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Abstract

Topographical features on sliding contact surfaces are known to have a significant impact on friction and wear. Indeed, various forms of surface texturing are being used to improve and/or control the tribological performance of sliding surfaces. In this paper, the effect of random surface texturing produced by a mechanical impact process is studied for friction and wear behavior of 304L stainless steel (SS) under dry and marginal oil lubrication. The surface processing was applied to 304L SS flat specimens and tested under reciprocating ball-on-flat sliding contact, with a 440C stainless steel ball. Under dry contact, the impact textured surface exhibited two order of magnitude lower wear than the isotropically ground surface of the same material. After 1500 s of sliding and wearing through of the processed surface layer following occurring of scuffing, the impact textured surface underwent a transition in wear and friction behavior. Under marginal oil lubrication, however, no such transition occurred, and the wear for the impact textured surface was consistently two orders of magnitude lower than that for the ground material. Mechanisms for the tribological performance enhancement are proposed.

Keywords: Surface texture, Friction, Wear

1. Introduction

Friction occurs when two surfaces are in contact with relative motion. Control of friction is important in engineering applications. Sometimes high friction is desirable such as in brakes, but most often high friction is detrimental, especially when durability and energy consumption are major concerns. Overall, friction does cause damage of the surfaces in contact, resulting in poor reliability and durability in machinery. Consequently friction control, primarily friction reduction, is desirable in many mechanical components such as gears, bearings, and seals when durability and energy consumption are major concerns. A common approach to friction reduction is lubrication. Effective lubrication can be achieved by the use of a liquid (oils and greases), solid (such as graphite and MoS_2), or gas (air bearing). However, there are limits to the systems that can be lubricated and the kind of lubricant that can be used in different components and applications.

Another approach to control friction is surface engineering. Morphological alterations, compositional changes, and coatings are all used to modify component surfaces and lessen friction. Mechanistically, friction involves shearing of the surface in the real area of contact. It is plausible, then, that controlling the nature of the real area of contact can result in friction control. Surface texturing is a way to influence surface interaction and may be useful for friction control. Indeed, several forms of surface texturing are currently used to reduce friction, such as laser surface texturing, super finishing, and cross-honing [1-6]. This paper presents our evaluation of the effect of a novel application of surface morphological modification technique,

“SiC particle impact nano-texturing,” on the friction and wear behavior of 304L stainless steel, a material that is known to exhibit poor tribological performance. Studies were conducted for both dry and oil-lubricated sliding contact.

2. Material and Methods

2.1 Materials

AISI 304L stainless steel was selected for the study of the new surface texturing technique because it, in addition to 316 steel, is commonly used for tribological applications where corrosion resistance is desirable. Its main properties are given in Table I. Because 304L is a metastable austenitic stainless steel susceptible to martensitic transformation, normally induced by plastic deformation at low temperatures [7], its frictional behavior is very poor, and it is susceptible to scuffing. Therefore, an urgent need exists for approaches to enhance the tribological behavior of this material.

2.2 Surface Texturing

Two surface preparation techniques were used in this study to produce isotropic features: isotropic grinding (denoted 304-IG), and the new application of impact texturing with SiC particles in the 5-300 μm range and polygonal shape (denoted 304-IT), as shown in Fig. 1. For the latter, the particles, with an average hardness of 2300 Hv, were blasted with a pressure of 80 psi (552 MPa), perpendicular to the 304L steel surface until the surface was completely textured. After impact texturing, the surface was lightly polished and cleaned in an ultrasonic bath for 4 hours in order to remove loose impacting particles. The final surface textures for the

304-IG and 304-IT specimens were analyzed by optical microscopy, optical profilometry, and scanning electron microscopy (SEM). The surface morphology of 304-IG (Fig. 2a) shows randomly oriented scratches, while that of 304-IT (Fig. 2b) reveals no obvious scratches on the impact textured surface but rather randomly distributed dark features. The optical profilometries of both surfaces (Figs. 2c and 2d) show obvious differences. The dark features in Fig. 2b are indeed craters, with average size in the range of 20-50 μm diameter. The surface differences are reflected in roughness measurements: 491 nm (S_a) for 304-IG and 978 nm (S_a) for 304-IT.

2.3 Friction and Wear Test

Friction and wear tests were conducted with a ball-on-flat contact configuration in reciprocating sliding, shown schematically in Fig. 3. The 304-IG and 304-IT flat specimens have nominal dimensions of 25 x 50 x 6 mm, and hardness of 1.7 GPa (87 Rb) while the counterface material is a 440C stainless steel bearing ball with 12.7 mm (0.5 in.) diameter, a hardness of 6.0 GPa (56 Rc), and surface roughness of 30 nm S_a . Tests were conducted at loads of 5 N, 10 N, and 25 N, which imposes Hertzian contact pressures of 0.69, 0.87, and 1.17 GPa, respectively. The reciprocating frequency was 1 Hz with a stroke length of 10 mm, equivalent to a linear sliding speed of 1 cm/s. All tests were run for 30 min at room temperature under dry and marginal lubrication. For the latter, one drop of unformulated poly-alpha-olefin (PAO10 with viscosity of 66 cSt at 40 °C) was used at the start of testing.

The friction coefficient was continuously measured during the tests. Flat wear was determined at the conclusion of the tests by a 3-D profilometry technique. Worn surfaces were also

characterized by optical and scanning electron microscopy to evaluate wear and surface damage mechanisms.

3. Results and Discussion

3.1 Friction and Wear Tests

Fig. 4 shows the variation of friction coefficient with time during sliding contact at the different loads for the 304-IG and 304-IT flats. Under dry sliding, the impact texture surface consistently showed lower friction coefficient than the ground surface, although the differences were minimal at the relatively low loads of 5 and 10 N. Under the high load of 25 N, the frictional behavior of the two surface preparations differed significantly (Fig. 4a). For the ground surface, the friction coefficient was relatively high and noisy, ranging from 0.6 to 0.8. Such friction behavior is indicative of severe wear. For the impact textured surface, the friction coefficient for the first 1400 sec was remarkably low (<0.2) for dry sliding contact. At about 1400 sec, the friction coefficient rose sharply, indicative of scuffing, which is due to plastic shear instability at the sliding contact interface [8]. In the marginally lubricated condition, the friction coefficient for both types of surface treatments at a load of 5 N was nearly identical (Fig. 4b), about 0.06 for the duration of the test. At 10 N load, the friction coefficient for the impact textured surface remained constant at about 0.06 for the entire test, while the ground surface exhibited higher (0.15) and noisier friction for the first 1000 sec, followed by a transition to a lower friction coefficient of 0.06 for the remaining test time. Again, the largest difference was observed in the frictional behavior of the two surfaces at the high load of 25 N. For the ground surface, the friction coefficient decreased over the first 1200 sec from an initial value of about 0.55 to a near

constant value of about 0.16 for the remaining test time. For the impact textured surface, the friction coefficient was nearly constant at about 0.15 for the entire test.

No measurable wear was detected on the 440C ball in all the tested cases. Similarly, wear was minimal in the flat specimens at relatively low loads of 5 and 10 N. Fig. 5 shows a comparison of wear volume in the flat specimens tested at 25 N under both dry and lubricated conditions (plotted on a log-scale). The wear volume in the impact textured surface is substantially lower than that of the ground surface, especially under lubricated conditions (by nearly two orders of magnitude). The bulk of wear in the dry test of the impact textured surface occurred after the friction transition. In a test that was stopped before the friction transition, the measured wear was only about $5 \times 10^5 \mu\text{m}^3$ compared to $1 \times 10^8 \mu\text{m}^3$ for the ground surface.

Fig. 6 shows optical micrographs of the wear tracks in the ground and impact textured surfaces tested under the lubricated condition at 25 N. For the ground surface, Fig. 6a shows the occurrence of abrasive wear as indicated by scratches of various sizes in the direction of sliding, while the plastic fatigue wear mechanism is indicated by the presence of dark pits on the wear track. . For impact textured surface, although the wear track is evident (Fig. 6b), it is for the most part covered by a surface film, and minimal material removal has occurred (Fig. 6c).

3.2 Tribological Mechanisms

Results of this study showed that impact texturing resulted in a dramatic reduction in friction and wear, especially at high loads, when compared to a ground surface. Although the mechanisms behind the friction and wear reduction in the IT-304 surface are not fully understood, and certainly warrant further investigation, plausible mechanisms include phase

transformation in the near surface, particle embedment, and altered surface morphology, as discussed next.

Phase transformation of near surface material: 304L stainless steel, a metastable austenitic phase, is susceptible to transformation into martensitic phase under stress at low temperatures [9-11]. Compared to the austenite phase, the martensitic phase has higher hardness and reduced plasticity. Given that plastic deformation is one of the major mechanisms of friction, and that materials with less plasticity generally exhibit lower friction, martensitic transformation during impact texturing can indeed result in a significant reduction in friction. X-ray diffraction (XRD) of the samples before and after texturing was conducted to assess possible phase transformation during impact texturing. Fig. 7 shows the XRD of the ground and impact textured surfaces. There is clear evidence of the martensitic phase in the impact textured surface. Transformation of austenitic to martensitic phase is accompanied by a volume increase, which imposes some compressive residual stresses in the near surface layer. More importantly from a tribological perspective is the higher hardness of the martensitic phase when compared to the austenitic phase [12-14]. The higher hardness of martensite is expected to reduce the extent of plastic deformation and friction as well as wear.

Particle embedment: Improved tribological performance in steel by blasting with Si_3N_4 particles was recently reported [15]. This improvement was attributed to particle embedment in the steel substrate. In the present study we also observed particle embedment, as shown in Fig. 8. EDS analysis of the particle in Figure 8 indicates it consists of impacting SiC. Such embedded particles can enhance the near-surface material properties and wear resistance. Adequate

incorporation of hard secondary phase particles will essentially create a metal-matrix composite in the near surface region. This composite will increase the material strength, hardness, and other mechanical properties, all of which can contribute to better friction and wear performance. Of course, the extent of the effect of such surface material modification will be dependent on several parameters, including properties of the embedding particles (size, shape, and hardness); the volume fraction of embedment; and the bond strength between the matrix material and the embedding particles.

Surface morphology: Surface texture and morphological variations can lead to changes in tribological performance. Considerable reduction in friction and wear as a result of morphological changes in steel has been reported by Ivanov et al. [16]. As shown in Fig. 2, the morphologies of the ground and impact textured surfaces are quite different and can, in part, be responsible for differences in friction and wear, especially under lubricated conditions. Indeed, surface morphological design is a common approach to tribological performance improvements, especially in lubricated contacts. Techniques based on this principle in use today include plateau honing, isotropic finishing, and superfinishing.

There is a possibility of a synergistic effect among these identified mechanisms, and even the possibility of other yet unknown mechanisms. More work is needed to conclusively elucidate the operating mechanisms responsible for friction and wear improvement by impact texturing reported in this paper. Such understating can provide a pathway for process optimization and establishment of the limits of the process.

4. Conclusions

Results of the present study showed that impact texturing of 304L stainless steel with SiC particles significantly improved tribological performance under dry and lubricated conditions, especially at higher loads (25 N). The friction coefficient under dry sliding contact was reduced from 0.7 to 0.15 by impact texturing. Wear of the textured surfaces was reduced by up to two orders of magnitude compared to an un-textured ground surface. A transition to higher friction was observed after some period of sliding at higher loads, coinciding with scuffing and severe plasticity eliminating the surface texture and its effects. Under marginal lubrication, the friction was consistently lower for the textured surfaces, and no transition was observed under the range of loads tested. Although the mechanisms responsible for the enhancement in tribological performance are not fully understood, there is evidence of phase transformation, particle embedment, and surface morphological modification. More work is needed to fully understand the operating mechanisms in particulate impact texturing that makes a relatively simple process so effective in terms of friction and wear control.

Acknowledgments:

This work was supported by U.S. Department of Energy, Energy Efficiency and Renewable Energy, Office of Vehicle Technologies, under contract DE-AC02-06CH11357.

The electron microscopy was accomplished at the Electron Microscopy Center at Argonne National Laboratory, a U.S. Department of Energy Office of Science Laboratory operated under Contract No. DE-AC02-06CH11357 by UChicago Argonne, LLC.

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Figure Captions:

Fig. 1. Scanning electron microscopy of SiC particles for surface texturing.

Fig. 2. Optical micrographs of 304L surface: (a) isotropically ground and (b) impact textured;
3D profile of 304L surface: (c) isotropically ground and (d) impact textured.

Fig. 3. Schematic of ball-on-flat contact configuration under reciprocating sliding.

Fig. 4. Evolution of friction coefficient with time of textured 304L steel surfaces: (a) dry and (b) lubricated conditions at 5-25 N loads.

Fig. 5. Wear volume of textured 304L steel surfaces under dry and lubricated conditions at 25 N load.

Fig. 6. Optical micrographs of the wear track in (a) ground surface and (b-c) impact textured surface for lubricated condition at 25 N load.

Fig. 7. XRD patterns of 304L SS with different surface treatment.

Fig. 8. SEM image of SiC particle embedment in impact textured surface and EDS data.

304 L	PROPERTIES
Composition	Fe/Cr18/Ni10
Density	8.00 g/cm ³
Melting Point	1400-1450°C
Modulus of Elasticity	193 GPa
Electrical Resistivity	0.072x10 ⁻⁶ Ω.m
Thermal Conductivity	16.2 W/m.K at 100°C
Thermal Expansion	17.2x10 ⁻⁶ /K at 100°C
Tensile Strength	500 MPa
Compression Strength	210 MPa
Hardness Rockwell B	92