FRICTION SCIENCE SAVES ENERGY

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Friction and wear are part of our every day life. Friction is needed when we start walking or accelerate our car, it is needed for steering actions and for braking. We do not think so much about this because we have developed routines to deal with friction and wear.

Friction is also a major consumer of energy in our society. About one third of all energy used in industrial countries goes to overcome friction. High friction results often in high wear and more than 30 per cent of the production in industry goes to replace worn our products with new ones. A better control of wear would result in longer product lifetimes and less energy consumed for replacement production.

Both friction and wear are major reasons for disturbances and break down of vehicles and machinery in factories. VTT carried out a survey of breakdown costs in transportation and industry and found the following expenses for one week loss of production:

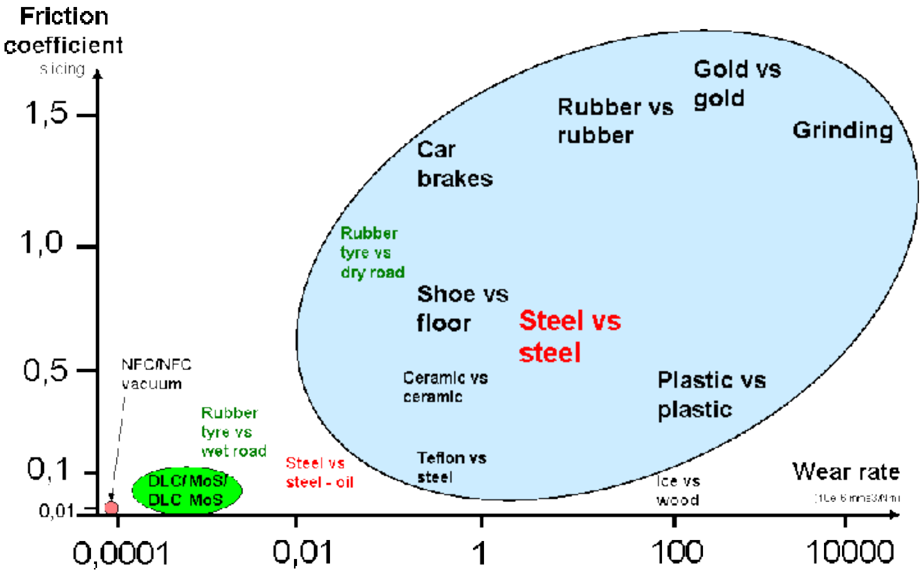
- 80 000 € for a cargo ship stand still
- 400 000 € for an oil refinery stand still
- 800 000 € for a chemical plant stand still
- 800 000 € for a coal power plant stand still
- 1 500 000 € for a paper mill stand still
- 2 200 000 € for a nuclear plant stand still.

Breakdown of machinery may, in addition, result in safety risks and environmental pollution. Controlling and reducing friction and wear is one major challenge in our achievements to reach a sustainable society with low energy consumption and reduced environmental climate change effects.

The good news is that recent scientific development and technical innovations have opened new possibilities to reduce friction and wear in some applications even with several orders of magnitude. Figure 1 shows a plot of typical values for the coefficient of friction and the wear rate in sliding contacts with different material combinations. Steel sliding on steel in dry contacts results in a friction coefficient of 0.6 and a wear rate of $10 \odot 10^{-6} \odot mm^3/Nm$. Rubber versus rubber or gold versus gold result in high friction and wear while Teflon (polytetraflouroethylene) is known for its low sliding resistance. The traditional way of reducing friction is to introduce a lubricant between the sliding contacts, typically some mineral or synthetic oil. A thin oil film between two sliding steel surfaces reduces the friction to 0.1 and the wear rate by up to three orders of magnitude.

It is well known that surface treatment techniques such as carburising and nitriding can strengthen the surface structure and reduce the wear resistance in many applications. A number of new vacuum technology based coating deposition techniques such as physical vapour deposition (PVD) and chemical vapour deposition (CVD) and their combinations have extended the possibilities to change surface properties and radically reduce both friction and wear. Very thin diamond-like carbon (DLC) or molybdenum disulphide (MoS_2) coatings of only a few micrometre thickness have been observed to reduce the coefficient of friction in a sliding steel contact from 0.6 down to 0.01. This means that the surface becomes 60 times more slippery and the wear resistance is at the same time reduced with about four or five orders of magnitude (Donnet and

Erdemir, 2008; Holmberg and Matthews, 2009). Thicker coatings, such as thermally sprayed coatings, have been developed for improved wear resistance and lower friction (Barbezat, 2006). The benefit of the thermal spray process is a large freedom in tailoring of material composition.



DLC = diamond-like carbon coating, MoS = molyhdenidisulfidi coating, NFC = nearly frictionless carbon coating

Figure 1. New scientific discoveries enable to produce surfaces with nearly zero friction and excellent wear resistance. Typical values for the coefficient of friction and the wear rate in dry sliding are shown.

The importance of controlling friction and wear and its economic impact in industry was shown by Jost (1966) and resulted in establishing a new discipline of science named tribology. Tribology is defined as the field of science and technology of interactive surfaces in relative motion and basically includes friction, wear and lubrication. This multidisciplinary and more systematic approach was soon globally accepted by the scientific community and resulted in intensive research activities.

TRIBOLOGY FROM NANO- TO TERASCALE

The multi-genius Leonardo da Vinci was the first to scientifically study friction between two sliding solids. In the 15th century he made observations of frictional behaviour when a solid object was sliding down on an inclined plane and he formulated the three basic laws of friction: (1) there is a linear relationship between the normal load and the friction force, (2) the apparent contact area does not influence on friction and (3) the friction is independent of sliding velocity. The two first laws of friction have shown to be very generic while the third one is less generic with a number of exceptions.

The development of the Atomic Force Microscope (AFM) and Molecular Dynamic Simulations (MDS) brought two new tools for the physicists to study the phenomena of friction both empirically and by modelling and simulation on nano level (Israelichvili and Tabor, 1972; Landman et al., 1992). New theories to explain the mechanisms of friction on atomic level with the use of absorbate vibration modes to estimate the binding energy variation to a surface as one atom moves from one position to another has been presented by Krim (2002) and others. It is interesting that the two first friction laws have recently been shown to apply also on atomic level where continuum mechanics is no longer valid (Mo et al., 2009).

This new understanding formed the platform for atomic level studies of ultralow sliding friction. Carbon surfaces including crystalline diamond and amorphous carbon as well as molybdenum disulphide surfaces were of special interest since they showed extremely low friction approaching zero. The most slippery surface conditions reported scientifically in dry sliding are the molybdenum disulphide coatings sliding against steel investigated by Martin et al. (1993) and the Nearly Frictionless Carbon (NFC) coatings sliding over a similar surface studied by Erdemir et al. (2000). Both showed in vacuum conditions a coefficient of friction as low as 0.001 and below.

These most interesting ultralow friction conditions have been shown to work on laboratory level. But the low friction coatings like DLC with friction coefficients down to 0.01 and very good wear resistance have been tested with good results in a variety of different every day conditions and environments and they are today already in commercial use in some components for computers, cars, medical instruments and consumer products. This development forms a most promising base of scientific knowledge and technology for future innovative solutions to largely reduce the energy consumption due to friction in our society.

The requirement is, however, to mange the scaling up process of frictional understanding from atomic level to engineering level. The knowledge of friction, the influencing parameters and their impact on the surrounding environment is today studied and formulated on size scales from nano level all the way to giga level. The scales of tribology that represent different approaches to identify and understand characteristic friction and wear related phenomena are illustrated in Figure 2.

They cover a diverse range of scientific problems and technological applications from molecular scale friction to reliability and availability aspects of heavy machinery systems that can be as large as ship machinery, paper machines and automatic production lines in plants. Our improving understanding of tribological phenomena on the nanoscale creates the need to scale-up our nanoscale knowledge to conclusions on improved prediction and control of friction and wear that take place on a more macroscopic scale, such as in practically observable everyday life. Here we move over extremely large ranges of size from 10^{-9} m to 10^{3} m and of time from 10^{-15} s to 10^{9} s (Singer and Pollock, 1992). The complexity of the physical, chemical and mechanical phenomena involved in the tribological contact process makes the scaling task extremely challenging (Israelachvili and Spikes, 2001; Holmberg et al., 2007).

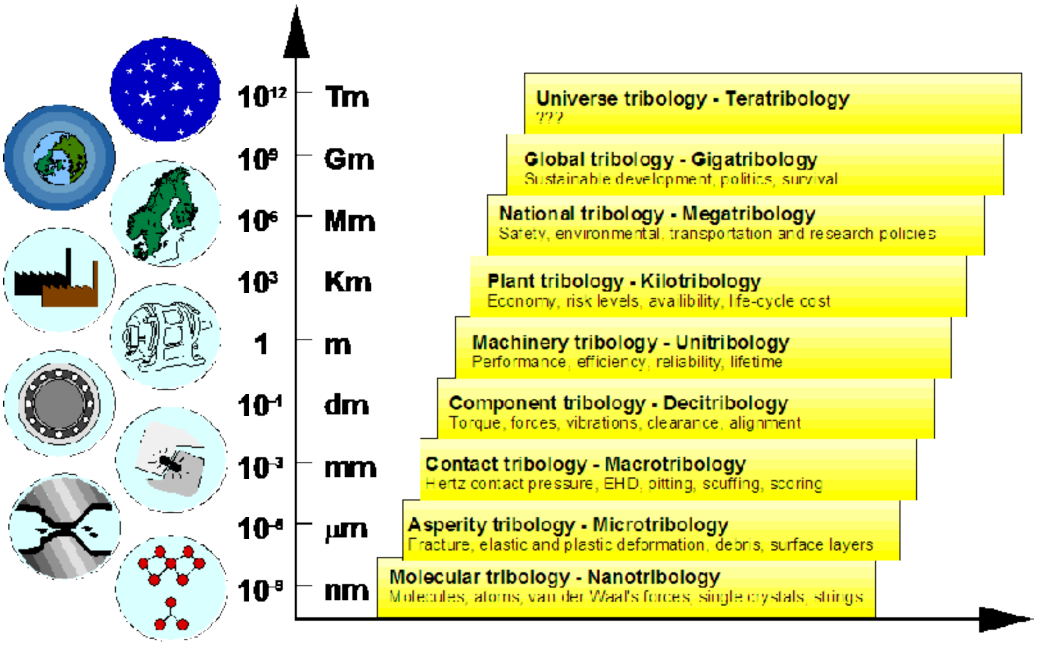


Figure 2. The impact of friction on the surrounding environment is today studied on levels from atomic interaction on nanolevel to global issues on gigalevel – ranging in length scale over 18 orders of magnitude.

We may talk about tribology and its impact on nine different size scale levels:

Nanotribology could also be called molecular tribology, because here the investigations concentrate on phenomena related to the interaction between molecules and atoms, such as the effects of van der Waal's forces and the crystal structures of materials.

Microtribology or asperity tribology take place at the peaks of the surface topography. Phenomena such as fracture, elastic and plastic deformation, debris formation, surface layer formation and topography effects are of central importance.

Macrotribology or contact tribology is related to contacts between gears, bearing elements and rollers, and phenomena like Hertzian contact pressure, elastohydrodynamic lubrication, and wear mechanisms clearly observable by the naked eye.

Component tribology or decitribology is related to defining and measuring typical parameters originating from the interaction of components and related to their performance such as torque, forces, vibrations, clearance and alignment.

Machinery tribology or unitribology describes the performance-related phenomena for a system of components assembled in a machine or a piece of equipment. The parameters of interest are performance, efficiency, reliability and lifetime estimation.

Plant tribology or kilotribology deals with a whole system of machinery, structures and equipment – and how parameters such as costs, risk levels, availability and life-cycle costs are used.

National tribology or megatribology extends the effects and consequences on a nationwide perspective to include parameters of relevance such as safety policy, research policy, transportation policy and environmental policy.

Global tribology or gigatribology considers the effects on a worldwide basis as one interacting system; effects dealt with are sustainable development, politics and cultural and human survival.

Universe tribology or teratribology is the largest perspective today that the author can think of in this scaling up exercise. But what does this mean? Is it interactions of material in our cosmos? Is it mechanisms for space expansion, or is it mechanisms for the creation of new life and cultures?

MODELLING AND SIMULATION OF MICROCONTACTS

Friction and wear empirical testing is today not the only way to increase our knowledge of prevailing tribological mechanisms. The rapidly increasing computer capacity, the new material modelling tools and the improved micro- and nanolevel characterisation techniques makes it possible to perform computer simulations where the stresses, strains and deformations are calculated for a defined contact with defined surface properties. The calculated loading conditions can then be compared with the strength of the material and the risk for deformation, cracking, fracture and wear as well as friction can be estimated. The simulations show the interaction between the different influencing parameters and helps to find the dominating parameters to be optimised.

Depending on the studied contact conditions the modelling and simulation may be relevant to perform either on macro-, micro- or nanolevel (Olsson, 1997; Holmberg et al., 2007). VTT has propsed a holistic modelling and simulation approach that supports a logical fundamental understanding of the influencing parameters. The effect of different parameters can be precisely calculated without any problem of scatter and repeatability. The computer modelling and simulation approach is believed to be the future route to better understand and control the wear process.

The modelling and simulation approach has been used in contact mechanics and in fracture mechanics of structures. The same FEM-based approach has successfully been used for improved understanding of the friction and wear process of a sliding contact with one of the surfaces coated by a thin surface coating (Gong and Komvopoulos, 2004; Holmberg and Mathews, 2009). Precise measurements of the elastic (elastic modulus), plastic (yield strength) properties at and close under the surface and the contact geometry made it possible to simulate stress and strain conditions, deformations and calculate fracture behavior and evaluate the wear performance of the coated surface and the effect of influencing parameters (Figure 3).

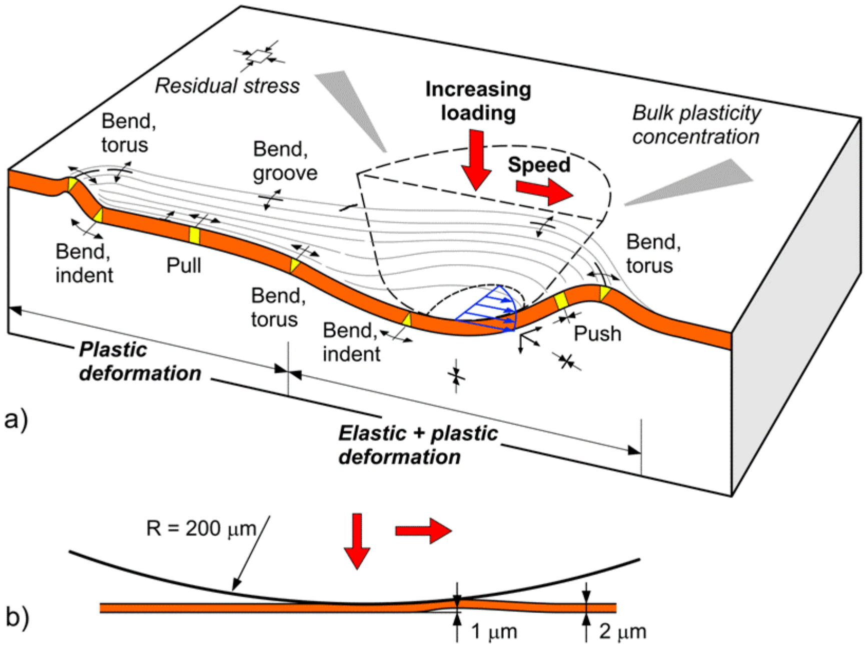
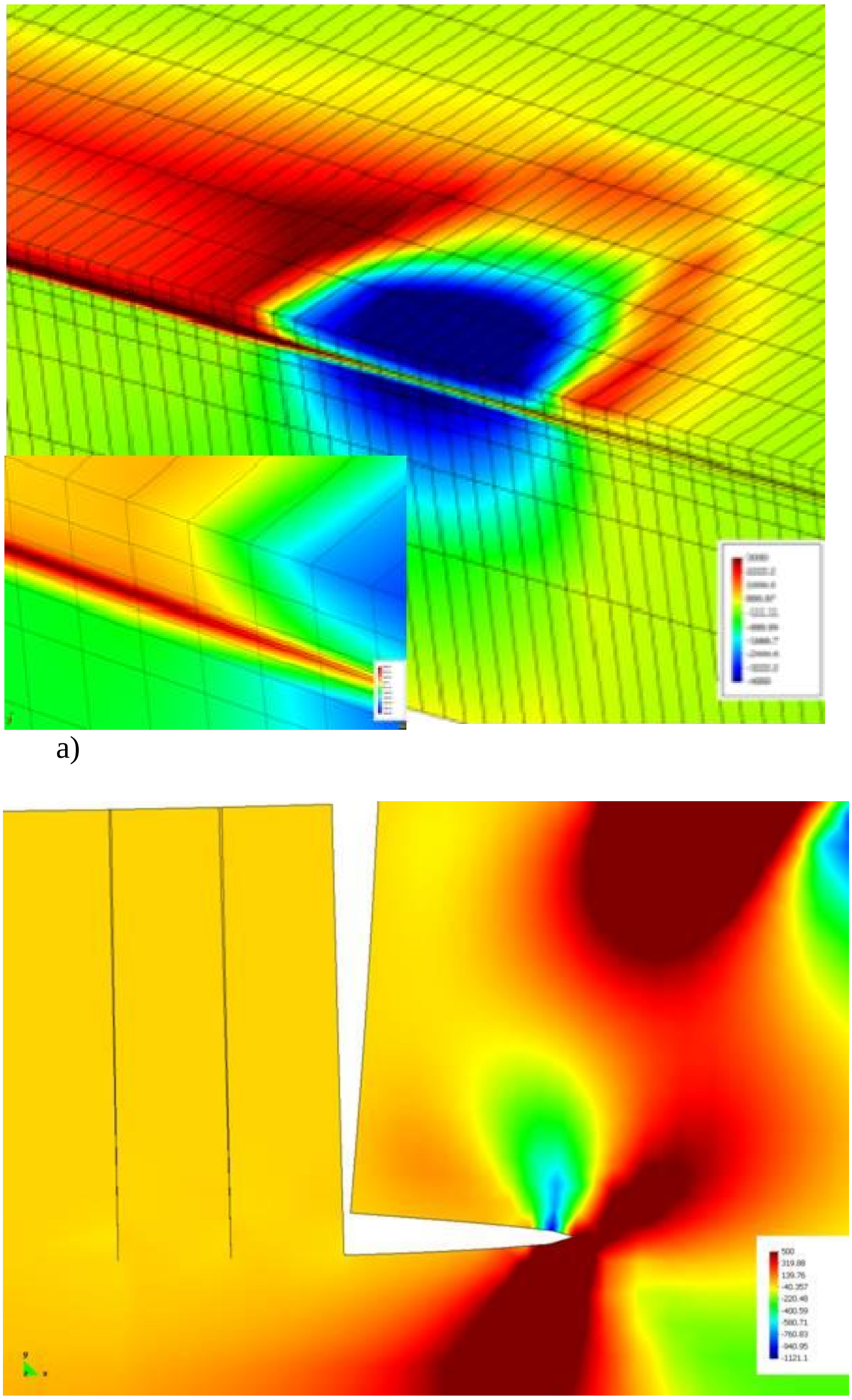


Figure 3. The stress field in a coated surface resulting form a sliding spherical counter surface is a result from four loading effects: friction force, geometrical deformations, bulk placticity concentration and residual stresses. Illustration (a) shows the loading effects with exaggerated dimensions and deformations and (b) with correct dimensional relations.

The modelling approach is fairly laborious and requires a good fundamental understanding but when a good model has been developed the information is very generic and can be used for different applications. A requirement is always that the validity of the model must be tested by comparing the results with some suitable empirical test.

This approach has successfully been used by VTT researchers that have modelled the link from surface material mechanical properties to the surface fracture, wear and friction performance for steel surfaces covered by a thin, 1-5 µm thick, hard ceramic titanium nitride coating (TiN), diamond-like carbon coating (DLC) or molybdenum disulphide coating (MoS_2). In experimental studies these coatings have excellent wear resistance and low friction properties. The stresses, strains and deformations in a loaded contact were simulated. The crack initiation effects and the crack growth mechanisms were studied and the fracture toughness of the surfaces was calculated. The influence of coating hardness, coating elasticity, coating thickness, bond layer thickness and Young's modulus between coating and substrate, as well as residual stresses have been reported (Holmberg et al., 2003, 2007). Figure 4a shows the first principal stress field on a coated surface loaded by a sliding rigid sphere. The steel substrate is coated with a 2 µm thick titanium nitride coating having a 500 nm stiff interface layer. Figure 4b shows the stress field in a pre-cracked surface behind the sliding sphere.



a)

b)

Figure 4. Micro finite element method (FEM) modelling based simulated topographical stress field map of first principal stresses (a) on the surface and at a vertical section through the sliding direction of a 2 µm thick titanium nitride coating on steel and (b) at a vertical section through the sliding direction of a pre-cracked surface. Red corresponds to tensile stresses and blue to compressional stresses. The scale is given in MPa.

THE PROCESSING-PERFORMANCE CONCEPT – PPSP METHOD

VTT has taken a pioneering role in developing a novel concept for the development of low friction and wear resistant materials. The novel PPSP method (Performance-Properties-Structure-Processing) is a systematic approach starting from product lifetime and reliability requirements, transferred to requirements in terms of wear performance. The wear rate of the defined contact system is directly influenced by the material properties of the surfaces which are determined by the microstructure of the materials. The microstructure again is a result of the material processing which includes a large variety of influencing parameters as shown in Figure 5a. The following three links are needed to be modelled for a holistic modelling of the wear performance of a surface:

1) the interactions between the manufacturing process of the surface and the surface microstructure,
2) the interactions between the surface microstructure and the surface material properties, and
3) the interaction between the material properties and the friction and wear process.

A better understanding of these opens completely new possibilities to optimised surface design and to tailor surfaces for specific low wear applications. Each tailored product surface is related to the estimated prevailing wearing conditions that might include adhesive, abrasive, fatigue and chemical wear or a combination of these. The choice of different surface designs may include bulk surfaces with optimised microstructure, thick coatings, thin surface films with, e.g., nanocomposite, multilayer, gradient or lattice structures, as shown in Figure 5b.

Typically interaction between manufacturing process and material structure is affected by large number of cross-linking parameters. VTT has been in the front edge in developing a Process Mapping concept for thermal spraying (Sampath et al. 2003; Turunen, 2005; Turunen et al. 2006) that links the processing parameters to surface microstructure and residual stress and further to material properties in thermal sprayed coatings. With this systematic approach a complex multi-variable thermal spray process has been simplified and logical cause and effect interactions demonstrated. This is an important step for introduction of the thermal spray process into the PPSP method.

CONCLUSIONS

The recent scientific and technological achievements in tribology related to understanding friction and contact mechanics on atomic level, advanced surface characterisation techniques, multilevel modelling and performance simulation methods and improved understanding of physical scaling effects over up to ten orders of magnitude offer new possibilities to control friction and wear in various applications. There is a huge potential in applying existing and new scientific knowledge to reduce friction and wear in the society. This demonstrates one important path of using technology for reducing the energy consumption and decreasing the human impact on climate change.

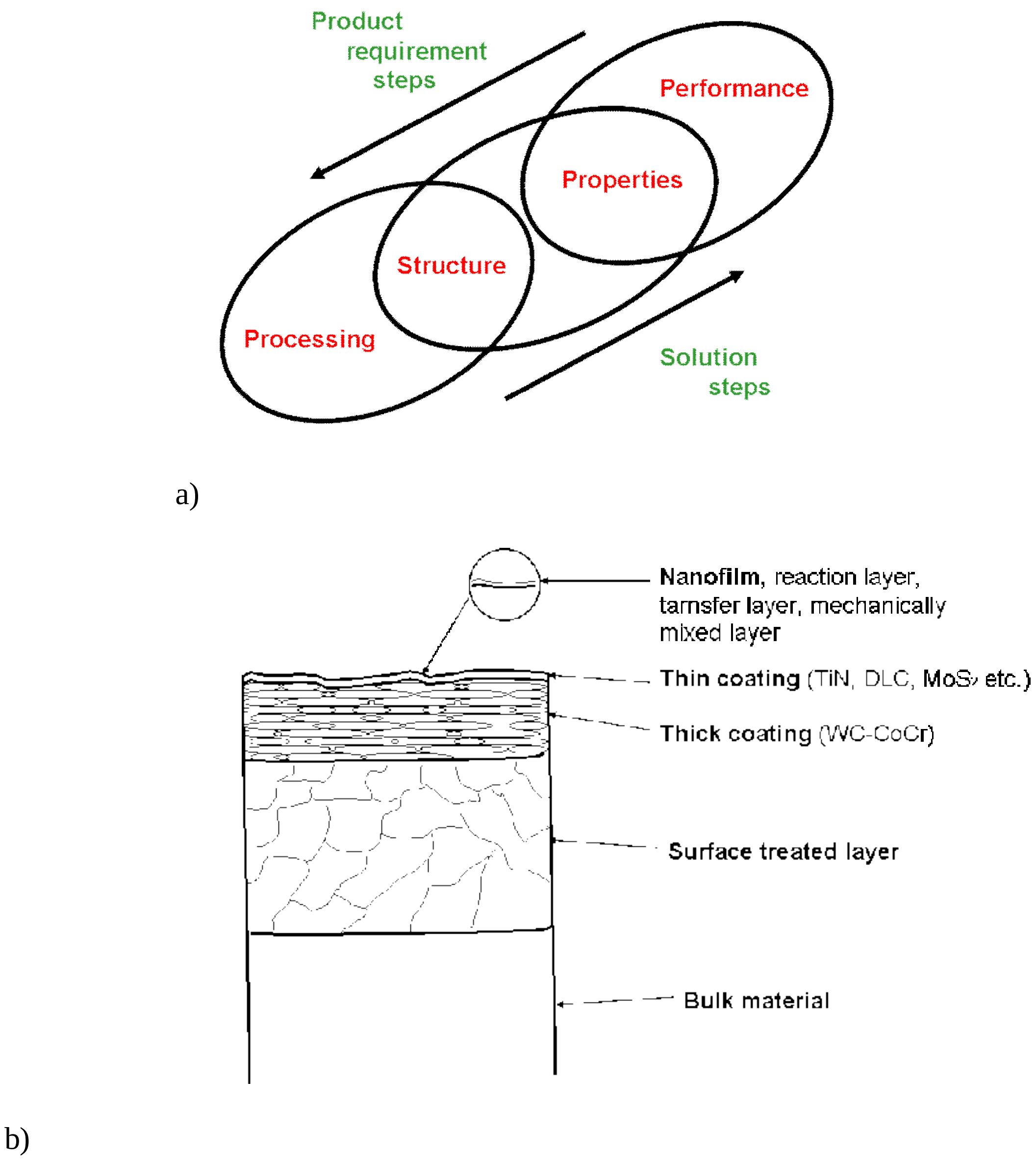


Figure 5. (a) The PPSP approach links the friction and wear performance of the contact to the material properties, to the microstructure and to the surface processing methods. (b) The optimal designed surface is processed by advanced nanotechnology based coating deposition and surface modification techniques.

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