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Reduction of friction in the cylinder running surface of internal combustion engines by the finishing process

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Abstract

Recent investigations on internal combustion engines show a relationship between the energy input due to the finishing process and the development of friction and wear during running-in, as well as of the subsequent operating state. The aim is to describe the correlation of the operational behavior on the mechanical modification of the inner boundary layer and to draw conclusions about the machining process. Honing process parameters are investigated using a special force monitoring setup. An optimized manufacturing process focused on chemical and mechanical boundary layer properties has been developed to reduce frictional forces in the system piston ring/cylinder running surface.

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1. Introduction

The energy input during finish machining in combination with the running-in conditions for tribological loaded components is of particular interest [1, 2]. Especially during honing of the cylinder running surface of internal combustion engines, roughness parameters and boundary layer properties can be modified [3]. The optimal adjustment of the residual stress state, chemical reaction layers and microstructure determines the friction and wear behavior of the piston group and, finally, the efficiency of an internal combustion engine. Previous scientific studies in this context focus primarily either the influence of finish machining [4] or running-in [5, 6] on the tribological behavior. A lack of knowledge exists regarding the dependencies between them, so correlations are rarely considered in detail [7]. In analogous experiments, *Berlet* shows the relationship between the coolant and process forces used in the finish machining and the tribological performance [8]. Irrespective of underlying mechanisms, *Mezghani* links the energy input during honing with the friction behavior [9]. But the element concentration in the boundary layer of cylinder running surfaces is of high importance [10]. A recent thesis in this context is the advantageous finish machining with low process forces.

2. Experimental setup

With different production settings, the influence of the finish honing operation for cylinder running surfaces made of grey cast iron EN GJL 250 with a diameter of d = 81.01 mm ± 0.005 mm is investigated. For this purpose, a honing machine “Nagel Variohone VSM 8-60SV-NC” and honing oil “Castrol Honilo 930” are used. All samples are produced by a conventional 3-stage honing process with a honing angle of 45 °, to ensure comparability of the surface topography for the following tribological tests. The first and second honing step is realized with metallic bonded diamond honing stones (D) and grain sizes of D107 and D56 microns. Therefore, the infeed is performed electro-mechanically. Honing stones made of silicon carbide (C) and metallic bonded diamonds are used in the finish honing step with the hydraulically infeed system. In addition to the third honing step, two brushing operations (Br) with steel wire or Anderlon™ and a conditioning process (Co) with carbide inserts are applied, see Fig. 1. By brushing, burr can be eliminated with minimum process forces and by conditioning with the utilization of honing or engine oil (SAE 5W-30 containing additives), high friction power can be transferred without material removal.

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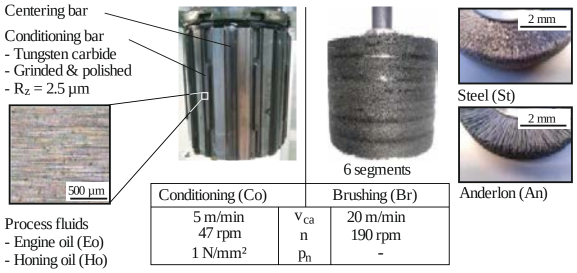

Conditioning (Co)		Brushing (Br)
5 m/min 47 rpm 1 N/mm²	v_{ca} n p_n	20 m/min 190 rpm -

Constants: $\alpha = 45°$ $v_c = 60$ m/min	Test series finish machining					
	Cutting material / tool				Additional process	
	Silicon Carbide Sc400Ke20		Diamond D15/118/X33		Brushing (**Br**)	
					Steel (**St**)	Anderlon (**An**)
p_n [N/mm²]	0.21	**C1**	0.15	**D1**	Conditioning (**Co**)	
	1.53	**C2**	1.6	**D2**	Engine oil (**Eo**)	Honing oil (**Ho**)

Fig. 1. Conditioning and brushing tool (top) and parameters of the test series.

The axial and tangential cutting force components are measured in-situ by a developed piezoelectric force measurement platform, see Fig. 2. The design ensures a minimum of disturbances caused by temperature fluctuations or vibrations. On the machine control side all the settings are expressed as a percentage. Therefore, a calibration of the radial expansion forces for each honing tool is necessary and realized by special measurement brackets with strain gauges.

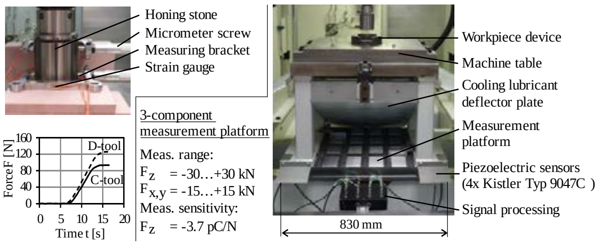

Fig. 2. Normal force measuring brackets and exemplary chart (left), piezoelectric force measurement platform (right).

The tribological behavior of the cylinder running surfaces is investigated with an SRV®3 test rig (Optimol Instruments Prüftechnik) with a friction force resolution of 0.01 N. For the oscillating friction wear (OFW) test, the honed samples are prepared by electrical discharge machining with a size of 10 x 15 mm. As counterpart an original piston ring segment made of spheroidal graphite cast iron with a wear resistant DLC coating is used. An OEM surface serves as reference. The experimental conditions are comparable to the conditions in the top dead center of the real combustion process, where mainly mixed friction conditions occur. Apart from dynamic effects the coefficient of friction (CoF) is measured in the running-in process at a stroke of s = 3 mm and a frequency of f = 20 Hz for a period of t = 3 h. The samples are fixed in an oil bath of SAE 5W-30 at a temperature of T = 130 °C. The cylinder running surface is characterized before the OFW test by a tactile measurement (3D profilometer Form Talysurf PGI 800, Taylor Hobson) with a measurement range of 1.2 x 1.2 mm, a point distance of 1 micron and a resolution of 3.2 nm. In contrast, the workpiece surface integrity is analyzed by X-ray diffraction (XRD), secondary ion mass spectroscopy (SIMS) and focused ion beam (FIB).

3. Results

3.1. Cutting force measurement and surface topography

In preliminary tests, shown in Fig. 3, a suitable process window for honing stones made of silicon carbide could be defined. Only at high honing pressure $p_n = 1.53$ N/mm², an influence of the cutting speed v_c on the cutting force F_c can be determined. An optimum in terms of small cutting forces is reached at $v_c = 60$ m/min. The settings are analogous to the conventional process with diamond honing stones. In general, the surface roughness increases at high contact pressure except low cutting speeds. In each case a minimum of the roughness is reached at $v_c = 60$ m/min. Here the reduced peak height R_{pk} and the reduced valley height R_{vk} are comparable and independent of the honing pressure, only the core roughness R_k differs. Therefore, this cutting speed is kept constant for all further investigations.

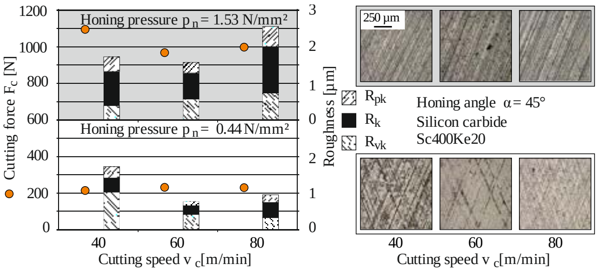

Fig. 3. Influence of the cutting speed on cutting forces and surface characteristics.

The test series in finish machining with all process variations verifies advantages of ceramic honing stones in terms of low process forces (Fig. 4). For similar honing pressure, significantly lower cutting forces appear compared to metal bonded diamond honing stones based on a beneficial cutting ability. The results confirm those mentioned in [10].

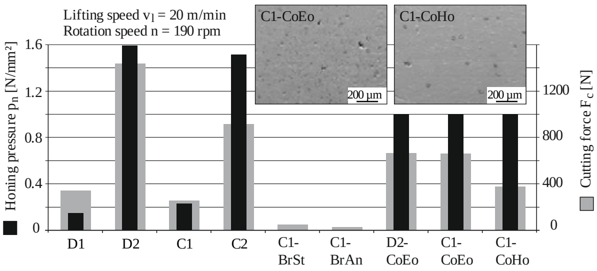

Fig. 4. Correlation of honing pressure and cutting force in finish machining and REM-images with artefacts on the conditioned surfaces (top).

As expected, the lowest cutting forces are generated by brushing processes. The measured cutting force for conditioning represents the friction between the tungsten carbide inserts and the cylinder running surface without chip removal. The different cutting forces for C1-CoEo and C1-CoHo results from the different viscosity of the process fluids. Using raster electron microscopy, round cavities with oxide inclusions are detected. This assumes an increased reactivity of the base material. However, the surface roughness remains constant. The samples exhibit a rugged topography with scratches on the surface, see Fig. 5. The brushed cylinder running surfaces show a comparable surface roughness with an increased waviness. In sum, all manufactured surfaces are in terms of topography in a similar range, even though the function-oriented characteristics of the Abbott-Firestone curve differ slightly depending on the finish machining. An increasing contact pressure lead at diamond honing stones (D2) to a reduction of the profile depth in contrast to the cylinder running surface honed with silicon carbide (C2).

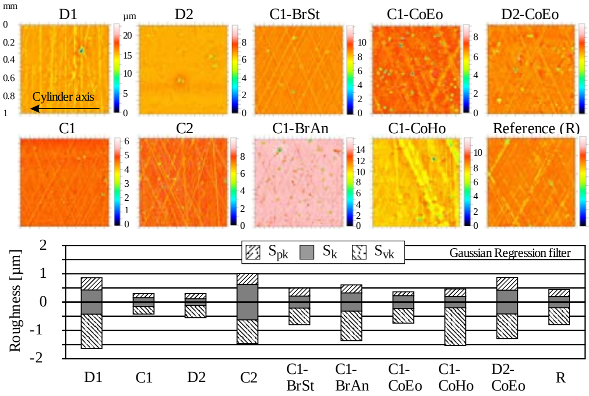

Fig. 5. Tactile measured 3D-surface texture (top) and S_k-parameters of the Abbott-Firestone curve (bottom) after finish machining.

3.2. Tribological tests

The mean values of the CoF are presented in Fig. 6. Without additional processes, the samples finished applying low honing pressure shows for both cutting materials (D1, C1) the best CoF, regardless of the surface roughness. In this case, also the friction loss of the silicon carbide honed samples is lower compared to the diamond honed samples for each honing pressure. A constant trend of the CoF indicates a completed running-in and steady operating conditions. The other variations cannot improve the tribological behavior compared to the reference (R). It must be taken into account, that 5 % friction reduction of the piston group is equivalent to approximately 1 % less engine friction. For all samples after the OFW test, a negligible quantity of wear occurs and the roughness parameters tend to converge. However, the tribological tests confirm the thesis stated at the beginning and verifies the advantage of finishing with low process forces.

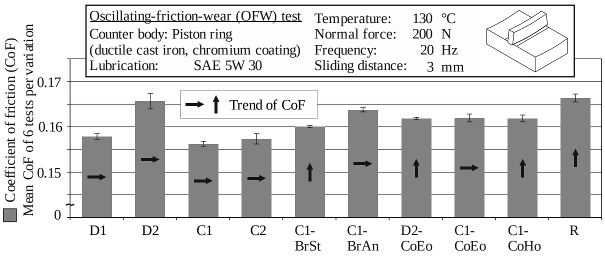

Fig. 6. Mean values of the CoF and trend measured during the OFW-test.

3.3. Boundary layer characterization

A variety of analyses are necessary to characterize the workpiece boundary layer. The mechanical deformation of the inner boundary layer can be determined through the residual stress state, detected by a 3-axis X-ray diffractometer. In correlation to the finish machining, no preferential direction of residual stresses at a depth of 5 microns could be proven. The detailed results are presented in [7]. To detect a depth profile of the gradient of the residual stresses, sequential measurements after multiple etching (each of 5 microns) are carried out on the surfaces. Fig. 7 represents exemplary two depth profiles of the cylinder running surface honed with silicon carbide before and after the OFW test. The initial state of the residual compressive stresses σ_{ax} after finishing is identical with a maximum close to the workpiece surface. Only at a depth below 10 microns the level of σ_{ax} is different. Here, the surfaces honed with low process force C1 show increased compressive residual stresses with a comparable curve progression. After the OFW test, σ_{ax} decrease close to the workpiece surface. In contrast, the depth profiles of the equivalent stresses σ_v are almost identical for all the samples. This is based on the shear stress term contained in the von Mises yield criterion, which must be taken into account for the evaluation of residual stress states. In addition, the inhomogeneous structure of grey cast iron is subject to further restrictions for XRD. Except the brushed samples with high shear stresses, all other variations show an identical behavior.

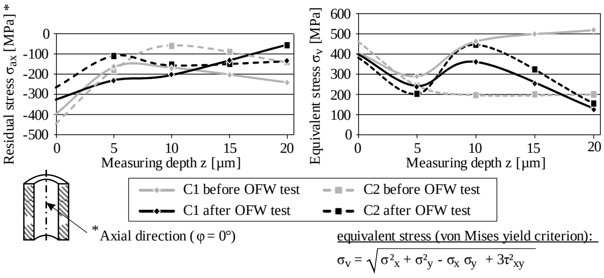

Fig. 7. Residual stresses of the boundary layer of two silicon carbide honed surfaces detected with X-ray diffraction before and after the OFW test.

As stated in [10], the oxygen concentration represents a first indicator of the penetration depth of elements from the cooling lubricant and engine oil, which are to be expected in the outer boundary layer. Therefore, the high depth resolution and sensitivity of SIMS is suitable to examine the chemical composition in the sub-micron range. The necessary calibration is performed with Auger electron spectroscopy. The results of the analysis for the different finished samples before and after the OFW test are depicted in Fig. 8. After finish machining, no significant changes in the elemental composition of the outer boundary layers can be detected. After the OFW test, the boundary layers with a thickness of up to 200 nm contain a significant proportion of additive elements from the engine oil used in the OFW test like sulfur, calcium, zinc and phosphorus. For identical tribological test conditions, the element concentration differs depending on the finish machining. Thicker outer boundary layers are obvious in the cylinder running surface honed with silicon carbide and low process forces (C1). This may be in correlation to a low CoF. The conditioning of C1 CoHo has the least effect on the outer boundary layer. It can be assumed, that an additional input of friction power during finishing in the subsequent running-in leads to a lower thickness of the boundary layer, thus the friction during engine operation increases. An influence of the surface roughness could not be observed. On the contrary, it is presumed that thin reaction layers are more wear resistant, what has to be investigated in further tests. A comparison to the boundary layers after real engine tests can be found in [3]. However, the impact on the wear behavior cannot be conclusively clarified at this point.

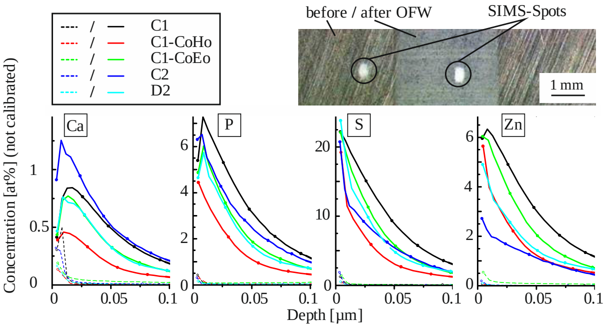

Fig. 8. Element concentration of the outer boundary layer determined with SIMS before and after the OFW test.

To confirm the determined chemical and mechanical changes and to visualize the boundary layers, a preparation with FIB is done. For example, Fig. 9 shows the sample C2 before and after the OFW test. The detected reaction layers in SIMS are emerging as black artifacts, with a different frequency of occurrence depending on the element concentration. In the FIB cross section the inner boundary layer is visible. At a depth of 2-3 microns, beneath the tribological loaded areas (honing plateaus), a fine crystalline structure can be identified. This indicates a mechanical deformation, whereas in the unloaded areas no structural changes can be observed. So the importance of the real contact area for the expression of reaction layers during engine operation is marked. An influence of the cutting force during finish machining on the structural alteration could not be detected.

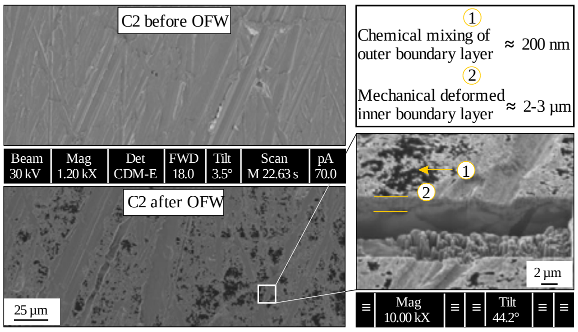

Fig. 9. Images of the exposed boundary layer with FIB for the silicon carbide honed surface C2 before and after the OFW test.

4. Conclusion

This paper clarifies the complexity of the optimization of the piston ring-cylinder system and the need for a full understanding of the honing process in conjunction with the running-in conditions. The topography of the cylinder running surface is only one of many influences. It was shown that even comparable roughness parameters after various honing settings can lead to different friction forces. Honing with low process forces and the use of silicon carbide honing stones can reduce the friction losses. The finish machining with high process forces, independent of the cutting material, is generally disadvantageous. The last process step has an impact on the formation of boundary layers during running-in. A different concentration of additive elements in dependence of the finish machining is verified beneath the honing plateaus. The tribological load in combination with high temperatures on the real contact areas is an important factor therefor. A pre-conditioning during finish machining could not be detected. The wear behavior has to be analyzed in separate investigations. The paper shows that for an overall characterization a solely roughness measurement is partly satisfying. But the investigation of boundary layers is not suitable for mass production and only applicable in the context of scientific work. From the manufacturing point of view, a division of the cylinder running surface in friction- and wear-related areas for a specific optimization would be favorable and will be part of future work. Understanding the interactions of honing process and reactions during running-in is the key for an optimized finish machining strategy.

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