
Influence of plasma-electrolytic rounding on chemical composition, roughness and cutting edge radius of cemented carbide cutting tool inserts

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Abstract

The shapes of the cutting edges of cutting tool inserts (CTI) have an essential influence on the machining results and economic aspects. Well-defined rounding and slight chipping of the cutting edges are aspired to achieve high surface qualities and to assure long tool life. Until now, cutting edge preparation is usually realized by mechanical grinding or by laser ablation processes. Both processes require precise alignment of the CTI against the grinding tool or the laser treatment zone, respectively. Moreover, the respective mechanical or thermal impacts might lead to negative influences through an increase in brittleness of the CTI material. Using a plasma-electrolytic process offers the possibility for rounding cutting edges without mechanical impact and low thermal influence by immersion into an electrolyte basin. Previous analyses in plasma-electrolytic rounding (PeR) of a CTI made of WC-TiC-TaC-Co indicated that an aqueous electrolyte based on sodium carbonate and voltages between 240 V and 400 V represent applicable parameters for successful process initiation.

In this study, influences of the PeR process on the chemical material composition and the roughness of the CTI surfaces are analyzed. In addition, different orientations of the relevant cutting edges are investigated with respect to the resulting radii after the rounding experiments. The results of energy dispersive X-ray analyses indicate an increase in oxygen content due to anodic oxidation effects. A preferred removal of tungsten is detected, while cobalt is hardly dissolved in the alkaline solution. A certain increase in surface roughness was detected due to the inhomogeneous elemental dissolution. However, the cutting edge radii with initial values between 18 μm and 26 μm were increased, which represents very promising results regarding the aspired maximum target radius of 30 μm .

Keywords: cutting edge preparation, cemented carbide tools, plasma-electrolytic rounding

1. Introduction

The cutting edges of cutting tool inserts influence in a high degree the surface properties resulting from cutting processes. Precise preparation with high accuracy is a prerequisite to realize high surface qualities [1]. In addition, tool life, which is influenced by thermal and mechanical impacts during cutting, can be increased by cutting edges with slight chipping, which can help save costs [2].

Currently, cutting edge preparation is mainly carried out by grinding or laser-ablative processes. On the one hand, precise alignment of the cutting edges is necessary for both processes. And on the other hand, thermal or mechanical impacts need to be considered. Thermal impacts of the laser process might negatively influence the mechanical characteristics of the surficial edge zones. This can be avoided by ultra-shortly pulsed laser ablation, but results in significant increase in processing time. The mechanical impact from conventional grinding might lead to deviations especially on very sharp edge radii and cause micro cracks that can reduce tool life.

Plasma-electrolytic rounding (PeR) is an innovative ablation process that offers removal with negligible mechanical forces at electrolyte temperatures below their boiling point of approximately 100°C. In addition, there is no need for precise alignment. The setup is comparable to electrochemical polishing with the specifications of plasma-electrolytic polishing (PeP). I.e., the basic principle is an electrochemical cell with initial

electrolyte temperatures of (70...90) °C and maximum DC-voltages of 400 V. Usually, environmentally friendly electrolytes with low salt concentration and only low-acidic or low-alkaline pH are applied [3].

On the one hand, sufficient power needs to be provided by sufficiently high voltage in combination with a heated electrolyte temperature to create boiling effects and the formation of a plasma-gas layer that covers the workpiece by means of a closed envelope. This is realized by transfer of electric energy [4] and results in significantly lower electric current density compared to electrochemical machining. But on the other hand, too high voltages need to be avoided, since increasing numbers of electrical discharges result in negative influences of the part's surfaces. Hence, thorough investigation of applicable process parameter combinations is essential to assure reliable initiation and retention of a plasma-electrolytic process with the individual electrolyte composition in combination with the present workpiece material.

Characteristic correlations of the average electric process current as function of the applied voltage are a useful method to investigate applicable voltages for successful initiation of the PeP process [5]. According to [4] it can be assumed that comparable voltages are applicable for PeR to round edges of cutting tool inserts. Hence, a similar strategy was successfully carried out in a previous investigation indicating that PeR is feasible with the analyzed voltages and electrolyte composition [6]. A cutting tool inserts (CTI) made of WC-TiC-TaC-Co was machined with an aqueous electrolyte based on sodium

carbonate at voltages between 240 V and 400 V, which represents applicable PeR parameters.

2. Experimental

Indexable insert types of MI-MPMW090308 UTi20T from Mitsubishi Materials Corp. were chosen as demonstrative CTI. They provide a sufficiently simple setup for basic analyses, since they are not equipped with specific chip guiding shapes nor any coatings that could influence the PeR process or reduce electrical conductivity. Laser markings were applied by means of one and two circular spots to be able to retrace the orientation the symmetric CTI after PeR as shown in Figure 1.

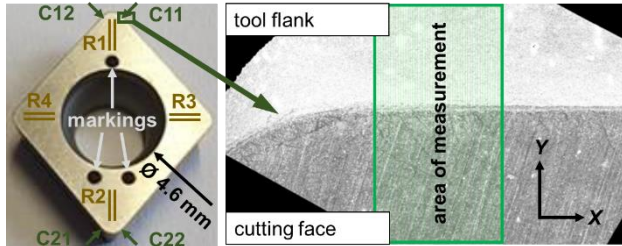


Figure 1. Top view image of a CTI with laser markings, black lines at positions R1...R4 indicate roughness measurements and C11...C22 cutting edge radii measurements (left), microscope image with green-colored measuring lines for cutting edge detection with a lateral distance of 10 μm (right)

Optical measurements were carried out with a Keyence VK-9700 confocal laser scanning microscope with an objective magnification of 50. The roughness values were investigated using MountainsMap7.2 analysis software. The linear roughness values R_a and R_z were analyzed before and after PeR for comparison at the four measuring positions R1...R4 to investigate influences of the CTI orientation in the electrolyte bath. Two measuring lines were arranged at each position and the average values were determined.

The measuring positions C11 and C12 indicate the positions for measuring the cutting edge radii on the side marked by one laser spot, while C21 and C22 refer to the side marked by two laser spots, respectively. The cutting edge radii were measured using a Bruker Alicona μCMM optical coordinate measuring machine, as shown by the green-colored measuring lines in the exemplary microscope image. For the evaluation of each radius, 50 individual measurements in Y-direction with a distance of 10 μm in X-direction were arranged orthogonally to the cutting edge and their average value was determined.

The chemical composition of the CTI was detected before and after PeR for comparison via energy dispersive X-ray (EDX) analyses using a scanning electron microscope (SEM) Zeiss EVO 25. SEM images were captured with the same setup to examine the micro-structure of the initial state of the CTI as shown in Figure 2.

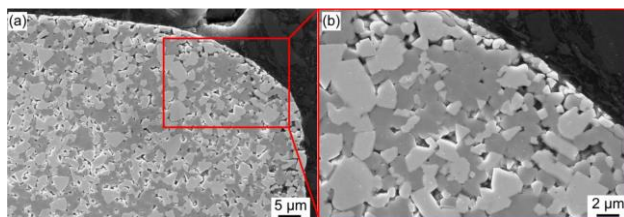


Figure 2. SEM images of grain structure from cross-sectional cut sample, top view (left) and detailed view (right) of the cutting edge

The indexable inserts were cleaned with acetone in an ultrasonic bath and then rinsed with deionized water. Before the

experiments, the initial weight of the indexable inserts was determined using a Sartorius ME36S precision microbalance.

The laboratory setup for experimental analyses on PeR is shown in Figure 3.

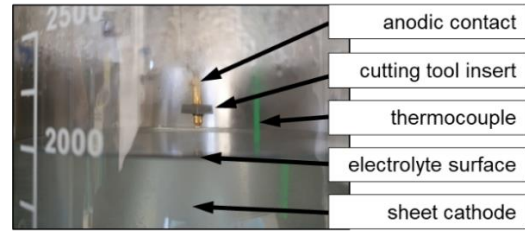


Figure 3. Photograph of the laboratory setup with electrical contacts and a CTI with downward orientation of the cutting edge before immersion into a 2000 ml electrolyte reservoir pre-heated in a beaker glass

The mechanical fixture and electrical contact were realized via the CTI's bore using a bunch plug. To assure chemical resistance, a gold-coated bunch plug was selected. No material removal of the gold-coating was detected after the experiments, which proves its applicability. A linear stage was used for full immersion of the CTI into the electrolyte, approximately 10 mm below the 2000 ml calibration mark. The electrolytes were heated to a temperature of 70 $^{\circ}\text{C}$ and the CTI were immersed for ten seconds before starting the experiments for pre-heating. After the immersion procedure, the voltage was switched on and the current transients were detected via a NI USB-6215 multi-functional device used as a digital multimeter in this case with a sampling rate of 3 Hz. The electric power was provided by a Keysight N8762A energy source.

3. Process parameter investigations

Initial investigations were carried out to analyze applicable electrolyte compositions in combination with useful voltages from the characteristics of the average process current over the whole PeR process [6]. The results showed that aqueous electrolytes of sodium carbonate (Na_2CO_3) with weight concentrations of 5 % and 10 % of the conducting salt is applicable with a processing voltage of 300 V. Experiments were carried out with fully submerged CTI and a processing time of 20 s based on own preliminary experiments, where edge rounding with only negligible influences on the remaining shape of the parts were realized.

3.1. Influence of cutting edge orientation

Figure 4 shows the electric current transients recorded during the PeR experiments with an electrolyte of 10 % of Na_2CO_3 .

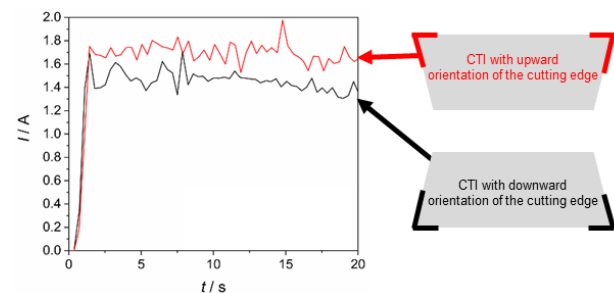


Figure 4. Current transients for cutting edge orientation downward (black line) and upward (red line) during PeR in a 10% Na_2CO_3 electrolyte

The current peak at process initiation with a duration of a few milliseconds is not displayed here since the focus was on investigations of the current development over the whole PeR process with a low sampling rate of 3 Hz. Average processing

currents were between 1.3 A and 2.0 A during the PeR processes. Approximately (10...20) % higher current values were measured when the cutting edge was oriented upward compared to the downward orientation. As a reason, it is expected that the larger horizontal surface oriented downward in the latter case leads to accumulation of more gas bubbles, while for the upward orientation, a larger amount of gas bubbles is released, which results in a lower electric resistance. Influences of the differing current transients on the machining results are discussed in the following sections.

3.2. Electric charge efficiency

The electric charge exchange was integrated from the electric current values over time using trapezoidal calculation. The average current density was calculated from the average electric current over the whole process divided by the surficial area of the CTI, which was 0.603 cm² constantly. The dissolved material weight was measured by differential weighing. The results are shown in Table 1.

Table 1 Dissolved material weight, exchanged electric charge and average current density of PeR experiments with different orientation of the cutting edge (OCE: U...upward / D...downward) and electrolyte concentration

OCE	Concentration [%]	Dissolved material weight [mg]	Exchanged electric charge [C]	Current density [A/cm ²]
U	5	4.31 ± 0.1	13.56 ± 1.74	1.1 ± 0.3
D	5	4.41 ± 0.5	8.29 ± 2.65	1.7 ± 0.2
U	10	3.91 ± 0.1	10.34 ± 0.86	0.9 ± 0.1
D	10	3.74 ± 0.5	6.98 ± 0.58	1.3 ± 0.2

Both electrolyte concentrations 5 % and 10 % of Na₂CO₃ were investigated. The initial CTI weight was 2957.148 mg measured before PeR as an average of 30 samples. The dissolved material weight is almost comparable for upward orientation and downward orientation of the cutting edge in each single electrolyte. But less material weight was dissolved in the higher concentrated solution. The reason is that significantly lower electric charge was exchanged in the higher concentrated electrolyte, which is also cognizable from the lower average current density values. In both electrolytes, downward orientation of the cutting edge results in significantly lower current density and charge exchange.

The charge effectivity was calculated from the dissolved weight divided by the electric charge exchanged. The highest charge effectivity of 0.54 mg/C was determined with 10% Na₂CO₃ and downward oriented cutting edge, which should be preferred with respect to prospective economic applications focusing on high energy efficiency and short processing times. Hence, this electrolyte was chosen for further investigations. The comparative result for the same electrolyte with 10% concentration and upward orientation is 0.38 mg/C. For the lower concentrated electrolyte of 5%, 0.53 mg/C was measured in downward orientation and 0.32 mg/C in upward orientation. In summary, downward orientation with both the 10% and 5 % electrolyte solutions show the highest charge efficiency with comparable values, which appears useful in an economic point of view but might result from unwanted removals in regions outside from the desired rounding regions.

4. Machining results

The surfaces of the machined CTI were analyzed and compared to the initial surfaces, which are characterized by typical grinding marks from mechanical pretreatment as shown in the microscope image of Figure 5 (a).

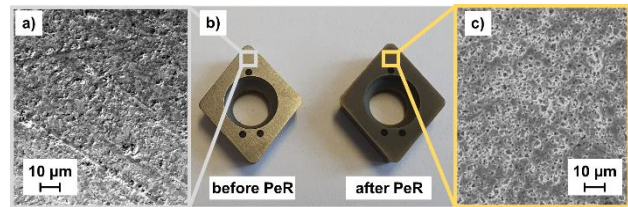


Figure 5. Top view photograph of two CTI, one before (initial) and one after PeR in a 10% Na₂CO₃ electrolyte (b), detailed microscope images of the surface before (a) and after PeR (c)

The grinding marks were smoothed by the PeR process as cognizable from the comparative microscope image in Figure 5 (c). After PeR, the surfaces of the CTI appeared uniformly darker than before as visible in Figure 5 (b). Surficial pores with estimated diameters of ≤ 3 μm already cognizable on the initial surface were exposed by the PeR process.

4.1. Chemical composition

The change of the chemical composition as a result from the PeR process was investigated by EDX analysis. The result is shown in Table 2.

Table 2 Chemical composition of a CTI surface before PeR (bP) and after PeR (aP) in a 10% Na₂CO₃ electrolyte, values in percentage of atoms

	C	O	Ti	Co	Nb	W	Na	Ca
bP	9.9	2.0	7.9	5.3	7.5	67.5	-	-
aP	8.3	9.9	12.3	25.4	9.4	33.9	0.6	0.2

The CTI with WC-Co as basic material composition mainly consist of tungsten (W) and carbon (C) as well as other alloying elements such as niobium (Nb) and titanium (Ti) in addition to the metallic cobalt (Co) binder, which corresponds to the manufacturer's information. The comparative analysis show that mainly the mass fraction of tungsten was decreased, which indicates that tungsten carbide was dissolved preferably, which is also cognizable from the slight carbon reduction. It should noted that the carbon reduction is less significant, since it is overlaid by an accumulation of carbon from the electrolyte. Similar effect is cognizable for small residues of sodium (Na). And negligible residues of calcium (Ca) are cognizable that result from the final flushing process with water.

All the remaining elemental contents were increased. While the oxygen content raised as expected due to anodic oxidation, especially the significant increase of the cobalt content indicates a certain homogeneity in the dissolution of the basic material.

4.2. Surface roughness

The bar charts in Figure 6 show the results of the comparatively measured linear roughness values *Ra* and *Rz* before (light gray, dark gray) and after PeR (green, yellow). The exemplary results of two CTI represent cutting edges oriented upward and downward, which were measured before and after machining with a 5% Na₂CO₃ aqueous electrolyte.

As can be seen, all roughness values were increased. The initial values of *Ra* of (0.1...0.2) μm were increased to (0.3...0.4) μm and the initial *Rz* values of (0.7...1.3) μm were increased to (3.0...4.0) μm after PeR. The reason is the preferred dissolution of tungsten carbide as discussed before, while the dissolution rate of cobalt was significantly lower, which led to a more uneven surface topography.

The results of the four measuring positions show comparable values after PeR, which indicates an even distribution of the process. In upward orientation, the relative roughness increases are slightly stronger than in downward orientation due to easier gas bubble release. Also, at positions R1 and R3 slightly stronger increases were detected, which results from a slight inclination

of the immersed sample in relation to the electrolyte surface and stronger impacts on these regions. The results achieved with lower concentrated electrolyte revealed comparable changes of the surface roughness.

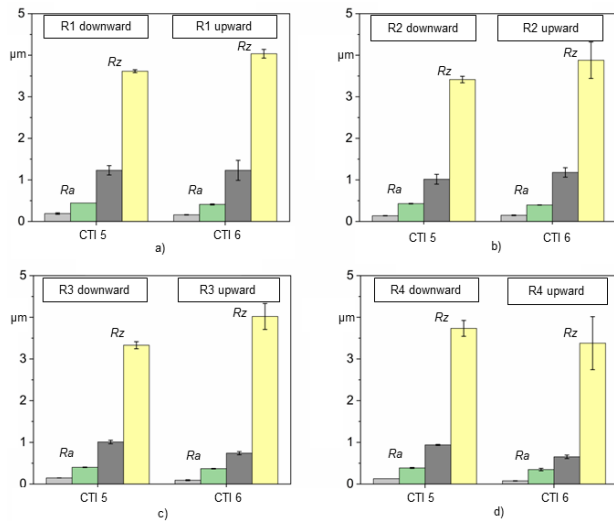


Figure 6. Linear roughness values R_a (light gray / green) and R_z (dark gray / yellow) detected at the measuring positions R1...R4 of two exemplary CTI with different cutting edge orientations before (gray) and after PeR (green, yellow) with an electrolyte of 10% of Na_2CO_3

4.3. Cutting edge radius

Analyses results of 30 CTI before PeR led to an average initial cutting edge radius of $(24.1 \pm 2.9) \mu\text{m}$. A comparison of the single initial cutting edge radii (gray) and the radii after PeR (orange) is shown exemplarily in Figure 7.

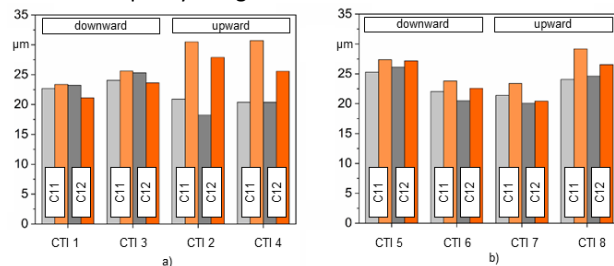


Figure 7. Radii of the cutting edges at positions C11 and C12 of a CTI, initial values (gray) and values after PeR (orange) in aqueous solutions with concentrations of 5% (a) and 10% of sodium carbonate (b)

As cognizable from the results, most of the radii were increased. CTI 2 and CTI 4 machined with the 5% electrolyte solution and upward orientation, which is shown by the two right-handed results of Figure 7 (a), indicate the most significant increase in cutting edge radius between $5 \mu\text{m}$ and $10 \mu\text{m}$. Consequently, the targeted cutting edge radius of $30 \mu\text{m}$ was realized on initial values of approximately $20 \mu\text{m}$ at positions C11 on both samples, and only slightly missed at positions and C12.

Also, with upward orientation on sample CTI 8, which was machined in the higher concentrated electrolyte, the target radius was realized. However, the remaining samples show only slight rounding, especially in downward orientation. On the two samples CTI 1 and CTI 3, even a slight radius reduction of approximately $2 \mu\text{m}$ was detected, which can be attributed to measuring errors. Consequently, upward orientation of the cutting edges appears to be most applicable to realize sufficient rounding.

5. Conclusion and Prospects

The results show that PeR with a voltage of 300 V in electrolytes of Na_2CO_3 at weight concentrations of 5 % and 10 % of the conductive salt was successful. The lower concentrated electrolyte should be preferred in further investigations since it offers the highest charge efficiency and the best rounding results.

However, inhomogeneous dissolution of the single elements of the basic work piece material was detected, which led to significant increase of the surface roughness, regardless of the measuring position and the electrolyte concentration. Hence, the process parameter combination of electrolyte composition and voltage should be analyzed more in detail in future investigations.

For the targeted cutting edge radius of $30 \mu\text{m}$, the orientation of the CTI during PeR should be upward, to assure sufficient release of gas bubbles and avoid too strong gas bubble accumulation in the near of cutting edges, which reduces rounding effects.

External longitudinal turning experiments are planned to prove the applicability of the rounded CTI and to assess their tool life in comparison with CTI not treated with PeR.

Acknowledgment

This project is supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK) on the basis of a decision by the German Bundestag.

Supported by:



on the basis of a decision by the German Bundestag

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