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# Monitoring of a single-mode cw-laser process for texturing of aluminum cylinder bore surfaces of combustion engines for coating preparation

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## Abstract

Aluminum cylinder crankcases are more lightweight and thermally conductive than their conventional predecessors made of cast iron, but the cylinder bore surfaces must be coated with a wear-resistant material to achieve better or similar tribological performance. Thermally sprayed coatings can only achieve required adhesive strength when applying a roughening process. This enhances the mechanical form fit between the coating and the cylinder bore. The described laser system technology for texturing cylindrical inner surfaces enables helical trench-like structures to be inserted into the cylinder bore surfaces to improve the adhesion mechanism of the coating to the substrate. The laser-based process has additional manufacturing benefits compared to conventional roughening regarding tool wear and soiling of the produced parts. The presented work describes the development of the technology from fundamental process development via application in serial production to inline process monitoring.

Keywords: surface structuring; coating preparation; laser texturing; engine manufacturing; process monitoring

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## 1. Introduction

### *1.1. Laser structuring in engine manufacturing*

Novel aluminum cylinder crankcases for passenger cars are lighter than grey cast iron models and save fuel due to reduced weight and increased thermal conduction. However, in aluminum crankcases the cylinder inner surfaces must be applied with additional steel or grey cast iron bushings, as they have a higher strength and better tribological properties enhancing resistivity against mechanical wear. The smaller the wall thickness of the bushing used, the better the thermal conductivity and the protection of the engine against overheating. In addition, the cylinders can be arranged more closely, allowing a more compact crankcase design for lighter engines with resulting fuel savings and efficiency benefits. (Mahle GmbH 2010; Braess and Seiffert 2013; Weisheit 2016)

In addition to press-fitting or casting the liners, it is also possible to apply a layer of steel to the inner surface of the cylinder using a thermal spray process. This steel layer can be manufactured significantly thinner than the liners and therefore has advantages in terms of thermal conductivity and heat dissipation. (Mahle GmbH 2010; Braess and Seiffert 2013; Weisheit 2016; Flores et al. 2019)

In order to ensure the steel layer adhering firmly to the aluminum, the inner surface of the cylinders is roughened before coating. This process was previously carried out using conventional machining processes or corundum/ water blasting (Tucker 2013; Schmidt et al. 2017). Problem of jet blasting technologies are the undefined structure they produce where geometrical deviations happen easily depending on nozzle, abrasive fluid and aluminum cast quality. Mechanically roughened structures suffer from limits in aluminum surface enlargement for the adhesion process to the iron coating, due to the defined cutting edge and the kind of chip removal.

### *1.2. Process technology for structuring of cylinder bores*

The Laser Zentrum Hannover e.V. (LZH) developed a concept for a laser-based roughening process overcoming the weakness of blasting and mechanical roughening. Unlike cutting tools, the laser processing head is not prone to wear due to the contactless structuring process of the cylinder bore surface. A special cleaning step after roughening and pre coating is not necessary. This makes the laser process superior to conventional roughening processes, as additional set-up times and costs for tool replacement or a washing process are eliminated (Tegtmeier and Fischer 2020).

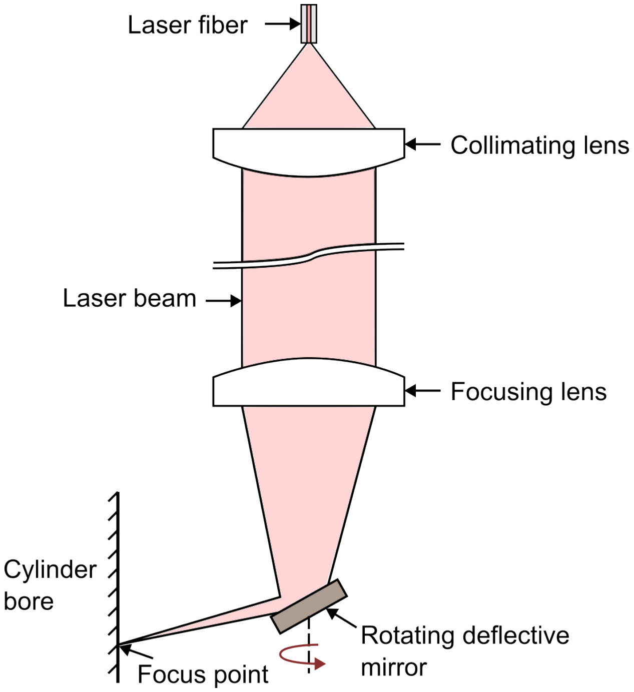

Fig. 1. Principle of the laser roughening system for cylinder bore surfaces by means of a rotating mirror.

The laser processing head for internal surfaces (IBK) has a spindle with a rotating beam deflection mirror (see Fig. 1). The collimator and the focusing lens are located above the deflective mirror. A single-mode cw-fiber laser is used as the beam source. For the roughening process, the chosen laser source is the first choice producing high quality parts with high productivity and reproducibility. An optical fiber guides the laser beam to the collimator. During processing, a focused laser beam emerges, the spindle descends into the bore and the mirror simultaneously rotates with high speed. In this way, trench-like structures are introduced into the surface. (Lammers and Kramprich 2018; Tegtmeier and Fischer 2020)

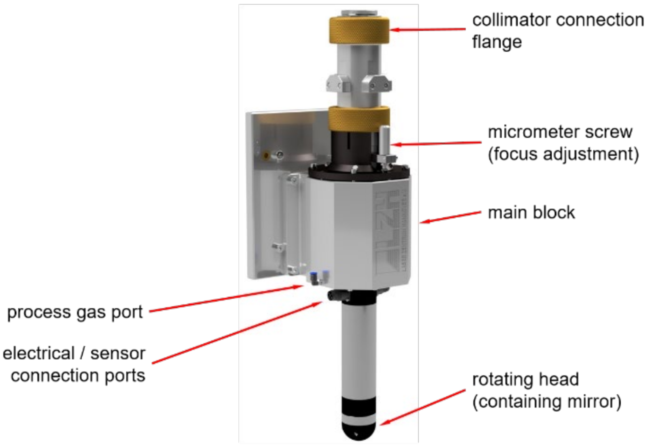

Fig. 2. Laser processing head for internal surfaces (IBK)

As shown in Fig. 2 the laser collimator is connected to the upper end of a tube which is clamped by means of a union nut. The focusing lens is attached to the lower end of the tube. A micrometer screw connected to the tube allows the position of the focusing lens in the main block to be corrected. In this way, the focus position can be adjusted for the process and it is possible to process cylinders of different diameters. The process gas nitrogen is supplied below the focusing lens. The spindle is mounted to the bottom of the main block. It contains the hollow shaft motor with the corresponding electrical connections and the mirror head with the beam deflection mirror. The mirror head is designed with a small bore coaxially to the beam path, where the laser beam and the process gas leave the laser processing head. The process gas protects the optics from contamination as well as it expels the molten aluminum of the cylinder surface. The mirror head is designed in such a way that the mirror can be changed quickly for maintenance and in case of contamination with particles from the process zone. With the IBK, rotational speeds of up to 9,000 rpm can be achieved. The system is implemented in serial production at three different car manufacturing plants.

### *1.3. Roughening of surfaces by laser structuring*

Roughening belongs to the thermal ablation laser processes. A distinction is made between sublimation ablation and melt ablation. With sublimation ablation, the amount of energy supplied leads to local evaporation. Due to the vapor pressure, molten material can be expelled at high speeds. (Brunner and Junge 1989) Structures created by sublimation ablation are characterized by high contour and structure accuracy and no melt adhesion. Sublimation removal is possible from intensities of $10^6$ W/cm² to $10^8$ W/cm². Pulsed laser systems are usually used to achieve the necessary amount of energy for these processes. (Bliedtner, Müller, and Barz 2013)

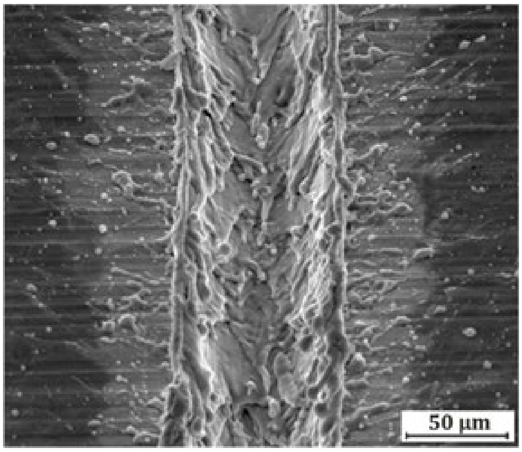

Fig. 3. Scanning electron microscopy image of a laser structured cylinder bore

During melt ablation the material is molten and expelled by a gas jet. This process allows higher ablation rates, but the contour accuracy is lower and melt build-up is present (Bliedtner, Müller, and Barz 2013). For the structuring of the inner surfaces of the cylinder, the parameters are in a manner that the power density is in the transition area between sublimation ablation and melt ablation. In this way, structures with good adhesion properties at high removal rates can be realized. As shown in Fig. 3, generated structures have a width of about 50 µm and a depth between 30 µm and 70 µm. Due to the form-fit connection with the steel layer occurring during thermal shrinking, high adhesive tensile strength values can be achieved. (Lugscheider 2002; Flores, Vits, and Bösner 2019)

## 2. Materials and methods

The developed process monitoring system is based on a pyrometer (infrared temperature sensor), which is integrated in the processing head and measures the thermal radiation generated during the process. As the pyrometer and the laser beam operate through the same beam path, polluted optics will cause deviations to the thermal radiation measured. If the measured value deviates from previously empirically determined limit values, an indication for a defect in the laser beam path is given.

The TW2001 pyrometer by ifm electronic GmbH with a wavelength range of 1.0 to 1.7 µm and a temperature range of 250 °C to 1,600 °C was chosen for process monitoring. The pyrometer has an analogue current output. A resistor converts the current into a voltage signal which is recorded. The pyrometer is installed between collimator and focusing lens in an IBK. The processing wavelength of the laser and the measuring wavelength of the pyrometer are separated from each other by a beam splitter with a long pass filter up to 1,200 nm. The experimental setup is shown in Fig. 4.

Tests with soiled and intact mirrors are carried out in different operating conditions. The soil was applied to the center of the mirror with a felt-tip pen. For each combination of parameters, three aluminum cylinder bores have been textured and the corresponding pyrometer signal was recorded. Functionality of the process monitoring system is proven and the threshold values for the shutdown conditions of the plant are determined.

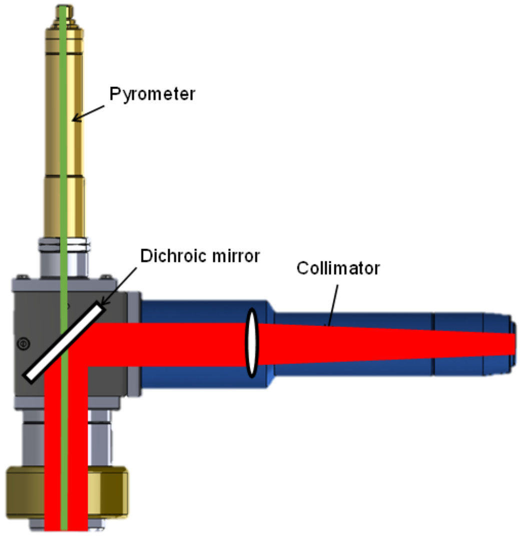

Fig. 4. Schematic of the process monitoring system

Aluminum cylinders with a bore diameter of 74 mm were used for the experiments. At the lower end of the crankcase, a suction unit removes the particles detached by the laser process. A single-mode fiber laser with a power of 1 kW, a wavelength of 1,070 nm and a fiber core diameter of 14 µm is used to produce a trench like structure. The system ensures a stable structuring process under ideal mirror properties.

## 3. Results and Discussion

The pyrometer output signals during the structuring of a cylinder bore are shown in Fig. 5. The grey curve shows the course during the start-up of the system (system temperature 20°C) and the yellow line shows the course during continuous operation (after at least 10 structured cylinder bores) of the system in combination with an intact and clean deflective mirror. In both cases the voltage signal rises sharply at the start of structuring and reaches values between 4.3 and 5.1 V during processing. Towards the end of processing, there are larger fluctuations in the signal and a slight voltage drop to 3.5 - 4.3 V. This is due to the fact that the laser beam no longer structures the cylindrical surface, but rather the upper part of the main bearing bore. The greater distance between the processing head and the structured surface leads to processing with a defocused laser beam. As a result, the spot intensity is decreased and the process behavior changes. Thus, the temperature signal decreases. After structuring is completed, the voltage signal drops steeply to 1 V.

The blue and orange curves show the voltage curve during start-up and continuous operation of the system in combination with a soiled mirror. The voltage curve is subject to greater fluctuations and the voltage signal drops below a value of 4 V during machining of the cylinder surface. After completion of the structuring process, the voltage signal does not drop as steeply as in the curves described above, but drops slowly to 1 V, so that a voltage of 2 V can still be measured 2 seconds after completion of the machining process. This can be explained by excessive heating of the rotating mirror head when the mirror surface is contaminated. The laser beam does not exit through the laser beam exit opening but couples into the contaminated mirror surface and causes severe damage to the mirror that eventually results in destruction of the mirror surface.

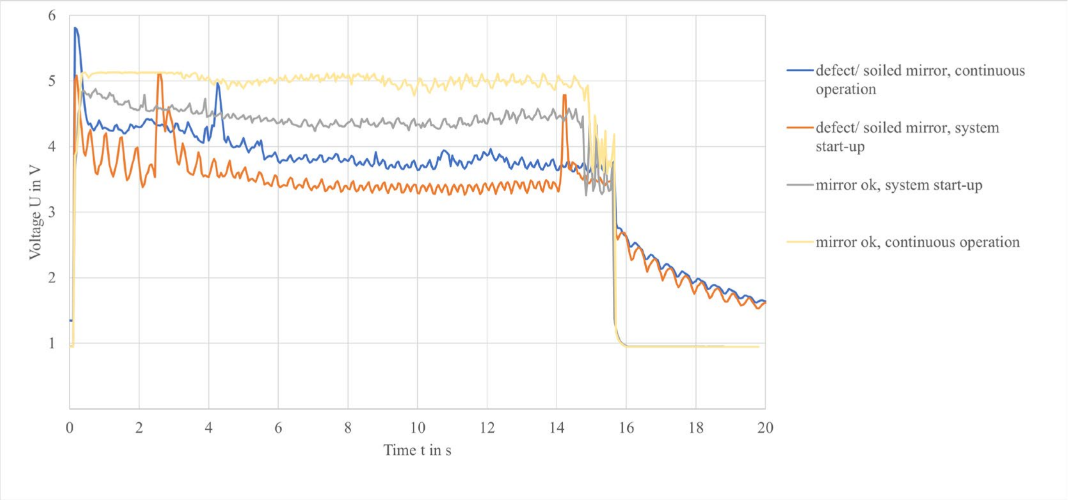

Fig. 5. Voltage signals for different operating conditions of the mirror

Shutdown criteria can be defined by two areas for monitoring the process and protecting the system technology. During machining of the inner surface of the cylinder bore, voltages between 4.3 and 5.1 V are measured, depending on the operating state (start-up of the system or continuous operation). If the mirrors are soiled or defective, the voltage drops below 4 V in the course of machining. A voltage drop to less than 4.2 V at this stage of processing can be used as a criteria for terminating the process and issuing a fault condition. In this case, the melt pool temperature is not sufficient to produce a quality surface structuring.

As a further criterion, the voltage signal after completion of the structuring process can be used. The signal drops to 1 V immediately after structuring in case the mirror is intact. As for a defective or soiled mirror, the signal drops over a period of several seconds. If there is still a signal of more than 1V, 0.1 seconds after completion of the structuring, further structuring processes must be aborted since heat accumulation in the rotating mirror head is present which indicates a defective mirror.

In addition to the detection of soiled or damaged mirrors, it is also possible to detect optomechanical deviations with the process monitoring system. A change of the focus position relative to the surface results in changes of the process behaviour. The reduced intensity of the laser beam leads to higher fractions of melt ablations and lower fractions of evaporation ablation during the roughening process. The resulting changed thermal energy leads to changes in the voltage signal. The voltage signal drops below 4 V, which is lower than the shutdown criteria. A change of the focus position can occur when optical elements such as the collimator or the focusing lens are replaced due to manufacturing tolerances affecting the focal length of these elements. Furthermore, a focus shift can occur due to temperature changes of the processing head.

In summary, it can be said that process monitoring can detect both soiled and damaged mirrors as well as deviations between the desired and the set focus position and therefore are an effective method to reduce downtimes in production systems.

## 4. Conclusion and outlook

In this paper, the observation of the mirror surface quality in the laser processing head for inner surface structuring has been investigated by means of temperature signal occupied by a pyrometer. Depending on the temperature signal, changes in the process behaviour can be detected pointing at a deviation in surface quality of the rotating deflective mirror. A significant drop in the temperature signal shows that the energy input to the cylinder bore surface is not sufficient thus being an indicator to abort a running process and change the damaged mirror. This increases the reliability of the IBK which, as a production-ready system for structuring cylindrical inner surfaces of combustion engines, is supposed to provide quality surface structuring results. Furthermore, a misalignment of the cylinder bore can be detected early by means of deviations in the temperature signal which is caused by a focus shift along the bore diameter. The integration of process monitoring technology therefore is a promising approach to reduce machine downtimes in production plants. Further approaches in the Laser Zentrum Hannover e.V. focus on the adjustment of the focus position, aiming at a highly accurate beam alignment to ensure highest process accuracy. Furthermore, different approaches to enhance positioning of the processing head in the cylinder bore are investigated to further increase reproducibility and minimize scrap parts.

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