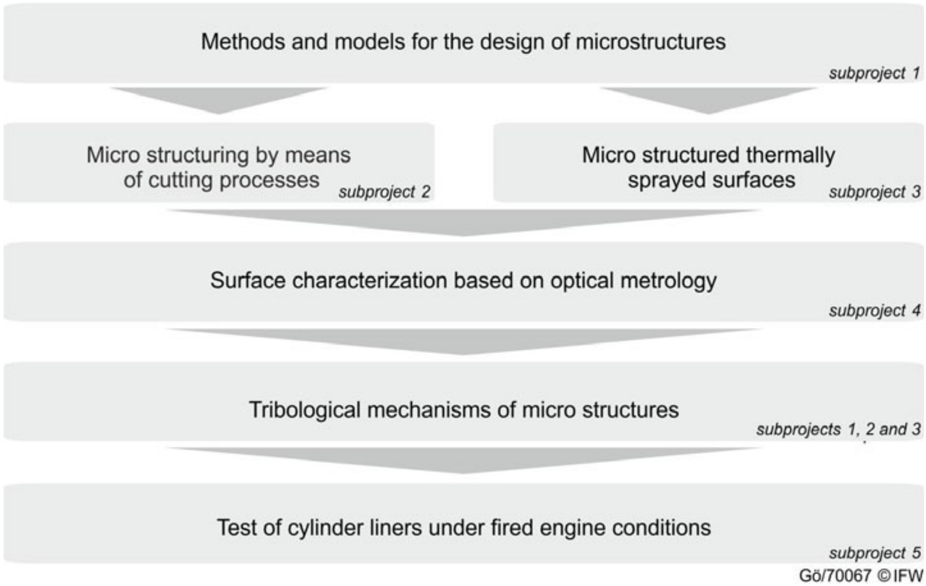

Figure 1-1: Subprojects of the research group

2 Project overview

2.1 Consortium

The interdisciplinary consortium in the fields design, manufacturing, characterisation and scientific testing of microstructured surfaces pursues the above-mentioned subprojects. The coordinator and spokesman of this consortium as well as the participating institutions of the Leibniz Universität Hannover and the Universität Kassel are listed below:

Coordinator and spokesman of the research group:
Prof. Dr.-Ing. Berend Denkena
Institut für Fertigungstechnik und Werkzeugmaschinen IFW
(Production Engineering and Machine Tools)
Leibniz Universität Hannover
An der Universität 2
30823 Garbsen

Subproject 1: Methods and models for the design of microstructures
Lehrstuhl für Maschinenelemente und Tribologie IMK
(Machine Parts and Tribology)
Universität Kassel
Mönchebergstraße 3
34125 Kassel

B. Denkena et al. (eds.), *Microstructuring of Thermo-Mechanically Highly Stressed Surfaces*,
Lecture Notes in Production Engineering, DOI 10.1007/978-3-319-09692-6_2

www.uni-kassel.de/maschinenbau/institute/imk
Senior scientists: Prof. Dr.-Ing. Adrian Rienäcker, Prof. Dr.-Ing. habil. Gunter Knoll
Scientists: Dr.-Ing. Sven Brandt, Dipl.-Ing. Herman Fast

Subproject 2: Microstructuring by means of cutting processes

Institut für Fertigungstechnik und Werkzeugmaschinen IFW
(Production Engineering and Machine Tools)
Leibniz Universität Hannover
An der Universität 2
30823 Garbsen
www.ifw.uni-hannover.de
Senior scientist: Prof. Dr.-Ing. Berend Denkena
Scientists: Dipl.-Ing. (FH) Jan Kästner, Dipl.-Ing. Tim Göttsching

Subproject 3: Microstructured thermally sprayed surfaces

Institut für Werkstoffkunde IW
(Materials Science)
Leibniz Universität Hannover
An der Universität 2
30823 Garbsen
www.iw.uni-hannover.de
Senior scientists: Prof. Dr.-Ing. Hans Jürgen Maier, Prof. Dr.-Ing. habil. Dr.-Ing. E.h. Dr. h.c. Friedrich-Wilhelm Bach
Scientists: Dr.-Ing. habil. Kai Möhwald, Dipl.-Min. Martin Erne, Dipl.-Geow. Christoph Hübsch

Subproject 4: Surface characterisation based on optical metrology

Institut für Mess- und Regelungstechnik IMR
(Measurement and Automatic Control)
Leibniz Universität Hannover
Nienburger Straße 17
30167 Hannover
www.imr.uni-hannover.de
Senior scientist: Prof. Dr.-Ing. Eduard Reithmeier
Scientists: Dr.-Ing. Dipl.-Phys. Markus Kästner, Dr.-Ing. Dipl.-Wirtsch.-Ing. Martin Bretschneider, Dr.-Ing. Omar Abo-Namous, Dipl.-Phys. Florian Engelke

Subproject 5: Test of cylinder liners under fired engine conditions

Institut für Technische Verbrennung ITV
(Technical Combustion)
Leibniz Universität Hannover
Welfengarten 1A

30167 Hannover
www.itv.uni-hannover.de
Senior scientist: Prof. Dr. Friedrich Dinkelacker
Scientist: Dipl.-Ing. Hubertus Ulmer

2.2 Starting situation and need for action

Combustion engines are widely distributed in the world and, barring an unforeseen development, will maintain their dominant position in the near and middle future, as alternative mobility concepts like electric cars cannot compete with the power density of conventional combustion engines. In some fields of transport industry, as for example long-haul trucks or container ships, electrification does not seem feasible at all. When designing combustion engines, the main focus is laid on efficiency, since it is directly related to specific fuel consumption as well as to CO_2 emissions. This is reflected by continuously stricter exhaust-gas limits and taxation regulations, which take into consideration the amount of CO_2 emissions as well as the planned obligatory fleet consumption of 120 g CO_2 per km.

Since up to 50 % of the mechanical losses are related to the piston group depending on the operating point, their reduction represents one of the most effective means for reducing the total friction in combustion engines. The tribological functional properties of components sliding against each other are determined by load, relative speed, material combination, and to a significant extent, by their surface properties as well. Thus, performance and lifetime of such tribological systems can be improved by optimising the surface topography. For this reason, cylinder liners are generally honed which ensures not only their high shape accuracy but also the characteristic criss-crossing groove microstructure on the surface. As a result, oil retention volume and properties can be adjusted by means of the surface roughness and the crossing angle of the grinding grooves. In general, the aim is to achieve high load capacities and thus favourable sliding properties via low roughness and high contact ratios. Furthermore, a certain minimum roughness is required for the oil retention. However, the criss-crossing groove structure, developing on the surface, is a communicating system where the lubricant is not only evenly distributed but is also displaced by the sliding partner. This is a disadvantage especially for low sliding speeds, such as those typical for the dead centre area (top dead centre), with regard to the development and the maintenance of hydrodynamic lubrication conditions [FLO85].

Here, micro-dimples cut into cylinder liners have been providing, for some time now, a promising approach to improve friction and wear properties as well as to reduce oil consumption. Figure 2-1 shows the friction force for one cycle for a normally honed as well as for a finely honed and additionally laser-structured cylinder liner as published by one of the partner institutes of this research group in 2004. It can be seen that friction forces can be significantly reduced by the creation of micro-dimples, especially in mixed friction areas [TOM08, GOL04, HEU07].

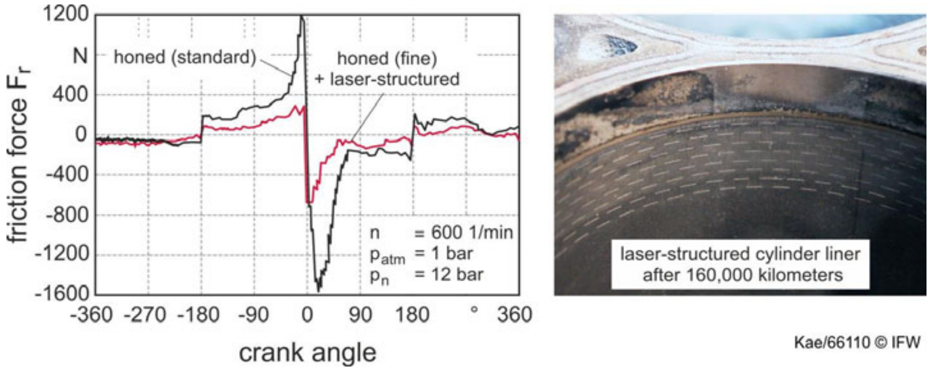

Figure 2-1: Reduction of the friction losses at the piston group by laser-structured cylinder liners [GOL04]

By combining a low basic roughness and the hydrodynamic pressure increasing effect of laser dimples, a reduced piston group friction of up to 53% during fired operation could already be reached. The simultaneous reduction in oil consumption of 70% to 85% can be explained by the lower basic roughness and the smaller oil retention volume of the cylinder liners [ABE06]. The creation of micro-dimples in piston rings can result in a reduction in fuel consumption of up to 4% [ETS09]. In the field of thrust bearing technology, surface structures and micro-dimples also show a great potential to minimise friction, as demonstrated by several research papers on analogue components [ETS99a, ETS99b, WAN03].

However, previous findings concerning the tribological functioning of microstructured surfaces are mostly based on particular test series, random tests and idealised contact geometries. As a consequence, only limited methods and tribological models for an application-oriented, and thus load-specific, design of such surfaces are available. Therefore, it is difficult to transfer existing knowledge and methods to other tribological contact and load conditions. To obtain essential knowledge of microstructures, which would allow their usage in a wide range of applications, fundamental experiences based on extensive, systematic theoretical as well as experimental test series have to be gained, thus ensuring perfect transferability.

In recent years, laser machining as a microstructuring method has been further developed [ETS05, SIE09]. When creating geometrically defined micro-dimples within minimum tolerances, the rather high productivity of this method decreases immensely due to low removal rates. Furthermore, laser-structured surfaces need refinishing in order to remove melt protrusions [ABE06]. In many fields, the high equipment costs pose a serious obstacle to the use of this technology. Additional methods, which could be used to create micro-dimples, are micro-spark erosion [GRU97, MAS89, UHL06], micro-forming [HIR07, KLO07, PET05] or electrochemical machining [COS09, STÖ08]. Nevertheless, small workpiece surfaces, necessary refinishing as well as difficult integration into the existing process chains remain a challenge for the large-scale industrial application of these methods onto cylinder liners.

Cutting processes already show a multitude of innovative approaches for microstructuring of surfaces. Common cutting processes, such as turning, milling or grinding, can be scaled down for the microstructuring process. Due to the high flexibility of these processes, various structures can be machined on the workpiece surface. The use of mono crystalline diamond tools, in particular, allows the creation of minuscule structure dimensions with high aspect ratios, geometry and surface qualities [BRE04, BRI07]. However, diamond cutting is primarily suited for the machining of non-ferrous materials [GLA04]. Thus, it cannot be used for cutting of micro-dimples into cylinder liners, which are generally made of ferrous materials. Furthermore, the small cutting thickness which results from the application of diamond cutting tools limits the surface capacity. Consequently, no cutting processes are suitable for cutting geometrically defined micro-dimples with high reliability and accuracy into large tribologically stressed surfaces.

Another effective approach to a tribological functionalisation of thermo-mechanically highly stressed surfaces is the coating with friction-reducing, wear-resistant coats. These coating systems are already used in the field of diesel engines, showing great tribological potential. It has been proposed that the possible elimination of cast iron cylinder liners could lead to a considerable reduction in weight, and thus reduce the "blow-by", because there would be no distortion of the cast iron liner and the aluminum motor engine [FLO11]. Thereby, the use of specifically produced porosities which exhibit positive effect on friction, wear and oil retention is of a special interest because they can act as micro-dimples [HOL11, BAR05]. Moreover, a major focus was put on the investigation of molybdenum spray materials since using molybdenum as a coating material has been shown to improve friction and wear properties [OVE79]. However, systematic knowledge concerning the load-specific tribological design and manufacturing of such coatings does not exist as of yet. [FLO03].

In order to evaluate the tribological functioning of microstructures, their arrangement and geometry must be known. For this purpose, parameters for their characterisation, but also methods to identify them quantitatively, are required. Small dimensions as well as highly-complex geometries of microstructures (pores, steep flank angles) and components (bores) pose a major challenge to measurement technology. Consequently, measuring methods for an extensive automated characterisation of structured surfaces are still in development. Furthermore, a certain lack of meaningful parameters which can be used for the evaluation of the changes of the tribological behaviour of structured surfaces has been identified [DON95].

The characterisation of surface roughness is currently based on tactile measurements [VOL05, WEI06, BIC12], but tactile measurements of large lateral dimensions require long measurement times and, by the nature of the technique, risk damaging the tested surface. Moreover, the accuracy of the measurements is limited for surfaces with high aspect ratios caused by morphological filtering of the stylus [STO93, KRY04]. Using optical measurement devices for point measurements, such as confocal chromatic sensors, provides a less time-consuming alternative without the risk of inflicting damage to the workpiece [BRO04]. For this reason, optical measurement techniques are frequently used for the characterisation of surfaces in industrial projects [SCH07, OFE07]. Hence, norm texts, such as the EN ISO 25178, regulating the application of optical surface measurements are currently being designed and are to be published in the near future. Additionally, 3D surface data obtained by optical measurements can be analysed with methods of image processing to extract the surface structures relevant for the further research of their tribological effect [BOD98, STO93, WEI06]. Using chromatic sensors, for example, is suitable for large slopes, as it exhibits a lateral resolution of 1 µm and a vertical uncertainty of about 100 nm in a measuring range of 500 µm. By integrating a chromatic sensor within a coordinate measuring machine, it is possible to measure large surface fields with a minimised uncertainty.

2.3 Summary of main results

The wide-ranging expertise of the research group was reflected in the five subprojects. In the first subproject, numerical simulation tools (KORI3D / PRO) were enhanced in order to calculate the tribological properties of microstructures. Using a Lattice-Boltzmann model to describe the physical properties of the engine oil inside the microstructures, a new approach was developed. Through the novel simulation technique, it was possible to determine the ideal layout of the microstructures. This knowledge was used as an input for the manufacturing processes and for further layout developments within the tribological experiments (see chapter 3).

Two different approaches regarding the manufacturing of microstructures were utilised. In the first stage, a machining process that uses an axially parallel turn-milling strategy was developed. By adjusting the feed rate and the rotational frequencies, various micro-dimple arrangements could be machined continuously. Typical dimensions varied from 1 mm to 2 mm in length, 50 µm to 100 µm in width and 5 µm to 30 µm in depth. To investigate the basic correlations between process variables, quality characteristics and chip formation mechanisms, fly-cutting tests were carried out (see chapter 4). Subsequently, a thermal spray process that allows the manufacturing of coatings with a defined porosity was developed. The microstructures were formed by the porosity of non-molten and re-solidified spray particles (see chapter 5).

In the next sub-project, optical sensors were developed in order to characterize the technical surfaces. A white light interferometer was used to measure small surface excerpts with high resolution. A coordinate measuring machine was modified with a confocal chromatic sensor in order to allow in-cylinder-measurements. Furthermore, data processing methods and optimised image alignment techniques were developed to ensure high resolution images of the microstructures (see chapter 6).

The tribological mechanism of machined and thermally sprayed microstructures was analysed by means of tribometer testings and a test rig specially designed for the cylinder liners (see chapter 7). During the testing, the creation of machined micro-dimples led to the reduction of the minimum friction coefficient by up to 79% as well as to its shift towards lower relative speeds by 77%. The identified effects indicate that machined micro-dimples support hydrodynamic pressure build-up between the friction partners under planar contact conditions (see chapter 7.1). When testing thermally sprayed microstructures, coated surfaces consistently exhibited enhanced frictional properties compared to those of uncoated steel or cast iron. In comparison with the reference samples, the coatings provide the potential of using the microstructures to build a hydrodynamic pressure and additionally use the microstructures as an oil retention capacity. Due to the lamellar structure of the coatings, a new microstructured surface with the same properties is exposed after wear (see chapter 0).

An experimental analysis of a microstructured cylinder liner was carried out on a single cylinder heavy-duty research engine under fired conditions. The friction, in terms of the friction mean effective pressure (FMEP), was determined using the “indication method”. Additionally, oil consumption measurements were carried out using an advanced mass spectroscopy system. The surfaces of the investigated cylinder liner were plateau honed, fine honed with machined micro-dimples and coated by thermal spraying. Depending on the micro-dimple arrangement, cylinder liners with machined microstructures showed a decrease of FMEP by a maximum of 19 % and significantly less oil consumption at low and medium engine loads compared to an ordinary plateau honed liner (see chapter 8).