Research Signpost
37/661 (2), Fort P.O.
Trivandrum-695 023
Kerala, India

Recent Developments in Wear Prevention, Friction and Lubrication, 2010: 137-157
ISBN: 978-81-308-0377-7 Editor: George K. Nikas

3. Laser surface texturing and applications

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Abstract. Surface texturing has emerged in the last decade as a viable option of surface engineering resulting in significant improvement in load capacity, wear resistance, friction coefficient etc. of tribological mechanical components. Various techniques can be employed for surface texturing but Laser Surface Texturing (LST) is probably the most advanced so far. LST produces a very large number of micro-dimples on the surface and each of these micro-dimples can serve either as a micro-hydrodynamic bearing in cases of full or mixed lubrication, a micro-reservoir for lubricant in cases of starved lubrication conditions, or a micro-trap for wear debris in either lubricated or dry sliding. The present article reviews the current effort being made world wide on laser surface texturing and the potential of this technology in various tribological applications.

1. Introduction

Surface texturing as a means for enhancing tribological properties of mechanical components is well known for many years. Perhaps the most familiar and earliest commercial application of surface texturing is that of cylinder liner honing. Today surfaces of modern magnetic storage devices are commonly textured and surface texturing is also considered as a means for overcoming adhesion and stiction in MEMS devices. Fundamental research work on various forms and shapes of surface texturing for tribological applications is carried out worldwide and various texturing techniques are employed in these studies including machining, ion beam texturing, etching techniques and laser texturing. Of all the practical micro-surface patterning methods it seems that laser surface texturing (LST) offers the most promising concept. This is because the laser is extremely fast and allows short processing times, it is clean to the environment and provides excellent control of the shape and size of the texture, which allows realization of optimum designs. By controlling energy density, the laser can safely

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process hardened steels, ceramics, and polymers as well as crystalline structures. Indeed, LST is starting to gain more and more attention in the Tribology community as is evident from the growing number of publications on this subject. LST produces a very large number of micro-dimples on the surface (see Fig. 1) and each of these micro-dimples can serve either as a micro-hydrodynamic bearing in cases of full or mixed lubrication, a micro-reservoir for lubricant in cases of starved lubrication conditions, or a micro-trap for wear debris in either lubricated or dry sliding.

The pioneering work on LST started at Technion in Israel as early as 1996 [1, 2]. At about the same time work on laser surface texturing was done in Germany but unfortunately, most of it is published in the German language and hence, is not even referenced in English archive journals. A few exceptions are papers coming from the group lead by Geiger at the University of Erlangen-Nuremberg e.g. [3, 4].

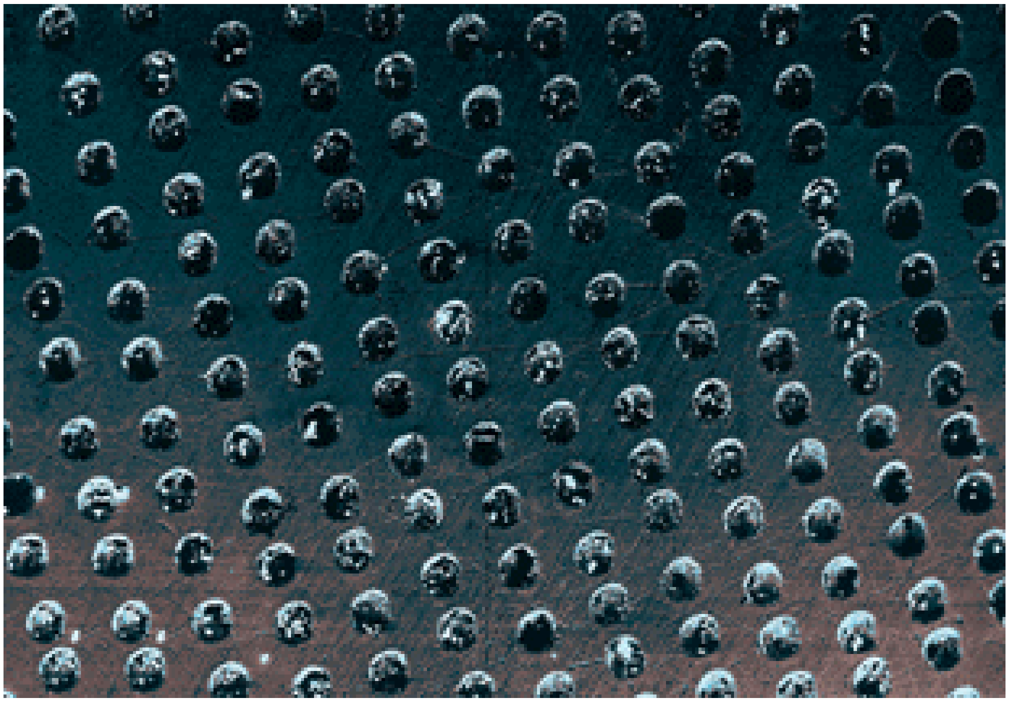


Figure 1. LST regular micro-surface structure in the form of micro-dimples.

This group uses an excimer laser with a mask projection technique, a mask is illuminated with the laser beam and its geometrical information is projected onto the textured surface. This method was applied to a punch, used in a backward cup extrusion process for the production of rivets, and showed a substantial increase of up to 169% in cold forging tool life. These as well as many other papers on LST are described in a review of the state of the art of LST covering this subject until 2005 [5]. In the next sections the work that was done on LST prior to 2005 will be described briefly followed by the new developments since 2005. Laser surface texturing has been used in the magnetic storage industry [6, 7] mainly to prevent stiction during start up. This issue will not be dealt with in the present review. Instead, the potential of LST in enhancing Tribological performance during continuous operation will be described.

2. LST prior to 2005

Laser was used at Tohoku University, Japan [8] to texture SiC surfaces for studying the effect of LST on the transition from hydrodynamic to mixed lubrication regime. An extensive research work on laser surface texturing was done at the Institute of Applied Physics of the University of Bern in Switzerland utilizing Q-switched Nd:YAG but mostly femtosecond lasers [9–13]. A fundamental research work on LST was carried out at Argonne National Lab. in the USA to study the effect of LST on the transition from boundary to hydrodynamic lubrication regime [14].

By far most of the work on LST prior to 2005 was done on dynamic seals. The earlier simple modeling [1] and experiments [2] of LST in mechanical seals were followed by more in-depth theoretical and experimental studies [15]. It was found that the actual shape of the micro dimple does not play a significant role and that the most important parameter for optimum load capacity is the ratio of the dimple depth over diameter. A high stiffness of the fluid film below a clearance of 1 μm and a very good agreement between theory and experiment was shown in [15]. Further testing of actual seals in water [16] showed dramatic reduction of up to 65% in friction torque. Similar results of lower friction and face temperature with laser textured seal face were found in East China University of Science and Technology [17] where textured SiC rings were tested against Carbon rings in oil. In all these cases full LST was used meaning that the texturing covered the full width of the sealing dam. It was found that with full LST the reduction in friction torque is gradually diminishing at higher sealed pressures. To overcome the poor performance at high pressures a special treatment was developed that enhances hydrostatic effects in high-pressure seals [18]. This treatment consists of applying higher density LST over a portion of the sealing dam adjacent to the high-pressure side and leaving the remaining portion non-textured (partial LST). The textured portion provides an equivalent larger gap so that the end result is a converging seal gap in the direction of pressure drop, which produces hydrostatic effect. A Standard commercial seal that is rated to a maximum pressure of 11 bar could be easily operated up to 23 bar when textured with the partial LST providing high pressure sealing capability that is substantially greater than that of the standard non-textured one. Another study [19], on both full and partial LST seals demonstrated the potential positive effect of micro-surface texturing on reducing breakaway torque and blister formation in carbon-graphite mechanical seal faces. The LST advantages are not limited to liquid lubrication only, and dry gas seals can benefit from LST as well [20, 21].

Laser surface texturing for other lubricated applications was also investigated prior to 2005. This was done mainly for piston rings [22, 23] where optimum texturing parameters for minimum friction force were found for full LST rings showing a potential reduction of about 30 percent compared to non-textured rings under full lubrication conditions. The use of laser texturing in the form of micro-grooves on cylinder liners of internal combustion engines was presented at the 14th International Colloquium Tribology in Esslingen Germany [24] showing lower fuel consumption and wear. This technique called "laser honing" is commercially available from the Gehring Company in Germany [25].

Analysis of LST in hydrodynamic thrust bearings of the simplest form of parallel sliding disks [26] has shown the potential of LST in this application. It was found that partial LST can improve substantially the load carrying capacity of these simple bearings and make them comparable to more sophisticated tapered or stepped sliders. Test results in water [27] showed that textured bearings operated with a clearance that is about 3 times larger and friction that is about 3 times smaller than non-textured bearings.

Laser texturing is also used extensively in metal forming as a mean for a secondary hydrodynamic lubrication mechanism which is called micro-pool or micro-plastic hydrodynamic lubrication [28].

The potential benefit of LST in providing micro-traps for wear debris in dry contacts subjected to fretting has been demonstrated in [29] and [30]. The results in [29] showed that the escape of oxide wear debris into the LST micro-dimples resulted in up to 84% reduction in electrical contact resistance of textured fretting surfaces compared to the case with non-textured surfaces. Eventually, the dimples may fill-up with wear debris but the useful life of the LST device would be substantially prolonged. The potential effect of LST on fretting fatigue life was demonstrated in [30] showing improved fretting fatigue resistance and almost doubled fretting fatigue life.

3. LST since 2005

In the period from 2005 through 2007, a growing number of publications on surface texturing appeared in the literature, inspired by the LST development prior to that period. The validity of the Reynolds equation when applied to textured features that have large aspect ratio (the ratio of depth over diameter or width) was questioned and several studies were made to resolve this problem. The Navier-Stokes (NS) equations were solved [31], using a commercial CFD code, for two geometries, cylindrical and spline, of infinitely long single groove in parallel sliding relative to a smooth wall in the presence of incompressible fluid. It was found that fluid inertia was the main contributor to load carrying capacity, which increases with increasing depth and width of the groove. Above a certain aspect ratio a vortex appears in the groove and the load carrying capacity saturates. The groove also reduces the friction between the sliding parallel walls. Similar technique was used in [32] to study the effect of a single rectangular groove for the case of an infinitely long linear convergent slider bearing, and of a 2D pocket for the case of a square bearing pad. It was found that cavitation at the pocket inlet occurs only at very low bearing convergence ratios. The closed pocket can reduce the friction coefficient both at high and low convergence ratios due to its effect on load carrying capacity or on friction force. The pressure distribution and load carrying capacity for a single 3D dimple representing the LST and facing a parallel surface was studied in [33]. Both the full NS equations (using a commercial CFD code) and the Reynolds equation were solved for the case of a compressible fluid at no sliding but with a pressure differential to simulate a hydrostatic gas seal. Comparison between the two solution methods illustrates that in spite of potential large differences in local pressures the differences in load carrying capacity are small for realistic geometrical parameters of LST. Hence, the Reynolds equation can be safely used for most LST applications.

One of the main problems in theoretical modeling of surface texturing effects is the need to deal with a very large number of textured dimples or other features that may consume large computing times. Hence, homogenization techniques may be very helpful in easing this burden. A mathematical analysis based on combination of homogenization techniques and perturbation analysis was presented in [34] to study the effect of periodic textures on the static characteristic of infinitely wide convergent thrust bearings. A multiscale method for modeling surface texture effects in a mixed lubrication journal bearing model was presented in [35]. The local (micro) flow effects for a single surface pocket were analyzed using the NS equations and flow factors were derived that can then be added to the macroscopic smooth flow problem that is modeled by the 2D Reynolds equation. The analysis also accounts for pocket squeeze effect due to surface deformation.

Texturing optimization was studied in [36] using numerically generated textured surfaces technique that was named "virtual texturing". The method was used for preliminary exploration of the relationship between a dimpled texture design, typical of LST, and the mixed lubrication characteristic for a counterformal contact. An interesting optimization technique was presented in [37] where the

Reynolds equation was solved for several micro-textured slider bearing configurations. The dimples were square and arranged in a square pattern. It was shown that non uniform texture provides better performance than the commonly used uniform one.

General experimenting with LST became also popular in the period since 2005. Unfortunately, most of these general experiments were not based on previous theoretical findings and were therefore performed using a trial and error approach when attempting to identify optimum LST parameters. Different test configurations were used in these experiments with different materials and lubricants. Mostly Nd:YAG laser was used for these general experiments [38-41] but also a much shorter pulse femtosecond laser [42]. In [38] a cylinder was reciprocated along its axis against smooth or textured flat plates in distilled water. In [39] a pin-on disk machine was used in unidirectional sliding. The pin was a steel ball with a flat contact area to simulate conformal contact. The disks were polished, ground, and textured with various LST parameters, and tests were performed with both low and high viscosity oils. LST was observed to expand the range of hydrodynamic lubrication regime in terms of load and sliding speed for both high and low viscosity lubricants. Furthermore, a substantial reduction of the friction coefficient in boundary lubrication regime was obtained with LST compared to untextured surfaces under similar operation conditions. In [40] a steel ball was used in oscillating linear sliding against a steel disk that was either polished or textured with different LST parameters. Tests were performed with three different metal working oils. The tests in [41] were performed with a reciprocating flat pin against ceramics and steel plates in distilled water. The plates were textured with different grooves and dimples. The femtosecond laser [42] produces clean texture without the common raised material at the edge of textured features caused by the Nd:YAG laser, which in many cases, require post LST lapping to remove the raised bulges. However, much larger number of pulsed incidents is needed to obtain about 10 μm deep features compared to the Nd:YAG laser. It therefore, took some 25-30 minutes to texture an area of 8x8 mm^2 while with the Nd:YAG laser the required time would be at least an order of magnitude shorter. The tests in [42] were performed with a reciprocating cylinder on flat surfaces that were either smooth or textured and lubricated with oil. A common finding in all these experiments that were carried out in Germany, USA, Finland and Switzerland [38-42] is that textured surfaces have improved tribological performance in terms of friction and wear compared to untextured surfaces under the same test conditions.

A very interesting technique based on interfering laser beams [43] allows minimization of the textured surface features down to the micrometer or even sub-micrometer scale. This laser interference direct structuring can therefore produce lateral feature sizes from sub-micron up to several micrometers by making minor changes in the optical system. What is even more interesting in this technique is the ability to combine topographic texturing of surfaces with micro structural changes for a hierarchical order that can further improve tribological performance. Some applications like centrifuge cast die mold, computer hard disk and automotive engine block, where this technique was implemented are mentioned in [43].

Some additional techniques other than LST were also described in the literature since 2005 as options for surface texturing. These include: Cr-N coating with a randomly crater-like topography [44], diamond embossing tool to create large array of small indents in metallic surfaces [45], and impulse indentation where special ending act as hammers to form oil pockets on metal surfaces [46].

4. Applications

Like in the period prior to 2005 several applications of LST were considered in the years to follow. These include mainly automotive applications such as in-cylinder friction reduction, various types of bearings, seals, elasto-hydrodynamic (EHD) lubrication, magnetic storage and a few others. These applications will be described next.

4.1. Automotive

The early work on LST piston rings [22, 23] considered full width texturing but very soon it was realized that partial texturing may be more beneficial. The difference between these two types of LST is demonstrated in Fig. 2 and the rational for the better performance of partial LST is fully described in Ref. [26]. Basically, in the full width LST the area density of the dimples is relatively small and each dimple acts individually as a micro-hydrodynamic bearing with negligible interaction between neighboring dimples. In the partial LST case the dimple area density is higher and the dimples act collectively to form an equivalent step bearing with higher load carrying capacity and much better performance under high pressure differential.

Both theoretical modeling [47] and experimental verification [48] of the concept of partial LST piston rings were done on relatively simple flat face "piston ring" specimens. The LST parameters for the experiments [48] were: dimple diameter of about 80 μm, dimple depth of about 8 μm, area density of 10% for full LST, and 50% for partial LST. It was shown in [47] that in partial LST an optimum textured

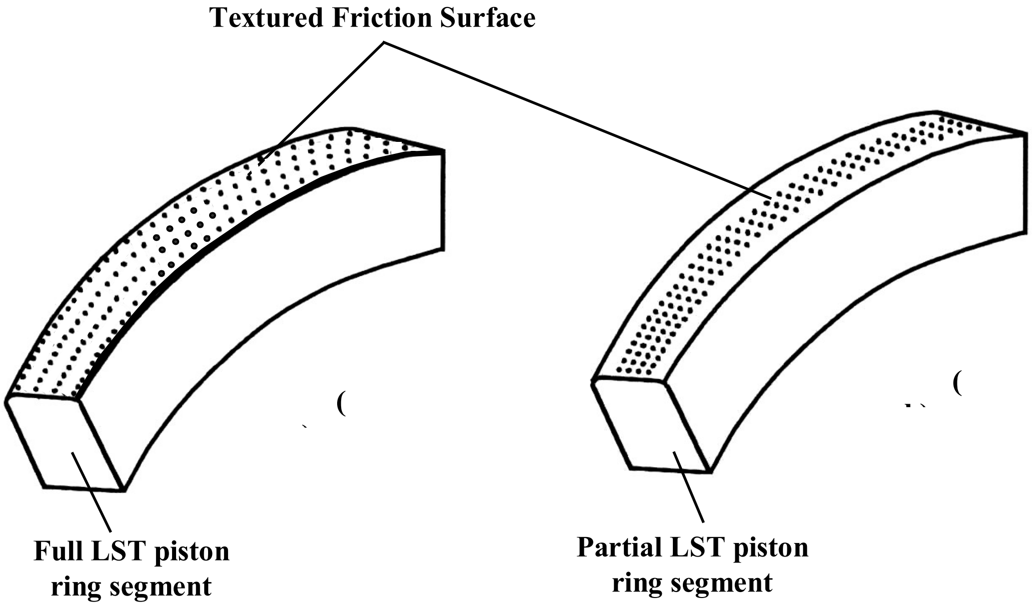


Figure 2. Segments of piston rings: (a) fully textured; (b) partially textured.

portion (the ratio between the width of the textured portion to the total ring width) of 0.6 holds for a wide range of LST parameters and operating conditions regardless of the position of this textured portion on the ring face. Hence, a total textured portion of 0.6 was applied to the partial LST specimens symmetrically at their ends. As expected it was found that the LST has a substantial effect on friction reduction compared to the un-textured reference case. The average friction obtained with the full LST was about 40 to 45 percent lower than in the reference case at low speeds around 500 RPM, and 23 to 35 percent lower at higher speeds around 1200 RPM. These percentage differences between the average friction in the un-textured and full LST cases were almost independent of the external normal load. The results clearly showed additional reduction in friction that can be obtained with partial LST over that of the full LST case as was predicted in [47]. This additional reduction varies from 12 to 29 percent depending on the load and speed.

Some preliminary real firing engine tests that were performed with LST barrel shape rings showed very little friction reduction compared to same un-textured rings. It seems that the barrel shape, which presumably was arrived at by trial and error experience over many years, is not a good candidate for LST. The crowning of the ring face by itself provides strong hydrodynamic effect that masks the weaker hydrodynamic effect of the surface texturing especially at high speeds. Indeed, a more appropriate comparison between the performance of non-textured barrel shape and optimum partial LST cylindrical shape rings, which was performed on a laboratory reciprocating test rig [49], showed a friction reduction of up to about 25 percent with partial LST cylindrical face rings.

A 4-cylinder, Ford Transit, naturally aspirated, 2,500 cc Diesel engine was used at the Ben Gurion University in Israel to test the effect of the LST as applied to the upper set of rings in a firing engine [50]. The rings outer diameter was 93.7 mm and their nominal width was 2.5 mm.

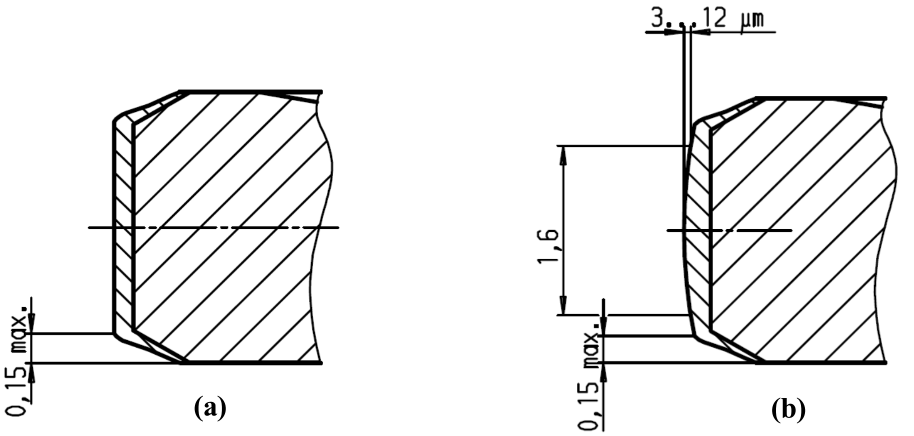
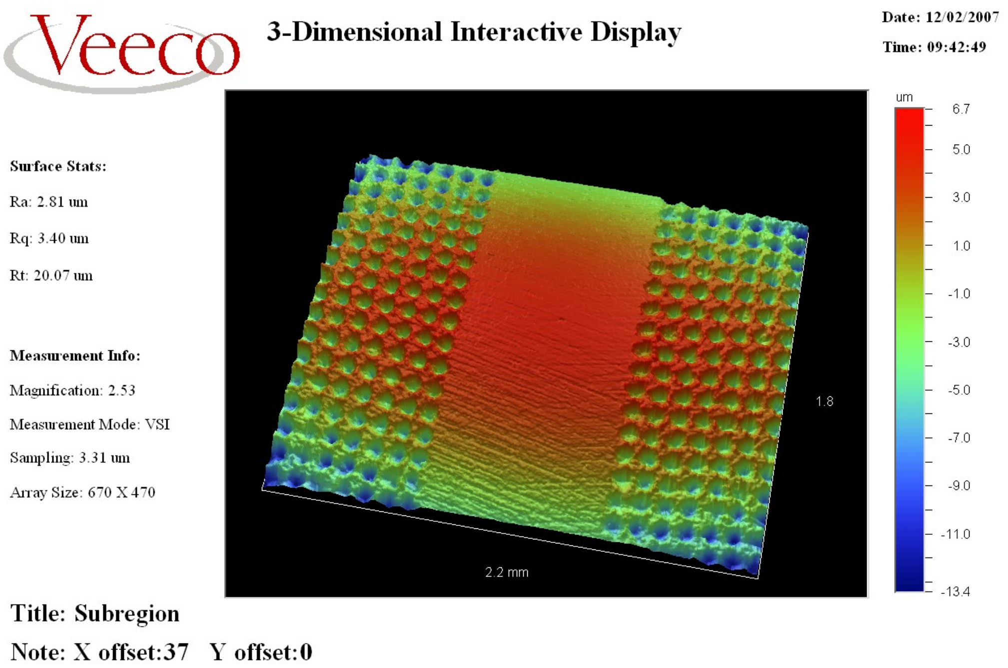


Figure 3. Cross sections of cylindrical (a) and barrel shape (b) Cr coated piston rings.

The peripheral faces of the rings were coated with a Chrome base coating that forms the ring profile in contact with the cylinder liner. Figure 3(a) shows a cross section of a ring with a cylindrical face profile to which partial laser texturing was applied. Figure 3(b) shows a ring with a barrel face profile that is a series production ring and was used as the baseline without texturing. In addition, cylindrical face rings identical to these shown in Fig. 3 but without the Chrome coating were also obtained for texturing.

The laser texturing was applied at both axial ends of the cylindrical face rings with a total textured portion of 0.6. Figure 4 shows a 3D optical profilometer scan of the partial LST cylindrical face ring with the Cr coating. The dimples are located symmetrically along the circumference of the ring on both ends of its width, leaving the central portion of the ring width un-textured. Note also from Fig. 4 that the laser texturing results in bulges of raised material around the rim of the dimples. From previous test rig tests it was found that these bulges are easily removed during the first few reciprocating cycles and hence, no special post LST process is needed to remove them prior to testing.



Date: 12/02/2007
Time: 09:42:49

Surface Stats:
Ra: 2.81 um
Rq: 3.40 um
Rt: 20.07 um

Measurement Info:
Magnification: 2.53
Measurement Mode: VSI
Sampling: 3.31 um
Array Size: 670 X 470

Title: Subregion
Note: X offset:37 Y offset:0

Figure 4. Partial LST Cr coated cylindrical face piston ring.

A comparison between the performance of the reference un-textured conventional barrel shape rings and optimum partial LST cylindrical shape rings with and without the Cr coating is shown in Fig. 5. Clearly the laser treated rings are superior to the baseline reference rings over the entire range of engine speeds. The partial LST piston rings exhibited up to 4 percent lower fuel consumption at 1800 RPM, which corresponds to the maximum torque of the engine.

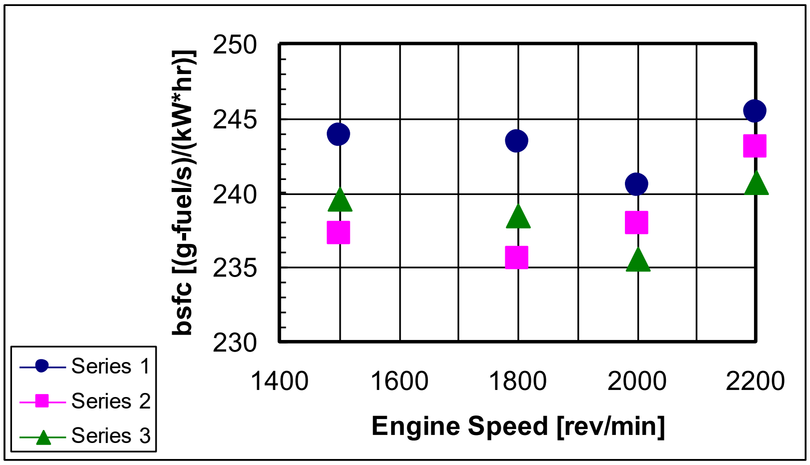


Figure 5. Engine specific fuel consumption vs. engine speed. Series 1: Barrel, chrome coated, baseline ring, Series 2: Flat, chrome coated, laser treated ring, Series 3: Flat, no chrome, laser treated ring.

Other in-cylinder components that were studied for the effect of surface texturing are the cylinder liner [51] and the piston pin [52]. The aim of the research in [51] was to undertake a comparative study between standard cross-hatched (honed) super finish cylinder liners for high-performance engines and those of identical material construction but with surface laser-etched profiles to retain a lubricant film through entrapment. The groove patterns and their interspacing and depth were optimized through a number of numerical simulation studies in order to maximize film thickness at reversal positions. A 449 cm^3 four-stroke, single-cylinder engine was used to test the concept. Interestingly a 4.5 percentage gain in torque was obtained with the laser etched pattern cylinder in Ref. [51], which is very similar to the percentage gain in fuel consumption reported in [50]. Here too the maximum benefit was obtained at the pick torque. Scuffing resistance of piston pin provided by laser surface texturing in comparison with CrN and diamond-like carbon (DLC) coatings and a base-line standard piston pin was studied in Ref. [52]. Scuffing inception could be obtained with low viscosity base oil. In this case, all the treated pins performed better than the standard one, with the laser surface texturing offering the best performance. The search for better texturing in reciprocating sliding suitable for in-cylinder application is still going on as can be seen for example in Ref. [53] where the influence of surface topography on lubricant film thickness has been investigated for reciprocating sliding of patterned plane steel surfaces against cylindrical counter-bodies under conditions of hydrodynamic lubrication.

Inspired by previous finding of the function of surface texturing as micro-traps for wear debris, e.g. [29], a study was carried out on the effect of surface texturing in disk brakes [54]. In order to prevent the dispersion of particles into the surrounding environment a surface texturing in the form of radial microgrooves on the disk was utilized to trap wear particles immediately after their formation. The microgrooves entrapped wear particles from the brake pad/disk sliding interface and also reduced the total wear mass.

4.2. Bearings and seals

An impressive amount of work was done on the effect of surface texturing on hydrodynamic bearings. Several theoretical studies, that were inspired by the earlier publications [26, 27], can be found in Refs. [34] and [55] to [61].

The effect of periodic texture on the static characteristic of thrust bearing was studied in [34] were a question was raised whether a uniform texture can improve the tribological performance of a general non-parallel thrust bearing. The authors concluded that the optimum texture for best performance of such bearings is no texture at all. The same conclusion was stated in [55] where the same technique of

[37] was applied to both incompressible and compressible lubricants. It should be noted however, that in both [34] and [55] cavitation was completely neglected and hence, the conclusion mentiond above is questionable. Indeed, several other studies involving the effect of texturing in convergence film cases do not agree with that conclusion of [34] and [55]

The idea of "inlet suction" was studied in [56] for parallel thrust bearing containing a single pocket near the inlet to the bearing. It was shown that cavitation in this pocket causes lubricant to be "sucked" into the bearing through the inlet land and thus provides load support. This idea of inlet suction was extended in [57] to a linear convergent thrust bearing. It was shown, contrary to the conclusion in [34] and [55], that a textured bearing with realistic cavitation in the pocket performs better than an untextured bearing even with convergent film up to a certain convergence ratio. Only above that convergence ratio the texturing beneficial effect vanishes.

Another theoretical study on partial texturing of parallel thrust bearing is presented in [58]. Here the optimum geometrical parameters of square shaped micro-dimples which give the bets tribological performance of the bearing in terms of load capacity and friction coefficient were sought. An analysis of surface textured air bearing sliders with rarefaction effects is presented in [59]. Both full and partial LST were studied and the optimum LST geometry for best tribological performance of a single row of dimples was found. Here again, like in [57], it was shown that textured slider bearing perform better than untextured bearings even with a small convergence film that can reach 350 μrad in the case of partial texturing. It seems that the conclusion in [34] and [55] regarding the inefficiency of convergent textured bearing was only partly correct and textured bearings do in fact perform better than untextured ones not only in parallel sliding but also with small convergence as well.

The performance of a journal bearing having a smooth journal and a textured bush with square shape micro-dimples was studied theoretically in [60]. Two different cavitation models were used, the Reynolds model and the Elrod and Adams mass conservation model. It was claimed by the authors that, unlike in most untextured bearing configurations, a mass conserving cavitation model is crucial when evaluating the performance of micro-textured bearings. In another theoretical study on textured journal bearings [61] a finite difference numerical model was used to solve the Reynolds equation for a bearing with spherical dimples. It was found that an appropriate re-partition of textures on the bearing surface improves the performance of the bearing. The dimples used in [61] were of relatively large diameter in the order of 1 mm with depth of the order of several μm, and the bearing eccentricity was at least 0.6. With such eccentricity the film thickness convergence is substantial and once again puts in question the conclusion of [34] and [55].

Experimental studies on textured thrust and journal bearings are described in Refs. [62] to [65]. The effect of surface texturing on the performance of tilting pad thrust bearings was studied in [62]. The working faces of six pads from a 228.6 mm outer diameter bearing were textured by milling channels of less than 10 μm in depth into the Babbitt surface. Although no significant change in collar and pad temperature could be observed the textured bearing showed a tendency to exhibit lower power loss, and the inlet and outlet film thicknesses of the textured pads were larger than those for the plain Babbitt pads. The influence of shaft surface texture on the pressure development of journal bearing was investigated experimentally in [63]. Unfortunately, it is not very clear from this paper how the texture affects the bearing performance. It seems that the textured shaft had circumferential grooves, which would not provide the expected hydrodynamic effect of a conventional texturing but this is not clearly specified in the paper. A very well designed and explained experiment with textured journal bearings is described in [64]. The friction characteristic of a journal bearing with different dimpled bushings was investigated. The bearing has a steel shaft and a bronze bushing that was dimpled using two techniques; machining by indenting carbide ball shape burs, and chemical etching. The dimples are rather large with diameters of 2 and 4 mm and depth ranging from 0.13 to 1.04 mm. With proper dimple size, shape and depth a clear benefit of the textured bearing in lowering friction was demonstrated when low viscosity oil was used. A mechanical indentation technique, which the authors named "percussive burnishing", was used to texture the inner diameter of a cylindrical block made of bronze that was loaded against a rotating steel ring [65]. This block-on-ring configuration was used to simulate a journal bearing and study the effect of textured oil pockets on the bearing wear resistance. It was found that the textured oil pockets may increase wear resistance under mixed lubrication condition.

An interesting concept of combining two types of texture geometries is presented in [66] for a configuration simulating parallel thrust bearing or mechanical face seal. A large 350 μm diameter circular dimples with low area density of 4.9% in combination with 4% area density small square dimples having side length of 40 μm were textured onto a flat surface of SiC disk by lithography and reactive ion etching. The textured disk was tested in water while in relative rotation against a SiC ring under gradually increasing normal loading. It was found that the combined texturing performs better than each of the large or small dimples alone in terms of load capacity.

Two theoretical studies [67] and [68] were devoted to analyze the effect of partial LST on hydrostatic gas seals similar to the previous work [18] that was done on liquid seals. The seal efficiency in terms of the ratio of load capacity [67] or gas film stiffness [68] over gas leakage was maximized in these studies by optimization of the texturing geometry. In [67] it was found that a textured portion of 0.5 provides the best efficiency for load capacity compared to the optimum 0.7 value that was found in [68] for the best efficiency of gas film stiffness.

4.3. Elastohydrodynamic lubrication

Differently from the previous applications where the pressure in the fluid film did not cause any deformation of the mating surfaces in relative sliding, some work was also done to evaluate the effect of surface texturing in elasto-hydrodynamic lubrication (EHL), where elastic deformation of the surfaces is important.

An extensive study on the effect of a single dimple on the EHL between a sphere and a disk is presented in [69]. This study includes both experimental and theoretical results with good correlation of the two. For the experiments a 52100 steel ball having a 25 mm diameter was tested with an EHL tribometer against a silica disk with a 60 mm diameter. The rotational speed of the ball and the disk are independently controlled to obtain different slide-to-roll ratios. Isolated circular dimples with a diameter varying from 20 to 120 μm and depth from 0.2 to over 100 μm were produced on the ball surface by a femtosecond pulse laser. Under the test conditions the contact radius between the ball and the disk was maintained at 136.5 μm. It was found that in pure rolling conditions the micro-dimple does not induce any significant variation compared to a smooth ball. When sliding is introduced the film thickness may decrease or increase depending on the dimple depth where shallower dimples are the ones with the positive effect, moving the transition between EHL and boundary lubrication towards more severe operating conditions. The slide-to roll ratio is an important parameter too, showing greater effect of the texturing when the disk is moving faster than the ball. Very similar effects are reported in [70] and [71] where an array of several dimples, produced by micro-indentation of the ball surface instead of just one single dimple as in [69], were passing through the EHL contact. The depth of the micro-dents in [70] varied between 1100 and 1900 nm and their diameter at the ball surface between 90 and 120 μm. An attempt to change the micro-dents depth by polishing the sphere surface changed the micro-dents diameter as well. In the second paper by the same authors [71] the depth of the micro-dents was smaller to begin with, varying between 513 and 1453 nm, but apparently not small enough to show the absolute positive affect of shallower dimples the depth of which according to [70] should be less than 500 nm.

A theoretical study [72] reports virtual texturing and simulation of a group of textured surfaces in a lubricated concentrated contact. The focus of the study is on selecting the best texture distribution patterns for best lubrication performance. The area density of the texture was about 10% and the depth of all the textured features was 3 μm. The geometrical configuration consisted of a textured crowned steel cylinder with radii of curvature 21.5 and 700 mm inside a smooth hollow aluminum cylinder with inside radius of 22.5 mm. Hence, the simulation is of a conformal concentrated contact which is different from the non-conformal concentrated contact cases described in [69] – [71]. It was concluded that narrow short grooves perpendicular to the motion direction seems to be the best choice.

4.4. Magnetic storage

Laser surface texturing was used in magnetic storage mainly to reduce adhesion and stiction at start up e.g. [7]. However, the hydrodynamic lubrication provided by the dimples can be also beneficial during the flying phase of the recording device. The effect of LST on both hard disk sliders and magnetic tapes was studied in [73], [74], and [59]. A theoretical investigation on friction reduction between a magnetic tape and its guide is presented in [73]. It was shown that the friction coefficient can be minimized by creating micro-dimples on the cylindrical surface of the guide (see Fig. 6).

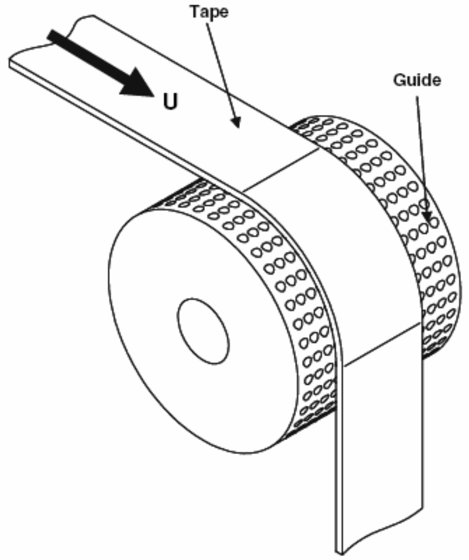


Figure 6. Tape moving over a laser surface textured guide.

The dimples enhance the formation of an air bearing and reduce the friction coefficient between the tape and the guide due to increased spacing. A parametric analysis was performed in [73] to find the optimum LST geometry. It was found that the optimum dimple aspect ratio (depth over diameter) for maximum average air bearing pressure is 0.006 and the best area density is between 0.1 and 0.3. The model results in [73] confirmed previously observed experimental results [74] with two different magnetic tapes and several guide types. Lower friction coefficient was observed in these tests when the performance of LST guide was compared with that of an un-textured commercial guide over a wide range of sliding speeds from 1 to 8 m/s. The LST guide provided earlier take-of speed at 1 m/s with up to 50 percent reduction in friction coefficient at that speed compared to the commercial guide.

A numerical model was developed in [59] to analyze surface textured air bearing sliders in hard disk drives. The effect of the texture on the steady state flying characteristics as well as the flying height modulation, and pitch and roll motion of an actual magnetic recording slider excited by a disturbance on the disk were evaluated. It was found that textured sliders show better dynamic performance compared to untextured sliders in terms of stiffness and damping.

4.5. Miscellaneous

Several other potential applications of surface texturing can be found in experimental studies presented in [75] to [79]. A study of applying micro-texture to cast iron surfaces to improve the tribological properties of reciprocating sliding guideways of machine tools is presented in [75]. It was clearly shown in [75] that the texture can be beneficial or detrimental depending on the texture geometry. For example, groove pattern texture led to a higher friction coefficient while circular dimple pattern texture led to a lower friction coefficient compared to untextured surfaces. In [76] an attempt was made to use surface texturing for improved lubrication at high pressure and low sliding speed of roller/piston in hydraulic motors. The simulated piston surface was textured using embossing tools that generate micro-grooves pattern. It was found that the friction level was only marginally influenced by the textures. An important conclusion that can be drawn from both [75] and [76] is that thorough theoretical modeling, to optimize the texturing geometry, is required to ensure successful texturing. The experimental trial and error approach can easily lead to poor performance with wrong conclusions regarding the benefit of surface texturing.

A somewhat different potential application for surface texturing is described in [77] and [78] where textured dimples are used as reservoirs for solid lubricant. In [77] a UV laser beam was used to LST the surface of hard TiCN coatings with area density between 0.5% and 50%. Solid lubricants based on MoS_2 and graphite were then applied by burnishing and sputtering to the textured surfaces. Friction tests against steel balls indicated an optimum area density of about 10% resulting in an order of magnitude longer life of the solid lubricant on the textured surfaces compared to that on untextured ones. A very similar concept is presented in [78] where the surface texturing was performed by using pulsed air arc treatment. Here too friction tests were performed against steel balls showing between 1.75 to 3 times longer life of the solid lubricant. Finally a new Electrolytic plasma technology EPT is claimed by the authors of [79] of being capable to combine the benefits of LST in texturing with coating and alloying of surfaces.

5. Summary

A review of surface texturing, and more specifically laser surface texturing (LST), has revealed the potential of this technology in improving tribological performance of various mechanical components over a wide range of different operating conditions. The micro-dimples produced on the surface by a pulsating laser beam can act as micro-hydrodynamic bearings in cases of full or mixed lubrication with either incompressible or compressible lubricants. These dimples can serve as micro-reservoirs for lubricant in cases of starved lubrication conditions, in EHL, and for solid lubricants, and they can also provide micro-traps for wear debris in either lubricated or dry sliding.

Many theoretical and experimental studies on surface texturing were performed by a large number of researchers with various types of texturing geometries and with different texturing technologies. These researchers come from many countries around the world as shown in Table 1. The Table presents the distribution of researchers by countries of origin and references corresponding to work done in the period from 2005 through 2007. In almost all these studies surface texturing showed a beneficial effect on the tribological performance. Some of the experimental studies involve limited trial and error approach which not always was able to produce the expected benefit. On the other hand whenever a thorough theoretical modeling was performed with extensive parametric analysis to optimize the texturing geometry, success during following experiments was inevitable. Of all the various technologies used for surface texturing like, for example, machining, embossing, ion beam texturing, etching etc the LST is probably the most advanced so far. It is friendly to the environment, can be used on almost any material, is very precise and can be incorporated in production lines for fast processing. LST is finding its way into different applications and will probably become a widely accepted technology of surface engineering.

Table 1. Distribution of researchers by countries of origin and by references corresponding to work done in the period from 2005 through 2007.

Country	**References**
Algeria	61
Argentina	34, 38, 55, 60
Brazil	60
Czech Republic	70, 71
Finland	40*
France	34, 37, 55, 60, 61, 69*
Germany	38*, 40*, 41*
Greece	40*
Israel	33, 39* 47, 48*, 49*, 50*, 52*, 59, 67, 68, 73, 74, 78
Japan	66, 72, 75
Netherlands	35
Poland	46, 65
Sweden	31, 40*, 45, 62, 76
Switzerland	40*, 42*, 44
Turkey	63
UK	32, 44, 51*, 53, 56, 57, 58, 62
USA	36, 39*, 43*, 54, 59, 64, 72, 73, 74, 77, 79

* indicates experimental work involving LST

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