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# Effect of Powder Mixture Conditions on Mechanical Properties of Sintered $Al_2O_3$-SS 316L Composites under Vacuum Atmosphere

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## Abstract

$Al_2O_3$-SS 316L composites belong to new generation materials which should be characterized by a specified combination of properties. This study is concerned with the effect of the preparation method of the starting mixed powders upon the properties of $Al_2O_3$-SS 316L composites sintered under vacuum atmosphere. The composites were produced using powder mixtures with various weight shares between $Al_2O_3$ and SS 316L as well as varying size of $Al_2O_3$ particles. The mixtures were prepared by a conventional mechanical mixing. It was found that the addition of $Al_2O_3$ particles resulted in a slight decrease in the sintering density, the ultimate tensile strength and elongation, but a slight increase in the hardness. A decrease in the strength was attributed to poor sintering between 316L and $Al_2O_3$ particles, poor distribution of very fine $Al_2O_3$ particles in the composites as well as a high amount of voids and/or porosities after sintering.

**Key words:** metal-matrix composites, SS 316L, $Al_2O_3$ particles

## Introduction

The need of appropriate materials- which concerns certain technical engineering fields, has stimulated continuous and rapid developments of composite materials, such as e.g. metal-matrix composites, which combine good plastic properties of metals with the high mechanical strength of ceramic materials.[(1)] Some composites are resistant to thermal shock and oxidation at medium to high temperatures for high mechanical strength such as compressive and bending strengths including higher hardness.[(2)] Some composites were designed with lower thermal conductivity to store heat inside components for longer time resulting in a reduction in thermal gradient leading to better resistance to thermal shock and thermal fatigue failures.

Powder metallurgy (P/M) is very useful and has some advantages for fabricating of particulate reinforced metal matrix composites. Benefits of P/M include materials and energy saving, new net-shape part fabrication, high productivity as well as dimensional accuracy of parts. These composites are mainly produced by various sintering techniques. The properties of these composite materials significantly depend on the technological parameters of powder mixtures, as well as pressing and sintering processes (which includes temperature, type of atmosphere, gas pressure and sintering duration). However, geometrical parameters of the starting powders also greatly effect the properties.[(3)] These parameters are grain size and roughness of grain surface, type and form (particles or fibers) of the reinforcing phase, distribution of the reinforcing phase within the matrix, kind of matrix, and type of bonds at the reinforcing phase/matrix interface.

There have been efforts to produce a material with combined properties of high strength, good corrosion resistance and also sufficient hardness for tooling applications.[(4-6)] It has been previously reported that particulate-reinforced steel

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matrix composites.(7-9) showed some interesting properties for wear resistance applications. The simplest method of fabricating metal-matrix composite products consists of mixing the metal powder(s) as a matrix and the reinforcement, then pressing and sintering. The method does not always work well to obtain a uniform distribution of the reinforcing powders throughout the matrix. This was usually due to the fact that the reinforcement particles agglomerate together in some parts of the mixture. Furthermore, when the grain sizes of the two powders differ too strongly, it would lead to the difficulty of producing a uniform distribution of these very fine reinforcement particles. The agglomeration of these reinforcement particles could occur due to a result of the intensive action of the Van der Waals inter-particle forces.(10)

The present study aims at producing the $Al_2O_3$-SS 316L composites with various proportions of the starting constituents and examining their mechanical properties. The powder mixtures of composites were produced using conventional mixing in a ball mill, then pressing and finally sintering under vacuum atmosphere.

## Materials and Experimental Procedures

The SS 316L powders (Coldstream, Belgium) were premixed with 0.8% Acrawax + 0.2% lithium stearate and have a mean diameter of 20 μm. Figure 1 shows the morphology of the powders. The alumina powder ($Al_2O_3$) has three different grain sizes of 0.05, 0.3 and 1 μm. Figure. 2 shows the $Al_2O_3$ powders with the mean diameter of 1 μm.

The proportions of the weight of the individual powders in $Al_2O_3$-SS 316L mixtures examined were classified as follows:

Set 1: 0.5, 1.0, 1.5 and 2.0 wt.% $Al_2O_3$ (mean diameter size: 0.05 μm) + SS 316L
Set 2: 0.5, 1.0, 1.5 and 2.0 wt.% $Al_2O_3$ (mean diameter size: 0.3 μm) + SS 316L
Set 3: 0.5, 1.0, 1.5 and 2.0 wt.% $Al_2O_3$ (mean diameter size: 1 μm) + SS 316L

All powder mixtures were compacted under a pressure of 450 kN, using a uni-axial pressing machine into tensile test bars, followed by sintering at 1300°C for 45 minutes in a vacuum furnace with $1.0E^{-0.2}$ mbar. Mechanical properties of the samples were measured and compared among the different sintered materials. Sample microstructures were also examined using optical microscopy and scanning electron microscopy (SEM).

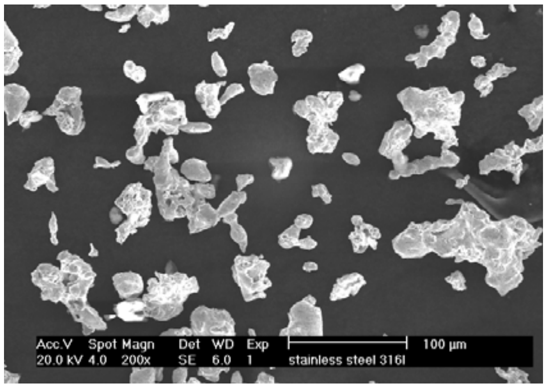


**Figure 1.** SS 316L powders.

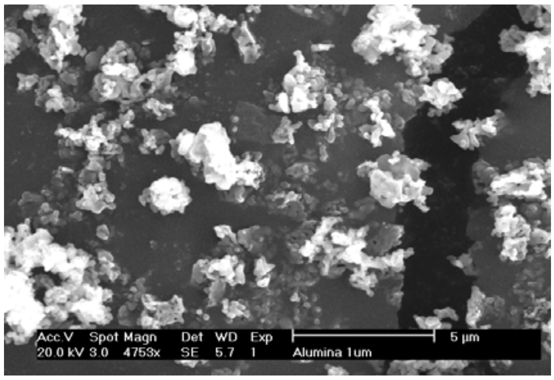


**Figure 2.** $Al_2O_3$ powder with 1 μm size.

## Results and Discussion

### *Microstructure*

Figures 3 and 4 show microstructures of composite samples after pressing and sintering processes viewed in SEM secondary and back-scattered modes, respectively. It can be seen that the microstructures consist of a uniform dispersion of both individual and agglomerated $Al_2O_3$ powders located in SS 316L matrix and along grain boundaries. These microstructural characteristics indicate that the powders were not properly mixed in order to generate a fine and even dispersion of $Al_2O_3$ particles. This results in a non-uniform microstructure, leading to poor mechanical properties. Therefore, it is suggested that the powder mixing method should be modified and developed in order to produce a uniform microstructure. However, it can also be seen that annealing twins in grains appeared after the sintering process. Moreover, voids and porosities were formed, as shown in Figure 4.

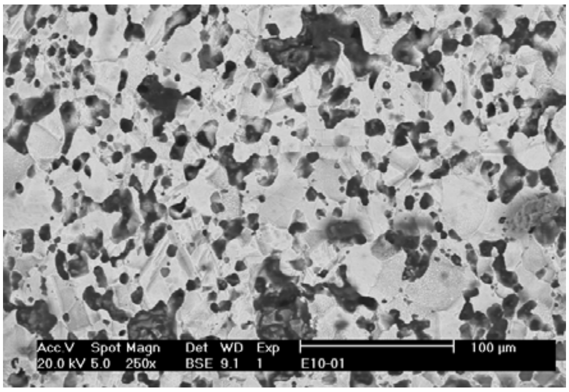


**Figure 3.** Composite micrograph (BSE mode): SS316L mixing with $Al_2O_3$ 0.05 µm 1.5 wt.%

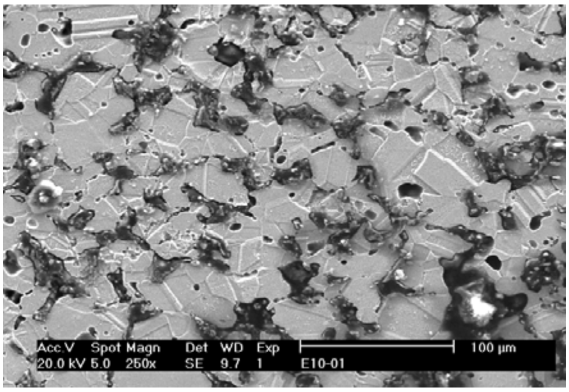


**Figure 4.** Composite micrograph (SE mode) : SS316L mixing with $Al_2O_3$ 0.05 µm 1.5 wt.%

From Figure 5 it was found that increasing $Al_2O_3$ contents of every 0.5% by weight resulted in a slight decrease in density. However, it can also be seen that coarser size of $Al_2O_3$ particles provided a slightly lower density compared to those of the composites with finer $Al_2O_3$ sizes. It may be that coarser $Al_2O_3$ particle sizes cause a slightly higher volume fraction of porosities inside the samples during sintering.

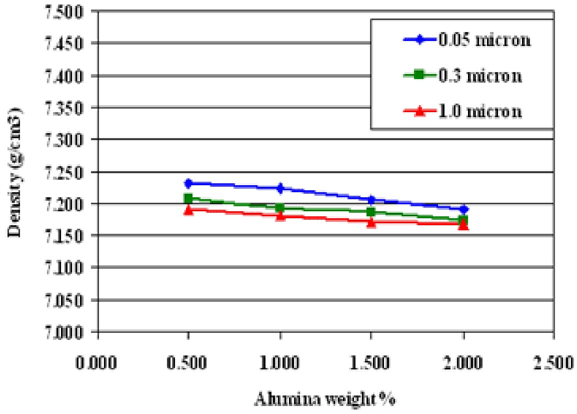


**Figure 5.** The relationship between density, amount and size of $Al_2O_3$ particles

### *Mechanical Properties*

Figure 6 shows the relationship between hardness (HRB) and weight percentage of $Al_2O_3$ powders. It was found that increasing $Al_2O_3$ amount resulted in higher hardness. This might be due to the effect of $Al_2O_3$ powders (which themselves have higher hardness) and to their dispersion to resist metal-matrix deformation during hardness testing.

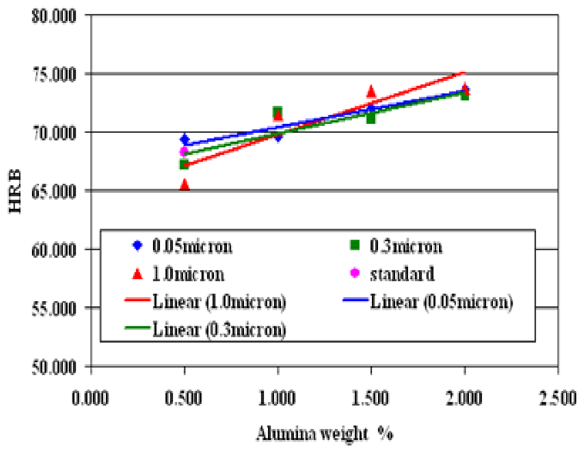


**Figure 6.** The relationship between hardness (HRB) and amount of $Al_2O_3$ particles

Figure 7 shows the effect of $Al_2O_3$ particles on elongation after tensile tests. The addition of $Al_2O_3$ resulted in a decrease in the elongation. Compared to the elongation of pure SS 316L powders, the maximum of $Al_2O_3$ addition of 2 wt.% resulted in a lower elongation of about 5% of all $Al_2O_3$ sizes. The dispersed $Al_2O_3$ particles generally reduced the area of metal-metal cohesion, leading to lower tensile strength and elongation as well as becoming more brittle as $Al_2O_3$ weight increased.

From Figures 8 and 9 it can be summarized that the increase in $Al_2O_3$ amount provided lower tensile strength. Furthermore, coarser size of $Al_2O_3$ particles addition resulted in the lower tensile strength. This may be explained by the fact that smaller size of $Al_2O_3$ particles (in the same $Al_2O_3$ wt.% addition) provided much more uniform dispersion of very fine particles or less particle agglomeration, leading to smaller grain size and/or better resistance to plastic deformation. However, in Figure 9 it can also be seen that the effect of coarser size of $Al_2O_3$ particles was less pronounced for decreasing tensile strength with increasing $Al_2O_3$ addition due to the obtained coarser grain size and more agglomerated $Al_2O_3$ particles.

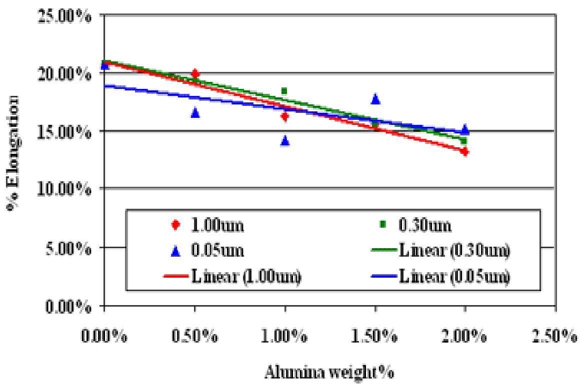


**Figure 7.** The relationship between percent elongation and amount of $Al_2O_3$ particles

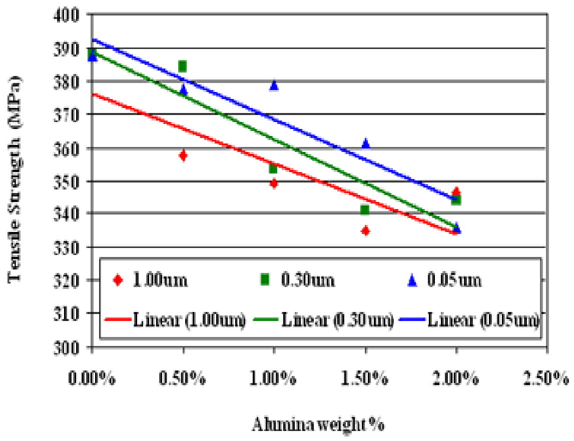


**Figure 8.** The relationship between tensile strength and amount of $Al_2O_3$ particles

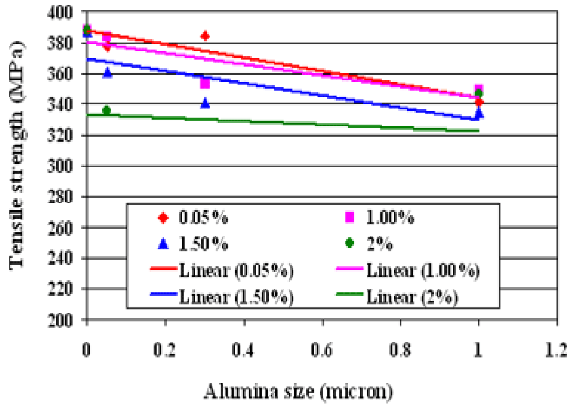


**Figure 9.** The relationship between tensile strength and size of $Al_2O_3$ particles

### *Fractography*

Figures 10 and 11 show representative fractographs of sintered pure 316L austenitic stainless steel powder and 316L powder mixed with $Al_2O_3$ powders, respectively. Conventionally sintered pure 316L shows a distinct cleavage morphology with porosities, which is a characteristic of brittle failure. Similarly, the sintered mixing composites fail through transgranular decohesion.
The inferior mechanical properties in all cases of sintered powders can be attributed to the elongated pore morphology, which acts as a stress-concentration site and leads to premature failure at a relatively lower load. Figure 11 also shows $Al_2O_3$ particles on a fracture surface. The present study therefore underscores the need for fine-tuning the sintering conditions through amount and size of added $Al_2O_3$ powders in a way that does not result in the degradation of mechanical properties.

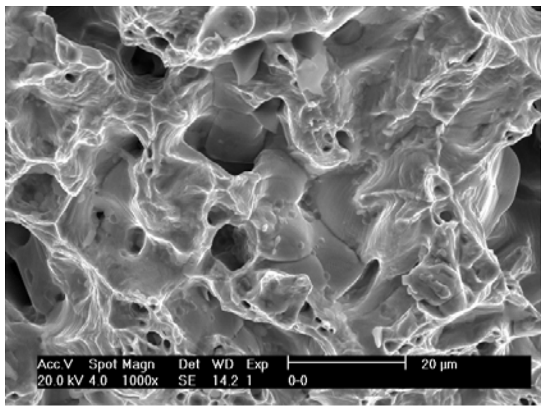


**Figure 10.** Fracture surface of sintered SS 316L tensile specimen

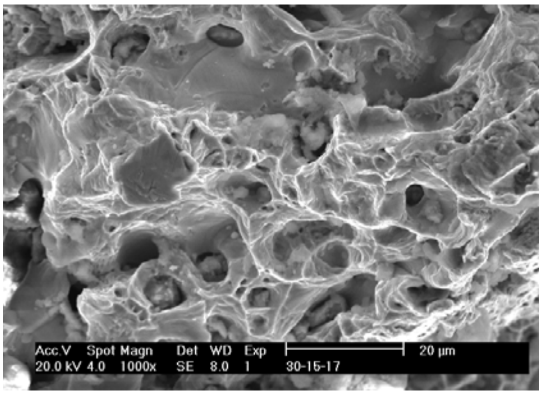


**Figure 11.** Fracture surface of sintered composites SS 316L with $Al_2O_3$ particles tensile specimen

## Conclusions

1. The addition of $Al_2O_3$ powders into the SS 316L matrix resulted in a decrease in sintering density, tensile strength and elongation, but an increase in hardness.

2. The prohibition of sintering by $Al_2O_3$ particle aggregation was attributed to a decrease in strength.

3. The distribution of $Al_2O_3$ particles in the matrix has to be improved to produce better mechanical properties.

4. The composites that have lower weight and better hardness than pure sintered SS 316L might be useful for application as tooling materials (low weight and good hardness) or may be used at low to medium elevated temperatures.

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