Wear Transition in Alumina and Silicon Carbide Ceramics During Sliding

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Abstract—Sliding experiments have been conducted on alumina and silicon carbide ceramics. Wear and friction data of both materials indicate that wear proceeds in two distinct stages. The wear occurs by a relatively mild plastic-grooving process in the initial stage, but eventually gives way to a severe grain pull-out process after a defined period of sliding test. The datails of the transition mechanism are presented. The effects of grain size and second phase particle on the wear transition are also presented.

Key words : Wear transition, Alumina, Silicon Carbide, Mechanism, Residual stress

1. Introduction

Ceramic materials, because of their outstanding mechanical and physical properties, are increasingly being considered in various tribological applications. However, several concerns need to be addressed before they can be widely utilized. One of these concerns is wear mechanism. Therefore, I have investigated the wear mechanisms occurring during sliding in alumina and silicon carbide caramics which were selected as model materials. Most important thing I have found in the investigation is the fact that the wear prodeeds in two distinct stages even under constant sliding conditions, i.e., constant loads and sliding speeds. Initial stage of wear is characterized by plastic grooving process while the final stage is characterized by grain pull-out process. The wear transition from relatively mild grooving process to severe grain pull-out process has an important practical implication because the transition can result in an abrupt change from acceptable to catastrophic wear. In this paper, the details of the wear transition mechanism will be presented. Based on the transition mechanism, it is expected that inherent residual stress is harmful for the wear resistance, though it improves fracture toughness. The effect of grain size and second phase particles will also be presented and discussed in the light of the residual stress.

2. Experimental procedure

Materials studied were alumina and silicon carbide ceramics. Three aluminas with different grain sizes (grain size, 4, 8, 20 μm) and three silicon carbide ceramics with different microstructures (i.e., solid state sintered silicon carbide with B_4C additive, liquid phase sintered silicon carbide with Al_2O_3 additive and TiB_2 particulate reinforced silicon carbide with Al_2O_3 additive, respectively) were prepared by hot pressing.

Sliding wear tests were conducted on disk samples of 6.4mm diameter and 1.5mm thickness using a ball-on-three-flat contact configuration [1,2]. Prior to testing, the test surfaces of the disk samples were polished using diamond paste, finally with 1μm paste. A ball of 12.7mm diameter rotates at 100rpm (giving a linear sliding speed of 0.04m/s) on three flat disk samples, which are aligned with their surface normals in tetrahedral coordination relative to the rotation axis of the ball. Commercial silicon nitride and silicon carbide balls were used for alumina and silicon carbide ceramics, respectively. Paraffin oil was used as lubricant.

3. Results and discussion

3-1. Alumina

Fig. 1 shows the wear data for 4 μm grain size alumina. Logarithm of wear scar diameters are plott-
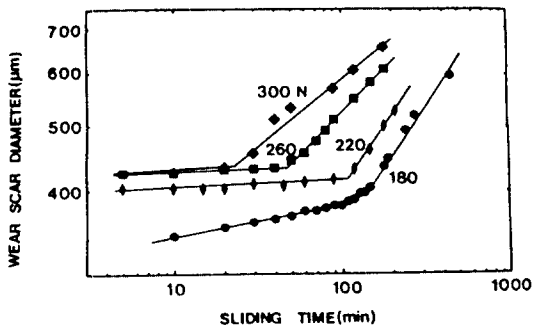
Fig. 1. Change of wear scar diameter as a function of sliding time. Note the abrupt change in slopes of wear curves indicative of two stage wear behavior. Numbers shown are applied loads.
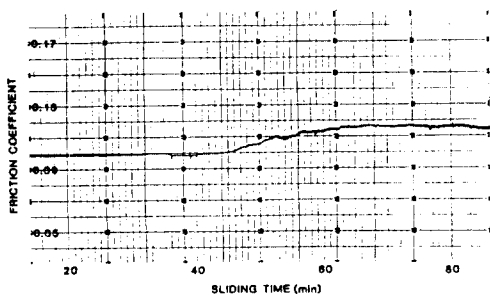

Fig. 2. Typical change of friction coefficient as a function of sliding time.

Fig. 3. Micrographs showing wear surface typically produced (a) before and (b) after wear transition.

ed against logarithm of sliding time for each applied load. Under all conditions, the slope of wear curves increases abruptly after a definite sliding time, indicating that an abrupt change in wear mechanism occurs during the period of the sliding tests.

In addition to the wear data, friction curves also give an indication of the transition in wear behavior. Fig. 2 shows a typical change of friction coefficient during the test as a function of sliding time. A modest but definite increase in the steady state value of the friction coefficient occurs during the period of testing. This change in friction coefficient invariably coincided with the observed change in wear rate.

Examination of the alumina wear surfaces after various periods of wear confirmed that the observed changes in friction and wear rate behavior related to a fundamental change in the process of wear. Fig. 3(a) and (b) show wear surfaces typically produced before and after the wear transition, respectively. During the initial stage of wear, the wear surface is primarily characterized by the presence of fine
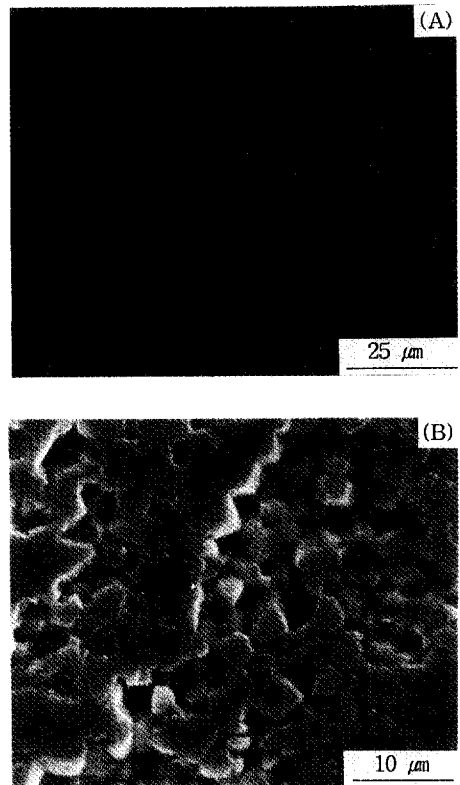
scratches or furrows in the direction of sliding (Fig. 3(a)). In contrast, prolonged sliding ultimately resulted in rough, irregular wear surfaces (Fig. 3(b)). The onset of appreciable material removal coincides with intergranular fracture such that grain pull-out occurs.

The result showing that the grain pull-out occurs only after a definete period of the test indicates that a damage accumulates during the test. Examinations of the wear surface just prior to the transition give a clue to this damage. As shown in Fig. 4, optical examination of samples from tests interrupted just prior to the transition revealed the presence of subsurface intergranular cracking, which is evidenced by specular reflection from isolated regions whose size and shape corresponded to the grain structure of the alumina. The wear surface observations thus suggest a process by which relatively mild wear leads to the initiation of subsurface cracks which then propagate to the surface resulting in whole grain pull-out and extensive wear.

Fig. 4. Wear surface observation illustrating the development of subsurface grain boundary cracking just prior to the wear transition. Note white spots which reveal subsurface grain boundary cracks.
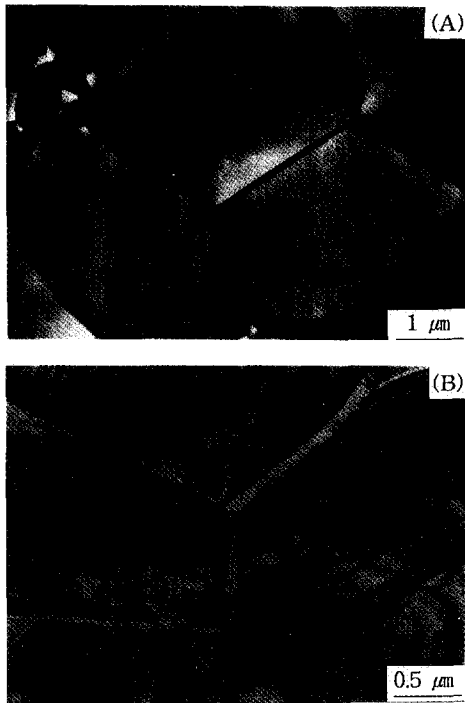

Fig. 6. Wear data for different grain size alumina under 180 N of applied load.

Fig. 5. Representative view of TEM microstructures (a) inside and (b) outside wear scar.

The damage which causes subsurface grain boundary cracking was examined by TEM observations. The samples were thinned primarily from the backside. Examination of the unworn area revealed no evidence of residual damage (Fig. 5(a)). By contrast, the worn areas of t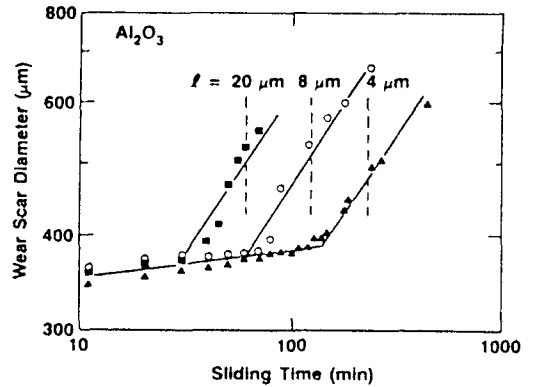he samples contained high densities of dislocations and deformation twins (Fig. 5(B)). In the absence of secondary dislocation generation within adjacent grains-which is considered unlikely in ceramics-dislocations and/or twins will inevitably lead to grain boundary stresses, which can lead to grain boundary fracture. In this regard, extensive grain boundary cracking is observed within the worn areas of the thinned foils (see Fig. 5(b)). While much of this cracking can be related to the unavoidable foil buckling that occurs during the thinning of highly stressed TEM samples, it nevertheless confirms that grain boundary cracking can occur by the residual stresses accumulated during the sliding test.

Grain size effects on the wear transition were also investigated. Fig. 6 shows the wear data for three different grain sized alumina under 450 N of applied load. Characteristically similar plots were obtained under other applied loads. The figure shows that the wear transition occurs earlier as the grain size increases. This relates to the residual stress induced by thermal expansion *anisotrophy*. The thermal stress reduces the critical damage stress required for the wear transition and thus expedites the transition. Because the effect of thermal stress increases with the increase of grain size (as may be perceived from the fact that spontaneous fracture occurs in large grained alumina after cooling from the processing temperature while it does not occur in small grained alumina) [3], the wear transition occurs earlier in large grain size alumina.

3-2. Silicon carbide
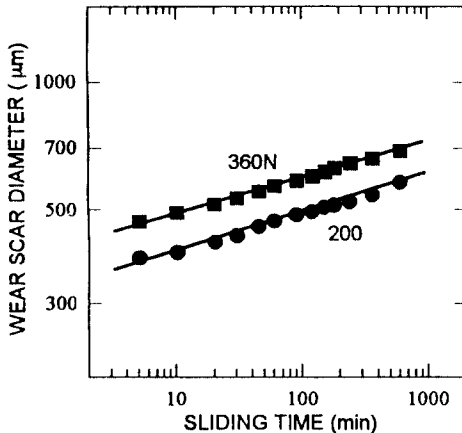The transition in wear behavior can also occur in

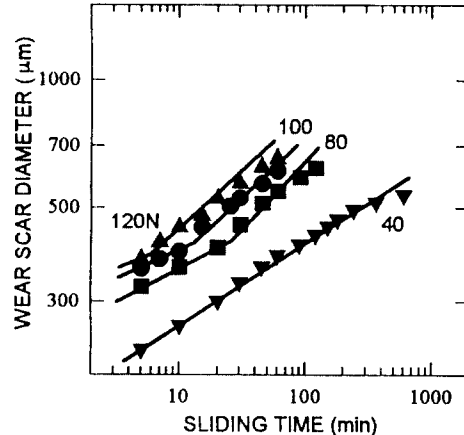Fig. 7. Wear data for solid state sintered silicon carbide with B_4C additive.

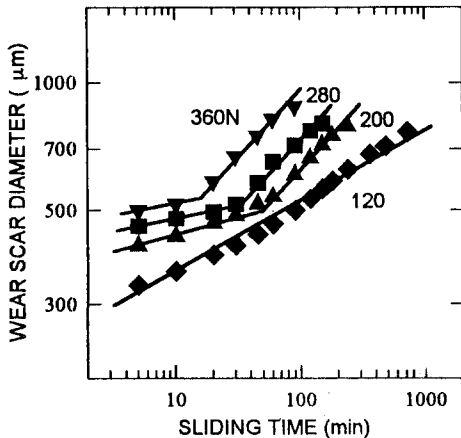Fig. 9. Wear data for liquid phase sintered SiC-TiB_2 composite.

Fig. 8. Wear data for liquid phase sintered silicon carbide with Al_2O_3 sintering additive.

silicon carbide depending on the microstructure. Figs. 7-9 show the wear data for liquid phase sintered silicon carbide, liquid phase sintered SiC-TiB_2 composite and solid state sintered silicon carbide, respectively. In liquid phase sintered silicon carbide and SiC-TiB_2 composite, the wear transition occurs. Examinations of wear surfaces before and after the transition revealed that fundamental wear processes were the same as those in alumina. However, in solid state sintered silicon carbide, the transition did not occur even under higher applied loads. In this material, the wear occurred by the plastic grooving process througout the tests until it finished.

Different wear behaviors in three different silicon carbide ceramics are attributed to the different thermally induced microstresses. TEM examinations revealed that the grain boundaries of the solid state sintered silicon carbide were relatively 'clean', i.e., no amorphous phase existed. As a result, the grain boundary strength is relatively high as may be perceived from the transgranular nature of fracture in this material. By contrast, TEM observations revealed that the liquid phase sintered silicon carbide had amorphous phases in the grain boundaries [4]. Thus, due to thermal expansion mismatch between silicon carbide grains and the amorphous phase, the grain boundaries are weakened, and this was confirmed by the intergranular fracture. In liquid phase sintered SiC-TiB_2 composite, grain boundaries between silicon carbide grains and TiB_2 particles are weakened further by the thermal expansion mismatch between them. Therefore, though the wear transition does not occur in the solid state sintered silicon carbide, it can occur in the liquid phase sintered silicon carbide and its composite. Futhermore, because the thermally induced residual stress is larger in the composite than in the liquid phase sintered silicon carbide, the transition occurs much easier in the composite than in the silicon carbide.

References

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