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Reproducible, fast and adjustable surface roughening of stainless steel using pulse electrochemical machining

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Abstract

Pulse Electrochemical Machining (PECM) is known to produce finished surfaces with a typical roughness in the region of conventional machining methods like grinding or lapping. Furthermore, the process characteristics support the leveling of a rough anodic surface by using an either smoother, equally rough or even rougher cathode. This research focuses on an empirical investigation of the contrary approach, since for some applications surfaces with a well-defined roughness within small tolerances are needed. Examples are forms for injection molding, medical implants and friction pairs. In this contribution the copying accuracy to specifically produce and reproduce a localized as well as adjustable rough surface structure in steel is analyzed under different process conditions. The surface structure and roughness of the used PECM cathodes are initially produced by Electrical Discharge Machining (EDM) using copper as electrode. This study will show how surface roughnesses can accurately be produced with PECM in a range of typical conventional and non-conventional machining methods. Furthermore, the possibility of adding a surface texture by PECM is pointed out which will create a similar result as an EDM process but without the disadvantages of heat affected zone, tool wear and long machining time for fine finishes. The changes of the surface roughness during the process chain - producing the electrodes by turning, machining the PECM cathodes with EDM and finally machining the parts with PECM - are measured in all stages and correlated to the process conditions and influencing parameters. For all PECM experiments a commercially available PEMCenter8000 with sodium nitrate as electrolyte and for all EDM experiments a FORM20 with IonoPlus IME-MH as dielectric was used.

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Keywords: Electrochemical machining; Electrical discharge machining; surface topology; surface roughness

1. Introduction

Most empirical studies using an industrial size Pulse Electrochemical Machining (PECM) setup [1-4] report about rather smooth surface finishes even down to a roughness average R_a value as low as $0.05\ \mu m$. In this contribution the smoothing and roughening possibilities using PECM are investigated. Therefore, different surface topologies are produced with Electrical Discharge Machining (EDM), using a FORM20 from +GF+ AgieCharmilles Switzerland, and then transferring the produced surface structure onto a steel workpiece, using an industrial size Pulse Electrochemical Machine, a PEMCenter8000 by PEMTec SNC France. The PECM results are then compared to the already established non-conventional machining process EDM.

2. Experimental Setup

2.1. EDM and PECM setup

In this contribution, a ball bearing steel (1.3505, soft annealed) and a stainless steel (1.4112, martensitic) are investigated as workpiece materials with regard to the possibility of structuring the surface in a reproducible, fast and adjustable way. Since two different processes, EDM and PECM, are compared, also two different tool materials are used to machine the workpiece materials.

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As listed in Table 1 and schematically shown in Fig. 1, the EDM electrode (EDM tool) material is electrolytic copper, and the material machined during the EDM process, representing the workpiece and later on used as PECM cathode (PECM tool), is a stainless steel (1.4571).

Table 1. Materials

EDM Electrode Material		
Material	**Electrical resistivity**	**Purity (%)**
Electrolytic Copper	*max. 0.01754* $\Omega mm^2/m$	*Min. 99.90*
PECM Cathode and PECM Anode Materials		
EN 10027-2	**DIN / DIN EN**	**AISI**
Steel 1.3505	*100 Cr 6*	*52100*
Steel 1.4112	*X 90 CrMoV 18*	*440B*
Steel 1.4571	*X 6 CrNiMoTi 17-12-2*	*316 Ti*

Table 2. Initial surface values

		Electrodes before EDM	PECM Cathodes before EDM	PECM Anodes before PECM	PECM Anodes before PECM
	Material	*Cu*	*1.4571*	*1.3505*	*1.4112*
Maximum values measured [µm]	R_a	*0.84*	*0.73*	*0.72*	*0.58*
	R_z	*4.04*	*2.96*	*3.30*	*3.25*
	R_{max}	*4.30*	*3.04*	*3.47*	*3.42*
Minimum values measured [µm]	R_{mr}(-1,5)	*27.73*	*46.28*	*18.86*	*32.25*
	R_{mr}(-2,5)	*57.55*	*76.95*	*56.85*	*85.85*
	R_{mr}(-3,5)	*93.67*	*100.00*	*99.69*	*100.00*

All materials used are grinded or precision-turned to assure comparable initial surface parameters as input to the machining experiments, using EDM or PECM. These initial surface values are measured according to the rules and standards in EN ISO 4287 and EN ISO 4288 - using a Mahr MarSurf XR/XT 20 profilometer - and listed in Table 2.

In this contribution all the measurements and values presented focus on the roughness average R_a *[µm]*, the mean roughness depth R_z *[µm]*, the maximum roughness depth R_{max} *[µm]* and the material ratio $R_{mr}(c,h)$ *[%]* - with *c* indicating the intersection line in *µm* and *h* the reference height in %. For each sample two surface measurements are performed at a *90°* angle to each other.

The stainless steel PECM cathode material was chosen due to its good corrosion resistant properties in the chemical PECM environment. In this process a water based $NaNO_3$ containing electrolyte is used. The properties of the electrolyte entering the PECM process are in the range of $\sigma = 65.7 - 72.1$ *mS/cm* for the conductivity, $T = 19.9 - 22.3°C$ for the temperature and *7.4 - 7.5 pH*.

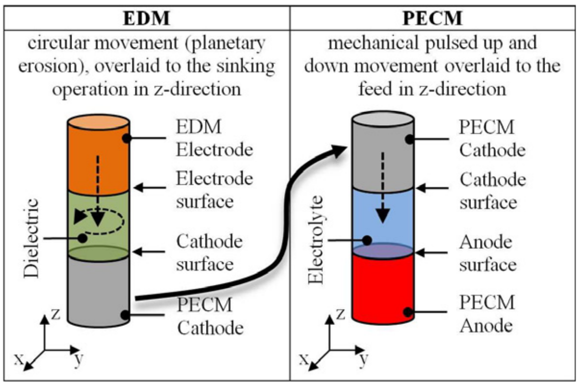

Fig. 1. Experimental Setups

The dielectric used during the EDM process of the PECM cathodes is the commercially available IonoPlus IME-MH from Oelheld Gmbh Germany. The dielectric entering the process is constantly cooled to a temperature below $T = 23°C$ during all experiments. The machine-integrated technology *"copper-steel"* in combination with a circular movement overlaid to the sinking in negative z-direction (see Fig. 1) is used to machine six PECM cathodes (I – VI) towards a different surface roughness.

2.2. The PECM process

The PECM process, schematically shown in Fig. 2, is a variation of the ECM process. During this process, the feed towards the workpiece (anode) is overlaid with a mechanical oscillation of the tool (cathode). The amplitude of the oscillation in this contribution is *200 µm*, which results in two different process phases. During the minimum gap size, a pulsed current with a pulse duration ranging from *0.1-5 ms* can be applied. The small gap size, achievable through the oscillation of the cathode, and the short current pulses lead to an effective material removal process resulting in good surface and copying accuracy. The upward movement during the oscillation results in the phase of maximum gap size, which enables enhanced flushing possibilities and consequently a better removal of the processed material as compared to the conditions at minimum gap size.

Two different approaches are investigated to implement a specific surface roughness using PECM. The PECM roughening, as schematically shown in Fig. 3 left, is based on the transfer of the initially EDM-machined tool's surface topology onto the anode's surface, using the copying accuracy of the PECM process. The PECM smoothing on the other hand is based on the leveling of a previously roughened anodic surface, see Fig. 3 right, by using a pulsed current (frequency $f_{electric}$ *[Hz]*) without a mechanical oscillation or feed of the cathode (frequency $f_{mechanical} = 0$ *Hz*) at a constant voltage *U [V]*. The leveling process can therefore be regarded similar to the electrochemical polishing process schematics presented for example in [5].

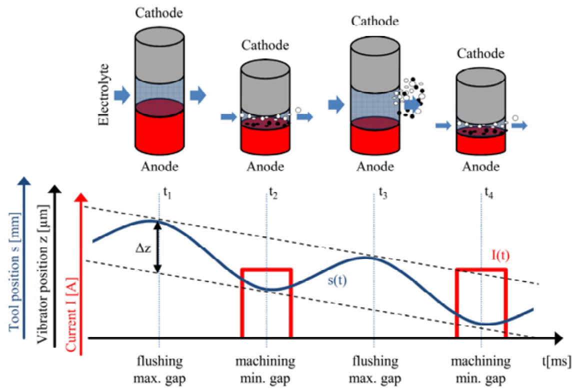

Fig. 2. PECM process schematic

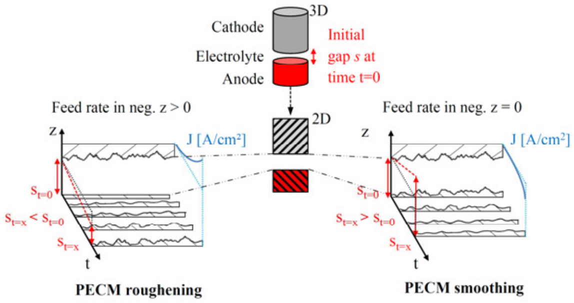

Fig. 3. Surface generation during PECM

2.3. EDM and PECM process parameters

The geometric dimension of the cylindrical EDM copper electrodes is *20 mm* in diameter and the PECM cathodes used have also a diameter of *20 mm*. The PECM anodes have a diameter of *19 mm* with a *45°* angle and a revolving *1 mm* chamfer to ensure better flushing conditions. Two-step PECM programs are used for all experiments. The parameters presented in Table 3 considering step 1 of each program (A1, A2, B1, B2) are chosen to be identical. Taking into account the variation possibilities arising from the ten herein presented variables, the experimental complexity had to be narrowed down to assure comparability in the results using the tool's surface roughness as main input parameter. These specific program parameters for step 1 and step 2 were therefore experimentally evaluated in advance to the actual study to assure stable and reproducible process conditions for the use of different PECM cathodes. Furthermore, the possibility to machine a workpiece with a tool having a rough, uneven surface and using PECM shall be proven in each program step 1. Whereas in each program step 2 the possibility of reusing the exact same tool to either roughen (program A1 step 2 and A2 step 2) or smoothen a workpiece surface (program B1 step 2 and B2 step 2) by process parameter variation shall be investigated.

Table 3. PECM process parameters

Program	*A1*		*A2*		*B1* *B2*		
PECM Anode Materials	*1.3505*		*1.4112*		*1.3505* *1.4112*		
Program Step	***1***	***2***	***1***	***2***	***1***	***2***	
Total feed [mm]	*-0.05*	*-0.12*	*-0.05*	*-0.18*	*-0.05*	*20,000*	ECM Time [ms]
Feed rate [mm/min]	*0.1*	*0.2*	*0.1*	*0.25*	*0.1*	*0*	
Pressure p [kPa]	*350*	*350*	*350*	*350*	*350*	*350*	
Voltage U [V]	*15*	*12*	*15*	*12*	*15*	*16*	
$f_{mechanical}$ [Hz]	*50*	*50*	*50*	*50*	*50*	*0*	
$f_{electric}$ [Hz]	*50*	*50*	*50*	*50*	*50*	*100*	
P_{shift} [%]	*85*	*116*	*85*	*118*	*85*	*50*	
t_{on} [ms]	*4*	*1.8*	*4*	*1.8*	*4*	*5*	
Initial Gap [µm]	*40*	*-*	*40*	*-*	*40*	*-*	

The Phase shift P_{shift} *[%]* - as mentioned in Table 3 - relates to the shift of the pulse on-time t_{on} in relation to the bottom dead center of the mechanical vibrator. The starting time t_{shift} *[ms]* of the rising flank of the pulse on-time t_{on} *[ms]* can be calculated in relation to the point in time when the vibrator reaches the bottom dead center according to formula (1).

$$t_{shift}[ms] = -P_{shift}[\%] \cdot t_{on}[ms] \qquad (1)$$

3. Results and discussion

3.1. EDM machining results

The underlying program parameters during all EDM experiments are unchanged in relation to the already implemented manufactured technology values within the control of the machine. No further investigations or changes to the process or the used parameters were carried out. The main objective in this contribution is the manufacturing of differently structured surfaces. The reproducibly roughened workpieces by EDM are used as the tools (PECM Cathodes) in the PECM process. The achieved surface values by EDM (always using a total feed of *-0.2mm*) are presented in Table 4.

Table 4. EDM machined surface values

		PECM Cathodes after EDM machining					
		I	*II*	*III*	*IV*	*V*	*VI*
Average values [µm]	R_a	*11.49*	*9.34*	*8.11*	*5.08*	*2.63*	*1.23*
	R_z	*70.49*	*57.85*	*48.28*	*30.83*	*19.07*	*10.21*
	R_{max}	*81.85*	*68.23*	*60.66*	*35.95*	*22.88*	*12.43*
Average values [%]	$R_{mr}(-1,5)$	*5.57*	*5.63*	*6.55*	*7.57*	*10.99*	*19.41*
	$R_{mr}(-2,5)$	*6.19*	*6.22*	*7.78*	*10.48*	*20.00*	*46.09*
	$R_{mr}(-3,5)$	*7.07*	*6.86*	*9.05*	*14.00*	*31.77*	*71.04*

3.2. PECM machining results

The chosen range of parameters and the experimental setup allow the machining of all samples without causing a shortcut between cathode and anode. Therefore, all conducted experiments using the four different programs in step 1 prove the possibility to use either a smooth or rough surface as tool for a PECM process. During step 2 in program A1 and A2 current densities between *70 - 114 A/cm²* are reached, whereas during step 2 in program B1 and B2 only current densities between *34 - 56 A/cm²* are reached. Here, as mentioned as well in [3] and [4] for material 1.3505 under different electrolyte conditions, a thin, dull surface layer is observed for low current densities using program B1. Therefore, the samples are cleaned with 10 wt% Hydrochloric Acid (HCl) before measuring the surface parameters.

The results presented in Fig. 4 and Fig. 5 for different surface parameters prove the concept of an adjustable surface roughening using PECM. While using the same PECM cathode, the variation of the program allows a variation of the PECM anode’s (workpiece) surface. The small measured deviations in the surface roughness average R_a for all conducted experiments, indicated by the lines representing the absolute maximum and minimum variance in relation to the median values measured indicated in each graph, prove the reproducibility and process capability of PECM.

Even though using the same setup, geometry and boundary conditions for all experiments with material 1.4112, more flow lines can be visually observed when using a smoother PECM cathode compared to the findings on the surface of material 1.3505 during the programs B1 and B2. Since the flushing of the gap is only performed from one side to the other, the flow lines only appear in one direction and are measured to be in the range of below *1µm* when visually observed. Due to the way the surface measurements are performed under a *90°* angle and the size of the slightly visible flow lines under *1 µm*, a major influence on the measured results and therefore a distortion of the measured values can be ruled out. As presented in Fig. 4, the possibility to roughen and smooth a surface according to the previously shown schematic in Fig. 3 could be substantiated by experimental data.

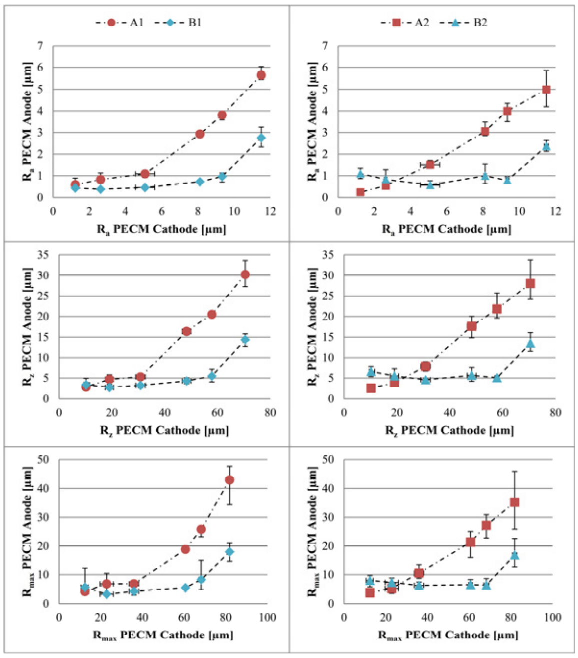

Fig. 4. PECM results - R_a, R_z and R_{max}

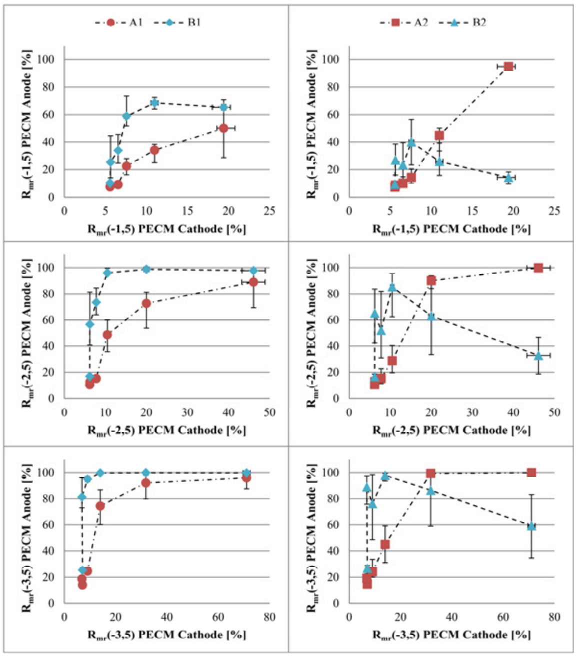

Fig. 5. PECM results - R_{mr} for different cut levels

The intersection of the approximated curves representing the measured data resulting for program A2 and B2 could be explained by the erosion-corrosion models presented in [3] and [4]. Nevertheless, the presented results allow the conclusion that a rough surface being produced through the herein used programs A1 and A2 can be smoothened towards at least the achieved minimum values presented through the experimental data B1 and B2, using the same rough PECM cathode.

While the indicated curve shapes with small variances can be observed in the diagrams in Fig. 4, the results for the material ratio R_{mr} in Fig. 5 vary in a wide range. This observation is more distinct for material 1.4112 compared to 1.3505 and specifically for program B2. A reason for this behavior, which clearly does not totally conclude from the measured corresponding R_a, R_z and R_{max} values, cannot be explained by the experimental investigations yet.

Still, the presented corresponding values in Fig. 5 clearly show an enhanced material ratio during most PECM experiments compared to the previously produced EDM surface finishes.

3.3. EDM and PECM machining times

As already presented in Fig. 4, the relation between EDM and PECM results for all surface values shows a reduction of the transferred values in R_a, R_z and R_{max} but also an increase in the material ratio R_{mr} in all experiments. While the PECM process only allows to cover a certain range of values, Fig. 6 points out the difference in machining times in these areas (R_a ranging between roughly $0.2\ \mu m$ and $6\ \mu m$). While at the same, time as indicated in Fig. 7, the results in terms of material ratio are comparable to the results achieved by EDM machining.

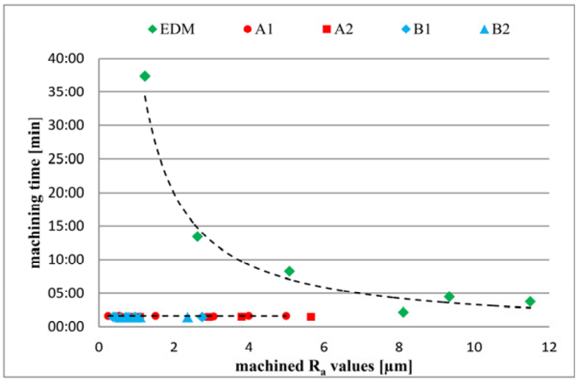

Fig. 6. EDM and PECM comparison for different machining times and machined R_a values

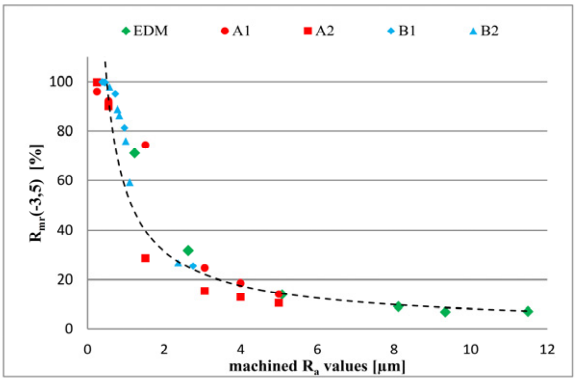

Fig. 7. EDM and PECM comparison for different R_{mr}(-3,5) and machined R_a values

4. Conclusion

The presented approach could prove the possibility to produce not only smooth but also rough surfaces in steel using PECM. In comparison to EDM, the PECM process thereby offers the possibility for roughening and smoothing metallic surfaces in a fast and adjustable way using a single tool and just varying process parameters in a software program. As a result of the basic underlying PECM process characteristics and the therefore necessary electrolytic medium inside the process gap, a one-to-one copying accuracy cannot be achieved. Yet considering the herein presented and for the aim of the study necessary limitation in complexity of process parameters, it is already possible to accomplish a surface roughening in about half the range of conventional EDM. In addition, the fast process times and the reproducible anodic surface topologies without the disadvantages of tool wear and heat affected zone prove the PECM process to be a reliable and secure alternative to EDM when specific surface roughnesses are required. While having some major benefits, the knowledge about material influence as well as characterization, chemical side effects, e.g. passivation, and process control, is yet a field requiring more detailed research efforts. As a consequence of the smoothing effects present in a PECM process as well as the different effects caused by the variation of program parameters, the initial roughness of the PECM cathode always has to be higher than the PECM anode surface roughness aimed to be produced.

Acknowledgements

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