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Micro structuring tool steel components using Precise Electrochemical Machining (PECM)

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Abstract
Surface structuring offers great potential for modifying frictional properties for various applications, such as complex forming processes like sheet-bulk metal forming. The production of surface structures in micrometre range is challenging for manufacturing processes in particular when machining hard-to-cut materials like hardened tool steels. Precise electrochemical machining (PECM) has great potential for surface structuring and shaping of metallic materials regardless of their hardness with high surface quality and comparatively very short process times, especially when structuring large areas and batches. Micro structuring of hardened tool steel surfaces using PECM is investigated in this paper. Surfaces of high-speed tool steel and hot-work tool steel are structured using a commercial PECM machine with neutral solution of $NaNO_3$ as electrolyte. In a process sequence, PECM tools were manufactured in a first step producing selected structures by high-feed milling (HFM) and micromilling (MM). In a further process step, the negative shape of these complex structures was machined using the PECM process. Through this process chain, new types of structures can be generated which have different tribological properties than their corresponding negative shapes of HFM and MM structures. Tribological behaviour and wear properties of the structured surfaces are investigated through ring compression test (RCT).

Keywords Micro structuring · Precise Electrochemical Machining (PECM) · Ring compression test (RCT) · Tool steels

1 Introduction

Surfaces offer various functional properties for technical and industrial applications such as optical, biological and technological properties. Among the technological functional properties, the mechanical ones in terms of hardness and fatigue behaviour as well as the hydrodynamic and tribological properties are of great importance [1, 2]. For high-performance applications, such as tools in bulk forming, various approaches such as polishing or coating have been established to modify the surface properties and improve the process [3]. In general, surface structuring has been extensively investigated, especially in the last two decades, to improve functionality and performance of surfaces. Different types of microstructures have been produced and tested for numerous applications [4, 5]. The surface topography has an influence on friction and wear behaviour of the contacting surfaces. The targeted reduction of friction as well as wear is of great importance in many applications to save energy and costs by increasing the life time of the mechanical components and avoid failures. Surface structuring is a proven technique to realize tailored surfaces with application-specific properties. This includes structure elements serving as small oil reservoirs and decrease friction and wear [1]. Surface structuring is also designed to increase friction at the contact point between the mechanical parts in special applications [4, 6]. Several fabrication techniques have been investigated to structure heat-treated high carbon and high speed tool steels. Laser structuring is one of the unconventional and fast process, but it induces heat affected zones (HAZ) resulting in unfavourable subsurface conditions and adversely affect the performance of microstructures [7]. Cold ablation using ultrashort pulse lasers such as p-second laser is highly expensive and therefore not suitable for mass production [8].

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Additional approaches to surface structuring by mechanical processing are high-feed milling (HFM) [4] and micromilling (MM) [6, 9]. Due to its high flexibility in five axis machining and small cutting tool dimensions with MM even hard-to-reach areas such as cavities in dies can be machined [10]. In addition to the achievable high surface quality, the machining process has the potential to enhance the fatigue behaviour of components through the characteristic process-induced compressive stress state [11]. Based on the process advantages, various functional surface structures have been developed in the mechanical and medical fields or with regard to microelectronics [12]. When machining large areas in hard to machine materials, increased tool wear and micro burrs can be challenging and reduce productivity [13]. Furthermore, small diameter of tool and low feed rates make this process time-consuming and primarily suitable for smaller surface areas [14, 15]. The HFM is actually a cutting process for high material removal rates, needed in efficient roughing hard materials [16]. In comparison to the conventional milling process, high feeds per tooth are combined with a low axial cutting depth [17].

Electrochemical machining (ECM) has also been investigated to manufacture micro-structures on surfaces of different materials. Arrays of micro dimples and micro grooves have been produced with micro ECM on AISI 440C carbon steel and 304 stainless steel, respectively, using thin electrodes [18, 19]. However, micro-ECM is very slow process because individual structure elements are machined one at a time [18].

Precise Electrochemical Machining (PECM) is the latest ECM which employs oscillatory motion of the tool for improved cleaning of the machining area from the dissolved material and better exchange of fresh electrolyte [20]. PECM has the potential to produce structures which could not be produced by conventional micromilling because of the cutting tool size and shape limitations. PECM in combination with micromilling further increases the potential for machining innovative structures due to the process specific inversion of the tool surface to the workpiece. However, PECM has not been sufficiently investigated for its potential to structure surfaces. Fang et al. [21] investigated replicating laser-structured PECM tools with individual structural elements on Ti6Al4V workpieces using PECM process. These results show high geometrical deviations from the structural elements on PECM tools' surface. Non-uniform material dissolution across the machining area is also observed in these investigations.

This paper presents detailed investigations about structuring hot work and high speed tool steels with innovative structures using PECM process. The resulting PECM structures have reduced deviations and uniform shapes across the surface. The surfaces have also been investigated for their tribological behaviour.

2 Materials and methods

2.1 Materials

The hot work tool steel (HWS) AISI H11 and high speed tool steel (HSS) AISI M3:2 are considered as workpiece materials while 304 stainless steel (1.4301) is the PECM tool material. The blanks have a diameter of $d = 42$ mm and a thickness of $t = 5.5$ mm. Both HWS and HSS samples have high hardness of approx. 51 ± 1 HRC (Hardness, Rockwell C Scale) and 62 ± 1 HRC respectively.

2.2 Methods

Microstructures on the tool surface were machined with a micromilling machine tool (KERN Microtechnik, HSPC 2522), providing a working accuracy of 2.5 µm. The surface structures were machined with two-fluted micro ball nose end mills with a diameter of d = 1 mm. The tool substrate was a solid carbide coated with a TiAlN PVD coating.

The high-feed milling was performed using a five-axis CNC machining center (DMG MORI, HSC 75). A cutting speed of v_c =50 m/min and a lead angle of 3° were used for the parameterization of the high-feed milling operation. The slight lead angle results in lower radial and higher axial forces. Both milling processes, the MM and the HFM can be used to produce different structural variants.

2.3 PECM process

PECM is an advanced machining process based on electrochemical machining [20]. Material of the workpiece is dissolved by controlled anodic dissolution at extremely large current densities j, up to 100 A/cm^2. The tool called cathode is specially designed which defines the final shape of the workpiece. The inter electrode gap, IEG, is kept very small (10–30 µm) to realize such large current densities and achieve high geometrical precision of the shapes. The electrolyte, a neutral salt solution for most steels and alloys, is circulated in a closed circuit with high pressure to flush the machining gap and rinse the dissolved products from the machining area and is filtered out in a special filtration unit [22–24]. The tool oscillates according to the chosen frequency and the current pulses accordingly to create better machining and flushing conditions [25].

Anodic metal dissolves in contact with water according to Eqs. 1 and 2 [23, 26].

Anodic reaction:

$$Me \longrightarrow Me^{n+} + ne^{-} \quad (1)$$

Cathodic reaction:

$$nH_2O + ne^{-} \longrightarrow nH_2 + nOH^{-} \quad (2)$$

Formation of metallic hydroxides:

$$Me^{n+} + nOH^{-} \longrightarrow Me(OH) \quad (3)$$

The cathodic reaction at tool is hydrogen evolution and some reduction products of NO_3^{-} will be formed [23]. The exact reaction products depend on the type of material and the type of electrolyte used however Eq. 3 describes in general the formation of metal hydroxides as reaction products.

2.4 Experimental setups

A commercially available PECM machine (PEMTec SNC, PEMCenter 600) is used to reproduce the structures on workpiece surfaces. It can generate short voltage pulses in the range of 0.1–4 ms. The electrolyte used is neutral solution of $NaNO_3$ and the conductivity of electrolyte k is in the range of 69–75 mS/cm. The Ph value and temperature t of electrolyte is 8.2 ± 0.2 and 22–25 °C, respectively. The experimental setup is shown in Fig. 1. The electrolyte flushing is a closed chamber flushing system.

Confocal microscope (NanoFocus, µsurf C,) and scanning electron microscope (SEM) (Tescan, Mira III XMU) are used for the surface topography measurements. Surface roughness analysis of the microstructures is done by post-processing software of Nanofocus AG, µ soft analysis premium. The measured areas for MM and HFM structures are 1.3 × 1.3 mm and 4.0 × 4.0 mm respectively.

In order to evaluate the frictional properties of the machined surface structure variants, ring compression tests (RCT) were carried out according to [27], shown in Fig 1b, c. Specimens made of DP600 dual-phase steel were used, exhibiting high hardness due to the presence of martensite and ferrite. The outer and inner diameters were set at $d_o = 15$ mm and $d_i = 9$ mm, respectively, and the compression was set from $s_0 = 2$ mm to $s_1 = 1$ mm sheet thickness, which was ensured by a spacer ring. A positioning unit was used to place the sample exactly in the center of the punches, see Fig. 1c). For lubrication, Beruforge 150 was dosed (0.1 ml/315 mm^2) with a syringe. All specimens were marked in the rolling direction to compensate the influence of material anisotropies by controlling the orientation (0° and 90°), and the ring compression tests were repeated $n = 6$ times ($n = 3$ times per orientation). The deformation of the specimen causes a material flow in radial direction of the ring, changing the dimensions of the inner and outer diameters measured with a digital microscope (Keyence, VHX950F). The inner diameter was used to determine the friction factor [28] according to Male and Cockcroft [29], with a larger inner diameter corresponding

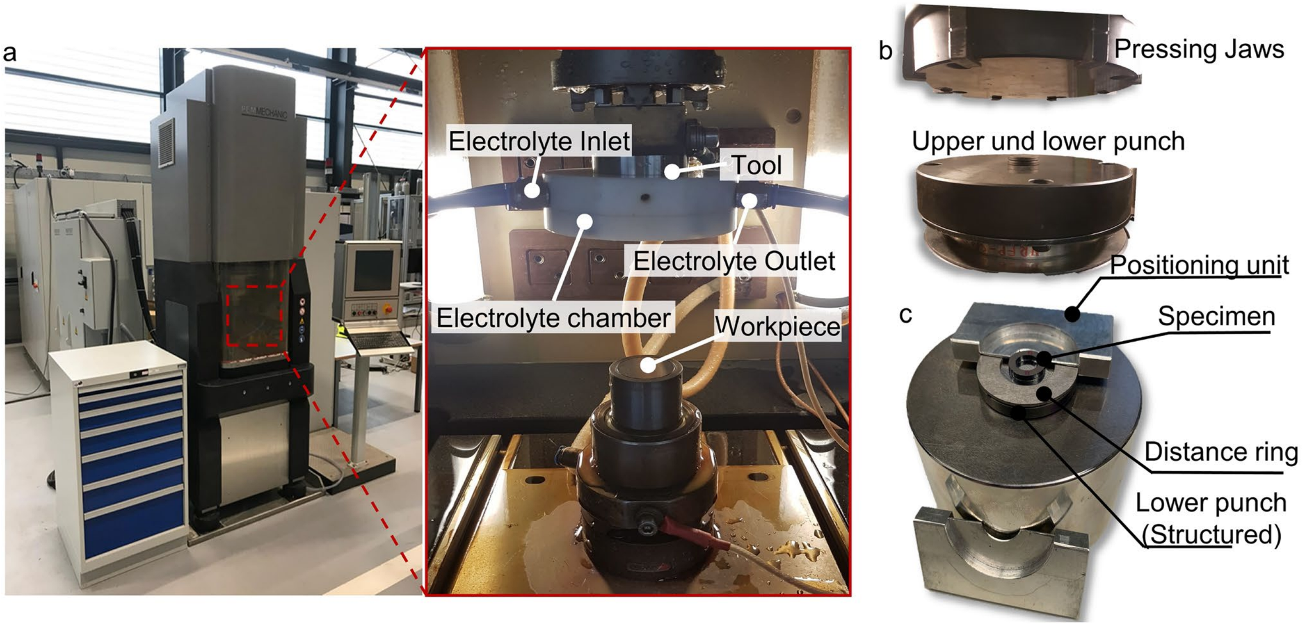


Fig. 1 Experimental setups for PECM structuring and RCT (**a**) PEMCenter 600; (**b**) pressing jaws and punches (RCT); (**c**) positioning unit and the specimen for RCT

to a lower friction value. Mean and standard deviation were determined for the measured values.

2.5 PECM structuring

Two types of surface structures were produced with PECM process, micromilling structures (MM) [6] and high-feed milling (HFM) structures [14]. These structures were produced using microstructured tools as cathode and workpiece as anode in the PECM process (Fig 1a). Process parameters for PECM structuring are listed in Table 1. The initial IEG is set to 10 µm (the lowest possible IEG of this machine). The process is carried out in two steps: step 1; structuring of the workpiece surface and step 2; polishing of the structured surface. PECM process parameters were optimized to achieve high localization of the material dissolution and consequently achieve high precision and resolution of the microstructures. This can be realized by using very low voltage, short pulse duration and smaller inter electrode gap (IEG). For better cleaning of the machining area from the dissolved material and hence improved process stability, lower frequency of the tool oscillation is used. To clean the tool surface from adhering dissolved material and avoid any process short circuits, bipolar volage U_b, is activated during the process. PECM polishing, resulting from high current densities, is required to introduce a polishing film on the workpiece surface which protects the surface from undesirable pitting and corrosion. The polishing effect suppresses oxygen evolution in the process which causes pitting and corrosion on workpiece surface [30]. The polishing film is composed of nitrate (NO_3) compound with base Iron (Fe) [31]. The thickness of the film is reported to be in the range of 100–1000 nm depending on current density and electrolyte flow rate.

3 Results

3.1 Surface topography measurements

To evaluate the surface topography of the PECM-produced structures in terms of profile heights and structure shapes compared to the initials structures on tool surface, white light microscopic measurements of the micromilled (MM) and high feed milling (HFM) structures and the corresponding PECM structures on HSS surface were performed (see Fig. 2). Since the white light microscope measurements of HWS workpieces did not exhibit any significant differences to HSS, only the HSS surface measurements are presented and analysed here. It is evident from the measurements that shapes of PECM structures were accurate and uniform across the surface. The PECM produced structures have lower height compared to the negative structures on tool surface. This deviation is approx. 10 µm for the parameters set, see Fig. 2a. The HFM structures on PECM tool and PECM structured surface (Fig. 2b) are measured to have a maximum total height of the profile (Pt) of approx. 12 µm and 7 µm, respectively. The gap between two consecutive peaks is approx. 25 µm on both tool and PECM structured surface. The deviation in height in case of HFM structures is about 5 µm. No significant deviation has been observed in lateral dimensions in MM or HFM structures. The deviation in height increases with increasing polishing voltage and time duration and decreases with decreasing polishing voltage and polishing time. The reduced height of the PECM structures need to be considered and compensated during the machining of negative structures on tool surface. The roughness measurements of the tool surface structures and PECM produced structures are presented in Table 2. The resulting PECM structures have a lower surface roughness in comparison to PECM tool surfaces.

Surfaces of PECM structures are further analysed using SEM measurements. The SEM micrographs (Fig. 3a, b) reveal that PECM-produced structures have smooth and burr-free surfaces. However, some small powder like particles on the HSS workpiece surface are visible (Fig. 3a). These particles are apparently undissolved tungsten (W) contained in HSS, as tungsten (W) does not dissolve in neutral electrolyte solution [32]. Surface of

Table 2 Measured roughness of PECM Tool and workpiece

Component type	*Rz_x*(µm)	*Rz_y*(µm)	*Sz*(µm)	*Sa*(µm)
Tool (HFM)	0.962	2.05	13.1	0.15
Workpiece (HFM)	0.834	0.895	4.5	0.148
Tool (MM)	3.66	3.73	11.6	0.651
Workpiece (MM)	1.4	1.92	2.96	0.108

Table 1 PECM Process parameters

Process steps	Voltage, U (V)	Feed rate, v_f (mm/min)	Pulse width, t_p (ms)	Freq. f (Hz)	Elect. Pressure, p (Kpa)	Elect. flow rate, Q (l/min)	Bip. Voltage, U_b (V)	Bip. Pulse, t_{bp} (ms)
Step 1	7.4	0.01	0.5	25	500	24	2.3	0.3
Step 2	15	0.4	0.3	30	650	29	2.5	0.3

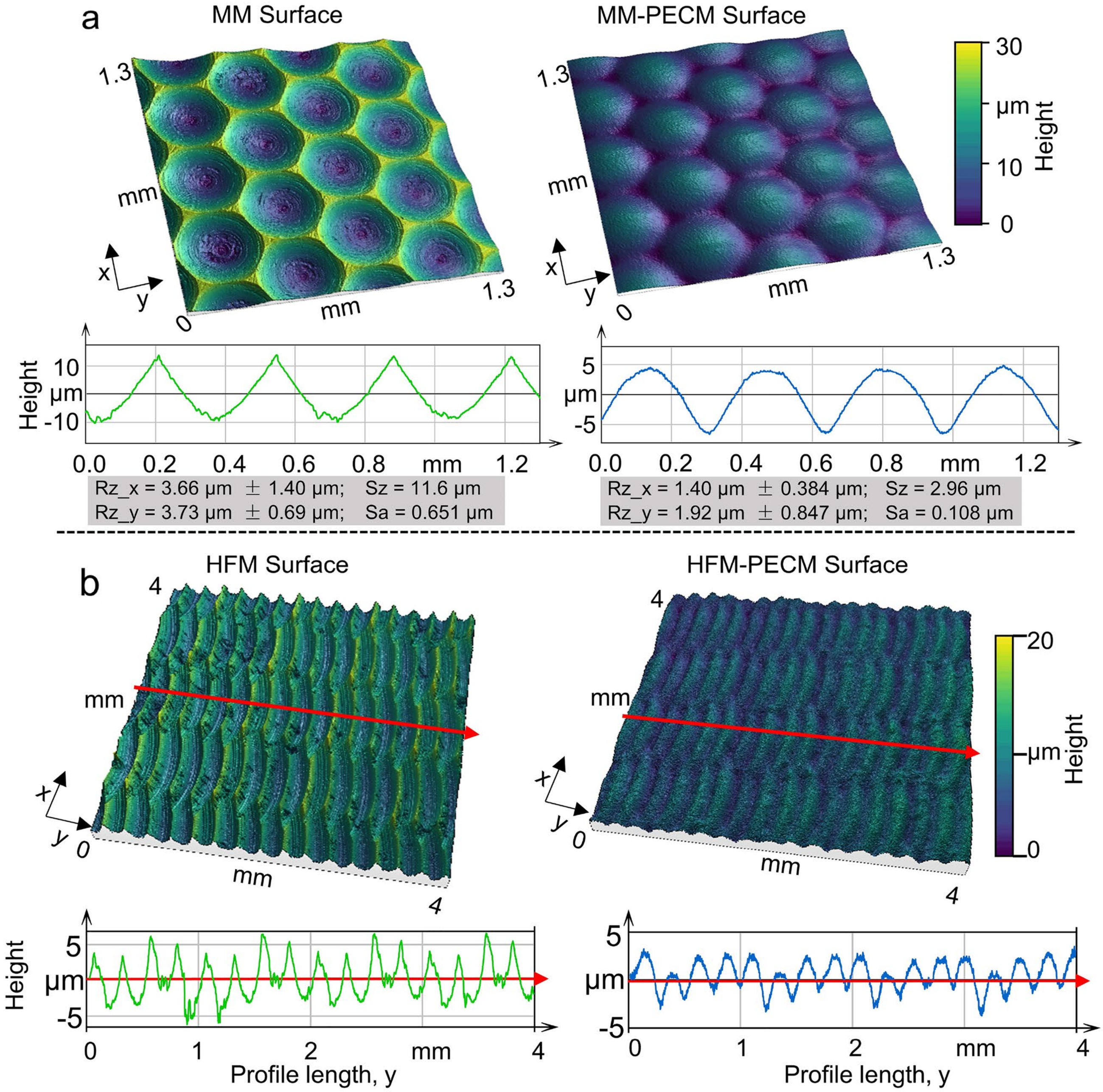


Fig. 2 Confocal microscope measurements of the (**a**) MM and the MM-PECM structure on HSS and (**b**) HFM and the HFM-PECM structure on HSS

PECM-structured HWS (Fig. 3b) was also smooth and polished with some micropores on the surface. These micropores typically appear on PEMed surfaces because of erosion of inclusions (e.g. oxides, carbides) [30]. Since HWS contains silicon, the pores can be due to the erosion of silicon oxides.

It has been observed from SEM and white light microscope measurements (Figs. 2 and 3a, b) that the shape and dimensions of PECM structures were uniform across the surface. The influence of electrolyte flushing direction is not observed as reported in the literature [21]. This is because the high pressure p, (500–600) kPa of electrolyte in the closed flushing chamber maintains similar flushing conditions across the machining area resulting in uniform material dissolution rates.

The deposition of dissolved materials (metallic oxides and hydroxides) on the working surface of tool is an important phenomenon in electrochemical machining, leading to process instability and inaccuracy. The adhesion of dissolved precipitates to the tool surface greatly influences micro

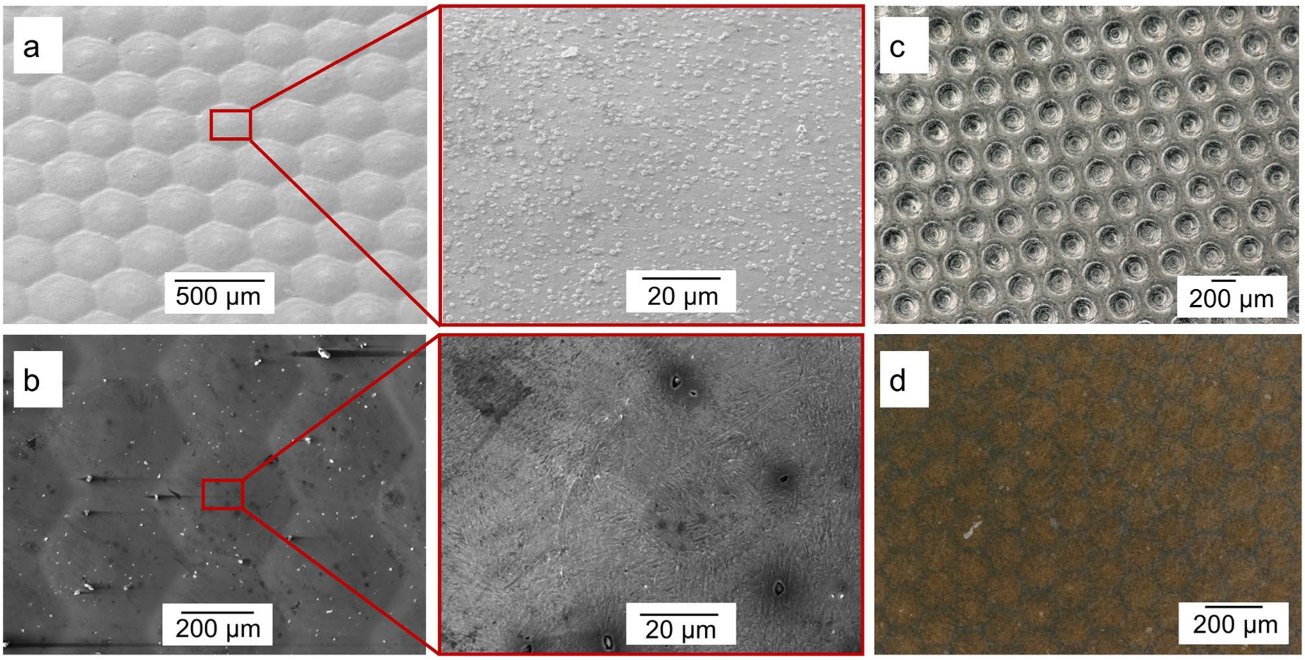
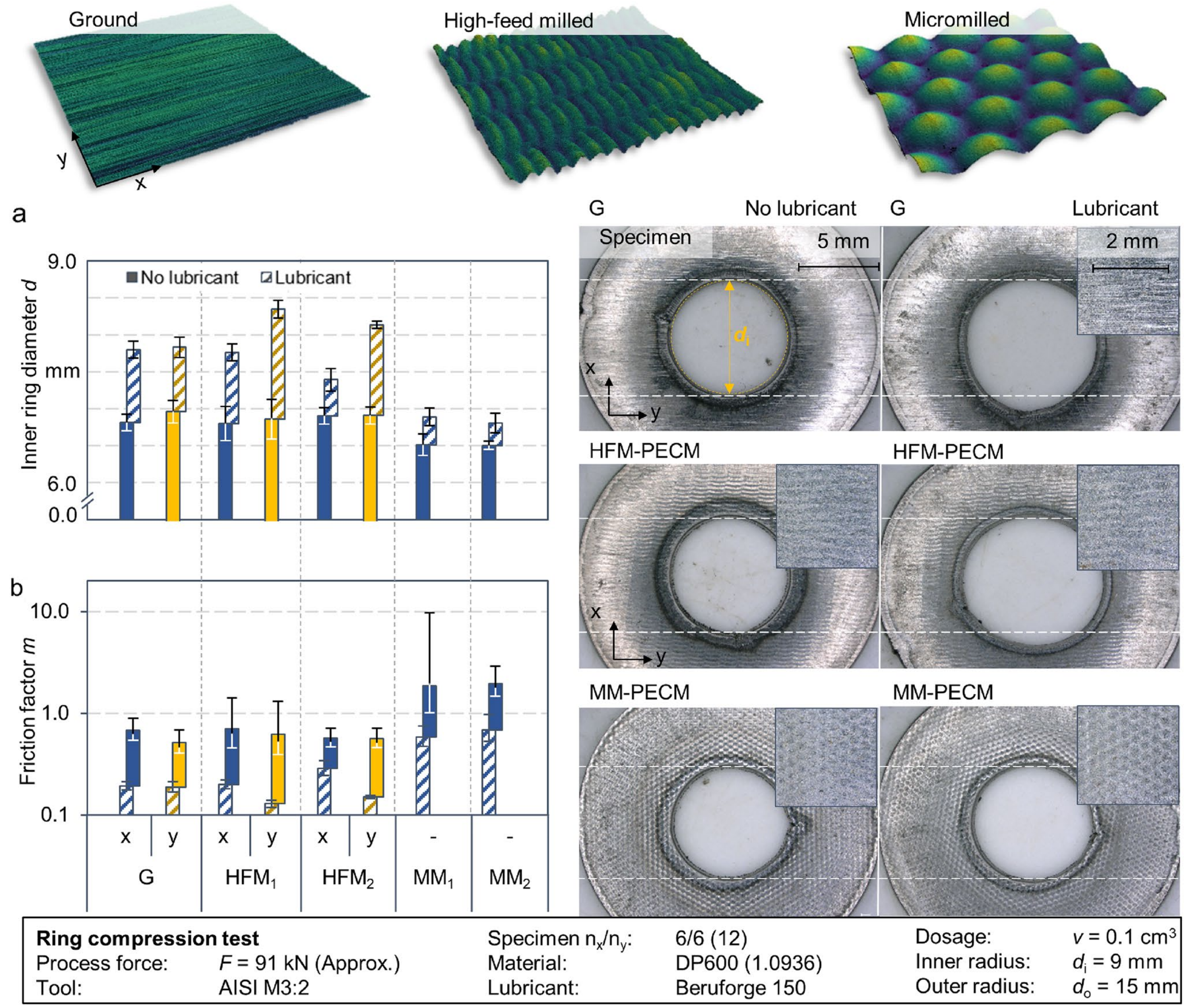


Fig. 3 Micrographs of PECM-structured surfaces (**a**) HSS surface; (**b**) HWS surface; (**c**) PECM Tool surface before use and (**d**) formation of layer on tool surface

profiles on tool surface and reduces material removal rates from the workpiece [33]. The decrease in MRR will start decreasing the IEG which results in process short circuit. Figure 3c shows the tool surface before PECM process and Fig. 3d shows the tool surface after deposition of precipitates. The thickness of deposited layer increases with time and it becomes necessary to clean the tool surface for stable and precise machining operations. The deposited layer can be cleaned from the tools using bipolar voltage (changing the polarity of current alternatively). By changing polarity of the current, tool (cathode) becomes workpiece (anode) and anode becomes cathode. Thereby, the material is dissolved from tool surface for the set pulse duration of bipolar voltage. High bipolar voltage or longer pulse duration may remove additional material from the tool surface which will deteriorate the micro shapes on tool surface. Therefore, the tool cleaning process needs to be optimized to remove only the deposited layer.

3.2 Tribological tests of the PEMed structures

In the following section, the friction properties of the machined surface structures determined in an RCT are discussed. Figure 4a shows the measured inner diameters in *x* and *y*-direction and the calculated friction factors based on the deformed specimens using forging tools modified with HFM and MM-PECM structures and ground surfaces. Since material anisotropies, e.g. due to the rolling direction of the sheets, have been shown to affect material flow during RCT [14], specimen orientation was chosen equally at 0° and 90°. By calculating mean values, the mentioned effect can be reduced, which enables the selective analysis of a structure-related influence. The tests performed without lubricant show almost equal values of the inner diameter in the *x* and *y*-direction for nearly all surfaces, indicating a low anisotropy of the friction values of the modified surfaces. Merely for the ground surfaces a slight difference from $d_x = 7.80$ to $d_y = 7.83$ mm (+2%) was measured. A comparison of the respective structures with the ground samples showed inner diameters in the same range of values for the HFM-PECM structures, whereas the MM-PECM structures achieved a strong decrease in diameter from $d = 6.82$ to 6.51 mm(88.3%), respectively. Obviously, the dimple structure of the modified dies indent into the surface of the specimens during the RCT, leading to a form closure in the micrometre range that prevents the material flow outward. This plastic imprinting of the structures shape becomes apparent by the measured indentation of the structure elements up to 13 µm on the specimens after RCT (see Fig. 4b). When lubrication (Beruforge 150) is added, the measured diameters increased significantly, whereas also the functionality of the structures gets affected in relation to the direction dependencies. The ground surfaces led to an increase in diameter in *x*/*y*-direction from $d = 6.82/6.96$ mm to $d = 7.80/7.83$ mm (114.4%/112.5%). The HFM-PECM structures showed a smaller or equal increase in diameter in *x*-direction, while the structure increased in *y*-direction by up to $d = 8.35$ mm (121.7%) exceeding the ground structure



Ring compression test					
Process force:	F = 91 kN (Approx.)	Specimen n_x/n_y:	6/6 (12)	Dosage:	v = 0.1 cm^3
Tool:	AISI M3:2	Material:	DP600 (1.0936)	Inner radius:	d_i = 9 mm
		Lubricant:	Beruforge 150	Outer radius:	d_o = 15 mm

Fig. 4 Determined (**a**) inner diameter with photographs and (**b**) calculated friction factor for DP600 steel specimens in the ring compression test using HFM and MM-based PECM structured dies

by $\delta d = 0.52$ mm (6.6%) diameter increase. The observed strong structure-dependent anisotropy can be explained by the anisotropic structural shape and the presence of valleys in the quasideterministic structures, which can serve to build up hydrostatic pressure after initial indentation. In addition, the resulting inner ring diameter in case of the MM-PECM structures show a slight increase in diameter when adding lubricant.

Referring to [34], the resulting inner ring diameter using an RCT is a sufficient indicator for deriving the frictional properties of a surface topography based on the determination of a friction factor (see Fig. 4b). Accordingly, compared to the ground surfaces with a friction factor $m = 0.189$, the values for PECM-HFM decrease to (78.8%) 0.129 when lubrication is used. Analyzing the surface friction behaviour without lubrication, the friction factor increases for each surface variant. Compared to the friction factor for the ground surface with $m = 0.675$, a significant increase in friction properties up to 288% is observed for the PECM-MM with a friction factor $m = 1.95$. However, these high values must be evaluated qualitatively. The model used is the one established in Transregional Collaborative Research Centre 73 (TCRC 73) for the determination of friction factors [34]. In this particular case, the diameter reduction is very strong, so that it can be assumed that the used model is not sufficient for an accurate quantitative evaluation in these areas, which is evident to the partly very high values for the standard deviation of the friction value, even if the standard deviation of the inner diameter was small. However, the large reduction in the inner diameter can be attributed to the plastic deformation of the workpiece material caused by the compression test. The micro-deformation around the structural hills reduces the material flow and thus increases the friction coefficients. In applications without plastic deformation (lightly loaded contact e.g. pin-on-disc test), the potential of frictional properties may shift towards friction reduction due to a decrease of the so-called real contact area and the associated interlocking between roughness peaks of the round shaped structure elements and the workpiece material [35]. In summary, the structure variants produced by PECM, with their fine, complex formed valleys and these rounded peaks, exhibit properties that are difficult to machine by cutting. In addition to the specific functionality that potentially can be suitable for different friction applications, good shape-related conditions for coatability can be assumed due to the absence of sharp, brittle edges or burrs. In particular, the high-feed milling structures are very new and have not been machined or tested before. This indicates the need for further investigation into the structure design and associated functionality.

4 Conclusion and outlook

In this study, the potential of PECM process for microstructuring components made of high hardness tool steels was investigated by using a subsequent process chain of (1) micro and high-feed milling to structure the PECM tool followed by (2) a PECM process to produce the inverse shape of the reference structures. To characterize the generated structure variants in terms of roughness values *Ra* and *Rz*, white light microscopy was used. In addition, a qualitative analysis of the resulting structure quality in terms of shape and surface was conducted using SEM images. The performance of the developed structure variants with respect to friction properties was evaluated in a ring compression test. The following conclusions can be derived from the investigations:

- By using a complex process chain that combines surface structuring processes such as micromilling or high-feed milling with a PECM process, a procedure was identified that has high potential for modifying surfaces with functional structures.
- With regard to the geometry of the observed structures extremely fine cavities (HFM) and rounded peaks (MM) demonstrate a uniform and reproducible quality. Deviations in height as well as particles and pores on the resulting surface indicate the need for further improvement of the specific process. In addition, the study of tool cleaning to precisely remove the dark layers of dissolved material formed on the tool surface is necessary to increase process stability.
- The friction properties for the developed structures were determined in a ring compression test. The strong influence on the friction factor, with reduced values for the HFM and increased values for the MM structures, showed the potential of these new structure variants for material flow control, e.g. in forming processes.
- The investigated process chain is a promising approach for the development of new complex-shaped structure variants by means of reverse engineering. In particular, structure geometries that are difficult to machine by cutting can be processed with PECM. In addition, PECM can increase productivity for large areas or quantities compared to structuring with micromachining processes, which makes this process chain economical and thus potential attractive for mass production in industrial applications.
- In further investigations, the process limits in terms of structure shape and scale are to be determined and, based on this, new structure variants such as bionic structures could be developed and produced. In addition, the potential transfer to industrial applications is to be demonstrated on the basis of the application on complex shaped forming tools such as gears.

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Declarations

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