Compressive Strength and Thermal Properties of Spark Plasma Sintered Al-Al₂O₃ Nanocomposite

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Abstract: In this work, compressive and thermal properties of aluminum, milled aluminum, and Al-10Al₂O₃ composite processed via ball milling (BM) and spark plasma sintering (SPS) were investigated. The microstructural features of powders and sintered samples were characterized using optical and scanning electron microscopy. A universal testing machine was used to determine the compressive properties of the consolidated samples. The thermal conductivity and coefficient of thermal expansion of the developed materials were characterized using a hot disc thermal constant analyzer and a dilatometer, respectively. The Al-10Al₂O₃ composite possessed hardness of 1309.7 MPa, yield strength of 311.4 MPa, and compressive strength of 432.87 MPa compared to hardness of 326.3 MPa, yield strength of 74.33 MPa, and compressive strength of 204.43 MPa for aluminum. The Al-10Al₂O₃ composite had thermal conductivity value 81.42 W/mK compared to value of 198.09 W/mK for aluminum. In the temperature range from 373 K to 723 K, the composite had lower CTEs ranging from 10 × 10⁻⁶ to 22 × 10⁻⁶/K compared to 20 × 10⁻⁶ to 30 × 10⁻⁶/K for aluminum.

Keywords: Aluminum; Ball Milling; Spark Plasma Sintering; Metal Matrix Nanocomposites; Mechanical Properties; Thermal properties.

1. Introduction

Nanoparticle reinforced metal matrix composites (NPMMCs) are candidate materials suitable for various applications in the aerospace, automotive, and transportation industries. These materials consist of a ductile metal matrix reinforced with a hard and stiff ceramic phase [1-4]. The design goal for the development of these composites is to obtain materials with improved mechanical and/or functional properties. These properties are influenced by not only the attributes of the individual components, the interface between the matrix and reinforcement, and the extent of reinforcement dispersion, but also the synthesis and consolidation processes [2, 5-7]. Several powder metallurgy methods have been used to synthesize and consolidate Al-based composites including ball milling [8] furnace sintering [9], hot pressing [10], hot isostatic pressing [11], microwave sintering [7], spark plasma sintering [4, 12], and dynamic compaction [13]. Ball milling is a solid-state powder processing technique used to synthesize composites. During the process of milling, particles are cold-welded, fractured, and rewelded. The method was used to synthesize homogenous Al-Al₂O₃ nanocomposite powders that have

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the reinforcement uniformly distributed in the matrix [8]. The SPS is a novel process used to consolidate powdered materials and obtain dense materials with tailored microstructures and properties. In this process, a uniaxial pressure and a pulsed direct electrical current are simultaneously applied to the dies [14, 15].

The advantages of SPS include: (i) high heating rates, (ii) enhanced densification, at relatively low temperatures and short times, (iii) very limited grain growth, and (iv) promoted diffusion mechanisms. This permits retaining the excellent intrinsic properties of the nanopowder in the final bulk material. Furthermore, the process is binder-less, direct, and cost-effective compared to other powder metallurgy processes. The SPS process was used to consolidate submicron and nanostructured aluminum [16-19], nanocrystalline aluminum alloys [20-22], and Al-Al2O3 [3, 23-25] nanocomposites.

Almost fully dense Al-1 vol.% Al2O3 composite was obtained by SPS, however, the density of other composites decreased with further increase in Al2O3 content. The Al-7 vol.% Al2O3 nanocomposite possessed the highest nanohardness value of 0.85 GPa [23]. In another work [24], the density, hardness, and compressive as well as tensile strength of spark plasma sintered Al-Al2O3 composites were found to increase with the increase in Al2O3 content. The Al-20 vol.% Al2O3 composite had the largest hardness (1355 MPa) and compression strength. The porosity of the composites was in the range 1.27 % to 5.07 %. In a recent work [3], Saheb et al. successfully synthesized nanocrystalline aluminum and homogenous Al-Al2O3 nanocomposites using BM and SPS techniques and investigated the influence of reinforcement content, milling and sintering conditions, on the microstructure, densification, and hardness of the developed materials. They found that milling improved hardness of aluminum but reduced its densification. Addition of Al2O3 nanoparticles resulted in further improvement of hardness. The Al-10 vol. Al2O3 nanocomposite had the highest Vickers hardness value of 1460 MPa. [3]. The effects of SPS on the structure, microhardness, and strength of AlMg5 monolithic alloy and AlMg5-0.4Al2O3 composite were reported in a recent study [25]. It was found that the nanocomposite exhibited higher microhardness and strength compared to the unmilled and milled AlMg5 alloys. The improvement in the properties was attributed to the matrix grain refinement and the presence of Al2O3 nanoparticles.

Although, mechanical and thermal properties are among the most important factors used in materials selection for engineering design, published work on the properties of Al-Al2O3 nanocomposites, prepared via BM and SPS, is very scarce [3, 23-25]. Furthermore, analysis of the literature shows that not only the evaluation of mechanical properties was not comprehensive but also the characterization of thermal properties has seldom been reported. The aim of this study is to characterize the compressive strength, thermal conductivity, and coefficient of thermal expansion of aluminum, milled aluminum, and Al-Al2O3 nanocomposite, synthesized by BM and consolidated by SPS. The properties of the developed materials will be correlated with microstructure features and possible strengthening and thermal conductivity mechanisms will be discussed.

2. Materials and Experimental Procedures
2.1 Processing of powders

In this investigation, pure commercial Al powder, 99.88 % purity obtained from Aluminum Powder CO. LTD, and α-Al2O3 nanopowder, 99.85 % purity, obtained from ChemPUR Germany, were used as starting materials. The composition and particle size distribution of the Al powder, as provided by the manufacturer, are presented in Tabs I and II, respectively. Although, agglomeration of nanoparticles is one of the main challenges in the development of nanocomposites, the use of suitable synthesis and processing techniques, such as BM, allowed for the preparation of homogenous nanocomposite powders. In this work, ball milling was used to mill pure aluminum, as a reference material, and prepare Al-10
vol.%\(\text{Al}_2\text{O}_3\) composite powder. Fritsch Pulverisette ball mill, model P5, stainless steel vials and balls were used to perform the milling experiments. The powders were milled in argon inert gas to avoid oxidation. The ball-to-powder weight ratio of 10:1 and speed of 200 rpm were maintained constant in all experiments. The sticking of the powder to milling balls and vials was minimized using stearic acid (1.5 wt.%). It is worth mentioning here that the time to reach uniform dispersion of the reinforcement in mechanically alloyed nanocomposites strongly depends on the metal matrix, amount and type of the reinforcement, as well as milling conditions. Therefore, an optimum milling time of 24 h was used [3]. The powders were sintered using SPS equipment (FCT system, model HP D 5) and graphite dies of 20 and 25 mm diameter to prepare specimens for thermal and mechanical characterization, respectively. The as-received aluminum, aluminum milled for 24 h, and \(\text{Al}-10\text{Al}_2\text{O}_3\) nanocomposite were sintered using a sintering temperature of 550 °C, holding time of 20 min, compaction pressure of 50 MPa, and heating rate of 200 °C/min [3]. The as-received \(\text{Al}_2\text{O}_3\) nanopowder and milled powders were characterized using transmission and scanning electron microscopy, respectively. A Philips transmission electron microscope, model CM200 200 kV, and a Tescan Lyra-3 field emission scanning electron microscope, model CM200 200 kV were used. The crystallite size of the \(\alpha\)-aluminum matrix was determined from X-ray diffraction experiments performed using a diffractometer (Bruker D8, USA, with a wavelength \(\lambda = 0.15405\) nm). The density of consolidated samples was measured using Mettler Toledo balance, model AG285. The relative density of sintered samples was obtained from the measured and theoretical density values. Theoretical density values of 2.69 and 3.97 g/cm\(^3\) were used for aluminum and alumina, respectively.

**Tab. I** Chemical composition of the aluminum powder.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Al</th>
<th>Fe</th>
<th>Si</th>
<th>Ti</th>
<th>Ga</th>
<th>Ni</th>
<th>Cu, Mn, Pb, Zr, Zn, Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt.%</td>
<td>99.88</td>
<td>0.074</td>
<td>0.024</td>
<td>0.006</td>
<td>0.006</td>
<td>0.005</td>
<td>0.001 each</td>
</tr>
</tbody>
</table>

**Tab. II** Particle size distribution of the aluminum powder.

<table>
<thead>
<tr>
<th>Size (µm)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>0</td>
</tr>
<tr>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td>45</td>
<td>11</td>
</tr>
<tr>
<td>38</td>
<td>11.4</td>
</tr>
<tr>
<td>&lt; 38</td>
<td>76.6</td>
</tr>
</tbody>
</table>

**2.2 Mechanical Characterization**

The Vickers hardness of sintered materials was measured using a Buehler hardness tester (load of 100 gf and a time of 12 s). Compression tests, at a rate of 0.5 mm/min, were carried out using Instron universal testing machine model 3367, following the ASTM E9-89a standard. Standard cylindrical specimens, diameter of 6 mm and length of 12 mm, were machined from sintered samples (25 mm diameter and 12 mm thickness) using wire electrical discharge machining (EDM). Four specimens from each sample i.e. aluminum, milled aluminum, and composite were tested and the average value was reported. The compaction pressure was applied parallel to the direction of the uniaxial SPS pressure.
2.3 Thermal Characterization

Thermal properties were directly measured based on the theory of the Transient Plane Source technique [26], following the ISO/DIS 22007-2.2 standard. The technique allows for the determination of thermal properties in a single step. A Hot Disc Thermal Constant Analyzer model TPS 2500 S was used to measure the thermal properties. Disc shaped specimens with diameter of 20 mm and thickness of 9 to 10 mm were used for thermal measurements taken in the direction of the applied pressure. Each measurement was repeated five times and the average value was reported. The coefficient of thermal expansion of the samples was measured using a LINSEIS MESSGERATE GmbH, Germany, dilatometer model L75 PT 1400.

3. Results and Discussion
3.1. Microstructure

![TEM image of Al₂O₃](image1.png) ![FE-SEM image of Al](image2.png) ![FE-SEM images of Al-10Al₂O₃ powder ball milled for 24 h at (c) low and (d) high magnification.](image3.png)

Fig. 1. (a) TEM image of Al₂O₃, (b) FE-SEM image of Al, and FE-SEM images of Al-10Al₂O₃ powder ball milled for 24 h at (c) low and (d) high magnification.

Fig. 1 shows the morphology of particles of the as-received powders. Particles of the Al powder have irregular shapes, as can be seen in Fig. 1(b), and a maximum particle size of 53 μm. Almost 76.6 % of particles have a particle size less than 38 μm as shown in Tab. II.
The Al$_2$O$_3$ nanopowder has a particle size distribution with an average particle size of 200 nm as can be seen from the TEM image presented in Fig. 1 (a). Typical SEM images, at low and high magnification, of Al-10Al$_2$O$_3$ composite powder milled for 24 h are presented in Fig. 1(c) and 1(d), respectively. It can be noticed that milling not only decreased the particle size but also led to the formation of more equiaxed particles. This is because during ball milling the particles are subjected to fracturing and cold welding [27, 28]. The crystallite size of the α-Al phase in the as-received monolithic aluminum, estimated using XRD, was 298 nm. Milling of aluminum for 24 h decreased it to 62 nm; and in the presence of the Al$_2$O$_3$ reinforcement, it was further reduced to 32 nm. It is known that during milling, particles are subjected to heavy plastic deformation, which generates defects such as dislocations that recombine to form new grain boundaries [22, 29]. In addition, the Al$_2$O$_3$ nanoparticles act as grinding medium and enhance the milling effect, which contribute to further refinement of the α-aluminum phase.

![Fig. 2. Optical micrographs of sintered (a) aluminum (x500), (b) milled aluminum (x500), and Al$_2$O$_3$ composite at magnifications of (c) (x100), and (d) (x200).](image)

Typical optical microscopy images depicting microstructures of samples, sintered under the same condition, are presented in Fig. 2. The aluminum milled for 24 h, Fig. 2(b), had a grain size smaller than aluminum, Fig. 2(a). This clearly shows the role of ball milling in microstructure refinement. The addition of Al$_2$O$_3$ significantly contributed to grain growth inhibition; and the composite material had a microstructure characterized by sharp and elongated grains as can be seen in Figs. 2(c) and (d) at magnifications of x100 and x200, respectively.

Fig. 3 shows the relative density of sintered samples. The as-received pure aluminum had relative density value of 99.8 %. The full densification of aluminum is attributed to the
advantages of SPS, which include enhanced densification and promoted diffusion mechanisms [14]. In SPS, it is believed that sintering is enhanced because of: (i) formation of plasma, (ii) local high temperature due to spark discharge between particles, (iii), high diffusion rate because of vaporization and melting particles’ surfaces, and (vi) the compaction pressure. Milling aluminum for 24 h reduced its relative density to 97.02 %. This is because milling yield cold worked structures, which reduces the compressibility [30]. On the other hand, contamination may influence the densification [31-33]. Milling for 24 h and addition of 10 vol.% of Al₂O₃ decreased the relative density to 96.57 %. This supports the fact that incorporation of a hard and stiff reinforcement in the matrix lowers the densification of composites [23, 24]. It was reported that although almost fully dense composites (containing 1 vol.% Al₂O₃) were obtained, the density decreased with further increase in Al₂O₃ content [23]. A similar trend was observed by Garbiec and co-workers who found that the relative density of spark plasma sintered Al-Al₂O₃ composites decreased to 95 % [24].

![Fig. 3. Relative density of sintered samples.](image)

3.2 Mechanical Properties

The mechanical properties of sintered samples are presented in Fig. 4. The hardness of the composite is greater than the milled aluminum, which in turn is greater than aluminum as can be seen in Fig. 4(a). Mechanical milling of aluminum for 24 h increased its hardness from 326.3 to 421 MPa i.e. an increase of 29 %. The increase in hardness because of ball milling is attributed to the decrease in the average grain size, as it can be clearly seen from the microstructure of aluminum and milled aluminum samples presented in Fig. 2 (a) and (b), respectively. The increase in hardness of metallic materials because of the decrease in grain size can be expressed as:

\[
\Delta H = \frac{K}{\sqrt{d}}
\]

(1)

where \( k \) and \( d \) are the strengthening coefficient and grain size, respectively. Equation 1 indicates that the smaller the grain size, the larger the increase in hardness. This is because grain boundaries hinder the movement of dislocations.
The addition of 10 vol.% $\text{Al}_2\text{O}_3$ nanoparticles to aluminum and ball milling the mixture for 24 h significantly increased the hardness to 1309.7 MPa i.e an increase by 300 and 208 % with respect to aluminum and milled aluminum, respectively. This value of hardness is comparable with hardness value of 1355 obtained for Al-20 vol.%$\text{Al}_2\text{O}_3$ [24] and 1411 MPa reported for $\text{AlMg}_5$–0.4$\text{Al}_2\text{O}_3$ [25] spark plasma sintered nanocomposites. However, it is far greater than the nanohardness value of 850 MPa reported for Al-7 vol.% $\text{Al}_2\text{O}_3$ nanocomposite [23] prepared via SPS. This large increase in the hardness of the composite is due to the reduced grain size, as explained above and seen in Fig. 2(c) and (d), as well as the role of $\text{Al}_2\text{O}_3$ particles in impeding the movement of dislocations.

Fig. 4(b) and 4(c) show that values of the yield and compressive strength of the composite are larger than those of the milled aluminum, which in turn are larger than those of aluminum. The yield strength of aluminum increased from 74.33 to 166.9 MPa (increase of 124.5 %) because of milling for 24 h; and reached 311.4 MPa because of the incorporation of 10 vol.% $\text{Al}_2\text{O}_3$. The composite sample showed an improvement in yield strength by ~319 and ~86.5 %, with respect to aluminum and milled aluminum samples, respectively. The value of 311.4 MPa obtained for the yield strength of the Al-10$\text{Al}_2\text{O}_3$ nanocomposite is higher than the 274 MPa exhibited by $\text{AlMg}_5$–0.4$\text{Al}_2\text{O}_3$ nanocomposite [25]. Mechanical milling of aluminum for 24 h increased its compressive strength from 204.43 to 371.69 MPa i.e. an increase of 82 %. The addition of 10 vol.% $\text{Al}_2\text{O}_3$ to aluminum and mechanical milling of the mixture for 24 h increased the compressive strength of the composite to 432.87 MPa i.e. an increase in compressive strength by 112 and 16.4 %, with respect to milled aluminum and aluminum, respectively.
Fig. 4. (a) hardness, (b) yield strength, and (c) compressive strength of sintered samples.

The value of 432.87 MPa obtained for the compressive strength of the Al-10Al₂O₃ nanocomposite is much higher than the compressive strength of 196 MPa recorded for Al-10Al₂O₃ nanocomposite prepared by mixing and spark plasma sintering [24]. This clearly shows the role of ball milling in enhancing the compressive strength of the composite.

The increase in strength of the composite could be attributed to: (i) grain size strengthening, (ii) load transfer effect, (iii) Orowan strengthening, and (iv) increased dislocation density. The latter is due to mismatch in thermal expansion and stiffness between the reinforcement and matrix. The decrease in the average grain size leads to the increase in grain boundaries, which restrict dislocation movement. This is because the different orientation of adjacent grains and the discontinuity of the slip plane [34]. The increase in yield strength because of structure refinement is usually quantified through the Hall-Petch equation as [34]

$$\Delta \sigma_{H-P} = \frac{k_y}{\sqrt{d}}$$

(2)

where \( k_y \) is a strengthening parameter and \( d \) is the average grain size.

In particle reinforced metal matrix composites, the externally applied load is transferred from the ductile matrix to the stiff and hard reinforcement, this leads to increase in strength [35-38]. For equiaxed particle, the increase in strength can be predicted using the Shear Lag model proposed by Nardone and Prewo [35]:

$$\Delta \sigma_{LT} = \frac{1}{2} \nu_p \sigma_m$$

(3)

where \( \nu_p \) and \( \sigma_m \) are the volume fraction of the reinforcement and the yield strength of the matrix, respectively.

On the one hand, particles contribute to the refinement of the matrix, since they can pin grain boundaries and hinder their movement, which prevent or minimize grain growth. The refinement of the matrix could be modeled by Zener formula [38]:

$$d_m = \frac{4\alpha d_p}{3\nu_p}$$

(4)

where \( \nu_p \) and \( \alpha \) are the volume fraction of the reinforcement and a proportionality constant, respectively; and \( d_m \) and \( d_p \) are the average diameters of the matrix and reinforcement, respectively.
On the other hand, particles interact with dislocations leading to the so-called Orowan strengthening. The hard ceramic particles pin the moving dislocations and promote dislocations bowing around the particles (Orowan loops). These loops restrict dislocation movement. The increase in yield strength due to Orowan mechanism can be quantified using [34]:

\[
\Delta \sigma_{ov} = \frac{0.13bG}{r} \ln \left( \frac{r}{2b} \right) - \frac{1}{2} v_p \left( 1 - v_p \right)
\]  

where \( b \) is the Burgers vector and \( G \) is the shear modulus of the matrix, and \( v_p \) is the volume fraction of the reinforcement.

In powder metallurgy processed materials such as spark plasma sintered materials, at the end of the sintering cycle, during cooling to room temperature, the difference in thermal expansion coefficients and moduli of elasticity between the matrix and reinforcement is accommodated through the formation of geometrically necessary dislocations which strain harden the material. The density of geometrically necessary dislocations can be expressed as [38]:

\[
\rho_{CTE} = \frac{A\Delta \alpha \Delta T v_p}{bd_p (1 - v_p)}
\]

\[
\rho_{EM} = \frac{6v_p}{\pi d_p^2} \varepsilon
\]

where \( A \) is a geometric constant, \( \Delta \alpha \) is the difference in coefficient of thermal expansion and \( \Delta T \) is the difference in temperatures.

The increase in strength due to the formation of geometrically necessary dislocations can be estimated using the Taylor equation [39]:

\[
\Delta \sigma_{CTE+EM} = \sqrt{3 \beta Gb \left( \sqrt{\rho_{CTE}^2} + \sqrt{\rho_{EM}^2} \right)}
\]

where \( \beta \) is a constant.

The above equations clearly indicates that small grain size (Eq. 2 and 4), high volume fraction of the reinforcement (Eq. 3), presence of particles (Eq. 5), and the large difference in the coefficients of thermal expansion and moduli of elasticity (Eq. 8) contribute to the increase in the hardness and yield strength of the composite material.

### 3.3 Thermal properties

Thermal conductivity values of the consolidated samples are presented in Fig. 5. The thermal conductivity of aluminum is greater than that of milled aluminum, which in turn is greater than that of the composite material. Aluminum, milled aluminum, and the composite had thermal conductivity values of 198.09, 92.2, and 81.42 W/mK, respectively. Milling decreased the thermal conductivity of aluminum by 53%. The addition of 10 vol. % \( \text{Al}_2\text{O}_3 \) particles and milling for 24 h decreased the thermal conductivity by 59% with respect to aluminum.
It is known that metals have excellent thermal conductivity because of the large mobility of electrons. However, thermal conductivity of metal matrix composites depends on the microstructure, thermal properties of the matrix and reinforcement, the interface between the two phases, and the volume fraction of the reinforcement, its distribution, and geometry [40]. The reduced thermal conductivity of the Al-10Al₂O₃ composite can be attributed to the low thermal conductivity of Al₂O₃ (20-30 W/mK) [40] compared to that of aluminum 237 W/mK [41], in addition to the 3.43 % fraction of pores. Thermal conductivity in ceramic materials is due to phonons and it is low because of the absence of free electrons. It depends on the atomic mass, bonding between atoms or ions, and the type of crystal structure [40]. However, in metals it is due to electrons and can be expressed by the Wiedemann–Franz law: [42]

\[ K_e = \frac{\pi^2 (k_B/e)^2}{3} \sigma T \]  \tag{9}

where \( K_e \) is the electrical thermal conductivity, \( k_B \) is Boltzmann constant, \( e \) is electron charge, \( \sigma \) is electrical conductivity, and \( T \) is temperature.

Therefore, heat conduction in the composite is dictated by electrons in the aluminum matrix and phonons in the alumina ceramic particles. The electrons and phonons are scattered by the interface between the matrix and reinforcement, defects, and pores, this leads to low thermal conductivity. The milled aluminum also showed low thermal conductivity despite the very small fraction of remaining pores and the absence of Al₂O₃ particles. The large amount of defects, such as grain boundaries, generated during milling, and preserved during sintering because of limited grain growth, reduces the thermal conductivity. The fully dense aluminum characterized by relatively large grain size, and therefore less grain boundaries, had higher thermal conductivity than the milled aluminum and the composite.

3.4 Coefficient of thermal expansion

The coefficient of thermal expansion (CTE) of a metal matrix composite and the mismatch in CTE values between the matrix and reinforcement play a key role in geometrical and mechanical property changes, respectively, of the composite material [43]. Fig. 6 shows the relationship between CTE and temperature for aluminum, milled aluminum, and Al-10Al₂O₃ composite. The CTE of all samples increased with the increase in temperature. Milling decreased the CTE of aluminum and the addition of Al₂O₃ particles led to further decrease in the CTE. In the temperature range from 373 K to 723 K, milled aluminum had lower CTEs ranging from 16×10⁻⁶ to 26×10⁻⁶ /K compared with 20×10⁻⁶ to 30×10⁻⁶ /K for
aluminum. The CTE is reduced by approximately 20 % and 13 % at 373 K and 723 K, respectively. Metals are known to have high CTE because of their moderate bonding strength compared to ceramics [40]. In the same temperature range, the composite had lower CTEs ranging from $10 \times 10^{-6}$ to $22 \times 10^{-6}$/K compared with $20 \times 10^{-6}$ to $30 \times 10^{-6}$/K for aluminum. The CTE decreased as much as 50 % and 26 % at 373 K and 723 K, respectively. The CTE displayed the same trend observed for the thermal conductivity and as discussed above. The lower CTE values of milled aluminum compared to aluminum could be attributed to its fine microstructure. The reduced CTE values of the composite may be attributed to the lower CTE of alumina ($6.5 \times 10^{-6}$/K) between 298 to 423 K [40] than that of aluminum ($22 \times 10^{-6}$/K to $25 \times 10^{-6}$/K) between 298 to 373 K [44]. In addition, agglomeration of Al$_2$O$_3$ particles and the remaining pores contribute to the reduction in the CTE of the composite [43]. It is worth mentioning here that internal stresses may be released and thermal stresses may be generated during heating and cooling of metal matrix composites. It was reported that during heating, thermal stresses generate tensile stress on Al$_2$O$_3$ particles and compressive stress on the copper matrix. However, during cooling the thermal residual stresses exhibit a compressive stress on the Al$_2$O$_3$ particles and tensile stress on the copper matrix [43]. The decrease in thermal conductivity and coefficient of thermal expansion of aluminum reinforced by Al$_2$O$_3$ nanoparticles is in agreement with the trend reported in literature on the decrease in these properties when copper is reinforced with Al$_2$O$_3$ nanoparticles [43]. It was found that the thermal conductivity of copper decreased from 384 to 78.1 W/mK with the increase in Al$_2$O$_3$ content from 0 to 12.5 wt.%. Also, between 323 and 723 K, the coefficient of thermal expansion of pure copper ranged from $18 \times 10^{-6}$ to $33 \times 10^{-6}$/K compared with $11 \times 10^{-6}$ to $17 \times 10^{-6}$/K for copper reinforced with 12.5 wt.% of Al$_2$O$_3$ [43].

![Fig. 6. Coefficient of thermal expansion of sintered samples.](image)

The present work showed that ball milling and addition of Al$_2$O$_3$ nanoparticles to aluminum lead to: (i) significant improvement in the hardness and compressive strength, (ii) decreased the thermal conductivity, and (iii) reduced the coefficient of thermal expansion. It is believed that not only the thermal conductivity of Al-Al$_2$O$_3$ nanocomposite could be increased but also the coefficient of thermal expansion may be further reduced, to reach the high thermal conductivity and low CTE required for thermal management applications [40]. This can be achieved by the addition of a second nanoreinforcement phase such as carbon nanotubes [45] or graphene [46], to produce hybrid nanocomposites. CNTs have very high thermal conductivity, with room temperature measured values of 3000 and 3500 W/mK for MWCNTs...
[47] and SWCNTs [48], respectively. Single layer graphene has room temperature thermal conductivity of up to 5300 W/mK [49]. The development of aluminum hybrid nanocomposites that have tailored mechanical and thermal properties will be the subject of future work.

4. Conclusion

Compressive strength and thermal properties of aluminum, milled aluminum, and Al-10Al2O3 composite processed via BM and SPS were investigated. The Al-10Al2O3 composite possessed hardness of 1309.7 MPa, yield strength of 311.4 MPa, and compressive strength of 432.87 MPa compared to hardness of 326.3 MPa, yield strength of 74.33 MPa, and compressive strength of 204.43 MPa for aluminum. This constitutes an increase in hardness, yield strength, and compressive strength of 300, 319, and 112 %, respectively, with respect to aluminum. The Al-10Al2O3 composite had thermal conductivity value 81.42 W/mK compared to value of 198.09 W/mK for aluminum. This constitutes a decrease in thermal conductivity of 59 % with respect to aluminum. In the temperature range from 373 K to 723 K, the composite had lower CTEs ranging from 10×10−6 to 22×10−6 /K compared to 20×10−6 to 30×10−6 /K for aluminum. This constitutes a decrease in linear coefficient of thermal expansion of 50 % and 26 % at 373 K and 723 K, respectively, with respect to aluminum.

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5. References


Садржај: У овом раду, испитивана су компресивна и термичка својства алуминијума, млевеног алуминијума и композита Al-10Al2O3 добијених млевењем у млину и спарк плазма синтеровањем. Микроструктурна својства прахова и синтерованих узорака окарарактерисана су уз помоћ оптичког и скенирајућег електронског микроскопа. Универзалне методе су коришћене за одређивање компресивних својстава узорака. Термичка проводљивост и коэффицијент термалног ширења материјала мерена су уз помоћ топлог диска термалног анализера и дилатометром. Al-10Al2O3 композит поседује тврдоћу од 1309,7 MPa, снагу од 311,4 MPa, и отпорност на притисак од 432,87 MPa у поређењу са тврдоћом 326,3 MPa, снагом 74,33 MPa, и отпорношћу на притисак од 204,43 MPa за чист алуминијум. Композит Al-10Al2O3 има вредност термичке проводљивости од 81,42 W/mK, док алуминијум има 198,09 W/mK. У температурском интервалу од 373 K до 723 K, композит поседује мањи коэффцијент термичког ширења у опсегу од $10 \times 10^{-5}$ до $22 \times 10^{-6}$ /K у поређењу са $20 \times 10^{-5}$ до $30 \times 10^{-6}$ /K за алуминијум.

Кључне речи: алуминијум, млевење, синтеровање у плазми, метал-матрикс нанокомпозити, механичка војства, термичка својства.

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