FABRICATION AND CHARACTERIZATION OF SS316L –AL_2O_3 COMPOSITES FOR WEAR APPLICATIONS

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Abstract

The low cost and excellent mechanical properties of steel and alumina make them outstanding candidates for fabricating composites for highly demanding wear applications. Therefore, SS316L-Al_2O_3 composites were fabricated using mechanical alloying and powder metallurgy. The microstructure, hardness and abrasive wear behavior were investigated. The final composites consisted of 1-3 μm alumina particles homogeneously dispersed in the SS316L matrix. The porosity, hardness and wear rate were 5.3 vol. %, 1085 HV and 0.004 mm^3 / m, respectively. Compared to SS316L reference steel, the composites showed 9 times increase in hardness and 7.3 times decrease in wear rate. However, they exhibited 5.7 times higher wear rate compared to WC–Co due to lower ceramic content and higher porosity. Improved densification using hot isostatic pressing may result in substantial further improvement. It is concluded that the addition of Al_2O_3 particles, together with optimized powder metallurgy processing can produce low cost steel based composites with excellent wear resistance.

1. Introduction

Increasing the wear resistance and the lifespan of wear components would contribute to reducing maintenance and wear damage costs and ultimately to increasing the equipment efficiency. Ceramic–metal composites are known as excellent candidates to meet this challenge. Machines, equipment and other devices that are designed or adopted for activities such as drilling, cutting, digging, crushing and grinding are subject to harsh application conditions. They are exposed to direct contact with abrasives that are entrapped between the components during operation resulting in 50 % of components failing by wear [1 – 4]. As a result, machines, pumps and other equipment used in such environment can fail prematurely leading to short lifecycles, increased maintenance and replacement costs in addition to loss of revenue in downtime. Therefore, mining components must possess high hardness to prevent wear, excellent hot strength to prevent distortion, sufficient toughness to prevent cracking due to impact, and fatigue strength to prevent failure due to vibrations.

WC–Co is commonly used as a highly wear resistant material in cutting tools, drilling and mining equipment because of its exceptional combination of strength, hardness and wear resistance [5, 6]. However, its toughness and impact resistance are often limited. Therefore, steel components are generally preferred for heavy wear applications such as mining due to their higher toughness and impact resistance.

The presented research focuses on the fabrication of SS316L–Al_2O_3 composites using the powder metallurgy route. SS316L and Al_2O_3 are widely available at low cost making them viable for potential industrial use.

2. Methodology

SS316L steel and Al_2O_3 composite powders were mechanically alloyed using a custom made attritor mill. Steel and alumina initial powders were 44 and 27 μm in size, respectively. The powder-to-powder weight ratio was 1 : 1 while the ball-to-powder ratio was 10 : 1. Mechanical alloying was performed wet at 720 and 800 rpm milling speeds till a homogeneous distribution of the reinforcement in the matrix was attained. Ethanol was used as milling aid and the alloyed powders were dried for 24 h in air. The produced SS316L–Al_2O_3 composite powders were uniaxially pressed in a cylindrical die at compaction pressures ranging between 662 and 863 MPa. Pressureless sintering was performed in a vacuum furnace under argon atmosphere. A heating rate of 12 °C / min was used and the samples were maintained at 1400 °C for one hour. The sintered samples were furnace cooled. The bulk density was determined using the Archimedes principle according to ASTM B311–93 and distilled water. The percentage relative density was obtained by comparing the bulk density to the theoretical density. Microstructural characterization was carried out using a Clemex optical (OM) and a Carl Zeiss scanning electron (SEM) microscopy.

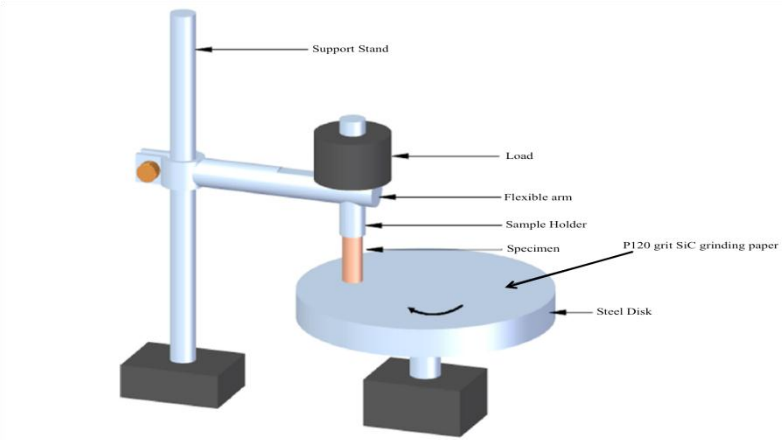

Figure 1. Schematic illustration of the pin-on-disk wear test apparatus [7].

Vickers hardness tests were conducted using a Wilson Beuhler machine and the wear behavior was investigated using a custom made pin-on-disk testing machine as seen in **Figure 1** according to ASTM G132. The pin samples were made to slide against a P120 grit SiC abrasive disk with a linear velocity of 1 m/s and a load of 2 N over a 3000 m distance. The pins were thoroughly cleaned with alcohol and weighed using an electric scale of accuracy ± 0.1 mg to determine the weight loss. The wear coefficient was calculated using the Archard wear Eq. (1) [8]:

$$Q = \frac{KW}{H}, \tag{1}$$

where Q is the volume loss per unit sliding distance, K is the wear coefficient, W is the load and H is the hardness of the pin.

3. Results and discussion

Two sets of SS316L–Al_2O_3 composites were successfully fabricated as summarized in **Table 1**.

Table 1. Summary of fabrication parameters for SS316L–Al_2O_3 composites.

Composites	Vol. fraction Al_2O_3 (%)	Milling speed (rpm.)	Milling duration (hrs.)	Compaction pressure (MPa)	Sinter holding time (mins.)	Sinter temperature (°C)	Sinter atmosphere	Furnace heating rate (°C/min)	Cooling	Particle size (μm)
SET1	67	720	30	794.4	60	1400	Argon	12	Furnace cooling	1-3
SET2	67	800	20	794.4	60	1400	Argon	12	Furnace cooling	1-3

3.1. Microstructure

Figures 2a – d show the microstructural evolution during compaction and sintering. Overall, SET1 samples showed a finer grain structure as well as a more homogeneous distribution of Al_2O_3 particles in the steel matrix, which altogether are known to result in composites with improved mechanical properties for low temperature applications [9 – 11].

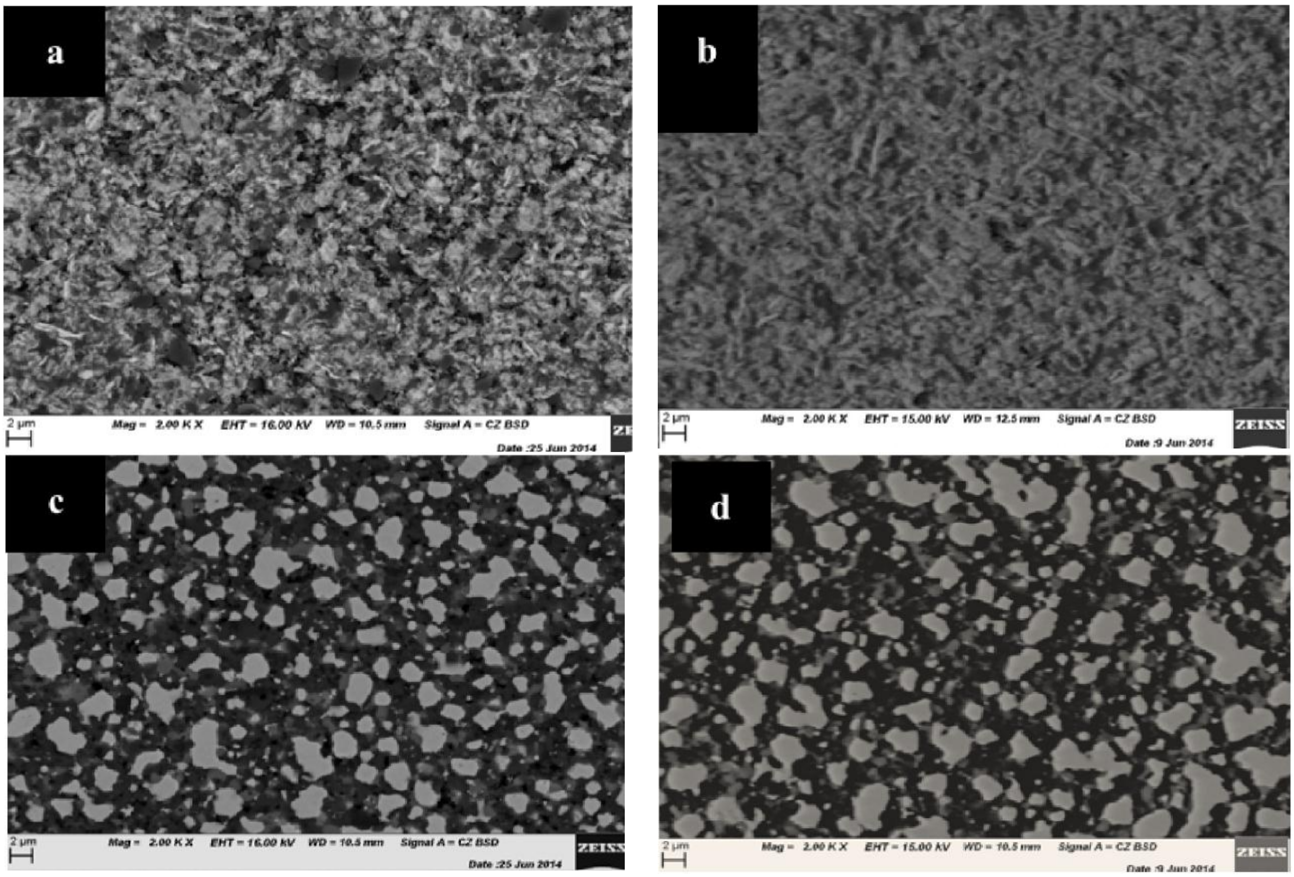

Figure 2. Micrographs of SS316L–Al_2O_3 composites: a) SEM micrograph of a SET1 green; b) SEM micrograph of a SET2 green; c) SEM micrograph of sintered SET1 composite; d) SEM micrograph of sintered SET2 composite.

3.2. Densification and hardness

Figure 3 shows that as the compaction pressure increases, the green and sinter hardness first increases and then decreases with the peak hardness achieved at the optimum compaction pressure of 794.4 MPa. The lower speed milling at 720 rpm together with the longer milling duration in SET1 produces finer Al_2O_3 particles in the steel matrix. This results in the observed increased hardness approximately 1.5 times higher than SET2 samples.

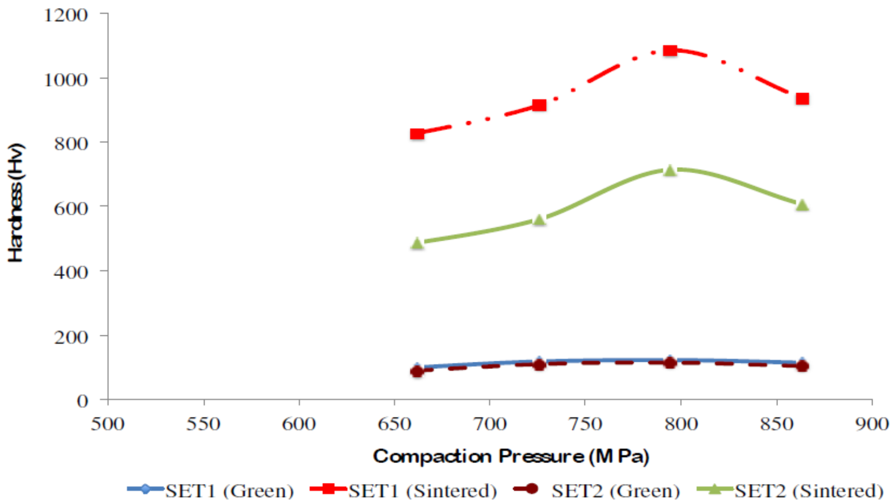

Figure 3. Variation of green and sinter hardness of SS316–Al_2O_3 composites as a function of compaction pressure, milling parameters and sinter conditions.

All sintered samples showed a lower porosity than the green compacts, which illustrates the success of the sinter process. As can be seen in **Figure 4**, milling at 720 rpm produces the lowest porosity. Also, the samples compacted at the optimum pressure of 794.4 MPa showed the lowest sinter porosity of 5.3 %. The porosity decreases up to the peak density due to more advanced closing of gaps between individual powder particles. Beyond the densification peak, further increase in pressure leads to cracking resulting in a decrease in density.

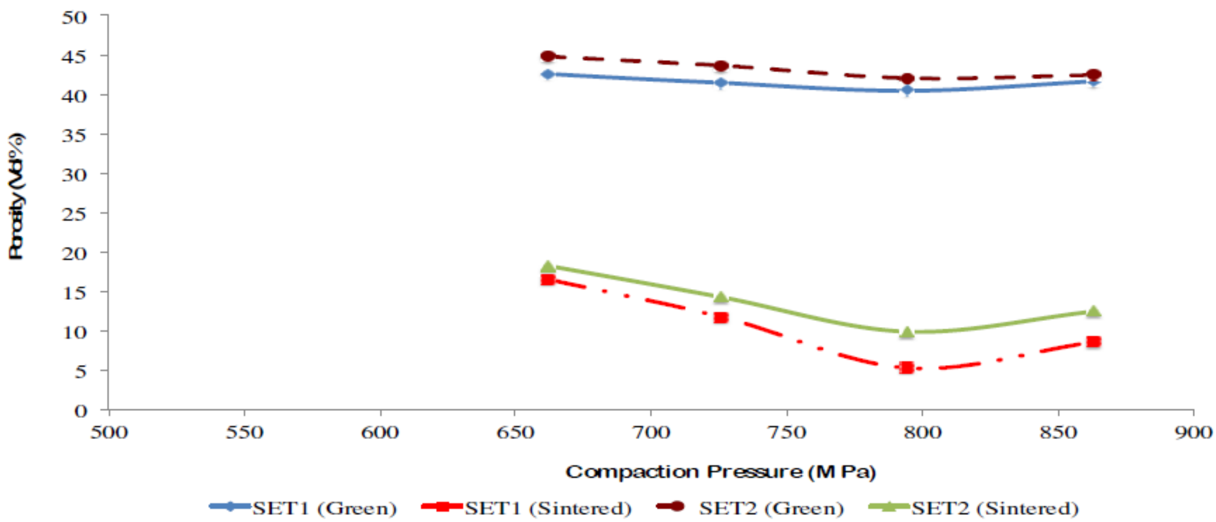

Figure 4. Porosity of green and sintered SS316L–Al_2O_3 composites as a function of compaction pressure, milling speed and sinter conditions.

3.3. Wear behavior

The SEM images in **Figure 5** show scars on composite surfaces following wear testing. The composite wear primarily takes place by slow micro-cutting (see **Figures 5c** and **d**) in contrast to rapid wear of unreinforced steel as illustrated by the deep grooves in **Figures 5a** and **b**. The higher wear resistance of steel-alumina composites is due to their much higher hardness that efficiently limits plug-in of the SiC abrasive particles [12]. **Figure 5d** illustrates occasional dimples observed on some worn composite surfaces as a result of dislodging of some alumina particles or inclusion during wear testing.

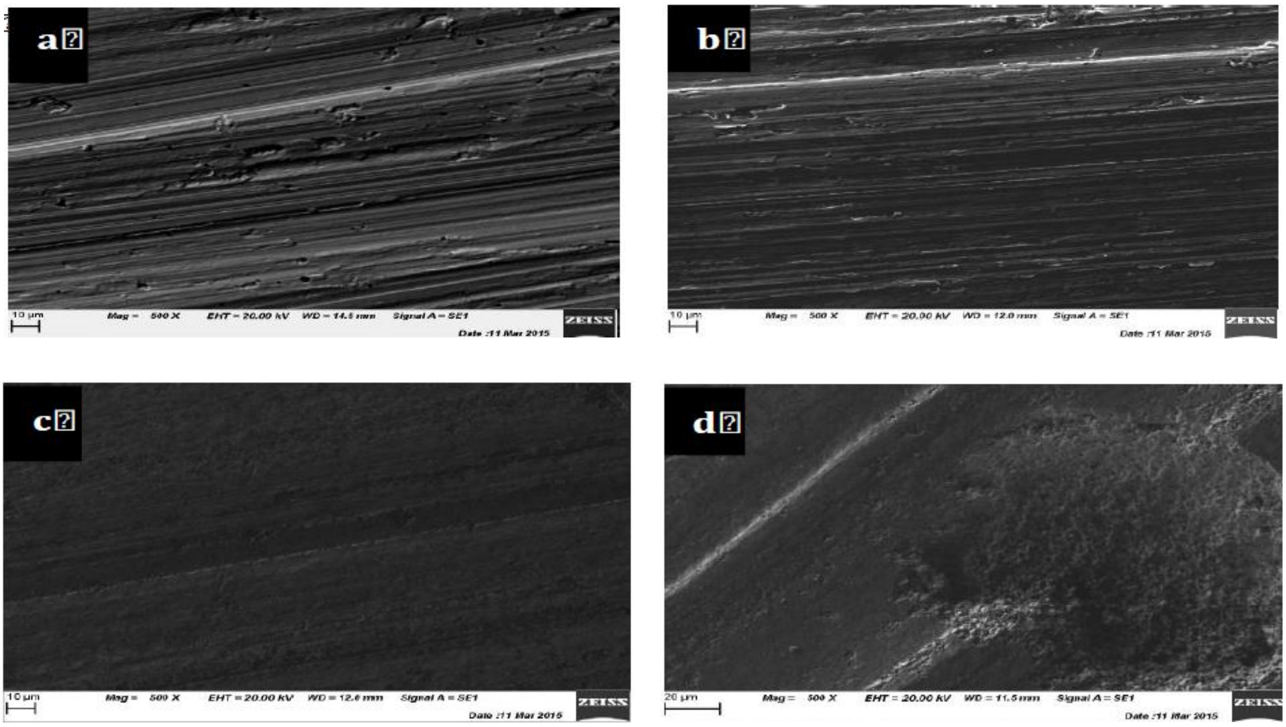

Figure 5. SEM images of worn sample surfaces: a) Fabricated SS316L; b) Commercial SS316; c) SET1 composite; d) SET2 composite.

Figures 6 and **7** show the comparative plot of the wear rates and hardness of the existing materials and fabricated composites (SET1 and SET2). The SET1 and SET2 composites have measured hardness values of 1085.2 and 714.3 HV with wear rates of 0.004 and 0.011 mm^3/m, respectively, compared to commercial SS316 with a hardness of 140 HV, a wear rate of 0.0195 mm^3/m, and unreinforced SS316L with a hardness of 121 HV and a wear rate of 0.0288 mm^3/m as seen in **Figures 6** and **7**. The higher wear rates of unreinforced steel (commercial 316 and fabricated SS316L) are due to their lower hardness compared to the SiC abrasives used for wear testing with a hardness of 2500 HV. The abrasives can therefore remove materials more rapidly from the wear surface [11] by deep plug-in and rapid micro-cutting [12]. The substantially higher wear resistance of the composite is due to the added Al_2O_3 particles and the resulting higher hardness [13], which limit plug-in and micro-cutting [14]. However, compared to commercial 90WC–10Co, 5.7 and 15.7 times higher volume loss was measured for SET1 and SET2 over a sliding distance of 3000 m, respectively. This corresponds to an increase in wear rate by 93.6 to 83 % for SET2 and SET1, respectively. This can be rationalized by the two major differences: First, the used Al_2O_3 particle content of 50 wt. % is much lower than the 90 wt. % WC content in 90WC–10Co. Second, the remaining porosity of 5.3 % or higher observed in the fabricated Al_2O_3–steel composites is much higher than in conventional WC–Co composites. Therefore, it can be expected that more advanced processes such as hot pressing or hot isostatic pressing may further substantially improve the density, the hardness and the wear resistance of the Al_2O_3–steel composites.

The relationship between the hardness and the wear rate is nonlinear [15]. The wear resistance depends on both the hardness and the toughness. As an increase in hardness mostly leads to some reduction in toughness, an optimum balance must be obtained to prevent the material from either being too soft or too brittle.

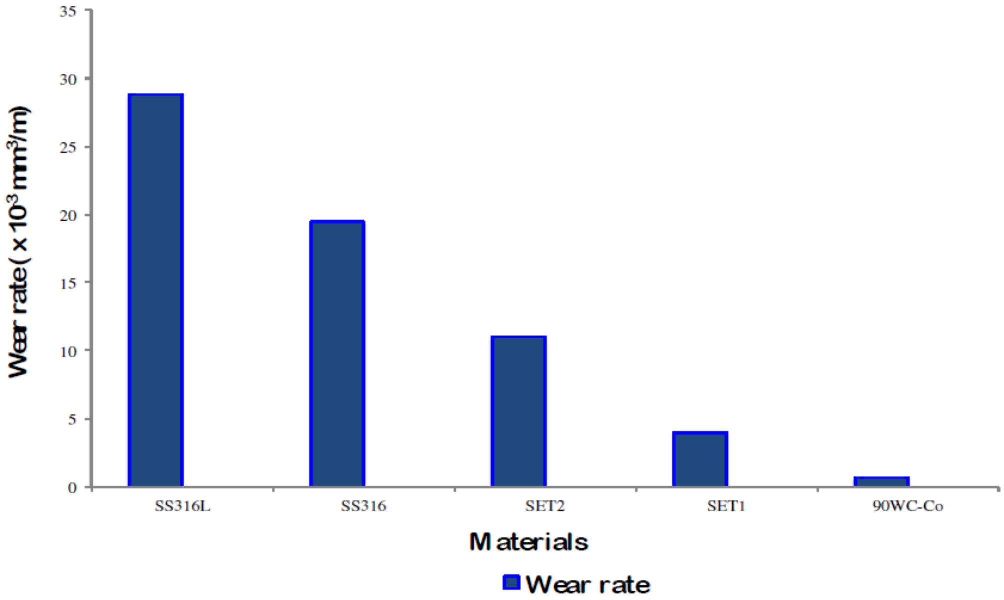

Figure 6. Comparative plot of wear rate of fabricated unreinforced SS316L, commercial SS316, fabricated SS316L–Al_2O_3 composites (SET1 and SET2) and 90WC–Co composites.

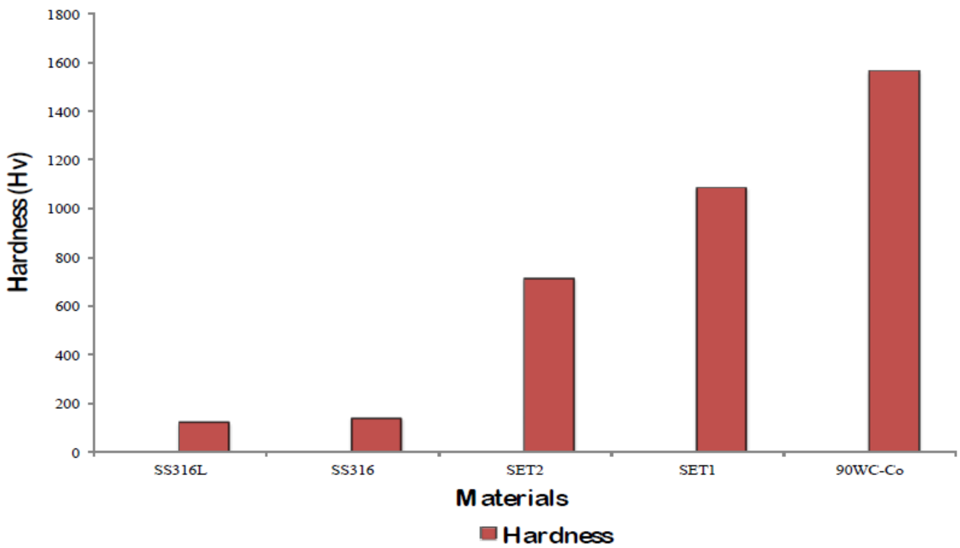

Figure 7. Comparative plot of hardness of fabricated unreinforced SS316L, commercial SS316, fabricated SS316L-Al_2O_3 composites (SET1 and SET2) and 90WC–Co composites.

4. Conclusions

50 wt. % Al_2O_3 and 50 wt. % SS316L steel composites are successfully fabricated using the conventional powder metallurgy technique. The lower milling speed of 720 rpm combined with a longer milling duration of 30 h is more appropriate for the mechanical alloying of SS316L–Al_2O_3 composite powder. The compaction pressure of 794.4 MPa yielded the lowest porosity, highest hardness and wear resistance. The sinter temperature of 1400 °C in an argon environment produced good densification, hardness and wear resistance. The addition of 50 wt. % alumina particles led to up to 86 % reduction in wear rate resulting in up to 7.3 times decrease in volume loss compared to unreinforced SS316L. Due to the remaining porosity and lower ceramic content however, commercial 90WC–Co composites showed about 5.7 times lower wear rate compared to the best SS316L–Al_2O_3 composite samples fabricated so far. Therefore, higher Al_2O_3 contents as well as better densification by hot pressing or hot isostatic pressing are expected to further substantially improve the wear resistance of SS316L–Al_2O_3 composite properties.

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