K. Laser Surface Texturing of Lubricated Ceramic Parts

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Objectives

- Determine the effectiveness of using regular patterns of micro-scale dimples produced by a laser to reduce the friction coefficient of 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 micro-fractures due to the laser-induced thermal pulses used to form the dimples.
- Conducted transmission electron microscopy (TEM)of zirconia specimens and determined that a difference in crystal structure occurs in shallow zones affected by LST.
- Obtained nanohardness data on the thermally affected zones in the material below dimples.

- Established the sensitivity of LST effects to precise surface alignment, and the need for sufficiently high sliding velocity to detect frictional effects of the dimpled surfaces. In our experience, achieving friction reduction by LST in reciprocating sliding contacts requires taking extraordinary measures in alignment and apparatus design.
- Explored the effects of solid lubrication with graphite powder on the friction of LST zirconia surfaces under reciprocating motion. There was no apparent improvement due to dimpling.

Future Direction

- Summarize the results of this study in a final report.

Introduction

Improving the fuel efficiency of diesel engines, while still enabling them to meet requirements for emissions, presents both design and material challenges. Reducing parasitic frictional losses in engines can be achieved by a combination of strategies such as

- redesigning the engine components
- reformulating the lubricants
- improving methods of lubricant filtration and delivery
- reducing churning losses in fluids
- changing the operating conditions of the engine
- substituting more durable, low-friction materials
- 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 (developed by I. Etsion of Surface Technologies Ltd., in Israel).

LST was successfully demonstrated by reducing the friction and wear of water pump seals in which the mating surfaces were wide and flat. Work by Japanese investigators on water-lubricated silicon carbide, dimpled by different methods, showed the importance of both dimple spacing and running-in on the extent to which dimpling was able to reduce the friction coefficient.[1]

Initial studies at Oak Ridge National Laboratory (ORNL) in FY 2002–2003 involved conducting reciprocating sliding friction tests with flat-sided (both dimpled and non-dimpled) cylindrical rods oscillating on a flat ceramic specimen. Water, mineral oil, and diesel oil were used as lubricants. By carefully analyzing the data, friction lowering effects of LST were seen. In FY 2003, microstructural characterization of laser-surface-processed ceramics continued, as did the friction experiments. It was eventually concluded that the benefits of LST for reciprocating, narrow contacts could be detected only for very precisely aligned surfaces, and even that was difficult. In fact, the difficulty of detecting LST effects without special experimental procedures was confirmed by a paper by Kato[2] in which more than a day of water-lubricated sliding was required to wear-in the surfaces of the ceramics sufficiently to reveal the frictional benefits of LST. Unspectacular test results on liquid-lubricated LST ceramics during FY 2003 prompted a change in approach for FY 2004.

During the past year, the focus was shifted from using liquid lubricants to filling the dimples with solid lubricants, in this case, graphite. The hypothesis to be tested was that LST-produced dimples in surfaces might help catch abrasive debris and at the same time re-supply solid lubricating material to both lower friction and extend the life of ceramic sliding surfaces. This annual report summarizes the experiments designed to explore the latter approach.

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. ORNL efforts have focused on ceramic materials. The approach is two-pronged: (1) to conduct controlled reciprocating friction experiments on LST ceramics to evaluate the effects of both velocity and lubricant type on friction and (2) to 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 TEM and scanning TEM (TEM). Results of acoustic microscopy and nanoindentation tests were described in the previous annual report. TEM images and diffraction patterns of the laser-affected zone at the dimple bottoms will be provided in the final report to be prepared during FY 2005. They show indications that the crystal structure of TTZ is affected at a nanometer scale in a thin region near the surface of the dimple.

Results

In FY 2004, experiments were conducted to test the hypotheses that dimples in LST surfaces could serve both as reservoirs to replenish worn-away lubricant and as traps for any harmful, abrasive debris that happened to enter the interface. A flat-on-flat reciprocating sliding configuration was used (see Figure 1). TTZ surfaces in three conditions, as-ground (non-dimpled), laser-dimpled, and dimpled and polished, slid against ground Gall-Tough™ stainless steel (upper specimen) in an ambient air environment. Pressure-indicating plastic film was used to help pre-align the two contact surfaces before each test. The nominal contact area of the sliding contact was 10 × 4 mm. A constant 10-N normal force, 2-Hz reciprocating frequency, and 10-mm stroke length were used. The lubricant was Dixon Ticonderoga 1651 graphite powder. A layer of graphite powder was distributed on the zirconia surface before each test, and no additional lubricant was supplied thereafter. The level of friction force was monitored using a high-speed data acquisition system. Worn surfaces were examined to assess their morphology and to study the distribution of graphite and debris created by prolonged sliding contact.

Results of the first graphite-lubricated test conducted on LST zirconia against Gall-Tough™ were promising. Without re-lubricating, the initially formed graphite lubricating film lasted nearly 90 hours before failure (see Figure 2a). At the beginning of the test, the graphite powder quickly formed a lubricating film under pressure from the

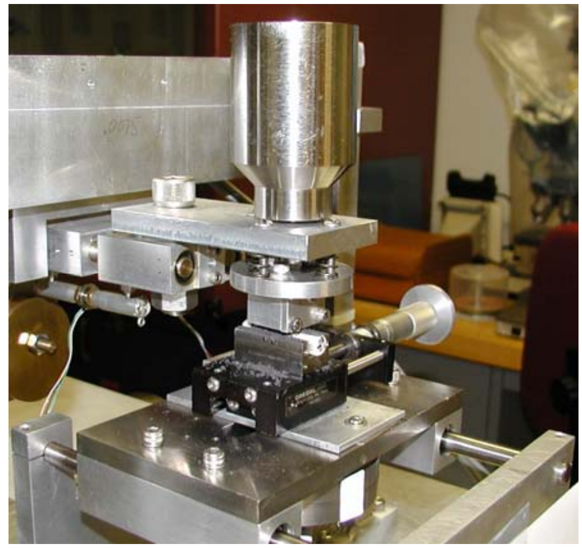
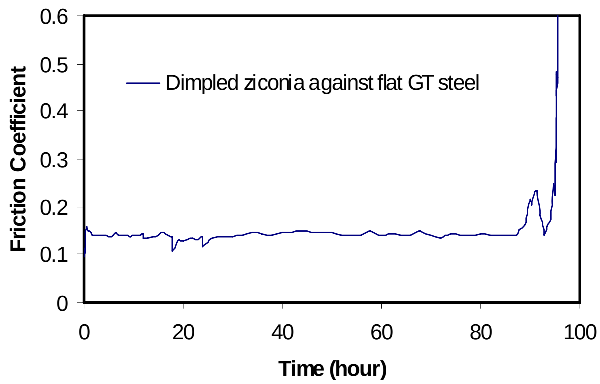


Figure 1. Flat-on-flat reciprocating sliding test setup showing the dead-weight load.

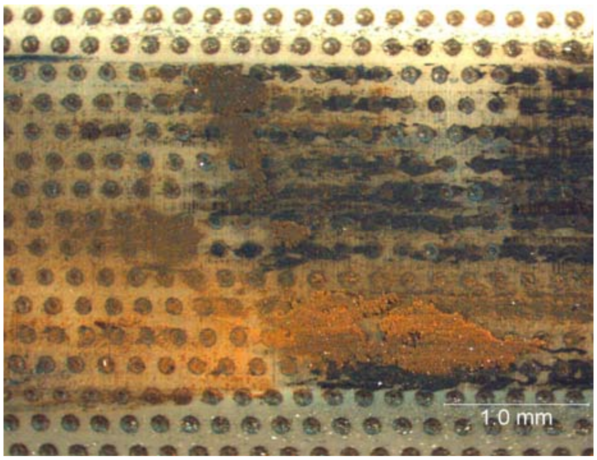
mating surfaces. Since the two sliding surfaces were fully separated by a compressed graphite film, the frictional response reflects the resistance to sliding from adhering graphite particles. Initially, the friction coefficient remained relatively low at ~0.15. However, since this was an open system that allowed particles to escape, the graphite particles were gradually wiped off and the film became progressively thinner. When the lubricating film began to fail, asperity contact occurred between the mating surfaces. In this second stage, the tangential force resulted from a combination of metal/ceramic asperity contacts and the shear of the incomplete graphite film. The friction coefficient in this stage therefore fluctuated more noticeably. Eventually the lubricating film collapsed, leading to large areas of steel-on-zirconia in nominally unlubricated contact. The friction coefficient quickly transitioned to a much higher level, 0.5–0.6 (i.e., stage 3 in Figure 2a). This final frictional transition was used as the criterion for lubrication failure.

The worn LST TTZ surface is shown in Figure 2b. Patches of wear debris, evidently containing both iron oxides and metallic particles, were observed. Many dimples were filled with wear debris, while others still retained some graphite powder. As hypothesized, the dimples acted both as reservoirs for the lubricant and as traps for wear debris.

Although the first test results seemed promising for solid lubricant-filled dimples, subsequent tests



(a) Friction trace



(b) Worn surface

Figure 2. Results for LST TTZ reciprocating against Gall-Tough™, a commercial stainless steel lubricated by graphite powder: (a) friction trace, (b) TTZ surface appearance (optical microscope image).

designed to verify the repeatability of frictional behavior gave inconsistent results. Frictional increases that suggested film failure occurred much earlier in the latter tests. A repetition of the first test failed after only 8 hours, compared with more than 85 hours for the first run. The two causes for this are alleged to be (1) slight variations in the initial alignment of the specimens and (2) an alignment change due to the effects of fixture vibration and loosening during sliding. These minute, but not insignificant, misalignments turned the relatively large, rectangular area of initial contact into a more concentrated line or point contact, which in turn caused the lubricating film to break through much more quickly. Considering the three stages of frictional behavior shown in Figure 2, initial alignment controls the length of the first sliding stage in which the friction is fairly low, the sliding is relatively smooth, and the vibration is minimal. When the lubricating film starts to fail and frictional behavior enters the second stage, the higher and more erratic level of friction induces more vibration. Higher vibration loosens the fixtures, changing the alignment and accelerating lubricant failure. After this behavior was observed, modifications were made to the equipment to eliminate vibration-induced misalignment. Tests were then rerun on both the dimpled and non-dimpled surfaces.

As shown in Figure 3, the lubricating films survived fairly long in both tests. Although the low-friction stage did not last as long as on the first run, the second stage, with its partially lubricated surface, persisted for more than 100 hours. After 115 hours of sliding, the friction behavior of dimpled and non-dimpled tests diverged. In the test of the dimpled surface, the friction coefficient became unstable and quickly transitioned to 0.5, indicating lubrication failure. However, the friction coefficient for the non-dimpled surface fluctuated between 0.2 and 0.3 for another 50 hours or more, implying that it could survive under partial coverage by lubricant better than the dimpled specimen. Thus for solid lubrication by thin films, smoother surfaces seemed to perform better than dimpled surfaces. Perhaps if the surface wore down, it would expose more solid lubricant from the dimples to replenish the film, but in the case of ceramics such as zirconia and silicon carbide, their high wear-resistance would not allow this to happen.

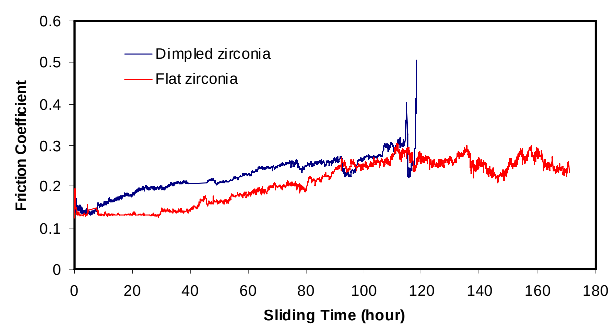


Figure 3. Friction traces for laser dimpled and non-dimpled zirconia surfaces after stabilizing the test fixtures.

A final report that summarizes the current research findings on LST ceramics will be prepared in FY 2005. It will include both tribology results and microstructural characterization.

Conclusions

Although dimples can serve as reservoirs for graphite powder and traps for wear debris, they did not appear to effectively re-supply the lubricating film. In fact, the smoother non-dimpled surfaces sometimes remained at a low-friction condition longer than the LST dimpled ones.

The present results on solid lubricated surfaces have reinforced earlier conclusions from experiments with liquid lubricants: contact alignment is critical for optimizing the effects of dimpled surfaces. With utmost care in establishing good initial alignment and fixture stability, the lubricating film that formed from an initial application of graphite powder can be made to survive more than 100 hours of sliding (10-N load, 2-Hz frequency, 10-mm stroke length). But even with added care in testing, LST offered no apparent advantages over non-dimpled, smooth surfaces tested under graphite lubrication.

References

1. X. Wang, K. Kato, K. Adachi, and K. Aizawa, "The Effect of Laser Texturing of SiC on the Critical Load for the Transition of Water Lubrication Mode from Hydrodynamic to Mixed," *Tribology International*, **34**, 703–711 (2001).
2. K. Kato, "Water Lubrication of Textured Silicon Carbide," presented at the conference on Boundary Lubrication for Transportation, Copper Mountain, CO, August 3–8, 2003.

Publications/Presentations

P. J. Blau, "Challenges for the Application of Engineered Surfaces to Tribosystems with Multiple Contact Modes," invited presentation at the Symposium on Integrated Surface Engineering, ASME/STLE Tribology Conference, Ponte Vedra, FL, October 28, 2003.

P. J. Blau with J. Qu and L. Riester, *Laser Surface Dimpling Effects on the Frictional Behavior and Microstructure of Transformation-Toughened Zirconia and Silicon Carbide Ceramics*, Milestone Progress Report, submitted October 2003.