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Microstructure, Physical Properties and Wear Behavior of SS316L/h-BN Composites

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ABSTRACT

316L stainless steel (SS316L)/hexagonal boron nitride (h-BN) composites were prepared by powder metallurgy method. This was achieved by embedding hexagonal boron nitride powder, as a second phase, into the stainless matrix. The loading of the h-BN powder was varied at 0, 10, 15 and 20 vol. %, and the SS316L/h-BN powder compacts were then sintered in the H_2 atmosphere for 1 h at the sintering temperatures of 1200°C and 1250°C. Density, hardness, wear behavior and microstructure of the sintered SS316L/h-BN composites were monitored. Experimental results indicated that a boride phase formed in the composite microstructure and its volume fraction appeared to increase at the sintering temperature of 1250°C. Dry sliding wear test was performed on a pin-on-disc test rig at the sliding speeds of 0.1 and 0.2 m/s and the varying loads of 1–5 N. The boride phase was found to affect the friction and wear behavior. It was found that wear resistance decreased with improvement of friction coefficient with h-BN addition. Increasing sliding speed also reduced the wear resistance whereas increasing sintering temperature improved the wear resistance and hardness. The specific wear rate of the SS316L/h-BN composites decreased with increasing applied load.

Keywords: *composite, hexagonal boron nitride, powder metallurgy, sliding wear, stainless steel*

INTRODUCTION

Stainless steel parts produced by powder metallurgy are employed in a wide range of applications including aerospace, automotive, hardware, electrical and electronic, medical, agriculture and appliances [1]. One of powder metallurgy method benefits is to combine at least two materials in powdered forms to produce a composite material with promising properties. Addition of hard particles generally leads to improved wear resistance of a composite [2] whereas addition of soft particles is targeted for friction modification and to produce a self-lubricating composite which is applicable for tribological purposes [3-6]. Tribological properties of composite materials are associated with their physical and mechanical properties and microstructures [1, 7]. The tribological properties are greatly influenced by a number of factors, such as, type of testing, test temperature, test speed, applied load, type and loading of secondary materials (additives) and composite fabrication techniques used [5, 6, 8-11]. Previous study [4] suggested that increase of sintering temperature for SS316L/h-BN composites could improve wear resistance which could be explained through the changes in physical and chemical properties of the composites. Wear behaviors and microstructures of the SS316L/h-BN composites are worth for further investigation on other related factors, such as test speed, h-BN content and applied load.

In this work, 316L stainless steel (SS316L)/hexagonal boron nitride (h-BN) composites were prepared and effects of h-BN content, sintering temperature, sliding speed and applied load on density, hardness, and wear on behaviors of the sintered SS316L/h-BN composites were experimentally assessed. Wear mechanism was evaluated from images taken by using by scanning electron microscopy (SEM).

EXPERIMENTAL

The SS316L/h-BN composites in this work were produced by powder metallurgy process. The h-BN powder was added into the 316L stainless steel matrix as a solid lubricant phase with the various volume fractions, ranging from 10 to 20 vol. %. The SS316L/h-BN composites were prepared by mixing water atomized 316L stainless steel powder (Coldstream of Belgium) and h-BN powder (Momentive Performance Inc., USA) using a tumbling mixer. The particle size ranges of stainless steel and h-BN powder were in the range of 45-150 μm and 7-11 μm, respectively. The disc specimens with 30 mm in diameter were produced by cold compaction. With the compaction pressure of 570 MPa, green density of the compacts reached 80% of the theoretical densities. The green specimens were de-lubricated at the temperature of 600ºC under argon atmosphere for 30 min and sintered at temperatures of 1200ºC and 1250ºC under hydrogen atmosphere for 60 min. The green and sintered densities were determined according to MPIF 42 standard. Microstructures of sintered specimens were investigated by SEM. Hardness of sintered specimens was measured by Brinell hardness tester with the spherical indenter of 5 mm diameter and a 306 N load.

Dry sliding wear test of the composites was carried out using a ball-on-disc tribometer. The high chromium steel balls with 7 mm in diameter were used as counterface. Wear tests were performed by varying loads of 1-5 N with sliding speeds of 0.1 and 0.2 m/s at room temperature. The friction coefficient was continuously recorded during the test. The average of four measurements of wear track was used to calculate the wear volume loss and specific wear rate. Worn surfaces and balls were examined through SEM.

RESULTS AND DISCUSSION

Physical properties and microstructure

Table 1 shows sintered density and hardness of the SS316L/h-BN composites at 1200ºC and 1250^{o}C for different h-BN contents. The results suggested that density and hardness decreased with increasing h-BN content, but increased with increasing sintering temperature. Microstructures of sintered stainless steel matrices without h-BN addition at both sintering temperatures showed rounded pores with inter-connection pore networks. Original particle boundaries were observed in microstructures of the stainless steel specimens sintered at 1200°C

(Figure 1a). Sintered neck sizes were increased and particle boundaries were eliminated when sintering temperature of 1250°C was employed (Figure 1b). These experimental evidences may be the reasons for specimen hardness increase when sintering temperature is increased to 1250^{o}C as given in Table 1. [12] Large pores, the sites occupied by h-BN, and strips of boride phase were observed along grain boundaries in the microstructures of the sintered SS316L-20%h-BN composite as given in Figures 1c and 1d. The boride phase is suspected to form by a reaction between h-BN and SS316L stainless steel powder particle surface at sintering temperature equal to or higher than 1200ºC. Dissolution of B in Fe can lower melting points of the Fe-B solid solution as given in the Fe-B phase diagram [13]. During cooling, the melt is converted to boride phase.

Table 1 Density and hardness of SS316L/h-BN composites sintered at 1200ºC and 1250ºC

Composites	**h-BN content (vol. %)**							
	0		10		15		20	
Sintering temperature (ºC)	1200	1250	1200	1250	1200	1250	1200	1250
Sintered density (g/cm^3)	7.24	7.21	6.84	6.84	6.52	6.56	6.23	6.52
Hardness (HB)	49.03	50.95	33.65	46.12	20.23	28.29	12.68	17.55

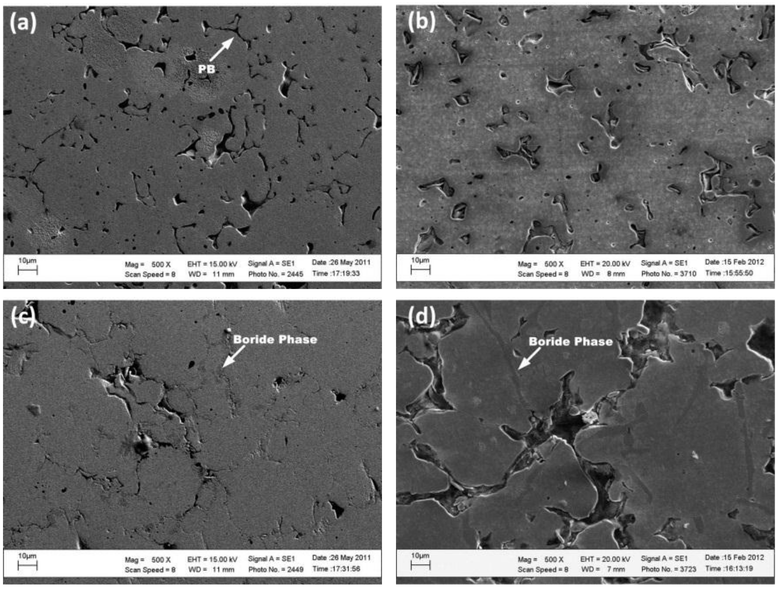

Figure 1: Microstructure of SS316L/h-BN composites
(a) 316L sintered at 1200ºC, (b) 316L at 1250ºC, (c) 20%h-BN sintered at 1200ºC and (d) 20%h-BN sintered at 1250ºC

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Wear behavior

Effects of sintering temperature and sliding speed on volume loss of the sintered stainless steel and the sintered SS316L/h-BN composites with 20% h-BN are shown in Figure 2. For the effect of sintering temperature, the volume losses of the sintered stainless steel at two different temperatures were very similar whereas those of the sintered SS316L/h-BN composite were lower with increasing sintering temperature. This is attributed to better sintering of the SS316L/h-BN composites at 1250^{o}C. Improved sinterability is evidenced by the increased neck sizes, associated with more boride phase occurring in the composites sintered at 1250^{o}C [14]. The volume loss for the sintered SS316L/h-BN composite was greater than that of the sintered stainless steel. This is due to the fact that h-BN is relatively soft as compared with the stainless steel and h-BN itself is difficult to be sintered [15]. In addition, h-BN particles added into the composite can prohibit sintering between stainless steel powder particles. Sintering prohibition results in poor bonding and poor wear resistance. It was also found that the volume loss generally increased with increasing applied load as one would expect. For the effect of sliding speed, increasing sliding speed resulted in greater volume losses for both unfilled sintered stainless steel and the sintered SS316L/h-BN composites.

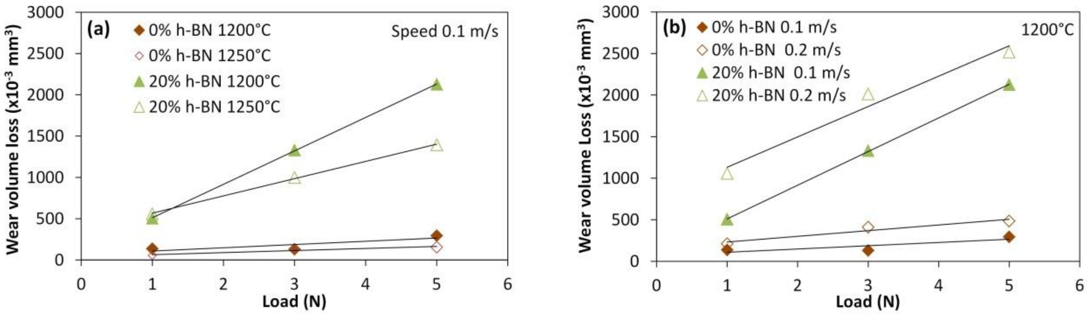

Figure 2: Wear volume loss of composites as a function of applied load
(a) Effect of sintering temperature, (b) Effect of sliding speed

Effects of sintering temperature and sliding speed on specific wear rate of the sintered stainless steel and the sintered SS316L/h-BN composites with 20% h-BN are shown in Figure 3. It can be seen that the effects of sintering temperature and sliding speed on the specific wear rate corresponded well to those on the volume loss as given in Figure 2. However, the specific wear rates of both the sintered stainless steel and the sintered composites were surprisingly found to decrease with increasing applied load. One interesting aspect to mention is that the effect of sliding speed appeared to be more pronounced for the wear intensity of the sintered SS316L/h-BN composites as compared with the sintered stainless steel.

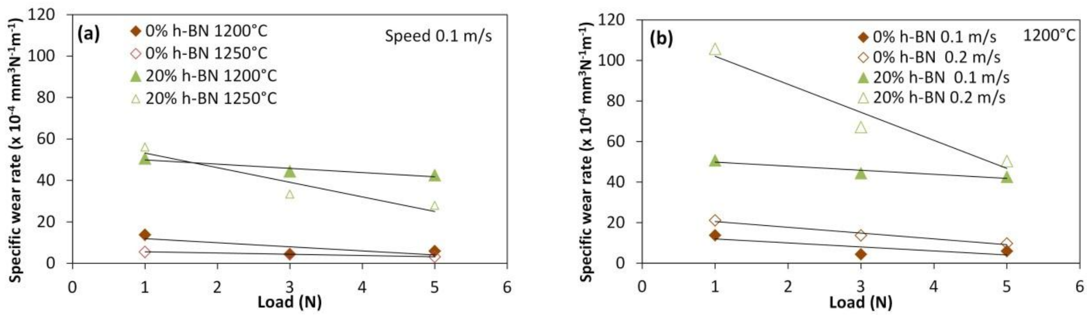

Figure 3: Specific wear rate of composites as a function of applied load.
(a) Effect of sintering temperature, (b) Effect of sliding speed

For materials sintered at two temperatures, variation of friction coefficients with testing distances using 3 N loads is given in Figure 4. Friction coefficient of the SS316L/20vol% h-BN sintered at 1250ºC was higher than that sintered at 1200ºC. The friction coefficients of the sintered SS316L/h-BN composites were lower than that of the sintered stainless steel. This confirms the lubricating properties of the h-BN.

SEM images of the typical worn surfaces of the sintered stainless steel and the sintered SS316L/h-BN composites are shown in Figure 5. For the sintered stainless steel, fine particles and smooth compacted layer of wear particles were found on the worn surfaces at the sliding speed of 0.1 m/s as (Figure 5a). There were plastic deformations on the compacted layer and cracks perpendicular to the sliding direction on the worn surfaces at the sliding speed of 0.2 m/s (Figure 5b). This is why the volume loss and specific wear rate for the sintered stainless steel at the sliding speed of 0.2 m/s is greater (see Figures 2b and 3b). In the sintered SS316L-20 %h-BN composite at h-BN 20%, fine wear debris and h-BN powder and deformed grains on worn surfaces were found at sliding speed of 0.1 m/s (Figure 5c). Highly deformed grains, abrasive furrow marks and h-BN phase cracks and delaminations were generated on the worn surfaces at the sliding speed of 0.2 m/s (Figure 5d). This is why the volume loss and specific wear rate of the composites at higher sliding speed (0.2 m/s) is greater (see Figures 2b and 3b).

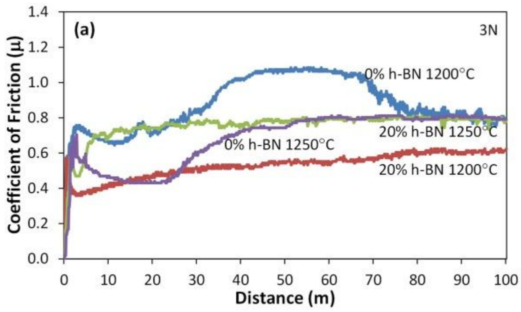

Figure 4: Friction coefficient as a function of sliding distance under applied load of 3 N using sintering temperatures of 1200 and 1250°C

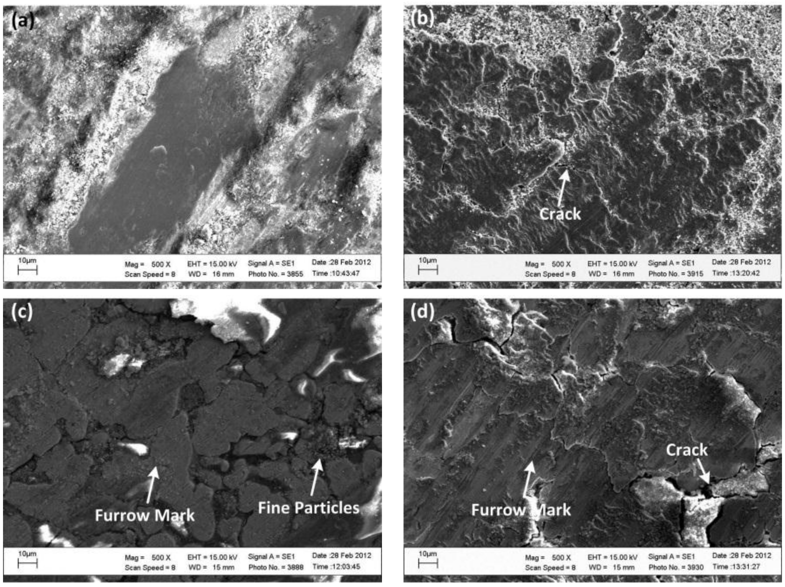

Figure 5: Worn surfaces of SS316L/h-BN composite sintered at 1200ºC with applied load of 3 N.
(a) 316L sliding at 0.1 m/s, (b) 316L sliding at 0.2 m/s,
(c) 20vol% h-BN sliding at 0.1 m/s (d) 20vol% h-BN sliding at 0.2 m/s

CONCLUSION

The wear behavior of sintered stainless steel and sintered SS316L/h-BN composites sintered at 1200°C and 1250°C against the high chromium steel ball was studied. The experimental results demonstrated that the density and hardness decreased with increasing h-BN content, but improved with increasing sintering temperature. Addition of h-BN in stainless steel reduced the wear resistance with a reduction of friction coefficient. Increasing sliding speed appeared to deteriorate the wear resistance, but the opposite effect was found with increasing sintering temperature. The specific wear rate of the sintered SS316L/h-BN composites decreased with increasing applied load. The wear mechanism of the sintered stainless steel and the sintered SS316L/h-BN composites involved adhesive, abrasive and delamination phenomenon, especially at high sliding speed.

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