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Special Issue

History of Tribology in Finland 1881 – 2023 and the Finnish Society for Tribology 1977 - 2023

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ABSTRACT

The field of Tribology defined as the "science and technology of interacting surfaces in relative motion, that is friction, lubrication and wear" was introduced to the scientific community in a UK governmental report 1966. UK experts and scientists introduced this new approach to solve industrial problems in engineering design, material technology and lubricant chemistry to Finnish colleagues in the late 1970s. The foundation of the Finnish Society for Tribology 1977 boosted academic and technological activities in the area. Tribology as a topic was introduced in the Finnish universities. Investments were made in collaborative research activities with universities, research centers and industry involved. The international collaboration expanded and the Finnish tribologists initiated and started the 1st NORDTRIB regional tribology conference series in Tampere 1984 and hosted the worldwide 5th EUROTRIB International Tribology Congress in Helsinki 1989. The Finnish Journal of Tribology was established 1982. Large joint research activities were generated especially with the Nordic and European countries, Soviet Union and China. Internationally recognized top research groups were initiated and flourished in Tampere and Helsinki on the topics of abrasive, slurry-erosion and fretting wear; engineering ceramics; thin coating tribology; biotribology; computational modelling in tribology; and calculations on global economic and environmental impact of tribology.

This article is modified from the report which the Finnish Society for Tribology contributed to the project "History of Science in Finland" by The Federation of the Finnish Learned Societies (Tieteellisten Seurain Valtuuskunta, TSV).

Contents

1. Background and early lubrication and wear research in Finland

The technology and science of friction, lubrication and wear has a very long history. Friction was an obstacle to overcome and to reduce when transporting heavy loads such as building blocks or weapon equipment in the very early history of mankind. Important and elegant solutions were the invention of the wheel and the use of water and vegetable oils as lubricants already about 5000 years ago (Dowson 1998).

Leonardo da Vinci (1452-1519) was the first to scientifically study and report the fundamental mechanisms of friction in the late medieval period. He studied the effects of load, speed and contact area on the force that resisted motion, that is on friction. He used as research equipment an inclined plan where solid pieces of different size, weight and material were sliding down. Similar studies were later carried out in France by Guillaume Amontons (1663-1705) who formulated the basic laws of friction.

The industrial revolution was a result the inventions of several ingenious novel machineries and constructions that could take advantage of the development of strong steel, steam power and oil lubrication. The machines included many moving heavy loaded contacts that were hoped to last for many years to give long lifetimes. Wear of machine parts reduced lifetime and was a major problem. New design and lubrication solutions were needed especially for the bearings where machine power shafts rotated at high speeds. The theory of hydrodynamic lubrication was formulated by Osborne Reynolds in 1886 based on Beauchamp Tower's experimental lubricated sliding bearing studies (Reynolds 1886).

The development of better bearings required a good understanding of the fundamental flow mechanisms of the lubricating oil in sliding bearings. The internal friction of the flowing oil has a key role. This phenomenon was studied simultaneously in Helsinki University by Karl Fredrik Slotte (1848-1914). He was the first to develop a formula for the influence of temperature on the internal friction of a fluid, also called the viscosity of the fluid (Slotte 1881). The equation is still frequently referred to as the Slotte equation. The equation was developed based on experimental observations of the influence of temperature on the dynamic flow of some salt mixtures: potassium, sodium, ammonium and magnesium chromates.

Wear was a major problem in agricultural machines both in engine parts and earth plowing tools. These were studied in Helsinki at the Finnish Research Institute of Engineering in Agriculture and Forestry (VAKOLA) by Kauko Aho (1922-2009). Kauko Aho was at that time one of the few persons in Finland with a doctoral degree in the field of mechanical engineering (Aho 1968). He was appointed professor in machine design at Tampere University of Technology (TUT, today named Tampere University TAU) in 1972. His expertise was tribology, in which field he carried out a lot of pioneering work in education and research. During his professorship, many well known international tribologists visited the University giving guest lectures on various topics of tribology. The lectures were open for experts from industry. He was a founding member, first chairman and a honorary member of the Finnish Society for Tribology. The international tribology community remembers him as a founder and first chairman of the NORDTRIB conference series, first hosted by him in Tampere in 1984. He was the chairman of the Eurotrib 1989 conference held in Finland. He was active in the field of systematic machine design including design methods and innovation. Kauko Aho served as a bomber pilot during the Second World War. He was very keen on sports, especially on cross-country skiing.

2. Introduction of the concept of Tribology

On the initiative of the UK government a group of industrialists and academic scholars carried out a study on the economic impact of lubrication and wear in British industry in the 1960´s. In the so called "Jost report" they reported that by a very largescale implementation of newer and more advanced technologies, 515 million pounds could be saved annually in UK, and this would correspond to 1.36 % of the GNP at that time (Jost 1966). The UK government invested 1.25 million pounds for further development and implementation of the technology needed. This technology and the field of science it was based on was in the report suggested to be named "Tribology". They defined Tribology as the "science and technology of interacting surfaces in relative motion, that is basically friction, lubrication and wear".

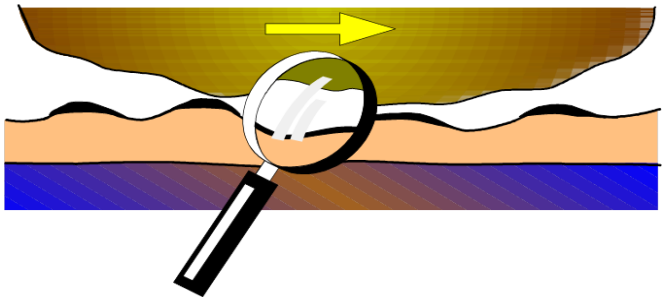

Figure 2.1 Tribology is the science of interacting surfaces in relative motion – that is friction, lubrication, and wear.

Tribology was soon introduced in UK universities and technology centers and from there it spread out to other countries. One of the first professors with a chair defined as Tribology was professor John Halling at Salford University. He had personal contacts with professor Martti Sulonen at Helsinki University of Technology (HUT, today part of Aalto University). Sulonen invited Halling to come to Finland to give lectures about this new field of science and technology.

The interest in friction, wear and lubrication in Sulonen's Laboratory of Metal Forming and Heat Treatment at HUT was originally raised from the wear problems of gear drives in 1973. Endurance of case-hardened steel gears was the topic and the failure mechanism was rolling contact fatigue. A large literature survey was carried out by Heikki Sundquist and a new type of testing equipment, a "twin-disc testing machine", was constructed in co-operation the Kymi Kymmene Company (Sundquist 1976). This co-operation led to a wider general interest in tribology at HUT. Sundquist joined the Finnish Academy of Sciences as a research assistant first to investigate the rolling contact fatigue and later on to develop plasma assisted coating process technology for wear resistant TiN coatings.

In the autumn of 1977 professor Halling, supported by the British Council in Finland, arrived in Helsinki and gave two half-day lectures on the basics of tribology at HUT. The lectures were attended by about 50 persons that represented mainly the mechanical engineering and

Figure 2.2 Two tribology pioneers who have boosted the introduction of tribology in Finland, professors Bengt Jacobson from Chalmers University of Technology in Sweden and professor John Halling from Salford University in the UK. Picture taken at Eurotrib '89 welcoming reception in 1989.

materials technology professionals in Finnish universities and industry. Professor Halling was a charismatic lecturer and presented the new field devoted to friction, wear, and lubrication in a fascinating, most interesting, and challenging way. After the lectures the experts in the audience agreed that they wanted to enhance similar implementation of the new technology in Finland. They thought that this could best be done by forming a national Tribology Society.

Visits of tribologists from the Halling group were followed by visits of two eminent tribologists, professor Duncan Dowson from Leeds University and professor G. H. Higgisson from Durham University in UK. They visited and gave lectures on tribology at Helsinki University of Technology and Tampere University of Technology and participated with presentations in the annual meeting of the newly founded Finnish Society for Tribology 6.2.1979.

The collaboration between Finnish tribologists and Salford University continued for several years. In 1981 professor Halling returned to Finland and this time he had a group of tribology researchers with him visiting HUT, the Technical Research Centre of Finland (VTT), Kymi Kymmene Group and Kone Oy. They gave a three-day course on principles of Tribology organized by INSKO, the Continuing Engineering Education Centre of the Engineering Societies in Finland. The team included in addition to professor J. Halling, who was specialized in contact mechanics, also Dennis Teer, a specialist in thin film deposition by Physical Vapor Deposition (PVD); T. Whomes, a specialist in elasto-hydrodynamic lubrication; D. Arnell, a specialist in tribology design; Allan Matthews, specialist in thin coating tribology; P. B. Davies, specialist

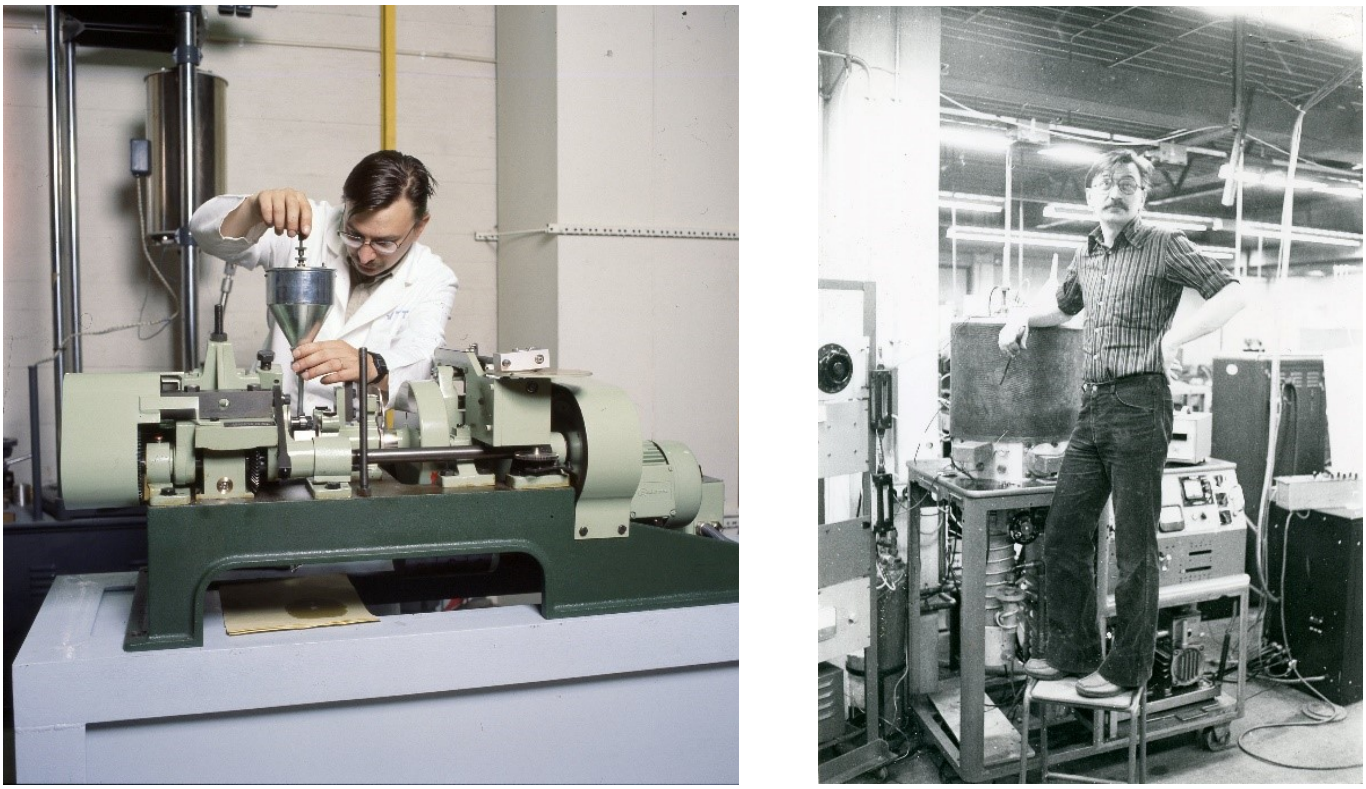

Figure 2.3 Heikki Sundquist a) carrying out wear measurements at the twin-disc machine at the Laboratory of Heat Treatment at Helsinki University of Technology in 1981 and b) at the newly constructed deposition rig for TiN ion plating thin film deposition in the coating laboratory at Salford University, UK in 1979.

in hydrostatic lubrication; B. Mills, specialist in metal cutting; and B. Fogg, specialist in metal forming.

Professor Halling invited Heikki Sundquist to Salford University for some years to learn about tribology and especially about the ion plating coating technology. The visit of Sundquist in Salford resulted in the introduction of thin film tribological coating deposition and application technology first at Sulonen's laboratory at HUT, then at the VTT and from there to Finnish industry. As the marketing value of TiN wear resistant coatings was realized (Matthews, Sundquist, 1983) a startup company, Plasmatekniikka Inc, was established in the year 1982 to commercialize this technology both in Finland and globally. The company was a pioneer in offering a commercial service for wear resistant and low friction TiN coatings intended mainly for high-speed tool steel components for various industries. It offered this service over ten years until commercial TiN coatings were widely offered by many other commercial vendors and produced internally by mechanical engineering companies.

3. Founding of the Finnish Society for Tribology and present activities

The founding meeting of the **Finnish Society for Tribology** was held in Otaniemi, Espoo on 31.8.1977 and was attended by 20 technology experts and researchers. In the meeting the name of the society was agreed and a group for the further planning of actions was established. The first meeting of the society was held 1.11.1977.

The first activities of the Finnish Society for Tribology were decided to be the following:

1. introduce the concept of tribology to Finnish technical universities by taking initiatives to start courses for students in tribology,
2. introduce the concept of tribology and its applications to Finnish industry by regular seminars for technology experts held both in company sites and at universities,
3. network internationally with tribology experts worldwide and for this purpose apply for full membership in the International Tribology Council (ITC), and
4. establish a new scientific journal dedicated to tribology to be called the Finnish Journal of Tribology.

An Education Committee was established for the first task of introducing tribology in the universities. The introduction of courses in tribology at HUT and TUT are described below in section 5.

A glossary on the main tribology terminology was worked out and published out in 1980. It included 52 of the most central tribology words in Finnish, Swedish, English and German. For some terms no proper Finnish equivalent existed so new Finnish words were created. One such word was the word "stick-slip" for which the new Finnish word "tihkomisvärähtely" was introduced, based on the suggestion of Kauko Aho and inspired from the same kind of phenomena in traditional Finnish skiing.

A series of tribology related regular lectures was held annually as an integrated part of the Society's activities and

Figure 3.1 Honorary members (from left) professor Matti Kleimola (HUT), Dr Heikki Sundquist, professor Kauko Aho (TTKK), professor Kenneth Holmberg (VTT) and the society chairman Jorma Niskala in the 20 year celebration in November 1997.

ITC membership was applied as described below in section 6.1.

The Society initiated a study on the role of tribology in Finland and potential benefits for the Finnish industry. The study was carried out by Kauko Aho and Ossi Helander at Tampere University of Technology (Aho and Helander 1979). The structure and methodology of the study was similar to that in the Jost report, but the focus was now on Finland. It showed that tribological problems appeared especially in the wood processing, steel and mining industry where wear often resulted in maintenance costs of up to 10 % of the company turnover. They estimated that implementing the new tribological approach and knowledge would result in 143 million UK pound annual cost savings in Finland (in 1978 year currency) within three years. Actions for improving the teaching of tribology in Finnish universities and research topics to be studied with importance for the Finnish industry were suggested.

Over the years the Finnish Society for Tribology has arranged several seminars covering a wide range of tribological topics, such as surface phenomena in tribology, lubrication, and tribology of different materials, coatings, and surface treatments. Also, tribological challenges in several areas of engineering, such as combustion engines, manufacturing, and transportation were covered. The latest seminar was given in 2023 on tribology of polymer materials. The visits to companies and research organisations have been arranged once or twice a year with discussion topics relevant for the host organisation. In the year 1980, the Society established an award for the best MSc or Dr Thesis work in the area of tribology. The award has been granted ever since annually for the students.

The Finnish Society for Tribology has celebrated the anniversaries by arranging celebration seminars combined with anniversary dinners. The 10th Anniversary was held on Silvia Regina ferry between Helsinki and Stockholm. The 20th and 25th anniversaries were celebrated in Hotel Lord, Helsinki (former Vanha Poli). Besides the formal speeches and other presentations, the society nominated professor Matti Kleimola, professor Kenneth Holmberg and Dr Heikki Sundquist as new honorary members of the society following the nomination of professor Kauko Aho. On the 40th anniversary the seminar with evening celebration was arranged in Tampere.

4. Tribologia - Finnish Journal of Tribology

The **Tribologia - Finnish Journal of Tribology** was established 1982 and Heikki Sundquist was appointed its first Editor in Chief. The Research Council of Finland funded the Finnish Society for Tribology in this effort. Over 40 years, the journal has served as a good link between academic and industrial professionals. It has supported networking and the development of research collaboration both nationally and internationally. The journal has also worked as a publication forum of the NORDTRIB and EUROTRIB conferences.

Tribologia - Finnish Journal of Tribology is an open access journal publishing both practical and scientific articles related to tribology. The scope of the journal is to publish interesting new results of tribology and tribology

Figure 3.2 Invited speakers of the 40th anniversary of The Finnish Society for Tribology held 2017, from the left: Guillermo E. Morales-Espejel, SKF Engineering & Research Centre; Marke Kallio, Metso Minerals Oy; Anssi Laukkanen, VTT; Aki Linjamaa, TUT; Arto Lehtovaara, TUT; Helena Ronkainen, VTT; Thomas Norrby, Nynas AB; Elina Huttunen-Saarivirta; Roland Larsson, Luleå University of Technology; and Kenneth Holmberg, VTT.

related research. The articles are peer reviewed (single-blind) by experts in the field. During the last three years, the publication percentage has been 39%. In addition to peer reviewed articles, the journal publishes media releases of recent Finnish doctoral theses, and other tribology related news. Typically, 2 - 4 issues have been published annually. The current Publication Forum (JUFO) level is one (1).

There are several benefits to authors that are publishing in the journal. Although the Finnish Journal of Tribology is open access journal, there are no publication fees, and the authors remain as the copyright owners (CC BY 4.0 license). The current editorial board (Vuokko Marjamaa, Kati Valtonen, Janne Juoksukangas) has made several improvements to the publication process and the appearance of the journal. Since 2016, the publication has been managed by the Open Journal Systems software in Journal.fi journal management and publishing service. Since 2018, the articles have also been identified digitally by DOI number. The Federation of Finnish Learned Societies and Finnish Association for Scholarly Publishing have supported financially the development and publishing work of the journal.

5. Initiating tribology teaching in the universities

One of the first tasks for the Finnish Society for Tribology was to introduce tribology in the Finnish universities. The established Education Committee was chaired by Kenneth Holmberg (HUT), and consisted of professors Kauko Aho (TUT), Tatu Leinonen (Oulu University, OY) and Niilo Teeri (Lappeenranta University of Technology, LUT). The Education Committee discussed

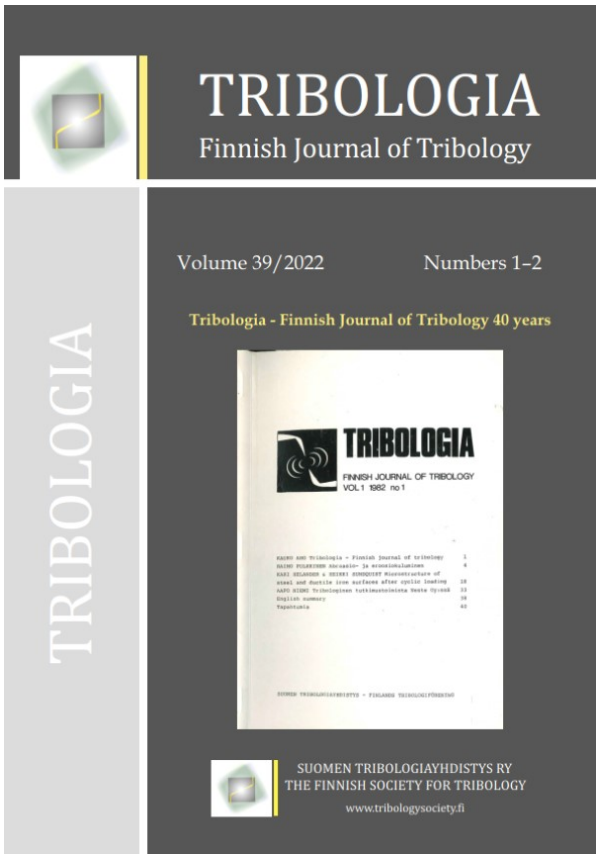

Figure 4.1. Cover of the 40th anniversary edition of the Tribologia - Finnish Journal of Tribology.

the structure of such courses and planned actions in the universities involved.

At Helsinki University of Technology, the greatest

interest for tribology during the early years was in the areas of materials technology and machine design. New tribology courses were planned by Heikki Sundquist from the Laboratory of Metal Forming and Heat Treatment and Kenneth Holmberg from the Laboratory of Machine Design and in collaboration with the related professors Martti Sulonen and Jaakko Wuolijoki. In 1978 the university approved two new courses into the tutorial program. The first lecturer for machine design related tribology was Seppo Kivioja and the first lecturer for materials related tribology was Heikki Sundquist, starting in the autumn 1978. To support the lecturing Heikki Sundquist wrote and published a book on the basics of tribology in Finnish (Sundquist,1986). The book was updated at the end of the millennium by Seppo Kivioja, Seppo Kivivuori and Pekka Salonen and it has been used as a basic Finnish text book on tribology in universities.

At Tampere University of Technology professor Kauko Aho started a tribology course for the third year students at the Department of Machine Design in 1974. Some years later the course was upgraded with laboratory exercises having topics such as friction and wear, performance of hydrodynamic bearing, oil viscosity, material rolling resistance and stick-slip. Around the 1980´s, the number of students per year was 20-30. This course has been continued on yearly basis up to today, the responsible members being prof. Kauko Aho, prof Veli Siekkinen, prof. Asko Riitahuhta and Dr Arto Lehtovaara. In 1994 two courses ”Introduction to tribology” and ”Advanced tribology” were introduced to replace the single course.

When Tampere Wear Center was established in 2008, the need for a special course “Wear of materials” for material scientists was soon recognized. It started in 2011 and was combined with the corrosion course in 2017 with the name “Materials performance” (later “Corrosion and wear of materials”) and the wear part is currently lectured by Assoc. prof. Auezhan Amanov and Dr Kati Valtonen.

Tribology was an integrated as part of the teaching in machine design in Oulu University under the leadership of professor Tatu Leinonen, in Lappeenranta Technical University under the leadership of professor Niilo Teeri and in Helsinki University in the department of Physics under the leadership of professors Erik Spring and Asko Anttila.

The tribology teaching in Finnish universities in present days is described in chapter 9.

6. International contacts and collaboration

6.1 ITC International Tribology Council

International Tribology Council (ITC) is the international organization that brings together Tribology Societies and Groups from all over the world (https://www.itctribology.net). It was founded in 1973 and brings today together tribology experts from about 50 countries from all continents. ITC had in 1971 initiated the EUROTRIB International Congress on Tribology conference series to be held every fourth year and selected the hosting national tribology organization. It was later renamed to World Tribology Congress and has been the most international and largest gathering of tribologists worldwide.

Figure 6.1.1 Kenneth Holmberg received the Tribology Gold Medal 2017.

ITC initiated the Tribology Gold Medal that has been awarded every year since 1972 for outstanding and supreme achievements in tribology and is considered the world’s premier award in tribology. Kenneth Holmberg of VTT received the Tribology Gold Medal in 2017.

From its founding years, the Finnish Society for Tribology has been a member of the ITC. Every member society of ITC can appoint as its representative an ITC Vice President who represents the society in the in-session meetings of the ITC. Kauko Aho was the first Finnish ITC Vice President, and he was followed by Kenneth Holmberg 1987-2020 and Helena Ronkainen from 2020.

Professor Peter Jost is commonly called the father of tribology as he chaired the UK governmental committee that labelled the term “Tribology”. He was over the years the active spokesman and missionary for the tribology concept travelling and lecturing very successfully about its importance all over the world. Peter Jost acted as the ITC President from its founding 1973 until his death 2016. Kenneth Holmberg was appointed the Acting ITC President for the transition period from 2016 to 2017 until a new ITC president, Ali Erdemir was elected. Holmberg was during that transition period leading the restructuring work of ITC to a modern scientific international society and he served in the ITC Executive Committee during 2017 -2022.

6.2 Nordic tribology research collaboration

The biennially held NORDTRIB Symposium was indeed the central contact event and place for networking

Figure 6.1.2 Attending World Tribology Congress 2009 in Kyoto (from left) professor Koiji Kato from Sendai, Japan, Dr Helena Ronkainen (ITC Vice-President 2020-), professor Peter Jost (ITC President 1973-2016) and professor Kenneth Holmberg (ITC Vice-President 1987-2020).

for tribology collaboration between the Nordic countries. In the 1980s before Finland and Sweden entered the European Union was the Nordic Industrial Fund a platform that offered funding for joint research projects in the interest of the Nordic countries. Such projects focusing on tribology were:

- Project on "**Abrasive wear**" 1980-84 coordinated by professor Olof Vingsbo from Uppsala University in Sweden with participation of VTT and Technical University of Helsinki in Finland.
- Project on "**Tribology of Vacuum Deposited Surface Coatings**" 1983-86 coordinated by Kenneth Holmberg from VTT in Finland with participation of Uppsala University in Sweden, SINTEF in Norway, and Aarhus University in Denmark.
- Project on "**Tribology in metal cutting**" 1991-1994 coordinated by Kenneth Holmberg from VTT in Finland with participation of Uppsala University, Technical University of Denmark (DTU), Technological Institute of Iceland (ICETECH), SINTEF in Norway, and Swedish Institute for Metal Research.
- Project on "**Tribology of ceramic materials**", 1991-1994, with partners from all Nordic countries.
- Project on **"Components and Smart Machines with Micro-Nano Surface Embedded Sensors, COSMOS I & COSMOS II"**, coordinated by Danish Technology Institute with participation of VTT, SINTEF in Norway and Acreo in Sweden.

6.3 European tribology research collaboration

Finland and Sweden joined the European Union 1995. This opened the possibility for universities and research organizations to take part in the R&D programs of EU. Over the years tribology has been a topic of EU research collaboration in several programs and projects.

One of the first EU projects in which Finland participated was a European Union funded BRITE-EURAM Project on **Surface Coatings for low wear applications** coordinated by Allan Matthews from Hull University in UK and with participation of Helena Ronkainen from VTT in Finland and Darmstadt University in Germany. The first tribology related EU-project in which Tampere University of Technology (TUT) Laboratory of Machine Design participated was led by professor Lehtovaara, **Improving competitiveness and conserving the environment through high-durability nanocomposite coatings –** HIDUR (2001-2005). It was coordinated by Peter Dearnley from Leeds University, UK. Participants came from UK, Germany, Italy and Finland. The main action of TUT was an evaluation of life and friction of coated gears using the FZG test machine.

Other more recent EU-projects with involvement of Tribology group of VTT and Tribology and Machine Elements group of TUT (TribME):

- i-TRIBOMAT – EU funded project **Intelligent Open Test Bed for Materials Tribological Characterisation Services**, coordinated by Franz Pirker from AC2T with participants VTT, Tekniker, Luleå Technical University, Moventas, Trygonal and Toyota Europe.

- INNTERESTING – EU funded project **Innovative future-proof testing methods for reliable critical components in wind turbines**, coordinated by Mireia Olave at Tekniker, Spain, with participation of VTT, Katolische Universitet Leuven, Belgium, Siemens Industry Softare, VITO, Belgium, and a Basque Energy Cluster.
- HERCULES – **High efficiency engine R&D on combustion with ultra-low emissions for ships,** 2004-2007, the project developed new technologies to drastically reduce gaseous and particulate emissions from marine engines and concurrently increase engine efficiency and reliability, reducing fuel consumption, CO2 emissions and engine lifecycle costs. VTT Tribology group participated by performing experimental research on piston rings and cylinder liners.
- ECOBEARINGS – **Environmentally compatible bearing materials**, 2009-2011, led by Metso Minerals. The aim of the project was to develop a substitute metallic or composite bearing material, which has similar tribological and mechanical properties as the currently used lead bronze but consists of none or less the hazardous constituent. TribME group focus was on tribological performance evaluation (friction, wear and life) of lubricated sliding bearings. Total of four participants from Spain and Finland. MNT-ERA-Net
- ArTEco – **Arctic Thuster Ecosystem**, 2015-2017, led by VTT, nine participants from Germany, Sweden and Finland. TribME group focused on a scuffing and subsurface fatigue in a lubricated rolling/sliding contact with dynamic loadings. MarTech II, EC ERA-Net scheme.
- OPMO - **Operation monitoring of mineral crushing machinery**, 2019-2021, led by Lehtovaara, TAU. The project focused on the development of a combined monitoring and diagnostic system to improve operation monitoring of mineral crushing machines. The TribME group focused on rolling bearings. Six participants from Poland and Finland. EIT RawMaterials project (Horizon)
- ENGINE – **Zero-Defect manufacturing for green transition in Europe**, 2022-2025, lead by VTT. The main objective is to develop a first-time-right (FTR) and zero-defect metal product design and manufacturing system, then demonstrate it on marine engine supply-chain. Total of 17 participants from eight European countries. TAU tribology part will focus on fretting (fatigue and wear) contact modelling and experimental testing using the in-house fretting test rigs as well as material characterization and development of related manufacturing methodology. HORIZON-IA

The active co-operation and participation in the European projects gave Finnish tribology researchers good opportunities to work and form relationships with international top scientists and rise the national technological and scientific level. For Finnish companies the activities in international joint projects provided often direct contacts to possible international customers and formed a base for internationalization of the companies and export from Finland.

Finland and Finnish tribologists had a major and leading role in initiating and coordinating two large **European COST** (European Cooperation in the Field of Scientific and Technical Research) **actions focusing on tribology**. The first research action "COST 516 – Tribology" was carried out over the years 1994 to 2000 and the second "COST 532 – Triboscience and Tribotechnology" over the years 2001 to 2007. The two actions included about 70 universities and research organisations and 150 companies from twenty-eight European countries and 4 non-European countries.

This was the time just after the collapse of Soviet Union and the independence and opening of the Eastern European countries. The COST Tribology actions formed a platform for tribologists from nearly all European countries from east to west to come together, change scientific results, discuss, collaborate, and plan future joint research work on tribology on international scale. The COST action steering groups were large with participation from each participating country. They came together twice a year for meetings and seminars rotating between the participating countries.

- The **COST 516 Tribology** action (1994-2000) focused on three new industrially important tribology topics: grease lubrication, tribology of renewable environmentally adapted lubricants, and coatings and surface treatments. The coordinator of the action was VTT from Finland with Kenneth Holmberg acting as program coordinator. Twenty-one European countries and two non-European countries (India and Russia) joined the action. A total of 64 research projects were carried out by 42 tribology institutes including about 200 research work years, with a total research funding of more than ten million Euros and 100 European industrial companies supporting the projects. There was published 423 reports and of them 295 in international journals or proceedings and 17 new commercial products were launched. The benefits of this research are especially in European transportation, manufacturing industry, process industry and energy production.
- The **COST 532 Triboscience and Tribotechnology** action (2001-2007) focused on tribology in three application areas: engine systems, transmissions and tribochemistry. The coordinator of the action was VTT from Finland with Kenneth Holmberg acting as program coordinator. Twenty-eight European countries and two non-European countries (Israel and USA) joined the action. A total of 42 research projects were carried out by 58 tribology institutes including about 260 research work years, with a total research funding of more than twelve million Euros and 103 European industrial companies supporting the projects. There was published 628 reports and of them 484 in

Figure 6.4.1 The Finnish delegation visiting Guangzhou Machine Tool Research Institute in 1988 together with hosts. From left: Matti Kleimola, Kenneth Holmberg, Chen Kedong, Martti Annala, Lin Heng Yao, and Kauko Aho.

international journals or proceedings and 32 new commercial products were launched. The benefits of this research are especially in European engine and transmission producing industry, that is in the automotive industry but also in other sectors such as ship and rail industry, powerplants and automated production.

The Finnish tribologists had an active role in the **International Research Group on Wear of Engineering Materials (IRG-OECD)** acting in association to the OECD. The Group arranged Tribology Seminars annually or biennially at various sites in Europe starting from 1970. Members were tribology groups from the OECD countries. Kenneth Holmberg from VTT acted as president of this group 1992-2006.

6.4 China collaboration

An opening and restructuring of the Chinese society started around the year 1980 and one of the priority actions was to restructure and modernize the whole educational system in schools and universities. Part of this was to actively build up international collaboration and send out excellent scholars to learn from the scientific societies and organisations especially in the USA and Europe. In Finland VTT and Kenneth Holmberg was in 1987 contacted by the second secretary of the Embassy of the Peoples Republic of China in Finland, Dr Fan Mingyi. He had a background in tribology research and suggested collaboration in this field between China and Finland.

The discussions resulted in including tribology as a topic in the official Scientific and Technological Cooperation Agreement between the governments of China and Finland. The board of the Finnish Tribology Society decided at its meeting 12.1.1988 to send a delegation of Finnish tribologists to visit tribology experts and laboratories in China. The visit took place 14 - 22.10.1988 under the leadership of the chairman of the Finnish Tribology Society professor Kauko Aho from TUT, and participated by professor Matti Kleimola from HUT, Dr Kenneth Holmberg from VTT and DI Martti Annala from Rautaruukki Ltd. The group visited Chinese Mechanical Engineering Society, Tsinghua University and Research Centre for Reliability in Beijing, Guangzhou Machine Tool Research Institute in Guangzhou (Kanton), Shanghai Research Institute of Materials and Research Institute of Petroleum Processing in Shanghai.

Both parts gave lectures on tribology during the visit and discussed further collaboration. The coordinating partners of the collaboration were in China the Guangzhou Machine Tool Research Institute (GMTRI) and in Finland VTT. The topics of joint interest were tribology of ceramics, polymers as wear resistant materials, lubrication at low temperatures, coating tribology and tribological computational calculation methods.

The next step in the collaboration was a visit of a Chinese tribology delegation in Finland 5-16.6.1989 for visits at Finnish technical universities, VTT and companies. The delegation attended the EUROTRB 89 Tribology

Figure 6.4.2 Visit in the tribology laboratory of Guangzhou Machine Tool Research Institute in 1988. The host Lin (left) demonstrates the experimental tribometer to the visitors Kauko Aho, Martti Annala, Matti Kleimola, and Kenneth Holmberg. Research director Chen Kedong is to the far right.

Congress held during that time in Helsinki. The discussions resulted in actions for further collaboration and tribology researcher exchange to both collaborating countries: Petri Enwald from VTT to GMTRI in Guangzhou and from GMTRI Lin Heng Yao to VTT and Ou Bo Ming to HUT in Espoo. A second visit of Chinese experts to Finland was arranged 4-16.6.1992 including participation in the NORDTRIB 92 Symposium held on a cruise ship m/s Silja Symphony between Helsinki and Stockholm.

A second delegation from Finland was sent to China 13-23.3.1993 to visit Tsinghua University and Academy of Agricultural Mechanization in Beijing, Xian University in Xian, Guangzhou Machine Tool Research Institute and South China University of Technology in Guangzhou. The delegation consisted of Dr Kenneth Holmberg from VTT as a leader, professor Veikko Komppa from VTT and professor Tapio Mäntylä from TUT. A Sino-Finnish Seminar on Tribology and Advanced Materials was held 18 -19.3.1993 in Guangzhou. The program included lectures by Holmberg on coatings tribology and accelerated testing, by Komppa on tribology of polymers and chemical analysis in research and by Mäntylä on plasma coating technique of thick ceramic coatings and abrasive wear of ceramics. The Chinese colleagues presented research results on design of hydrostatic and hydrodynamic bearings, tribology of high molecular anti-friction materials and plastic alloys and their tribological performance.

The collaboration resulted in several joint investigations, patents and articles in scientific journals and continued based on bilateral contacts between the involved institutes after the restructuring of the scientific and technological collaboration from agreements on governmental level to direct contact collaboration in the late 2000´s.

6.5 Russia collaboration

A first contact between the Finnish and Russian (Soviet) tribologists was taken in 1979, when Kenneth Holmberg, then representing Helsinki University of Technology (HUT), visited the Institute of Problems of Mechanics of the Academy of Science of the USSR in Moscow headed by one of the great pioneers in tribology, professor Igor Kragelski. The discussions resulted in the addition of "Tribology and arctic machine technology" as a topic of collaboration within the framework of the Scientific and Technological Collaboration Commission between Finland and Russia (in Finnish: Suomen ja Neuvostoliiton välinen tieteellis-tekninen yhteistoiminta komitea, TT-komitea).

Some years later in 1982 two experts from Russia, professor Igor Cherski and Dr Marat Bronovetz visited VTT, TUT, HUT and several companies in Finland and an agreement of collaboration was signed. The result was an extensive research collaboration during the years 1982 to 1986, including 11 research exchange visits by five researchers from both sides and a total of 300 research visit days. The main topics for this collaboration was the reliability of machines in arctic temperatures down to -60° C and especially the functionality of hydraulic systems, lubrication and hydraulic fluids, seals and bearings and friction in the contacts between metals and ice and snow. Other tribological topics of collaboration were polymer bearings, tribological experimental measurement

Figure 6.5.1 Negotiations on Finnish-Soviet tribology collaboration in Jakutsk, Siberia 1985. From left Harri Vainio, Kenneth Holmberg, Marat Bronovetz, a Russian researcher, and Igor Cherski.

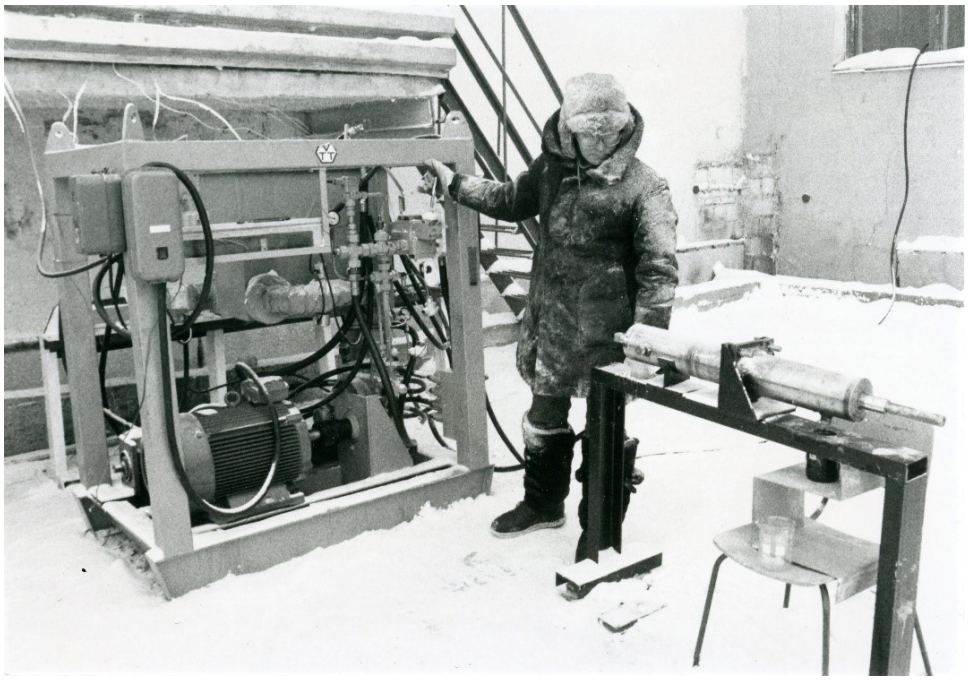

Figure 6.5.2 Raimo Soudunsaari from VTT is testing the Finnish hydraulic assembly in natural arctic environment at an outside temperature of -52° C in January 1985.

techniques and lubrication in highly loaded tribological contacts.

The largest collaboration action was to send a hydraulic power unit composed by components manufactured by eight Finnish companies to Jakutsk in Siberia for reliability and tribological testing in real natural arctic conditions and temperatures down to -52° C. The experiments were carried out in January 1985 with two Finnish VTT researchers participating on site in the experiments.

The second period for research collaboration, which took place during the years 1987-1992, included joint research in the following areas: tribological systems with magnetic fluids, selective transfer lubrication under friction, tribology of polymers, wear, and lubrication of slow speed Kymenite gears, development of the additives of gear oils, tribology in arctic conditions, tribology of new materials, space and vacuum tribology and development of tribological testing. The program was coordinated on the Soviet/Russian side by Academician Avduyevsky and on the Finnish side by Dr Holmberg from VTT. The

Figure 7.1 The participants in the First Nordic Symposium on Tribology arranged in Tampere, Finland, 15-17.8.1984. Among the attendees you may find starting from the left Seppo Mikkonen, Kurt Fager, Sture Hogmark, Heikki Sundquist, Sakari Viitamäki, Olli Ylöstalo, Erkki Kuusisto, Ulla Mäkelä-McNiven, Aapo Niemi, Kristian Tönder, Jörgen Jacobsen, Elisabeth Kassfelt, Kenneth Holmberg, Sören Andersson, Bo Jacobson, Kauko Aho, Statis Iaonides, Bengt Jacobsson, Antti Kari, Czeslaw Kajdas, Kauko Suontama.

collaboration included nine research institutes and the companies Internauka, Moplen Plant and Design Byro Polyus on the Russian side, and on the Finnish side six VTT research laboratories and the Finnish companies Safematic, Kone, OMG Kokkola Chemicals, JOT-companies/Santasalo Gears, Teknikum and Neste.

A third period of collaboration took place from 1992 to 1994. During these years, the research focused on "Industrial applications of magnetic fluid seals and advanced lubrication" between the Interdisciplinary Scientific Tribology Council of Russia (ISTC) and VTT in Finland. Both magnetic and magnetorheological fluids were designed for seal applications in hydraulic pumps and drums. The calculations were made by the Russian side and the experimental testing by VTT in Finland. The results were reported jointly.

The research collaboration on tribology and arctic machinery was extensive and included both theoretical and experimental work in both countries, about 30 research visits to several institutes and sites and about ten commercial industry companies from Finnish side and about five companies from the Russian side. The results were directly benefited by the involved companies and to some part published jointly as journal articles and patents.

7. NORDTRIB - The Nordic International Symposiums on Tribology

The chairman of the newly founded Finnish Tribology Society, Kauko Aho, was invited to attend the EUROTRIB 1981 International Congress on Tribology in Warsaw, Poland. He also attended the in-session meeting of the International Tribology Council chaired by its president Peter Jost and held on the same site. Jost and Aho discussed the possibility of arranging an EUROTRIB congress in Finland sometimes in the future.

Kauko Aho was interested in the idea to arrange a large tribology congress in Finland but at the same time he hesitated. Was there enough competence and capacity among the Finnish tribologists to act as host for such a large scientific event? After some thoughts he came up with the idea that perhaps it would be good to test the capability to arrange a large meeting in this area first on the Nordic scale. Kauko Aho suggested that the Finnish Tribology Society would take an initiative to arrange a First Nordic International Symposium on Tribology in Tampere in the summer of 1984.

During his licentiate studies on tribology Kenneth Holmberg spent some time in the Laboratory of Machine Design at Chalmers University of Tribology in Gothenburg, Sweden. The professor at the laboratory was Bengt Jakobson, a pioneer in hydrodynamic lubrication

research and a founding member of the ITC. Supported by Jakobson Holmberg made visits to leading tribology researchers in the Scandinavian countries to present and discuss the idea of arranging a joint tribology meeting, NORDTRIB. He visited professor Helge Christensen at Trondheim University of Technology in Norway; professor Gunnar Sörensen at Århus University and professor Jörgen Jacobsen at the Technical University of Copenhagen in Denmark; and professor Bo Jacobson at Luleå University in Sweden.

The suggestion to start a series of Nordic tribology meetings received enthusiastic support from all Nordic tribology colleagues. A first planning meeting to establish the organisation for the NORDTRIB Symposiums was held 1982 at VTT in Tapiola, Finland, and attended by Kauko Aho, Kenneth Holmberg, Bengt Jacobson, Bo Jacobson, Helge Christensen, Gunnar Sörensen, Jörgen Jacobsen, and Nils Mustelin from the Nordforsk Nordic research organization.

The initiative to arrange such a regional conference on the topic of tribology was remarkable in that sense that it was the first of that kind globally. It received large attention in the global tribology community and has been a model for regional and regular tribology meetings arranged later in other parts of the world. Such are BALTTRIB arranged by tribologists in the Baltic countries, BALKANTRIB by the Balkan countries, ASIATRIB by South-East Asian countries, ECOTRIB by the Middle European countries Spain, Slovenia, Austria and UK; and IBERIATRIB by the Iberian Peninsula countries.

The First Nordic Symposium on Tribology was arranged in Tampere, Finland on the 15th to 17th August in 1984 with 60 participants from 8 countries. From the beginning there has been a special character of the NORDTRIB meetings:

- all main tribology research groups in the Nordic countries have attended and contributed,
- it has been a meeting point especially for young tribologists and the place to give their first international scientific presentation,
- most of the attendees have been from the Nordic countries, perhaps some 80 %,
- there has always been an attendance of international tribology experts from other parts of the world,
- the site has typically been outside the large cities in some smaller community close to the beautiful Nordic nature, and
- in the early years all presentations were given in one session for everyone to attend but later when the symposium grew in number of attendees it became necessary to introduce a model with some parallel sessions.

Since the start, the NORDTRIB Symposia has been arranged every second year and rotating among the four Nordic countries Finland, Sweden, Norway, and Denmark. In the year 2004 the NORDTRIB symposium was arranged in Tromsö in Norway which is to our knowledge the most northern site where a tribology conference has ever been held. The most eastern site has been Porvoo in Finland, the most western Bergen in Norway, and the most southern Helsingör in Denmark. In the year 1992 the NORDTRIB was arranged on board the ferry M/S Silja Symphony sailing from Helsinki to Stockholm and back to Helsinki, which may be the most unstable site for a tribology conference ever arranged. The Finnish Society for Tribology has been actively participating in the conference arrangements in Finland. In 2016 the NORDTRIB was arranged in Hämeenlinna by VTT and the Society, with half of the plenary lecturers being female for the first time in the history of NORDTRIB. This progressive gender approach was followed up by NORDTRIB 2022 in Ålesund, Norway, where all six keynote speakers were female.

Over the time of 38 years, altogether nineteen NORDTRIB conferences have been arranged in the four Nordic countries. and each time with new views of Scandinavian nature in the surroundings. The latest one was arranged in the fjord landscape of Ålesund in Norway in June 2022. Up to now altogether 1921 scientific papers, 228 of them as posters, have been presented, 2570 tribologists participated from about 50 countries all around the world. The history of NORDTRIB in numbers is presented in Appendix 13.2.

8. EUROTRIB 89 in Helsinki

The first NORDTRIB 1984 Symposium was a success and showed that there were many highly qualified experts on different aspects of tribology both in the academia and in industry who had a strong commitment to the subject and were willing to support its further development jointly on Nordic base. Encouraged by this the Finnish Society for Tribology decided to apply for hosting the EUROTRIB 1989 International Tribology Congress. The International Tribology Council decided at its in-session meeting in Lyon 1985 to select Finland and Helsinki for the site of the next congress to be held 1989 and to be hosted by the Finnish Society for Tribology.

The EUROTRIB Congresses were by that time the largest and most international conference dedicated to tribology. They were held every fourth year starting from 1973 in different parts of Europe. The organizer of the congresses was the International Tribology Council, which for each congress selected a local organizer with full responsibility of all practical arrangements and for the scientific program. The congresses attracted continuously an increasing number of international participants from all parts of the world. The name was changed to World Tribology Congress starting from the conference help in 1997.

Professor Kauko Aho was elected chairman of the Local and Scandinavian Organizing Committees of the 5th International Congress on Tribology – EUROTRIB 89. The event took place during 12-15.6.1989 in the facilities of Helsinki University of Technology in Otaniemi, Espoo. The Organizing Committee consisted of Kauko Aho (chairman)

Figure 8.1 Professors Kauko Aho and Peter Jost chairing the opening session of the EUROTRIB 89 International Tribology Congress held 12-15.6.1989 in Helsinki, Finland.

Figure 8.2. Honorary table at the EUROTRIB 89 Congress Banquet. From left Maurice Godet, Andrea Holmberg, Koiji Kato, Czeslaw Kajdas, Olof Vingsbo, Yukoke Kato and Kenneth Holmberg.

Tampere University of Technology; Kenneth Holmberg (EUROTRIB 89 manager), Technical Research Centre of Finland; Kristian Tönder, Norwegian Institute of Technology; Bo Jacobson, SKF Ltd, Sweden; Gunnar Sörensen, Aarhus University; Olof Vingsbo,

Uppsala University; Matti Kleimola, Helsinki University of Technology; Erkki Kuusisto, Technical Inspection Centre in Finland; Arto Lehtovaara, Tampere University of Technology; Aapo Niemi, Neste Ltd, Finland; Heikki Sundquist, Lohja Ltd, Finland; and Juhani Valli, WP Ceramics Ltd, Finland.

The congress program covered all aspects of tribology from fundamental tribology, methods and material development to industrial applications. New front edge topics such as surface engineering, tribology of ceramics and polymers, tribometry and tribosensors, expert systems in tribology, robotics and precision instruments, magnetic storage systems, and space and vacuum tribology were presented in lectures given by the best experts in the world.

At the EUROTRIB 89 conference, the magnetic storage systems were a very virgin topic that was both scientifically and technically extremely advanced. It offered the whole emerging computer business as a most challenging field of tribological application. The topic was presented by Bharath Bushan, who was the top expert from IBM research centre in San Jose, USA. The topic of space tribology attracted great attention as this was the first time that top experts on space tribology from east and west, academician Avduevsky from USSR and Dr Todd from the European Space Agency in UK, met in a joint session and presented their new findings openly.

A long list of the most eminent great scientist in tribology gave plenary lectures, presented research papers and chaired sessions at the congress including: Peter Jost, UK; Ward Winer, USA; Maurice Godet, France; Harem Block, The Netherlands; Horst Czichos, Germany; Jacob Israelichvili, USA; Mike Furey, USA; Czeslaw Kajdas, Poland; Bo Jacobson, Sweden; Koji Kato, Japan; RM Matveevsky, USSR; Ernest Rabinowicz, USA; David Rigney, USA; A. Enomoto, Japan; Jean-Marie Georges, France; John Halling, UK; Alister Cameron, UK; Karl-Heinz Zum Gahr, Germany; Ian Hutchings, UK; AV Chichinadze, USSR; VN Vinogradov, USSR; Allan Matthews, UK; Ali Erdemir, USA; Bernard Hamrock, UK; Juri Drozdov, USSR; William Roberts, UK; Hans Hinterman, Switzerland; Mark Gee, UK; Yoshi Kimura, Japan; Jean-Michel Martin, France; Mike Gardos, USA; K. Miyoshi, USA; Tony De Gee, The Netherlands; Desmond Moore, Ireland; Statis Iaonnides, The Netherlands; Wilfried Bartz, Germany; Lou Rozeano, Israel; Teddy Eyre, UK; Freidrich Franek, Austria; Bengt Jacobson, Sweden; Olof Vingsbo, Sweden; Kristian Tönder, Norway; Ian Scherrington, UK; Michael Armbruster, France; J. Sharma, India; Sture Hogmark, Sweden; Bharath Bushan, USA; Subbiach Ramalingam, USA; Kauko Aho, Finland; and Kenneth Holmberg, Finland.

A total of 200 oral scientific papers were presented and 200 posters. The 500 participants attending represented tribologists from about 50 countries worldwide. Thus EUROTRIB 89 was by that time the largest and most international tribology conference arranged so far. The practical arrangements were taken care by the Congress Service Leena Aarrejärvi Ltd.

9. Tribology research groups in universities and research center

9.1 Aalto University (former Helsinki University of Technology, HUT)

The **Laboratory of Machine Design** in Aalto University carried out numerous development and research projects in tribology since early 80s. Professor Matti Kleimola together with his teaching staff Seppo Kivioja, Veikko Holvio, Pekka Salonen, Jari Juhanko, and laboratory experts Olli Ylöstalo, Pekka Hautala, Olof Calonius, and his successor Petri Kuosmanen coordinated several both academic research and industrial development projects.

Extensive research was carried out on biotribology with focus on the development of synovial joints. The work by Dr Vesa Saikko on synovial joints is internationally highly recognized. This research started 1987 with a project on total hip joint replacements. The preliminary study was funded by the Finnish Innovation Fund Sitra and included co-operation with the Orthopedic Hospital of Invalid Foundation. The master thesis of Saikko dealing with hip joint's tribology was the start of designing and manufacturing several hip joint simulators over the past four decades (Saikko 1993).

The tribology of oil films in hydrodynamic journal bearings was investigated by Dr Antti Valkonen to determine the oil film pressure in real hydrodynamic journal bearings under realistic operating conditions. High load-carrying hydrodynamic journal bearings are critical in power transmission components. The true operating conditions of hydrodynamic journal bearings is essential to machine design and oil film pressure is one of the key operating parameters describing the operating conditions. Test rig experiments, simulations and calculations were carried out to determine the oil film pressure and to understand its relationship with other operating parameters. The oil film pressure was measured by optical pressure sensors integrated in the bearings. The work included the development of these sensors.

The tribology of internal combustion engines was investigated. A study on medium-size and large multi-cylinder diesel engines was carried out. It was shown that the piston rings largely operate under starved lubrication conditions at the top and bottom dead centers, and that hydrodynamic lubrication is active in the mid-stroke region. The main mission of the piston ring pack is to keep the gas pressure on the combustion chamber side and the lubricating oil on the crankcase side of the piston.

Figure 9.2.1 The tribology laboratory at Tampere University with doctoral student Erkka Virtanen (left) supervised by Gabor Szanti from Ata Gears Oy and professor Arto Lehtovaara (right). Photo: Jonne Renvall, Tampere University 2022.

9.2 Tampere University (former Tampere University of Technology, TUT) and Tampere Wear Center

In the early days of 1975-1995 the main tribology research topics at TUT were the stick-slip sliding phenomenon (Hannu Tarvainen 1982), boundary lubricated sliding bearings (Markku Reunanen 1987), modelling of elastohydrodynamic lubrication (co-operation with B. Hamrock, Ohio University), fretting and on-line ferrography (Hannu Iivonen 1990), ski friction (Arto Lehtovaara 1986, 1989), and mechanical face seals (Juha Miettinen 1994).

The **Tribology and Machine Elements research group** has been led by professor Arto Lehtovaara, the follower of professor Kauko Aho, over the years 1999 - 2022. The group provides advanced tribological expertise and solutions for developing future design concepts for machine elements. The group's research focus is on tribology, which investigates the friction, wear and lubrication of contacting surfaces as well as related fundamental failure mechanisms. This gives the basis for the analysis and dimensioning of machine elements and systems in terms of their performance and service life. Theoretical research concentrates on numerical modelling and simulation of dry and lubricated contacts targeted at various applications. Experimental work is carried out for the verification of the models as well as for the testing and monitoring of real applications. Special interest is focused on determining the micro-scale contact effects on macro-scale designs. Main applications are frictional joints (fretting), bearings and gears related to, for example, combustion engines, mineral crushers and gear drives in wind turbines and marine applications.

The research topics are typically derived from real industrial problems. The main research project categories have been company sponsored projects, national public and private funded collaborative projects and national programmes, international EU-based projects and in the recent years TAU Doctoral School of Industrial Innovations projects. The group is known for the close collaboration with industry. The group has published over 80 peer-reviewed journal papers. Professor Lehtovaara initiated the course "Dimensioning of Machine Elements", focusing on gears, bearings and shafts, and since 2022, it has been given by Dr Janne Juoksukangas.

Tampere Wear Center (TWC) was established in 2008 to better coordinate and manage research of wear processes and wear mechanisms in different environments, as well as to facilitate the development of new wear resistant materials at Tampere University of Technology. The wear research is being conducted in the operational research groups in the department of Engineering Materials Science: materials characterization, plastics and elastomer technology, metals technology, surface engineering, and ceramic materials. Moreover, the tribology and machine elements research group joined Engineering Materials Science in 2014. The founders of TWC were prof. Toivo Lepistö and prof. Veli-Tapani Kuokkala and the project manager has been Dr Kati Valtonen since 2008.

Figure 9.2.2 (a) The doctoral student Juuso Terva (left) designed and built a dual pivoted jaw crusher for wear studies at Tampere Wear Center supervised by professor Veli-Tapani Kuokkala (right) in 2015. (b) Dr Kati Valtonen attaching samples to the impeller-tumbler device. Photos: TAU/archive

Tampere Wear Center concentrates on both scientific and practical aspects of wear and tribology, trying to bridge the gap between scientific basic research and applied industrial research and product development. The aim of TWC is to provide in-depth insight into the mechanisms of wear and thereby facilitate the development of new wear resistant materials and to find solutions to the practical wear problems constantly faced by the industry. TWC has excellent infrastructure for wear research, as well as highly qualified scientists and research engineers for the needs of both long-term scientific research and product development for the industry. Special expertise areas are heavy abrasion, impact wear, fretting and tribology of machine elements, such as gears, bearings, brakes, seals, and frictional joints as well as numerical contact modeling and experimental verification of the models.

The background of TWC was in the extensive industrial collaboration started by professor Pentti Kettunen in 1970's and continued by materials science professors Toivo Lepistö, Tapio Mäntylä, Tuomo Tiainen, Petri Vuoristo, and Veli-Tapani Kuokkala. Therefore, Tampere Wear Center rapidly developed into an internationally recognized concentration of advanced tribology and wear expertise and test facilities. It is one of the largest and high-quality research centers in the field of heavy abrasive and impact wear research worldwide. Since 2008, over 100 peer -revied scientific articles have been published in international journals by TWC researchers. Moreover, 16 doctoral theses and several master and bachelor theses have been completed.

The infrastructure of Tampere Wear Center was originally funded by European Regional Development Fund, industry, and Tampere University of Technology. During 2007, almost one million euros was expended for characterization and wear testing facilities, such as ultra high-resolution field emission scanning electron microscope (UHR FEG-SEM), high speed video systems, versatile pin-on-disk / ball-on-disk tribometer, crushing pin-on-disk, uniaxial crusher, ball-on-block, and biomaterial crusher. After that, the development and designing of new wear testing devices has been constantly going on. The latest systems are the high velocity particle impactor, dual pivoted jaw crusher, impeller-tumbler, high -speed slurry-pot type erosion tester, and pulse jet erosion tester. In 2022, Academy of Finland funded Hub for Hydrogen-Materials Interaction Research Infrastructures - H2MIRI and during that project for example a new multipurpose tribometer will be part of the TWC infrastructure.

Wear research is conducted in close collaboration with several international partners, such as the National Research Council of Canada (NRC), the Austrian Excellence Center for Tribology (AC2T), Mines ParisTech, VITO, TEKNIKER, the University of Sheffield, the University of Southampton, the University of Manchester, Luleå University of Technology, and Tallinn University of Technology.

TWC collaborates widely with other domestic universities and research institutes. Examples of such research activities are the FIMECC (Finnish Metals and Engineering Competence Cluster) programs 2009-2014 followed by the DIMECC programs 2014-2017. The domestic partners of TWC were, in addition to several industrial companies, Aalto University, University of Oulu, Lappeenranta University of Technology, and VTT. TWC was participating in several projects where novel breakthrough materials with improved performance for applications in demanding operational and service environments were developed. The program included 29 companies in the metals and engineering industry, their supplier and customer companies, as well as 11 high-level research groups. International activities included both research cooperation with foreign universities and partner

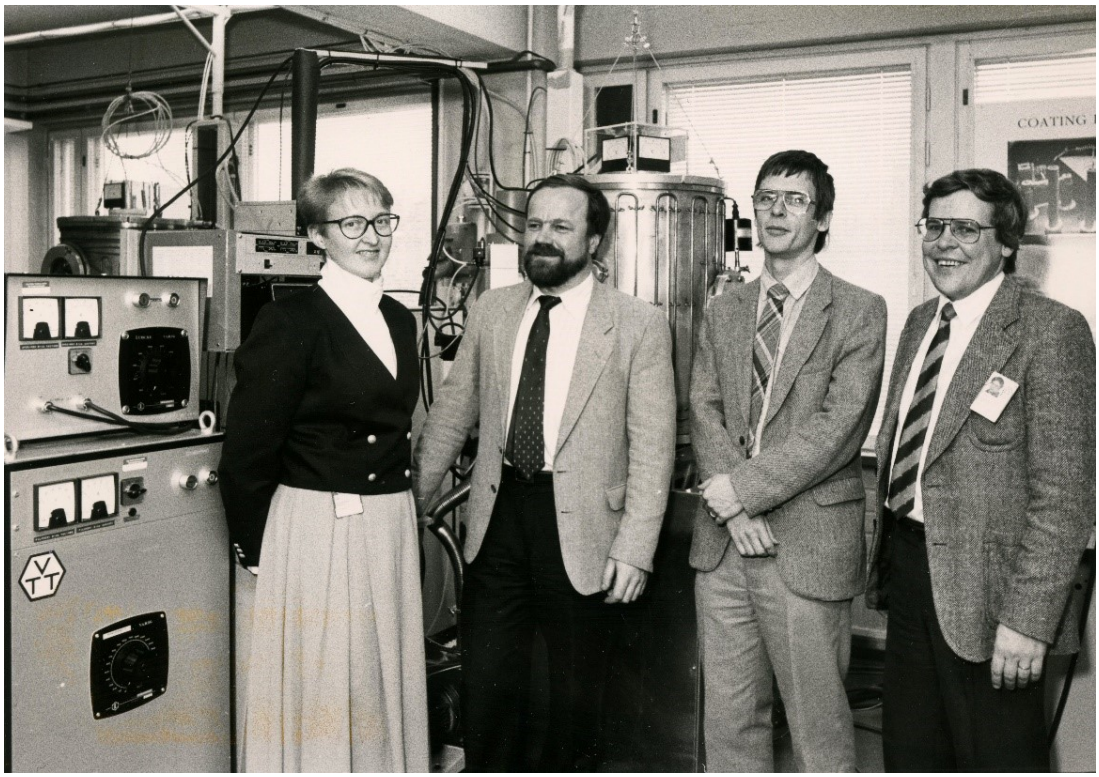

Figure 9.3.1 The VTT Machine Technology Group received the Euromaintenance Award 1990 of the European Federation of National Maintenance Societies (EFNMS) for achievements in tribology and maintenance technology research. From left: Helena Ronkainen, Rauno Kuoppala, Erkki Jantunen, and Kenneth Holmberg.

companies. Novel high-performance ultrahigh strength steels and stainless steels in combination with low-density materials were developed as well as research on abrasion-resistant and ultra-high-strength steels and hybrid and polymer materials.

9.3 VTT Technical Research Centre of Finland

VTT decided in 1979 to start a new research group on Machine Technology. It consisted of four research teams and one of them was Tribology. Kenneth Holmberg was contracted as the first tribology researcher at VTT 1980. The activity started with establishing basic tribology testing equipment like an Amsler twin disc machine, a pin-on-disc tribotester, and an ASTM abrasive wear tester. The early tasks were related to analysis of industrial wear failures and basic adhesive and abrasive wear studies.

Two tribological research topics were growing quickly in accordance with the general research trends in Finland at that time. It was tribology of thin surface coatings and arctic tribology, as explained in sections 6.5 and 11.4. Heikki Sundquist, Juhani Valli and Helena Ronkainen joined VTT to build up the surface coating research activity and Harri Vainio, Raimo Soudunsaari and Seppo Mikkonen joined the arctic tribology and hydraulics research activity. The research was carried out largely in jointly funded research projects with the Finnish Technology Agency (TEKES), later Business Finland, and VTT as main national funding contributors. Finnish industrial companies were involved as co-sponsors and often there was also some international research performance funding involved like typically Nordic Industrial Fund or some European Union research program, as described in sections 6.2 and 6.3.

Over the years different areas of tribology have been covered at VTT. The coating development and evaluation of tribological properties started with ceramic TiN and TiAlN coatings during 1980´s (Ronkainen 1990). From the beginning of 1990´s the development and tribological characterization of diamond-like carbon (DLC) coatings was one of the main research paths. The research covered both hydrogenated a-C:H coatings deposited by plasma-assisted chemical vapour deposition (PA-CVD), and hydrogen free ta-C coatings deposited by arc discharge based physical vapour deposition (PVD) methods (Ronkainen 2001), see section 11.4. The effect of hydrogen content on the tribological performance of DLC coatings was studied (Ronkainen 2001) as well as the friction and wear of DLC films in water and oil lubricated conditions (Ronkainen 2001). Tribological studies also evolved to different application areas covered in several national projects covering later also Atom Layer Deposited (ALD) thin films (Kilpi 2018).

Besides coatings research the tribological performance of ceramic materials was intensively studied from 1990´s covering tribological performance of several ceramic materials in dry and water lubricated sliding tests (Andersson 2006). The performance of ceramics was also studied in water and gas lubricated journal bearings tests (Andersson 1994). Tribology of metal cutting and related tool wear issues were investigated jointly together with

Figure 9.3.2 Celebration of the doctoral dissertation of Helena Ronkainen in 2001. From left: Jari Koskinen, Kenneth Holmberg, Helena Ronkainen, Jukka Vaari, Petri Vuoristo and Martti Vilpas (custos).

tribologists from all Nordic countries. This time also colleagues from Iceland, Iceland Institute of Technology, participated in tribotesting and development activities. Magnetic and electrorheological lubrication for zero leak sealing purposes was studied jointly with Russian colleagues. The concept of pasta lubrication was developed by tribomodelling for contacts with high friction in material handling equipment.

The FIMECC cluster launched 2008 two large national strategic research programmes on material research for the metal product and machinery industry. VTT was involved in several tribology projects on material testing, developing design criteria for tribological design and materials modelling and simulation of tribological contacts for different applications, such as rope-sheave contacts, vibrating machine parts and mineral cruching tools and equipment.

The tribological evaluation of polymers and polymer composites was early studied jointly within the Finnish-Chinese collaboration. Starting from 2014 the polymer tribology research was started within FIMECC and Finnish Academy projects by developing the polymer composites at VTT and by carrying out abrasive and adhesive wear and friction tests (Pelto 2020). Later the work was contimued with focus on industrial applications financed by the national research programmes.

The computational modelling and simulation of tribological contacts started already year 2000 by modelling the material modification in scratch testing of TiN and DLC coated surfaces. It was a joint effort of the tribology, fracture mechanics, materials and computer science research groups at VTT. Unique and detailed stress and strain graphs on micro- and nanocontact level illustrated the microtribological dynamics in the moving contact and opened a new avenue of research. The focus enlarged to thicker thermal sprayed coatings, polymeric and biomaterials and various applications, as described in section 11.5. One important funding source was the material modelling and simulation actions within the FIMECC material research programmes.

The tribological material modelling and simulation research was carried out in large international collaboration first in the COST programmes (section 6.3) and later in collaboration within the International Energy Agency (IEA) programme on Advanced Material for Transportation. In the IEA modelling work was for the first time tribological contacts with real topographies modelled by multimodelling on fractal multiscale levels down to micro- and nanolevel. Key collaborators in the action on modelled based design of tribological coating systems were Cutin University in Australia, National Physical Laboratory in the UK, Saarland University in Germany, City University of Hong Kong, Technion in Israel, and George Washington University in the USA.

The first Finnish research project financed by the European Commission was the Brite/Euram project in 1987 related to tribology and applications of ceramic coatings. After that several EU funded research projects have been carried out. Recently EU financed research related to the generation of single entry point for

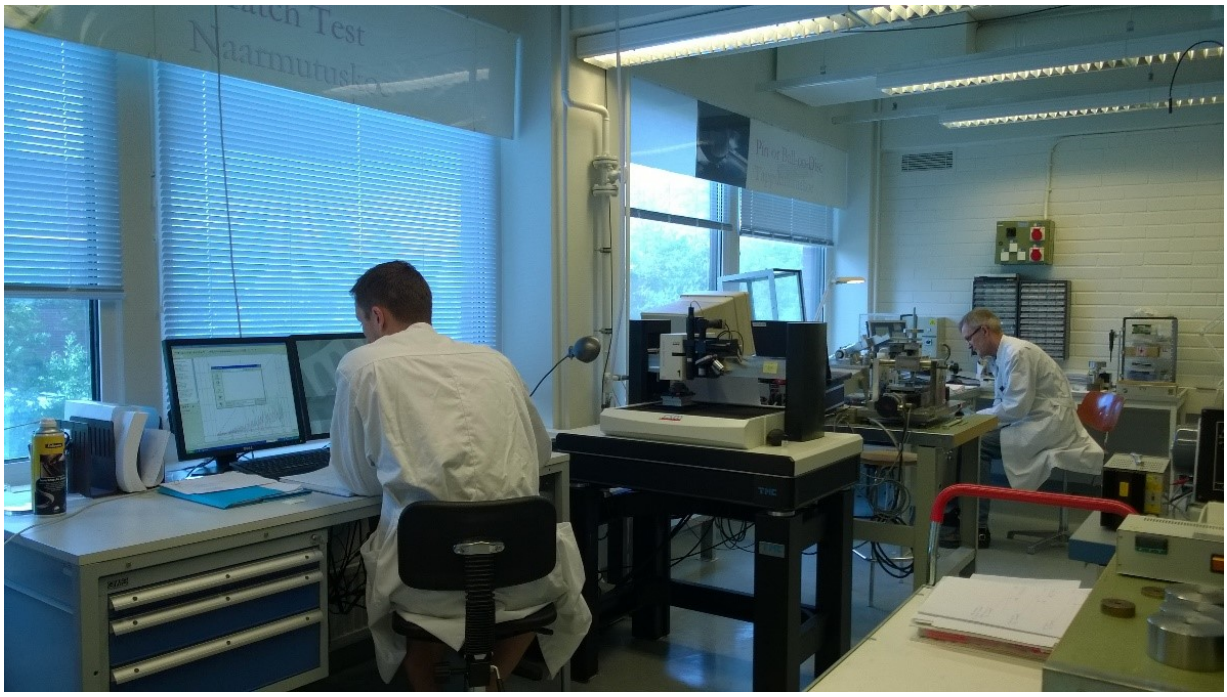

Figure 9.3.3 The Tribology laboratory at VTT with controlled humidity (50 ± 5 %RH) and temperature (21 ± 1 °C). Research scientist Antti Vaajoki and research engineer Simo Varjus busy with carrying out tribological testing of advanced materials 2010.

tribological characterization of materials and lubricants was carried out and the European Tribology Centre was launched where VTT is acting as a service provider with research partners, such as AC2T, Tekniker, and BAM. In another EU project the new research approach was established by utilising the digital twins of tribological tests. Related to journal bearing research, a data-based lubrication regime detection method was developed utilizing the computational modelling based digital twin of a journal bearing test rig, experimental data and Machine Learing (ML) tools (Tervo 2023). Similar digital twins have been generated for the gear test rig and ML based tool generated for efficiency estimations.

The newest research area at VTT is hydrogen tribology. Already in 2013 the first steps in tribological research in hydrogen was carried out in collaboration with Kyushu University (Vaajoki 2013), and now the Finnish Academy financed project "Hydrogen and tribointerfaces" starting in 2023 studies the friction, lubrication, and wear of steel, polymers, and coatings in hydrogen atmosphere. VTT is building specific infrastructure in Espoo for hydrogen related research covering e.g. materials and engine technologies besides tribology.

VTT is mostly carrying out applied research, and therefore engineering tribology has been one focus area over the years at VTT, e.g. the research related to engine and power transmissions was covered in several projects during 1990 to 2010. On these application areas e.g., the influence of coatings and surface roughness on tribological performance was studied with close collaboration with companies. Besides jointly funded project-based research, VTT has carried out over the years direct contract research for companies. Research work carried out on different machine components and even large machine systems has increased the tribological understanding in wide range of engineering organizations and companies.

In the period 2010 to 2020 VTT together with Argonne National Laboratory in the USA carried out breakthrough calculations on the impact of friction and wear on global energy consumption, environment and economy. A novel multiscale friction calculation method was applied on cars, trucks, lorries, busses, paper machines, mining equipment and extended to main industrial and societal sectors, as described in section 11.6.

Research infrastructure and laboratory facilities have evolved over the years, yet the main trend at VTT has been that the tribometers have been designed and built in-house. Peter Andersson has been the main designer of many test devices, such as pin-on-disc, journal bearing test rig, and piston-ring test rig. Some devices have also been manufactured and sold abroad. Tribology laboratory facilities were improved particularly in 1990´s when the tribology laboratory facility with controlled humidity and temperature was built to enable controlled and repeatable friction and wear testing (Figure 9.3.3). The tribology group of VTT has over the years published more than 500 peer-reviewed scientific papers on various aspects of tribology.

10. Tribology based R&D in industry

Research and development activities related to wear was carried out in Finnish companies already before publishing of the "Jost-report". The companies were actively involved immediately when tribology research under this name started in Finland.

The steel industry has been very active in tribology

research. It had the aim to develop new wear resistance, toughness and manufacturability of their products that enhance the competitiveness of the products. In addition to this knowledge of tribology has improved the operational reliability and energy efficiency of companies' own production.

The process industry is in the landscape of tribology mainly end user. The companies have been interested to improve operational reliability, life-time and efficiency of their production equipment with tribological knowledge and technologies.

The internal combustion engines have lots of moving components and thus the companies developing and manufacturing machine parts has been an important industry branch in funding and carrying out tribology research globally. The engine manufacturing enterprises have been active. In the early days of tribology research, the main interest area was controlling the wear and prolonging the life-time of the engine components, for example utilization of new materials and lubricants. In the recent decades this industrial branch has met tightening regulations that aim for minimizing emissions that are harmful to climate, environment and health. Those have affected on fuel composition and quality, that have their effects on tribological phenomena occurring in the engines. At the same time the customer requirements and expectations for the reliability and cost effectiveness have increased. Engine manufacturing companies have thus put large efforts to create in-house tribology capabilities and to co-operation with domestic and international partners.

Manufacturing companies of machine elements and components, such as cylinders, seals, valves and bearings, aim to enhance the quality and performance of their products. Alternative enhanced materials, coatings, constructions and lubricants and interactions between them are main factors to improve the operational performance of the components. Typically, component manufacturers carry out research and development in co-operation with their customers or component end users.

Lubricant suppliers do their development actions to find solutions to fulfil increasing and changing needs to decrease the losses due to friction and wear. During recent decades synthetic and bio-based lubricants have been developed to replace traditional lubricants based on mineral oils. Also, the development in additives improving the lubricant operational characteristics has been active. The Finnish lubricant developing and producing enterprises have made intensive research together with research organizations and international partners.

Finnish companies focusing on new materials for tribological applications have especially developed coating technologies. Their products have been both thin film coatings improving friction and wear properties and thick hard coatings for aggressive wear and corrosion applications. Construction ceramics and new polymers or metals replacing steel as construction material of tribological components have been studied by Finnish companies during the years.

Power transmission manufacturers in Finland produce gear components and systems for example to moving working machines, process industry machinery, energy production and ships. Typically, operational conditions are demanding and performance requirements high. Capability to control the tribological behavior is in the center of the competitiveness. The companies have carried out active research on manufacturing technologies affecting characteristics and operational performance of tooth surfaces as well as in the development of new tooth profiles and lubrication technologies.

Production and working machinery manufacturing companies are one of the most important export industry branches in Finland. From their point of view tribology is important for the operational reliability and quality, safety, economical efficiency and over-all productivity of their products. The machine manufacturing companies have made tribology related research and development in the applications being in their technology and business interests. System integration companies have usually carried out research and development in co-operation with component and system suppliers and research organizations.

Tools are in a significant role for the product quality and productivity of companies manufacturing components and products with cutting or forming processes. Thus, the companies producing these tools have studied during the years for example tool materials, coatings and fluids used in the manufacturing processes. Also changes and development in the materials to be processed bring new development needs to tool manufacturing enterprises.

11. Significant international scientific contributions from Finland

The fast growing and large tribology research and development activities in the Finnish universities, research centres and industry has resulted in a large number of new tribological findings, inventions, theories, empirical results, test equipment constructions and businesses. Several of them have been internationally recognized and the contribution to the international tribology community has been remarkable. Below we shortly describe some of the internationally most recognized top contributions from high level established tribology groups in Finland producing excellent results over a period of many years and even decades.

11.1 Abrasive wear

Tampere University / Tampere Wear Center, SSAB, Metso, AC2T

The wear environment has a significant role in the prediction of wear rates. Proper understanding of the variables and the effects that abrasives have on wear can affect the outcome of the material selection processes quite dramatically. Thus, the material selection based on laboratory wear tests needs test methods that simulate as well as possible the in-service conditions. Consequently, careful analysis of the relevance of the laboratory test

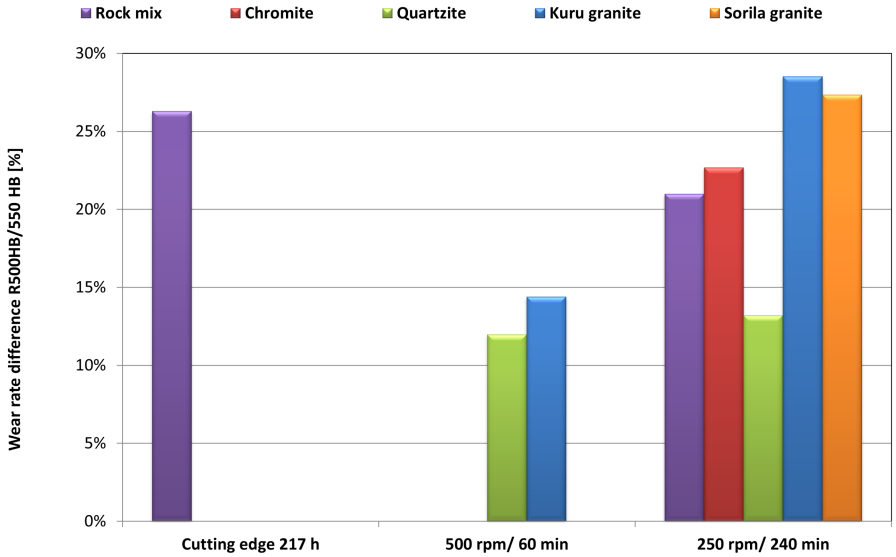

Figure 11.1. Reduction of the wear rate when R500HB is replaced by 550HB in the in-service conditions in a chromite mine and in the laboratory tests with different abrasives and test conditions (Valtonen et al. 2018).

methods is essential. Moreover, the effects of different rock species on the in-service performance of wear parts have to be taken into account in the material selection practices in the mineral processing industry. Detailed knowledge of the materials used in mining tools and wear parts, and how they perform in contact with different minerals, can improve the productivity of mining operations considerably.

The variables affecting the frictional behavior of rock surfaces (Heino 2018) and the effect of rock types in high-stress abrasion tests (Valtonen et al. 2017) were studied. The wear behavior in various in-service cases was simulated on laboratory scale using several application-oriented wear testing methods that produce high-stress abrasive or impact-abrasive conditions with large natural rock abrasives. Thus, they simulate the harsh conditions in mining and mineral processing. The wear behavior in the in-service cases was compared with the wear tested samples by analyzing the wear rates and by characterizing the wear surfaces and microstructures (Valtonen et al. 2018, Vuorinen et al. 2016, Valtonen 2018).

Crushing of minerals consumes a very high amount of energy and the efficiency is quite poor. A laboratory-scale jaw crusher with uniform movement of the jaws, the Dual Pivoted Jaw Crusher (DPJC), was used to determine the relationship between wear and work (Terva et al. 2018, Terva 2018). The extent of wear was determined as the mass loss of the jaw plate specimens, while the amount of work (or consumed energy) was measured directly from the force and displacement of the instrumented jaw, which allowed work to accumulate only from the actual crushing events. The wear and work results obtained from the tests with different lateral movement of the jaws enable the determination of the wear coefficient K for each test configuration. A higher initial crushing speed decreases the amount of work needed to remove material from the specimen surface, that is, to cause wear in a DPJC crushing test.

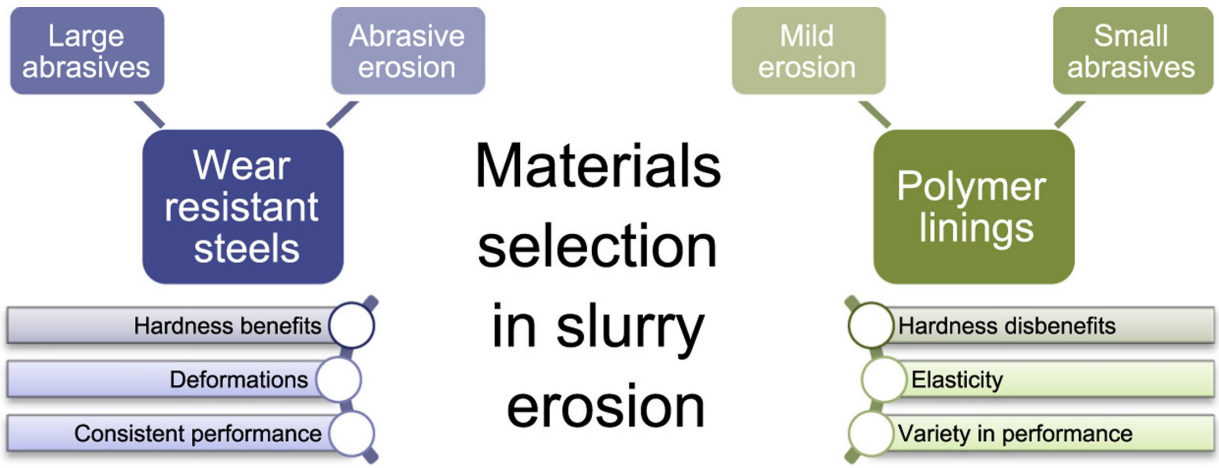

Figure 11.2. Material selection in slurry erosion (Ojala et al. 2016).

11.2. Slurry-erosion

Tampere University / Tampere Wear Center, SSAB, Metso, Outotec, Valmet, Luleå University of Technology

As the pumping of slurry through pipelines is an increasingly more profitable alternative when transporting minerals or slurry away from mines or dredging sites, the technological boundaries in terms of wear resistance of the materials involved must be pushed forward. Currently, polymeric lining materials, such as rubbers or polyurethanes, have become a standard choice for combined wear and corrosion protection in slurry pipelines transporting minerals. However, such linings can be rather expensive and also quite sensitive to surface defects. A slurry-pot tester, enabling the simulation of various wear conditions with different minerals, particle sizes, and abrasive concentrations was developed to simulate these harsh conditions (Ojala et al. 2014).

Slurry-pipe wear tests on high-strength steels and reference materials (polymers) were conducted with large and fine abrasives, various concentrations, and different sample angles. The purpose was to reveal the differences in the behavior of the studied materials in slurry erosion conditions, and to find the best solutions for demanding applications. A slurry-pot tester was used to simulate different industrial slurry applications (Ojala et al. 2016, Ojala et al. 2017). The results show that abrasion is the dominant wear mechanism already from a particle size of 2 mm, and that in demanding high-stress abrasive slurry erosion conditions, quenched wear-resistant steels can compete with polymers in wear resistance.

The developed slurry-pot tester has been used to study thermally sprayed coatings. A special edge-protection sample holder was designed for coating studies (Matikainen et al. 2019, Ojala 2017, Matikainen 2022). The study focused on the performance of tungsten carbide (WC -10Co4Cr) and chromium carbide (Cr3C2-25NiCr) based hardmetal coatings sprayed with gaseous and liquid fuelled high-velocity oxygen-fuel (HVOF) spray processes and a modern high-velocity air-fuel (HVAF) spray process. The coating characterization revealed reduced carbide dissolution with decreasing process temperature and denser feedstock powder particles. Smaller carbide size in the Cr3C2-25NiCr material significantly reduced the carbide rebounding leading to higher carbide content in the sprayed coating and improved erosion wear resistance.

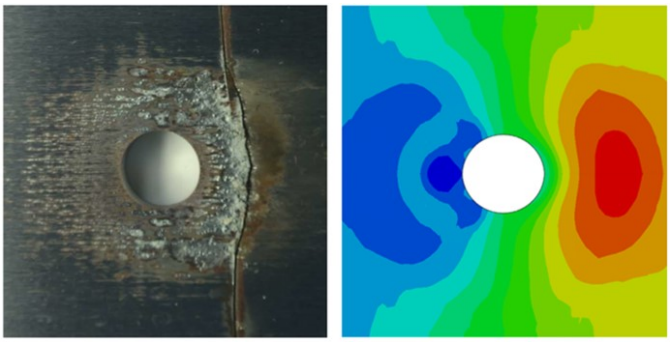

Figure 11.3. Fretting fatigue damage in a laboratory test specimen and a simulation result showing the stress distribution on the surface (Juoksukangas 2016).

11.3 Fretting wear and machine element tribology

Tampere University

Machine components like frictional joints, lubricated bearings and gears related to combustion engines, mineral crushers and industrial gear drives has been studied. In bearing research the main application has been hydrodynamic sliding bearings in mineral crushers, operating in harsh environment with dynamic loading (Linjamaa et al. 2018). Gears research has mainly focused on gear contact fatigue, friction and scuffing. Test set-ups are covering from mini rolling/sliding contact (Bayat 2022), high-pressure twin-disc (Savolainen 2019), FZG (Kattelus et al. 2018) up to large-scale, full-power (1,5 MW) spiral bevel gear (in collaboration with ATA Gears) applications.

From a scientific point of view, the most intensive topic has been fretting induced friction, wear, and fatigue. Fretting stands for small amplitude, reciprocating surface sliding causing potential outcome for fretting wear and fretting fatigue. It may cause catastrophic failure due to crack grow in contacts out of visible inspection. Traditional fatigue calculations are not always enough to avoid this risk of damage. The focus has been on the role of friction (Hintikka et al. 2019) and crack initiation in the fretting damage process. We have published a total of 35 international peer-reviewed fretting related journal papers during 2006-2022 and two dissertations (Hintikka 2016, Juoksukangas 2017). Research and its application to combustion engines has been intensively co-operated with Wärtsilä's R&D-group. In the last years, the role of materials characterization (Nurmi et al. 2019) and collaboration with Tampere Microscopy Center has been increased steadily.

11.4 Thin coating tribology

Technical Research Centre of Finland VTT

The research on thin film tribology in Finland started with intensive collaboration between Helsinki University of Technology, VTT and Salford University. In Salford the thin film laboratory was led by Dennis Teer, one of the world leading scientists in the field. The focus was on depositing extremely hard ceramic films of a thickness of only 1-5 micrometer on metallic substrates. An early breakthrough application was to coat metal cutting tools with thin titanium nitride coatings, which increased the lifetime of the tool by 10 to 20 times. The deposition technology developed and used was plasma enhanced physical vapor deposition, (Sundquist et al. 1983).

The collaboration continued over the years with the coating laboratories at Hull University and later with Sheffield University, both under the leadership of professor Allan Matthews and on the Finnish side by Dr Helena Ronkainen from VTT. The topic was broadened to multilayer coatings, duplex coatings, various composite coatings and especially the extremely hard and low friction

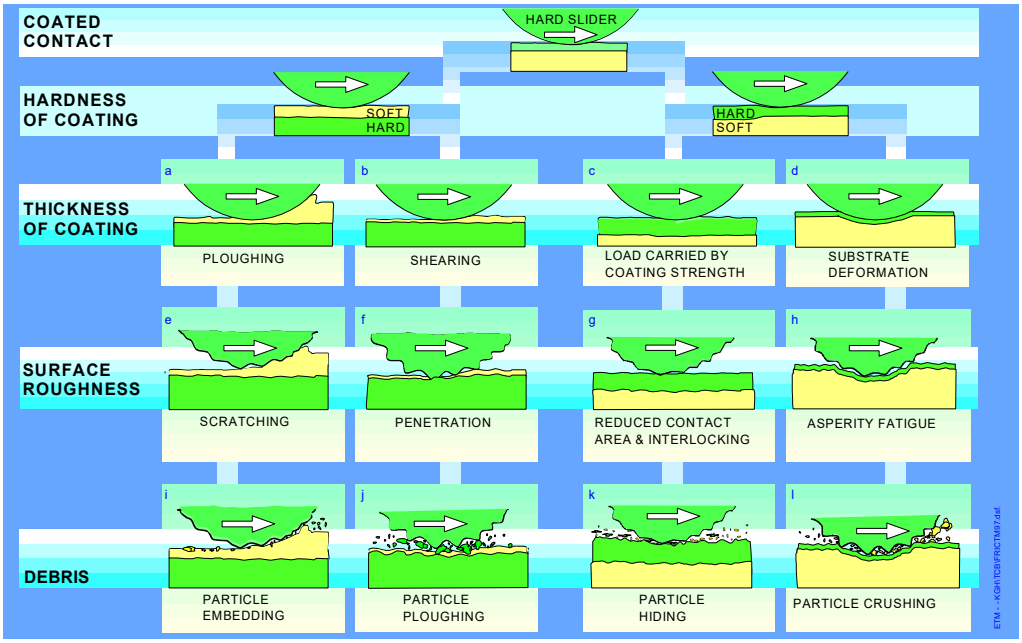

Figure 11.5 Tribological contact mechanisms dominating the frictional behaviour in sliding thin coating contacts as determined by six main influencing parameters: coating hardness, substrate hardness, coating thickness, surface roughness and debris size and hardness in the contact (Holmberg & Matthews 1994).

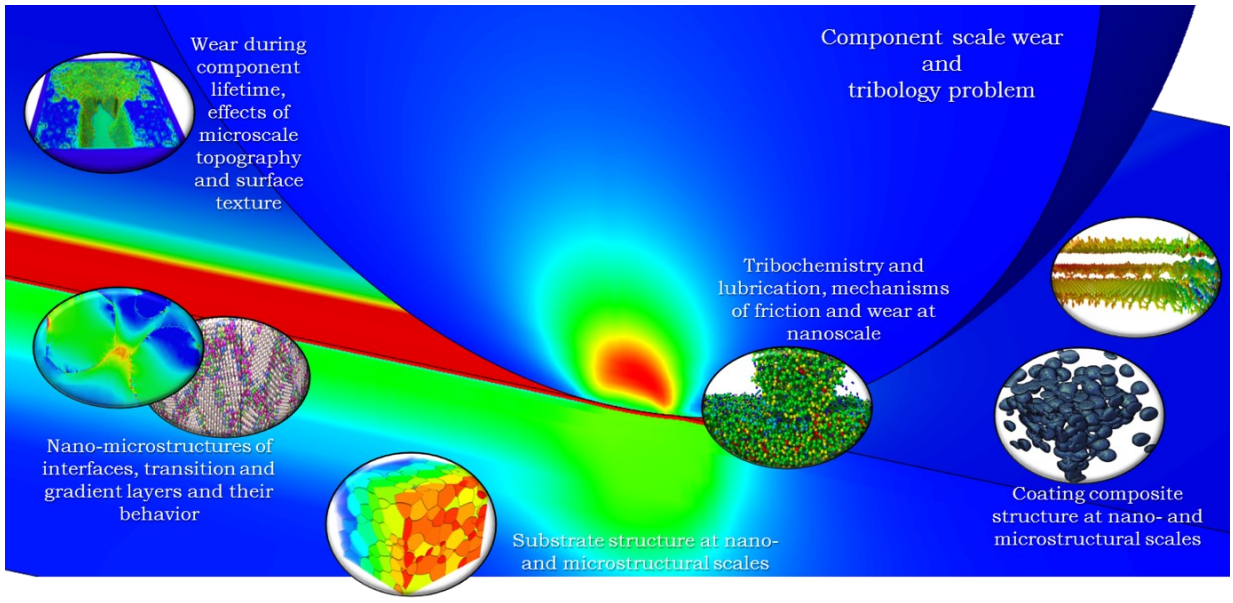

Figure 11.6 VTT Propertune© computational multiscale integrated material modelling approaches for simulation of material behaviour and sustainability in tribological contacts (Holmberg 2014b).

diamond like hard carbon coatings (DLC). Much of the work was carried out in large research institute consortia funded by research programs of the European Union. The work has been published in a great number of joint journal papers (Holmberg et al. 2000, Ronkainen et al. 1998, 2001).

In 1994 Holmberg and Matthews published the first monography textbook on the topic of thin film tribology where they explained the fundamental tribological friction and wear mechanisms involved in a sliding contact with one or both surfaces coated by such extremely thin hard or soft surface coatings (Holmberg & Matthews 1994). The book was widely recognized and is still used as textbook worldwide. A second extended edition was published 2009 (Holmberg & Matthews 2009).

Applications of thin film technology is today used widely for low friction and reduced wear purpose in fields, such as automotive components, manufacturing tools, medical instruments, industrial components, precision instruments, and space equipment.

11.5 Computational modelling in tribology

Technical Research Centre of Finland VTT

The analysis of friction and wear mechanisms of coatings was first largely based on empirical experience,

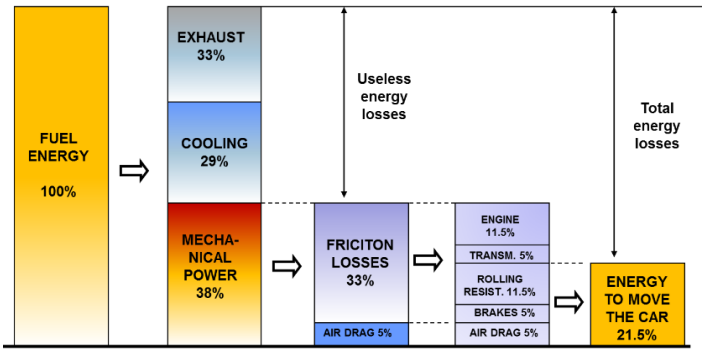

Figure 11.7 Breakdown of passenger car fuel energy consumption and energy losses due to friction (Holmberg et al. 2012). Illustration republished in a review article on sustainable energy future in Nature 488(2012)296 by Steven Chu, then Minister of Energy in the US Obama Government.

but a deeper and more general understanding was needed for larger material property optimization in various applications. The rapid development in computer technology including hardware with increased calculation capacity and advanced software packages for complex calculations and visualization offered new possibilities. In early 2010ies Anssi Laukkanen, Kenneth Holmberg and Helena Ronkainen started to develop computational material modelling and simulation techniques applied to tribology in scratch test contact conditions with thin coatings (Holmberg et al 2003, Laukkanen 2018). This was an international breakthrough in bringing computational modelling and simulation as a complementary tool to empirical testing for the understanding basic tribological contact mechanisms on general level.

Coordinated by Laukkanen a growing team of multiskilled computing, materials and applied technical experts was gathered at VTT. They broadened the modelling and simulation techniques to a large range of materials, contacts and loading conditions and applications (Holmberg et al 1014a, Holmberg et al 2014b, Laukkanen et al 2011, Hakala et al 2021). They developed the VTT software package for this purpose named Propertune©. It has been widely applied in steel, manufacturing, and process industry in Finland and in numerous countries worldwide. By 2020 the VTT Propertune team had grown to a research area of about 50 people focusing on further technology development and applications in four areas: metals and ceramics; biomaterials, polymers and elastomers; surface coatings; and composites. Over the last few years, the role of artificial intelligence (AI) has significantly increased, in addition to the development of a materials accelerator platform (MAP) incorporating also tribology, and as a subject area biotechnology has been added (Propertune 2023).

11.6 Global economic and environmental impact of tribology

Technical Research Centre of Finland VTT

Since the study of the Jost committee in UK 1966 it has been known that tribology has a great societal and economic impact. Still this information was on a general level and based on estimations not documented in much detail. Around 2010 a collaboration started between the groups led by Kenneth Holmberg at VTT and Ali Erdemir

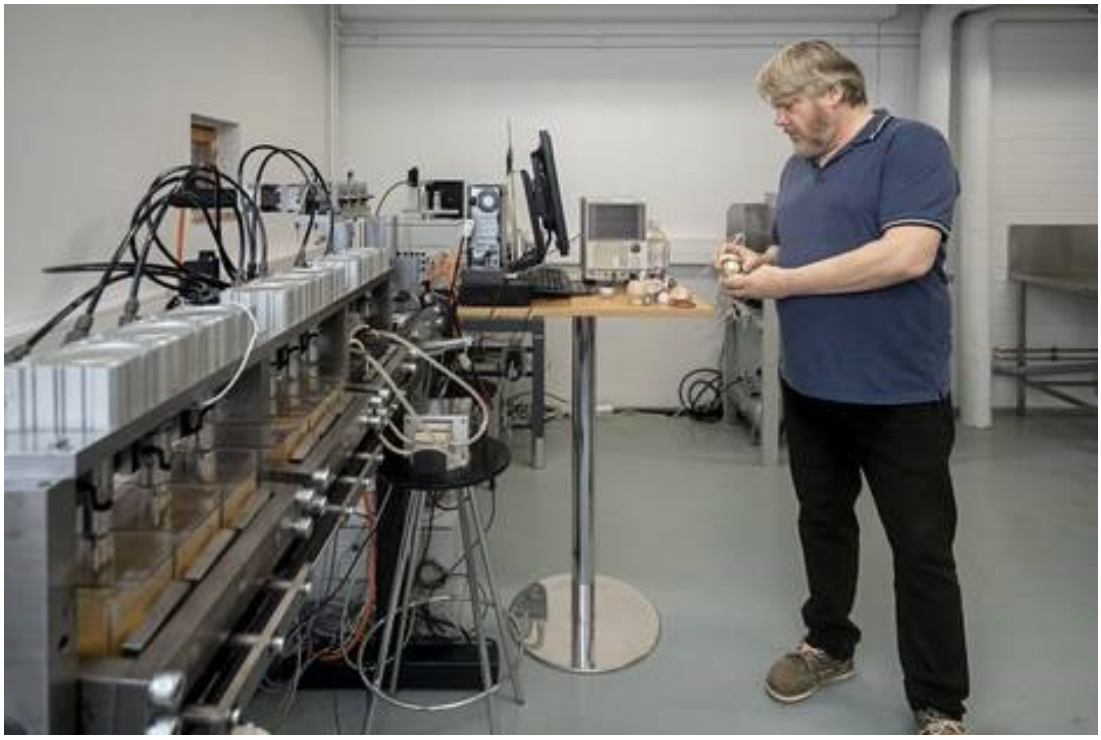

Figure 11.8 Vesa Saikko in the biotribology laboratory at Aalto University working with the multistation hip joint simulator in 2022 (HS Digi: https://www.hs.fi/tiede/art-2000008762714.html).

at the Argonne National Laboratory in the USA. They carried out a first study focusing on the impact of friction, energy losses, economy, and environmental effects of passenger cars on global level. They found that in passenger cars globally one-third of the fuel energy is used to overcome friction in the engine, transmissions, tires, and brakes. Only 22 % of the fuel energy is used to move the car and 88 % goes to energy losses. Worldwide 208 000 million litres of fuels (gas and diesel) were used in 2009 to overcome friction in passenger cars. This paper was an international breakthrough and became a seminal paper now frequently referred to (Holmberg et al. 2012).

The study on passenger cars was followed up by similar studies focusing on paper machines, trucks and busses, mining industry and electric cars. It was now possible to use iteration techniques based on these more detailed case studies and calculate that of the world's total energy consumption 119 EJ or 23 % originates from tribological contacts. Of that 103 EJ or 20 % is used to overcome friction and 16 EJ or 3 % is used to remanufacture worn parts and spare equipment due to wear and wear-related failures (Holmberg & Erdemir 2017). Implementing advanced tribological technologies can result in 450 000 million Euros cost savings and reduced CO_2 emissions by 1 460 $MtCO_2$ on the short term, and 970 000 million Euros savings and 3 140 $MtCO_2$ reduced emissions on longer term. This information has been an eyeopener for researchers, industrialists, economists, environmentalists, and politicians all over the world and is thus frequently referred to.

11.7 Engineering Ceramics

Aalto University, Tampere University, Åbo Akademi, VTT

A three-year research programme on engineering ceramics during 1986-89 was aiming to initiate the research and development in the new field of material science in Finnish universities and research institutes in order to increase the competitiveness of the Finnish metal and engineering industries. The programme was coordinated by the Finnish Technology Agency (TEKES) and the Federation of Finnish Metal and Engineering Industries.

The total programme included investigations on the structure and properties of engineering ceramics, applications of engineering ceramics in industry and ceramic design, and processing of engineering ceramics. The programme set up active research groups and made it possible to buy or build the necessary equipment for the major testing techniques for engineering ceramics in different laboratories. It produced a great deal of relevant information about these new materials and stimulated universities and postgraduate courses. The programme enabled significant educational contribution, with seven licentiate degree dissertations and 12 master theses. At VTT the tribological performance of different ceramics was evaluated in dry and water lubricated conditions, as well as in application related test conditions. Peter Andersson made his licentiate work on the tribological performance on ceramic materials.

11.8 Biotribology

Aalto University (former Helsinki University of Technology HUT)

Biotribology has been a consistent research area in Aalto University. Vesa Saikko and his team has created, designed, built and utilized over 20 different types of tribological research and test equipment during the last 35 years. Three of the created simulators have been licenced with royalties by Phoenix Tribology Ltd (former Cameron-Plint) in England and several other equipment have been sold to USA, Japan, Switzerland, England, Holland, Belgium and China.

The wear simulation of total hip prostheses and the creation of different simulators for that has been the driving force for developing the research equipment. Such topics as a multidirectional motion pin-on-disc wear test method for prosthetic joint materials, effect of contact pressure on wear and friction, slide track analysis of the relative motion of a hip joint, effect of counter face roughness on the wear of UHMWPE in pin-on-disc tests and effect of lubricant protein concentration on the wear in sliding between UHMWPE and CoCr were studied (Saikko 1993, 1998, 2022; Saikko et al. 1993, 2001).

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13. Appendices

13.1 Milestones in tribology in Finland

Milestones in tribology in Finland:

1881 Karl Slotte publishes the equation on thermal impact on fluid viscocity

1968 Kauko Aho's dissertation on tractor power transmission loading conditions

1973 Research on pitting wear in gear drives starts at Martti Sulonen's laboratory in Helsinki University of Technology

1977 John Halling from Salford, UK, lectures on tribology in Helsinki for university staff and industrial experts

1977 Founding of Finnish Society for Tribology

1978 Finnish Society for Tribology joins the International Tribology Council

1978 The first university courses dedicated to tribology start in Helsinki and Tampere Technical Universities

1979 A study on the impact of tribology for Finnish industry is published

1979 Heikki Sundquist works as visiting Research Fellow of the Research Council of Finland in Salford University, UK, and brings the plasma assisted coating technology to Finland

1979 Technical Research Centre VTT starts a Tribology research group led by Kenneth Holmberg

1980-1995 Five joint Nordic tribology research projects funded by Nordic Industrial Fund

1980 Glossary of tribology terminology in Finnish is published

1982 The Finnish Journal of Tribology is established

1982-1995 Finnish-Soviet research collaboration on tribology and arctic technology as part of the Scientific Governmental Collaboration Agreement

1984 First NORDTRIB Nordic Symposium on Tribology held in Tampere and hosted by Tampere University of Technology, Kauko Aho

1987-1995 Finnish-China research collaboration on tribology as part of the Scientific Governmental Collaboration Agreement

1989 Fifth EUROTRIB International Tribology Congress held in Helsinki and hosted by Finnish Society for Tribology, Kauko Aho

1992 Fifth NORDTRIB Nordic Symposium on Tribology held on M/S Silja Symphony and hosted by Helsinki University of Technology, Matti Kleimola

1994-2007 Two COST Tribology actions coordinated from Finland, VTT with academic and industrial partners from thirty European countries involved

1995-2023 Ten to fifteen EU research program projects on tribology with Finnish partners involved

2000 Ninth NORDTRIB Nordic Symposium on Tribology held in Porvoo and hosted by VTT, Kenneth Holmberg

2008 13th NORDTRIB Nordic Symposium on Tribology held in Tampere and hosted by Tampere University of Technology, Arto Lehtovaara

2008 Tampere Wear Center was established by Veli-Tapani Kuokkala and Toivo Lepistö

2016 17th NORDTRIB Nordic Symposium on Tribology held in Hämeenlinna and hosted by VTT, Helena Ronkainen

2017 Kenneth Holmberg receives the Tribology Gold Medal

2023 Up to present 40 PhD Thesis on tribology have been published in Finnish Universities, see section 12.2.

2023 Up to present has 118 issues in 40 volumes of Finnish Journal of Tribology been published including a total of about 500 scientific peer revied articles.

2023 Up to present 19 NORDTRIB symposiums has been arranged with a total of 1921 scientific papers presented, attended by 2570 participants from about 50 countries worldwide.

13.2 NORDTRIB history in numbers

Date	Place	Organising institute and conference chairman	Partici-pants	Count-ries	Papers*	Comment
1st NORDTRIB 15-17.8.1984	Tampere, Finland	Tampere University of Technology, Kauko Aho	60	8	28	
2nd NORDTRIB 15-18.6.1986	Luleå, Sweden	Luleå University of Technology, Bo Jacobsson	90	12	39	
3rd NORDTRIB 27-29.6.1988	Trondheim, Norway	Norwegian Institute of Technology, Kristian Tönder	90	11	51	
4th NORDTRIB 10-13.6.1990	Hirtshals, Denmark	Technical University of Denmark, Jørgen Jakobsen	103	15	52	
5th NORDTRIB 8-11.6.1992	M/S Silja, Symphony, Finland	Helsinki University of Technology, Matti Kleimola	101	16	62	Onboard ferry Helsinki-Stockholm
6th NORDTRIB 12-15.6.1994	Uppsala, Sweden	Uppsala University, Sture Hogmark	128	17	76	
7th NORDTRIB 16-19.6.1996	Bergen, Norway	Norwegian University of Science & Technology, Kristian Tönder	88	13	69	
8th NORDTRIB 7-10.6.1998	Ebeltoft, Denmark	DTI Tribology Centre, Christen Straede	150	27	124	51 posters
9th NORDTRIB 11-14.6.2000	Porvoo, Finland	VTT Technical Research Centre, Kenneth Holmberg	142	23	92	19 posters
10th NORDTRIB 9-12.6.2002	Stockholm, Sweden	Royal Institute of Technology, Sören Andersson	154	28	122	35 posters
11th NORDTRIB 1-4.6.2004	Tromsö, Norway	Norwegian University of Science & Technology, Kristian Tönder	108	29	88	Tromsø 2 days; Harstad 1 day; Coastal Express 1 day
12th NORDTRIB 6-9.6.2006	Helsingør, Denmark	Technical University of Denmark, Jørgen Jakobsen	117	22	86	
13th NORDTRIB 10-13.6.2008	Tampere, Finland	Tampere University of Technology, Arto Lehtovaara	177	31	136	18 posters
14th NORDTRIB 8-11.6.2010	Storforsen, Sweden	Luleå University of Technology, Roland Larsson	178	30	134	
15th NORDTRIB 12-15.6.2012	Trondheim, Norway	NTNU & SINTEF, Nuria Espallargas	165	22	126	15 posters
16th NORDTRIB 10-13.6.2014	Århus, Denmark	Danish Technological Institute, Lars Nielssen	148	25	137	16 posters
17th NORDTRIB 14-17.6.2016	Hämeenlinna, Finland	VTT & Finnish Tribology Society, Helena Ronkainen	202	28	164	19 posters
18th NORDTRIB 18-21.6.2018	Uppsala, Sweden	Uppsala University, Staffan Jacobson	236	26	202	48 posters
19th NORDTRIB 14-17.6.2022	Ålesund Norway	NTNU, Nuria Espallargas	133	20	133	7 posters
Total			2570	~ 50	1921	228
* = Accepted oral and poster presentations						

13.3 Finnish Tribology Society officials

	President	Vice-president	Treasurer	Secretary
1977	Kauko Aho	Heikki Sundquist	Kenneth Holmberg	Liisa Muurinen
1978	Kauko Aho	Heikki Sundquist	Kenneth Holmberg	Liisa Muurinen
1979	Kauko Aho	Heikki Kleemola	Kenneth Holmberg	Marjut Ruotsalainen
1980	Kauko Aho	Heikki Sundquist	Kenneth Holmberg	Hannu Tarvainen
1981	Kauko Aho	Heikki Sundquist	Kenneth Holmberg	Hannu Tarvainen
1982	Kauko Aho	Heikki Sundquist	Kenneth Holmberg	Hannu Tarvainen
1983	Kauko Aho	Heikki Sundquist	Kenneth Holmberg	Arto Lehtovaara
1984	Kauko Aho	Heikki Sundquist	Kenneth Holmberg	Arto Lehtovaara
1985	Kauko Aho	Heikki Sundquist	Erkki Kuusisto	Arto Lehtovaara
1986	Kauko Aho	Kenneth Holmberg	Erkki Kuusisto	Arto Lehtovaara
1987	Kauko Aho	Kenneth Holmberg	Erkki Kuusisto	Juhani Valli
1988	Matti Kleimola	Kenneth Holmberg	Erkki Kuusisto	Juhani Valli
1989	Matti Kleimola	Kenneth Holmberg	Erkki Kuusisto	Juhani Valli
1990	Matti Kleimola	Kenneth Holmberg	Matti Kytö	Pekka Salonen
1991	Matti Kleimola	Kenneth Holmberg	Matti Kytö	Pekka Salonen
1992	Matti Kleimola	Kenneth Holmberg	Matti Kytö	Mika Salonen
1993	Peter Andersson	Jouko Perttula	Matti Kytö	Mika Salonen
1994	Peter Andersson	Jouko Perttula	Jarmo Vihersalo	Pekka Salonen
1995	Peter Andersson	Jorma Niskala	Jarmo Vihersalo	Pekka Salonen
1996	Peter Andersson	Jorma Niskala	Jarmo Vihersalo	
1997	Jorma Niskala	Jari Juhanko	Topi Volkov	
1998	Jorma Niskala	Jari Juhanko	Topi Volkov	
1999	Jorma Niskala	Arto Lehtovaara	Topi Volkov	
2000	Arto Lehtovaara	Tiina Ahlroos	Juha Miettinen	
2001	Arto Lehtovaara	Tiina Ahlroos	Juha Miettinen	
2002	Arto Lehtovaara	Tiina Ahlroos	Juha Miettinen	
2003	Arto Lehtovaara	Tiina Ahlroos	Juha Miettinen	
2004	Pekka Salonen	Tiina Ahlroos	Jaakko Kleemola	
2005	Pekka Salonen	Tiina Ahlroos	Jaakko Kleemola	
2006	Pekka Salonen	Tiina Ahlroos	Jaakko Kleemola	Carl-Erik Sandström
2007	Pekka Salonen	Tiina Ahlroos	Leif Eriksson	Jussi Lehtiö
2008	Pekka Salonen	Matti Säynätjoki	Leif Eriksson	Jussi Lehtiö
2009	Pekka Salonen	Matti Säynätjoki	Aino Helle	Jussi Lehtiö
2010	Pekka Salonen	Matti Säynätjoki	Aino Helle	ei nimetty
2011	Pekka Salonen	Matti Säynätjoki	Aino Helle	ei nimetty
2012	Aino Helle	Matti Säynätjoki	Lauri Kilpi	ei nimetty
2013	Aino Helle	Matti Säynätjoki	Lauri Kilpi	Janne Juoksukangas
2014	Helena Ronkainen	Matti Säynätjoki	Lauri Kilpi	Janne Juoksukangas
2015	Helena Ronkainen	Matti Säynätjoki	Lauri Kilpi	Janne Juoksukangas
2016	Helena Ronkainen	Matti Säynätjoki	Lauri Kilpi	Janne Juoksukangas
2017	Helena Ronkainen	Matti Säynätjoki	Lauri Kilpi	Aki Linjamaa
2018	Helena Ronkainen	Matti Säynätjoki	Ville Oksanen	Aki Linjamaa
2019	Helena Ronkainen	Matti Säynätjoki	Ville Oksanen	Aki Linjamaa
2020	Helena Ronkainen	Matti Säynätjoki	Ville Oksanen	Aki Linjamaa
2021	Helena Ronkainen	Matti Säynätjoki	Ville Oksanen	Elina Huttunen-Saarivirta
2022	Helena Ronkainen	Matti Säynätjoki	Ville Oksanen	Vilma Ratia-Hanby
2023	Helena Ronkainen	Matti Säynätjoki	Ville Oksanen	Vilma Ratia-Hanby

13.4 Finnish Journal of Tribology Statistics

Tribologia – Finnish Journal on Tribology has published 39 volumes, altogether 118 issues, part of them being double issues. Nine Finnish tribology scientists have acted as Editors in Chief and the journal has had six editorial assistants. The scientific editorial board has supported the journal during the years by evaluating the articles to be published.

Volume	Year	Issues	Editor in chief	Editorial assistant	Editor
1	1982	1,2	Heikki Sundquist	Liisa Muurinen	
2	1983	1,2,3,4	Heikki Sundquist, Seppo Mikkonen	Kirsi Merikunnas	
3	1984	1,2,3,4	Seppo Mikkonen	Irina Granfors	
4	1985	1,2,3,4	Seppo Mikkonen	Maritta Ojala	
5	1986	1,2,3,4	Ulla Mäkelä	Maritta Ojala	
6	1987	1,2,3,4	Ulla Mäkelä	Maritta Ojala	
7	1988	1,2,3,4	Ilkka Nieminen	Maritta Ojala, Erja Mörsky	
8	1989	1,2,3,4	Ilkka Nieminen	Erja Mörsky	
9	1990	1,2,3-4	Ilkka Nieminen	Erja Mörsky	
10	1991	1,2,3,4	Ilkka Nieminen	Erja Mörsky	
11	1992	1	Ilkka Nieminen	Erja Mörsky	
12	1993	1,2,3,4	Ilkka Nieminen	Erja Mörsky	
13	1994	1,2,3,4	Ilkka Nieminen	Erja Mörsky	
14	1995	1,2,3,4	Ilkka Nieminen	Erja Mörsky	
15	1996	1,2,3,4	Ilkka Nieminen	Erja Mörsky	
16	1997	1,2,3,4	Ilkka Nieminen	Erja Mörsky	
17	1998	1,2,3-4	Ilkka Nieminen Jyrki Tervo	Erja Mörsky	
18	1999	1,2,3,4	Jyrki Tervo	Erja Mörsky	
19	2000	1,2,3,4	Jyrki Tervo	Erja Mörsky	
20	2001	1,2,3,4	Jyrki Tervo	Erja Mörsky	
21	2002	1,2-3,4	Jyrki Tervo	Erja Mörsky	
22	2003	1,2,3,4	Jyrki Tervo	Erja Mörsky	
23	2004	1-2,3-4	Jyrki Tervo	Erja Mörsky	
24	2005	1,2,3-4	Jyrki Tervo	Erja Mörsky	
25	2006	1,2,3,4	Jyrki Tervo	Erja Mörsky	
26	2007	1,2,3,4	Jyrki Tervo	Erja Mörsky	
27	2008	1,2-3,4	Jyrki Tervo	Erja Mörsky	
28	2009	1-2,3-4	Jyrki Tervo	Erja Mörsky	
29	2010	1	Jyrki Tervo	Erja Mörsky	
30	2011	1-2	-	Erja Mörsky	
31	2012	1-2,3-4	Tiina Ahlroos	Erja Mörsky	Kati Valtonen
32	2014	1,2	Päivi Kivikytö-Reponen	Erja Mörsky	Kati Valtonen
33	2015	1,2	Elina Huttunen-Saarivirta	Erja Mörsky	Kati Valtonen
34	2016	1-2	Elina Huttunen-Saarivirta	Erja Mörsky Janne Juoksukangas	Kati Valtonen
35	2017	1-2,3	Elina Huttunen-Saarivirta	Janne Juoksukangas	Kati Valtonen
36	2019	1-2	Vuokko Heino	Janne Juoksukangas	Kati Valtonen
37	2020	1-2,3-4	Vuokko Heino	Janne Juoksukangas	Kati Valtonen
38	2021	1-2,3-4	Vuokko Heino	Janne Juoksukangas	Kati Valtonen
39	2022	1-2,3-4	Vuokko Marjamaa	Janne Juoksukangas	Kati Valtonen
40	2023	1-2	Vuokko Marjamaa	Janne Juoksukangas	Kati Valtonen