F. Laser Texturing of Propulsion Materials

Principal Investigators: Ali Erdemir, Oyelayo Ajayi, Robert Erck, Osman Eryilmaz, George Fenske, and Izhak Etsion (Technion University)
Affiliation: Argonne National Laboratory
Address: Energy Technology Division, Argonne, IL 60439
(630) 252-5190; fax: (630) 252-4798; e-mail: gfenske@anl.gov

Chief Scientist: James J. Eberhardt
(202) 586-9837; fax: (202) 587-2476; e-mail: James.Eberhardt@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax:(865) 576-4963; e-mail:skladps@ornl.gov

Contractor: Argonne National Laboratory
Contract No.: W-31-109-ENG-38

Objective

- Assess and optimize the tribological performance of laser-textured (or dimpled) surfaces under a wide range of sliding contact conditions.
- Determine durability and tribological operational limits of laser textured surfaces.
- Elucidate fundamental tribological mechanisms that control friction and wear of these surfaces.
- Design and produce novel hard coatings over dimpled surfaces and explore their synergistic effects on friction and wear.

Approach

- Control and optimize dimple size, depth, and density. Determine their effects on friction and wear.
- Develop a reliable test protocol, specify test conditions, and perform well-controlled tests using a number of friction and wear test machines.
- In collaboration with Prof. Izhak Etsion (who supplies the dimpled surfaces), analyze test results and make judgments on the performance of the dimpled surfaces.
- Specify and apply hard coatings over laser-dimpled surfaces. Perform friction and wear tests to assess performance improvements.
- Characterize worn surfaces; elucidate mechanisms that control friction and wear.
- Promote/present findings at appropriate forums and generate more industrial interest.

Accomplishments

- Demonstrated significantly lower friction and wear under mixed lubrication regimes in tests using a unidirectional pin-on-disk machine.
- Demonstrated up to 90% increase in resistance to scuffing on laser-dimpled surfaces using a reciprocating wear test machine.
- Designed and built a test rig that simulates sliding motion between the ring and liner of an internal combustion engine.

- Completed a series of screening tests and found that the bulges around the dimples caused severe wear damage on the ring side. Parallel studies performed by Prof. I. Etsion at the Technion University have confirmed that up to 30% reduction in friction is feasible with laser-textured surfaces.
- Applied copper and superhard coatings on dimpled steel substrates and demonstrated much higher resistance to wear and scuffing.
- Completed work on laser-textured SiC seals and demonstrated 40 to 50% reductions in frictional torque.
- Performed a series of new tests to measure the lubricant film thickness of laser-textured surfaces.

Future Direction

- Concentrate on laser-dimpled piston rings and cylinder liners; determine effects of partial laser surface technology (LST) on friction and wear; optimize size, shape, and density of dimples to achieve the greatest beneficial effect.
- Develop and implement a reliable test protocol that is more prototypical of actual ring-liner sliding conditions; characterize worn surfaces; assess benefits of standard and partial LST and LST+superhard coatings.
- Assess friction reduction and energy-saving benefits of laser-dimpled rings and liners.
- Determine effects of LST on scuffing performance of superhard coatings.
- Determine effects of oil viscosity and/or ambient temperature on friction and wear behavior of dimpled and/or superhard-coated surfaces.
- Finalize current work on laser-textured piston rings and cylinder liners after removing the bulges around dimples. We will also explore the effects of surface roughness on friction and wear and determine if texturing of ring, liner, or both sides gives the best overall performance.
- Determine microstructural, chemical, and mechanical characteristics of heat-affected zones at or near the dimpled areas and determine their impact on friction and wear.
- Improve imaging technique to achieve better measurement of lubricant film thickness.
- Apply electrohydrodynamics modeling to LST-treated surfaces and correlate film thickness prediction with experimental measurements.

Introduction

Argonne has been evaluating the potential usefulness of laser texturing for a wide range of engine applications, including rings and liners, piston pins, water pump seals, and other tribological components where a significant amount of energy is spent to overcome friction. Laser texturing was originally developed by Prof. I. Etsion of the Technion University and was optimized over the past several years to become more cost-effective and, hence, viable for large-scale applications in diesel engines.

Laser texturing has enormous potential for increasing efficiency and durability of these engines. Specific components that can benefit from laser texturing are piston rings and liners, tappets, cam and follower interface, gear systems, water pump seals, and other bearing systems. Many of these components operate under different lubrication regimes during actual engine uses; hence, combining laser texturing with advanced coating technologies may have beneficial synergistic effects on friction and wear. Specifically, such coatings on textured surfaces may further reduce friction and wear and prevent scuffing under severe loading conditions, where direct metal-to-metal contact occurs.

The dimples created by pulsating laser beams on a surface are typically 4-10 μm deep and 70 to 100 μm wide. During the dimpling process, material melts and/or evaporates to create the dimples. A portion of the molten material is accumulated around the edges of the dimples and requires post-process removal; otherwise, the dimples can cause severe wear and high frictional losses during sliding contacts.

The micro dimples created by this method can act as miniature hydrodynamic bearings that reduce friction and wear by increasing the load-bearing capacity and, hence, the hydrodynamic efficiency of such sliding surfaces. They can also trap wear debris particles that generate during sliding contacts and hence prevent them from causing third-body wear. Accordingly, the primary objective of this project is to produce and further optimize the size, shape, and density of shallow dimples on sliding and rotating contact surfaces and to explore their effectiveness in reducing friction and wear in critical engine components. Furthermore, synergistic effects of soft and hard coatings on friction and wear of laser-dimpled surfaces are explored.

Experimental Procedures

Friction and wear testing of laser-textured surfaces was performed in a pin-on-disk machine while scuffing tests were conducted in a reciprocating test machine. The pins used in friction and wear tests were made of 9.55-mm-diameter hardened 52100 steel balls with a nominal hardness value of 60 HRC. On these balls, we created a flat spot having a diameter of about 4.7 mm. The disc samples, 50 mm in diameter and 10 mm thick, were made from hardened H-13 steel with 60 HRC. Dimpled and un-dimpled samples were used for the generation of friction maps that can show regions for hydrodynamic, mixed, and boundary lubrications. For the generation of these maps, we used normal loads ranging from 2 to 20 N that corresponded to nominal contact pressures of 0.16 to 1.6 MPa. The rotational speed varied between 10 and 500 rpm, corresponding to linear sliding speeds of 0.015 and 0.75 m/s. Two fully formulated, commercially available engine oils with differing kinematic viscosities were used for this study. Each friction test was conducted at a constant load starting with the lowest speed of 0.015 m/s. The sliding speed was increased in a stepwise manner after 3 min at each speed, until the maximum speed of 0.75 m/s was reached. With this procedure, each test starts with a very thin fluid film, and as the speed increases, the lubricant film thickness increases, allowing the contact to move from a boundary to a mixed, and, finally, to a hydrodynamic lubrication regime. Indications of the operating lubrication regime were assessed from the friction coefficients.

Reciprocating tests were performed in two test machines. One was used to study the friction and wear performance of cut segments of piston rings and cylinder liners, while the other was used to determine the resistance of laser-textured surfaces to scuffing. Scuffing is defined as a sudden catastrophic failure of a lubricated surface. It is poorly understood and a major source of reliability problems in numerous engine and drivetrain components. In the literature, the scuffing has always been associated with lubrication breakdown, wear particle and deposit formation, and steep temperature rise due to severe contact conditions. Scuffing tests were performed in a reciprocating test rig, and the specific test conditions involved stepwise increasing of the sliding speed from 1 to 5 Hz in 1 Hz increments. The time interval for each step was 2 minutes. If scuffing did not occur under a given load and up to 5 Hz, then the normal load was increased, and the above procedure was repeated at a different location with a different ball. The stroke length was 21 mm, and the lubricant used during these tests was a fully formulated synthetic commercial motor oil (10W/30).

Results and Discussion

Using the pin-on-disk machine and the specific test conditions described earlier, we generated a series of lubrication maps showing the regions where full hydrodynamic as well as mixed lubrication can be achieved with the laser-textured surfaces. Figure 1 shows that with laser-textured surfaces, the hydrodynamic regime has been greatly expanded to cover almost all of the load and speed ranges evaluated in this study. For un-dimpled surfaces, however, the hydrodynamic regime could only be maintained under light loads and at high speeds. These results can clearly illustrate the beneficial affects of laser texturing on controlling friction even under severe sliding conditions. We believe that shallow dimples created on the sliding surfaces increased the load-bearing capacity of these surfaces by acting as miniature hydrodynamic bearings and thus reduced friction. Microscopic inspection of

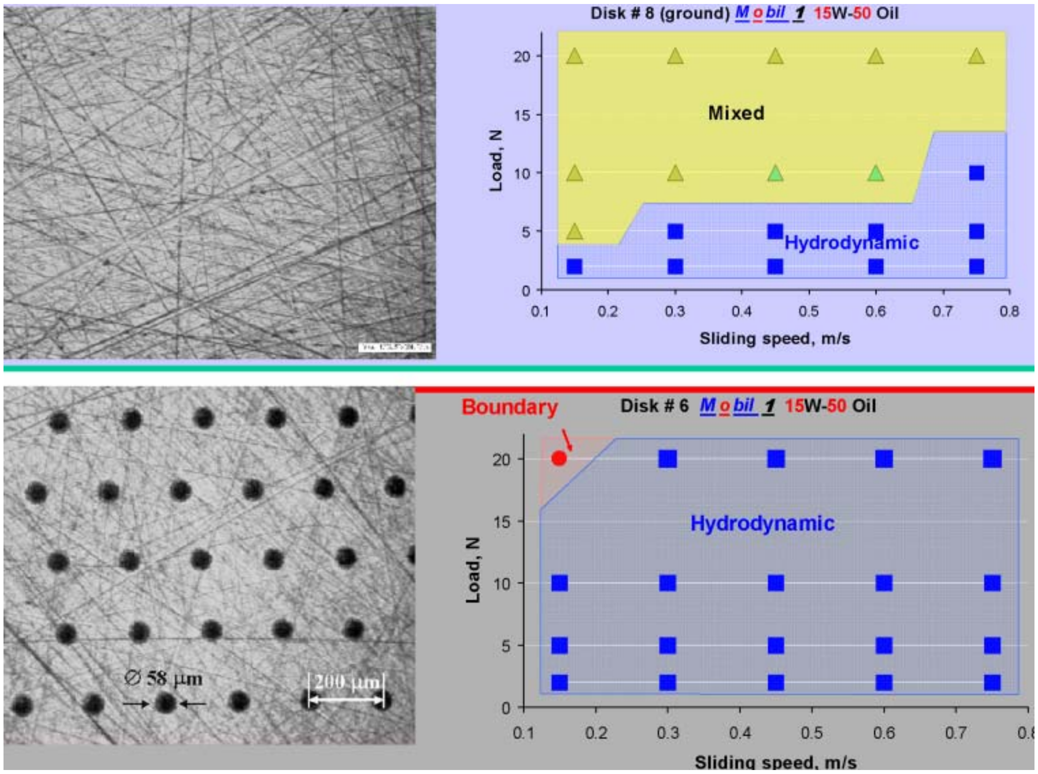

Figure 1. Comparison of lubrication performance of un-textured (top) and laser-textured (bottom) surfaces.

sliding surfaces after the sliding tests has revealed very little wear (mostly in the form of minor scratches) on these surfaces, while significant wear damage had occurred on the un-dimpled surfaces. We feel that the superior wear performance of dimpled surfaces may have been primarily due to the fact that very few metal-to-metal contacts had occurred on dimpled test pairs. Furthermore, any wear debris that may have been generated during sliding contact was trapped within the dimples, and hence third-body wear did not take place on dimpled surfaces.

The results of sliding friction and wear tests under reciprocating sliding contact conditions are shown in Figure 2. These tests were run with 9.55-mm diameter M50 steel balls. As is clear, the un-textured surface exhibits the highest friction, while the laser-textured surface has the lowest friction. The friction coefficient of a laser-textured surface with additional hard coating (included in this figure for comparison) was between that of the un-textured and textured surfaces.

Using the same reciprocating test machine, we also explored the scuffing resistance of laser-textured surfaces. As shown in Figure 3, compared to that of the un-textured surface, the scuffing resistance of the laser textured surface was much higher. In an attempt to determine the scuffing limit of laser-textured surfaces, we pursued further tests by increasing the test load stepwise until sliding surfaces scuffed. As shown in Figure 4, these surfaces could endure loads of up to 890 N without scuffing. However, upon further increasing the load to 1100 N, they scuffed. During post-test investigation of scuffed surfaces, we noticed that the dimples on the laser-textured surfaces were destroyed and filled with plastically flowed steel (see inset in Figure 4); hence, they were no longer able to store lubricant and perhaps act as miniature hydrodynamic bearings. We concluded that severe metal-to-metal contact had occurred on these laser-textured surfaces at high loads, and this greatly diminished their ability to resist scuffing.

In an effort to further increase the resistance of laser-textured surfaces to scuffing, we applied a soft

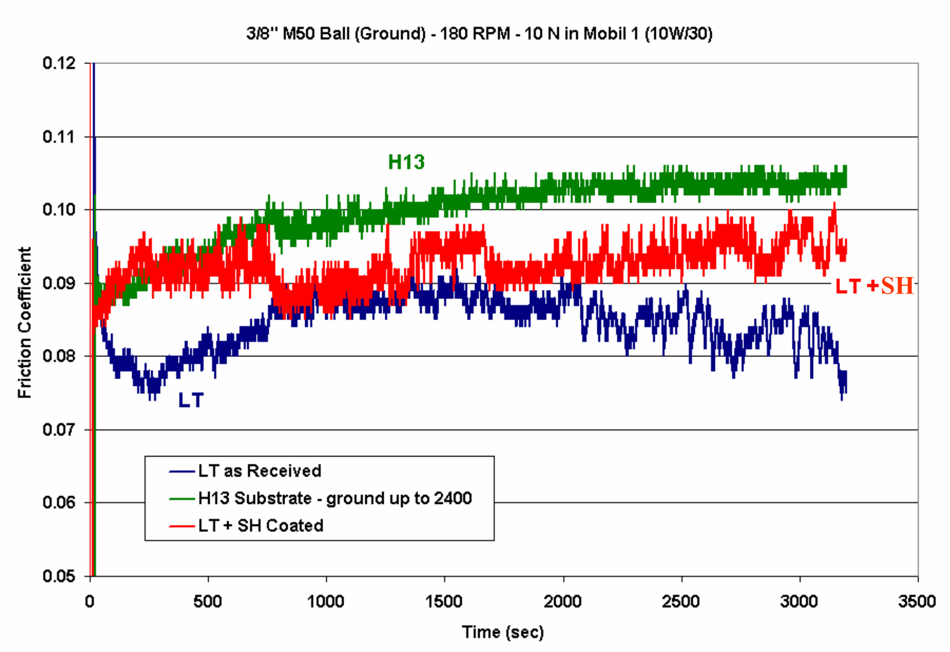

Figure 2. Friction performance of as-received H13, laser-textured (LT) H13, and laser-textured and superhard (SH) coated H13 under boundary-lubricated sliding conditions.

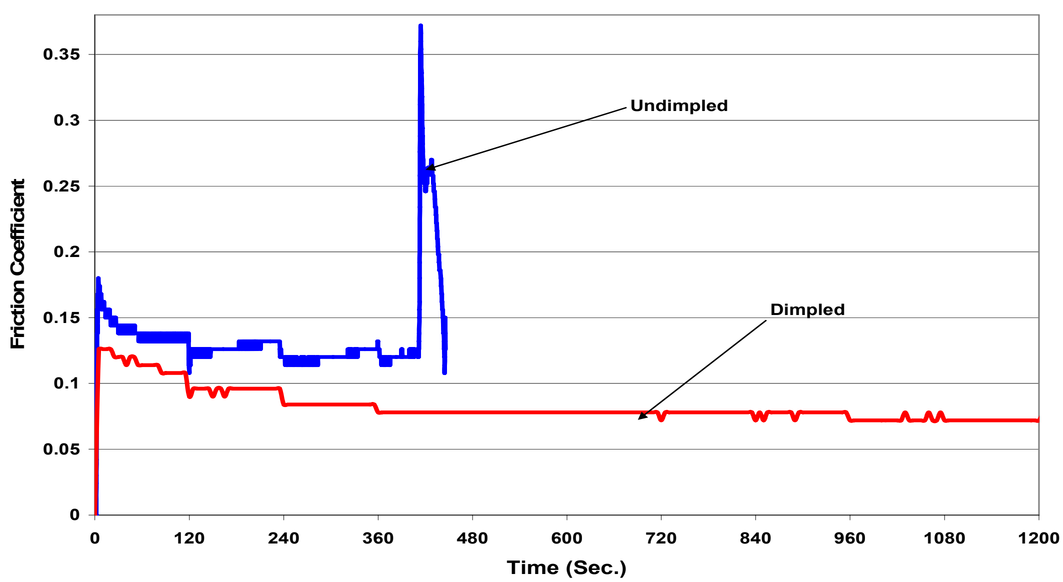

Figure 3. Comparison of scuffing resistance of an un-dimpled and laser dimpled steel sample. The undimpled sample scuffed rather quickly after sliding for about 6 min, while the dimpled sample kept sliding without any sign of scuffing for more than 20 min.

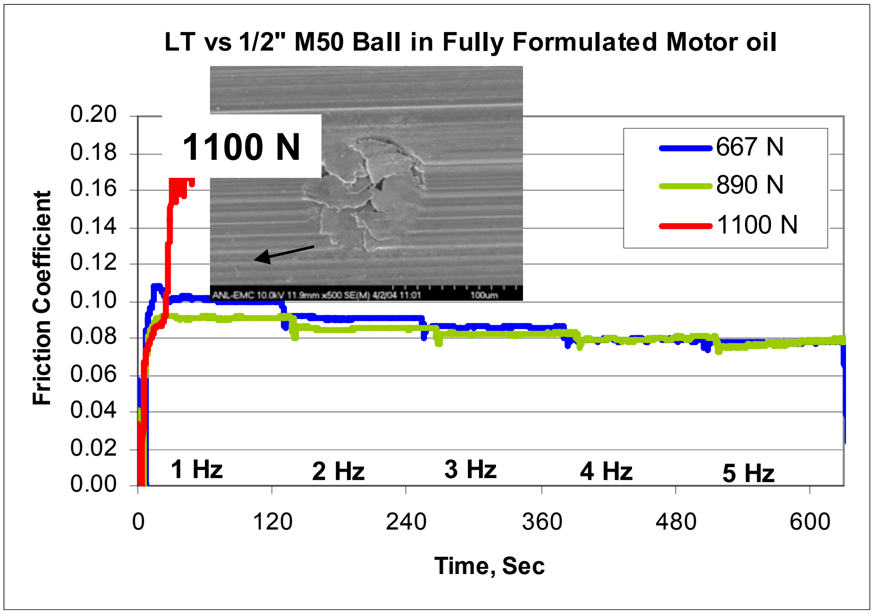

Figure 4. Scuffing performance of laser dimpled steel surfaces that passed the 667 and 890 N load tests, but failed at 1100 N.

(Cu) and a superhard coating over the laser-textured surfaces. We felt that such coatings may have beneficial synergistic effects on the scuff resistance of dimpled surfaces. The dimples were completely filled with Cu, and then the excess Cu was removed from the surfaces by progressively grinding them until the steel substrate was reached, as shown in Figure 5. In the case of a superhard coating, the thickness was kept uniform at around 2 µm inside and outside the dimpled areas. Figure 6 compares the scuffing performance of all samples tested in our study. As is clear, laser texturing combined with Cu and superhard coatings provides the best overall resistance to scuffing. In the case of Cu-filled dimples, microscopic inspection revealed that Cu was smeared on the sliding surfaces and was able to act as a solid or back-up lubricant. Cu is mechanically soft and chemically reactive toward certain ingredients (such as S) in the additive package of lubricant oil and hence can form a low-shear boundary film to prevent scuffing.

In the case of superhard coated surfaces, the resistance to scuffing was the highest of all samples tested, as shown in Figure 6. Superhardness in combination with the hydrodynamic lubrication effect of dimples seems to provide the best surface engineering strategy for preventing scuffing on

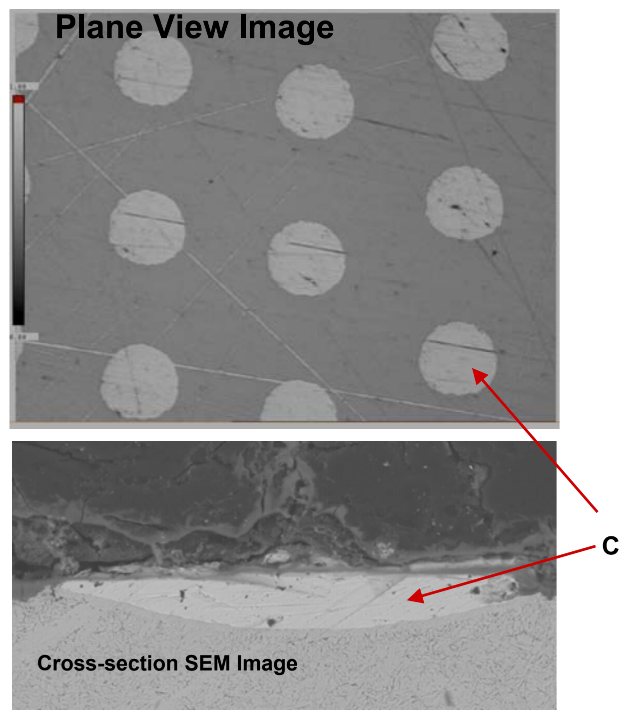

Figure 5. Plane view and cross-sectional SEM images of dimples filled with Cu.

laser-textured surfaces. In short, integration of surface coatings (both soft and hard) with laser texturing has a beneficial synergistic effect on the scuff resistance of textured surfaces.

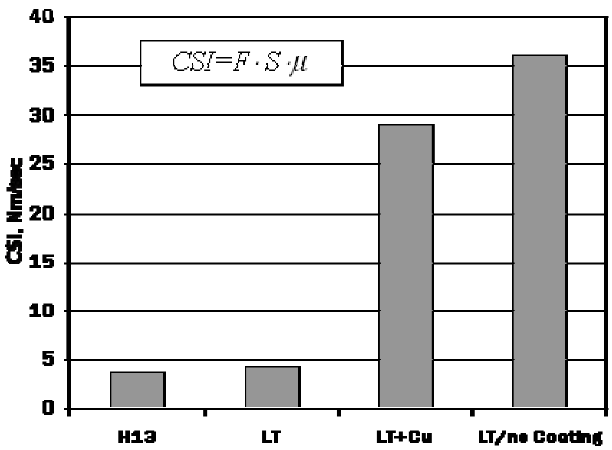

Figure 6. Scuffing performance of H13 base steel, laser-textured H13 steel (LT), laser textured and superhard coated H13 steel (LT/nc-coating), and laser-textured and copper coated (LT+Cu) surfaces. (CSI is the contact severity index, where F is the critical scuffing load in newtons, S is the critical scuffing sliding speed in m/sec, and μ is the friction coefficient shortly before scuffing.)

During this period, we also performed numerous tests on laser-textured rings and liners using a ring-on-liner test machine. The results of these tests have shown that extremely detrimental bulges formed around the dimples. Specifically, these bulges caused high friction and severe wear losses on the counterface rings. Figure 7 shows the shape and morphology of these bulges. We are removing these bulges from sliding surfaces and will soon run new tests to determine the beneficial effects of dimples on friction and wear of rings and liners. With the polishing of these bulges, we expect to significantly reduce the friction of such sliding pairs. To achieve even better tribological performance, we plan to create partial laser texturing on the ring side and to apply copper and superhard coatings on both rings and liners.

Conclusions

During this work period, we have concentrated on assessing the friction, wear, and scuffing performance of laser-textured surfaces. We have demonstrated that laser texturing can have a significant beneficial effect on friction and wear of lubricated sliding surfaces. Specifically, it increases

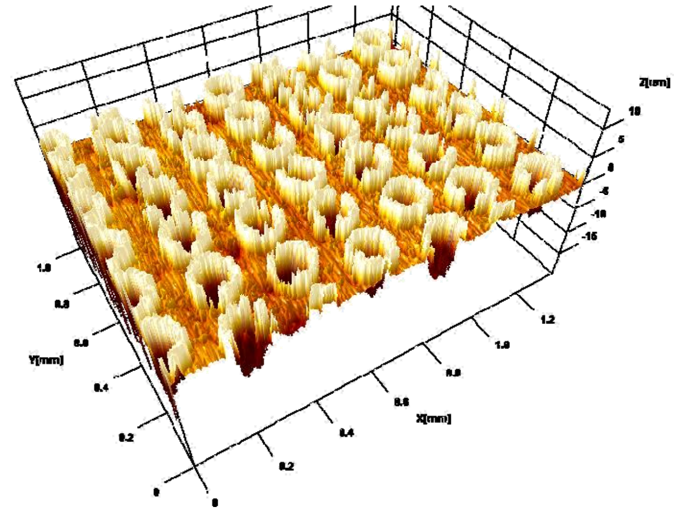

Figure 7. Physical shape of bulges that formed around the dimpled regions during laser texturing.

the boundaries of hydrodynamic lubrication toward lower speed and higher load values. Applying a soft or hard coating over laser-textured surfaces has additional beneficial effects on friction and wear. Such coatings can also dramatically increase the resistance of laser-textured surfaces to scuffing. At present, we are focusing our attention on laser-textured piston rings and cylinder liners. Initial tests with as-dimpled liners revealed the detrimental effect of bulges found around the rims of dimpled areas. With effective removal of such bulges, we expect to significantly improve friction and wear of rings and liners as well.

Publications

During this period, we published and/or presented several new papers on laser texturing. The following is a list of these papers.

1. The Effect of Laser Surface Texturing on Transitions in Lubrication Regimes during Unidirectional Sliding Contact, A. Kovalchenko, O. Ajayi, A. Erdemir, Tribology International, 38 (2005) 219-225.

2. Review of Engineered Tribological Interfaces for Improved Boundary Lubrication, A. Erdemir, Tribology International, 38 (2005) 249-256.

3. Effect of Counterface Properties on Laser Textured Surfaces, A. Kovalchenko, O. O.

Ajayi, A. Erdemir, G. Fenske, I. Etsion, Presented at the 60th Annual Meeting of the Society of Tribologists and Lubrication Engineers, Las Vegas, NV, May 15-19, 2005.

4. Scuffing Resistance of Laser Textured Surfaces. M. K. Kazmanli, O. L. Eryilmaz, A. Erdemir, L. Ajayi, I. Etsion, and M. Urgen, Paper to be Presented at the World Tribology Congress, Washington, DC, September 12-16, 2005.

5. Tribological Behavior of Oil-lubricated Laser Textured Surfaces in Conformal and Point Contacts, A. Kovalchenko, O. O. Ajayi, A. Erdemir, G. Fenske, I. Etsion, Paper to be Presented at the World Tribology Congress, Washington, DC, September 12-16, 2005.

6. Integrated Surface Engineering Approaches to Improved Boundary Lubrication: Merging Multifunctional Surface Coatings with Laser Texturing, A. Erdemir, Presented at the International COST 532 Conference, Porto-Portugal, October 12-14, 2005.

7. Investigation of Scuffing Resistance and Tribological Performance of Laser Modified Surfaces, S. Aldajah and O. O. Ajayi, Presented at the World Tribology Congress, Washington DC, September 12-16, 2005.