N. Laser Surface Texturing of Lubricated Ceramic Parts

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Objectives

- Determine the effectiveness of using regular patterns of microscale dimples produced by a laser to reduce the friction coefficient of liquid-lubricated surfaces of ceramics.
- Determine the extent to which the laser surface texturing (LST) process affects the structure of the ceramic materials to which the process is applied.

Approach

- Select the proper tests and analyses needed to reveal potential friction reduction benefits of dimpled ceramic surfaces for use in lubricated sliding contacts.
- Obtain transformation-toughened zirconia (TTZ) and silicon carbide ceramic materials, design and fabricate test specimens, and provide them to Surface Technologies Ltd. for laser dimpling.
- Characterize the ceramic materials after LST using a variety of techniques, including electron microscopy, nanoindentation, and scanning acoustic microscopy (SAcM).
- Conduct friction tests in lubricants with different viscosities to determine the extent to which the laser surface treatment can reduce friction. Compare results for reciprocating motion, like that in engine components, with results for unidirectional sliding, like that found in rotary bearings or seals.

Accomplishments

- Conducted reciprocating friction tests of LST ceramics in various lubricants–including diesel oil, mineral oil, and water–to determine which frictional conditions benefit more from LST.
- Investigated the use of SAcM to identify near-surface microfractures due to the laser-induced thermal pulses used to form the dimples.
- Obtained nanohardness data on the thermally affected zones in the material below dimples.
- Determined the importance of precise alignment and sliding velocity to enable the detection of frictional effects of dimpled surfaces. Found that friction reduction in reciprocating contacts is difficult to achieve using LST.

Future Direction

- Test LST ceramics in constant-velocity, unidirectional sliding (rather than reciprocating sliding as before) to more clearly reveal LST effects on the lubricated friction of ceramics couples.
- Conduct additional characterization of LST effects on ceramics, especially as compared with other methods of surface engineering of these materials.

Introduction

Improving the fuel efficiency of diesel engines while enabling them to meet emissions requirements presents both design and material challenges. Parasitic frictional losses in engines can be reduced by a combination of strategies such as (a) redesigning the engine components, (b) reformulating the lubricants, (c) improving methods of lubricant filtration and delivery, (d) reducing churning losses in fluids, (e) changing the operating conditions of the engine, (f) substituting more-durable, low-friction materials, and (g) altering the finish or microscale geometry of the bearing surfaces. This project specifically addresses the last approach by investigating the potential of a technique called LST that was developed by Surface Technologies Ltd. in Israel.

In FY 2002 and FY 2003, tests were conducted to examine the efficacy of laser-produced dimples on the frictional characteristics of TTZ and silicon carbide (Hexaloy SA) sliding against flat surfaces of ground silicon nitride. In addition, detailed microstructural examination and characterization of the LST regions was performed by a variety of techniques to evaluate the possible effects of the process on ceramics. Early introduction of LST involved its successful application to water pump seals in which the mating surfaces were wide and flat. Recent work by Japanese investigators on water-lubricated silicon carbide dimpled by different methods showed the importance of dimple spacing and running-in to the extent to which dimpling reduced the friction coefficient.[1] In 2003, microstructural characterization of laser–surface-processed ceramics continued, as did additional friction experiments using lubricants that vary in viscosity. Results of that work suggested several future directions for FY 2004.

Approach

This project is being conducted in parallel with a complementary effort at Argonne National Laboratory (ANL) on LST metals and LST used in conjunction with coatings. Oak Ridge National Laboratory (ORNL) efforts have focused on ceramic materials. The approach taken is two-pronged: (a) conduct controlled friction experiments of LST ceramics to evaluate the effects of both velocity and lubricant type (viscosity) on friction and (b) characterize the effects of LST on both the microstructure and the near-surface micro-mechanical properties of ceramics. To accomplish the latter, various techniques are being applied, for example, nano-indentation hardness and elastic modulus determination, SAcM, and scanning and transmission electron microscopy.

Results

During FY 2002, reciprocating friction tests were conducted on LST-treated flat areas on cylinders of zirconia (TTZ), sliding against ground silicon nitride tiles in various lubricants. Results presented in earlier project reports indicated that the most noticeable effects of LST occurred with low applied loads and high oscillating speeds. That finding was consistent with a lubrication theory developed by Petroff, Stribeck, and others in the early 1900s,[2] namely, that the magnitude of the friction coefficient in lubricated systems is proportional to both the velocity of sliding and the viscosity of the lubricant, and inversely proportional to the force holding the surfaces in contact. That work helped define the concepts of boundary lubrication, mixed film lubrication, and hydrodynamic lubrication for plain bearings. Key engine components such as piston rings oscillate back and forth; that complicates the application of Stribeck's analysis to the current project because it was intended for components, such as shafts, that always rotate in the same direction.

Further studies on the friction of silicon carbide LST cylinders were conducted during FY 2003 with less definitive results than the earlier work on TTZ. It was concluded that the benefits of LST for reciprocating, narrow contacts could be detected only for very precisely aligned surfaces, if at all. That was confirmed by a recent report by Kato[3] in which more than a day of water-lubricated sliding was required to wear-in the surfaces of the ceramics enough to reveal the benefits of LST.

The primary focus of the FY 2003 research was on characterizing the effects of the LST process on the surfaces and micro-mechanical properties of TTZ and silicon carbide. Figure 1 shows the surface of an LST zirconia specimen containing rows of round (~ 120 μm diameter), shallow (~ 15 μm deep) dimples. Figure 2 shows an inclined, polished prepared section prepared from the same specimen. The low angle of polish helps to artificially magnify the near-surface features. Slightly darker coloration marks the thermally affected zones encircling the dimple. Higher magnification reveals a fine network of microcracks, presumably due to rapid heating and cooling of the ceramic in the vicinity of the laser pulse.

SAcM, the image contrast of which is affected by the presence of subsurface flaws, revealed additional cracking features not visible in either the optical or scanning electron microscope (see Figure 3). The higher the acoustic frequency, the shallower the penetration into the surface, but the smaller the flaws that can be detected. The SAcM image in Figure 3 shows fringes associated with the change in height of the crater, but it also reveals subtle cracks around the edges of the dimple.

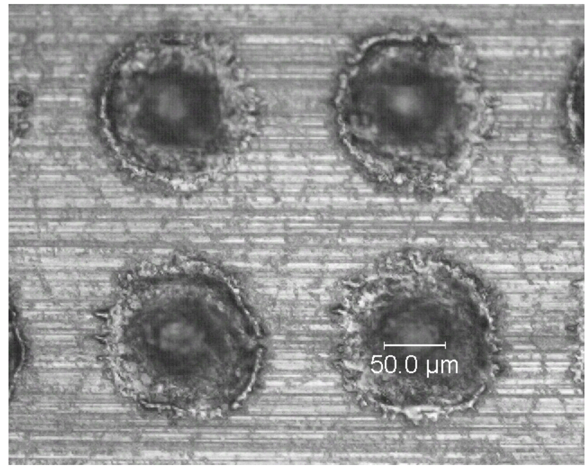

Figure 1. Pattern of dimples on a TTZ surface.

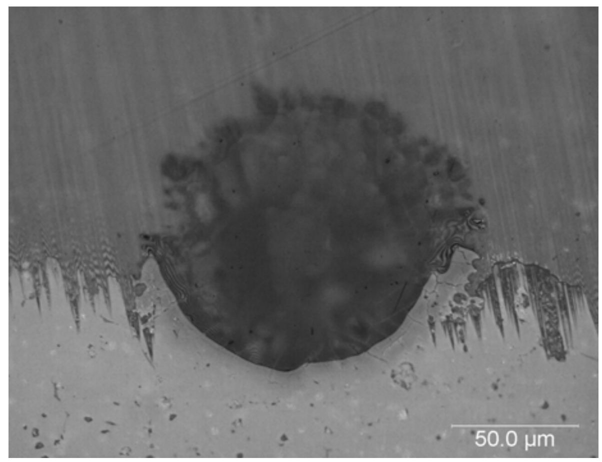

Figure 2. Tapered cross-section of a dimple in TTZ showing the "splash zone" near the dimple rim and the thin heat-affected area along the bottom of the crater. The splash zone must be removed by gentle grinding or by wearing-in of the contact surfaces for dimple effects to work properly.

Nanoindentation studies were conducted to determine whether LST had affected the micro-mechanical properties of the material.

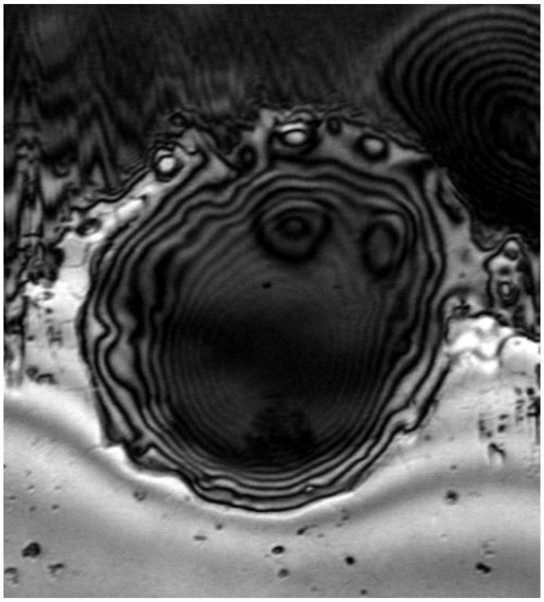

Figure 3. Scanning acoustic microscopy image of a crater, revealing both topography and fine-scale micro-cracking below the surface of the rim regions. Frequency 1.7 GHz.

Table 1 summarizes results for a series of nanoindentation tests in the LST-affected regions and in the material well below them (bulk). Despite the slightly lower average hardness values near the dimples on both ceramics, there was no statistical basis to conclude that the elastic modulus or the average nanoindentation hardness numbers were significantly different in the LST-affected areas.

Conclusions

- LST of zirconia ceramics results in the formation of a nanocrystalline zone that contains a network of microfractures. The mechanical properties of the regions between the microfractures are not different from those for the bulk material, and the main difference seems to be in the size of the grains and the presence of the microfractures. If wear occurs or if lubrication breaks down, it is possible that these fractures could serve to nucleate wear particles. Additional microscopy is planned.

Table 1. Nanoindentation hardness and elastic modulus data for polished cross-sections of TTZ and silicon carbide (SiC)

Quantity	Location	TTZ	SiC
Average nanoindentation hardness (GPa)	Bulk	16.1	37.0
Average nanoindentation hardness (GPa)	Near dimples	15.2	32.4
Average elastic modulus (GPa)	Bulk	262.	493.
Average elastic modulus (GPa)	Near dimples	257.	502.

- The effects of dimples on friction reduction can be obscured if the contact surfaces are not precisely aligned during sliding, if they are not well run-in, or if the fluid entrainment velocity and viscosity of the lubricant are insufficient to enable creation of a lubricant film.
- Additional work is needed to examine whether unidirectional, lubricated sliding of LST ceramic surfaces will reveal a more direct benefit from LST.
- The effects of LST should be compared with other emerging surface engineering methods to determine which of them provides the most robust means of friction reduction in ceramics under oscillating or unidirectional sliding.

References

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