Machine integrated optical measurement of honed surfaces in presence of cooling lubricant

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Abstract. The measurement of honed surfaces is one of the most important tasks in tribology. Although many established techniques exist for texture characterization, such as SEM, tactile stylus or white-light interferometry, none of them is suited for a machine integrated measurement. Harsh conditions such as the presence of cooling lubricant or vibrations prohibit the use of commercial sensors inside a honing machine. Instead, machined engine blocks need time-consuming cleaning and preparation while taken out of the production line for inspection. A full inspection of all produced parts is hardly possible this way. Within this paper, an approach for a machine-integrated measurement is presented, which makes use of optical sensors for texture profiling. The cooling lubricant here serves as immersion medium. The results of test measurements with a chromatic-confocal sensor and a fiber-optical low-coherence interferometer show the potential of both measuring principles for our approach. Cooling lubricant temperature and flow, scanning speed and measurement frequency have been varied in the tests. The sensor with best performance will later be chosen for machine integration.

1. Introduction
Within the production chain of combustion engines, the honing process for the manufacturing of tribological surface structures within cylinder liners is crucial for the efficiency and oil consumption of the engine. The quality inspection of honed textures today is mostly realized with tactile stylus, fax image analysis [1] or scanning electron microscope (SEM) [2], while tactile probing is the first choice for the production-related evaluation. For all of the existing measuring principles, the separation of the engine block from the production line and additional washing is needed, which is time consuming. While a complete inspection of all produced parts is impossible, the sample testing causes another problem: if the time delay to prepare and measure a cylinder liner is too long, a lot of engine blocks can be manufactured with possible defects in the meantime. Therefore, a machine integrated measuring method is highly demanded, which enables the fast inspection of the honed texture.

2. Optical measurement system
2.1. Conceptual design of the measurement set-up
As introduced above, the cooling lubricant has to be cleaned before the tactile measurement of the surface. Within this paper, an innovative approach with optical sensors is presented, in
which the cooling lubricant serves as immersion medium. As shown in the conceptual set-up in Fig. 1(a), the cylinder of the engine block is fully filled with the cooling lubricant. The sensing probe is totally immersed into the cooling lubricant during the measurement. The measurement signals are then transferred through a fiber to the measuring system, which also contains a positioning module and synchronization module.

Since the measuring system will be later integrated into a honing machine to conduct inline surface measurement, a test bench has been built up in order to simulate the production conditions during the honing process. Different factors, e.g. rough and fine surface, change of lubricant temperature and whirling, scanning speed etc., can be analyzed for selected optical sensors. The test bench is shown in Fig. 1(b).

2.2. Optical sensors
Due to the fine profile (average roughness Ra smaller than 0.5 \( \mu \)m) and small diameter (approx. 85 mm) of the cylinders of the engine block, the optical sensors should be sensitive enough and should be able to be miniaturized to enable a measurement in the cylinder. Two fiber based sensors, a chromatic-confocal sensor and a fiber-optical low-coherence interferometer, were selected based on their measuring principles.

The chromatic-confocal principle makes use of the high chromatic aberration of the sensor focussing lens. The measured distance is spectrally encoded and the spectrum is then analyzed by a spectrometer [3]. An optical fiber, which delivers the optical signal from the sensing probe to the spectrometer, serves as a confocal aperture. For our tests, a chromatic-confocal sensing probe with a diameter of 10 mm, a measuring range of 100 \( \mu \)m and a high numerical aperture (NA) of 0.9 for the measurement in cooling lubricant has been specially designed and built by Precitec Optronik GmbH of Rodgau, Germany.

The second sensor under test is a fiber-optical low-coherence interferometer, which has been developed at Fraunhofer Institute for Production Technology IPT and is now provided by fionec GmbH of Aachen, Germany. The sensing principle is based on low-coherence interferometry and is described in [4]. The sensing probe is built in all-fiber design, but has been integrated
Figure 2. Fiber optic distance sensor for machine integration

into a similar shaped probe housing (Fig. 2) as the chromatic-confocal sensor for compatibility reasons.

3. Evaluation measurements

To evaluate the performance of both sensors, a series of test measurements have been carried out, in which different objects have been measured with both sensors in cooling lubricant as follows:

3.1. Calibration

Prior to roughness measurements, the distance between the surface and probe had to be calibrated in cooling lubricant, since the refractive index of the lubricant serves as immersion medium and affects the optical path length of the measuring beam. Since the measuring processes of both sensors are similar to a tactile stylus profiler, a depth-setting standard has been used for calibration according to ISO 5436-1 type A 1 [5]. For calibration the length of measurement must be at least three times the width \( W \) of the groove. To discard data losses or batwings at the groove edges, a range of \( \pm W/3 \) is skipped on each side of the groove. With the remaining measurement data, ranging from point 1 to 2, 3 to 4, 5 to 6 in Fig. 3a, the groove depth \( D \) can be determined.

To calibrate the measurement scale and to compensate for a possible nonlinearity, a depth setting standard with two grooves, of which one is 20 \( \mu m \) and the other 50 \( \mu m \) deep, has been used (Fig. 3b). The depth setting standard was calibrated with a white-light interferometer Veeco NT1100. Since the refractive index of the cooling lubricant can change with many factors such as temperature, cleanliness or type of cooling lubricant, a calibration with the depth setting standard has been conducted for different measuring setups.

3.2. Test on roughness standards

Although both sensors have been characterized for roughness measurements in dry conditions [6], different roughness standards with Rz values of 3.2 \( \mu m \), 10 \( \mu m \) (Fig. 4) and 20 \( \mu m \) were measured in the test bench filled with cooling lubricant. Different measuring frequencies (constant sampling interval) and setups were tested.
Both sensors have proven capable for roughness measurement in the cooling lubricant under production conditions. The results show that the deviations from the calibrated value for the measured Rz values of both sensors are within ±15% and the deviations for measured Ra values are within ±6.6%.

3.3. Tests on honed cylinder surfaces
A series of test measurements on honed cylinder surfaces has been made with both optical sensors. Different factors, which may influence the measurement results, e.g. temperature, whirling, lateral resolution, and so on, have been varied according to a design of experiments test chart (see table 1).
Table 1. Experimental design of tests on cylinder surfaces

| Factors       | Factor level 1 (-) | Factor level 2 (+) |
|---------------|--------------------|--------------------|
| (A) Lateral resolution | 1 µm spacing      | 1,5 µm spacing     |
| (B) Measuring frequency | low (1 kHz)       | high (2 kHz)       |
| (C) Whirling   | Off                | On                 |
| (D) Tilting    | low (< 0,02°)      | high (> 0,1°)      |
| (E) Temperature| 21°C               | 39°C               |

Altogether 64 measurements have been conducted with both sensors. The results indicate that the optical measurements are mostly affected by the temperature effect, which causes a change in the density of the cooling lubricant and, related to that, a change of its refractive index. In real production processes, the lubricant temperature is actively cooled and kept constant within a few degrees of Kelvin, so that the temperature effects on the measurement are not considered to be problematical. Compared to results, that have been acquired with tactile stylus measurements, the expanded uncertainty for Ra (using a coverage factor of 2), is approximately 80 nm for both optical sensors. Light scattering methods, which have emerged in recent years, could be an alternative for a quick inline assessment within cooling lubricant. For a reliable determination of the feasibility, extensive optical simulation of the scattering behavior of the honed structure in cooling lubricant is crucial.

4. Conclusion
Within this paper we presented a new approach for a machine integrated inspection of honed surfaces. The used optical sensors provide the potential for the fast inline assessment of the honed texture. Different evaluation measurements show that the sensors are capable for use in cooling lubricant. In a next step, further evaluation measurements will be performed with cooling lubricant emulsion. One sensor will be chosen for integration into a honing machine, which can later be inserted into a production line for the automated quality inspection and closed-loop control of the honing process.

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