

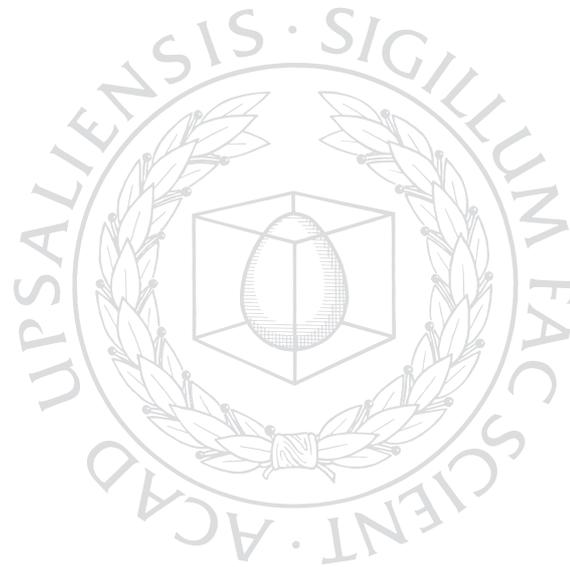


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Surfaces Designed for High and Low Friction

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Abstract

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This thesis comprises tribological studies of extremely well-defined surfaces of different designs. Both low-friction and high-friction surfaces were manufactured and experimentally evaluated.

In the low-friction studies, lithography and anisotropic etching of silicon was first used as a texturing technique. The textured surfaces were subsequently PVD coated with TiN or DLC to achieve tribologically relevant interfaces. The results showed that under starved lubricated conditions, fine surface textures lowered the coefficient of friction and the wear rate. It was shown that also the orientation of the texture is of major importance for the lubricating function.

Further, a novel embossing technique was developed, permitting texturing of steel and other materials. A micro mechanically designed diamond tool was used to emboss steel surfaces. The roller/piston contact from a hydraulic motor was simulated and introduction of an embossed texture on the piston decreased the level and the fluctuation of the friction. The effect of the texture was here similar to the effect of an additional polish step. However, in general it is not an easy task to substantially improve a boundary lubricated contact by introducing a texture.

Studies of high friction surfaces were performed on micro mechanically designed diamond surfaces equipped with sharp pyramids or ridges. Just as theory predicts, the coefficient of friction was dependent on the shape of the ploughing bodies, but not on the counter material or the load. The tested surfaces resulted in static coefficients of friction between 1.1 and 1.6, depending on surface design and orientation. These are extremely high values, and therefore very interesting for practical applications requiring a high static friction.

Conclusively, the present thesis shows that it is possible to design and produce surfaces both for improved lubrication in sliding contact and for substantially improved high friction performance in static contacts.

Keywords: tribology, friction, surface texture, surface design, low friction, high friction, boundary lubrication, DLC, embossing

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List of enclosed papers

- I Influence of surface texture on boundary lubricated sliding contacts*
U. Pettersson and S. Jacobson
Tribology International, 2003. 36: p. 857-864.
- II Friction and wear properties of micro textured DLC coated surfaces in boundary lubricated sliding*
U. Pettersson and S. Jacobson
Tribology Letters, 2004. 17(3): p. 553-559.
- III Tribological texturing of steel surfaces with a novel diamond embossing tool technique*
U. Pettersson and S. Jacobson
Submitted to Tribology International
- IV The effect of embossed surface textures on the friction and wear in a boundary lubricated contact*
U. Pettersson and S. Jacobson
Accepted for publication in Wear
- V Textured surfaces for improved lubrication at high pressure and low sliding speed of roller/piston in hydraulic motors*
U. Pettersson and S. Jacobson
Submitted to Tribology International
- VI Textured surfaces in sliding boundary lubricated contacts – mechanisms, possibilities and limitations*
U. Pettersson and S. Jacobson
In manuscript
- VII Extreme surfaces for high coefficients of static friction*
U. Pettersson and S. Jacobson
In manuscript

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The author's contribution

The author of this thesis has performed the major part of planning, all experimental work, the major part of evaluation and interpretation of the results and been the principal writer of all included papers.

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Introduction

Tribology

The subject of tribology was first defined in a British Department of Education and Science Report in 1966 as: “The science and technology of interacting surfaces in relative motion and the practices related thereto” [1]. The word tribology is based upon the Greek word *tribos*, which means rubbing. Tribology involves the study of lubrication, friction and wear. It is thus an interdisciplinary science, connecting knowledge of physics, chemistry, metallurgy and mechanics.

Although the science did not get its name until the 20th century, it is a very old subject. The first recorded tribologist is found on a painting from Egypt (2400 B.C.), see Fig. 1. Aristoteles (384-322 B.C.) was the first to recognize the force of friction. Leonardo da Vinci (1452-1519) studied and documented friction experiment and he concluded that the friction force is proportional to the normal force. In 1699 Amontons established the concept of asperity interaction. Leonhard Euler (1707-1783) was the first to introduce the parameter μ , denoting the coefficient of friction, and he was also the first to make a clear distinction between static and dynamic friction. In 1922, Sir William Bate Hardy introduced the term boundary lubrication [2].



Figure 1. The first recorded tribologist, pouring lubricant (probably water) in front of the sledge in the transport of a statue in Egypt (2400 B.C.) [2].

Extended knowledge in the field of tribology has always been of great industrial interest. Industry of today needs to be able to reduce or control friction and wear to improve safety and to save money, energy and environment.

Similar aims have historically been achieved by design changes, selection of improved bulk materials or lubricants. Recently tribologists have become more focused on surface engineering as a tool control friction [3]. Components can be optimized by using a bulk material that is selected for the mechanical strength and toughness combined with correct surface treatments or coatings for the best tribological performance. The surface is the most important part of many engineering components since it both sets the functional properties, such as friction and wear, and determines the lifetime.

The most common way of reducing friction and wear is to bring a lubricant between the two surfaces. If the lubricant separates the surfaces completely, a *full film lubricated* contact is formed. This requires a pressure in the fluid high enough to balance the load. Then viscous shearing of the lubricant is the only resistance to movement. If the pressure in the lubricant is too low to keep the surfaces separated and there is interaction between asperities, then the contact is *boundary lubricated*. In boundary lubrication the viscosity of the lubricant is of minor importance, while the ability of the lubricant molecules to bind to the solid surface and providing an easily shared interface contributes to the friction. The region between full film and boundary lubrication is referred to as *mixed lubrication*. Factors that improve the chances of achieving full film lubrication instead of boundary lubrication are: higher sliding velocity, higher lubricant viscosity, lower load and a higher degree of conformity between the surfaces.

The surface appearance is important for both the lubrication regime and the level of friction. A rough surface in boundary lubrication often gives a deformation component to the friction. The friction of a well-polished surface in boundary lubrication is dominated by the adhesive shearing of the interface. With the aim to control friction, either high or low, a control of the surface is of major importance.

Surface design for controlled friction

Introduction of a controlled surface texture can decrease the friction and improve the tribological properties of a sliding surface. Typically, surface textures for friction reduction comprise a flat surface interrupted by local depressions. The improving mechanism of the depressions depends on the contact situation. In full film lubrication the depressions can increase the hydrodynamic effect of the lubricant [4-6]. In boundary lubrication, the depressions can act as reservoirs to supply lubricant inside the contact even during sliding [7,8]. In dry and also sometimes in boundary lubricated cases the depressions can trap wear particles and thus the ploughing and deforma-

tion components of friction can be reduced and the lifetime of the contact increased [9,10].

A number of industrial tribological situations have been improved by surface texturing. Examples include the honing pattern on cylinder surfaces in combustion engines, the start and stop area on hard discs and the pattern on rolls for sheet metal forming. With a better understanding of the acting mechanisms it should be possible to find optimal surface designs to gain both low, stable and controllable friction and minimal wear. Designed textures could then be optimized for a range of new applications.

Surface design can also be utilized to increase the coefficient of friction. A high friction is desirable in numerous applications such as fixtures, couplings and bolted joints. The high friction can be achieved in two ways, either by choosing a high-friction material combination or by producing a rough surface on the harder member of the friction couple and thus increasing the ploughing component of friction. The material combination for high friction is very sensitive for surface contamination before the assembling of the component. Even a very thin layer of water or lubricant would reduce the friction. A rough surface gives a high friction against a softer surface irrespective of presence of lubricants. The sharper the tips of the rough surface, the higher the friction. Very sharp tips diamond, the hardest material of all, should be the ideal choice for demanding high-friction applications.

This thesis

The aim of this thesis is to further improve the understanding of surface design in relation to the acting friction mechanisms, primarily in boundary lubricated contacts. Both low-friction surfaces and high-friction surfaces are studied. This thesis begins with a chapter on industrial texturing techniques, then turns to the experimental texturing techniques developed and used in this thesis, including silicon micro machining, diamond micro machining and then the newly developed embossing technique. The tribological evaluation methods used are then presented. This is followed by two chapters on the contributions in the field of surface textures for first low-friction and then high-friction applications. Finally, a conclusive summary with proposed future work is presented.

Surface design techniques

Industrial texturing

The easiest way to texture a surface for low-friction applications is to simply make it rougher (*stochastic*) and then remove the protruding edges. Another possible way is to use porous materials where the pores can act as reservoirs for lubricants, with the advantage that new pores will appear as the material is worn. Stochastic texturing is used industrially for example in sheet metal forming, where the rolls are sometimes textured with shot blasting, electrical discharge texturing or electro chromium deposition. In shot blasting the surface is blasted with small, hard particles leaving a random rough and deformation hardened surface. In electrical discharge texturing small electrical discharges roughens the surface. Electro deposition of chromium is also used on steel sheet rolls and it results in a randomly textured surface with a top layer of relatively wear resistant chromium.

Other texturing techniques used in sheet metal forming are *electron beam* texturing and *laser* texturing. A deterministic pattern can be produced with a focused beam (laser or electron) that evaporates or ablates local spots on the surface resulting in circular crater-formed depressions, see Fig. 2. Laser texturing has recently attracted a lot of interest in many different application fields such as seals, bearings, cylinder bores and hard discs. Even laser texturing of thin tribological coatings is now investigated [11-13].

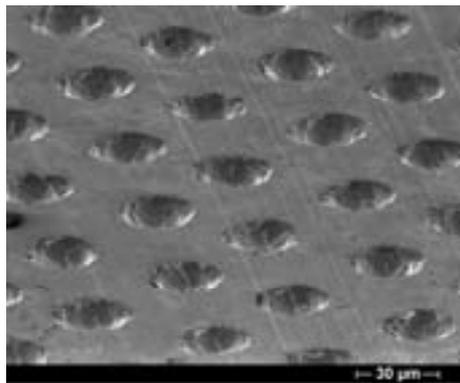


Figure 2. A ball bearing steel surface treated with laser texturing.

A well-established use of texturing for providing improved tribological properties is the *honing* of cylinder surfaces in combustion engines. The cylinder surface is treated with diamonds or stones to receive a cross-hatch pattern of fine scores. The purpose of this pattern is to retain oil and provide good piston ring lubrication. In the old days, the cylinders were honed to size and the rings did the final finishing of the bore surface. But this required a long break-in time and shortened the life of the ring. With today's thin engine blocks, low-tension piston rings and coated rings, the cylinder needs to be as close to a broken-in condition as possible when the engine is first fired up. Otherwise the engine might consume too much oil and never seal properly. Since the 1960s, the honing is finished with a step called plateau honing, which is a fine polish of the honed surface to remove the protruding edges from the honing step. With a smoother bore finish the ring lasts longer and wear less. A typical honed surface is shown in Fig. 3.

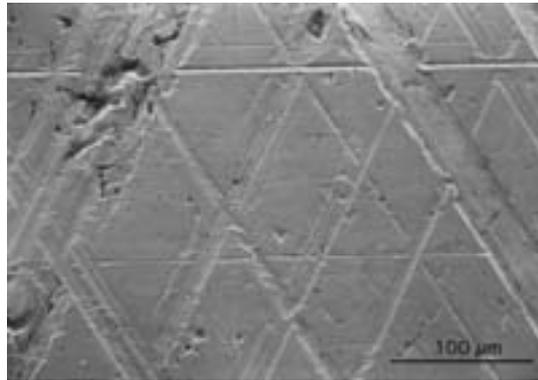


Figure 3. A plateau honed cylinder bore surface in a combustion engine.

Silicon micromachining

Wet bulk micromachining of silicon, widely used in the MEMS-industry, was the first choice of surface texturing in this work, since it is an interesting alternative for production of extremely well-controlled surface textures for fundamental studies. By lithography and anisotropic wet etching, textures with a precision in the sub-micrometer scale can be achieved. The technique leaves no protruding edges or other unintended features at the load bearing area.

In standard micromachining processes, a pattern is transferred from a mask to the substrate. The mask protects some areas of the substrate, while other areas are consumed, etched, by chemicals. A common way to transfer the pattern is to use a photosensitive polymeric film (resist) and lithography. In the case of silicon, silicon oxide is a perfect mask material since it is very

easy to produce by oxidation in a furnace, has chemical properties very different from silicon and the adhesion to the silicon is very good.

Wet etching is a process where material is removed by chemical reactions at the surface. The etching can be either isotropic or anisotropic. In isotropic etching the material is etched with the same rate in all directions, while in anisotropic etching the rate differs between different crystal planes. Etching of (100) silicon with potassium hydroxide, used in this study, leaves the slowly etching (111) planes as walls of the texture depressions [14].

The surface patterns produced for Paper I and II include squares placed in a quadratic array pattern and parallel grooves. Both grooves and squares were manufactured to three different widths; 5 μm , 20 μm and 50 μm consistently distributed to keep a load bearing area ratio of 75%, see Fig. 4.

High resolution, high precision and freedom in choice of shape, make etched silicon wafers an interesting alternative for optimisation and fundamental studies. However, this technique has some drawbacks; it is limited to silicon, which has poor tribological properties, and further, the recesses formed exhibit very sharp edges. This can be solved by combining the anisotropic etching with isotropic etching to blunt the edges. To achieve more suitable wear properties, the textured surfaces can subsequently be PVD coated with tribological thin films, as in Paper I and II.

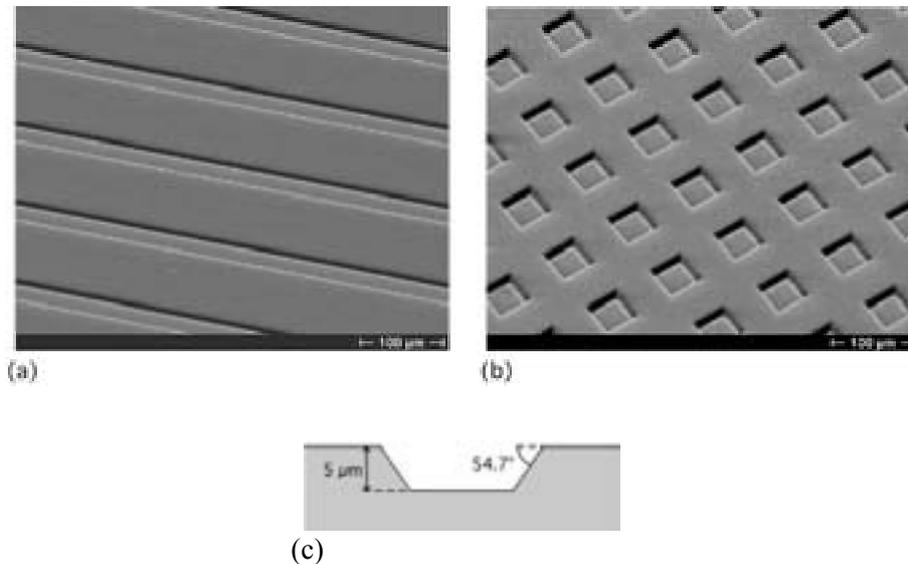


Figure 4. Silicon surfaces with anisotropically etched surface textures, all distributed to keep the load bearing area at 75%, (a) grooves and (b) square depressions. (c) Profile of both patterns, with the depth of 5 μm and the angle 54.7° between the original surface and the texture wall.

Designing diamond surfaces

In this thesis, all-diamond surfaces equipped with very sharp pyramids or ridges have been used for two different purposes. Firstly, they have been used as embossing tools to press textures into metallic surfaces in Paper III-V. Secondly, they have been used as high friction surfaces, as evaluated in Paper VII. The designed diamond surfaces were manufactured using a unique replica technique developed at the Ångström laboratory [15,16]. The technique involves production of a well-defined etched silicon surface as described above, but now to be used as a mould. The silicon mould is coated (“filled”) with diamond that is subsequently backed up with electroplated nickel, see Fig. 5.

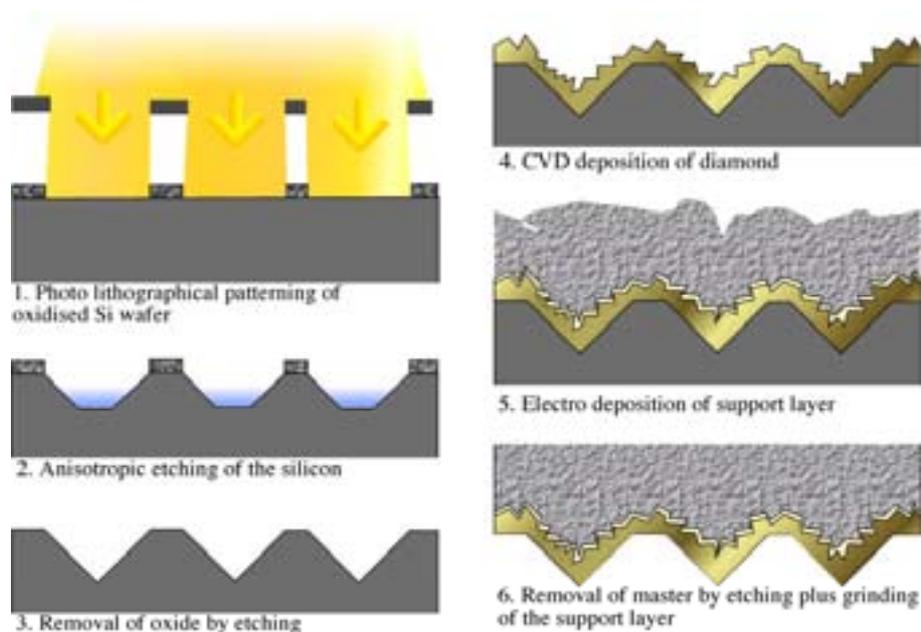


Figure 5. The replication technique involving six main steps; 1) patterning of a silicon wafer surface, 2) anisotropic etching to shape the mould, 3) removal of oxide layer 4) diamond deposition onto the mould, 5) nickel backing to offer the thin diamond coating support and finally 6) exposure of the final diamond surface by removal of the silicon plus planarisation of the backing.

The replica technique involves the following six main steps:

1-3) The silicon micromachining, as it is previously described.

4) An about 10 μm thick diamond film is deposited onto the wafers using Hot Filament Chemical Vapour Deposition (HFCVD). The film is grown in 1% methane in hydrogen atmosphere at approximately 30 mbar. The tungsten filaments are placed in an array to provide a large area of constant depo-

sition conditions. The estimated substrate temperature during deposition is 850 °C.

5) The diamond structures are mechanically supported by electro-plating a backing of nickel, a few millimetres thick. To enhance the adhesion, an intermediate layer of titanium is deposited on the diamond prior to the nickel deposition.

6) Finally the silicon is totally removed by isotropic offer etching and thus exposing the finished designed diamond surface shown in Fig. 6.

The diamond surfaces were made in two main designs: pyramids and ridges. The pyramid tops were spaced from 20 μm to 875 μm . The length of the ridges varied from 20 μm up to 30 mm, and their top spacing varied from 20 μm to 160 μm . The top angle of the pyramids and ridges is 70.5°.

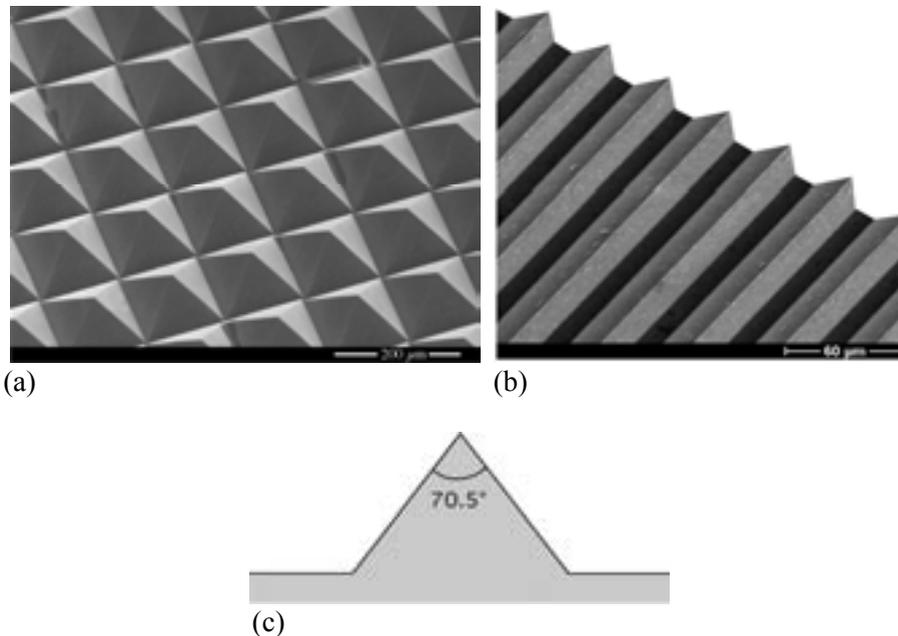


Figure 6. Designed diamond surfaces. (a) Close-packed 100 μm based pyramids. (b) Long protruding sharp ridges with a top spacing of 30 μm . (c) A cross section of a ridge or a pyramid.

The presented process to design diamond surfaces utilizes the advantages of lithographic etching of silicon wafers. Single crystalline silicon offers both the possibilities of photolithographical processing and a thermal expansion close to that of diamond, which is a necessary requirement for film adherence. The thickness of the diamond coating is determined by the growth rate (here $\approx 0.5 \mu\text{m} / \text{hour}$) and the deposition time. The films in this thesis have been about 10 μm thick. Diamond is the hardest of all materials, it is chemical inert and shows generally a very low friction coefficient and adhesion

against many different materials. It is therefore an excellent material for the applications presented here. The surface of a the as grown CVD diamond film is very rough, but by moulding the diamond, a surface roughness in the nanometre scale is achieved on the final designed diamond surface.

Embossing of metals

As part of this thesis work, a new technique has been developed to produce micro-scale textures by firstly manufacturing diamond embossing tools and then embossing a pattern of indents into a metallic surface, see Paper III. The embossing technique has so far been tested on spherical and on flat surfaces.

Embossing of ball surfaces

The finished embossing tools were used to micro texture local spots of ball bearing steel balls, see Fig. 7. Here, each ball was pressed with 1000 N load against the embossing tool, using a hardness tester. A release agent was applied to prolong the tool lifetime. This produced a pattern of identical indentations on a circular area of 1 mm in diameter on the ball surface.

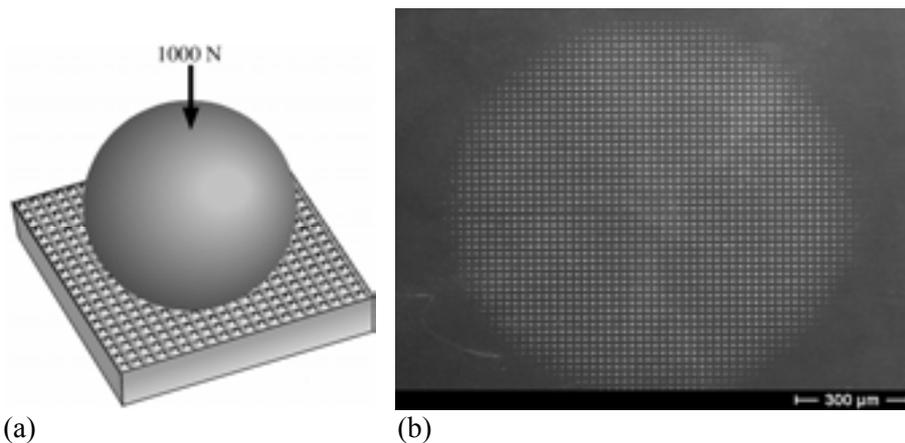
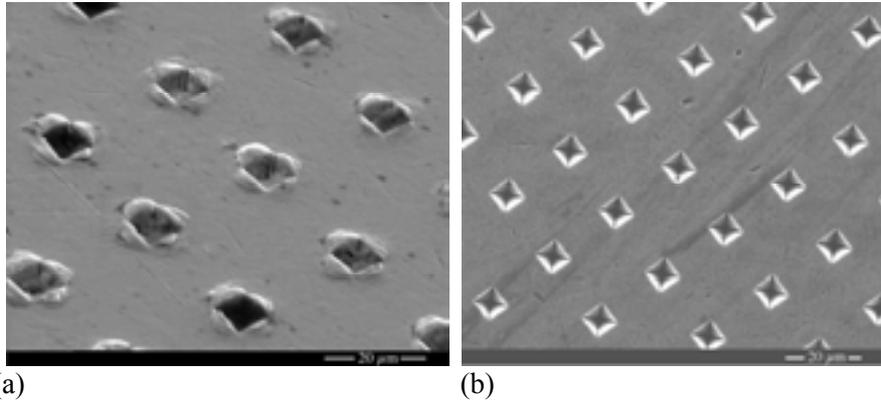


Figure 7. Embossing of ball by pressing against the textured embossing tool. (a) The principle. (b) Micrograph of ball surface textured with an embossing tool comprising 20 μm spaced pyramids. Note the uniform size of the depressions, almost out to the rim.

Each single indent exposes ridges of displaced material, as can be seen in Fig. 8a. These ridges are more prominent than typical ridges formed in Vickers hardness measurements, due to the sharper pyramid angle used here. The surfaces were lightly polished with 1 μm diamond particles on a cloth, to remove the ridges. This leaves the desired pattern of depressions in an otherwise flat surface, see Fig. 8b.



(a) (b)
Figure 8. Indentations of an embossed ball surface before (a) and after (b) polish, showing the removal of unwanted ridges and the regular and well-defined end-result. The embossing tool used comprised 20 μm spaced pyramids.

Since the ball bearing steel has a higher hardness than the nickel backing, a macroscopic ball-shaped indentation is produced on the flat tool surface, while the individual diamond pyramids make micro indents in the ball surface. Note that only the tips of the pyramids are indenting. The pressure is constant over the whole plastically deformed tool area, and thus all the indents, except for those in the outer rim, will be of equal size. The fraction of indented surface is limited by the hardness of the nickel backing in relation to the hardness of the ball. Hence, when the nickel is fully plasticized it is not possible to increase the area fraction or size of the individual indent, by increasing the load. One possible means to increase the fraction of indented surface is to emboss the surface repeatedly, interrupted by a small controlled displacement of the tool, as is shown in Fig. 9. Another way is to choose a backing material with a higher hardness than electroplated nickel.

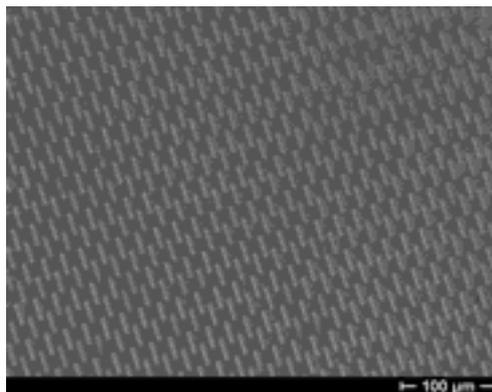


Figure 9. A micrograph showing an embossed ball surface, where a small diagonal displacement of the tool resulted in a higher density of depressions. The embossing tool comprises 20 μm spaced rooftop shapes of 20 μm in length.

Embossing of flat surfaces

In another set of experiments, published in Paper IV, flat surfaces were micro textured using a similar embossing technique. Here, squares of 2 x 2 mm of the embossing tool were cut out and placed with the diamond surface facing the steel surface. A release agent was applied to prolong the tool life. A load of 1000 N was applied using a hardness tester equipment. To facilitate self-adjustment, the load was transmitted through a 10 mm steel ball, located centrally on top of the tool piece, see Fig. 10. When properly embossed, the flat surfaces showed a pattern of evenly sized indents over the whole treated area. Also in this case the limitation of the indent size was the plastic deformation of the tool.

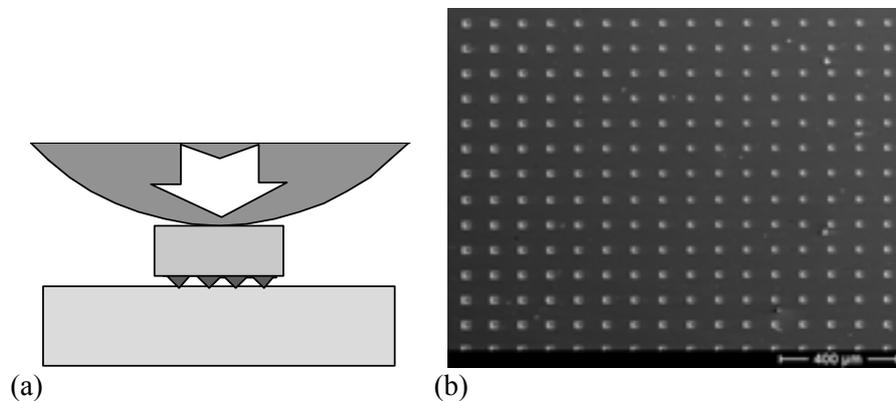


Figure 10. The technique of embossing relatively small flat metal pieces in a hardness tester. (a) The principle. (b) Micrograph showing a part of a steel surface, textured with an embossing tool comprising 80 μm spaced pyramids.

After proven useful to emboss small areas, the technique was scaled up to emboss larger areas (up to Ø 1 cm), by using a hydraulic press. Flat pieces of cemented carbide were used closest to the tool and the sample. A load of 45 000 N was successfully applied on a steel sample of 1 cm in diameter. This embossing technique was used for Paper V. An example of a surface textured in the hydraulic press is shown in Fig. 11.

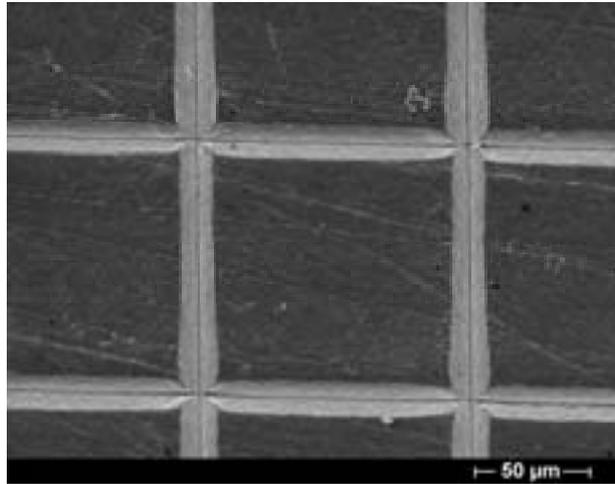


Figure 11. Example of embossed steel surface with a mesh pattern of 120 μm spaced grooves.

Use of the embossing technique

The embossing technique presented has proven successful in providing well-defined patterns in flat and curved steel surfaces. Evenly sized depressions were produced over the greater part of the textured areas (up to $\text{\O} 1 \text{ cm}$ in a single pressing).

The high quality of the surfaces produced makes this a promising lab scale technique for fundamental studies and for optimizing texture patterns and sizes for tribological surfaces.

Obviously, much development is still needed to transfer this into an industrial production technique. Techniques to produce much larger embossing tools, probably most efficient if made in the form of rolls, are needed to allow embossing of larger flat areas.

The embossing tools can also be used for fundamental studies on the hardness of materials. The uniform size of all the central indents in a ball surface, shown in Fig. 7, is an experimental evidence for the uniform pressure within large hardness indentations. By adapting and refining this experimental approach, more information could be collected regarding pressure distribution as a function of load of various materials, and also regarding the hardness distribution in multiphase materials, etc.

Tribological evaluation

The tribological performance of the textured surfaces presented in this thesis has been evaluated from tests in three different equipments, reciprocating ball on flat, rotating ball on flat and finally a reciprocating flat on flat set up, see Fig. 12. In all cases the friction force was measured continuously. The load was applied with a spring or a dead weight and the tests were performed in room temperature and lab environment.

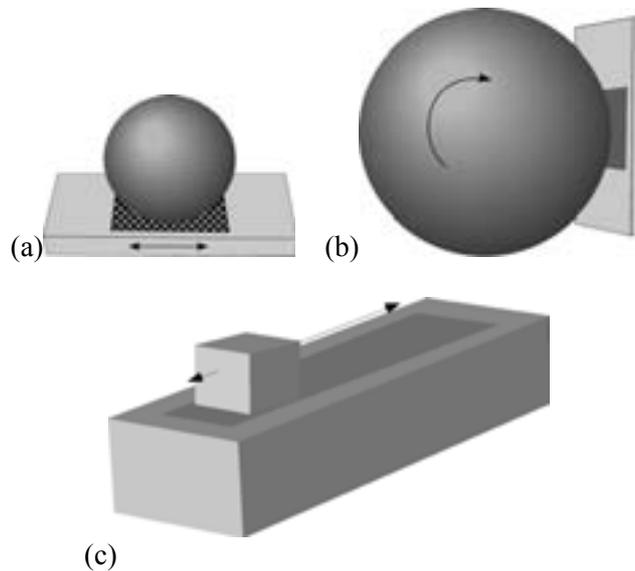


Figure 12. Sketches of the tribological test set ups used in this thesis, (a) reciprocating ball on flat, (b) rotating ball on flat and (c) reciprocating self-aligning flat on flat.

The reciprocating ball ($\text{\O} 10 \text{ mm}$) on flat shown in Fig. 12a was used in the studies of PVD coated textured silicon surfaces (Paper I, II). Lubricant was applied before starting the tests and the amount of lubricant in the contact was easily reduced to test also starved lubricated situations.

The rotating ball ($\text{\O} 20 \text{ mm}$) on flat shown in Fig. 12b was used in the studies of embossed steel surfaces (Paper IV). The lower part of the ball was continuously in an oil bath, supplying the contact with oil. A turning lath was used for this set up, and the normal load was continuously increased

through a spring mounted on the back of the flat sample. The radial feed of the lath was used to compress the spring.

The flat on flat shown in Fig. 12c was used when testing textured surfaces simulating the roller/piston contact of a hydraulic motor (Paper V). The lower part was taken from the roller and the upper smaller part from the piston. This set up was considered to be most closely resembling the real contact in the motor. The experiments were performed in an oil bath and the sample holder was designed to self adjust any miss alignment.

Also in the studies on high static coefficient of friction the flat on flat set up was used (Paper VII). The designed abrasive diamond surfaces were placed as the lower, larger sample.

Textured surfaces for low friction

This chapter briefly presents some main results from the low-friction studies as presented in Paper I-II and IV-V. In the final section an overview of textured surfaces in boundary lubricated sliding is presented, based on collected experimental experience and results published by other authors (Paper VI).

PVD-coated etched silicon

In one test series, DLC coated silicon surfaces were run in reciprocating sliding against ball bearing steel balls under unlubricated conditions. The flat DLC surfaces were tested both with different textures and without any textures. Interestingly, the untextured surfaces resulted in a lower friction than the textured, see Fig. 13. DLC has earlier turned out to provide excellent low friction and wear properties in dry sliding conditions. Studies have suggested that the low friction is due to transfer and build-up of a beneficial tribolayer on the counter surface [17,18]. The higher friction exhibited by the textured DLC surfaces was explained by the fact that the edges of the depressions here counteracts the build up of the beneficial layer. The thicker and better covering tribolayer on balls sliding against the smooth DLC surface explain the lower friction and might also protect the ball from further wear.

Two types of boundary lubricated conditions were tested, starved and amply lubricated, see Fig. 14. Prior to each starved lubricated test, a part of the ball was covered with a thin film of oil without additives. The lubricant was restricted to a very small volume, much too thin to exhibit any noticeable flow, to emphasize the ability of the textured surface to retain the oil within the contact area. In the amply lubricated tests, a drop of oil was applied to the flat surface before each test. In this way the lubricant flows over the surfaces after each pass, offering a possibility to refill the textures, and also to make possible full film lubrication if speed is increased.

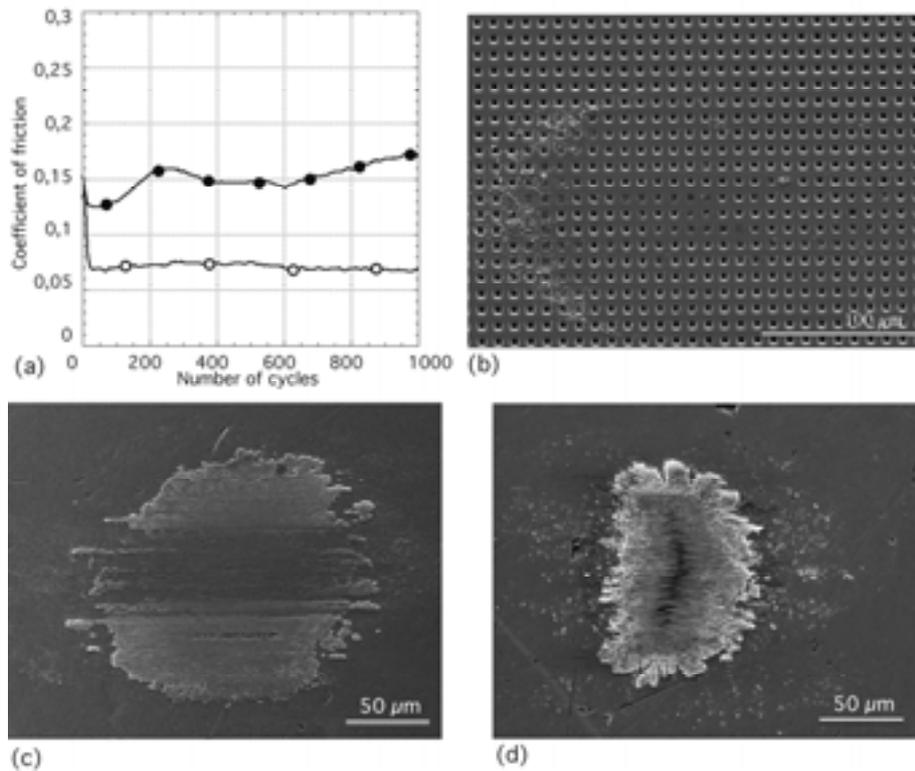


Figure 13. a) Examples of friction curves for unlubricated sliding of a ball bearing steel ball against untextured DLC (open circles) and textured DLC surface with 5 μm wide square depressions (filled circles). When sliding against a textured DLC surface (b) the texture counteracted the build up of a transferred tribolayer on the counter surface (c). In the untextured case the build up was successful (d) and the friction low.

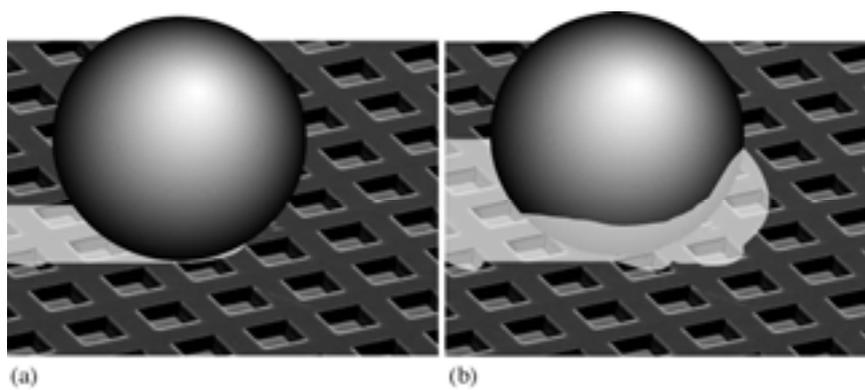


Figure 14. A schematic drawing of the two types of boundary lubrication used, starved (a) and ample lubricated (b). Note that the ball is drawn to a much smaller size, compared to the pattern, than in the real case.

The clearest results were achieved in the *starved* boundary lubrication mode. A low friction and minimal-wear situation was achieved when the depressions were sufficiently close and oriented so that the whole contact circle frequently passed these oil reservoirs, see Fig. 15. As evident from the Fig. 16, successful textures exhibit either

- a dense pattern of depressions within the contact area, or
- a less dense texture but an orientation that ensures that each part of the contact area frequently passes over a depression.

Less successful friction and wear behaviour was exhibited by textures with sparse depressions (or no depressions) and by textures that for local parts of the contact area allow long sliding distances without passing an oil reservoir.

Further, the load bearing area has to be sufficient to carry the load without plastic deformation or fracture. The coarse textures suffer from higher local pressures on the edges, a higher risk for vertical motion of the ball and thus a higher risk for wear and increased friction.

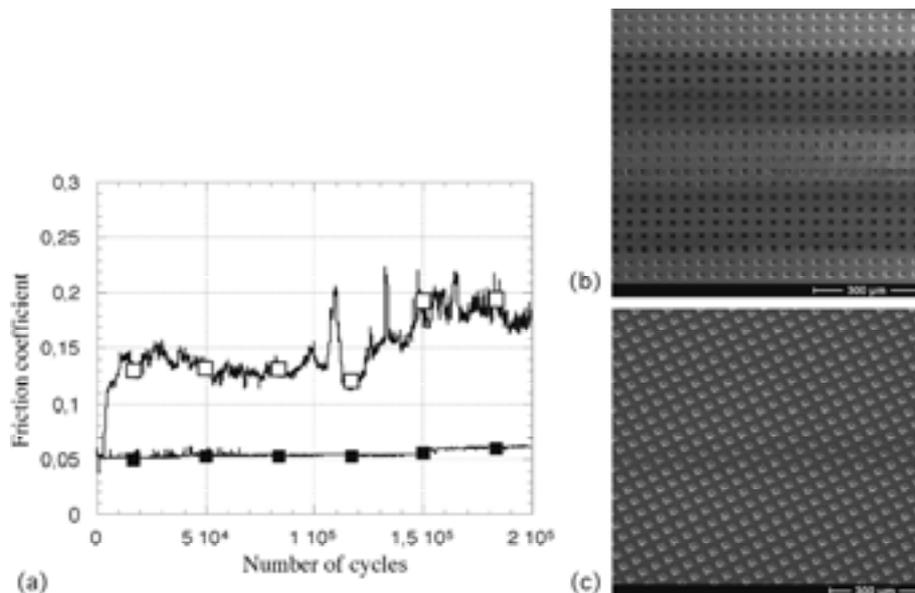


Figure 15. The influence of orientation on the friction and wear was very strong under starved boundary lubrication tests. (a) The coefficient of friction as a function of number of cycles for 20 μm squares oriented along the sliding direction (white squares) and turned 30° from the sliding direction (black squares). (b) 20 μm squared surface oriented in the sliding direction after 20,000 cycles. (c) 20 μm squared surface turned 30° from the sliding direction after 200,000 cycles.

Design (orientation)	Low friction and no measurable wear	High friction and severe wear
Ball sliding direction: ↔ Flat reference		
Grooves (perp. to sliding direction)		
Grooves (along sliding direction)		
Squares (along sliding direction)		
Squares (30° from sliding direction)		

Figure 16. Summary of the performance of textured surfaces in starved boundary lubricated sliding. The circles represent the elastic contact area of 120 μm in diameter, calculated according to the Hertzian equations with a load of 5 N on a ball bearing steel ball against silicon (influence from the 1 μm coating neglected). The depressions (grooves and squares) are of the three different widths: 5, 20 and 50 μm .

With *ample* supply of oil, the friction was rather insensitive to the choice of texture. Further the coefficient of friction was generally somewhat higher than in the successful starved lubricated cases (0.08-0.1 compared to 0.05). The higher level is probably due to the addition of a viscous friction component, not present in the starved case. The insensitivity to the choice of texture and orientation is probably due to an adequate amount of lubricant being present in the interface in all cases.

Severe flaking off of the DLC coating occurred for the flat reference surface and for all textured surfaces except for that with grooves oriented perpendicular to the sliding direction and for the fine square texture. It was observed that the coating removal had very little influence on the friction coefficient.

Embossed steel

In Paper IV the new embossing technique was used for texturing of steel surfaces. Some of the tested surfaces are shown in Fig. 17.

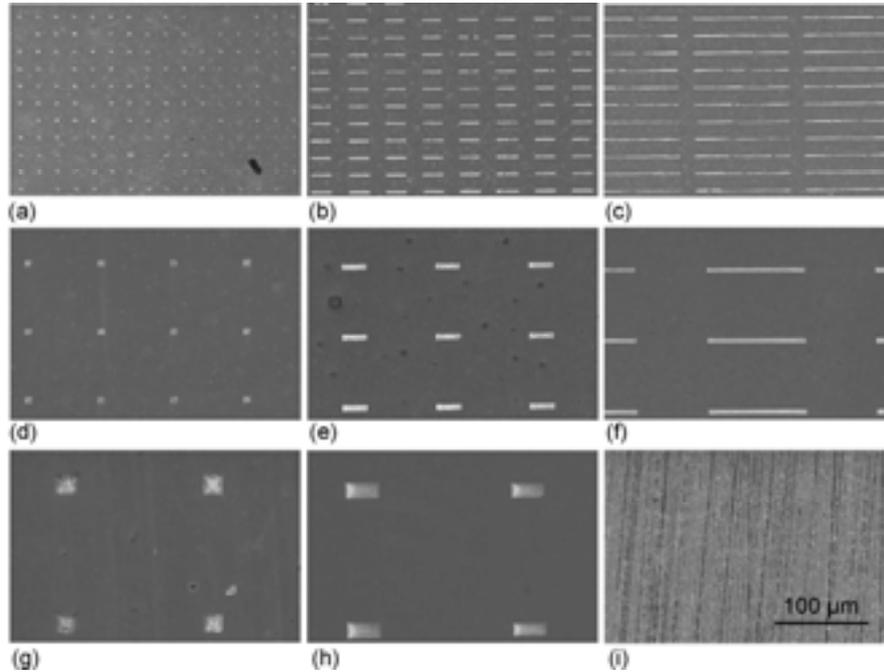


Figure 17. Micrographs of the same magnification of steel surfaces after single embossing (a-h) and a reference surface with R_a 0.2 μm (i). The pyramids, 20 μm long ridges and 100 μm long ridges are separated 20 μm in (a)-(c), 80 μm in (d)-(f) and 160 μm in (g)-(h).

The tests were performed under well-lubricated conditions as the lower part of the rotating ball continuously supported the contact with oil. The load was increased continuously from 9 N to 100 N during the test (corresponding Hertzian contact pressure is 0.65-1.45 GPa) and the sliding speed was 3.14 cm/s.

The smallest textures tested here were rapidly worn through and was obviously too shallow for the present wear rate. The sparse coarser textures proved to be too sparse. In the worst case, the full initial contact area could be positioned between the depressions.

Introduction of a texture into the present contact had only very limited improving effects. The reasons for this can be:

1. Some textures became filled by debris, so the texture volume was obviously too small in relation to the wear volume. The contribution to a fric-

tion decrease from trapping of wear particles is not very pronounced in this case.

2. The friction level is remarkably low in the present experiments (μ often 0.06-0.07). This indicates that the amount of oil in the contact is sufficient for all the surfaces, including the polished flat. Hence the extra supply from the indents makes little difference.
3. The differences in friction and wear levels of the tested surfaces seem rather independent of the presence of textures but primarily seem to be caused by the differences in local surface roughness, i.e. whether the sliding surfaces are polished or ground. Both sparsely textured and untextured polished surfaces showed substantially lower friction coefficient and less wear of the counter surface than did the ground surface. Thus, polishing is the obvious way to decrease friction and wear in these types of contacts. The increased friction found for denser surface textures indicate that introduction of a texture might even drain the contact from mixed towards boundary lubrication.

Embossed piston on roller contact

In the study presented in Paper V, embossed textures were applied on surfaces of real components. The start and stop situation of a piston/roller contact in a radial piston hydraulic motor was simulated with respect to the materials (grey cast iron/ hardened steel), surface roughness and finishing technique, lubricant, contact pressure (100 MPa) and speed (6 mm/s). A smaller part from the piston was sliding against a larger part cut out from the roller, see Fig. 18.

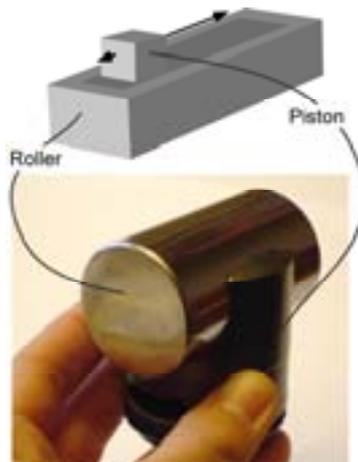


Figure 18. The upper smaller piston part is sliding against the lower roller sample. To ensure a flat parallel contact, the sample holders were designed to self-adjust continuously during the sliding.

Initially the un-textured reference sample ($R_a = 0.3 \mu\text{m}$) showed higher friction level than all textures and also the well-polished surfaces ($R_a = 0.02\mu\text{m}$). After 1000 cycles the difference in friction level is small, see Fig. 19. Note that 1000 cycles is a limited number compared to the number of starts and stops in the life of a real piston.

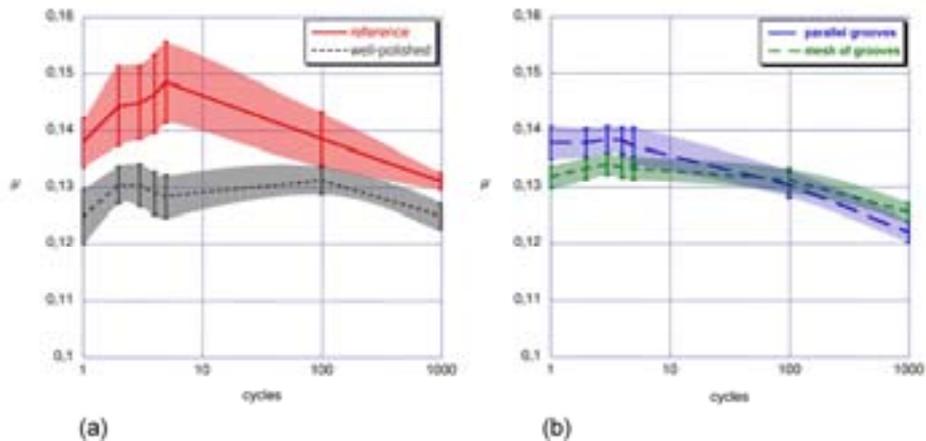


Figure 19. The friction coefficient as a function of number of cycles for the piston/roller test. (a) The un-textured – as tumbled – surface shows a higher friction than the well-polished reference surface. (b) The group of parallel groove textures and the group of mesh textures both show friction coefficients initially at a level between the reference and the polished surface and then approaching the level of the polished.

The difference in friction level was found to be very small between the different textures. However, it was found that the friction fluctuations were significantly reduced by the textures, especially by the mesh pattern textures. Microscopy investigations disclosed rather severe modifications of the surfaces during use, primarily involving substantial plastic deformation of the surface layer, see Fig. 20. This severe deformation of the material in the contact in this case is the explanation to the much higher friction level in this test series, compared to in the study on embossed steel presented above.

An explanation to the less fluctuating friction could be the grooves causing a restriction of the contact area growth. Smaller contact spots to shear results in a more frequent breakage and reformation, compared to larger ones. The reduced friction might be an effect of oil supply from the texture within the contact zone.

Perhaps texturing may constitute an alternative to polishing in this type of contacts, since it results in the same friction level, and less friction fluctuations.

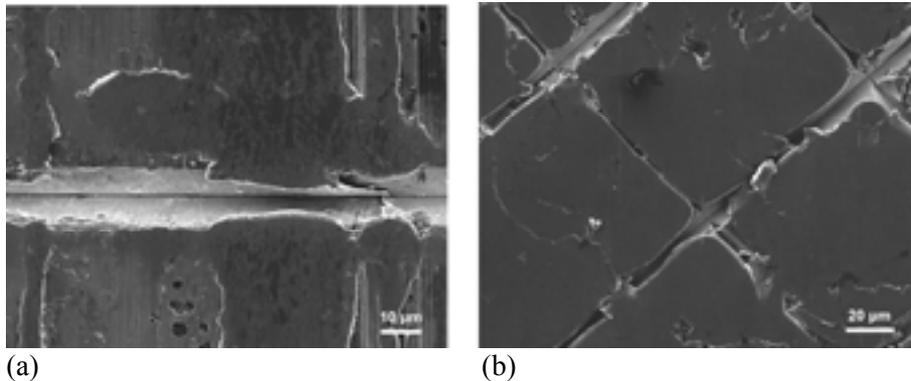


Figure 20. Piston appearance after 100 strokes. (a) The parallel groove surface with 120 μm spacing. (b) The mesh groove surface with 90 μm spacing.

Possibilities and limitations of low-friction surface textures

The papers written about textured surfaces in boundary lubricated contacts are based on a wide range of different experimental conditions and texture appearances (Paper VI). Despite the difficulties to make direct comparisons, some general characteristics of experiments where a texture has improved the boundary lubricated condition can be noticed.

If the intended function is to lower the friction by collecting wear particles, the texture volume should be maximized with a large texture depth and a short distance between the single depressions. Also a supply of lubricant is promoted with a short distance between the depressions, while the transition into hydrodynamic lubrication is not.

Of the papers presenting experiments with contact pressures exceeding 100 MPa, the improving mechanism of the texture was interpreted as mainly dominated by the improved supply of lubricant. The textures showing low-friction performance have then been 3-100 μm wide and with an area fraction of 5-40% [7-8, 11-13, 19-20, Paper I-II, Paper V].

In tests studying the transition into mixed or hydrodynamic lubrication (contact pressure 0.16-15 MPa) the best texture was 78-350 μm wide and the texture area fraction 2.8-12% [4-5, 21].

The best texture in the low-pressure case is obviously not automatically the best in the high-pressure boundary lubricated case. A lubricant supply seems to be gained of a higher area ratio and a smaller texture width compared to the best textures for improved transition into mixed lubricated regime.

A summary of conditions where an introduction of a texture in a low-friction contact might result in an improvement (the ideal case), in no effect or in a deteriorating effect is described in Table 1.

Table 1. The influence on the contact from introduction of a surface texture.

<p><i>The ideal case</i></p> <ul style="list-style-type: none"> • Introduction of the texture does not cause wear in the system. • The wear particles of the system fit into the depressions. • The surface texture remains, i.e. it does not get worn through or filled up with wear debris. • The texture is sufficiently dense and oriented so that all the contact area is lubricated. • There is a lack of lubricant in the untextured case.
<p><i>No effect</i></p> <ul style="list-style-type: none"> • The depressions are too small to stand any wear or fit any wear particles. • The texture is too sparse to give any effect. • The texture is oriented along the sliding direction, and is not lubricating the whole contact area. • The lubrication is already sufficient in the untextured case.
<p><i>Deteriorating effect</i></p> <ul style="list-style-type: none"> • The size of the depressions is large enough to increase the wear rate of the system. • The texture is so dense that the load bearing area is decreased and the surface worn. • Sharp edges of the texture prevent the build up of a lubricating tribofilm on the counter surface.

In general, it can be concluded that it is not an easy task to substantially improve a boundary lubricated contact by introducing a texture. The effect is often insignificant or even negative. A well-polished surface, often corresponding to μ in the range of 0.06-0.08 is not easily beaten. By being aware of all the possible mechanisms and their effects, the chances are improved. However, we are still far from full understanding and the point where we can present general design rules and dimensioning criteria.

Surfaces designed for high static friction

In Paper VII the micro mechanically designed diamond surfaces were used as high-friction surfaces. The static coefficient of friction was measured at the start of sliding against steel or aluminium lubricated with oil. Diamond surfaces comprising long ridges spaced from 30 μm to 120 μm and pyramids spaced 100 μm to 875 μm were tested at the three loads 43, 100 and 332 N. The orientation of the ridges was perpendicular to the sliding direction, while the pyramids were tested with either a face first (90° orientation) or a corner first (45° orientation).

An advantage with the shape of pyramids and ridges ploughing a surface is that there are several theoretical models on friction and wear based on these simple shapes. The theoretical results can be directly compared to the achieved experimental values. The ridges represent a two-dimensional ploughing and have been modelled according to the slip-line field analysis [22], and the pyramid with corner first according to the upper bound method [23]. The simplest model, with the ploughing component of friction, μ_p , as the relation between the ploughing area and the load bearing area is also easily applied on these ploughing diamond bodies.

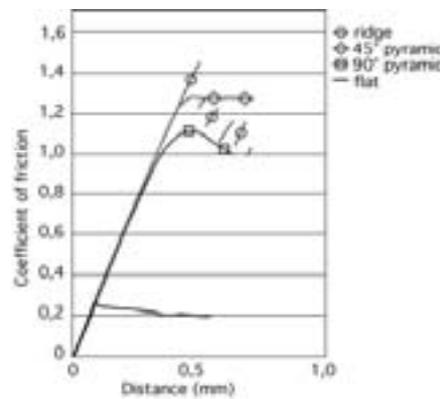
The static coefficient of friction showed to be very dependent on the shape and orientation of the abrasive diamond surface. The influence of abraded material and load was very low. This is in accordance with simple theory on these shapes, as the ploughing area increases with the load bearing area, and hence the ratio μ_p is independent of material and load. Changes in spacing did not influence the coefficient either. For a surface with larger spacing between the ploughing bodies, the load at each pyramid or ridge simply increases.

In Fig. 21 the static coefficient of friction for the four different surfaces are shown. The initial loading phase is followed by a maximum, indicating the static coefficient of friction, and an incipient sliding. The flat surface showed a friction just above $\mu=0.2$ for both materials. The pyramid surfaces showed static friction levels of around $\mu\approx 1$ for the face first orientation and $\mu\approx 1.25$ for the corner first orientation. These very high friction levels were however topped by the ridge surfaces, typically giving friction levels above 1.4.

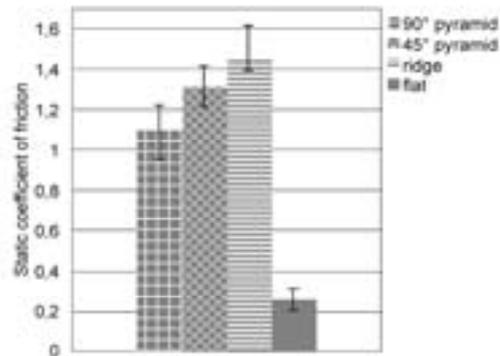
Examples of aluminium surfaces after test are shown in Fig. 22. The sliding of a pyramid with face first showed to be more prone to wedge formation,

while the corner first was more prone to chip formation. The ridges “shaved” the surface to a lower roughness than the original.

These coefficients of static friction are extremely high, roughly 5 to 10 times higher than what can be expected and dimensioned for in typical workpiece fixtures, bolted joints and similar applications. Further, the diamond surfaces have exhibited remarkably stable coefficients of friction. These properties make the present surfaces of great practical interest for demanding high-friction applications. Further, the well-defined shape of the indenting bodies renders these experimental results very useful for verification and testing of existing theoretical models of ploughing friction.



(a)

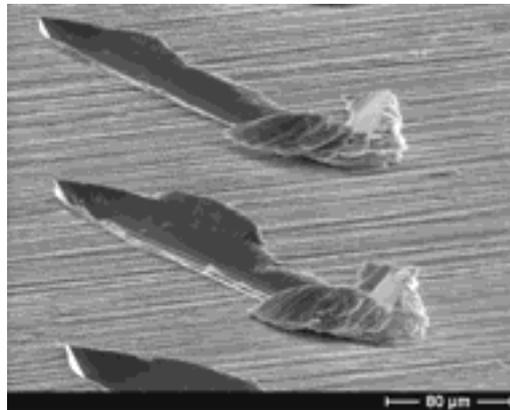


(b)

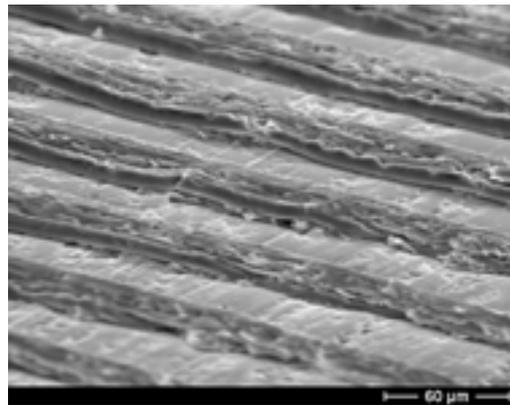
Figure 21. a) Typical friction curves including the (static) loading phase and incipient sliding, all diamond shapes against steel at 100 N load. The maximum indicated in (a) is followed by dynamic friction behaviours characteristic of the different indenter shapes. b) Average critical static coefficient of friction, with bars indicating max and min values. All four types of diamond surfaces tested against aluminium and steel at normal loads of 43-332 N are included.



(a)



(b)



(c)

Figure 22. Friction tracks on aluminium surfaces tested at a load of 100 N against a pyramid diamond surface with the pyramids (a) spaced 875 µm and oriented face first and (b) spaced 310 µm and oriented with the corner first (45° rotation) and ridges (c) spaced 60 µm.

Conclusive summary and future work

Texturing techniques

Silicon is a very good substrate material for fundamental studies of textures since the wafers are delivered with extremely well-polished surfaces, and texturing by photo lithography and etching gives high precision, huge freedom in choice of shapes, sizes and patterns and it leaves un-affected edges of the depressions. However, since silicon is not very useful as a material in tribological applications, alternative techniques must be used on tribologically favourable materials.

The embossing technique developed here resulted in very promising, well-defined and evenly distributed patterned surfaces. The technique offers the possibility to transfer a texture pattern onto all plastically deformable materials, including steel, which is the dominant material in mechanical components.

Textured low-friction surfaces

In the experiments involving unlubricated sliding between DLC and steel, the textures trapped wear particles but also prevented the friction reducing transferred DLC film to build-up on the steel surface. These counteracting mechanisms resulted in that no improvements were achieved by the textured surfaces. The scraping off effect could probably be utilized in situations where an oxidised layer is unwanted, such as for electrical contacts.

The experiments on starved boundary lubricated textured DLC coated surfaces showed very interesting and promising results. With the successful textures the friction stayed low and stable during the whole experiment and no wear was noticed. This compared very beneficially to the flat polished reference and the less successful textures, which showed flaked coatings, severe wear and higher friction levels. The successful textures had dense, small-scale patterns, with an orientation adjusted for the sliding direction. This indicates that a well working supply of lubricant over the whole contact surface requires a short distance between the reservoirs parallel to the sliding direction. With textures oriented along the sliding direction, parts of the contact surface never pass the oil supplies, resulting in local friction increase and severe wear.

Textures did also improve the contact situation for the simulated piston/roller contact. The initial fluctuation and level of friction was decreased by the introduction of an embossed surface texture on the piston surface.

Conclusively, there is a potential for surface textures in boundary lubricated contacts. As shown by some of the presented results, a low-friction behaviour can be achieved. However, a texture does far from always improve the properties of a sliding surface. In fact, in most of the experiments performed in this thesis the situation was deteriorated in comparison to a flat well-polished surface, by the presence of a texture. The point of full understanding, where design rules can be presented, is not reached. A well-polished surface is still difficult to beat.

Designed high-friction surfaces

The micro mechanically designed diamond surfaces comprising virtually identical sharp pyramids or ridges, showed very high static friction against aluminium and steel. The surfaces exhibited remarkably stable coefficients of friction of up to $\mu=1.6$, achieved under oil lubricated conditions. The levels were primarily set by the shape and orientation of the individual indenters, and showed minimum variations between different counter materials, loads, and spacings of the indenters. The friction values achieved are extremely high, roughly 5 to 10 times higher than what can be expected and dimensioned for in typical workpiece fixtures, bolted joints and similar contacts. This makes these surfaces very promising for highly demanding technical applications.

The coefficients of friction showed to be in qualitative accordance with the theoretical models, although slightly higher. The well-defined shape of the indenting bodies renders these experimental results very useful for verification and testing of existing theoretical models of ploughing friction.

As an amazing expansion of this work, it should now be possible to make a first step towards surfaces with intrinsic, predetermined friction levels, to be applied against different counter material. The spacings and heights of the protruding bodies can be designed to let the bodies become fully indented into the mating surface at any selected load. Since a further increase in load will not increase the indentation depth, the ploughing component of friction will not increase and the total friction variation with load will become small.

Summary in Swedish

Ytor utformade för hög och låg friktion

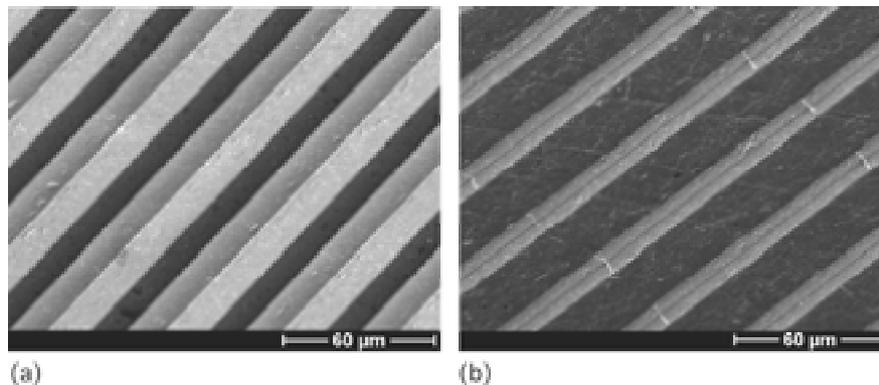
Tribologi är läran om friktion, nötning och smörjning. Namnet baseras på det grekiska ordet för glida, *tribos*. Även om ämnet inte fick sitt namn förrän 1966, så har det länge funnits tribologer, åtminstone sedan egyptierna byggde sina pyramider för mer än 4000 år sedan. Den förste avbildad tribologen är en av pyramidbyggarna i Egypten som häller smörjmedel under medarna till en släde med en staty på. Leonardo da Vinci (1452-1519) utförde och dokumenterade experimentella friktionsstudier och han var en av de första att konstatera att friktionskraften är proportionell mot normalkraften.

På rörliga detaljer är det ytan som är den viktigaste delen, då denna avgör både friktionen, nötningstakten och livslängden. För att kunna studera friktionens olika komponenter är det alltså viktigt att ha kontroll på ytan.

Vid smord glidande kontakt kan små gropar och kanaler i glidytorna sänka friktionen. Det kan ske med flera olika mekanismer. Dels kan de försörja mellanytan med smörjmedel och på så sätt minska friktionen. De kan också samla upp nötningspartiklar som annars kanske skulle ha kommit i kläm i mellanytan och medfört ökad nötning och friktion. Dessutom har man sett att texturer kan öka den lastbärande förmågan under fullfilmssmord kontakt.

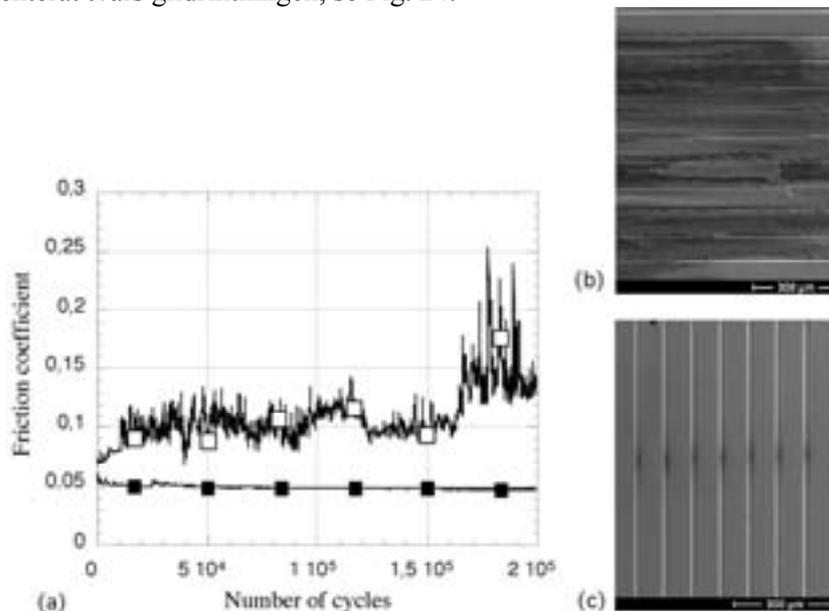
Den här avhandlingen handlar om ytans inverkan på de friktionsmekanismer som råder vid glidande kontakt mot en annan yta. Både mekanismer för att få låg friktion och för att få mycket hög friktion har studerats.

För att tillverka gropar och kanaler i stålytor har en ny teknik utvecklats. Speciella diamantverktyg har tillverkats, med ytor fulla av väldefinierade mikrometerstora pyramider eller åsar. Dessa diamantytar har sen präglats in i stålytor och lämnat efter sig en välbestämd yttextur. Ett exempel på ett diamantverktyg och en stålyta full av motsvarande präglade intryck visas i Fig. 23.



Figur 23. (a) Diamantverktygsyta bestående av långa spetsiga åsar med 30 µm mellanrum. (b) Stålyta som präglats med verktyget i (a) till en textur av långa v-formade kanaler.

När ytor utformas för att ge låg friktion vid glidande kontakt är syftet med groparna eller kanalerna att försörja kontakten med smörjmedel och/eller att samla upp nötningspartiklar. Avhandlingen har visat att storleken och orienteringen av groparna eller kanalerna är avgörande. En tydlig friktionssänkning erhöles när kontakten bara var väldigt knappt smord, mönstret tätt och orienterat tvärs glidriktningen, se Fig. 24.



Figur 24. Orienteringen av texturen har stor betydelse för hur effektiv smörjningen blir. Här visas friktionskoefficienten som funktion av antal cykler för ett test med kula mot plan under knapp smörjning (a). När kanalerna var orienterade längs glidriktningen (b) blev friktionen högre och ojämnare (vita kvadrater) än när texturen var orienterad tvärs glidriktningen (c) då friktionen blev låg och stabil (svarta kvadrater).

Texturerade ytor förbättrade också kontaktsituationen i ett test som simulerade kolv/rulle kontakten i en hydralmotor. Variationen och nivån på friktionen sjönk när en textur präglats in i kolvytan.

Tabell 2 är en sammanställning av de förutsättningar som leder till förbättring, ingen effekt eller till försämring av kontakten om en textur införs vid glidande gränsskiktssmord kontakt.

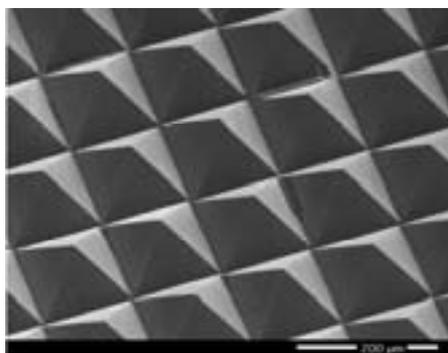
Generellt sett är det väldigt svårt att förbättra en gränsskiktssmord kontakt genom att föra in en textur. I de flesta experiment inkluderade i den här avhandlingen har införandet av en textur förvärrat situationen. En välpolerad plan yta är fortfarande svårslagen.

Tabell 2. Hur införandet av en textur inverkar på den gränssiktssmorda kontakten.

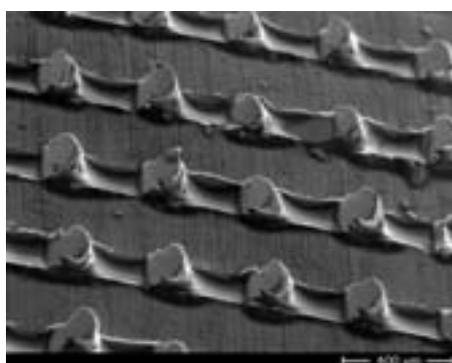
<p><i>I det ideala fallet</i> Införandet av en textur ökar inte nötningen av systemet. Nötningpartiklarna ryms i fördjupningarna. Texturen nöts inte bort eller fylls upp av nötningpartiklar. Texturen är tillräckligt tät och orienterad så att hela kontaktarean smörjs. Det råder smörjmedelsbrist i den otexturerade kontakten.</p>
<p><i>Det ger ingen effekt</i> Fördjupningarna är för små för att tåla nötningen eller för att nötningpartiklarna ska rymmas. Texturen är för gles för att ge effekt. Texturen är orienterad längs glidriktningen så hela kontaktarean smörjs inte. Smörjningen är redan tillräcklig i det otexturerade fallet.</p>
<p><i>Det leder till en försämring</i> Storleken på fördjupningarna är tillräckligt stor för att öka nötningen av systemet. Texturen är så tät att den lastbärande förmågan sjunkit och ytan nöts. Groparnas skarpa kanter motverkar uppbyggnaden av en friktionssänkande tribofilm på motytan.</p>

En yta kan också utformas för att ge maximal friktion. När en väldigt ojämn yta få glida mot en mindre hård blir friktionen hög oavsett om det finns smörjmedel i kontakten eller inte. Ju spetsigare toppar den ojämna ytan har, desto högre blir friktionen.

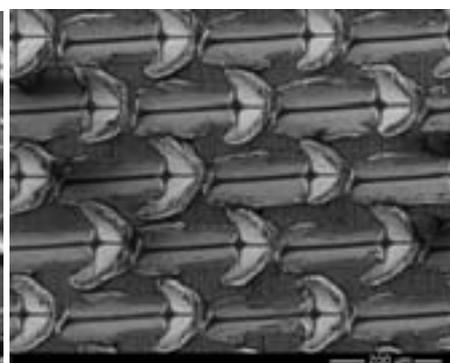
Den statiska friktionskoefficienten för diamantytor täckta av skarpa pyramider eller åsar testades mot aluminium och stål. Statiska friktionskoefficienter mellan 1 och 1,6 uppmättes, vilket är extremt höga värden. Exempel på en designad diamantyta och aluminiumytor efter friktionstestet visas i Fig. 25.



(a)



(b)



(c)

Figur 25. a) Diamantverktygsyta täckt av skarpa pyramidformade strukturer. b) Aluminiumyta efter test mot pyramider orienterade med en plan sida fram. Notera oljan som ligger kvar i groparna. c) Aluminiumyta efter test mot diamantyta med pyramiderna orienterade med ett hörn fram.

Det finns flera teoretiska modeller som behandlar just friktionen under plogning av en pyramid eller ås mot en plastiskt deformierbar yta. Resultaten stämmer bra överens med teorierna. Friktionskoefficienten var oberoende av material, last och av det enskilda avståndet mellan de plogande geometrierna. Det som avgör friktionen när dessa diamantytor plogar en motyta är de plogande geometriernas form och orientering. Åsar orienterade tvärs glidriktningen gav de högsta resultaten på ca 1,45. Därefter följer pyramiderna som orienterade med ena hörnet först som gav $\mu \approx 1,25$ och med en plan yta först $\mu \approx 1$.

Detta är extremt höga friktionskoefficienter, omkring 5 till 10 gånger högre än vad som kan förväntas och dimensioneras för i typiska fixturer, bultade förband och liknande kontakter. Därför är dessa ytor väldigt intressanta för mycket krävande högfriktionstillämpningar. Dessutom kan de användas till att testa och utvärdera befintliga teoretiska modeller av plogande friktion.

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Ernesto, thanks for being the nicest room mate and for all tips regarding car washing, deductions and investments in technical stuff!

Malin, thank you for sharing your thoughts on research and relations and for encouraging company at Svetlis.

Tack mina goda vänner för att ni finns!

Tack min familj och min släkt för att ni finns!!

Tack Pappa för stöd och uppmuntran.

Tack Mamma för värme och omtanke.

Tack Christopher. Du är finast!

Uppsala, 2005-04-25



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