A Study on the Effect of Ultrafine SiC Additions on Corrosion and Wear Performance of Alumina-Silicon Carbide Composite Material Produced by SPS Sintering

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Abstract: Alumina-silicon carbide (Al$_2$O$_3$–SiC) composites of varying compositions (15, 20, 25 and 30 vol.%)–SiC were produced by the ball milling of Al$_2$O$_3$ and SiC powders, followed by spark plasma sintering. The samples were sintered at a temperature and pressure of 1600 °C and 50 MPa, respectively, thermally etched at 1400 °C and mechanically fractured by hammer impact. The effect of SiC additions to monolithic Al$_2$O$_3$ on the densification response, microstructural and phase evolutions, and fracture morphologies were evaluated. The wear performance of the composites using a ball-on-sample configuration was evaluated and compared to that of monolithic Al$_2$O$_3$. In addition, the corrosion performance of the composites in a 3.5% NaCl solution was examined using open circuit potential and potentiodynamic polarization assessments. SiC additions to monolithic Al$_2$O$_3$ delayed densification due to the powder agglomeration resulting from the powder processing. SiC particles were observed to be located inside Al$_2$O$_3$ grains and some at grain boundaries. Intergranular and transgranular fracture modes were observed on the fractured composite surfaces. The study has shown that the Al$_2$O$_3$–SiC composite is a promising material for improved wear resistance with SiC content increments higher than 15 vol.%. Moreover, the increase in SiC content displayed no improvement in corrosion performance.

Keywords: SPS; corrosion; wear; alumina-silicon carbide; composite

1. Introduction

Currently, there has been increasing attention for ‘ceramic nanocomposites’ [1]. These consist of a ceramic matrix such as alumina (Al$_2$O$_3$) reinforced by dispersing nanoparticles of another ceramic material like silicon carbide (SiC). Besides SiC, mechanical properties can be improved by introducing other secondary hardened phases to the Al$_2$O$_3$ matrix, including TiB$_2$, TiC, Ti(C,N) and ZrO$_2$ particles. A study conducted by Kim and Lee showed that adding TiC particles to the Al$_2$O$_3$ matrix improved flexural strength and fracture toughness [2]. Properties such as flexural strength, fracture toughness, and hardness were later reported to be improved with an increment in TiB$_2$ [3]. Furthermore, the resistance to oxidation of the Al$_2$O$_3$ matrix can be improved by adding TiN particles [4]. Literature reported that SiC addition to Al$_2$O$_3$ as reinforcement enhances the mechanical properties significantly as related to other reinforcing additives [5–9].

The addition of ultrafine SiC particles to monolithic Al$_2$O$_3$ was reported to significantly improve the hardness [1,7,8], fracture strength [10,11], and toughness [12]. Creep resistance at elevated temperatures was also reported to be enhanced significantly by SiC additions [13]. Ceramics can be manufactured using traditional methods such as sintering, hot or cold pressing, and slip casting.
A new cost-effective ceramic production method, spark plasma sintering (SPS), is of interest [14–17]. SPS makes use of direct pulsed current and uniaxial pressure to consolidate different nanocomposite materials [18]. The benefits of using SPS compared to conventional methods include lower sintering temperatures, shorter holding times, and marked increases in the properties of materials [19]. In work carried out by Álvarez and colleagues [20], it was found that increasing the sintering temperature and dwell time of SiC contents around 17 vol.% limited Al2O3 grain growth. Earlier, a study by Chae and associates compared conventional hot pressing to SPS [21]. An increased rate of densification was reported when using SPS compared to the conventional process of hot-pressing.

Pure Al2O3 has been used as a structural material of high performance in corrosive environments due to its ability to resist salt corrosion at elevated temperatures [13]. The corrosion behavior of polycrystalline Al2O3 and Al12O3 with 5 wt.% of CaO5SiO2 additives was evaluated in a 3 wt.%NaCl solution by Galusková et al. [13,22]. The former was found to have corroded by the loss, dissolution, somewhat a degree of loosening and detachment of the Al2O3 grains. The later corroded preferentially by the temperature-dependent dissolution of the aluminosilicate grain boundary phase in conjunction with the precipitation of silicaceous phases. Additionally, the corrosion of Al2O3 with additives was reported to be three orders faster as compared to polycrystalline Al2O3 [23,24]. The addition of second phase nanoparticles such as SiC to Al2O3 can significantly improve functional performance. It is, therefore, worthwhile to investigate the effect of adding SiC nanoparticles on corrosion performance.

Another mechanical property greatly affected by ceramic processing is wear. The inconsistencies of the wear resistance of pure Al2O3 are greatly affected by the characteristics of the material such as sintering aids, grain size, and residual porosity [25]. According to previous studies, polycrystalline Al2O3 has three times greater resistance to erosion [26] and reduced dry sliding wear as compared to composites [27]. The addition of SiC nanoparticles into polycrystalline Al2O3 produces a noticeable improvement in surface quality during lapping and polishing [20]. SiC additions are also said to reduce grain pull-out during grinding, changing the monolithic Al2O3 fracture mode from intergranular to transgranular in SiC nanocomposites [21]. Other theories suggest that the transformation from intergranular to transgranular is due to the hindrance of the formation of long twins and dislocation pileups, which are intergranular crack initiation sites [25]. In the very same work, it is further suggested that the change is more chemistry-related, as opposed to mechanical interactions between Al2O3 and SiC.

Several investigators have researched the mechanical properties of Al2O3–SiC nanocomposites [5,11,12,28–32]. However, very few investigations on the corrosion and wear behavior of Al2O3–SiC nanocomposites consolidated by SPS have been published [33,34]. This paper offers the primary results of an investigation on the behavior of Al2O3–SiC ultrafine grained composites under a NaCl corrosive environment. This work aims at understanding the effect of SiC content on the wear properties and corrosion performance of alumina-silicon carbide nanocomposite material.

2. Materials and Methods

2.1. Powder Production

The Al2O3–SiC nanocomposites were produced using γ-Al2O3 (Sigma-Aldrich Pty Ltd., Johannesburg, South Africa) and β-SiC (Industrial Analytical Pty Ltd., Johannesburg, South Africa) powders with mean particle sizes of 0.1 and 44 µm, respectively. Oxygen contamination of the powders was prevented by handling the powders in an argon gas-sealed glove box. Al2O3 powder was milled using 2 mm alumina balls in a Reeves ball mill Szegvari attritor system type B® for 8 h using hexane as a dispersant. The same was done for the SiC powder using distilled water as a dispersant for 16.5 h. Four mixtures (15, 20, 25, and 30 vol.% SiC) were milled for 8 h inside a Fritsch Pulverisette 6 planetary mono mill® using hexane as a dispersant and oleic acid ((Monitoring & Control Laboratories Pty Ltd., Johannesburg, South Africa) as a process control agent. The slurries were dried using a digital HeidolphLaborota 4010 rotary evaporator (Heidolph Instruments GmbH & CO. KG, Schwabach,
Germany), sieved, and the dispersant burnt-off inside an Elite TSH17/75/150® tube furnace (Elite Thermal Systems Ltd., Leicestershire, UK) to aid consolidation during SPS.

2.2. Powder Characterisation

A Malvern Mastersizer 2000® (Malvern Panalytical Ltd., Worcestershire, UK) was used to confirm the particle size distribution of the powders: as-received and after milling. A Carl Zeiss Sigma® Field Emission Scanning Electron Microscope (FE-SEM) (Carl Zeiss Microscopy GmbH, Jena, Germany) was used to carry out particle morphology studies. Shimadzu X-ray Diffraction (XRD) machine (Shimadzu, Kyoto, Japan) was used to characterize the phases present in the powders. The average crystallite size was calculated by means of the Williamson–Hall (W–H) method (Equation (1)). Plots were drawn with $4 \sin \theta$ on the x-axis and $\beta_{hkl} \cos \theta$ along the y-axis for all the starting powders. By fitting the data, the crystallite size $D$ was extracted from the slope of the best fit line.

\[
\beta_{hkl} \cos \theta = \left( \frac{K \lambda}{D} \right) + 4 \varepsilon \sin \theta
\]  

(1)

2.3. Spark Plasma Sintering (SPS)

The prepared blends were sintered using an FCT Systeme GmbH HP D 5/2® Spark Plasma Sintering furnace (FCT Systeme GmbH, Effelder-Rauenstein, Germany) in a graphite mold using a graphite foil and hexagonal boron nitride (hBN) as a coating. A heating rate of 200 °C/min was applied to heat up the samples to the necessary sintering temperature. The samples were sintered at 1600 °C using a dwell time of 10 min in vacuum under a uniaxial pressure of 50 MPa. After sintering, the ram pressure was released, and the specimens cooled at 100 °C/min. After that, the samples were sandblasted and wiped with isopropanol (Monitoring & Control Laboratories Pty Ltd., Johannesburg, South Africa) to remove excess sand and graphite foil.

2.4. Sintered Samples Characterisation

Archimedes’ method was used to measure the densities of the sintered samples using distilled water as a medium. The sintered samples were metallographically prepared down to a 1 µm diamond finish and etched thermally at 1400 °C. Microstructure and phases present in the sintered samples were analyzed using Energy-Dispersive X-ray Spectroscopy (EDS) (Oxford x-act, Abingdon, UK) and SEM. The average grain size of the sintered composites was obtained by employing the linear intercept method.

The wear behavior of the composites produced was tested using an Anton Paar GmbH Standard Tribometer Version 7.3.13 (Anton Paar GmbH, Graz, Germany). A ball-on-flat geometry was employed with a 6 mm diameter alumina static partner. A load of 10 N was used for 1814 s and the coefficient of friction with time for monolithic Al₂O₃ and each composite was recorded. The wear scars were examined using a JEOL JSM-IT500 SEM (JEOL Ltd., Akishima, Japan).

A Digi-Ivy DY2300 potentiostat (Digi-Ivy, Inc., Austin, TX, USA) coupled to a standard three electrochemical electrode cell set-up was employed to study the corrosion behavior of the samples in a 3.5 wt.% NaCl (Alfa Aesar by Thermo Fisher Scientific GmbH, Kandel, Germany) solution at 25 °C. The electrochemical cell used consisted of a platinum counter electrode, silver/silver chloride reference electrode, and the working electrode as the sample. The samples were prepared for testing by connecting the sample face to an insulating wire with aluminum tape. Open-circuit corrosion potential measurements were carried out for 60 min, while potentiodynamic polarization measurements were performed using a scan rate of 5 mV/s at a potential initiated at −400 to −950 mV. A fresh electrolyte solution was used with each sample.
3. Results and Discussion

3.1. Powder Characteristics

Figure 1 gives the particle size distribution of the powders. The statistical parameters for the size distribution of powders are given in Table 1. The particle size distribution of the Al₂O₃ and SiC powder as-received was unimodal, with 50% of the particles above 6.37 and 48.0 µm in size and 10% above ~2.17 and 26.75 µm in size, respectively. The milling was sufficient for both the Al₂O₃ and SiC powders, with about 90% of the particles below 7.71 and 0.25 µm, respectively.

![Particle size distribution before and after milling for (a) alumina; (b) SiC powder.](image)

**Figure 1.** Particle size distribution before and after milling for (a) alumina; (b) SiC powder.

| Material | d₁₀ (µm) | d₅₀ (µm) | d₉₀ (µm) |
|----------|----------|----------|----------|
| Al₂O₃    | 2.172    | 6.37     | 18.76    |
| SiC      | 26.77    | 48.01    | 82.63    |
|          |          |          |          |
| Al₂O₃    | 1.448    | 3.344    | 7.712    |
| SiC      | 0.063    | 0.120    | 0.245    |

The morphology of the powder after mixing is shown in Figure 2. The blended powder seemed to be made of small particles evenly dispersed amongst much bigger particles. In Figure 2b, the same powder at high magnification reveals that bigger particles are agglomerates of fine particles, with voids between the agglomerated particles. Figure 3 shows the XRD diffractogram for blended and alloyed powders. It shows a shift of the Al₂O₃ peaks indicative of the alteration of the Al₂O₃ matrix due to the presence of SiC. Furthermore, peak broadening confirms the presence of ultrafine powders observed also in Table 2.
The displacement represents the shrinkage profile directly during the densification of the powders vol.% SiC composite and Al to that reported by Chae and colleagues [21]. The added SiC hindered the densification process. Respectively, densification for these samples finishes at about 1530 and 1580 °C, the temperatures for the onset of densification were raised by the addition of SiC. The Al in real time. The pure Al

3.2. Composite Response to SPS

The shrinkage behavior of the Al2O3–SiC composites during the SPS process is shown in Figure 4. The displacement represents the shrinkage profile directly during the densification of the powders in real time. The pure Al2O3 started to densify at about 850 and finished at about 1300 °C. However, the temperatures for the onset of densification were raised by the addition of SiC. The Al2O3-15 vol.% SiC composite and Al2O3-30 vol.% SiC composites started to densify at about 975 and 1550 °C, respectively. Densification for these samples finishes at about 1530 and 1580 °C, respectively, similar to that reported by Chae and colleagues [21]. The added SiC hindered the densification process.

Figure 2. Scanning electron microscope (SEM) backscattered electron micrographs of the Al2O3–SiC composite powder at: (a) low; (b) high magnification.

(a) (b)

Figure 3. X-ray diffraction diffractograms for the produced powder composites.

Table 2. Crystallite size as calculated by Williamson–Hall (W-H) approach.

| Sample     | Crystallite Size (nm) |
|------------|-----------------------|
| Pure Al2O3 | 0.049                 |
| Al2O3-15SiC| 0.315                 |
| Al2O3-20SiC| 1.107                 |
| Al2O3-25SiC| 0.109                 |
| Al2O3-30SiC| 0.169                 |

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According to Hsueh and colleagues [35], SiC particles act as tensile stress concentrations influenced by the different characteristics of the composite phases present (Al₂O₃ and SiC).

Figure 4. Shrinkage response of pure Al₂O₃ and Al₂O₃–SiC composites during spark plasma sintering.

3.3. Characteristics of the Sintered Composites

Table 3 shows the relative densities obtained. The samples were almost fully densified with all relative densities above 97% using the SPS conditions stated above. SPS can produce almost fully dense Al₂O₃–SiC composites at temperatures of ~1600 °C at a soaking time of 10 min compared to 1650 °C of hot pressing and an hour of soaking [33,34,36]. The microstructures of the pure Al₂O₃ and of the Al₂O₃–SiC composites are shown in Figure 5a–c,e–g. The relations between the Al₂O₃ grain size and the content of SiC are summarized in Table 3. The addition of 15 and 20 vol.% significantly decreased the grain size of the composites. Further SiC additions to monolithic Al₂O₃ increased the grain size. The microstructure of the monolithic Al₂O₃ (Figure 5a) was relatively coarser than the microstructure of composites with 15 and 20 vol.% in Figure 5f,g. The micrographs showed that the SiC particles were mainly located inside the grains and some at the Al₂O₃ grain boundaries. Figure 5b shows the SiC particles located both intergranularly and transgranularly. Related research described that SiC particles (~200 nm) were located within the Al₂O₃ grains, while larger SiC particles tended to be at the Al₂O₃ boundaries [37]. SEM micrographs of the fractured surfaces of pure Al₂O₃ and the Al₂O₃–SiC composites showed features resembling a transgranular fracture mode.

Table 3. Density and average grain size results of the sintered samples.

| Sample          | Theoretical Density (g/cm³) | Bulk Density (g/cm³) | Relative Density (%) | Average Grain Size (µm) |
|-----------------|-----------------------------|----------------------|----------------------|-------------------------|
| Pure Al₂O₃     | 3.97                        | 3.939                | 99.2                 | 15.5                    |
| Al₂O₃-15SiC    | 3.82                        | 3.797                | 99.4                 | 2.0                     |
| Al₂O₃-20SiC    | 3.78                        | 3.789                | 100                  | 2.3                     |
| Al₂O₃-25SiC    | 3.73                        | 3.724                | 99.8                 | 49.8                    |
| Al₂O₃-30SiC    | 3.73                        | 3.638                | 97.5                 | 43.3                    |
Figure 5. SEM secondary electron (SEM-SE) images of sintered (a) pure Al$_2$O$_3$; (b) fractured surface of pure Al$_2$O$_3$; (c) Al$_2$O$_3$-30SiC; (d) fracture surface of Al$_2$O$_3$-30SiC; (e) Al$_2$O$_3$-25SiC; (f) Al$_2$O$_3$-20SiC; (g) Al$_2$O$_3$-15SiC.

Figure 6 shows the friction coefficient as a function of added SiC for the studied composites, including pure Al$_2$O$_3$. The addition of 15 vol.% of SiC resulted in an increase in the mean coefficient
of friction as compared to pure Al$_2$O$_3$. In contrast, higher vol.% additions (20, 25, and 30) decreased the mean coefficient of friction values substantially. The previously stated phenomenon is made even more apparent when considering the distance covered to achieve the same coefficient of friction. For example, the same coefficient of friction was achieved after 22 m for monolithic Al$_2$O$_3$, while it took 47 m for the Al$_2$O$_3$-15SiC composite. In addition, as seen in Figure 7 and Table 4, the wear track size seems to decrease with the addition of 15 vol.% of SiC. This could be attributed to SiC pull-out, which has been previously reported in other investigations [38–40].

Further SiC additions of up to 30 vol.%, increased the track sizes to ~1242 µm, also resulting in a substantial reduction in wear coefficient compared to the composite with 15 vol.% additions and the monolith. Finally, the wear surfaces of the composites presented the presence of localized flaking and microcracking (Figure 8), similar to findings made by Guicciardi et al. [41]. The flaking and microcracking behavior were severe for Al$_2$O$_3$-15SiC composite and less severe with higher SiC additions of up to 30 vol.%. The brighter regions were previously reported [41–43] as Al$_2$O$_3$ and the darker regions could be a hydroxide phase.

**Figure 6.** Coefficient of friction as a function of SiC additions.

**Table 4.** Approximate wear track sizes for the study’s composites.

| Sample       | Approximate Wear Track Size (µm) |
|--------------|----------------------------------|
| Pure Al$_2$O$_3$ | 2324                              |
| Al$_2$O$_3$-15SiC | 375                               |
| Al$_2$O$_3$-20SiC | 637                               |
| Al$_2$O$_3$-25SiC | 823                               |
| Al$_2$O$_3$-30SiC | 1242                              |
(a) 

(b) 

(c) 

(d) 

(e) 

Figure 7. Optical microscope images of the wear tracks for (a) monolithic Al$_2$O$_3$, (b) Al$_2$O$_3$-15SiC, (c) Al$_2$O$_3$-20SiC, (d) Al$_2$O$_3$-25SiC, and (e) Al$_2$O$_3$-30SiC.
The Tafel plots for the composites in 3.5% NaCl solution (Figure 9) were utilized in carefully studying the corrosion behavior of the composites. The composites of vol.% 15, 25 and 30 generally displayed similar polarization curves and passivity characteristics. The Al₂O₃-20SiC composite displayed slightly different behavior from the other three variants. Table 5 lists the corrosion potential ($E_{corr}$) and current ($I_{corr}$) of the composites. The corrosion potentials ($E_{corr}$) of the composites were distinct and defined in the ranges of −0.731 to −0.499 V. The addition of 15 or 20 vol.% of SiC increased the $E_{corr}$, very similar to the observations made by Maahn and Roepstorff [44]. A slight change in $I_{corr}$ was observed with additions of 15 and 20 vol.% of SiC (0.16 difference in magnitude). Furthermore, the composites containing 25 and 30 vol.% displayed the same $I_{corr}$. Conclusively, there was no observed improvement in the corrosion performance of the composites.

**Table 5.** Corrosion potential ($E_{corr}$) and current ($I_{corr}$) of the composites in 3.5% NaCl.

| Sample      | $E_{corr}$ (V) | $I_{corr}$ (A/cm²) |
|-------------|----------------|--------------------|
| Al₂O₃-15SiC | −0.731         | 2.433 × 10⁻⁸       |
| Al₂O₃-20SiC | −0.499         | 3.841 × 10⁻⁹       |
| Al₂O₃-25SiC | −0.556         | 9.577 × 10⁻⁹       |
| Al₂O₃-30SiC | −0.694         | 9.577 × 10⁻⁹       |
4. Conclusions

In this work, a characterization study was conducted on pure $\text{Al}_2\text{O}_3$ and $\text{Al}_2\text{O}_3$–$\text{SiC}$ powders obtained by milling, as well as the composites consolidated by SPS. The conclusions are:

1. Ultrafine particles were produced after milling, evident from the peak broadening observed during XRD analyses. The morphology of the mixed powders revealed $\text{Al}_2\text{O}_3$ matrix with small $\text{SiC}$ particles evenly dispersed amongst much larger and agglomerated particles. A shift of the $\text{Al}_2\text{O}_3$ peaks during XRD showed that the presence of $\text{SiC}$ particles altered the $\text{Al}_2\text{O}_3$ matrix after mechanical alloying.

2. The addition of $\text{SiC}$ increased temperature from the onset of densification. Furthermore, the addition of $\text{SiC}$ delayed densification. In addition, the degree of agglomeration observed in the initial milling stage of the powders might have prolonged densification.

3. The resistance to wear decreased with the addition of 15 vol.% of $\text{SiC}$. Additions of higher vol.% (20, 25, and 30) of $\text{SiC}$ significantly improved the resistance to wear of $\text{Al}_2\text{O}_3$.

4. The study’s composites showed no improvement in corrosion performance with increments in $\text{SiC}$ additions.

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References

1. Jaafar, M.; Bonnefont, G.; Fantozzi, G.; Reveron, H. Intergranular alumina–$\text{SiC}$ micro-nanocomposites sintered by spark plasma sintering. *Mater. Chem. Phys.* 2010, 124, 377–379. [CrossRef]
2. Kim, Y.-W.; Lee, J.-G. Pressureless Sintering of Alumina-Titanium Carbide Composites. *J. Am. Ceram. Soc.* 1989, 72, 1333–1337. [CrossRef]
3. Jianxin, D.; Xing, A. Wear resistance of $\text{Al}_2\text{O}_3$/TiB$_2$ ceramic cutting tools in sliding wear tests and in machining processes. *J. Mater. Process. Technol.* 1997, 72, 249–255. [CrossRef]
4. Tampieri, A.; Bellesi, A. Oxidation Resistance of Alumina–Titanium Nitride and Alumina–Titanium Carbide Composites. *J. Am. Ceram. Soc.* 1992, 75, 1688–1690. [CrossRef]
5. Gustafsson, S.; Falk, L.K.L.; Lidén, E.; Carlström, E. Pressureless sintered $\text{Al}_2\text{O}_3$–$\text{SiC}$ nanocomposites. *Ceram. Int.* 2008, 34, 1609–1615. [CrossRef]
6. Galusek, D.; Klement, R.; Sedláček, J.; Balog, M.; Fasel, C.; Zhang, J.; Crimp, M.A.; Riedel, R. $\text{Al}_2\text{O}_3$–$\text{SiC}$ composites prepared by infiltration of pre-sintered alumina with a poly(allyl)carbosilane. *J. Eur. Ceram. Soc.* 2011, 31, 111–119. [CrossRef]
7. Shi, X.L.; Xu, F.M.; Zhang, Z.J.; Dong, Y.L.; Tan, Y.; Wang, L.; Yang, J.M. Mechanical properties of hot-pressed $\text{Al}_2\text{O}_3$/$\text{SiC}$ composites. *Mater. Sci. Eng. A* 2010, 527, 4646–4649. [CrossRef]
8. Dong, Y.L.; Xu, F.M.; Shi, X.L.; Zhang, C.; Zhang, Z.J.; Yang, J.M.; Tan, Y. Fabrication and mechanical properties of nano/micro-sized $\text{Al}_2\text{O}_3$/SiC composites. *Mater. Sci. Eng. A* 2009, 504, 49–54. [CrossRef]
9. Liu, J.; Li, Z.; Yan, H.; Jiang, K. Spark Plasma Sintering of Alumina Composites with Graphene Platelets and Silicon Carbide Nanoparticles. *Adv. Eng. Mater.* 2014, 16, 1111–1118. [CrossRef]
10. Gao, L.; Hong, J.; Miyamoto, H.; Torre, S.D.D. Bending strength and microstructure of $\text{Al}_2\text{O}_3$ ceramics densified by spark plasma sintering. *J. Eur. Ceram. Soc.* 2000, 20, 2149–2152. [CrossRef]
11. Parchovianský, M.; Galusek, D.; Sedláček, J.; Švancarek, P.; Kašiarová, M.; Dusza, J.; Šajgalík, P. Microstructure and mechanical properties of hot pressed $\text{Al}_2\text{O}_3$/SiC nanocomposites. *J. Eur. Ceram. Soc.* 2013, 33, 2291–2298. [CrossRef]
12. Borsa, C.E.; Jones, N.M.; Brook, R.J.; Todd, R.I. Influence of processing on the microstructural development and flexure strength of $\text{Al}_2\text{O}_3$/SiC nanocomposites. *J. Eur. Ceram. Soc.* 1997, 17, 865–872. [CrossRef]
13. Reveron, H.; Zaafani, O.; Fantozzi, G. Microstructure development, hardness, toughness and creep behaviour of pressureless sintered alumina/SiC micro–nanocomposites obtained by slip-casting. J. Eur. Ceram. Soc. 2010, 30, 1351–1357. [CrossRef]

14. Chuvil’deev, V.N.; Boldin, M.S.; Nokhrin, A.V.; Popov, A.A. Advanced materials obtained by Spark Plasma Sintering. Acta Aeronaut. 2017, 135, 192–197. [CrossRef]

15. Omori, M. Sintering, consolidation, reaction and crystal growth by the spark plasma system (SPS). Mater. Sci. Eng. A 2000, 287, 183–188. [CrossRef]

16. Hulbert, D.M.; Anders, A.; Andersson, J.; Lavernia, E.J.; Mukherjee, A.K. A discussion on the absence of plasma in spark plasma sintering. Scr. Mater. 2009, 60, 835–838. [CrossRef]

17. Song, S.-X.; Wang, Z.; Shi, G.-P. Heating mechanism of spark plasma sintering. Ceram. Int. 2013, 39, 1393–1396. [CrossRef]

18. Cuenca-Álvarez, R.; de la Torre, S.D.; López, F.J. Mechanical dispersion of platinum particles and its effect on the microstructure of MCrAlY alloy prepared by SPS. Powder Technol. 2016, 291, 199–200. [CrossRef]

19. Matizamhuka, W.R. Spark plasma sintering (SPS)—An advanced sintering technique for structural nanocomposite materials. J. South. Afr. Inst. Min. Metall. 2016, 116, 1171–1180. [CrossRef]

20. Álvarez, I.; Torrecillas, R.; Solis, W.; Peretyagin, P.; Fernández, A. Microstructural design of Al₂O₃–SiC nanocomposites by Spark Plasma Sintering. Ceram. Int. 2016, 42, 17248–17253. [CrossRef]

21. Chae, J.H.; Kim, K.H.; Choa, Y.H.; Matsushita, J.; Yoon, J.-W.; Shim, K.B. Microstructural evolution of Al₂O₃–SiC nanocomposites during spark plasma sintering. J. Alloys Compd. 2006, 413, 259–264. [CrossRef]

22. Galusková, D.; Saigalik, P.; Galusek, D.; Hnatko, M. Corrosion of Alumina Ceramics in an Aqueous Solution of Sodium Chloride. Key Eng. Mater. 2009, 409, 283–286. [CrossRef]

23. Sudha, P.N.; Sangeetha, K.; Jisha Kumari, A.V.; Vanisri, N.; Rani, K. Corrosion of ceramic materials. In Fundamental Biomaterials: Ceramics; Woodhead Publishing: Cambridge, UK, 2018; ISBN 978081022047.

24. Momohjimoh, I.; Hussein, M.; Al-Aqeli, N. Recent Advances in the Processing and Properties of Alumina–CNT/SiC Nanocomposites. Nanomaterials 2019, 9, 86. [CrossRef] [PubMed]

25. Sedláček, J.; Galusek, D.; Svančarek, P.; Riedel, R.; Atkinson, A.; Wang, X. Abrasive wear of Al₂O₃–SiC and Al₂O₃–(SiC)–C composites with micrometer- and submicrometer-sized alumina matrix grains. J. Eur. Ceram. Soc. 2008, 28, 2983–2993. [CrossRef]

26. Anya, C.C. Wet erosive wear of alumina and its composites with SiC nano-particles. Ceram. Int. 1998, 24, 533–542. [CrossRef]

27. Rodríguez, J.; Martín, A.; Pastor, J.Y.; LLorca, J.; Bartolomé, J.F.; Moya, J.S. Sliding Wear of Alumina/Silicon Carbide Nanocomposites. J. Am. Ceram. Soc. 1999, 82, 2252–2254. [CrossRef]

28. Borsa, C.E.; Jiao, S.; Todd, R.I.; Brook, R.J. Processing and properties of Al₂O₃/SiC nanocomposites. J. Microsc. 1995, 177, 305–312. [CrossRef]

29. Ishitsuka, M.; Tamai, M. Fabrication and Mechanical Properties of Pressureless Sintered Al₂O₃/SiC Nanocomposites. J. Jpn. Soc. Powder Powder Metall. 1992, 39, 1109–1112. [CrossRef]

30. Jeong, Y.K.; Niihara, K. Microstructural and mechanical properties of pressureless sintered Al₂O₃/SiC nanocomposites. Nanostructured Mater. 1997, 9, 193–196. [CrossRef]

31. Ji, Y.; Yeomans, J.A. Processing and mechanical properties of Al₂O₃–5 vol.% Cr nanocomposites. J. Eur. Ceram. Soc. 2002, 22, 1927–1936. [CrossRef]

32. Jiao, S.; Jenkins, M.L.; Davidge, R.W. Electron microscopy of crack/particle interactions in Al₂O₃/SiC nanocomposites. J. Microsc. 1997, 185, 259–264. [CrossRef]

33. Gao, L.; Wang, H.; Hong, J.; Miyamoto, H.; Miyamoto, K.; Nishikawa, Y.; Torre, S.D.D. Mechanical Properties and Microstructure of Nano-SiC–Al₂O₃ Composites Densified by Spark Plasma Sintering. J. Eur. Ceram. Soc. 1999, 19, 609–613. [CrossRef]

34. Picciacchio, A.; Lee, S.-H.; Messing, G.L. Processing and Microstructure Development in Alumina–Silicon Carbide Intragrular Particulate Composites. J. Am. Ceram. Soc. 1994, 77, 2157–2164. [CrossRef]

35. Hsueh, C.-H.; Evans, A.G.; Mcmeeking, R.M. Influence of Multiple Heterogeneities on Sintering Rates. J. Am. Ceram. Soc. 1986, 69, C64–C66. [CrossRef]

36. Zhao, J.; Stearns, L.C.; Harmer, M.P.; Chan, H.M.; Miller, G.A.; Cook, R.F. Mechanical Behavior of Alumina–Silicon Carbide „Nanocomposites”. J. Am. Ceram. Soc. 1993, 76, 503–510. [CrossRef]

37. Xu, Y.; Zangvil, A.; Kerber, A. SiC nanoparticle-reinforced Al₂O₃ matrix composites: Role of intra- and intergranular particles. J. Eur. Ceram. Soc. 1997, 17, 921–928. [CrossRef]
38. Limpichaipanit, A.; Todd, R.I. The relationship between microstructure, fracture and abrasive wear in 
$\text{Al}_2\text{O}_3/\text{SiC}$ nanocomposites and microcomposites containing 5 and 10% SiC. *J. Eur. Ceram. Soc.* 2009, 29, 2841–2848. [CrossRef]

39. Ortiz-Merino, J.L.; Todd, R.I. Relationship between wear rate, surface pullout and microstructure during 
abrasive wear of alumina and alumina/SiC nanocomposites. *Acta Mater.* 2005, 53, 3345–3357. [CrossRef]

40. Kara, H.; Roberts, S.G. Polishing Behavior and Surface Quality of Alumina and Alumina/Silicon Carbide 
Nanocomposites. *J. Am. Ceram. Soc.* 2000, 83, 1219–1225. [CrossRef]

41. Guicciardi, S.; Sciti, D.; Melandri, C.; Bellosi, A. Dry Sliding Wear Behavior of $\text{Al}_2\text{O}_3$-SiC Submicro-and 
Nano-Composites. *J. Am. Ceram. Soc.* 2005, 88, 179–183. [CrossRef]

42. Cherif, K.; Gueroult, B.; Rigaud, M. $\text{Al}_2\text{O}_3$–ZrO2 debris life cycle during wear: Effects of the third body on 
wear and friction. *Wear* 1997, 208, 161–168. [CrossRef]

43. Gee, M.G. The formation of aluminium hydroxide in the sliding wear of alumina. *Wear* 1992, 153, 201–227. 
[CrossRef]

44. Roepstorff, S.; Maahn, E. Corrosion Resistance of Aluminum-Silicon Carbide Composite Materials. 
In Proceedings of the 12th Scandinavian Corrosion Congress and Eurocorr, Espoo, Finland, 31 May–4 June 1992.

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