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A review on mechanical properties of aluminium-based metal matrix nanocomposites

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Abstract

Industrial production today requires new improved materials to meet market demands, which leads to the production of new materials with improved properties. One kind of response to those requirements is the development of metal matrix composites (MMCs) with the aim of obtaining materials with better properties when compared to conventional metals and alloys. Nowadays, metal matrix nanocomposites (MMnCs) are being increasingly investigated due to the possibility of achieving better machinability, high fracture toughness and improved ductility when compared to conventional composites. Considering the pace of development and the huge perspective of different classes of materials, this research aims to provide insight into the mechanical properties of aluminium nanocomposites. Aluminium nanocomposites are attracting a lot of attention due to their high strength-to-weight ratio, wear resistance and low costs, when compared to matrix alloy. In this paper, an attempt is made to review other research reports and make a connection between the characteristics of the microstructure and the mechanical properties, which are dependent on the method of fabrication and type and content of reinforcement.

1. Introduction

In recent years, there has been an increased need to reduce fuel consumption and emissions, which has led to the increased use of light alloys for the production of machine elements. More specifically, high-performance, lightweight materials are essential in a wide range of industrial applications. By combining different materials, it is possible to obtain a material with superior characteristics, compared to the individual materials used. According to the type of the matrix material, composites are classified as metal matrix composites (MMCs), ceramic matrix composites (CMCs) and polymer matrix composites (PMCs). Another criterion for classification is according to the size of the reinforcement, where macrocomposites, microcomposites and nanocomposites are distinguished [1-7].

By observing composites with a metal matrix, the most commonly used matrix material is aluminium and its alloys. Aluminium as the matrix of MMC (Al MMC) stands out from other metals (Cu, Ti, Mg and Fe) with its characteristics such as low density and high strength. By combining a light aluminium alloy with certain reinforcements, composite materials can be obtained for the production of components that achieve lower weight and high strength [7-9]. Tekale and Dolas, by reviewing the literature, found that for the production of MMCs, the most commonly used matrix is aluminium and aluminium alloys (Al, A356, Al359, Al2219, Al6061, Al7068, Al7075 and Al2024) with 75 %, followed by manganese with 10 %, titanium-based alloys with 3 %, copper and copper-aluminium alloys with 5 % and others with 7 % [10]. The type of reinforcement has been chosen based on the application of the Al MMCs, where the most commonly used are Al_2O_3 and SiC [7-9].

During the last decade, research has been focused on aluminium metal matrix nanocomposites (Al MMnCs) reinforced with nanoparticles. As a result of previous research, nanoceramic particles are used as reinforcements to meet the needs of the industry due to their exceptional strength-to-weight ratio, good thermal conductivity and better wear resistance. It was also established that the application of nanoparticles as a reinforcement in the aluminium matrix increases the strength resistance while maintaining the desired ductility if the appropriate dispersion of nanoparticles within the matrix is achieved. The largest application of Al MMnC materials is in the automotive industry in the production of components such as connecting rods, drive shafts and cylinder liners. In addition, their application is present in aeroplanes, shipping, transport and the defence sector and will continue to expand due to extensive testing and production of nanocomposites [11].

The fabrication process of the desired targeted nanocomposite is determined during the selection of the matrix material and reinforcement. It is known that centrifugal casting, vacuum casting, powder metallurgy, stir casting, in-situ casting, compocasting and squeeze casting, are the conventional methods for obtaining nanocomposites [8,10]. To obtain a material with favourable mechanical characteristics, it is necessary to promote the homogeneity of the reinforcement in the material matrix. To achieve the desired characteristics, it is necessary to choose the appropriate manufacturing process, as well as to determine the optimal values of the processing parameters, as well as the size, type and content of the reinforcement. To explain certain results achieved by the application of nanoreinforcement on the values of hardness, strength, elongation, modulus of elasticity, etc. it is necessary to establish which strengthening mechanisms occur. Dislocation density growth, Orowan and Hall-Petch effects are very important strengthening mechanisms in nanocomposites.

In the current work, a review on mechanical properties of aluminium-based nanocomposites was performed. The work aims to investigate and determine in which directions the current aluminium nanocomposite tests are taking place in terms of discovering the new production techniques that achieve a homogeneous distribution of nanoparticles, and the use of a new combination of the type and content of reinforcements (which directly affects the mechanical properties).

2. Mechanical properties of nanocomposites with an aluminium matrix

Aluminium alloys have found large industrial applications due to their characteristics, such as good castability, high toughness, corrosion resistance and other good mechanical properties. These alloys are generally easy to machine and weld, which makes them a suitable choice for applications in the aerospace industry, as well as for machine parts, truck chassis components, aircraft and rocket components and other structural parts that require high strength [12].

This paper provides a literature review of the following mechanical properties: hardness, elasticity, elongation, tensile strength and fracture strength. All the mentioned properties were studied by the researchers to analyse the improvement of the mechanical properties that influence the selection of materials [13-32]. Table 1 shows the mechanical properties of various nanocomposites with an aluminium matrix.

Researchers have dedicated significant efforts to the development of aluminium nanocomposites with ceramic reinforcements, such as: SiC [5,17,18,26-28,33]; Al_2O_3 [6,13-18,21,23-25,29,31,32,34]; TiC [24]; ZrO_2 [16,19]; B_4C [14,31]; TiO_2 [20]; TiB_2 [15,32,34]; Gr [21] and many more, obtained by different fabrication methods. Numerous researchers have reported that the production process, particle size, grain size, and the connection between the matrix and the reinforcement and dislocations, have an obvious effect on the mechanical characteristics of the composite. The mechanical properties of MMnCs depend on their microstructure and the amount and distribution of reinforcement. In the following, the emphasis will be on individual mechanical properties, observing the influence of particles and the production process on certain properties.

3. Fabrication of aluminium metal matrix nanocomposites

Depending on the state of materials during production, fabrication methods can be classified as solid-state processes, liquid-state and semi-solid state processes. In the solid-state processes, there are friction stir processing and powder metallurgy. Liquid-state processes include squeeze casting, ultrasonic casting, stir casting and gas pressure infiltration. The rheocasting and thixocasting belong to the semi-solid state processes. Newer fabrication methods are spark plasma sintering and ion plating, which fall into the deposition processes [8,12,35].

Table 1. Mechanical properties of aluminium-based nanocomposites

Reference	Mohammad Sharifi and Karimzadeh [13]	Alizadeh et al. [14]	Moghadam et al. [15]	Rostami and Tajally [16]
Material	Al + 5, 10 and 15 wt. % Al_2O_3–AlB_{12}	1050 + 1.35 wt. % Al_2O_3 + B_4C	Al + 1 wt. % Al_2O_3 + 1 wt. % TiB_2	A332 + 2 wt. % Al_2O_3 + ZrO_2
Reinforcement size	Al_2O_3 (40 nm); AlB_{12} (25 nm)	Al_2O_3 (50 nm); B_4C (50 nm)	Al_2O_3 (50 – 150 nm); TiB_2 (8 – 20 nm)	Al_2O_3 (30 nm); ZrO_2 (35 nm)
Fabrication method	powder metallurgy	accumulative roll bonding	liquid metallurgy	stir casting
Hardness	108 – 156 HV	49 – 90 HV	37.5 – 67.4 HV	115 – 142 HB
Elastic modulus	–	–	–	–
Elongation	–	–	43 – 59 %	1.5 – 3.8 %
Yield strength	–	–	33.2 – 64.6 MPa	100 – 161 MPa
Tensile strength	–	269 MPa	74 – 172 MPa	185 – 330 MPa
Reference	Behnamfard et al. [17]	Liu et al. [18]	Harsha et al. [19]	Sahandi Zangabad et al. [20]
Material	A356 + 1 wt. % SiC / 1 wt. % Al_2O_3	A356 + 1 wt. % SiC / 1 wt. % Al_2O_3	A356 + 2.5 and 5 wt. % ZrO_2	5052 + 2 and 3.5 vol. % TiO_2
Reinforcement size	SiC (70 nm); Al_2O_3 (40 nm)	SiC (50 nm); Al_2O_3 (20 nm)	ZrO_2 (50 nm)	TiO_2 (30 nm)
Fabrication method	vortex casting	ultrasonic cavitation	stir casting	friction stir processing
Hardness	117 – 159 HV	–	81 – 88 HB	–
Elastic modulus	–	–	–	75 – 85 GPa
Elongation	–	6.3 – 11.2 %	9.35 – 9.38 %	19 – 26 %
Yield strength	107 – 196 MPa	190 – 196 MPa	251 – 266 MPa	108 – 158 MPa
Tensile strength	175 – 292 MPa	263 – 283 MPa	299 – 331 MPa	213 – 252 MPa
Reference	Mostafapour Asl and Khandani [21]	Hosseini et al. [22]	Ahamed and Senthilkumar [23]	Jeyasimman et al. [24]
Material	5083 + Al_2O_3 + Gr	5083 + CeO_2 / CNT / CeO_2 + CNT	6063 + 1.5 wt. % Al_2O_3 / Y_2O_3 / Al_2O_3 + Y_2O_3	6061 + 2 wt. % Al_2O_3 / TiC / Al_2O_3 + TiC
Reinforcement size	Al_2O_3 (80 nm); Gr (10 – 50 µm)	CeO_2 (30 nm); CNT (15 nm × 15 µm)	Al_2O_3 (38 nm); Y_2O_3 (38 nm)	Al_2O_3 (40 – 50 nm); TiC (200 nm)
Fabrication method	friction stir processing	friction stir processing	powder metallurgy	powder metallurgy
Hardness	83 – 140 HV	≤ 173 HV	69 – 76 HV	62 – 86 HV
Elastic modulus	–	–	–	–
Elongation	–	–	–	–
Yield strength	200 – 290 MPa	–	429 – 484 MPa	–
Tensile strength	250 – 390 MPa	≤ 396 MPa	457 – 497 MPa	539 – 580 MPa*

Gr – graphite; CNT – carbon nanotube; *compressive strength

Table 1. *Continued*

Reference	Mohanavel et al. [25]	Kwon et al. [26]	Poovazhagan et al. [27]	Madhukar et al. [28]
Material	6082 + 1, 2 and 3 vol. % Al_2O_3	6061 + 1 vol. % SiC + 6 wt. % CNT	6061 + 0.5, 1 and 1.5 vol. % SiC + 0.5 vol. % B_4C	7150 + 0.5, 1.0, 1.5 and 2.0 wt. % SiC
Reinforcement size	Al_2O_3 (50 nm)	SiC (20 – 30 nm); CNT (20 nm × 10 μm)	–	SiC (40 – 60 nm)
Fabrication method	stir casting	powder metallurgy	ultrasonic cavitation	stir casting
Hardness	51 – 68 HV	64 – 334 HV	85 – 128 HB	168 – 188 HV
Elastic modulus	–	–	–	–
Elongation	–	–	3 – 6 %	–
Yield strength	–	–	200 – 230 MPa	–
Tensile strength	164 – 181 MPa	114 – 286 MPa**	210 – 270 MPa	131 – 182 MPa
Reference	Al-Salihi et al. [29]	Chak and Chattopadhyay [30]	Ramakoteswararao et al. [31]	Eskandari and Taheri [32]
Material	7075 + 1, 3 and 5 wt. % Al_2O_3	7075 + 0.1, 0.3 and 0.5 wt. % GNP	8011 + 3 wt. % Al_2O_3 + B_4C	8026 + Al_2O_3 + TiB_2
Reinforcement size	Al_2O_3 (20 – 30 nm)	GNP (5 – 30 nm)	Al_2O_3 (< 50 nm); B_4C (< 60 nm)	Al_2O_3 (70 nm); TiB_2 (5 μm)
Fabrication method	stir casting	stir casting	stir casting	friction stir processing
Hardness	58 – 72 HB	160 – 200 HV	85 – 95 HV	≤ 175 HV
Elastic modulus	72 – 72.8 GPa	–	–	134 – 139 GPa
Elongation	–	–	1.38 – 1.99 %	3.23 – 4.46 %
Yield strength	40 – 49 MPa	–	–	256 – 295 MPa
Tensile strength	142 – 152 MPa	220 – 460 MPa	149 – 162 MPa	233 – 257 MPa

GNP – graphene nanoplatelets; **bending strength

The following section of the paper provides an overview of the application of production methods for nanocomposites that are widely employed and lead to specific improvements in the properties of nanocomposites.

3.1 Powder metallurgy

Powder metallurgy (PM) is a simple method for the production of Al MMnC samples because the produced by this method do not require post-processing. This method consists of mixing metal and ceramic powder particles in a certain number of steps [36,37].

The first step involves turning the matrix material into powder particles (mechanical milling) so that the matrix powder and the reinforcement powder are mixed in the proper ratio. The resulting mixture is inserted into a mould and pressed to achieve a cohesive structure with dimensions close to those of the final sample. The final product is obtained by hot pressing. Mechanical milling represents the process of grinding a mixture of powders using different methods. Depending on the type of material from which the powders are obtained, different types of mills are used. The most commonly used are ball, vibration, vortex and planetary mills. Ball milling is usually used to obtain fine powders. The main objectives of the ball milling process are the reduction of powder particles and the homogenization of the powder mixture in a solid state. A ball mill can be defined as a cylindrical chamber with horizontal rotation around its axis, which is partially filled with powder and grinding balls [5]. By inserting the matrix material and reinforcement into the mill, the mill starts working for a certain period. During this process, energy is released by hitting particles against particles, particles against balls, and particles against the wall of the mill. In this way, the particles are deformed and change their shape and size. After a certain time and mutual reactions, the particles change size and reduce to nano-size. With this process, much smaller and finer grain particles are obtained compared to the particles before the process [12,16,35]. Therefore, this procedure can be used both for the matrix material grinding and for mixing powders of the matrix material and nanoparticles as reinforcement.

Secondary operations, such as extrusion, heat treatment, machining and others, can be applied after the final stages of this process. The process of obtaining nanocomposites through powder metallurgy is very expensive, but it leads to a significant improvement in the material's characteristics, such as strength and stiffness [12]. The researchers successfully applied the PM method with accompanying secondary operations to obtain nanocomposites, which were proved with better mechanical properties. [8,13,23,37,38] Ahamed and Senthilkumar [23] using the field emission scanning electron microscopy (FESEM) established a better distribution of Al_2O_3 particles compared to Y_2O_3 particles after 20 hours of milling. Using transmission electron microscopy (TEM) on hybrid nanocomposites revealed good interfacial integrity between the soft aluminium matrix and hard nano-size ceramic reinforcements.

Afkham et al. [38] found that extended milling time does not additionally affect the distribution of SiC and Al_2O_3 nanoparticles in the metal matrix consisting of copper and iron powders. Characterisation of the material surface using scanning electron microscopy (SEM), FESEM and X-ray diffraction (XRD), revealed that the nanoparticles were agglomerated before the grinding. To reduce particle agglomeration, 1.5 wt. % stearic acid was used as a process control agent. Based on the conducted research, they concluded that Al_2O_3 nanoparticles are not thermodynamically stable when they are mixed with copper powder in the process of obtaining nanocomposites. On the other hand, SiC nanoparticles have higher thermodynamic stability when they are mixed with metals. The conclusion is that high-energy mechanical milling of Al_2O_3 nanoparticles and metal, after a long time of milling, can lead to a reaction. It was also established that the distribution of nanoparticles is not affected by the type of ceramic particles or the milling time. The conclusion is that nanoparticles significantly affect the average particle size of composite powders [38].

Using TEM microscopy, Carreño-Gallardo et al. [39] established that the particles are homogeneously distributed in the alloy, which was proven by the improvement in mechanical properties. They used the aluminium alloy 2024 as a matrix with a variation of the reinforcement content from 0 to 5 wt. % SiC nanoparticles. Based on the conducted tests, they concluded that the optimal milling time in the process of obtaining nanocomposites is 2 hours and that results in strength and hardness improvement are a direct function of the particle content.

Mohammad Sharifi and Karimzadeh [13] applied mechanical milling of nanocomposite powders (Al and Al_2O_3–AlB_{12}), followed by hot pressing, to perform wear and hardness tests of the samples. It was found that with the increase of Al_2O_3–AlB_{12} particle addition, the hardness of the nanocomposite increases. In the TEM micrograph analysis of the nanocomposite, the reinforcement particles are well distributed in the matrix. Also, the reinforcement particles were broken during grinding and their average particle size was reduced to about 40 nm.

Kwon et al. fabricated aluminium alloy (6061) based composite materials reinforced with SiC and CNT using the high-energy ball milling and hot-pressing processes [26]. The high-energy ball milling time significantly affected the microstructure and mechanical properties of composites. By increasing the milling time, there was a notable reduction in the crystallite sizes of aluminium within the composites. They concluded that these composites can be used in various applications as industrial component materials with precisely controlled properties.

Mechanical milling was also applied in a study by Mohammad Sharifi et al. [40]. Aluminium nanocomposites were produced with hot pressing as the secondary operation. Ball milling lasted for 5 hours without interruption. The mass ratio of the reinforcement and steel balls was 10:1. The balls were made of chrome-plated steel with a diameter of 20 mm. The milling process was carried out in an argon atmosphere to prevent oxidation. A similar procedure was shown in the paper [23], where Al_2O_3 and Y_2O_3 were used as reinforcements in an aluminium matrix. The process was carried out in a planetary mill at 200 rpm for 20 hours. The balls had a diameter of 16 mm and balls to material particles the ratio was 10:1. Based on the uniform distribution of particles in the matrix and minimal porosity of the composite, it was established that nanocomposites were successfully produced using this method. The hardness values of the nanocomposite, for both individual and hybrid reinforcement, were similar without any detections in the interfacial reaction between the matrix and the reinforcement. Their general conclusion is that hybrid nanocomposites show better mechanical properties than nanocomposites.

The production and characterisation of aluminium nanocomposites, which is presented in the paper of Atrian et al. [41], includes the application of mechanical milling, followed by cold pressing and hot extrusion. To achieve the best quality of nanocomposite samples, they optimised the extrusion process by analysing parameters such as extrusion speed, temperature, extrusion ratio, lubrication and dimensions. Argon gas was used to prevent oxidation of the powder and 1 wt. % stearic acid was used as a process control agent to prevent cold welding during the milling. The goal of this procedure was to refine the grain of the aluminium matrix particles and achieve a homogeneous distribution of the SiC particles in the matrix. The duration of milling was chosen to reduce the ductile behaviour of aluminium particles and make them brittle, that is, closer to the brittle nature of the SiC reinforcement. With this research, the authors showed that nanocomposites can be successfully prepared by this procedure and concluded that the relative density was reduced by 1 % when adding 3 wt. % SiC nanoparticles. With this content of reinforcement, a uniform distribution of the SiC nanoparticles was observed, which resulted in an improvement of mechanical characteristics, such as microhardness and tensile strength, by approximately 50 %.

Taherzadeh Mousavian et al. [42] applied a new ball milling process to the production of nanocomposites with A356 matrix and SiC particle reinforcement. The ball milling of micron-sized SiC particles was carried out in the presence of Fe and Ni powder to reduce the particle size. After 36 hours of milling and continuous breaking of brittle SiC powder particles, multi-layered SiC powder particles with a size of 50 nm to 10 µm were formed. The powder was then cast into a semi-solidified aluminium alloy melt to facilitate the incorporation of fine SiC particles. Using the XRD analysis, they showed that after milling, there is no reaction between the SiC and Fe powder particles, as well as SiC and Ni. Through analysis, they found that Ni causes the formation of grains with high sphericity, while a needle-like morphology is obtained when Fe is used as an agent. It was observed that the hot extrusion process completely changes the microstructure of the composite materials leading to significant fragmentation of the silicon eutectic phases. A much better distribution of nanoparticles and submicron particles, with less agglomeration, is obtained when the milled Ni-SiC powders are incorporated into the molten metal. An improvement in mechanical properties of about 55 % has been proven for composites containing Ni-SiC powder, compared to those of extruded aluminium alloy [42].

El-Daly et al. [43] prepared aluminium nanocomposites with SiC nanoparticles (from 2.5 to 12.5 wt. %) as reinforcements, using energy ball milling with cold pressing and sintering at 550 °C for 1 hour. In order to produce the SiC powder with an average particle size of less than 70 nm, a milling process was applied in a high-voltage mill at room temperature and argon atmosphere. The SiC nanoparticles formation was achieved after 50 hours of grinding, which was confirmed by the TEM and XRD analyses. Further preparation of the nanocomposite consisted of high-energy circular milling with a ball-to-particle mass ratio of 10:1. Analysing the microstructure of the material showed a homogeneous distribution of nanoparticles, while porosity and cracks at the Al/SiC interface were not detected. As a result of the well-prepared nanocomposites, the authors concluded that the mechanical properties of the nanocomposite improved significantly, while Poisson's ratio of the nanocomposite remained unchanged [43].

3.2 Friction stir processing

Friction stir processing (FSP) is an innovative surface modification technique used for metallic components. In contrast to friction stir welding (FSW), which is used for joining materials, FSP focuses on altering the microstructure of monolithic specimens to achieve desired properties. During FSP, a rotating tool with a pin induces plastic flow in the material, leading to the creation of a modified microstructure [44]. This is a procedure used for the surface treatment of aluminium composites and homogenization of aluminium alloys obtained by powder metallurgy. The FSP technique is based on FSW, aiming to create a porosity-free surface layer with a homogeneous distribution of reinforcing particles in the matrix and a strong bond between the reinforcement and the matrix. It results in localised microstructural modification with specific surface improvement in metal properties. This process is a recognised method for mixing nano-scale particles of the secondary phase into the microstructure, thus forming the surface composites [12,34].

Applying the FSP process, Mostafapour Asl and Khandani [21] examined the effect of hybrid reinforcement on microstructural, mechanical and tribological properties of the surface hybrid nanocomposite 5083/Al_2O_3/Gr. To prevent powder splashing during FSP, they utilised the first tool (needleless tool) to seal the filled groove. Then, the second or main tool was immersed in the workpiece and moved along the closed groove. The processing parameters were defined so that the FSP region without defects would be obtained. All the samples were made with 3 passes of the FSP to obtain a more homogeneous dispersion of the reinforcement, which was proven by the SEM analysis. The results showed that expensive Al_2O_3 nanoparticles can be partially replaced by cheap micro-sized graphite particles and that the nanocomposite can have a higher tensile strength with a lower wear rate.

Vatankhah Barenji et al. [34] observed the presence of clusters with one FSP pass that were much larger than the size of the Al_2O_3/TiB_2 particles themselves (≈ 500 nm). Then, they executed more passes and noticed that with the increased number of FSP passes, the size of the clustered particles decreased. They found that with four passes, an even dispersion of Al_2O_3/TiB_2 particles is obtained, and thus the best characteristics of the material. Sahandi Zangabad et al. [20] applied the FSP process to investigate the fatigue behaviour of an Al-Mg alloy. They found that when using 2 and 3.5 vol. % TiO_2 to achieve a relatively uniform distribution of particles, and thus improved fatigue strength, it was essential to process the materials in the appropriate condition, which was proven by the achieved results.

The success of applying the FSP process was also proved by Eskandari and Taheri [32]. They found that a tool rotational speed of 800 rpm is more favourable since improvements in mechanical characteristics were achieved. Hosseini et al. [22] successfully applied the FSP process to incorporate multi-walled carbon nanotubes (MWCNT) and nano-sized CeO_2 particles into the matrix of Al5083 alloy to form surface-reinforced composites with three passes of FSP. The best mechanical characteristics were obtained by the MWCNT/CeO_2 reinforcement composition in a volume ratio of 75 – 25 %, respectively.

3.3 Spark plasma sintering

Production of unattainable configurations of materials with otherwise poor deformability is possible with spark plasma sintering (SPS). This method is used for the fabrication of highly pure materials with the use of pulsed direct current. This low-voltage, direct current, pulsed current–activated pressure technique provides good mechanical properties due to the possibility of using micro- and nanoreinforcements [45]. This method is a cost-effective powder fabrication method due to the short sintering time, fast heating, low energy consumption and cooling rates. The SPS suppresses grain growth and removes impurities, thus providing better properties of materials [46,47].

Khoshghadam-Pireyousefan et al. [48] produced aluminium nanocomposites reinforced with graphene by a combination of high-energy ball milling (HEBM) and molecular level mixing (MLM) processes, followed by the SPS method. The CuO/GO (graphene oxide) powders were reduced to Cu/RGO (reduced graphene oxide) at 400 °C for 3.5 hours. They used the ratio of RGO and Cu fractions to produce nanocomposites Al-4Cu/0.3, 0.5, 0.7 and 1 wt. % RGO. For the production of the Al-4Cu matrix, Cu powders were also synthesized under the same conditions without the RGO. Consolidation by the SPS process was performed on prepared nanocomposite powders that were compacted in a graphite mould. The powders were sintered with SPS at 500 °C for 10 minutes under a pressure of 50 MPa. The sintering and cooling processes were carried out under a vacuum. They concluded that by increasing the RGO content from 0 to 1 wt. % the coarse-grained microstructure changes to a bimodal microstructure. The results showed that the average grain size decreased from 3.9 to 1.6 mm and the density of dislocations increased significantly with the increase of RGO content. The SPS process also resulted in an improvement in the mechanical properties of the nanocomposite, compared to the unreinforced Al-4Cu alloy [48].

Singh et al. [49] produced Al/0.5 wt. % multi-walled carbon nanotubes (MWCNTs) nanocomposite by SPS using aluminium powders (average particle size of 7 – 15 µm) as the matrix and MWCNTs reinforcement (diameter 40 – 70 nm and length 0.2 – 0.5 µm). They observed the influence of sintering temperature and heating rate on the crystallite size, densification behaviour and mechanical properties of SPS. The conclusion was that the mechanical properties of sintered Al-MWCNTs nanocomposites were significantly improved with increasing sintering temperature. The maximum improvement in mechanical properties was shown for the nanocomposite sintered at 600 °C at a heating rate of 50 °C/min.

3.4 Stir casting

Stir casting is a fabrication process of nanocomposites that is very similar to the conventional casting process. Casting is performed by heating the matrix material to a temperature higher than the temperature of the molten material and then introducing the reinforcing particles into the matrix and mixing the mixture [12].

Mohanavel et al. [25] applied the stir casting method for the production of composites reinforced with Al_2O_3 particles and by the SEM analysis, they showed a homogeneous distribution of particles in the matrix alloy 6082. Al-Salihi et al. [29] also proved improvements in tribological and mechanical characteristics, which indicate the success of the applied method in obtaining nanocomposites reinforced with hard Al_2O_3 particles. Using reinforcements, such as graphene nanoplatelets [30], composites were successfully prepared by the non-contact ultrasonic vibrations-assisted stir casting process. Experimental studies have shown some improvements while heat-treated composites have shown an 83 % improvement in tensile strength.

Madhukar et al. [28] have achieved grain refinement by combining a sequence of the vortex, two-step stir casting and ultrasonication fabrication process of nanocomposite reinforced with particles, which represents a strengthening mechanism because it improves strength and toughness. They concluded that the optimal content of SiC reinforcement is 1.5 wt. % because such a nanocomposite has a uniform distribution of nanoparticles and the lowest porosity. In addition, they concluded that with content over 1.5 wt. % SiC, clusters and porosity of the composite are observed due to the high ratio of surface area to volume. Their previous research was based on an investigation of 1 wt. % SiC nanocomposites, obtained by ultrasonic vibration treatment and double stir casting method. They found that a uniform dispersion of nanoparticles was observed, compared to the casting method with double mixing and an improvement in mechanical properties was achieved [33]. Based on the SEM analysis, a good distribution of particles in the A356 matrix was also achieved by the researchers using ZrO_2 reinforcement during the fabrication of composites [19]. Another group of authors performed an investigation of mechanical properties when replacing nano-sized zirconia (ZrO_2) with alumina (Al_2O_3) and found a uniform distribution in samples with a higher content of ZrO_2 [16].

Ramakoteswararao et al. [31] produced hybrid nanocomposites with 8011 matrix and reinforcement content of 1, 1.5 and 2 wt. % Al_2O_3 and 2, 1.5 and 1 wt. % B_4C, respectively by stir casting process. Nanoparticles Al_2O_3 and B_4C had average sizes of < 50 nm and < 60 nm, respectively. The researchers observed a substantial increase in hardness and the tensile strength of the hybrid nanocomposites in comparison to the matrix alloy. The highest level of hardness was achieved by combining the reinforcements 2 wt. % Al_2O_3 and 1 wt. % B_4C.

3.5 Compocasting

The process of semi-solid casting is similar to stir casting, with the difference being that in this process, reinforcement particles are added and mixed into the semi-solid metal. A characteristic of this method is that the semi-solid metal requires more intense agitation compared to mild mixing in the stir casting process [12,50]. The production of aluminium nanocomposites using the thixocasting process was first demonstrated by Kandemir et al. [51]. The thixocasting process is a variation of the rheocasting process. Nanoparticles of SiC and TiB_2 with an average size between 20 and 30 nm are used, initially formed into compact powders, and then compacted, melted and treated with ultrasound. Analysis of the microstructures of the resulting materials revealed a uniform distribution of nanoparticles in the molten metal. The strength of the nanocomposites was significantly enhanced with the addition of nanoparticles at only 0.8 wt. %.

Nanocomposites were successfully produced using the thixocasting process with nanoparticle mass contents ranging from 0.65 to 0.70 wt. %. SiC nanoparticles were often found in clusters, while TiB_2 nanoparticles were primarily individual particles, likely due to the better wettability of TiB_2 nanoparticles in liquid aluminium. The porosity in the nanocomposites A356/SiC and A356/TiB_2, which was created in the process of casting the nanocomposites, was significantly reduced at 575 °C by the thixocasting process.

Veličković et al. [5] investigated aluminium nanocomposites with an A356 matrix and 0.2 – 0.5 wt. %. SiC nanoparticles of an average size of 50 nm using the compocasting process with mechanical alloying pre-processing. They concluded that for improvement of tribological characteristics, a reinforcement content higher than 0.45 wt. %. SiC [5] should be utilised, while for achieving the highest nanohardness value, the application of 0.5 wt. %. SiC [12] is optimal. Similar conclusions can be drawn from the results of aluminium nanocomposites produced through the compocasting process with 0.2 – 0.5 wt. %. Al_2O_3 reinforcement in the A356 matrix [6].

4. Analysis of mechanical properties of nanocomposites

4.1 Hardness

Based on the analysed literature, it is noticed that the hardness of the material is affected by the type of base material, type and size of reinforcement and its weight/volume content in the nanocomposite [9,13,15-21,24-32,34,49].

By using a small content of reinforcements, more precisely 1 wt. % SiC and Al_2O_3, Behnamfard et al. [17] achieved an improvement in hardness by applying the process of vortex casting and hot rolling for the production of nanocomposites. Improvements in the results were also due to the application of Cr, Cu and Ti powders as deagglomeration agents, of which Ti showed a greater potential for the dispersion of nanoceramic particles.

The application of only the SiC reinforcement in obtaining aluminium nanocomposites was applied in [28], in combination with a 7150 matrix and varying the content of 0.5 – 2 wt. % SiC. The highest values in the hardness of nanocomposites were achieved in [28], compared to the previously mentioned research [17,18] using the stir casting process followed by ultrasonic-assisted vibration. Application of SiC reinforcement, in combination with other reinforcements, more specifically with CNTs [26] and B_4C [27], when obtaining the aluminium hybrid nanocomposite, showed certain improvements in hardness. An improvement in hardness, compared to the matrix alloy, was recorded in all the aforementioned studies [26,27].

Application of Al_2O_3 reinforcement in combination with other reinforcements, specifically AlB_{12} [13], Gr [21], TiC [24], TiB_2, [15,34], ZrO_2 [16], Y_2O_3 [23] and B_4C [14, 31], proved to be very successful, i.e. improvements in hardness were recorded compared to the matrix material. The combination of reinforcements Al_2O_3 and AlB_{12} [13] achieved the greatest difference in the improvement of hardness when compared to the matrix of 372 %, followed by the combination of reinforcements Al_2O_3 and B_4C with an improvement of 350 % [14], while the least difference was recorded with the combination of reinforcements Al_2O_3 and TiC [24]. The reasons for the improvements obtained in [13] can be found in the weight content, which was from 5 to 15 wt. % Al_2O_3–AlB_{12}, as well as in the very nature of the used reinforcements. One of the most promising reinforcements is AlB_{12}, a ceramic material with high hardness (26 GPa), low density (2.58 g/cm^3) and neutron absorption capability. Aluminium matrix hybrid composite with Al_2O_3–AlB_{12} reinforcement has potential applications in automobile engine parts and for neutron-absorbing materials. The improvement in hardness in research [14] is attributed to grain refinement and the fabrication process of accumulative roll bonding (ARB). With the increase in the number of ARB cycles, the hardness also increases until the value stabilises, which occurs when materials reach a stable dislocation density.

Other reinforcements, used in the production of aluminium nanocomposites and hybrid nanocomposites, were TiO_2 [20], CNT + CeO_2 [22], GNPs [30] and ZrO_2 [19]. Analysing the obtained hardness in these researches, the reinforcement with 0.5 wt. % GNPs [30] is singled out, with an improvement of approximately 60 %, with the use of the stir casting fabrication method. The same fabrication method was applied by the authors of [19] who observed an improvement in hardness compared to the matrix material of approximately 22 %. In a large number of studies, it has been concluded that with an increase in the content of the reinforcement the value of hardness also increases.

4.2 Tensile strength and yield strength

Tensile tests are generally performed on a universal machine for material testing. Madhukar et al. [28] found an improvement in the mechanical properties of casted nanocomposites. The tensile strength increases with the increase of SiC nanoparticles (up to 1.5 wt. %) due to the large dislocations between the matrix and the nanoparticle, which leads to limitation in dislocation movement as well as grain refinement. Using the content of the reinforcement above 1.5 wt. % with an average particle size of 40 to 60 nm, the appearance of agglomeration occurs, which affects the reduction of the strength of the nanocomposite and the appearance of cracks. They concluded that nanocomposite with AA7150 matrix and 1.5 wt. % SiC nanoparticles showed an increase in microhardness by 24 % and tensile strength by 60 % and a decrease in porosity by 83 %.

Liu et al. [18] found that with the addition of SiC particles (approx. size 50 nm) and Al_2O_3 (approx. size 20 nm) to the A356 matrix, there was an improvement in the tensile strength by up to 24 % and yield strength by 8 %. By combining SiC (0.5, 1 and 1.5 vol. %) particles and B_4C particles with a fixed content of 0.5 vol. % [27] hybrid composites were formed and the tensile strength was significantly increased, while the ductility and impact strength were slightly decreased. The authors found that nanocomposite with 1 vol. % SiC achieved the best characteristics. The main reason is the relationship between the nanoparticles, their homogeneous distribution and the occurrence of the Orowan strengthening mechanism, where the particles act as a barrier to dislocation movements. They concluded that the addition of a small amount of nanoparticles leads to a significant improvement in tensile strength. The application of 6 wt. % CNTs in combination with 1 vol. % SiC reinforcement in 6061 matrix was performed by Kwon et al. [26] which showed that the milling time has a large effect (by 150 %) on the improvement of tensile strength.

By analysing the researches with SiC reinforcement [18,27,28] and observing the tensile strength of nanocomposites, it can be concluded that the highest improvement compared to the matrix alloy, of about 115 % was noted in the research [27]. Large improvements were also observed in other researches, i.e. by 140 % in [27], 92 % in [17] and 8 % in [18].

With the addition of only Al_2O_3 reinforcement [25,29,49] to the aluminium nanocomposites, certain improvements in tensile strength and yield strength were observed. However, with the combination of reinforcements, much greater improvements were achieved. More precisely, researchers [25,29] used a similar amount of Al_2O_3 reinforcements applying the stir casting process and reported improvements in the tensile strength of about 15 %, while for yield strength an improvement of 40 % was recorded [29]. The same amount of Al_2O_3 reinforcement in the A356 matrix was also used in [47], but they applied the SPS process for the production of composites, and greater improvements were observed compared to [25,29] in tensile strength (approx. 40 %) and yield strength (approx. 65 %).

Analysing the nanocomposite with a combination of Al_2O_3 and one of the reinforcements (Gr, TiB_2, ZrO_2, Y_2O_3, TiB_2 and B_4C), it is evident that the greatest improvement was achieved with the TiB_2 reinforcement [15] and application of the liquid metallurgy route, where it was 212 % for tensile strength and 156 % for yield strength. The lower influences were by Y_2O_3 nanoparticles [23], with an improvement of 106 % for tensile strength and 176 % for yield strength; TiB_2 nanoparticles [32], with an improvement of 86 % for tensile strength and 80 % for yield strength; ZrO_2 nanoparticles [16], with an improvement of 16 % for tensile strength and 4.5 % for yield strength; and B_4C nanoparticles [31], with an improvement of 2 % for tensile strength and 15 % for yield strength. In the production of aluminium nanocomposites, there was also the use of other reinforcements, such as TiO_2 [20], with an improvement of 30 % for tensile strength and 90 % for yield strength; GNP [30], with an improvement of 123 % for tensile strength, while an improvement of 48 % of tensile strength and 78 % of yield strength was achieved with the use of RGO [48].

4.3 Modulus of elasticity and elongation

Mostafapour Asl and Khandani [21] used Al_2O_3 and graphite (Gr) as reinforcements for the production of nanocomposites, where the graphite was in the micro-size of 10 – 50 µm and the average particle size for Al_2O_3 was 80 nm. By applying the FSP process with 3 passes, to obtain more homogeneous dispersion, they found that for mechanical properties the effect of nanoparticles is more important than the effect of microparticles. According to the stress-strain curves of the nanocomposites, it can be concluded that by increasing the Gr amount, elongation of the nanocomposites decreases, while the values for modulus of elasticity can be approximately determined and the highest is achieved with 50 % Gr.

Eskandari and Taheri [32] have established that by increasing the number of the passes of the FSP process, the elongation increases, but it is certainly less than the elongation of the matrix material, while there is an increase in modulus of elasticity, tensile strength and yield strength. Analysing the modulus of elasticity, it is noticed that its values increase with the increase in the number of passes, but up to 5 passes because after that it starts to slightly decrease. Al-Salihi at el. [29] analysed the microstructure of the nanocomposite with Al_2O_3 nanoparticles on SEM and found that the decrease of porosity and uniform distribution of nanoparticles slightly increased the modulus of elasticity from 71 to 72.8 GPa. Analysing the values for the modulus of elasticity obtained by other researchers, it is noticed that it increases with the increase in the content of TiO_2 [20] and CNTs [49] reinforcements.

Furthermore, the elongation of the nanocomposite was analysed in relation to the matrix material. The improvement of elongation was recorded with the use of different reinforcements, i.e. ZrO_2 [19], TiO_2 [20], CeO_2 + CNT [22] and Cu + RGO [48]. Elongation of nanocomposites was reduced by 92 % [22], 65 % [48] and about 43 % in [20]. In hybrid nanocomposites with Al_2O_3 as the main reinforcement and addition of Gr [21], TiB_2 [15,32], ZrO_2 [16], Y_2O_3 [23] and SiC [18], an improvement in elongation was observed. The highest reduction in elongation was noted in [18], followed by [16] and [15].

5. Conclusions

The mechanical properties of nanocomposites are greatly influenced by the manufacturing process, type of matrix material and reinforcement type, amount, size and distribution.

The stir casting method is identified as the cheapest and most productive method. However, uniform dispersion of reinforced particles is an important aspect in the preparation of nanocomposites, which is very difficult to achieve due to poor wettability and high viscosity. A longer duration of mixing is an essential parameter required for the uniform distribution of particles; however, this can lead to oxidation and gas formation in the matrix. Therefore, it is important to reduce the mixing time during composite production with improved quality. Recently, ultrasonic vibrations have been used to uniformly mix reinforcement particles because they create an ultrasonic cavitation effect. Spark plasma sintering is a relatively new manufacturing process which is proven to be cost-effective and provides better mechanical and microstructural properties. When compared to conventional sintering methods, it produces lower porosity of materials, which directly affects mechanical properties.

Compared to other classes of reinforcements, ceramic reinforcements are characterised by exceptional strength, so they are mainly used as primary reinforcement. In addition to strength, ceramic reinforcements have high hardness, heat resistance, low coefficient of thermal expansion, medium conductivity and corrosion resistance. Based on the reviewed research results, it is determined that Al_2O_3 and SiC can be selected as the main ceramic reinforcements for the aluminium matrix. These nanocomposites possess higher strength, stiffness and modulus of elasticity, better corrosion and wear resistance. The SiC particles are more preferred as reinforcement due to their low density (3.21 g/cm^3), high hardness, high modulus of elasticity and low cost when compared to Al_2O_3, whose presence can increase the oxygen content in the molten metal, which can increase the impurity content. Application of these reinforcements is generally combined with the secondary reinforcements (e.g. Gr, GNP and CNT) whose role is to increase machinability and reduce costs and density.

Regarding the reinforcement amount, the best mechanical properties are achieved with up to 2 wt. % Al_2O_3, while for SiC an optimal content is 1.5 wt. % or in some cases 1 wt.%. Particle sizes that are most commonly used for ceramic reinforcements are 30 to 50 nm for Al_2O_3 and 20 to 70 nm for SiC.

The analysed results in this paper point out the significance of applying ceramic particles, specifically in the mentioned content within the alloy, to achieve an enhancement in the mechanical properties of the nanocomposite compared to the matrix. By observing only one material property it is easy to conclude which combination is the best, but when analysing two or more properties the optimisation needs to be involved to select the material with appropriate properties.

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