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Hybrid tool for high performance structuring and honing of cylinder liners

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ABSTRACT

Micro-structuring of cylinder liners reduces friction of combustion engines. However, the process time of known fly-cutting and even laser micro machining is too long. This paper presents a hybrid tool for high performance structuring and finish-honing. The structuring tool is driven by a piezo actuator. A positioning system and control algorithms were developed to overcome the limited travelling range of the piezo and to deal with workpiece errors. Furthermore, the entire process chain and machined surfaces of the liners are examined. It is shown that the structuring of common grooves is up to 6 times faster compared to laser machining.

1. Introduction

Increasing power transmission in combustion engines in interaction with smaller design space leads to a significant heightening in power density. It is getting more difficult to ensure failure-free operation of tribological systems due to higher mechanical and thermal loads on components like cylinder liners [1]. Several ways have been investigated to deal with the problem such as coatings [2] and structured surfaces [3]. The structuring of the cylinder surface results in a reduction in fuel consumption between 4.5% [3] and 6% [4,5]. Moreover, it was shown that structuring lowered the oil consumption by 70–85% and the wear by 50–60% at a kilometre reading of 160 000 km [4,5].

These structures are often machined by laser which provides good flexibility and quality. However, the ablation rate is between 0.005 mm^3/s and 0.16 mm^3/s and, thus, low regarding the desired structures. Therefore, first tests with a multi scattered laser using an optical diffraction element were performed. The drawback is that diffraction elements are associated with further costs and the flexibility is drastically diminished [6]. Additionally, the optimal design of micro features must be well-defined in advance. Another approach is the machining of structures with a defined cutting edge. Denkena et al. examined the influence of different process parameters on the surface quality and formation of burr with a fly cutter. He substantiated that good quality structures can be achieved by choosing cutting velocities above 200 m/min. Furthermore, a specially designed tool allows dealing with alignment and workpiece errors. A support bearing guides the cutting edge while the tool is leant against the workpiece via a slender tool shaft [7,8]. However, the structuring rate is only 100 grooves/s. Tools with multiple cutting edges require high accuracy and are facing similar problems as the multi scattered laser. Piezo actuators appear to be promising in terms of productivity and flexibility [9,10]. These are often used in Fast Tool Servos and can achieve approximately 1000 Hz in closed loop control and significantly higher frequencies in open loop control, which means high structuring rates respectively. Nevertheless, the challenge is handling the confined travelling range of piezo actuators. The possibilities and limitations of a high-performance structuring tool are discussed in this paper.

2. Proposed process chain for structured liners

High accuracy and reproducibility of micro-scale features necessitate the design of the whole process chain for cylinder liners [11]. The examined process chain consists of two boring, two honing steps and the high-performance structuring. All processes are executed on a machining centre Heller H5000 at the IFW. The workpieces must not be re-clamped and remain in the same fixture. Therefore, a good alignment of the workpiece and tool axis is achieved. The boring processes as well as the pre-honing are done by conventional tools and must ensure a minimum roundness error. A hybrid tool is designed that executes the finish-honing and the micro-structuring (Fig. 1). The structuring is carried out prior to or in between the finish honing. The aim is to remove burr of the micro-structures but to avoid erasing the complete structure geometry itself. The combination of these steps in one tool accomplishes a fast processing.

Spheroidal graphite iron (GJS400) was chosen as workpiece material for most experiments. Each workpiece is axially clamped on a cylindrical flange. The lowest wall thickness is 9.2 mm after

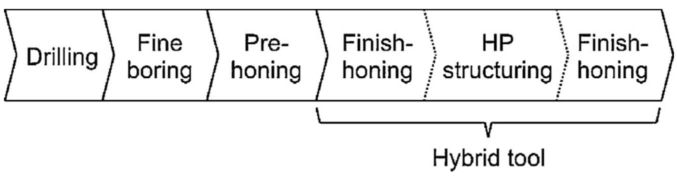

Fig. 1. Process chain for machining micro-structured cylinder liners.

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Table 1
Tool data.

Process	Tool data	Target diameter [mm]
Drilling	2 × CCMT120408	82.20
Fine boring	1 × CCMT060204	82.45
Pre-honing	8 × 80 × 4 × 5 D107 (diamond)	82.49
Finish-honing	6 × 80 × 3 × 5 D015 (diamond)	82.50

machining to minimize errors due to deformation. Information on the different tools is listed in Table 1.

3. Tool design and characterization

The hybrid tool is designed to machine engine blocks. The blind hole character of engines requires the placement of the honing section as the tool head. The cutting edge of the structuring unit is positioned as close to the head as possible. The structuring cannot be integrated between the honing stones since the choice to use a piezo actuator as a fast tool servo implicates a larger space requirement than that of a fly cutter. However, the top dead centre of the cylinders can be structured as planned. The structuring unit has a travelling range from 35 μm under quasi-static operation to 22 μm at 2500 Hz. At even higher frequencies the amplitude becomes too small for structuring. The structuring head is positioned by an additional axis with a travelling range of 2 mm to compensate the limited range. This positioning head is equipped with a capacitive displacement sensor for referencing against the inner diameter of the workpiece. An eddy current sensor would be more robust to particles and fluid in the gap but measuring against cast iron causes problems. The signal processing and motor control of the positioning system are inside the tool except for the power supply for the piezo actuator. The signals are communicated via the CANopen protocol and transmitted alongside the power supply by a slip ring. The tool with dissembled honing section is shown in Fig. 2. In this configuration, two covers protect the interface for the honing head. The honing stones are fed by the cutting fluid and reset by springs. In addition to the springs a retention mechanism fixes the honing bars at high rotational speeds for structuring.

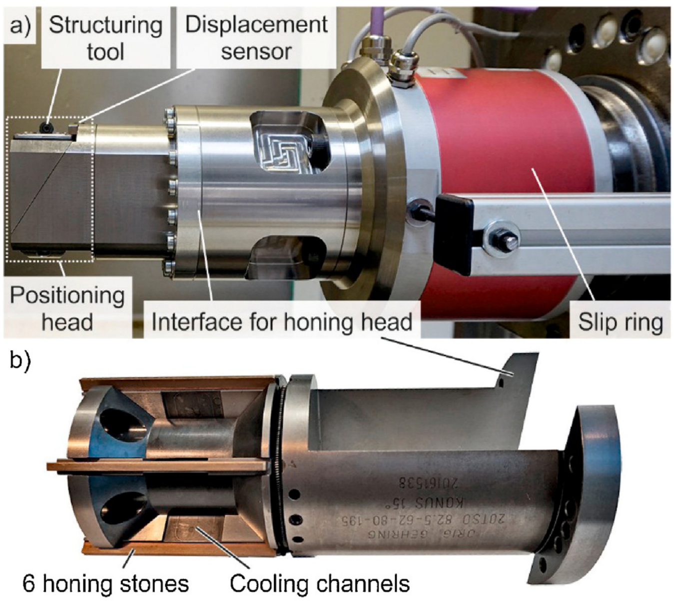

Fig. 2. Hybrid tool consisting of (a) positioning system, structuring head and (b) honing tool.

The positioning system is relatively large because of high accuracy and stiffness requirements. Otherwise, eigenfrequencies would limit the frequency range for structuring. An eccentric feed system was selected for this purpose (Fig. 3). The drive shaft of the system is guided by tapered roller bearings. It is rotated by a harmonic drive gear and a Maxon DC-motor with an integrated

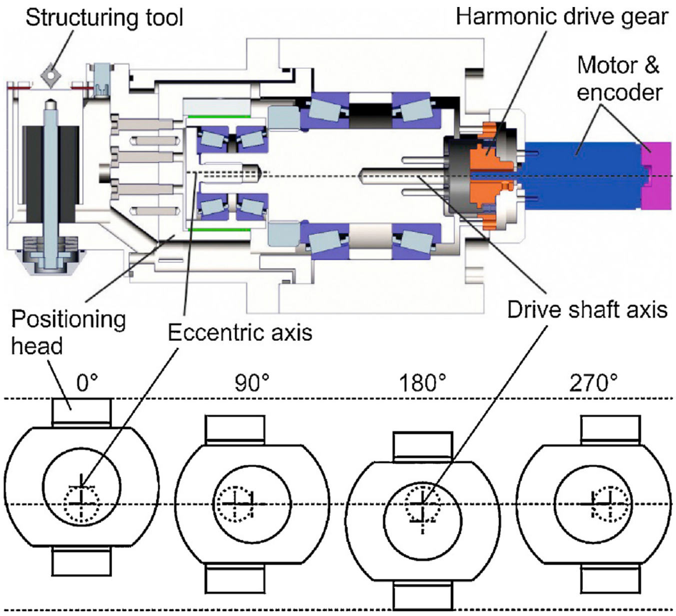

Fig. 3. Working principle of the eccentric positioning system.

encoder. The shaft is designed with an eccentric axis. On this eccentric axis, a ring with two guiding surfaces is located. The tool head for structuring is guided by high precision linear roller guideways. It is connected to the drive system by a component like a U-shape with two slide bearings. These are pre-tensioned against the planes of the ring in order to guarantee backlash-free positioning.

In order to prove that the stiffness of the axis is sufficient, eigenfrequencies of the system were investigated by an experimental modal analysis. Furthermore, the frequency response of the structuring unit to a sine sweep is measured (Fig. 4). The frequency response shows an eigenfrequency at 2200 Hz. At this frequency, the structuring amplitude is reduced because the tool resonates oppositely. The corresponding mode shape is a rotation of the positioning head around the z-axis that is caused by a disadvantageous stiffness of the roller guideways. This eigenfrequency did not occur in a previous but similar prototype with the same guide. That means that the drive system is capable of positioning the fast tool servo in principle, but is very sensitive to pre-load adjustment. In consideration of the sampling frequency of the control system frequencies of 1250 Hz and 2500 Hz are selected for structuring. The control system runs at 20 kHz which results in 8 and 16 set points over one period (see Fig. 8). The piezo is running in open-loop control.

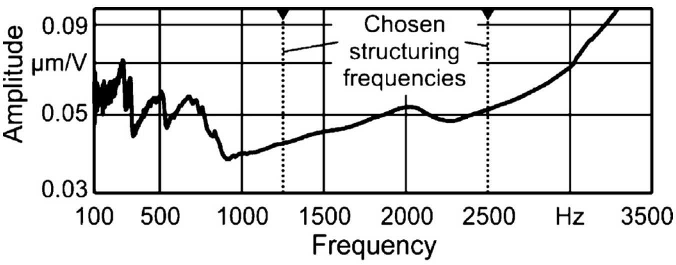

Fig. 4. Frequency response of the structuring unit to a linear sine sweep (f = 100–3600 Hz, u = 0–100 V, 5 repetitions).

A cross-sectional view of the fast tool servo is shown in Fig. 3. A high voltage piezo ring actuator drives the tool holder. The piezo is pre-loaded by disc-springs to achieve push-pull operation. The tool holder is guided via four flexure hinges.

Despite machining cylinder liners in one fixture, small errors such as axis alignment errors or roundness deviations of the workpiece occur (below 10 μm). Bandwidth of positioning system is too low to counteract these errors at desired speed. Consequently, the capacitive displacement sensor is not only used as a

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