Tribological Testing of PVD Coatings for Mechanical Components

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ABSTRACT

The tribological situation of machine components deviates significantly from that of forming and cutting tools. When the use of low friction wear-resistant coatings for machine components now is rapidly increasing, many of the wear tests traditionally used for PVD coatings are not applicable, but relevant tribological testing procedures must be developed.

The tribological situation of machine components deviates by being characterized by lower nominal pressures, lower temperatures, lubricated contact surfaces, softer substrate materials and possibilities to form solid tribofilms on the counter surface. Other differences include higher lifetime requirements and much tougher requirements on cost efficiency in manufacturing.

The present paper presents an overview of the tribological situation of machine elements and subsequent implications for the relevant mechanical and tribological properties and how to test them. Examples are given from recent research on the influence of surface roughness, counter surface material, nominal pressure, lubricant additives, test set-up characteristics and number of contact cycles on the friction coefficient level and type of surface damage.

BACKGROUND

When developing or selecting tribological PVD coatings, sound testing and evaluation has always been a necessity [1,2,3]. The dependence on testing is typical for the whole field of tribology, due to the complex conditions met at interacting surfaces in relative motion.

During the last couple of decades, the experience and theoretical understanding of PVD coatings for cutting and forming tools has matured. Simultaneously, the testing techniques have gradually improved and a lot of experience has been collected regarding correlation between test results and performance in the application.

Lately, development of new low temperature processes has allowed PVD coating also of the more temperature sensitive steels used in typical mechanical components and machine elements. This has initiated a very rapid development of new coatings tailored directly for the needs of components, and an escalating number of applications for low friction wear resistant coatings. Due to a number of key differences, many of the experiences and rules learned in the tool field are no longer applicable for coating of mechanical components. The tribological conditions differ vastly, the mechanisms of wear and failure differ, both surfaces are of the same interest, and the demand for a low friction level is now often vital. Thus, when it comes to tribological testing and evaluation we have to learn to walk again. This paper is set out to briefly present and discuss some of the important parts of this process, and present some illustrative examples.

TRIBOLOGICAL CONDITIONS OF MECHANICAL COMPONENTS AND THE BENEFICIAL MECHANISM OF LOW FRICTION COATINGS

When compared to tools, the tribological conditions of mechanical components are very different. In many respects they are less severe, but some of the functional demands are also much tougher.

Stresses and temperatures

Much of our collected knowledge about coatings comes from the tooling area. The tribological conditions of tools are characterized by the extremely severe contact against a constantly fresh countersurface. The contact has to be severe, since the mission of the tool is to cut or form the counterface, i.e. the workpiece. This requires the stresses to be high enough to plastically deform the work material, or the temperatures to be high enough to substantially soften or melting it. Often, both the temperature and the stresses are extreme. Hence, the substrate material has to be hard enough to resist the extreme stress levels and sufficiently thermally stable to resist excessive softening. These requirements are met by ceramics, cemented carbides, high speed steels and other high alloyed tool steels.

Most mechanical components operate at temperatures well below 200°C, which allows the use of ball bearing steel and other thermally less stable substrate materials. The contact conditions of a coated mechanical component are rather intricate. Typically, the technical design should ensure that the nominal pressures be low enough to keep both counter-

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parts fully elastic during normal use. Despite this, there is as a rule plastic deformation and wear on the asperity level, at least during the running-in.

PVD coatings are normally much harder than the substrate materials and would thus offer protection against plastic deformation and wear due to contact fatigue. However, in component conditions involving rolling contact and low friction (lubricated) sliding, the highest shear stresses appear at a depth below the surface of about half the contact zone radius, see Figure 1. This depth is typically in the 1/10 mm range, well below any PVD coating.

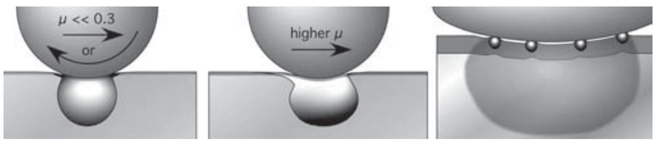


Figure 1: Illustration of the distribution of shear stress under a rolling or sliding contact between a curved and a flat body. Brighter shades indicate high stress. The thin grey line along the surface indicates the thickness of a PVD coating. a) In low friction contacts, such as rolling or lubricated sliding, maximum shear stress appears at a depth of about 0.5 times the contact radius, typically well below the coating. b) In sliding contact with $\mu \approx 0.3$ or higher, the shear stress has a maximum also along the trailing end of the contact surface, that is within the coating. c) Rough surfaces are always exposed to superficial stress concentrations, localized to the contacting asperities. Here, a hard coating may offer protection from plastic deformation.

However, the coating may still offer protection against the high stresses.

- In sliding contact with a higher overall friction coefficient, or at asperity contacts experiencing locally higher friction coefficients, the maximum shear stresses occur much closer to the surface, see Figure 1b. In these situations, the coating may offer sufficient protection against plastic deformation of the substrate. It may naturally also protect against gradual wear.
- If the surface is not sufficiently smooth, the load will be concentrated on the asperities. These may thus suffer plastic deformation and fatigue, although the nominal stress level, as calculated for smooth surfaces, is low, see Figure 1c. These local high-stress spots have small radii, and thus the maximum shear stresses occur superficially, again within the thin PVD coating.
- At the asperities the contact situation is often too severe for the lubricant to operate properly. The local friction stresses thus become high, which pose a direct risk of local plastic deformation. Again, a coating offering low friction also in dry contact, reduces the local friction stresses and thereby protects the surface.

Beneficial effects related to lubrication regime

Mechanical components may operate in any lubrication regime, and less frequently even unlubricated. When run unlubricated it easy to see the beneficial effect of a low friction coating. However, the coating may also be very beneficial in boundary and mixed lubrication conditions.

Also if normally separated by at least a boundary layer of lubricant molecules, both boundary lubricated and mixed lubricated conditions involve some direct contact between the mating surfaces. Addition of a low friction coating on such a surface may thus

- help reducing the friction between these spots of direct contact, which results in the friction reductions denoted A and B in Figure 2
- produce a tribofilm on the uncoated side by transfer of coating material. This tribofilm may also promote friction reductions, as shown by arrows A and B
- reduce the wear of the coated side
- facilitate efficient smoothening of the uncoated side (rounding off of the asperities)
- influence the shape, number and size of the direct contact spots.

The latter four points may affect the time for running-in as well as the wear rate and the life time. Moreover, the boundaries between the different lubrication regimes (C and D in Figure 2) may be shifted. Efficient smoothening and shape adaptation during running-in and tribofilm formation shift the boundaries to the left. This is explained by the fact that a smooth interface requires a less thick lubricant film to completely separate the surfaces. A shift from boundary to mixed regime involves substantial reduction of both friction level and wear rate, while a shift from mixed to full film regime mainly reduces the wear.

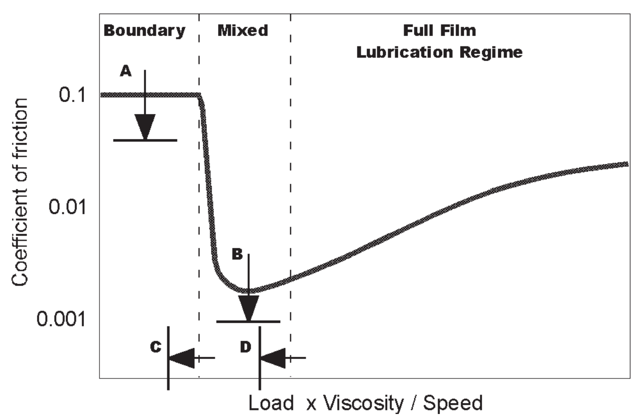


Figure 2: Possible effects of adding a low-friction coating to a lubricated component, visualized by corresponding shifts of the levels and boundaries of the Stribeck curve.

Wear life and friction losses

In summary, the successful application of low friction wear resistant coatings may offer a more rapid running-in, a lower friction once run-in and a lower steady state wear rate, see Figure 3. This results in a longer life to failure, reduced working temperature and reduced energy losses of the component.

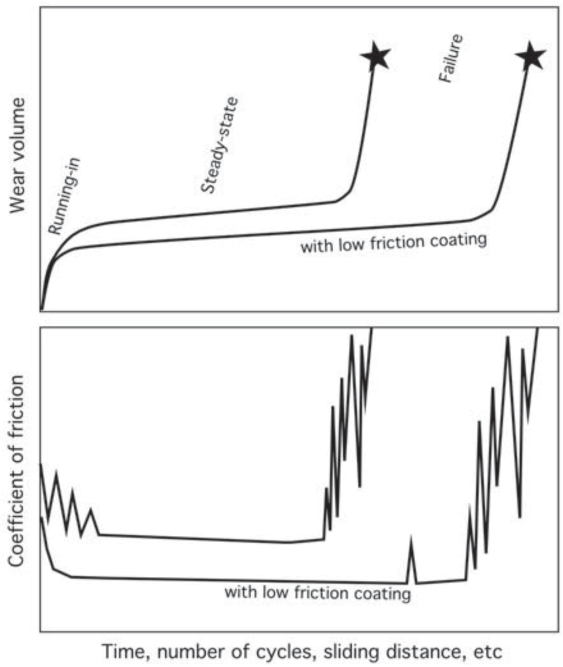


Figure 3: Schematic wear and friction graphs covering the life cycle of a tribological component. The typical behavior of an uncoated component and the possible positive effect of a low friction PVD coating is shown.

Potential problems

The application of a wear resistant coating onto one of the mating surfaces may substantially slow down the running-in of this surface. High and sharp asperities, that would normally quickly become worn off, are now protected by the coating, and the surface will stay rough. If the coating is thin compared to the roughness of the surface, it will partly wear through before the surface becomes smooth.

The mutual remedy to both these problems is to make sure that the substrate is very smooth before depositing the coating. The demands on the surface finish are thus much higher on components intended for coating, than on traditional component surfaces.

CURRENT COMPONENT COATING TECHNOLOGY

Today, the number of processes used for surface treatment and coating of mechanical components to improve their tribological performance is large and growing. Physical vapor deposition (PVD) is the most rapidly expanding group of process for thin tribological coatings. Two categories of coatings aimed for mechanical components can be identified, having a low friction as a mutual general requirement.

- Coatings for wear reduction in dry or sparsely lubricated situations. These include nitrides, carbides, oxides, DLC (diamond like carbon) and diamond.
- Coatings with good anti sticking properties, primarily used to maintain a low friction in starved lubrication, and to avoid pick-up of counter material. They are represented by the DLC and MoS_2 coatings.

The most common coatings from the first category offered commercially, are TiN, TiCN, TiAlN, TiC, TiB_2, Al_2O_3, CrN or CrC or combinations of these, in the form of various multilayered structures. All these coatings are deposited at relatively high temperatures, typically 400 – 800°C, which limits the number of possible substrate materials. However, they can also operate up to the same temperature levels. Typical component applications for this category include piston rings and valves for combustion engines. Here, the PVD coatings replace the more traditional electro deposited hard chromium or thermally sprayed molybdenum. Diamond and hard DLC coatings are also offered for similar wear protection applications, their maximum service temperatures are about 600 and 300°C, respectively.

The vast family of DLC coatings dominate the second category. DLC processes cover large spans of process temperatures (RT – 300°C), compositions, and properties (typical hardness levels being 1000 – 6000 HV). Their carbon based atomic structure contains different proportions of sp^2 and sp^3 bonds, which are the bonds between C atoms in pure graphite and diamond, respectively. DLC coatings typically exhibit friction coefficients in the range of 0.1 – 0.2 in dry sliding. Many DLC coatings marketed today are alloyed with metals such as Ti, Cr, Si or Ta, but also with carbides (WC, CrC). Among the unalloyed DLC coatings available, some have an amorphous structure (a-C) and some contain certain proportions of hydrogen (a-C:H). The hydrogenated coatings exhibit low friction in vacuum applications, whereas the a-C coatings require some humidity in the atmosphere to act beneficially [4]. Also the MoS_2 coatings can be obtained in pure or alloyed (Ti, Cr; Ta) varieties. They are typically produced at temperatures around 150°C.

Recently, composite coatings containing one wear resistant layer topped with a low friction layer have been brought to market. Examples include TiAlN + a-C and TiAlN + WC/C. The top DLC layer is also supposed to facilitate running-in. Examples of commercial low friction coatings for mechanical component applications are given in Table 1.

Table 1: Commercial low friction coatings for mechanical components

Coating	Typical deposition Technique	Thick-ness (μm)	Hard-ness (GPa)	Binding layer
Diamond (C)	CVD	1 - 5	100	-
a-C	Arc evaporation	≤ 0.5	20 – 60	-
(a-C:H) DLC	Plasma CVD	0.5-5	10 – 40	Ti
Cr/DLC	Sputtering	≈ 2	15	0.8 μm Cr
WC/C	Reactive sputtering	1-3	10 – 14	0.1 μm Cr
WC/C:TiAlN	Reactive sputtering:arc evaporation	2 : 4	8 : 30	0.1 μm Ti
MoS_2	Sputtering	1 - 2	4	Ti
Ti (5-20 at%)/ MoS_2	Sputtering	1 - 2	15	Ti

FAILURE MODES OF PVD COATED COMPONENTS

Knowledge of the mechanisms of friction, wear and failure in the intended application is crucial in all aspects of tribological testing and simulation [5, 6]. PVD coated surfaces in dry or boundary lubricated tribological contacts experience several mechanism of wear and types of surface damage, other than those that occur in homogeneous materials [7], see Figure 4 for a gallery of damage types.

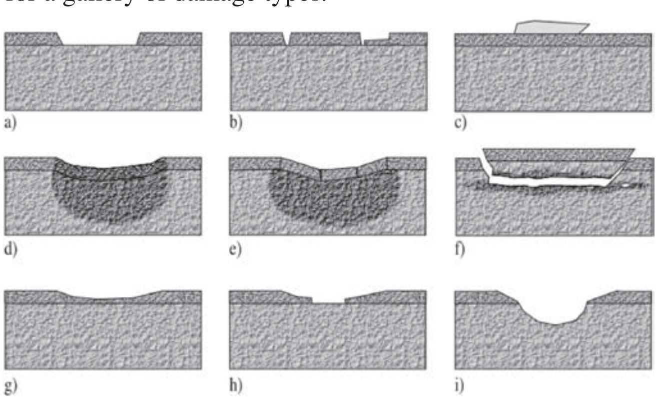


Figure 4: Classes of surface damage on coated components.

Coating detachment or delamination

Coating detachment resulting from insufficient adhesion to the substrate, is one of the most obvious types of failure, see Figure 4a. However, the means to avoid it through appropriate preparation and cleaning of the substrate prior to coating deposition are today well established. Usually, coating adhesion is assessed by scratch testing or Rockwell C indentation, followed by microscopical evaluation of the resulting scratches or indents [1, 8].

Ceramic PVD coatings almost always possess high compressive residual stresses, on the order of 1 – 10 GPa. Therefore, coating failure involving delamination or detachment resulting from the high residual stresses combined with too a rough substrate or too sharp edges, may pose a serious threat [9]. The delamination or detachment is caused by excessive tensile stresses, either within the coating or across the coating/ substrate interface. If the coating thickness is comparable to the substrate roughness (R_a), the tensile stresses across the interface may reach levels of the same magnitude as the compressive stresses in the plane of the coating. If externally induced tensile stresses are superimposed to this, e.g. by sliding friction, coating failure is to be expected.

The practical solution to avoid the above failure mode is to make sure that the substrate topography is ≤ 0.1 μm.

Insufficient load carrying capacity

Cracking or detachment of the coating can occur as a result of excessive deformation of the substrate material that is too soft or too compliant, or if the tribological contact is too concentrated [10, 11], see Figure 4 d and e. A too low *load carrying capacity* of the substrate is often quoted as an explanation to this mode of failure. A more adequate term would be *load spreading capacity*. This failure mode is avoided if the substrate is harder than the counter material, or if a sufficiently thick intermediate layer is applied, which also has to be harder than the counter material [10, 11]. Nitriding has been successfully applied to produce such intermediate layers on PVD coated forming tools. The nitriding process gives a sufficiently thick, hard surface with a beneficial hardness gradient [12].

If the above requirements cannot be fulfilled, smoothening through a gentle running-in can account for a gradually improved load spreading. This situation prevails when two identical and equally precious surfaces, such as those of gears, roller bearings, etc., are making contact. Here, the top PVD coating has to play an active role by being harder than the asperities of the counter surface and flatten them by plastic deformation or abrasive wear. A soft coating may also act beneficially by depositing wear fragments in between the asperities of the counter surface, and thereby account for sufficient load spreading to avoid excessive deformation of the substrate. This indicates that hard coatings applied to both mating surfaces may aggravate the situation, impeding a proper running-in.

Substrate fatigue

A sufficiently compliant coating may resist repeated tribological contacts without cracking, delamination, detachment, or significant wear, even if the substrate deforms. However, there is still a risk that the substrate material deteriorates through contact fatigue, often resulting in delamination of thin flakes, see Figure 4f. Fatigue is caused by excessively high repeated stresses, either on the level of the whole nominal contact area or localized to the surface asperity level. The fatigue fracture appears at the depth of maximum shear stresses, as indicated in Figure 1.

Localized fatigue may occur if foreign particles become entrapped and squeezed between the contacting surfaces. In rolling contact, this may result in relatively large permanent impressions, surrounded by ridges. The subsequent tribological contact may generate excessively high contact pressures on these ridges, resulting in premature fatigue of the coating or substrate material.

As indicated above, the solution may be to use a sufficiently hard and thick *load spreading layer* between the PVD coating and the substrate.

Gradual coating wear and micro fatigue

If only one of the two mating surfaces is equipped with a PVD coating, the intrinsic wear of the coating typically occurs on a very mild scale. The wear mechanism often involves microscopic fatigue and polishing tribochemical wear, as indicated in Figure 4b and g, respectively. The high wear resistance of PVD coatings is related to their relatively high intrinsic hardness and very good chemical and thermal resistance. Often, the coating surface reacts chemically with the counter material and/or the surrounding medium to form a weakened superficial layer, which is then mechanically removed. This results in very slow wear, and the mildly worn surface usually gets a shiny appearance, as if metallographically polished.

If the coating material is harder than any constituent in the counter surface, abrasive wear will not occur. Since a hard PVD coating usually is more brittle than a softer one, and consequently less compliant, the value of using superhard coatings is often questionable. A hardness level some 50% above that of the hardest constituent in the counter surface, eliminates abrasion as a wear risk. Other mechanism of wear are normally not strongly related to hardness, but other properties determine the wear resistance.

In the case of extremely slow tribochemical wear being the initial gradual wear mechanism, fatigue and decohesion within the coating material may dominate the wear after some time of incubation, see Figure 4b.

If both surfaces are coated with the same PVD coating, they may wear each other in an abrasive mode. However, it has often been experienced that it is more beneficial to coat only one of the surfaces. This is due to the fact that a hard coating may speed up the running-in wear of an uncoated counter surface. In addition, wear fragments from the coating may be incorporated in the tribofilm formed by reactions between the lubricant and the uncoated surface, and contribute to a lower friction and higher wear resistance.

SOME EXAMPLES OF TESTS RELEVANT TO MECHANICAL COMPONENTS

Below, examples of tests evaluating the load carrying capacity, the friction and wear of coated mechanical components will be demonstrated, following the initial description of a novel test.

The Load Scanner (LS)

This tester uses a configuration involving two crossed, cylindrical specimens typically of Ø = 10 mm, which are forced to slide reciprocally against each under a constant speed [13–15]. During forward strokes, the normal load gradually increases from a low to a high level, see Figure 5. On the reverse stroke, the load is correspondingly decreased. Each point along the contact path of both specimens will experience a unique load, also in reciprocal testing. Thereby, each point will experience a unique tribological history, which facilitates immediate friction and wear versus load evaluation in one single test, and rapid determination of any critical load. The tests can be run dry or lubricated, and the result is evaluated from the recorded friction history and by imaging the worn surface in the optical microscope (OM) or scanning electron microscope (SEM).

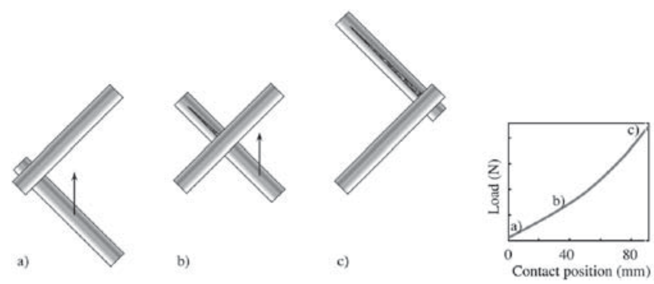


Figure 5: Principal function of the Load Scanner (LC), showing the lower of the contacting specimens moving upward under increasing load. The load versus position relation is fixed, so that any single point will only experience one unique load also in repeated reciprocal sliding.

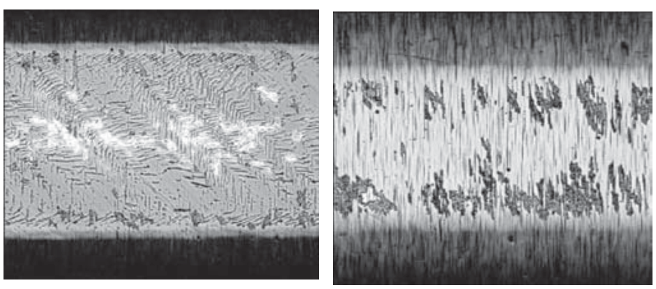
The Load scanner can be used in a single stroke mode to evaluate load carrying capacity of coated components or to establish critical loads for onset of high friction or seizure. In high cycle mode, the influence of load on running-in, friction, wear and fatigue damage is easily assessed. The technique offers a very rapid and convenient means of establishing 3-dimensional *friction maps*, i.e. diagrams over the friction versus load and number of strokes.

The present equipment allows the sliding speed to be set between 0.001 and 0.2 m/s, and the load range to be varied within the 0 – 2.400 N interval. Friction force and normal load are continuously recorded and the maximum number of strokes is unlimited.

Importance of substrate hardness

The importance of using a sufficiently hard substrate was demonstrated by testing DLC (Balzers WC/C) coated steel rods against uncoated steel in the load scanner rig [15], see Figure 6. The softer of the tested substrates deforms plastically when exposed to the sliding contact, and the relatively brittle coating cannot accommodate this deformation without fracturing (Figure 6a). With a harder substrate (Figure 6b) the coating suffers local and very shallow decohesive fracture, already at relatively low loads. This fracture is due to the excessively high pressure in the asperity contacts. The correlation to the asperity contacts is indicated by the fact that the fractured areas (darker grey) extend along the very shallow grinding groves rather than along the sliding direction.

The substrate should preferably be harder than the counter part, to avoid excessive plastic deformation under the coating.

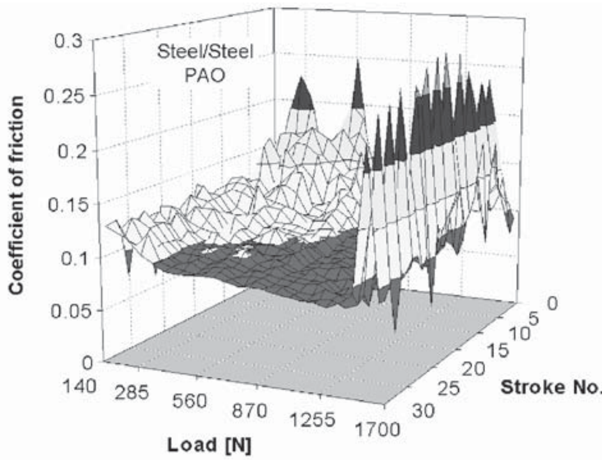


a. b.

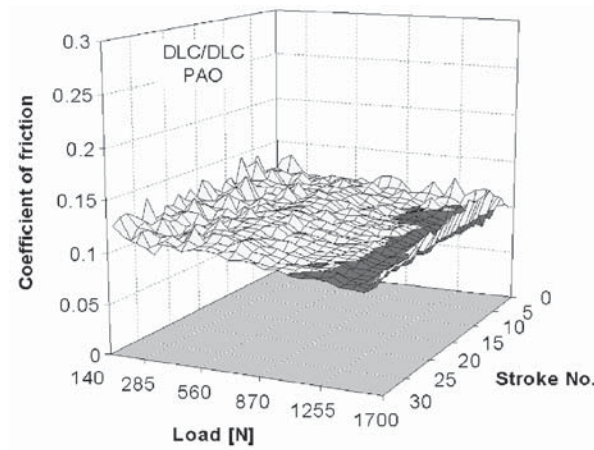
Figure 6: Different modes of coating failure after 15 000 sliding cycles against uncoated steel. Boundary lubricated load scanner test using poly-alpha-olephin (PAO) oil. The arrow indicates the direction of sliding [15]. a) Break down of the DLC coating due to excessive plastic deformation of the substrate. (Hardness of substrate 5.5 GPa and counter material 7.5 GPa, substrate roughness Ra = 0.09 μm, normal load 1060 N.) b) Local coating decohesion as a result of a too hard substrate in combination with a too high roughness. (Hardness of substrate and counter material of 7.5 GPa, substrate roughness Ra = 0.09 μm, and normal load 540 N.)

Effect of coating on one or both parts on lubricated running-in

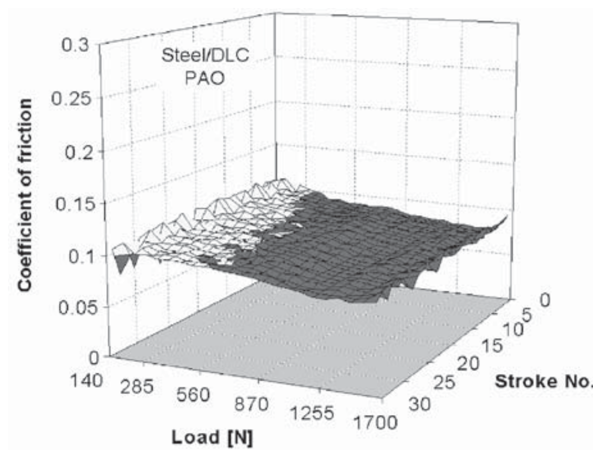
The running-in properties of boundary lubricated DLC coated components were investigated using the same load scanner set-up [16]. Steel rods (H=8.5 GPa) were used combined as self-mated uncoated steel (Steel/Steel), DLC coated steel against uncoated steel (DLC/Steel) and self-mated DLC coated steel (DLC/DLC). A load scan of 140 – 1700 N was used, and the friction coefficient during the first 30 strokes was recorded, see Figure 7. Again, the lubricant was PAO without any additives.



a.



b.



c.

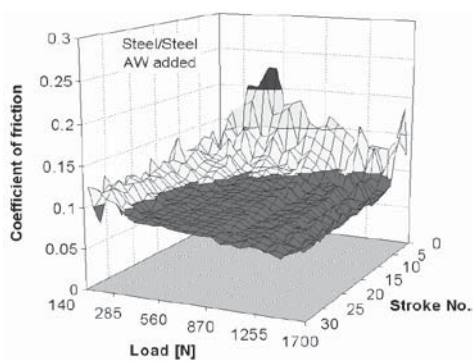
Figure 7: Friction maps demonstrating the influence of DLC coating on the ability of boundary lubricated mechanical components to minimize friction by running-in. Lubricant: Pure PAO oil. a) Uncoated steel against uncoated steel. b) DLC coated steel against DLC coated steel. c) DLC coated steel against uncoated steel [16].

The benefit of the DLC coating is obvious. The Steel/Steel combination initially exhibits rather high friction coefficient, especially at the low and high loads. For the intermediate loads, there is a rapid reduction of the friction coefficient to below 0.1 (dark shade in the diagrams) presumably due to surface smoothening by plastic deformation and wear of the asperities. The friction reduction is relatively slow at low, and especially at high loads, where the oil obviously is not capable of offering boundary lubrication.

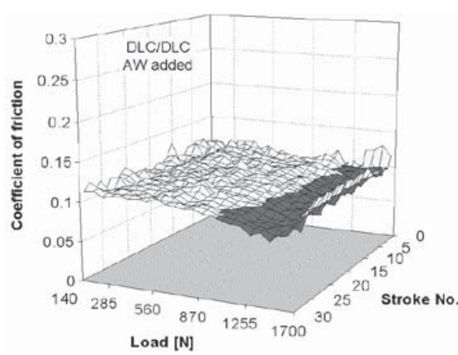
Having both surfaces DLC coated, dramatically reduces the initial friction at all loads, but a running-in toward $\mu \leq 0.1$ occurs slowly and initially only at a relatively high load level, due to the high wear resistance of this coating. The very best result is generated by the DLC/Steel combination, which instantly displays a friction coefficient below 0.1 for almost the whole load interval. The hard DLC coating obviously has the potential to rapidly smoothen the steel counter surface already during the first stroke.

Effect of coating on running-in with additivated oil

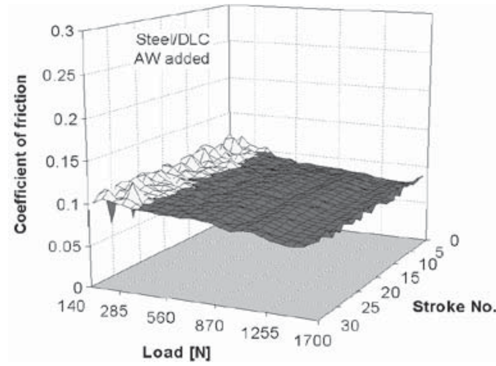
The above test was repeated with anti wear additives (AW) added to the PAO oil [16], see Figure 8. The additives efficiently reduced the high load friction for the steel/steel combination, see Figure 8a. However, again DLC coating can have a significant effect in further reducing the friction and totally avoiding the high friction during the first few strokes.



a.



b.



c.

Figure 8: Friction maps demonstrating the effect of DLC coating on the running-in friction of boundary lubricated mechanical component. Tests performed in the LS set-up. Lubricant: PAO + AW additives. a) Uncoated steel against uncoated steel. b) DLC coated steel against DLC coated steel. c) DLC coated steel against uncoated steel [16].

When extending the number of strokes to 8000, the friction coefficient was reduced even further, see Figure 9. The lowest friction coefficient, ≤ 0.05, was obtained for the Steel/DLC combination lubricated with PAO with extreme pressure (EP) or AW additives. Using a commercial additive package (corresponding to gear oil grade GL-4), did not give the same positive effect. Obviously, the tribofilms formed by the reaction products of steel and GL4, and possible fragments from the coating, generates a somewhat higher friction. It is also obvious that the long term friction of the DLC/DLC combination is virtually unaffected by the additives.

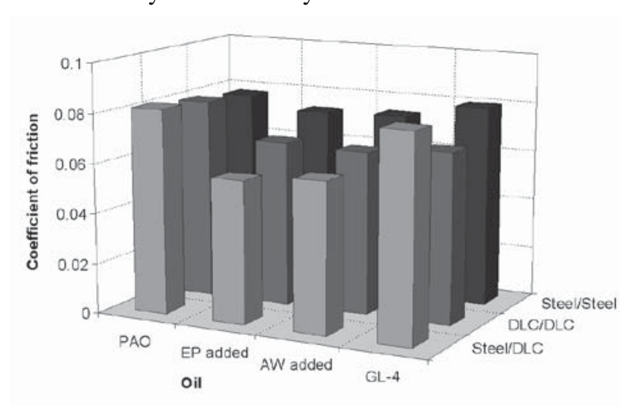


Figure 9: Friction coefficients obtained after 8000 strokes in the load scanner at 700 N load. GL-4 is a commercial additive package.

Effect of sliding speed

The sliding speed has a direct influence on the state of lubrication, as discussed and schematically shown in Figure 2. The influence of sliding speed on the friction level has been investigated in an experiment using low friction PVD coatings against steel contact. The test set-up involves a flat against rotating cylinder contact, mimicking the conditions of a specific cam regulated valve. As shown in Figure 10, the lubricated friction is sensitive to selection of the coating material, in both the boundary lubricated and the mixed lubricated regimes. The differences between the coatings may be due to different friction properties, in the spots of actual contact against the coating, but also due to varying abilities to form tribofilms, to run-in the countersurface and thereby promoting a more full film dominated contact, etc.

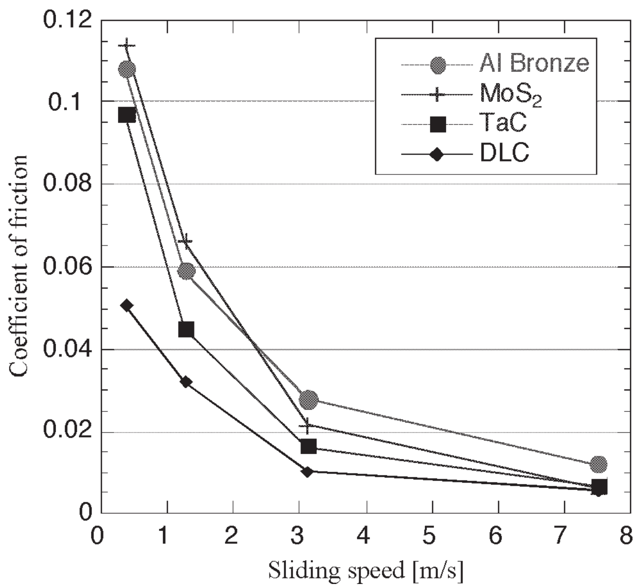


Figure 10: Friction coefficient versus sliding speed in a cam/follower test set-up lubricated by additivated PAO.

SEVEN IMPORTANT RULES IN TRIBOLOGICAL TESTING OF PVD COATINGS FOR MECHANICAL COMPONENTS

We can try to summarize the broad perspective on the specific conditions and materials for PVD coatings for mechanical components in a set of general rules.

Identify the state of lubrication

Since the state of lubrication (dry, boundary, mixed film, or full film lubrication, with or without additives, etc.) is directly decisive to the friction level and wear rate of the component, it has to be identified. It is of very limited value to perform e.g. a dry test, for a component that will be run lubricated. Exceptions could include lubricated components that momentarily may run dry by accident, but where the life time is limited by these occasions. Note, that the lubrication regime is very sensitive to the sliding speed and the viscosity of the lubricant, and that the viscosity falls quickly with increasing temperature.

Identify all included materials

It is not enough only to specify the coating, to do relevant testing. The friction level is naturally dependent also on the countersurface material, and the lubricant including additives. Moreover, the wear and failure mechanisms are dependent also on the substrate materials of both parts, and their relative moduli and hardness levels.

Be aware of condition changes

The tribological history of a component is not a steady state process, especially not so for coated components. Both the wear rate and the friction level varies during the running-in process. The friction may continue to shift slowly due to increasing partial wear through of the coating, slow establishment of tribofilms, etc. When the coating is totally removed from the contact area, wear and friction characteristic of the substrate establish.

Recognize the importance of initial roughness and running-in

A wear resistant coating may impair the possibility to run-in a rough surface, while an uncoated countersurface may be very efficiently run-in against the hard coating, but then continue to wear rapidly against the rough long lasting surface. To avoid these problems, the substrate to be coated should be very smooth, 0.1 µm R_a or better.

Recognize the importance of tribofilm formation

In lubricated contacts, the friction is often influenced by and the wear rate is often reduced by the formation of tribofilms. Tribofilms may be both demoted and promoted by PVD coatings. Often tribofilms form by reactions between additives in the lubricant and the oxide layer of a steel surface. If this surface is coated by a ceramic coating, the tribofilm reaction may not be possible. Once the coating has been worn through, the reaction can start.

Contrastingly, tribofilms containing fragments of the PVD coating, can be formed on an uncoated countersurface.

Identify the critical functional requirement or failure mechanism

It is, as in all tribological testing, necessary to now exactly what to test. If the component is not a life limiting part of an equipment, the friction level may be the only important parameter to test. If the component is life limiting, the failure mechanism must be established before a proper test can be run and evaluated. Will failure by gradual coating wear dominate, or will we see substrate fatigue, or coating delamination preceded by plastic deformation of the substrate, etc.?

Do not overvalue the importance of high coating hardness! Much too often, the hardness is given as the only materials parameter of a coating, reflecting a tendency to overvalue this property. The hardness of most PVD coatings is sufficient to avoid plastic deformation or abrasive wear against most other materials. Other wear and deterioration mechanisms are not particularly closely related to hardness. Super high hardness values have no tribological value per se, it is much more important to achieve increased ductility and resistance against tribochemical wear, micro fatigue, etc.

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