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Potentials for Improving Efficiency of Combustion Engines due to Cylinder Liner Surface Engineering

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Abstract

Despite new developments like E-mobility or hybrid concepts, the combustion engine will remain of great importance in individual mobility. The article highlights the recent trends, i.e. moving away from monolithic materials in the crankcase towards coated liners with adapted surface structures generated by honing processes. Results of tribological tests are presented for determined surface modifications and different materials to decrease frictional losses. Methods of process monitoring are outlined together with discussion of results from running-in experiments and boundary layer characterisation. Thus, conclusions for the specific finishing of cylinder running surfaces are drawn to improve the honing process.

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Keywords: Honing; Finishing; Suface integrity; Tribology; Friction

1. Introduction

In the conflict area with legal regulations and the customers' demands for economy, mobility and quality, the continuous improvement of the internal combustion engine is a decisive key point in the development of modern motor vehicles. Especially in the passenger car sector, currently two major development objectives can be identified in terms of reducing fuel consumption and reducing the pollutant emissions (e. g. CO_2, NO_x) [1,2]. Either it can be implemented by improving the power efficiency or reducing the power to weight ratio. So-called downsizing concepts lead to an increase of mechanical and thermal loads of specific engine components. On the other hand, a reduction of power to weight ratio by corresponding lightweight constructions can decrease the fuel consumption. For monolithic, quasi-monolithic and heterogeneous cylinder liner concepts, mainly aluminum alloys and other composite materials are used [3,4]. In addition to cast-in liners made of cast iron, thermally sprayed coatings are focused to ensure a friction-optimized and wear-resistant cylinder running surface [5,6,7]. Even in the context of electric mobility, combustion engines will remain of considerable importance. This shows the current market penetration of electric vehicles with a marginal rate of 0.06 % of the total registered cars at least in Germany [8]. Further new development potentials arise in hybrid vehicle concepts by using range extenders for steady-state operation. Depending on the operating point, nearly 50 % of the frictional losses of the combustion engine are caused in the crank mechanism [9,10]. This includes the tribological pairing piston ring - cylinder running surface as one decisive element. Here, a 5 % reduction of frictional losses can lead to a 1 % improvement in friction efficiency of the entire engine with a profitable cost-benefit ratio, corresponding to lower emissions of 1 g CO_2/km [11]. As the main quality determining process, finishing by honing is the key technology and subject of current research.

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2. State of the art

The honing operation of cylinder running surfaces is the last processing step in engine production. Therefore, the friction and wear behavior of the tribological system piston ring - cylinder running surface is determined. The quality of the surface finish directly affects the oil consumption and emissions of the engine. By honing, the micro and macro structure is specifically adjusted. Micro-hardness, residual stresses, lattice structure and chemical boundary layers define the surface integrity and can be seen as a function of honing process parameters and running-in conditions. Honing can be defined as an interaction of mechanical work and physical-chemical processes. The multitude of factors illustrates the complexity, see Fig. 1.

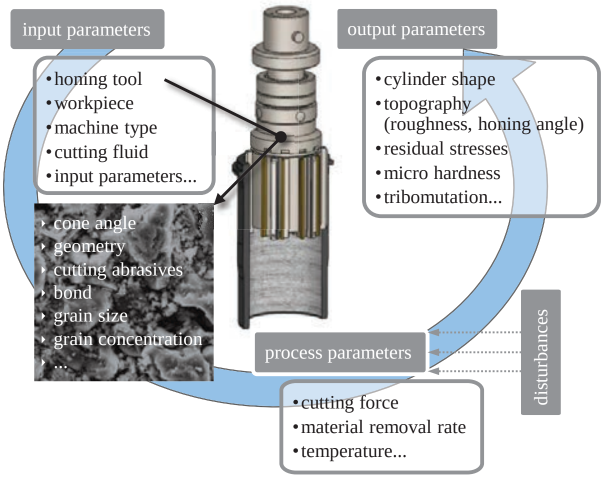


Fig. 1. Parameters of the honing process.

Key parameters of the process are the cutting and bond material, the feed or expansion system [12], the workpiece clamping and input parameters. Depending on the machining task, cutting materials such as diamond, cubic boron nitride, silicon carbide and corundum are used [13].

The prevailing conditions between cutting material and workpiece are significantly influenced by the cutting fluid. The viscosity and the additives of the lubricant determine the flushing and lubricating effect in the contact area. The influence of different cutting fluids for honing is evaluated in [14] and [15] with respect to the achieved material removal rate and surface topography. Benefits were observed when using ecologically advantageous polymer-based cutting fluids.

The cylindrical shape with a tolerance of less than 6 µm is also finally defined by the honing process and contributes a significant part to the engines performance [16,17]. A further approach for reducing mechanical losses relates to the so-called form honing [18], whereby a non-circular machining with actuatoric elements is performed. For this purpose, the finishing process is designed in consideration of pre-calculated dynamic cylinder form deviations occurring during engine operation. Recent developments illustrate ways to series production [19,20,21].

A significant aspect during honing is basically the topography of the cylinder running surface, which is adapted to each cylinder liner concept. For crankcases made of cast iron, a multi-stage plateau honing technique is state of the art. The honing plateaus form a large real contact area to reduce the surface pressure and friction, whereas the honing grooves serve as an oil reservoir. In contrast, the pores of thermally sprayed iron layers adopt this function and are exposed during honing, so the surface can be finished very smoothly [22,23]. A variety of studies aims at improving the surface topography by adjusting the honing parameters [24,25,26] or at the extension of the finishing process by new strategies [27,28,29,30,31,32,33]. Fig. 2 shows examples of different topographies for cylinder running surfaces.

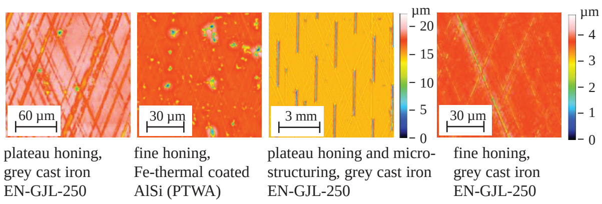


Fig. 2. Exemplary surface topography of various honed cylinder running surfaces.

The process parameters and the cooling fluids additionally influence the surface integrity. Depending on additives used during honing and engine operation, chemical reactions play a significant role for the outer boundary layer characteristics [34,35]. In the field of scientific studies relating to surface integrity issues, tribological models have to be considered and applied in production technologies [36]. Because of relatively low cutting speeds during honing resulting in low contact zone temperatures, the formation of chemical reaction layers tend to be insignificant [37]. However, the formation of these reaction layers depends on the concentration of chemical elements in the lubricant and the machining conditions [38,39]. Investigations related to the formation of reaction layers were previously realized in processes with defined cutting edges [40,41] and in grinding [42]. Due to the modified process kinematics during honing, depicted in Fig. 3, these studies can be transferred only conditionally. The characteristic cross-hatched structure of honed surfaces is a result of the superposition of the oscillating axial movement and the rotation of the honing tool with simultaneous radial infeed of the honing stones.

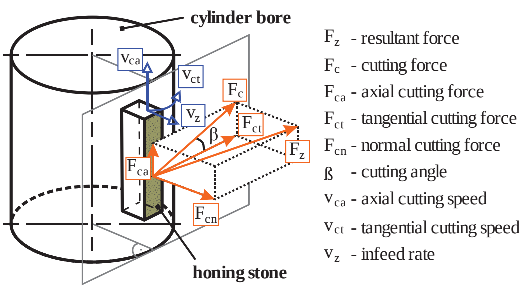


Fig. 3. Schematic image of input and process parameters in honing operation.

By honing of cast iron, the correlation between low cutting force ratios along with low deformation depths and the reduction of friction in operation is discussed in [43]. As demonstrated in [44], a tribological favorable nanocrystalline structure can be adjusted. Another approach is presented in [45,46,47], using an additional process for conditioning the surface and subsurface areas with a carbide tool. Thus the roughness peaks are smoothed and tungsten disulfide WS_2 diffuses into the boundary layer by adding a special additive to the lubricant. The composition of the formed tribological layer deviates considerably from the base material and reduces the frictional losses. Basically, friction and wear of oscillating tribologically stressed components can be influenced by surface topography and mechanical-chemical boundary layer properties. A separate analysis of these impacts, as for example *Keller* [48] and *Mach* [49] investigated, neglects the interactions and provides no holistic reflection of optimization approaches. Investigations of *Berlet* [50,51] establish a relationship between finishing process and tribological function. Small compressive stresses, low friction and low temperatures during honing reduce the coefficient of friction during running-in and in engine operation. These findings were achieved by appropriate choice of lubricant additives, binders, contact times and contact forces. But so far, this could only be verified on a pin on disk test. *Mezghani* refers in [52] and [53] to the changes in the surface topography during running-in and optimizes the honing process. In addition to the consideration of the roughness parameters determined by [54], the texturing and the type of finishing also affect the tribological behavior. In [55] and [56], further approaches are discussed reaching the result that low cutting forces respectively low energy input in honing and smooth surfaces are advantageous for operation. In addition to the finishing process, especially the running-in conditions during the first hours of operation, are critical to friction and wear behavior of a system, as described for example in [57,58,59]. In interaction with the additives of the engine oil, the temperatures and the initial stress, thin reaction layers on the honing structure of the cylinder running surface are formed. The decisive preconditions can be defined by the honing process to set a reactive and running-in optimized boundary layer. Tribological tests as described in [60] represent the first step to evaluate honed structures of the system piston ring / cylinder running surface to provide a first correlation between the finishing process and the engine operation. With solid knowledge of modern manufacturing technologies, simple and cost-efficient concepts can be derived. In the context of current optimization efforts for combustion engines, two approaches to the subject of cylinder surface engineering are presented below.

3. Macroscopic structure

Especially at aluminum crankcases with coated cylinder bores, the process forces are of great importance for the design of the honing operation. The different stiffness and wall thickness values of the cylinder bore have a considerable influence on the form deviations. Depending on the infeed system of the honing machine, the normal cutting force is a control or process variable. The feed rate in force controlled infeed systems is a result of the proceeding cutting process with constant normal cutting forces. In a path controlled infeed system, the radial infeed is defined and the required applied process force depends on the cutting ability of the honing stone. The purpose of increasing the machining force is to enhance the cutting rate of the honing stone, entailing a reduction of cycle time. However, higher machine forces have negative effects on the quality of the cylinder bore. The surface roughness can rise by an aggressive cutting behavior and elastic deformations cause roundness and straightness deviations. In the following approach, the acting forces at the machining location (tool model) and also the resulting deformations of the cylinder bore (crankcase model) are calculated by using the finite element method (FEM), based on investigations to calculate the longitudinal contour of a cylinder [61,62], see Fig. 4.

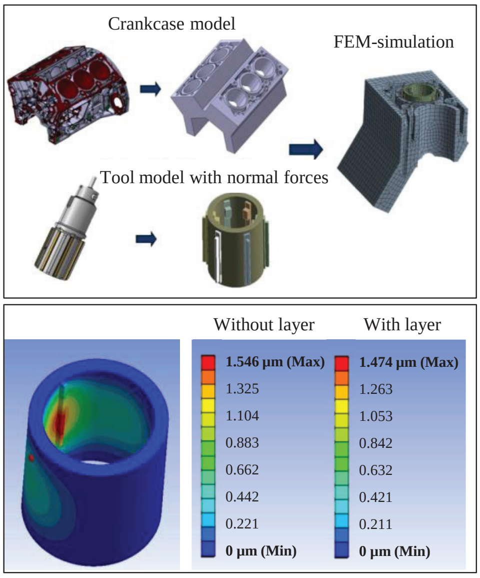


Fig. 4. Honing process model (top) and influence of the WAS-layer on the cylinder form deviation (bottom).

To determine the influence of the 0.1 mm thick layer, applied by wire arc spraying process (WAS) on the subsequent deformation simulation, a calculation of the deformations on a cylinder with and without the thermal coating is performed. The load of 500 N is initiated via only one honing stone in this simplified model. The influence of the WAS-layer on the deformations is marginal and can be neglected in further simulations to reduce computing time.

The chart in Fig. 5 depicts the deformation results of the FEM calculation compared with the real roundness deviations. The vertical primary axis represents the distance between the measured value of the shape and the nominal dimension. The difference between the maximum and minimum values represents the roundness deviation at this level. Less material has been removed at a negative distance to the nominal dimension, because the cylinder is deformed at the unstable points during machining and enlarges to its initial position. The calculated deformations are shown on the vertical secondary axis.

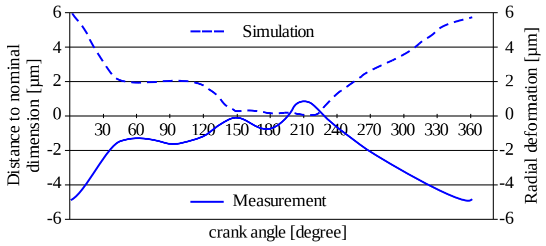


Fig. 5. Comparison of form deviation after FEM-simulation and roundness measurement.

With the presented tool and honing process model, critical positions in the crankcases of new engine generations can be identified early in the digital development phase. Based on results, constructive measures can be initiated to strengthen the crankcase and hence to reduce deformations and roundness deviations. Another approach to deal with the difficulty of cylinder deformation is the form honing process. By actuating control of each honing stone, the honing force could be adapted to instable respectively stable areas in the crankcase. The results of the model can also be used to optimize the honing stone specification to ensure the cutting ability at low machining forces to reduce deformation.

4. Microscopic structure

Regarding the micro-structure of cylinder running surfaces, a more detailed analysis of the tribological system piston ring - cylinder running surface is necessary. During a work cycle in the combustion engine mainly two different mechanically stressed areas occur. On the one hand, the maximum wear appears in a range of - 20° to + 20° crank angle at the reversal points of the piston. On the other hand, the friction in integral examination is on a high level for almost the entire stroke (especially + 20° to + 90° after top dead center), see Fig. 6.

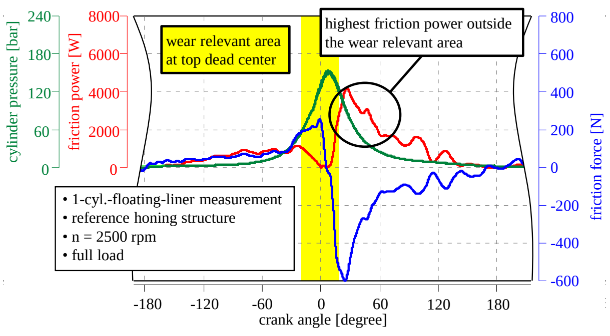


Fig. 6. Relevant areas during a work cycle of a combustion engine.

In order to focus on a specific optimization, the problem is divided into the areas of friction and wear reduction. Several research results and concepts are discussed in the following subchapters.

4.1. Friction reduction

All honing experiments are performed on a single-spindle vertical honing machine (Nagel VSM 8-60 SV-NC) and with honing oil (Castrol Edge 930). The nominal diameter of the cylinder running surface is 81.01 mm (± 5 µm). The first and second honing steps are performed path controlled with diamond honing stones (D107, D56) and a radial allowance of 45 - 35 µm. The analysis of the surface topography is realized using a Taylor Hobson 3D profilometer (Form Talysurf PGI 800) with a measurement range of 1.2 x 1.2 mm, a point distance of 1 µm and a resolution of 3.2 nm. After the honing operation, segments (10 mm x 15 mm) were prepared by electrical discharge machining and analysed in an oscillating-friction-wear (OFW) test (SRV®3, Optimol Instruments Prüftechnik). For this purpose, a piston ring is clamped under a normal force of 200 N on the cylinder segment and performs an oscillating movement with a stroke of 3 mm. An engine oil SAE 5W-30 with additives is used in an oil bath at a temperature of 130 °C. Over a test period of 3 h, the running-in is performed and the coefficient of friction (CoF) is measured in situ. For a concrete correlation of finishing process and tribology, the knowledge of process forces during honing is essential.

4.1.1. Experimental setup during honing

The measurement of tangential and axial cutting forces during the honing process is realized by a special piezoelectric force measurement platform. It is located beneath the machine table in the main power flow of the process. The workpiece side measurement method is robust and insensitive to vibration, temperature changes and cooling fluids. A calibration of the hydrostatic expansion pressure, given in percent (%) by the machine control, is carried out separately for each honing tool due to different cone angles and friction pairings. Two measuring brackets are equipped with strain gauges to measure pressure forces that occur during a real expansion of the honing tool to the desired diameter, as shown in Fig. 7. A full-process measurement is currently in development.

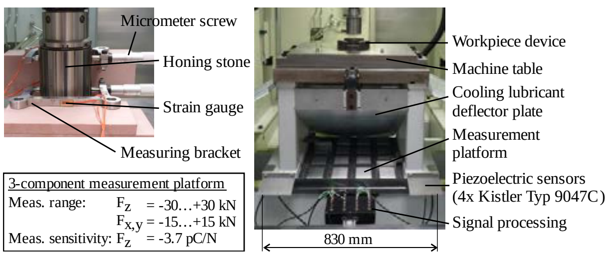


Fig. 7. Piezoelectric force measurement platform (right) and normal force measuring brackets (upper left).

4.1.2. Results

Welzel [63] decidedly analyses the thesis of finishing EN-GJL-250 with low process forces during honing. Various variations of the last processing step are performed. These include the finish honing with diamond (D) - and silicon carbide (C) - honing stones (D15 / 118 / X33 / 75, SC400

KE20) at high and low contact forces and two brushing processes (Br) with Anderlon[TM] (abrasive synthetic brush with ceramic particles) and steel wire. Moreover, previously honed samples are machined by a conditioning process (Co) with bars made of tungsten carbide and two process fluids, see Fig. 8.

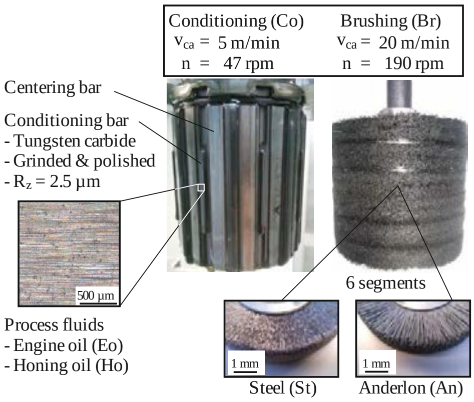


Fig. 8. Conditioning tool (left) and brushing tool (right).

The results of cutting force measurement and OFW tests are shown in Fig. 9. Lower cutting forces at comparable honing pressures for honing stones made of silicon carbide compared to those of diamond occur. The frictional behavior is also advantageous. As expected, the lowest average cutting force is realized when brushing, even with concomitant increase in roughness. In the optical surface analysis, pores are detected that indicate a leaching of the graphite by the brushing process. The conditioned samples show a similar appearance. For all samples, the roughness increased marginally and grooves are visible. Compared to the reference process a slight improvement in the coefficient of friction is noted.

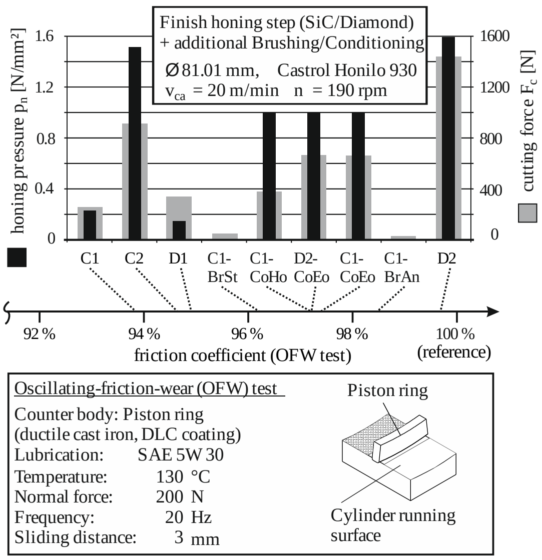


Fig. 9. Correlation between honing pressure, cutting force and tribological performance of cylinder running surfaces after different finish machining.

The honed samples differ in the surface topography as a function of the contact pressure and the cutting material, see Fig. 10. By using silicon carbide at high honing pressures (C2) and diamond at low pressures (D1), the roughness is increased. The different behavior can be traced back to the cutting materials. Diamond grains crack in the metallic matrix at high pressure, whereas the silicon carbide cutting material creates new micro cutting edges by a self-sharpening effect in various sizes depending on the honing pressure.

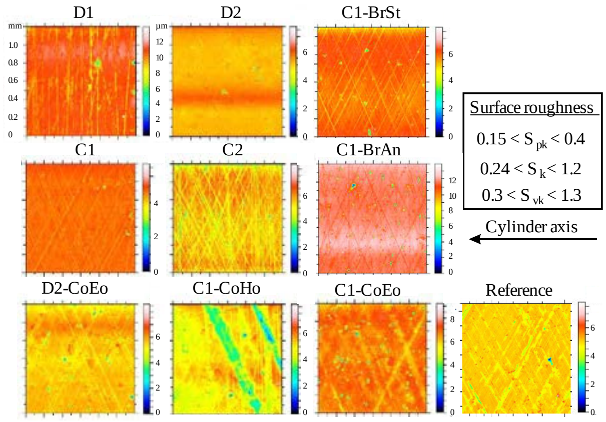


Fig. 10. Tactile measured 3D surface texture after different finish machining.

Detailed studies of the boundary layers of selected samples are carried out by X-ray diffraction (XRD), secondary ion mass spectroscopy (SIMS) and focused ion beam (FIB). Due to the inhomogeneous structure of lamellar grey cast iron, conclusions for residual stress states of the inner boundary layer can be drawn only partially. By finishing, compressive stresses can be formed generally. However, a differentiation according to a finish process variation and preferential directions could not be determined [64,65]. Clearer differences were observed according to the tribological stress state after OFW test with respect to the outer boundary layer. An integral measurement of element concentrations with SIMS and a subsequent visual inspection of the exposed boundary layer by FIB show oxidic compounds on the honing plateaus (dark regions). Therefore, the interaction of tribological load, engine oil and temperature on the real contact areas is of particular importance. Furthermore, additive elements of the engine oil used in the OFW test can be detected in the near surface areas in various concentrations. A thicker outer boundary layer tends to be advantageous in terms of the CoF. One reason for this might be the reduction of shear stress in the contacting surface regions. A complete conditioning by the finish process in preparation of the tribological load could not be realized. However, depending on the manufacturing processes, different manifestations of the reaction layers are formed during running-in. Silicon carbide cutting materials and low cutting forces cause the most significant reaction layers. A FIB-cut of a silicon carbide honed cylinder running surface at low honing pressure (C1) and the distribution of elements compared to the diamond honed surface at high honing pressure (D2) and a conditioned surface (C1-CoHo) is shown in Fig. 11.

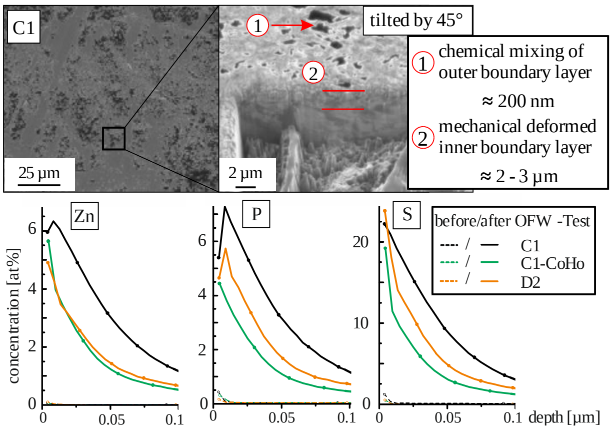
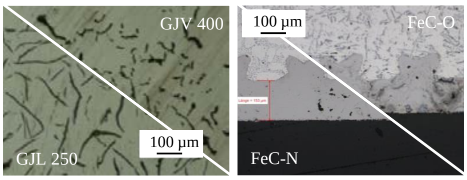


Fig. 11. Image of the exposed boundary layer with FIB of a silicon carbide honed surface (C1) after the tribological test (top) and element concentration of the outer boundary layer determined with SIMS before and after the tribological test of 3 different finish machining variations (bottom).

Based on these findings, the performance of silicon carbide cutting materials is studied in alternative cylinder running surface materials. Besides EN-GJL-250, an EN-GJV-400 and two thermally coated AlSiMg10 alloys are investigated. The iron layers produced by Plasma Transferred Wire Arc process (PTWA) differ in the used atomizing gas (oxygen and nitrogen). The coating morphology with the appropriate macro hardness (Martens) is shown in Fig. 12.



material	GJV 400	GJL 250	FeC-O	FeC-N
hardness HM [N/mm²]	2020 ± 348	1609 ± 126	2174 ± 247	3352 ± 262

Fig. 12. Morphology (cross-section, top) and macro hardness (Martens, bottom) of investigated materials.

For harder materials higher cutting speeds v_c are of advantage. Therefore, in honing tests $v_c = 60$ m/min as well as $v_c = 80$ m/min are applied. The pre-processing and the test procedure are equal to the procedure set in 4.1. For the thermal spray coatings, high honing pressures and high cutting speeds are not tested. In Fig. 13, the results of cutting force measurement and the tribological tests are presented. It can be stated, that a small cutting force during finishing is advantageous for the tribological behavior of the system. One reason is the increasing surface roughness due to increasing honing pressure. Another point that can be discussed is again the formation of advantageous boundary layers during running-in. It is presumed to occur on surfaces that are stressed with low energy input in form of cutting forces during finishing.

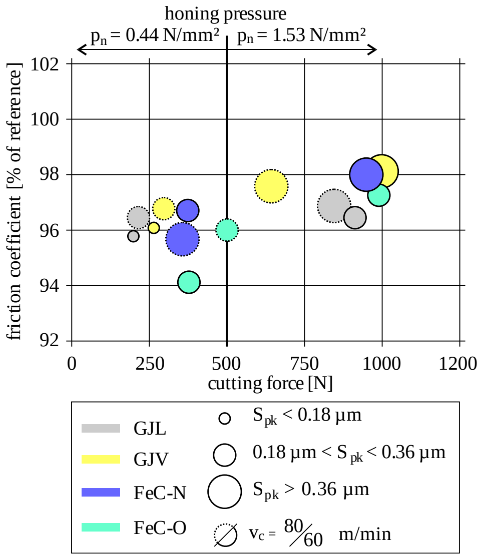


Fig. 13. Correlation between cutting force during honing and friction coefficient in OFW test of different materials including reduced peak height S_{pk} after different honing parameters.

4.2. Wear reduction

As shown in Fig. 5, the wear-relevant area of the cylinder running surface is located at the top dead center (TDC). In addition to the smoothening of roughness peaks and the plastic deformation of surface asperities, stable boundary layers are formed by mixed friction during running-in [48]. The procedure of running-in can have a direct impact on the formation of these boundary layers and thus on the wear behavior over the lifetime, see Fig. 14. In this context, the initial load of the system is of vital importance.

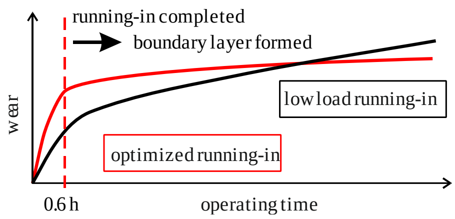


Fig. 14. Wear rate after different running-in procedures over the lifetime of the engine (schematic).

As a conditioning of the surface and subsurface of the TDC area can hardly be achieved during the honing process, a separate conditioning process has to be established. In an experimental test rig, the TDC-region is tribologically stressed over a length of 6 mm for duration of approximately 3 minutes (Fig. 15). Based on the optimal running-in procedure, a piston ring is pressed against the cylinder running surface with p = 160 bar, comparable to the load regime in ignition time of the real combustion process. The piston is guided through a liner and associated via a connecting rod to an eccentric shaft rotating at n = 2500 rpm. By using engine oils with special additives at a temperature of 90 °C, the running-in can be simulated in finish machining.

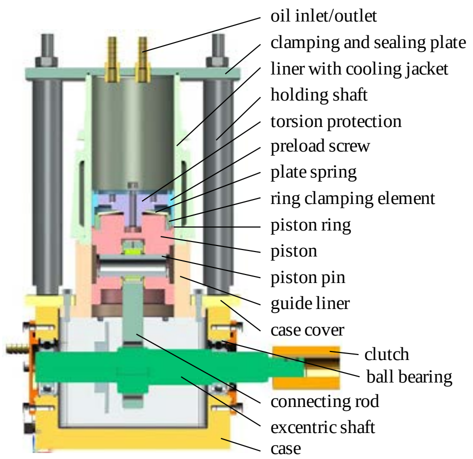


Fig. 15. Prototype of the friction-power-generator for conditioning the TDC of cylinder liners.

5. Conclusion

The requirements for the process reliability and high-quality production of crankcases increase in the wake of lightweight design and resource efficiency. To further optimize the finishing of cylinder running surfaces, a separate consideration of the macroscopic and microscopic effects is necessary. The approaches presented focus on the process parameters. So the maximum allowable honing pressure and related distortions can be determined by a simulation of the honing process. At the microscopic level, friction and wear-related areas have to be differentiated. Honing stones made of silicon carbide as well as the finishing with low process forces are advantageous in terms of an improved friction behavior in operation. This could be demonstrated for both, cast iron as well as thermally coated cylinder running surfaces. In addition to surface topography, the correlation of finishing and running-in has to be taken into account. The formation of beneficial boundary layers during finishing is not observed. However, the characteristic of the inner and outer boundary layer, formed during running-in, depend on the process forces occurring in honing. So additive elements in different concentrations can be detected in the outer boundary layer, whereby a detailed analysis is still part of the basic research and currently not practical for mass production. The wear-relevant area around the TDC requires a separate conditioning. By applying a friction-power-generator, the running-in process might now be simulated in finishing for an improved wear resistance. The optimization of the finishing process of cylinder running surfaces by honing can only be realized due to the consideration of all effects occurring whilst production and running-in. Therefore, an interdisciplinary work between research and industry is essential.

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