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Piezo-actuated hybrid tool for the micro structuring of cylinder liners in an energy-efficient process chain

Berend Denkena, Benjamin Bergmann, Miriam Handrup*

Leibniz Universität Hannover, Institute of Production Engineering and Machine Tools (IFW), An der Universität 2, 30823 Garbsen, Germany

* Corresponding author. Tel.: +49-511-762-5262; fax: +49-511-762-5115. *E-mail address:* handrup@ifw.uni-hannover.de

Abstract

Automotive traffic is one of the largest drivers of greenhouse gas emissions in Europe. In order to achieve energy savings both, during the process and during the use phase of passenger cars, the powertrain components and their process chains will be optimized as part of the "Powertrain 2025" project. For this purpose, the implementation of an innovative process chain for the production of non-circular, microstructured and honed cylinder liners is being researched. Therefore, the paper introduces a new piezo-actuated hybrid tool, which was developed for the combination of non-circular turning and microstructuring of the cylinder liners in one tool. An integrated optical distance sensor measures after the process the workpiece geometry. This is used for quality control and as an input value for a process chain control that optimizes the process parameters and thus reduces the reject rate. After a short introduction of the new, energy-efficient process chain, the paper focuses on the concept and dimensioning of the new hybrid tool.

Keywords: Micro structuring; Piezoelectric actuator; Process chain control; Tool

1. Introduction

Automobility is an important part of today's society. Despite climate goals, it is evident that the number of passenger cars is constantly increasing [1]. In 2016, greenhouse gas emissions from European cars accounted for 11% of total EU greenhouse gas emissions [2]. In view of climate change, it is therefore of great importance to reduce emissions from the production and use of passenger cars. Fuel consumption and emissions of passenger cars depend on the inner friction within the powertrain. Therefore, various approaches have been made to reduce fuel and oil consumption, such as improving the friction between piston and cylinder liner by means such as honing, coatings and microstructured surfaces [3–6]. It was shown, that the application of micro dimples to the inner surface of cylinder liners can reduce fuel consumption by 4.5% [7,8]. In addition, the oil consumption was reduced by 70 - 80% and the engine wear was lowered by 50% [9]. Micro dimples with a constant depth of cut can be inserted by machining with a fly cutting tool [10]. Dahlmann and Denkena developed an active tool that inserts variable micro dimples into a cylindrical form by machining [11]. Through the active displacement of a tool cutting edge by a piezo actuator, structuring frequencies of 2.5 kHz can be achieved, which increases productivity by a factor of six compared to laser structuring [11]. Besides microstructuring, an additional approach to reduce the friction in the piston-cylinder system is to compensate the thermal or mechanical induced distortions that occurs during the engine operation [12]. By machining a negative distortion shape into the cylinder liner (see Fig. 1), the occurring distortions during engine run are compensated, resulting in an ideal round shape of the cylinder liner and thus reducing friction. Free form honing with actively controlled honing stones is currently used to produce the negative distortion shape [13,14].

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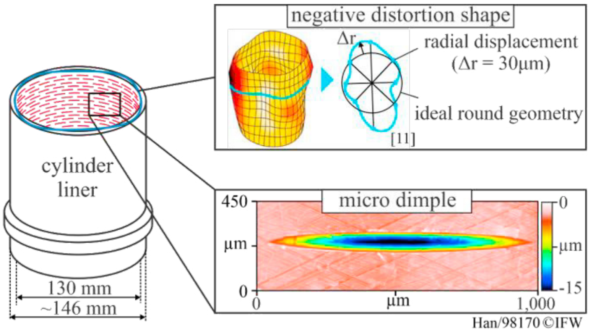

Fig. 1. Approaches to reduce the friction in the piston-cylinder system.

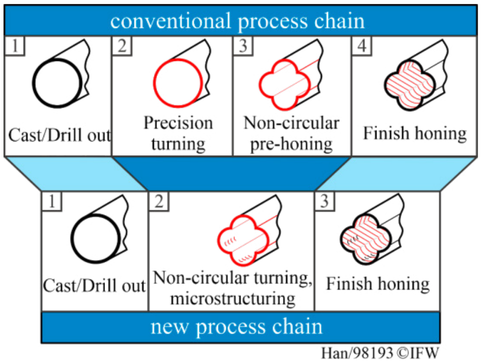

Fig. 2. Conventional and new process chain.

Besides modifications of components, the optimization of the process chains offers energy savings. A control of the process chain as a whole can therefore be useful to minimize defects and thus increase the energy efficiency of the process chain. A suitable application is the machining of bearing cages, for which Denkena et al. developed a process chain control [15]. Since the quality of the bearing cages is highly dependent on the interactions between machining and heat treatment, both processes are continuously monitored and controlled together to take advantage of interactions between them [16]. In this case, the process chain control controls the geometry of the machined components across all processes by adapting the process parameters for turning, microstructuring and honing.

Since the friction within the powertrain has a great impact on the fuel consumption and emissions of passenger cars, the research project "Powertrain 2025" aims to develop an energy efficient process chain for the production of optimized power train components. This paper focuses on the development of an energy efficient process chain for cylinder liners that are microstructured and have a negative distortion shape (see Fig. 1).

Therefore, first a new energy efficient process chain is introduced. By the combination of turning and microstructuring in this process chain, a new tool is needed that makes this process combination possible. Therefore, the second part of the paper focuses on the concept design and dimensioning of the new hybrid tool.

2. Energy efficient process chain

A cylinder liner of EN-GJL-250 with an inner diameter of 130 mm and a length of 240 mm is selected as the reference component for the process chain. In the current process chain the cylinder liners are casted, drilled out, precision turned, then non-circular honed and finish honed (see Fig. 2). Overall, the two honing processes are associated with a very high honing oil consumption. This has a negative effect on the energy efficiency of the production process due to the additional provision and preparation by auxiliary units.

Therefore, a non-circular turning process substitutes the non-circular pre-honing process. To substitute the rough honing process, the turning process must produce the surface quality required for finish honing. This roughness is defined with R_z = 12–20 µm. The material removal of the finish honing process will be around Δr = 30-40 µm. Therefore, a higher depth of cut for the microstructuring is required in order to take into account the material removal during honing. Simulations are used to determine the optimal micro dimple size (length x width x depth) of 800 µm x 90 µm x 20 µm. With regard to the following material removal, a micro dimple depth up to 60 µm has to be machined. In this case, only the part of the cylinder liner that comes into contact with the piston ring during operation is structured. Thus, the part of the cylinder liner that is structured is only 160 mm in axial direction.

Furthermore, a combination of the non-circular turning process and the microstructuring process in one tool additionally reduces the non-productive times. In addition, positioning errors can be reduced, which would result from reclamping workpieces between processes if two different machines were used.

3. Tool concept

The hybrid tool combines the non-circular turning and the microstructuring. Furthermore, it performs an inline-measurement and a process monitoring with additional sensors. As Dahlmann and Denkena showed, microstructuring by piezo actuators is more productive than the laser structuring. For this reason, the microstructures will be inserted as well by a highly dynamic infeed of a piezo actuator (see Fig. 3). So far, the micro dimples were only inserted into a round cylinder liner. Now they have to be machined into a non-circular cylinder liner, which results in new challenges.

The non-circularity of the cylinder liner will be produced with a dynamic infeed of a piezo actuator. Due to the necessity of using two different inserts for the processes non-circular turning and microstructuring, two different piezo units have to be integrated into the tool: a unit for turning and a unit for microstructuring.

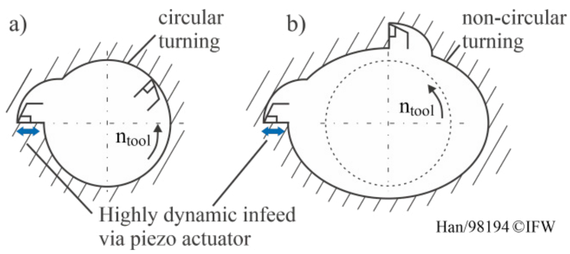

Fig. 3. Microstructuring into a) circular turned cylinder liner, b) non-circular turned cylinder liner.

Based on the geometric boundary conditions of the cylinder liner and the microstructures aligned in circumferential direction, different concepts for the active tool were developed. The space available and the layout of the microstructures allow both radial and axial arrangement of the piezo actuators. Axially arranged piezo actuators allow a greater overall length of the actuators because the length of the actuator is not limited to the diameter of the cylinder liner. Thus, a greater stroke can be realized. However, the necessary deflection for the radial deflection of the tool cutting edge can have a negative influence on the dynamics and increase the complexity of the tool.

Turning a fourth-order non-circularity ("four-leaf clover structure") requires four strokes per turn. With regard to the process parameters, this results in an infeed frequency of the piezo actuator of f = 163 Hz for a cutting speed of 1,000 m/min. To achieve a necessary cutting speed of v_c = 1,500 m/min, frequencies of up to 250 Hz are sufficient for non-circular turning. The dynamics in the structuring process with the desired structuring frequency of f = 2,000 Hz is significantly higher compared to the infeed frequency of the piezo actuator during non-circular turning (at constant cutting speed). As particularly high dynamics are required for microstructuing, an axially arranged piezo actuator is not advisable. Therefore, only concepts with radially arranged piezo actuators are considered.

The requirements on the geometry result in a necessary piezo stroke of h_A = 30-40 µm for the non-circular turning unit. In addition, there is a stroke of 20 µm for the microstructures. For the structuring unit, the piezo stroke of h_A = 60 µm is therefore significantly higher, since the following honing process with up to 40 µm material removal on the radius removes a large part of the structure depth.

To avoid the structuring edge having to additionally follow the unroundness of the cylinder liner, the structuring unit is equipped with a support bearing which follows the generated unroundness of the cylinder wall (see Fig. 4). The complete structuring unit is therefore moved against the inner cylinder wall by a pneumatic auxiliary drive and pretensioned in that position. Then the support bearing can run on the inner wall of the cylinder. This ensures a defined distance between the tool cutting edge and the cylinder liner's inner wall. Thus, the limited stroke of the piezo actuator can completely be used for the depth of the micro dimples. To enable a radial displacement of the whole unit, the structuring unit is mounted on radially aligned guide rails. In contrast to this, the turning unit is fixed to the tool and can only be positioned by movement of the machine axis.

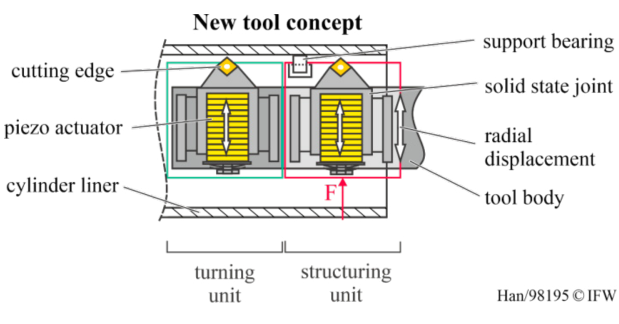

Fig. 4. Actuator concept of the hybrid tool.

Both units have piezo-actuated cutting inserts with a limited stroke of around 50 µm. For the structuring unit as well as for the non-circular turning unit a HP1-1600-60-VS piezo actuator from piezosystem jena was selected. This piezo actuator allows a stroke of ~50 µm at a frequency of f = 2,000 Hz. The units have integrated strain gauges in a full bridge configuration and Pt100 resistance thermometers to monitor the stroke of the piezo actuator and the temperature. For the less dynamic turning process a switching amplifier with 1,000 V and 3 A is used to actuate the piezo. For the highly dynamic microstructuring process a switching amplifier with 1,000 V and 7 A is used.

The cutting inserts are guided by solid state joints in a parallelogram arrangement. This will protect the piezo actuators from lateral forces. For that, the geometry of the solid state joints has to be adapted to the expected forces in the process.

4. Dimensioning of the solid state joints

Since piezo actuators are pure transmission elements that cannot perform any guiding functions, solid state joints are needed. They provide a stabilization of the piezo actuators and protect them from lateral loads. Solid state joints are arranged parallel to the direction of force of the piezo actuator. They need a high degree of flexibility in this direction to prevent the actuator stroke from being reduced too much. In all other directions, increased stiffness is required to protect the actuator from lateral loads.

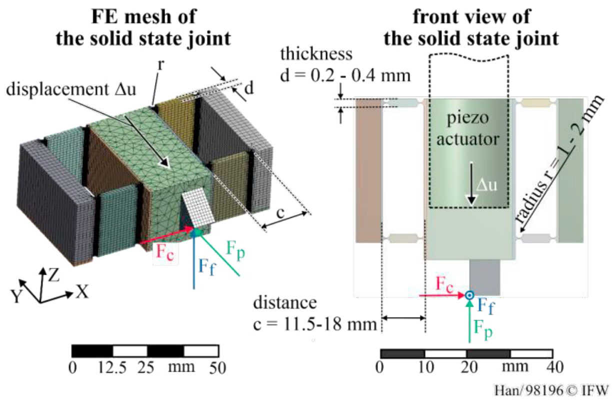

Fig. 5. Solid state joint.

The basic geometry of the solid state joint is shown in Fig. 5. The radius r in the joints, the thickness d between the radii and the distance c between the basic body and the connection to the solid state joint can be varied. Due to a limited construction space, the distance c is limited to 18 mm. The displacement Δu equals the stroke of the piezo actuator during the process. The FE simulation software ANSYS is used to optimize the geometry and to check whether the solid state joint can bear the predicted forces. The model assumptions and boundary conditions for the processes microstructuring and non-circular turning are shown in table 1.

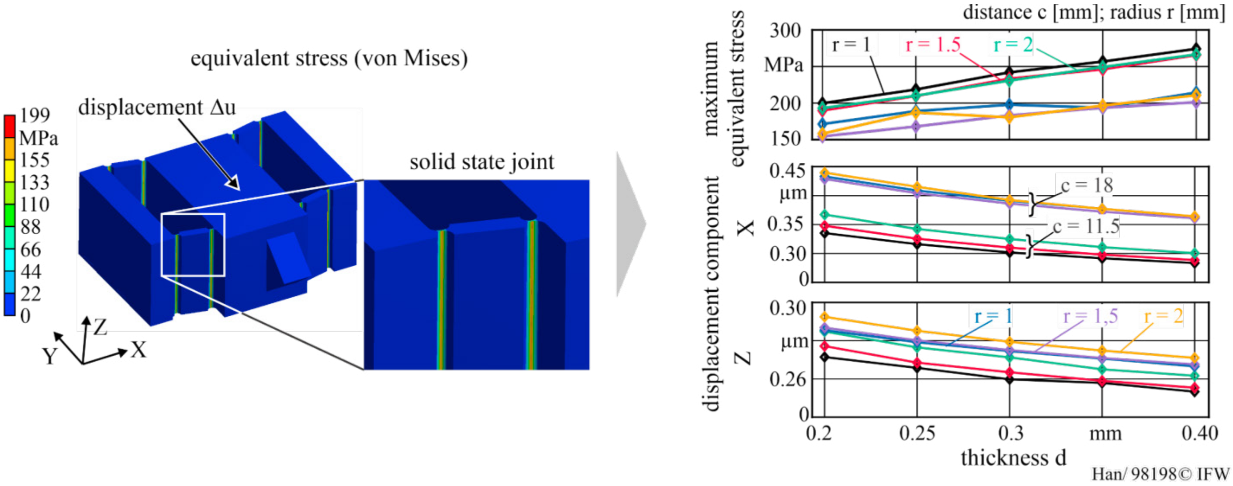

Fig. 6. Equivalent stresses due to the displacement Δu of the piezo actuator.

Table 1. Model assumptions for FE simulation.

Material properties	
Material of solid state joint	42CrMo4
Young's modulus E	210 GPa
Yield strength R_e	≥ 500 MPa
Tensile strength R_m	1,100-1,300 MPa
Microstructuring	
Stroke Δu	50 µm
Cutting force	10 N
Passive force	10 N
Feed force	10 N
Non-circular turning	
Stroke Δu	45 µm
Cutting force	250 N
Passive force	100 N
Feed force	100 N

Thereby, the process forces for microstructuring were estimated on the basis of investigations by Kästner [17]. For various materials and similar micro dimple sizes the maximum process force was 10 N. The process forces for turning EN-GJL-250 were only roughly estimated with the specific process forces for a depth of cut of 0.5 mm, a maximum cutting speed of 1,500 m/min and a maximum feed of 0.25 mm.

The simulation results for the structuring unit are shown in Fig. 6. The maximum equivalent stress in the joint results from the displacement Δu. In this case, the yield strength R_e is not exceeded for any of the modifications and thus only elastic deformation of the material is achieved. Therefore, all modifications are suitable. However, lower stresses are preferable in order to increase the tool life of the joints. With larger distance c, the stresses decrease, due to less deformation in the joint. Thus, a higher flexibility of the solid state joint is achieved, which results in a higher displacement of the joint in X- and Z-direction (see Fig. 6). The influence of the radii is minor.

In addition to low stresses, a small displacement due to the process forces is required. Due to the generally low process forces during microstructuring with 10 N, the displacement

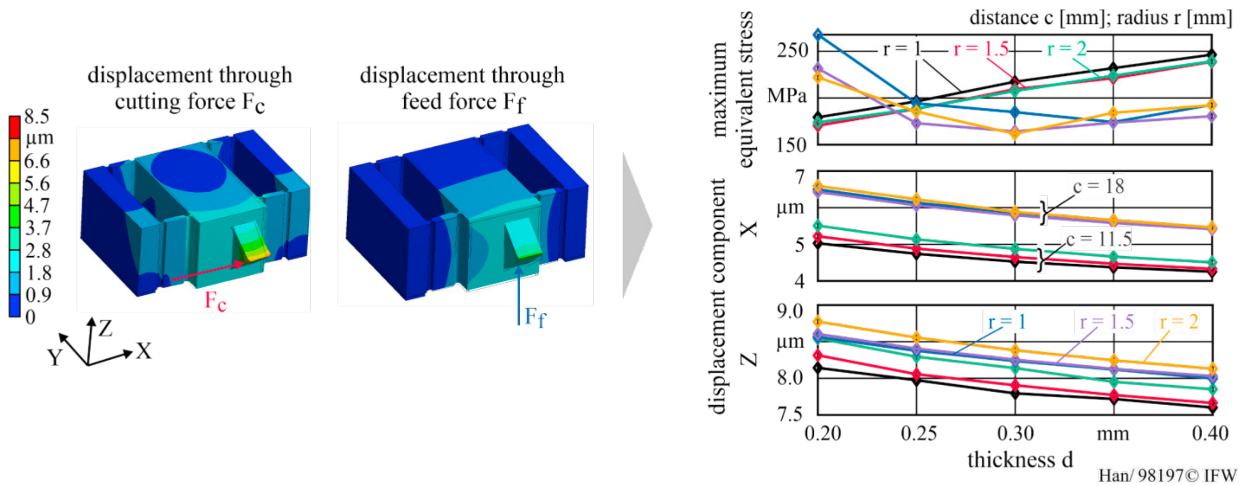

Fig. 7. Displacement of the cutting edge due to process forces.

caused by process forces is less than 0.4 µm and can therefore be neglected. In contrast to that, the process forces of the turning process lead to a distortion of the cutting edge of 8.5 µm (see Fig. 7). The displacement of the solid state joint in X- and Z-direction is much higher due to the process forces of the turning process than due to the displacement Δu of the piezo actuator. However, the yield strength R_e is not exceeded and thus all modifications are suitable. Nevertheless, lateral forces must be taken into account when connecting the piezo to the solid state joint.

5. Hybrid tool and connection to machine

The hybrid tool is shown in Fig. 8. The tool has a standard VDI-40 tool holder, so it can be mounted in a regular turning machine. The structuring unit is connected to the holder via an intermediate piece. A pneumatic actuator moves the structuring unit radially. Both, the turning unit and the structuring unit have a piezo actuator that infeeds the cutting insert and a solid state joint. Contrary to the arrangement of the solid state joints in Fig. 4, these are now positioned in the tool rotated by 90° around the axis of the stroke direction of the piezo to achieve a minimum length of the tool. The structuring unit additionally has a support bearing which ensures a constant distance of the structuring unit to the inner cylinder wall. A micropositioning table ensures thereby a precise mounting of the support bearing to the tip of the cutting insert.

Beside the previously introduced actuator concept the hybrid tool has several sensors integrated. Between the turning and the structuring unit a confocal sensor is integrated. This sensor is used for the geometric quality control of the machined cylinder liner.

Due to its small measuring spot diameter of 10 µm, it is suitable to measure not only the non-circularity of the cylinder liner but also the geometry of the inserted micro dimples.

Besides for quality control, this information will also be used as an input for a process chain control. This process chain control will control the process parameters of the whole process chain including the non-circular turning, the microstructuring and the finish honing. It therefore uses the geometry information to feedback optimal process parameters for the following workpiece. Thus, for example, defects due to wear can be detected with the confocal sensor and the process parameters for turning, structuring and honing the next cylinder liner can be adjusted to produce the cylinder liner within the tolerances.

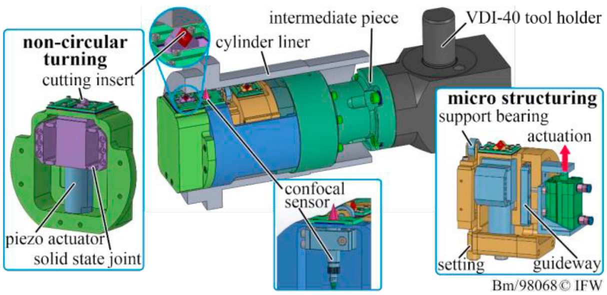

Fig. 8. Hybrid tool.

This adaption of the process parameters minimizes the defects of the process chain.

To ensure the process reliability, the information of the strain gauges and the Pt100 resistance thermometers of the piezo actuators as well as accelerations measured by acceleration sensors are used to monitor the process. Thus, process errors like tool breakage will be detectable in the process.

The sensor signals will be communicated to a Beckhoff-IPC. Via Profibus machine control signals like axis current or torque as well as the axis positions are transmitted to this IPC.

6. Conclusion and outlook

In order to reduce greenhouse gas emissions in the production and operation of passenger cars, energy-efficient process chains for optimized powertrain components are being researched in the research project "Powertrain 2025". First, a new, energy efficient process chain was presented that allows the production of non-round, microstructured cylinder liners with a lower honing oil requirement than the conventional process chain. For this process chain, an actuated tool was concepted and dimensioned that enables the combination of turning and microstructuring as well as an in-line measurement of cylinder liners.

In a next step, the tool will be commissioned and analyzed. Interactions of the processes turning and microstructuring as well as honing will be investigated. This knowledge will then be used to develop a process chain control system to minimize the reject rate in the manufacturing process chain and thus enable a more energy-efficient production of cylinder liners.

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