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Review Article

A review on the effects of micro-nano particle size and volume fraction on microstructure and mechanical properties of metal matrix composites manufactured via mechanical alloying

Sinem Aktaş[a]* and Ege Anıl Diler[b]

[a]*Interdisciplinary Division of Materials Science and Engineering, Ege University, Izmir, 35040, Turkey*
[b]*Department of Mechanical Engineering, Ege University, Izmir, 35040, Turkey*

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ABSTRACT

The major challenge for the production of the composites which are reinforced with nano and micro-sized particles is to obtain uniform distribution of reinforcement particles in microstructure. Powder metallurgy method can be used in order to obtain a homogeneous distribution of reinforcement particles. This method has three steps: 1) mixing and/or alloying of powders, 2) pressing, and 3) sintering. Mechanical alloying is a complex process which involves optimization of many parameters such as milling time, process control agent, particle size, ball to powder weight ratio, milling speed, milling atmosphere, mill types, etc. The main aim of the present study is to explain the roles of volume fraction and size of reinforcement particle on the microstructural properties and how these parameters affect the mechanical properties of aluminum based metal matrix composites with micro and nano-sized reinforcement particles produced by mechanical alloying.

1. Introduction

Metal matrix composites (MMCs) are manufactured by adding reinforcement particles with different sizes from micro to nano and various shapes into a metal matrix. The ceramic particles such as SiC, Al_2O_3 are usually used as reinforcement in MMCs. The addition of reinforcement particles into matrix can improve the mechanical properties of MMCs such as hardness, ultimate tensile strength (UTS), yield strength (YS) and wear resistance. For instance, Mazahary and Shabani [1] produced nanocomposite with SiC (50 nm) in A356 matrix. According to experimental results, strength values were increased by adding nano-sized SiC particles and this increment continued with the increasing of volume fraction of SiC particles until other mechanisms such as agglomeration and clustering took place. Many researchers have found similar results. For example, in a study [2] that the properties of Al-TiO_2 nanocomposites manufactured by powder metallurgy method were investigated, the results showed that wear resistance and the tensile strength of composites increased with an increase in volume fraction of nano particles.

There are several manufacturing methods in the production of metal matrix nanocomposites (MMNCs), which can be categorized into ex-situ and in-situ methods [3]. Ex-situ synthesis (for instance, powder metallurgy, mechanical milling, stir casting, etc.) consists of adding nano-sized reinforcement to a liquid or solid (powder) metal. On the other hand, in in-situ method, the reinforcements are synthesized in a metal matrix by chemical reactions among elements or between element and compound during the composite fabrication. Self-propagating high temperature synthesis (SHS), direct reaction synthesis (DRS) and reaction milling (RM) can be given as examples. Each of method in MMNCs production has some advantages and drawbacks [4-7].

Distribution of reinforcement particles in a metal matrix has a huge challenge as aforementioned. Heterogeneous distribution of reinforcement particles has a negative influence on the mechanical properties of

*Corresponding author. *Tel.: +90 555 020 1714*
E-mail address: synemaktas@gmail.com
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metal matrix composites. Especially, when the size of reinforcement particles decreases from microscale to nanoscale, this drawback influence increases. On the other hand, it is possible to minimize the agglomeration of particles by means of mechanical alloying [8]. In this process, mixtures of powders are mechanically milled together.

2. Mechanism of Mechanical Alloying

Mechanical alloying is a useful technique for producing both microcomposites and nanocomposites [10]. Figures 1 and 2 show the schematic drawings of a high-energy planetary ball mill and a ball-powder-ball collision of powder mixture during mechanical alloying. In this method, there are three repeated steps following each other, which are deformation, cold welding and fracture. During the milling process, whenever balls collide with each other some of the powders are trapped in between them. This collision gives energy to system so that the particles transforms physically; in other words, they deform elastically and plastically.

In the early stages of milling, collide mechanism creates flake and new surfaces because soft particles have tendency to weld together. As a result, particle size is larger than the starting particle [12] (Figure 3).

The continuation of deformation leads to work hardening and fracture by a fatigue failure mechanism or by fragmentation of fragile flakes. In such a system, the tendency of fracture dominates over cold welding progressively when a balance is occurred (steady state condition) between welding and fracture. Average composite particle size decreases, and particles are steadily refined. Figures 4-6 show the effects of mechanical milling on the morphology [13].

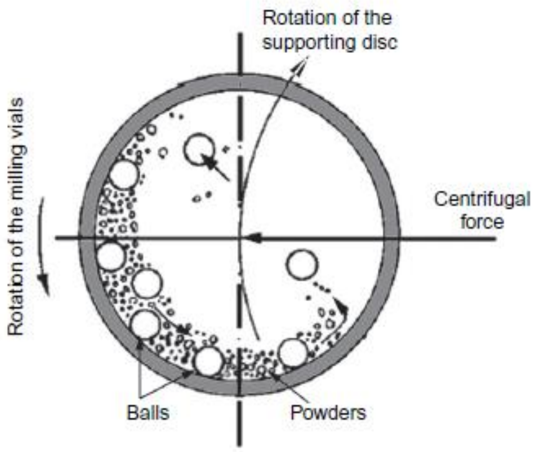


Figure 1. Schematic drawing of a high-energy planetary ball mill [9]

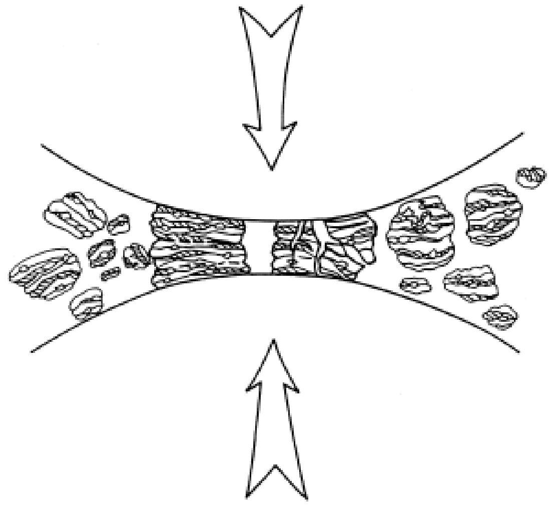
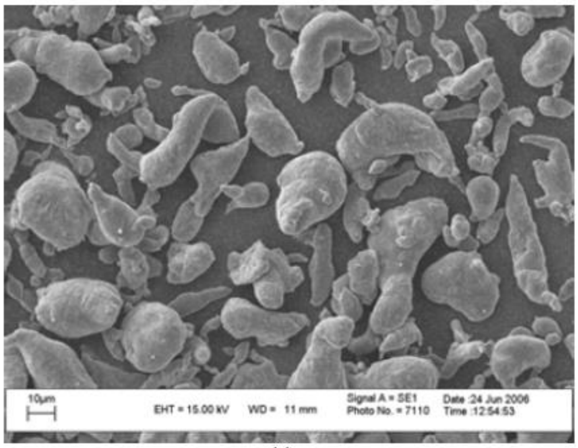
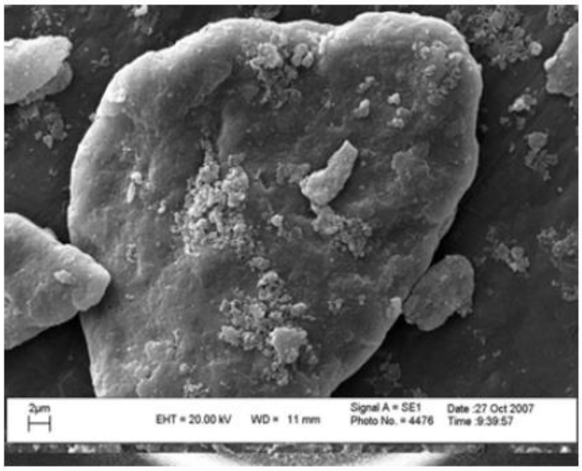


Figure 2. Ball-powder-ball collision of powder mixture during mechanical alloying [11]



(a)



(b)

Figure 3. (a) The initial aluminum powders with particle size smaller than 63 μm in Al-Al_2O_3 nanocomposite system and (b) after 4h milling, flake like Al particles [12]

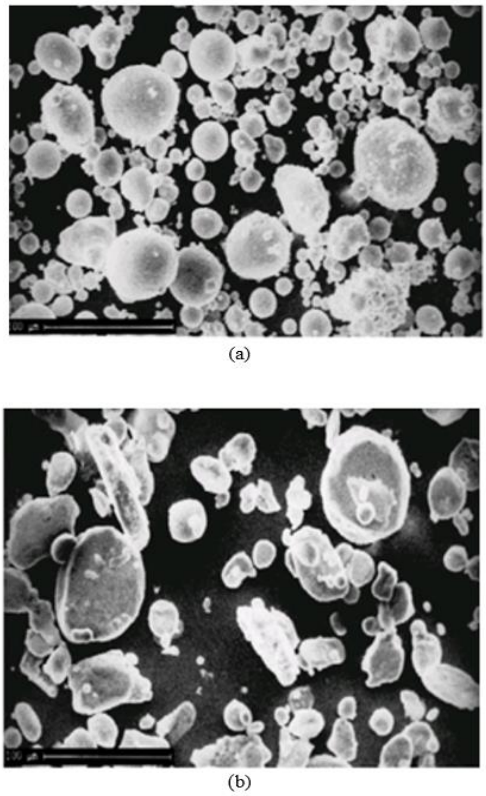


Figure 4. (a) Morphologies of the as received Al powder and (b) milled for 2 h [13]

As can be seen in figure 4, at the beginning of the milling process, particles deform plastically and their shapes start to change; also, average size of particles diminishes slightly. As milling time progresses, particles flatten with high aspect ratio and flake-like particles form (Figure 5). Also, micro welding can be observed between the particles.

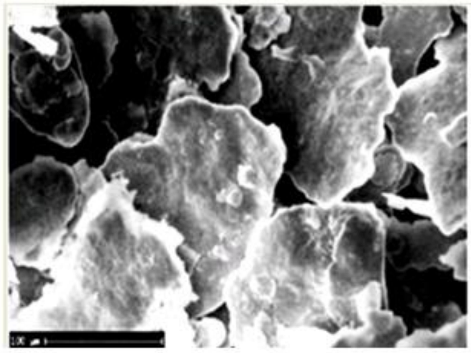


Figure 5. Morphology of Al powder milled for 12 h [13]

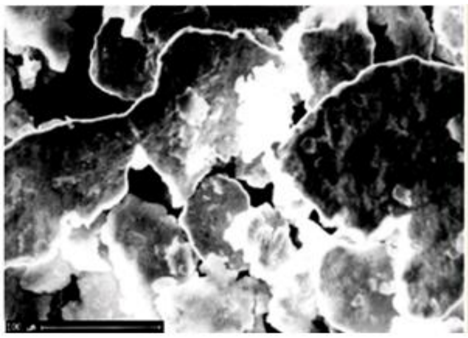


Figure 6. Morphology of Al powder milled for 18 h [13]

After long milling time, cold welded particles (Figure 6) start to fracture due to work hardening effect so particle size decreases and their shape converses from laminar to almost equiaxial. If welding and fracture are at equilibrium, the equiaxed particles are oriented randomly. It should be also noted that these stages of milling might occurs at the same time. All milling stages, namely, deformation, cold welding and fracture can be observed during manufacturing of ceramic reinforced metal matrix composite by mechanical alloying (Figure 7).

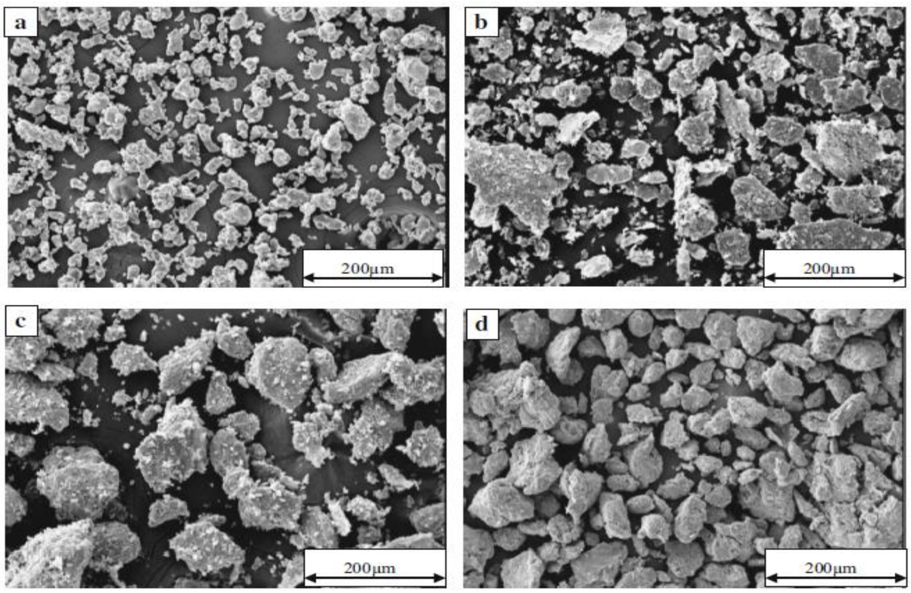


Figure 7. The evolution of morphology during mechanical milling of Al–2.5wt.%SiC nanocomposite powder milled for: (a) 2 h, (b) 15 h, (c) 20 h and (d) 25 h [14]

3. Effect of Particle Size

Particle size and volume fraction affect the milling stages of production and the microstructure of composite material, which define the mechanical properties of metal matrix composites with reinforcement particles. At early stage of milling, there is no remarkable and clear effectiveness of hard ceramic particles on alloying mechanism; however, at longer milling time, comparing to unreinforced metal particles, hard particles act as a milling agent. They initiate premature welding and fracture; in other words, reinforcement particles accelerate the milling process. Acceleration in a microcomposite is relatively faster than that in a nanocomposite [13]. Since when balls collide with each other or particles they give their energy to the system. Some amount of energy is spent to break and to separate the agglomerated and clustered nano particles.

Micro and nano scaled particles act as an obstacle against dislocation movement; furthermore, they can generate new dislocations. Comparing to microcomposites, dislocation density is higher for nanocomposites due to high interaction between reinforcement particles and matrix material. Decreasing of crystallite size depends on increasing dislocation density and work hardening. When dislocation density leads to work hardening, powders will be brittle, and finally, they will fracture. In others words, much more particles will fracture to smaller size. Also, it should be noted that Hall-Petch equation (1) defines to relation between mechanical properties and particle size.

$$\sigma_{y=}\ \sigma_0 + kd^{-1/2} \qquad (1)$$

Hall–Petch equation given where σ_0 is the friction stress in the absence of grain boundaries, σ_y is the yield stress, k is a constant and d is the grain size. According to Hall-Petch equation, the yield stress increases as grain size decreases.

However, if this size approaches threshold, inverse Hall-Petch will involve in this process [15]. After threshold value passes, particle size does not have positive effect on microstructure evolution and mechanical properties. Because, smaller particles have tendency for agglomeration which can deteriorate the uniform distribution of reinforcement particles and mechanical properties of composites reinforced with particles.

In a study about particle size effect on mechanical properties [16], the researchers produced aluminum matrix composites reinforced with 30 µm and 50 nm B_4C particles. The mixed powders were mechanically milled at 5, 10, 15 and 20 h (Figure 8).

After the 20 h milling, the crystallize size of the micro and nano composite were 55 nm and 40 nm, respectively (Figure 9). Also, hardness values of micro and nano composites were 118 and 130 HV, respectively (Figure 10).

As can be seen in figures 10 and 11, the hardness and strength values of nanocomposite are higher than microcomposite due to Orowan strengthening mechanism [17]. Orowan strengthening effect increases with decreasing particle size but there is a critical value and this effect drops suddenly below the critical threshold.

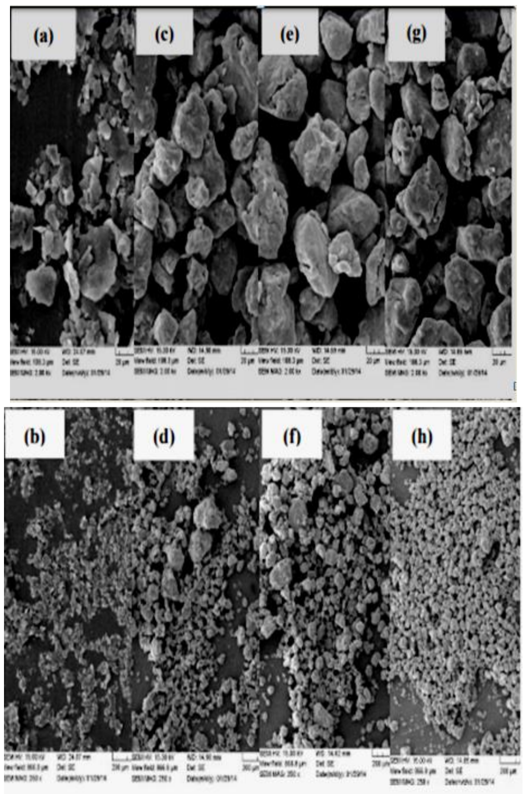


Figure 8. Morphology of nano-composite powders after (a) and (b) 5 h, (c) and (d) 10 h, (e) and (f) 15 h, and (g) and (h) 20 h milling time [16]

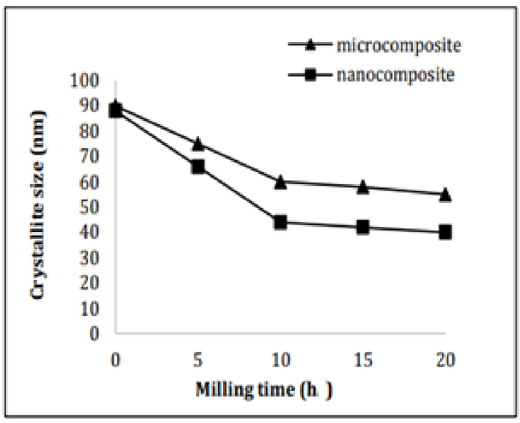


Figure 9. The change of the crystallite size for the microcomposite and nanocomposite [16]

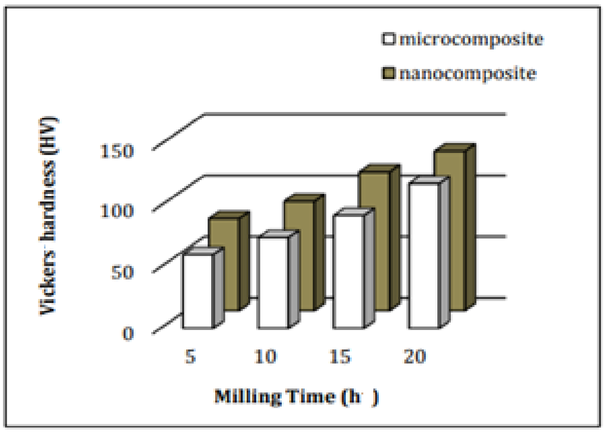


Figure 10. The variation of Vickers hardness of the microcomposite and nanocomposite with the milling [16]

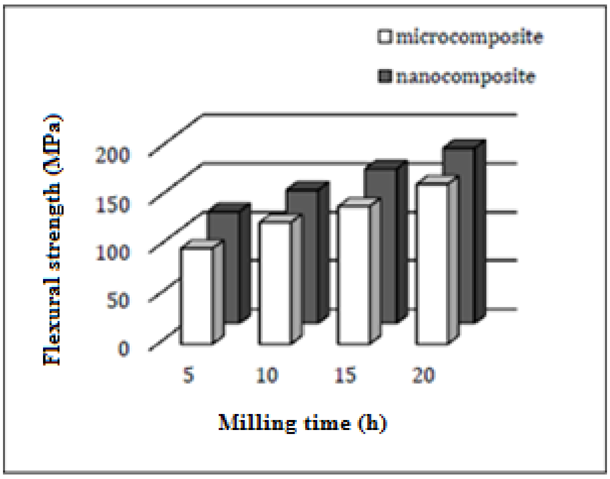


Figure 11. The variation of flexural strength of the microcomposite and nanocomposite with the milling [16]

4. Effect of Volume Fraction

The other parameter which affects microstructure, milling mechanism and mechanical properties is volume fraction of reinforcement particles. Firstly, increasing volume fraction of particles enhances grain refinement due to the fact that local plastic deformation increases. There are some reasons this increment. One of them is the formation of shear bands containing a high dislocation density depending on prevention of dislocation movement by particles. Also, formation of subgrains or cell conversing into grains and sliding these grains leads to increasing local plastic deformation [18]. This phenomenon is noticeable when nanometric particles are used because of Orowan strengthening mechanism.

In a study [19], the effect of volume fracture on average particle size, density and compressive stress were investigated (Figures 12 and 13). According to results, finer particle size has a positive effect on mechanical properties.

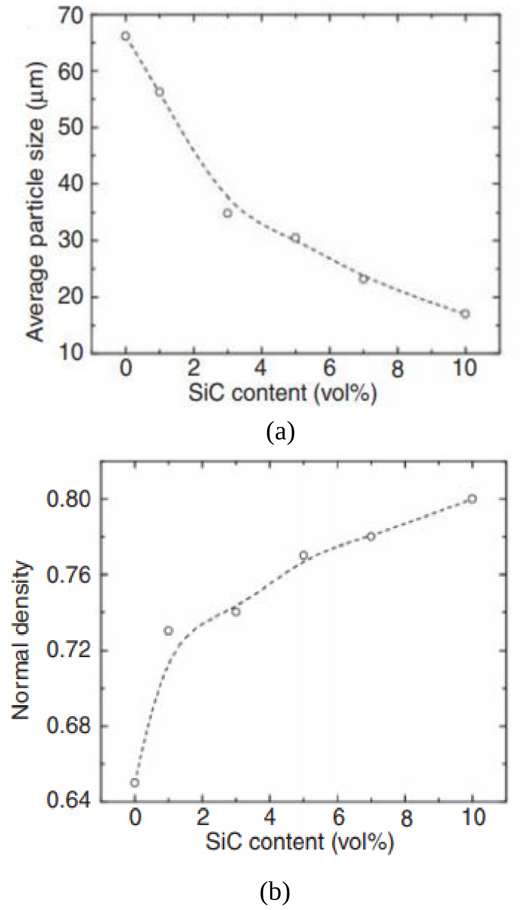


Figure 12. Effect of SiC content on (a) the average particle size and (b) density of mechanically milled powders [19]

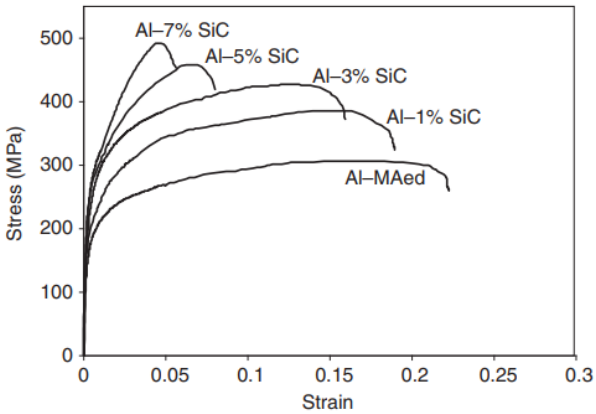


Figure 13. Compressive curves of Al and Al-SiC composites prepared by mechanical alloying and sintering [19]

Volume fraction has an influence on milling stages. Pakserethet A.H. et al. [14] examined the influence of different volume fractions (2.5, 5, 10, 15 and 20 vol.%) on microstructure and mechanical properties of Al-SiC nanocomposites. According to this study, when 2.5 vol.% SiC compared to 10 vol.% SiC in matrix, steady state occurred in shorter milling time. This correlation was observed as 25 h in 2.5 vol.% and 20 h in 10 vol.%

SiC; furthermore, while cold welding mechanism was showing up after 2 h in 20 vol.%, 2.5 vol.% SiC powder mixture needed 15 h to achieve the same condition because of the fact that nano-sized SiC particles rise the energy induced, which accelerates process.

Many researchers have found similar results. Amal and Nassar [2] studied the properties of Al-TiO_2 nano composites manufactured by powder metallurgy method and the results showed that wear resistance (Figure 14) and the tensile strength of composites increased with an increase in volume fraction of nano particles.

In a study found in literature, C. Suryanarayana [20] put forth how volume fraction and particle size affect the mechanical properties of Al metal matrix composites reinforced with Al_2O_3 particles of 50 and 150 nm. For a constant particle size (50 nm), compressive yield strength was measured as 488 MPa for Al-Al_2O_3 composites with 5 vol.% while this value increased to 515 MPa for Al-Al_2O_3 composites with 10 vol.%. As the volume fraction of reinforcement particles increased, the mechanical properties of composites improved. Also, it can be seen in Table 1 that the decreasing of particle size resulted in increasing strength.

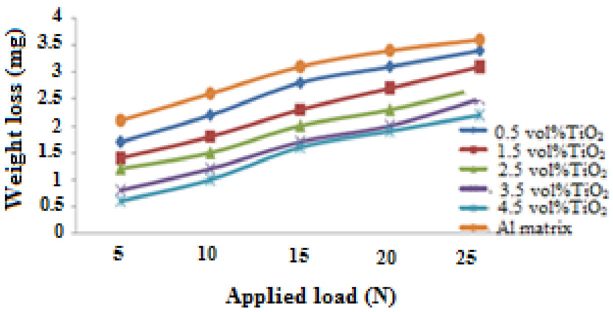


Figure 14. Effects of applied load on wear resistance [2]

Table 1. Mechanical properties of Al–Al_2O_3 nanocomposites obtained by milling and subsequent consolidation by vacuum hot pressing and hot isostatic pressing [20]

Particle size of Al_2O_3 (nm)	Volume fraction of Al_2O_3 (%)	Compressive yield strength (MPa)	Compressive strength (MPa)
50	5	488	605
50	10	515	628
150	5	409	544
150	10	461	600

5. Conclusion

The studies found in literature have shown that particle size and volume fraction have extremely significant influence on microstructure and mechanical properties of metal matrix composite reinforced with micro and nano-sized particles in production via mechanical alloying.

The addition of reinforcement particles into the metal matrix increases dislocation density and work hardening, which leads to enhancement of mechanical properties of particle reinforced metal matrix composites. However, this increment for a nanocomposite is higher than that for a microcomposite due to Hall-Petch effect and Orowan strengthening mechanism.

Comparing to unreinforced metal powders, hard particles act as a milling agent. They initiate premature welding and fracture mechanism. Reinforcement particles accelerate the milling process; therefore, acceleration in a microcomposite is relatively faster than that in a nanocomposite because of the fact that some amount of energy is spent to break and to separate the agglomerated and clustered nano particles.

Grain refinement effect increases as volume fraction of reinforcement particles increases; moreover, milling stage occurs earlier.

As a result, nano-sized reinforcement particle with increasing volume fraction has a stronger influence on microstructure and mechanical properties of metal matrix composites that are reinforced with particles and produced via mechanical alloying.

Acknowledgment

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