Overview of recent dissertations in the field in Finland

Towards better control of wear

Correct material selection for a certain wear environment will provide not only longer service intervals but also higher productivity, reduced use of energy, lower operating costs, as well as better environmental balance and lower climate impact. In her dissertation, **Vuokko Heino** studied the high-stress abrasive wear of several types of materials.

Mining and mineral processing is a challenging field of industry for many reasons, including technological, economical, as well as political aspects. The market prices are constantly changing, many of the mines are located in politically unstable areas, environmental issues are becoming more and more topical and, of course, technological requirements for the machinery used in various applications are constantly increasing. There are many ways to answer the technological challenges, and materials science is evidently one of the key areas where technological development can and must be expected.

Despite the many changes that have taken place in mineral handling over the years, still today the significantly highest fraction of mine products constitutes mineral fuels, ferro-alloys, and other industrial minerals. All these product lines are very different from each other, and therefore the material selection suitable for one type of production may not be applicable to the other ones. Also the location of the production plays a huge role, for example, whether it is in subtropical or in arctic regions of the globe.

In this work, high stress abrasive wear of several different types of materials was studied using four different natural abrasives, i.e., rocks, and several different test methods. The main aim was to identify such characteristics of the abrasives that affect the most the wear behavior of the studied materials. In the best case, with that kind of knowledge prediction of the material's performance at various mineral handling sites could be done just by knowing the composition of the soil or the bedrock in the area.

In addition to looking at the wear problems from the abrasive point of view, also the influence of the microstructure of the wearing materials was widely studied in this work. Different features in the microstructures of the studied steels, WC-Co hardmetals, and white cast irons were found to affect the high stress abrasion processes significantly, including the overall (bulk) hardness of the materials, hardness of the different constituents of the microstructure, and the size of the abrasives relative to the microstructural features of the materials.

The producers of engineering materials usually provide the customers with data sheets containing the basic material properties, such as the strength, ductility and hardness values. However, when used in circumstances where wear is the main mechanism of material deterioration, these values should be considered with caution. This is because the behavior of materials in wear related applications is strongly dependent on the entire tribosystem. In addition, when the materials become into contact for example with rocks, especially under high stresses, these properties may also be changed even quite drastically.

As wear of materials is a technological problem that causes huge expenses to the mining and mineral processing industry, it is only natural that this area is being under intense scientific and technological research, a part of which also this doctoral thesis is.

MSc Vuokko Heino's PhD thesis entitled "The Effect of Rock Properties on the High Stress Abrasive Wear Behavior of Steels, Hardmetals and White Cast Irons" is available online at: http://urn.fi/URN:ISBN:978-952-15-4224-4

An Investigation into Scuffing and Subsurface Fatigue in a Lubricated Rolling/Sliding Contact

Unexpected failures of gears still occur although their durability has been well studied and comprehensive dimensioning guidance has long been available. One of the reasons for these failures is thought to originate from occasional overload cycles, which the gear sets may experience under extreme operating conditions.

Scuffing is a failure mode which occurs under heavy contact pressure and intensive sliding between the interacting surfaces in elevated temperatures. Scuffing failures result in damaged surfaces and a consequent decrease in load carrying capacity of the gear. This may also lead to other failure modes and ultimately to the breakdown of the machine component. Although this phenomenon has been widely studied, there are still some uncertainties, that are reflected in the dimensioning and use of gear sets. Another failure mode typically occurring in gears can be described as subsurface initiated fatigue. In contrast to traditional fatigue failure, in this mode, the crack initiation originates beneath the hardened layer of the case-hardened surface of a gear tooth.

Firstly, the objective of this thesis is to shed light on the effect of occasional overloads on the initiation of scuffing. The second objective is to establish a procedure for investigating subsurface fatigue under rolling/sliding loading with high contact pressure; a typical condition in a gear contact. The experimental part consists of several tests with a pre-existing, but upgraded twin-disc test device with case-hardened specimens, where the loading in the tests mimics the various contact conditions between the tooth flanks in real gears. In addition to the analysis of the experimental results, the stress and strain states and the consequent formation of fatigue damage in the discs were calculated utilizing an elasto-plastic finite element model of the test assembly.

The scuffing test results demonstrate the importance of running-in the interacting surfaces as overloading during the running-in process increased the risk of scuffing. Conversely, the introduction of overload cycles in a controlled manner and having periods of nominal load cycles between each series of overload cycles enhanced the components resistance to scuffing. The tests also revealed that small deviations in the contact path allowed the use of increased normal load levels without the occurrence of scuffing failures.

The fatigue tests confirmed the suitability of the twin-disc test device for studying subsurface fatigue in case-hardened components. The related numerical analysis, including the influences of increased material hardness and residual stress, revealed critical depths beneath the hardened layer that coincided with the ones found in the experimental tests. Furthermore, a shear strain-based damage calculation method (Fatemi-Socie) seemed to be more sensitive to the effect of residual stresses, while inaccuracies in components due to manufacturing tolerances only have a minor effect on the formation of damage in the subsurface region.

M.Sc. **Matti Savolainen's** PhD thesis entitled "An Investigation into Scuffing and Subsurface Fatigue in a Lubricated Rolling/Sliding Contact" is available online at: http://urn.fi/URN:ISBN:978-952-03-1080-6

Determining damage tolerance improves the predictability of the lifetime of a component

The deterioration of a thermally sprayed ceramic coating is complex and depends on a multitude of factors, such as material properties and processing conditions. To extend the lifetime of the coating it has to be examined based on the requirements of the application and the possibilities of the processing methods. In his PhD thesis, **Jarkko Kiilakoski** has developed methods to determine and improve the damage tolerance of thermally sprayed ceramic coatings.

Thermally sprayed ceramic coatings are commonly used in the manufacturing industry in environments, where high temperatures, chemicals and mechanical wear is present. The drawback of ceramic coatings is their brittleness, which translates to even a small-scale impact with enough energy being able to cause component failure and subsequent machine shutdown. Damage tolerance is a property that cannot be deduced from other coating properties, and until now there has not been a method to its determination.

- The measurement of damage tolerance is well-know with traditional material groups, such as ceramics, metals and polymers. What makes coatings challenging is their small scale. When the thickness of a coating is roughly 0.3 mm on top of a base materials 10-100x thicker, we must be careful what we are measuring, Kiilakoski reveals.

In the thesis, measurement methods were evaluated for different mechanical stresses: high-energy; high-velocity impacts, slow bending of the coating inside an electron microscope and small-energy micro-impact fatigue. All of the methods aimed at filling a gap between laboratory tests and the requirements of real-life conditions.

- In R&D, for example, it takes courage to jump directly from lab results into manufacturing a pilot-scale component. The connection between the conditions of the two is rarely linear and, for now, there hasn't been many measurement methods in the middle for this property, states Kiilakoski.

The aim of the study was to develop ceramic coatings with improved damage tolerance after finding a suitable measurement method. A large European collaboration network was utilized in both developing the measurement methods and the coatings to ensure that the work would benefit from the latest knowledge in the field. Liquid feedstocks were utilized in producing ceramic coatings with improved damage tolerance, which allowed the implementation of nanostructured areas in the coatings. These areas can act as crack arrestor, slowing down the failure of the coating.

- The novel feeding system for liquid feedstock in to the high-velocity oxy-fuel spray system was a result of brainstorming with our collaborators and it is a big leap forward in the process know-how of this technology. Even though work remains to be done, the information sharing between the companies that have sponsored the work has strengthened the collaborative industrial network in the field of thermal spray.

Jarkko Kiilakoski is originally from Lahti and works currently for Saint-Gobain Coating Solutions in Avignon, France, in the business development of thermal spray equipment and consumables.

The doctoral thesis of M.Sc. Jarkko Kiilakoski "Damage Tolerance of Thermally Sprayed Oxide Coatings" is available online at http://urn.fi/URN:ISBN:978-952-03-1505-4

New ways to measure thin coatings and interfaces

The main focus has been on studying how well the coatings stick to the coated surface. Traditional measurement methods might not work when coatings are getting thinner and thinner and thus method development is needed. If the coating breaks or does not stick to the surface it is useless. Several critical components such as sensors or electronic circuits as well as micromechanical actuators can be severely affected causing malfunction in the case of coating failure. Especially in future transportation vehicles the fault free operation of components is absolutely critical. By developing improved measurement methods also coating properties can be improved. In the dissertation three new measurement methods are developed and demonstrated to study the mechanical properties of especially very thin atomic layer deposited coatings:

1) method using micromechanical structures

2) method using microrobotics and small spheres inside the coating

3) method combining nanoscratch and –wear testing

In the work it was demonstrated that it is possible to develop measurement methods where the loading to the coating surface is minimized to focus the study on the actual coating properties and how well it stays on the surface. The combination of micromechanical structures and microrobotis was seen especially interesting. These findings can be used to develop tailored measurement methods for specific purposes to create better coatings.

M.Sc. (Tech.) **Jussi Aav's** PhD thesis "Development of Mechanical Characterization Methods for Thin Films and Interfaces" is available online: http://urn.fi/URN:ISBN:978-952-60-8655-2

Advancements in the wear testing for industrial applications

There are huge incentives for in-depth wear research, as the development of new wear resistant materials, as well as efficient and precise materials selection from existing materials for example for the mining environment, can save significant amounts of money and energy.

In high-stress abrasion, rocks or minerals are being crushed between two moving bodies. In the mining industry, this kind of wear occurs for example in the haulage and grinding of minerals. Wear of materials causes also significant economic and ecological losses in the mining business, because the replacement of wear parts causes interruptions in the mining operations, and production of new wear parts creates a big carbon footprint for the mines. Therefore, the selection and development of better materials for the demanding wear environments is worth the effort.

Although the results of field wear tests are readily applicable for example for materials selection, such tests are challenging to conduct, overly expensive, and very time consuming. Thus, it is important to create substitutive application oriented wear test methods and research methodologies that produce relevant and repeatable results and are well controllable, unlike the in-service conditions. However, the relevance of the test method should also be somehow traceable and verifiable.

This study uses a multiscale approach to laboratory wear testing, i.e., tests ranging from single well-defined micrometer scale scratches to tests that yield a more macroscopic and averaged response of materials to the applied wear conditions. Furthermore, the tests are compared to the in-service cases. In addition, laboratory wear experiments and new practices with better correspondence to the in-service cases are being developed especially for mining industry applications.

Kati Valtonen comes from Tampere, Finland, and she works as a Staff Scientist at Tampere University.

Lic. Tech. Kati Valtonen's doctoral thesis "Relevance of Laboratory Wear Experiments for the Evaluation of In-service Performance of Materials" is available online at: http://urn.fi/URN:ISBN:978-952-15-4244-2

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