while the raw material cost of MMCs is higher than that of the material typically replaced, the DRA component would weigh considerably less than steel, significantly improving the cost comparison [58].

Although Al-based metal matrix composites offer many advantages over monolithic alloys, they present significant limitations, such as low fracture toughness and ductility, poor machinability and weldability. Moreover, tribological problems must be taken into account when considering their use in engine design.

For example, their use in pistons can induce relevant wear damage of the cylinder lines [14]. Commercial particle reinforced Al based composites are generally reinforced by 10–20 vol.% of ceramic particles, with a size ranging from a few micrometers to several tens of micrometers. It is known that fracture of composites is controlled by fracture of the larger particles, as well as formation of cavities and voids at the particle/matrix interface, which in turn depends on the particle size [59]. Large particles (above 1.5 μm) act as micro-concentrators of stress and may give rise to cleavage, while medium size particles (0.2–1.5 μm) lead to the formation of cavities or pits through the loss of interphase cohesion [13]. A key role in fracture is also played by the presence of particle clusters that locally reduce MMC fracture toughness in a significant fashion. This has a strong effect on the fatigue behaviour of MMCs and also on their tribological performance, because, even though it is widely accepted that they perform better than the corresponding unreinforced Al alloys, they also lead to relevant wear damage of the counter-material, due to the abrasive action of the ceramic reinforcement [13]. As a consequence, the machining of particulate reinforced metal matrix composites is characterized by extremely high tool wear due to the abrasive action of the ceramic particles. Only a small group of extremely hard and expensive materials, such as polycrystalline diamond, are then suited to this task, since the cutting tool must be able to withstand intermittent cutting of hard (reinforcement) and soft (matrix) materials [60, 61]. The need of frequent tooling together with the high cost of tools considerably increases the cost of the machining process when compared with that of the monolithic alloys. On the other side, non-traditional processes like electrical discharge machining, abrasive waterjet cutting, and laser cutting are very costly and characterized by slow machining rates [62, 63]. Machining of MMCs still remains an issue to be addressed, so as to produce the required close dimensional tolerances and surface finish with cost effective processes.

The traditional fusion welding techniques (TIG, MIG, laser) of Al-based MMCs generally lead to microstructural defects, related to the presence of the ceramic reinforcement, which result in a decrease in their mechanical properties. In particular, the addition of high volume fractions of ceramic reinforcement causes higher viscosity in MMCs melts, particle segregation, evolution of the occluded gas and undesired matrix-reinforcement reactions [10], so that friction welding processes are often required to obtain sound joints [64–66]. These occurrences clearly outline the compelling need for an aluminium-based material whose strength is stable at higher temperatures, whose ductility and toughness is maintained and whose manufacturing and machining processes can be adapted to existing industrial infrastructures, thus overcoming the limitations of both monolithic aluminium alloys and conventional MMCs reinforced with relatively high volume fraction of micrometric particles.

Al-based nanocomposite have recently emerged as a class of materials suitable for this goal. The most popular and versatile reinforcements are ceramic nanoparticles, such as Al_2O_3, SiC, TiC, AlN added to the Al alloys in relatively low volume fractions (usually lower than 5 wt%). Thanks to the presence of nano-sized particles homogeneously dispersed within the matrix, aluminium based nanocomposites can present some relevant characteristics, as also widely discussed in Sect. 4.1, such as: superior specific stiffness comparing to the unreinforced matrix [67, 68]; significant improvement in strength (UTS, YS) with respect to the unreinforced Al matrix and enhancement of ductility comparing to the traditional MMCs [17]; noticeable improvement of creep resistance and thermal stability with respect to Al alloys [69, 70]; better wear resistance with respect to both Al alloys and MMCs [71]. Benefits of using nanoparticles, rather than micro-sized particles have been clearly highlighted by several studies. Sajjadi et al. [21] compared two A356 based composites reinforced through 20 µm and 50 nm Al_2O_3 particles. Compression tests on the produced samples revealed that the nanometric reinforcing phase caused a sensibly higher increase of strength, even with a lower reinforcement content (610 MPa with 3 wt% of nano-alumina, 453 MPa for 10 wt% of micro-alumina). Ma et al. [72] found that a 1 vol.% nano-Si_3N_4/Al shows a UTS (180 MPa) similar to the one of a 15 vol.% micro-SiC-Al composite (176 MPa). A further study by Kang and Chan [13] compared nanocomposites with 1–7 vol.% of nano alumina, to a 10 vol.% micro-SiC reinforced composite, showing that YS and UTS of the 1 vol.% nanocomposite were comparable to the ones of the 10 vol.% micro-composite.

Despite their tremendous potential, aluminium based nanocomposites are still to be developed on a large industrial scale. Among possible production routes, liquid or semisolid based production routes are deemed to possess higher industrial scalability, although obtaining a homogenous particle distribution is still challenging. The state of the art on novel Al-nanocomposites, properties and manufacturing processes will be discussed in Chap. 2, with a particular focus on liquid-based production routes.

1.4 Mg-Based Nanocomposites

In the search for new light-weight materials for energy efficiency and emission reduction, magnesium (Mg), the lightest of the structural metals, is one of the most promising candidate, which is rapidly finding its niche in becoming the major high-volume structural metal. Considering the weight factor, pure Mg is ~33 % lighter than aluminium (Al) and ~75 % lighter than steel. Mg is also 100 % recyclable, energy efficient and sustainable (naturally abundant). It also exhibits good dimensional stability, machinability and damping capacity. In recent times, Mg-based materials are replacing conventional metals such as cast iron and steel in various applications, especially in automobile and aerospace applications. For example, replacing the cast iron engine block (~84.6 kg) in a V6 3.0 litre six-cylinder car by Mg (~30 kg) would result in a weight savings of ~65 % [73]. Reports indicate that the overall weight savings in using Mg-materials as a replacement for Al-parts would lead to a fuel saving of the order of ~20–30 %, without any requirement of changes in design. The use of Mg-based materials by automotive industry is an excellent example of materials selection, whereby material properties, processability, cost, availability, environmental issues, recyclability, fuel efficiency etc. are all taken into account. Mg-based materials prove to be robust for weight-critical structural applications.

Generally, Mg-alloy systems contain Al, Mn, Zn, Zr and rare-earth elements as alloying constituents and are designated by the alloy standards as AZ31 (Mg-3Al-1Zn), AM50 (Mg-5Al-0.1Mn), ZK60 (Mg-5.5Zn-0.7Zr) etc. [74]. However, certain drawbacks observed in these commercially available alloys include their low strength and poor ductility, which have limited their expansion as the major structural material for broader applications [75]. In order to overcome these limitations and also to enhance their performance, approaches such as: (i) incorporation of micron-scale ceramic reinforcements to form their metal matrix composites (Mg-MMCs) [76] and (ii) addition of metallic elements such as Ti, Mo, Nb etc., have been tried [77–79]. Considering the first approach, the low strength of Mg and its alloys are overcome by the addition of high strength/modulus micron-scale ceramic reinforcements (such as Al_2O_3 and SiC particles/fibers/whiskers). The introduction of such reinforcements into the Mg-matrix significantly improved the mechanical properties such as hardness, tensile strength, elastic modulus and yield strength, and also gave rise to excellent wear resistance, similarly to Al-metal matrix composites mentioned in the previous section. Although the Mg-MMCs show promising properties, the improvement in strength properties occurs at the expense of ductility, which has undermined their applicative potential for various real-time applications [76]. With the second approach, metallic elements such as Ti, Mo and Nb are added, in spite of the conventional alloying elements such as Al, Mn, Zn, Zr and rare-earth elements, which usually form brittle Mg-based intermetallic compounds such as $Mg_{17}Al_{12}$, $MgZn_2$ etc. thus reducing the ductility. Elements such as Ti, Mo and Nb are either insoluble or have negligible solubility in Mg, and do not give rise to any secondary/precipitate phase formation with Mg [80]. Reports show that these metallic elements can provide nominal improvement in ductility, while on the other hand they reduce the strength [77–79]. Given the above-mentioned facts, design and development of new Mg-materials becomes necessary.

In this context, it should be noted that similarly to Al-materials, Mg-materials are sought both in their cast and wrought forms (extrusions, rolling etc.). However, unlike Al-based materials, Mg-based materials (including Mg-alloys without any ceramic reinforcement) possess poor ductility. This is due to their inherent crystal structure, i.e. their low symmetry and the limited number of slip systems that exist in the hexagonal close packed (hcp) structure of Mg, when compared to the face centred cubic structure (fcc) of Al [81]. In Mg-systems, activation of dislocations slips and twinning modes is difficult at room temperature. The activation of these deformation modes are related to its critical resolved shear stress (CRSS) levels determined by Schmid factor, which in turn depends on the crystalline orientation (crystal texture) [82, 83]. The crystal texture may undergo evolution during casting, deformation, welding, and heat treatments. In Mg-castings, all possible orientations of the Mg-crystallites occur with equal frequency, whereby their orientation dependence disappears (random crystal orientation), and the material behaves isotropically [84]. In the case of wrought Mg-materials, strong orientation of crystallographic planes is observed (i.e. texture evolution) that gives rise to anisotropic behaviour [85]. As an example, thermo-mechanical processing of Mg such as extrusion results in a strong texture development. Here, the basal planes are aligned strongly into the extrusion direction, which are highly unfavourable for the basal slip to occur. Due to this reason, the tensile ductility of extruded Mg-materials is limited if testing is carried out parallel to the extrusion direction [85, 86]. This calls for the use of higher temperatures during deformation processes that are cost-ineffective. The strong basal orientation also gives rise to tension-compression asymmetry [85, 86]. A favourable texture development can promote room temperature deformation characteristics.

Considering these facts, it should be understood that in addition to the major strengthening mechanisms detailed in Sect. 1.2, the deformation behaviour of Mg-materials is also significantly determined by its crystallographic orientation (texture). It is important to note that, given that the poor ductility is a major concern that hinders the complete utilization of both Mg-alloys and Mg-MMCs, the ductility of the currently existing Mg-materials remains to be improved by novel methods. This need has to be addressed without affecting the strength properties. With the advent of nanoscale materials, the use of nanoparticle reinforcements in Mg-matrices (Mg-nanocomposites, Mg-MMNCs) has proved promising in this regard [87]. Such advanced materials can be produced using traditional or unique processing techniques [88–91]. These new materials exhibit exceptional properties that are unobserved in conventional alloys/composites [92]. For example, the ductility of pure Mg was improved by ~70–100 % when incorporated with nanoparticles/CNT [93]. These new materials have greater ductility with retained/improved strength at room temperature, owing to the texture modification due to nanoparticle addition. Such change in crystallographic orientation due to nanoparticle addition results in the activation of non-basal slip systems/twinning, thereby contributing to the ductility improvement and/or strengthening effect [93]. To characterize the texture, pole figures using X-ray diffraction techniques are utilized. Alternatively, for micro-texture analyses electron back-scattered diffraction (EBSD) in association with scanning electron microscopy (SEM) and rapid analysis of electron diffraction patterns of grains by transmission electron microscopy (TEM) are employed. Given that nano-sized reinforcements can make distinct positive contribution towards enhancing the overall properties of Mg-materials, it is also important to note that such enhancement in properties can be attained at lower volume percents (<3 %), whereas for micron-scale particle reinforced MMCs higher volume fractions (>>10 %) are required.

Mg-MMNCs can be produced by both liquid and solid-state processing routes. While there is a wide misconception that incorporating nanoparticles via the liquid metallurgy route is difficult due to poor wetting and nanoparticle agglomeration [94], these may be true only when conventional liquid-state composite processes such as stir casting followed by gravity die-casting or squeeze casting are employed. Some of the novel processing methods such as the ultrasonic dispersion method and the disintegrated melt deposition method (DMD), have been quite successful in producing nanocomposites with good dispersion, matrix/particle interfacial bonding and free of processing defects [91, 92]. Mg-MMNCs are seen to have enormous potential in diverse industrial and commercial sectors such as automotive, aviation, defense, biomedical, sporting equipments, consumer electronics, etc. To cater for such demands, the priority lies at first in improving the manufacturing technologies and followed with design/development of new Mg-nanocomposites. In the forthcoming sections, the state-of-the-art research trends that highlight the advancement in Mg-nanocomposite materials - their processing and novel Mg-nanocomposites development are presented. Research towards understanding the material characteristics under various loading/operating conditions using advanced characterization tools has also been presented.

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