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Tribological properties of carbon fiber-reinforced aluminum composites processed by spark plasma sintering

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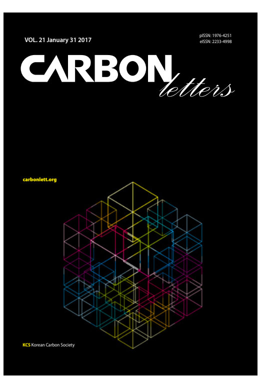

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The development of light-weight and high-strength materials have gained attention to meet the ever-growing demands for safer and fuel-efficient automobiles. Thus, the importance and applications of composite materials are gradually increasing [1]. In the field of metal-matrix composite manufacturing, reinforcing agents are added to the metal matrix in the form of powders, whiskers, and fibers to improve the mechanical properties of metals [2]. Fibers have been used since the 1950s as structural reinforcements to develop metal-matrix composites. However, the improvements in physical properties in terms of high strength under extreme conditions have not yet been achieved. Thus, research into versatile reinforcements such as carbon fibers (CFs) has been conducted. Choi et al. [3] developed and processed CFs from polyacrylonitrile precursor materials. The resulting polyacrylonitrile-based CFs are still used in a wide-variety of applications since they exhibit excellent elasticity with strength 10 times higher and density 1/5 less than those of steel. Aluminum (Al), on the other hand, is commonly used as an engineering material since it is abundant on the earth's crust and is lightweight (2.7 g/cm^3). Additionally, it can easily form an alloy with other metals at low or high temperatures with high ductility and corrosion resistance [4].

In practical applications, metal-matrix composites have failed to demonstrate promising results in terms of high strength and tribological properties. Such challenges arise from issues with uniform distribution of reinforcing agents throughout the metal-matrix during processing. Thus, most of the research and studies have focused on the homogenous features of metal-matrix composite processing to improve the tribological behavior. For instance, it has been confirmed that dispersing CFs throughout the polymer [5,6], ceramic [7-9], and metal [10-13] matrices reduce the overall friction coefficients and wear rates. While most research has emphasized the importance of processing parameters (such as wt% of CF in the matrix) in achieving low friction traits, it is also crucial to study the influence of structural modifications on the mechanical properties of composites. This is because one could easily assume that low-fiction materials exhibit a low shear strength (e.g., graphite). However, that is not the case for CF-reinforced Al composites. Godet [14] have suggested an alternate scenario of friction characteristics being involved in the formation of third bodies (phases) by using two parent materials [15]. The third bodies are usually shown as a thin film produced by the friction between the two parent materials; they accommodate the relative motion between the two bodies by transmitting stress. Thus, the formation of third bodies (transfer films) is a key to improving the overall tribological properties of CF-Al composites.

In this study, CF-Al composites were produced through spark plasma sintering (SPS). The SPS method has the advantage of preventing grain growth during the high temperature sintering process. Thus, the mechanical properties of the sintered material is improved. Here, the SPS was carried out under vacuum where the time for sintering is noticeably faster than the conventional methods. The ball milling process was used to uniformly disperse CFs throughout the Al particles. Afterwards, we analyzed the synthesized CF-Al composites with the hardness measurements. To evaluate the tribological properties, a ball-on-disk test was carried out to study the friction and wear behavior.

Mixed CF and Al composite powders were prepared with ball milling (BML-2; DAIHAN Scientific, Korea) and subsequently molded with SPS. First, Al powders (~50 μm; Changsung, Korea) were mixed into the chamber with T-700 grade CFs (3 mm length, 4 μm diameter) by 0, 5, 10, and 20 wt% by mass. Afterwards, zirconia balls milled the mixed powders with 15:1 ratio at 250 rpm for

72 h to prepare a CF-Al composite powder. During the ball milling process, the aspect ratio of CF decreased, while the average length of the CFs was crushed down to 50 μm or less. Furthermore, the shredded CFs were imbedded throughout the surface of Al particles due to repeated cold welding during the process. After ball milling, the composite powder was placed inside a graphite mold (30 mm diameter) for SPS.

The raw sintering powders were applied with pressure, heat, and electrical power below the melting temperature. Subsequently, the powders bonded and formed into a single sintered body. Hydraulic press was used to apply pressure (10 MPa) at room temperature for 60 min. Subsequently, the pressure was increased to 42 MPa while the temperature was raised at a rate of 50°C/min to 500°C. The sintering was carried out for 10 min once the composite powder reached 500°C.

For the microstructure characterization, scanning electron microscopy (SEM; VERIOS 460L, FEI, USA) was used to image the ball milled powder and the sintered surface of the CF-Al composite. A Vickers hardness tester (HM-200; Mitutoyo, Korea) was used to determine the hardness of the CF-Al composite. Accordingly, 0.05 kgf was applied to the sintered surface using the diamond indenter. A ball-on-disk friction test was carried out to acquire the wear properties of the composite. For the wear test, the coefficient of friction was obtained by spinning alumina balls (4 mm diameter) at 0.12 m/s under 30 N for 30 min. Afterwards, the mass of the composite was calculated by measuring the amount of wear. Fig. 1 illustrates the schematic of the wear test used in this experiment.

Fig. 2 shows the surface of the CF-Al composite synthesized by SPS; the SEM images confirm that the CFs are evenly dispersed on the Al. In Fig. 3, the hardness of the 5 wt% CF-Al composite was measured to be about two times higher than pure Al-sintered material. Therefore, it is confirmed that CFs, in combination with Al, act as reinforcing agents to improve the physical properties. There are several strengthening mechanisms that affect the Al-based matrix, including grain refinement, precipitation hardening, dislocation density, and strengthening employment. The composites from each mechanism differ in terms of the CF and Al volume ratio. However, it can be assumed that the strength of the Al matrix is comparable for each type of composite structure. Therefore, the improvement in strength can be confirmed through the strength

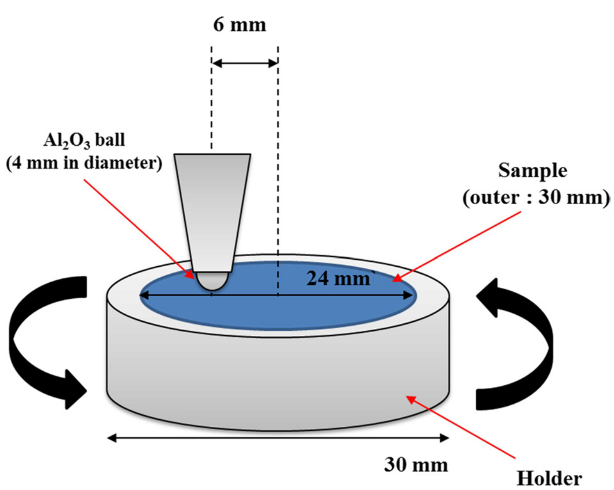

Fig. 1. Schematic illustrating the friction test.

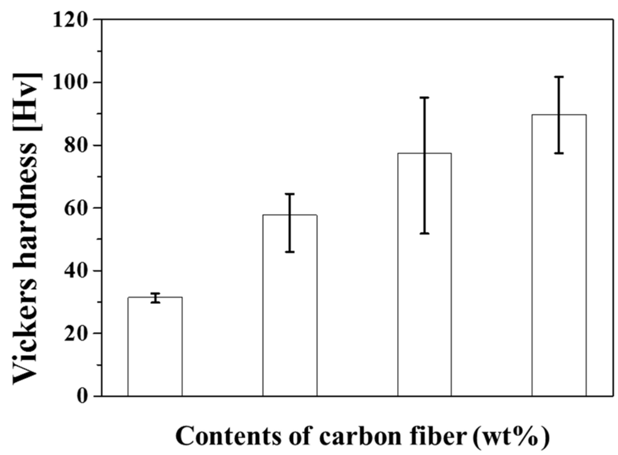

Fig. 3. Vickers hardness measurements of each carbon fiber content.

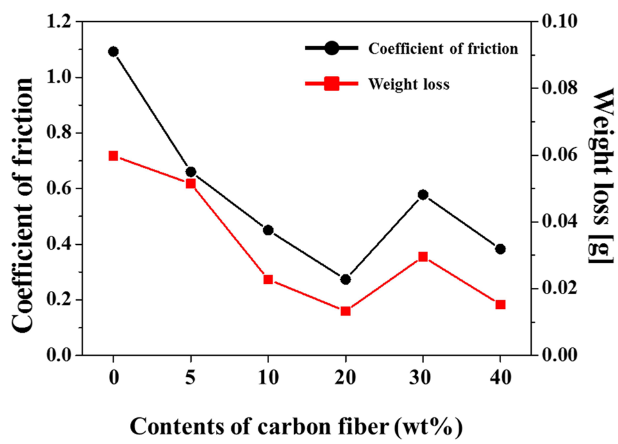

Fig. 4. The average coefficient of friction and weight loss of each carbon fiber content.

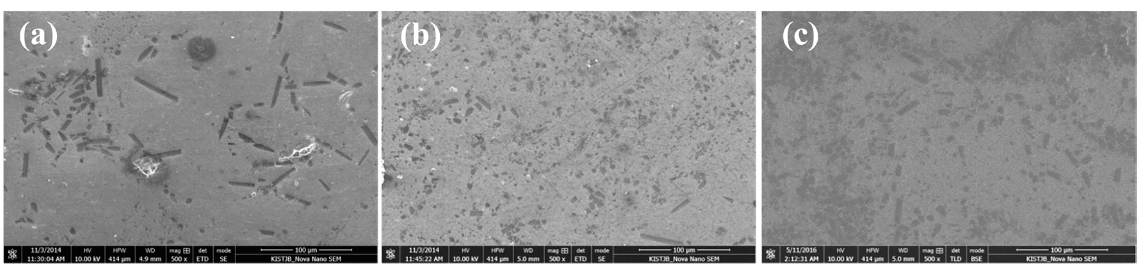

Fig. 2. Scanning electron microscopy images of the sintered surface displaying the distribution of carbon fibers: (a) 5 wt%, (b) 10 wt%, (c) 20 wt%.

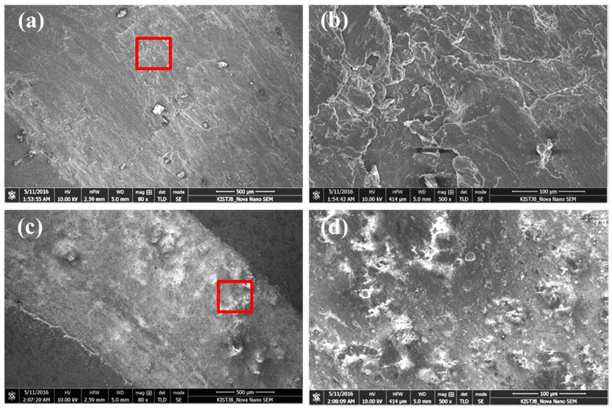

Fig. 5. Scanning electron microscopy images analyzing the surface of (a, b) the pure Al and (c, d) the 20 wt% after the wear test. (b, d) represent higher magnifications for (a) and (c), respectively (marked with red squares).

theory for the sintered CF-Al composite. Fig. 4 displays the coefficient of friction and the amount of wear acquired from the wear test. It is observed that the coefficient of friction, as well as the wear, tends to decrease as the mass ratio of CFs increases.

In order to confirm the existence of a transfer film (third phase body), SEM analysis was carried out. Fig. 5 shows the rough and highly worn morphologies presented on the surface of the sintered Al (Fig. 5a and b). In the case of 20 wt% (Fig. 5c and d), the worn area is noticeably less severe in terms of roughness. As a result, it is confirmed that a protective wear layer (transfer film) was formed during the test. Therefore, it is determined that the complex distribution of CF forms a layer on the surface of the sintered body during wear, which reduces the coefficient of friction.

Mechanical properties and friction characteristics were investigated to determine the tribological behavior for CF-Al composites. CFs exhibit high strength and low density while Al demonstrates excellent formability. Thus, they can be used in various applications. The advantages of these two materials could be applied to any automobile component that is subject to a high amount of wear such as gears, pistons, and bearings. For this reason, we carried out experiments using different amounts of CF content in the Al matrix. In this study, we used SPS to prepare CF-Al composites measuring 5, 10, and 20 wt% of CF reinforcements. Subsequently, we tested and analyzed each composite with respect to their frictional characteristics. We observed that the improvements in hardness and the reduction in the wear of the composites depend heavily on the content of CF. In terms of the microstructures of composite materials, the grain is generally refined with increasing contents of reinforcement [16]. Although grain size was attributed to changes in the friction coefficient, the tribological property is dominantly governed more by the lubricous carbon filler than the grain size of matrix [17,18]. Additionally, it is confirmed that the 20 wt% composite demonstrated the best wear performance with the lowest coefficient of friction. Therefore, it is concluded that the improved wear performance is attributed by the formation of a protective wear layer on the surface of the sintered body. With the improved hardness and wear performance of the CF-Al composites, we anticipate that our sintered materials can be used for applications requiring high abrasion-resistance.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

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