Analysis of wear difference according to surface morphology under 3-body abrasion test

Yong Seok Choi*, Kyeongryeol Park *, Seongmin Kang*, Unseong Kim*, Kyungeun Jeong* and Kyungjun Lee*

* Department of Mechanical Engineering, Gachon University, Gyeonggi-do 13120, South Korea,

1. Introduction

Mechanical durability is one of the major factors determining the performance of engineering materials, and wear resistance is an important property to ensure long-term uses, which can lead to economic efficiency [1-2]. Hence, extensive research efforts have been focused on enhancing and evaluating the wear resistance of materials over several decades. Previous approaches to improve wear resistance include thin-film coatings on material surfaces with nitride-based films that possess excellent anti-wear properties. Examples of the films include chromium nitride, aluminum nitride, vanadium nitride, and diamond-like carbon. However, the use of these thin-films can result in surface damage when exposed to harsh environments such as high operating temperatures, which leads to significant wear. Hence, stable materials with favorable hardness are required for coatings, but this can be costly. In addition, the process of depositing thin-films using sputtering makes it difficult to evenly cover surfaces that are not flat, like those with three-dimensional shapes, which hinders real-world applications. Furthermore, the detachment of the deposited films from the surfaces can significantly decrease the strength and durability of the target materials. Surface modifications have been suggested as methods to improve the mechanical durability of materials by enhancing surface mechanical characteristics, which allows for an improvement in wear resistance. In addition, surface-modified materials are basically homogenous, effectively addressing a concern related to delamination, which is one of the major problems affecting mechanical durability. These surface treatment methods can enhance durability and endow additional functionalities onto the surface, thereby expanding their functional applicability. These functionalities broaden the range of material applications, such as oil-water separations, robust heat exchangers, and energy harvestings. However, it should be noted that the presence of micro/nanostructures formed after surface modifications can trigger mechanical deformation due to stress concentration under mechanical stimuli, resulting in weakened mechanical robustness. Wear, which induces substantial shear stress on micro/nanostructured surfaces, is a major factor in the failures of engineering materials. Therefore, there have been many efforts to improve mechanical durability by reducing wear. However, few attempts have been made to develop surface treatment methods to increase wear resistance due to limitations in experiments and simulations. Optimal design of surface morphologies potentially improves wear resistance since tribological behavior can vary depending on the morphologies, but there is little research on this topic. Here, we have experimentally and theoretically studied the wear behavior, including wear resistance and mechanism on meso-scaled structures that are formed using 3D-printing method. Our study used 3D-printed structured surfaces using high-impact polystyrene (HIPS), known for its excellent reproducibility, heat resistance, and mechanical properties. Wear tests were performed using a self-developed 3-body wear tester to evaluate wear behavior depending on the surface texture. After the wear experiment, the mass loss of the samples was measured, and surface changes were investigated through scanning electron microscopy (SEM) and confocal profile images. The experimental results show that the optimal structures enable controlling the flow of abrasive particles, resulting in a significantly improved wear resistance; the wear rate can be reduced up to 77 % by meso-scaled structures. Additionally, to verify the reliability of the wear experiment, DEM (Discrete Element Method) simulation was used to compare and evaluate the experimental values. The results of the simulations were found to be in good agreement with the experimental outcomes.

2. Experimental procedure

The samples were fabricated using a 3D printing machine (CUBICON Single Plus 310) with High Impact Polystyrene (HIPS) filament. The three designs are: (1) The smooth surface without any patterns (SS), (2) Surface with uniformly distributed Pits (SP) with a hole diameter of 3 mm, and (3) Surface with uniformly distributed Bumps (SB) with a spherical diameter of 3 mm, with a conical shape of 35.64 mm in height and 22 mm in width. After the wear test was completed, the samples were cleaned by blowing air on the samples for 30 seconds using an air gun to remove any remaining wear particle powder on the surface. After cleaning, the samples were weighed using a precision electronic balance to determine the weight of the sample lost to wear compared to the weight of the sample before the wear test. The results were then compared to the EDEM program's analysis to ensure reliability. After the wear test was completed, the samples were cleaned by blowing air on the samples for 30 seconds using an air gun to remove any remaining wear particle powder on the surface. After cleaning, the samples were weighed using a precision electronic balance to determine the weight of the sample lost to wear compared to the weight of the sample before the wear test.

3. Results and discussion

All seven experiments confirmed the same wear trends, with SS, SP, and SB tending to show the highest weight loss in that order (Fig.1). This is because SS has a high amount of wear due to even and deep wear on all surfaces because there is nothing to reduce the contact with the wear particles, while SP has a relatively small amount of wear particles in contact with the surface in the grooves that are dug into the surface, so the overall amount of wear is less than SS. In the case of SB, the part of the groove that protrudes and encounters the flow of wear particles is highly worn, but it seems that the wear particles do not reach the back of the groove after the particle collision and spread outward. Furthermore, the spreading of the wear particles to the outside resulted in less and less overall wear towards the back of the sample, resulting in a lower final wear amount. To verify the change in wear rate in the simulation, Altair's EDEM simulation results were compared to the experimental results. The comparison of weight loss due to wear showed similar results to the actual experimental results (Fig. 1). In the case of the actual experiment, the SS sample lost 0.109g, the SP sample lost 0.059g, and the SB lost 0.025g over a period of 3 hours, showing a 46% and 77% reduction in wear loss for UPDS and SB, respectively, compared to the SS wear loss. In the case of EDEM simulation, the SS sample lost 0.097g, the UPDS sample lost 0.050g, and the SB sample lost 0.038g over a period of 3 hours, and the SP and SB lost 48% and 61% of the SS wear loss (Fig. 2), respectively, showing a similar trend to the actual experiment. When comparing the wear degree on the top and bottom surfaces, the top surface tended to be worn only on the top surface in both the experiment and the simulation.

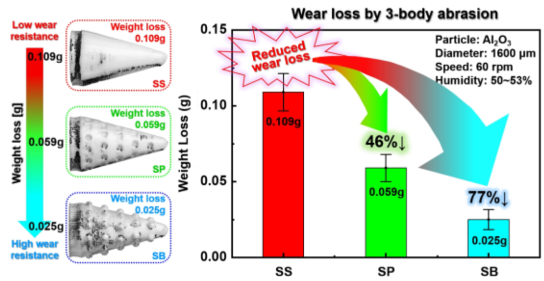

Fig. 1 Average weight loss of the samples after the wear test using 6.5 kg soils

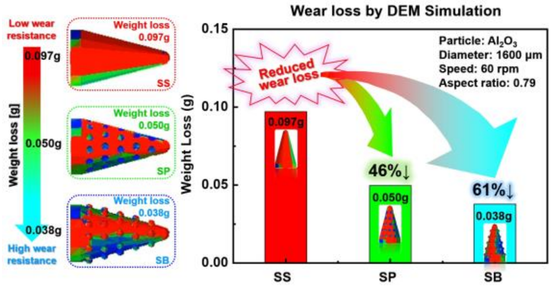

Fig. 2 Weight loss of the samples after DEM simulation

Conclusion

In the experiments, Smooth Surface (SS) was identified as having the poorest wear resistance, and the wear volumes for Surface with uniformly distributed Pits (SP) and Surface with uniformly distributed Bumps (SB) samples were reduced by 46% and 77%, respectively, compared to the SS sample. This is because the flow pattern of sand varies depending on the surface texture, and it was confirmed through experiments with three types of samples that there was a difference in the amount of wear. In particular, surface protrusions were found to reduce surface wear because they impede particle movement significantly. In 3-body abrasive wear, it can be seen that the surface roughness tends to decrease as the amount of wear increases gradually. This can be judged as sand particles leading to polishing wear, and it was confirmed that in areas where the surface roughness is high, small-sized particles become stuck on the surface and turn black. On the other hand, in areas where the wear was severe, the surface became smooth and sand could not be trapped, showing a white surface. The simulations also confirmed the same trends observed in the experimental results, thereby establishing reliability and identifying the correlation between surface texture and abrasive particles. Surface morphologies determine wear behavior and change in the flows of abrasive particles: For the SS case, no structures on the material surface disturb the flow of abrasive particles. Hence, kinetic energy is high when in contact with the surface, resulting in high abrasion. In addition, the contact area between the particles and the surface is large, which leads to significant abrasion. On the other hand, it is difficult for the abrasive particles to wear the material on SB because protruded structures have lowered the particles' energy due to the disturbed particles' flow by collision between bumps and particles. Furthermore, collisions between abrasive particles lead to their kinetic energy loss by increasing the compressive stress of the particles, resulting in reduced wear.

Reference

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