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Ecological and functional optimization of the pretreatment process for plasma based coatings of cutting tools

E. Uhlmann[a], H. Riemer[a,*], S. An[b], M. Fröhlich[b], H. Paschke[c], M. Petersen[d]

[a]*Institute for Machine Tools and Factory Management (IWF), Technische Universität Berlin, Pascalstr. 8-9, 10587 Berlin, Germany*
[b]*Leibniz Institute for Plasma Science and Technology (INP), Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany*
[c]*Fraunhofer Institute for Surface Engineering and Thin Films (IST), Eberhardstr. 12, 44145 Dortmund, Germany*
[d]*Albrecht + Schumacher Oberflächentechnik GmbH, Graf-Zeppelin-Ring 15, 27211 Bassum, Germany*

Abstract

Increasing demands in machining of high-tech materials and dry machining lead to higher thermal and mechanical loads on cutting tools. In response to these challenges, enhanced coating solutions are applied to increase performance and life of cutting tools. However, during the production process the cemented carbide substrates are contaminated with grinding oils and residues of organic material. For the subsequent physical vapor deposition (PVD) coating process an intensive and high-quality cleaning process is necessary. In this contribution, plasma electrolytic polishing (PEP) is used as a novel alternative to conventional ecologically harmful cleaning baths. Apart from the ecological advantage, the surface of the substrate can be optimized with regard to the coating adhesion. To examine the performance of the different cleaning processes, machining tests were performed at the IWF to evaluate the layer adhesion and tool life of the tools.

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Keywords: PVD-coating; Turning; Plasma electrolytic polishing

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1. Introduction

Cutting tools play a key role in manufacturing of products in various industrial sectors. A high amount of these tools is used in metal cutting applications, for example turning, milling or drilling. A production volume of about EUR 10 billion was achieved in 2017 by German manufacturers of precision tools. The included cutting tools achieved an increase in sales of 7 % in 2017 [1]. Main customers of cutting tools belong to the automotive industry and its associated suppliers as well as the electrical industry. Due to the extensive process chain for the production of these tools, the quality is influenced by a large number of factors. In addition to grinding processes, different post-treatment procedures are used to modify the microgeometry of cutting tools. These include, for example, brushing, drag finishing, abrasive flow machining as well as a wide variety of wet and dry blasting processes [2]. The post-treatment procedures use specific media which significantly increase the degree of contamination. Furthermore, an additional step of the process chain consists of the application of coatings. Cutting tools are often provided with wear-reducing hard coatings to increase tool life [3]. For machining of ferrous materials, coatings deposited by physical vapor deposition (PVD) are predominantly used. Prior to coating, the tool has to be cleaned thoroughly to remove residues from the manufacturing process, which can reduce or even prevent coating adhesion. The surface quality for PVD-coatings has higher demands compared to the pretreatment in chemical vapor deposition (CVD). Due to high substrate temperatures up to $\vartheta = 850$ °C, organic residues on the surface burn during CVD-coating [4]. In particular, the used DC magnetron sputtering PVD-technique responds more sensitive to contamination compared to cathodic arc deposition due to significantly lower proportion of ions of the target material [5]. As a result of the manufacturing processes, tools are contaminated with cooling lubricants, cutting oils and diamond pastes. Polishing pastes impose particularly high demands on the cleaning, as these partially penetrate into the surface [6, 7]. Currently, the cleaning of tools before coating via PVD is carried out with wet-chemical processes using acid and alkaline media in tempered ultrasonic baths [8, 9]. Between the sequential cleaning steps, the tools are cleaned by rinsing baths. Furthermore, corrosion-inhibiting protective films of e.g. amines or volatile substances are applied to the surface as a temporary protection. This protective film can be removed by plasma fine cleaning directly before coating deposition. Fig. 1 shows a contaminated milling tool after a standard cleaning process. The remaining contamination will affect the adhesion of the subsequent coating. This contribution presents a plasma based process using environmentally harmless electrolytes, denoted as plasma electrolytic polishing (PEP), as an alternative method for cleaning. Based on ecologically benefits and already approved advantages in surface modification its sustainable industrial application is investigated. The employment as a cleaning method for cutting tools represents a new approach.

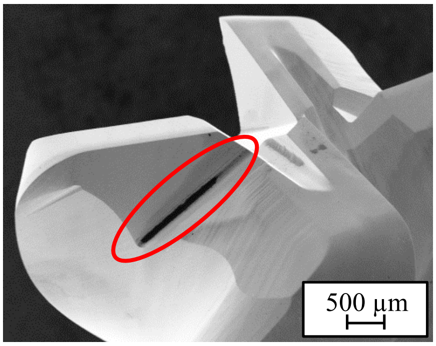

Fig. 1. Remaining contamination on a milling tool after cleaning [IWF].

Nomenclature

a_p	Depth of cut	r_β	Cutting edge radius
d_{max}	Maximum machining diameter	t_c	Cutting time
f	Feed	$t_{VB0.3}$	Tool lifetime at VB = 0.3 mm

l_{max}	Maximum machining length	U	Voltage
M_{max}	Maximum Torque	VB	Width of flank wear land
n	Rotational speed	VB_{max}	Maximum flank wear of VB = 0.3 mm
P_{max}	Maximum capacity of machine tool	v_c	Cutting speed
R_a	Arithmetic mean roughness	ϑ	Temperature
R_z	Roughness depth	σ	Electrical conductivity

2. Experimental procedure

2.1. Tools and Contamination

In the subsequent investigations cemented carbide indexable inserts from BOEHLERIT GMBH & CO KG, Kapfenberg, Austria, in the geometry SNMA120604 according to ISO 1832 were used. For the analysis and comparison between standard and PEP-process, a reference contamination was defined in cooperation with the cutting tool manufacturers BOEHLERIT GMBH & CO KG, GÜHRING KG, Albstadt, Germany, and HUFSCHMIED ZERSPANUNGSSYSTEME GMBH, Bobingen, Germany. Hence, a mixture of grinding oil, washing solution, abrasive and polishing agents was selected. This mixture was applied to all surfaces of the inserts before the tools were heated for t = 1 min at a temperature of ϑ = 700 °C to reproduce the boundary conditions of the grinding process. After both cleaning processes an AlTiSiN PVD-coating using DC magnetron sputtering was deposited by ALBRECHT + SCHUMACHER OBERFLÄCHENTECHNIK GMBH, Bassum, Germany.

2.2. Plasma electrolytic polishing

In context of the presented study, the cleaning performance of a standard wet-chemical process is compared to PEP. The principle of the PEP-process is shown in Fig. 2. The workpiece is anodically polarized with a voltage of $90\ V < U_- < 300\ V$. The cathodic bath is filled with an aqueous electrolyte solution possessing a temperature of $50\ °C < \vartheta < 90\ °C$. In addition to temperature variation, workpiece position and process time were altered. By adding various salts, the electrical conductivity and the pH value can be controlled up to $\sigma = 200\ S\ m^{-1}$ and pH = 14. Through voltage application, a thin plasma layer is formed around the tool. Within the plasma different ion species are formed leading to chemical reactions. These result in metal dissolution and, therewith, abrasion of surface peaks at the substrate in particular.

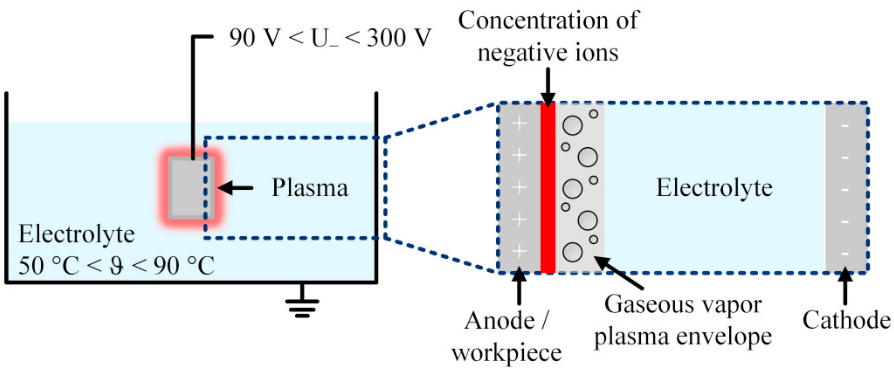

Fig. 2. Schematic illustration of the PEP-process [INP, IWF].

With this polishing process, an arithmetic mean roughness Ra < 0.02 µm is achievable on electrically conductive materials. Due to this high surface quality, the PEP-process is used for example for finishing of implants in medical industry [10]. Furthermore, contaminants that are located on the material surface are also removed by this process, based on chemical reactions (oxidation). Process parameters in the above-mentioned range were chosen to solely remove the contamination on the surface. No substantial effect on geometry of the tool was observed.

2.3. Machining tests

For the evaluation of tool life $t_{VB0.3}$ and the comparison of reference and PEP-cleaned tools, tests in cylindrical turning were carried out. For the investigations a universal lathe by DMG MORI, Bielefeld, Germany, type CTX gamma 1250 TC was used, see Fig. 3. The machine has a DC motor with a maximum capacity of P_{max} = 25 kW with a maximum rotational speed of n = 5,000 rpm and a maximum torque of M_{max} = 380 Nm. The universal lathe enables the machining of parts with a material length of up to l_{max} = 1250 mm and a diameter of up to d_{max} = 630 mm. For the comparison of different tool specifications carbon steel C45E was machined under dry conditions. The machining tests were carried out with a cutting speed of v_c = 250 m/min, a feed of f = 0.1 mm and a cutting depth of a_p = 0.5 mm. To determine the tool life $t_{VB0.3}$, the flank wear VB was measured until reaching the defined tool life criterion VB_{max} = 0.3 mm using a M3Z stereomicroscope by LEICA MICROSYSTEMS, Wetzlar, Germany.

Fig. 3. Universal lathe DMG MORI CTX gamma 1250 TC [IWF].

3. Results

3.1. Tool analyses

Fig. 4 shows the different states of the indexable inserts in preparation for the PEP-process and after polishing. Due to the high exposure temperature of ϑ = 700 °C, a high adhesion of the contamination on the surface can be observed. Initial investigations aiming at the mechanical removal of the contamination did not succeed. The PEP-process removed the entire contamination, as shown in Fig. 4c. Moreover, the surface peaks of the initial tool were reduced and the surface roughness decreased negligible from Ra = 0.1 µm and Rz = 0.715 µm to Ra = 0.096 µm and Rz = 0.601 µm.

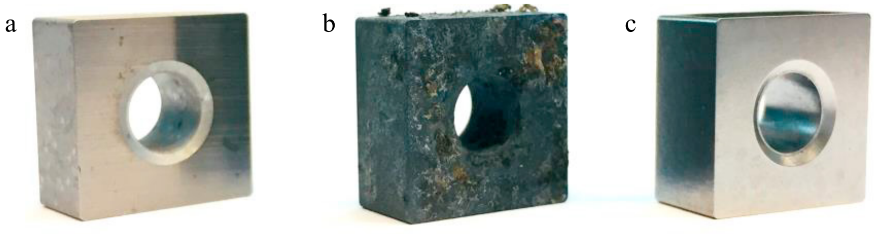

Fig. 4. Cutting inserts at different cleaning process steps; (a) initial state as delivered; (b) tool with reference contamination; (c) contaminated tool after PEP [INP].

The coated turning tools were examined via scanning electron microscopy (SEM), see Fig. 5. As shown in Fig. 5b, the contamination could not be removed by using the wet-chemical cleaning process. Due to the contamination, the coating delaminates at the rake face and at the cutting edge. After the PEP-process, coating delamination is also apparent, see Fig. 5c. These defects may be caused by minor residual contamination. However, preliminary investigations on coating adhesion with scratch tests show that the process not only influences the roughness. In comparison to untreated tools the coating layer adhesion is increased by the modification of the peripheral zone during the plasma chemical treatment.

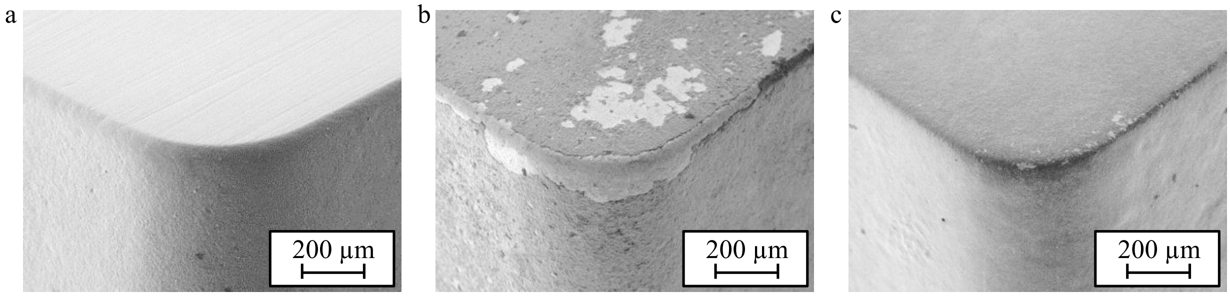

Fig. 5. Cutting edges after coating procedure; (a) without contamination and reference cleaning procedure; (b) with contamination and reference cleaning procedure; (c) with contamination and plasma electrolytic polishing [IWF].

In order to determine the influence of the PEP-process on the micro-geometry, the cutting edge radii r_β were measured using a MikroCAD[pico] by GFMESSTECHNIK GMBH, Teltow, Germany, see Fig. 6. Due to the material removal of the PEP-process, the cutting edge radii r_β can be increased. Consequently, the material removal has to be reduced to a minimum for not affecting the cutting edge. Coated tools without contamination show cutting edge radii of r_β = 39.2 µm with comparatively high deviations, whereas tools treated with the reference cleaning process show slightly lower radii of r_β = 36.9 µm. The measurements of PEP-cleaned tools show cutting edge radii of r_β = 35.9 µm. Hence, an influence of the PEP-process on the micro-geometry cannot be observed.

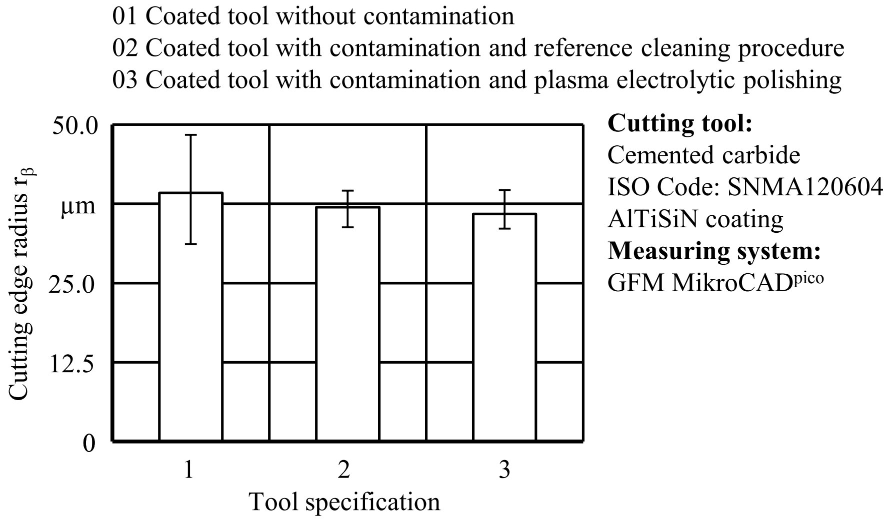

Fig. 6. Comparison of cutting edge radii r_β [IWF].

3.2. Machining tests

Fig. 7 shows the results of the machining trials with coated turning tools. For each tool, three tests were carried out. The coated tools without contamination reached an average tool life of $t_{VB0.3}$ = 7.5 min. Due to the coating delamination at the coated tool with contamination and reference cleaning process, the average tool life decreased to $t_{VB0.3}$ = 3 min.

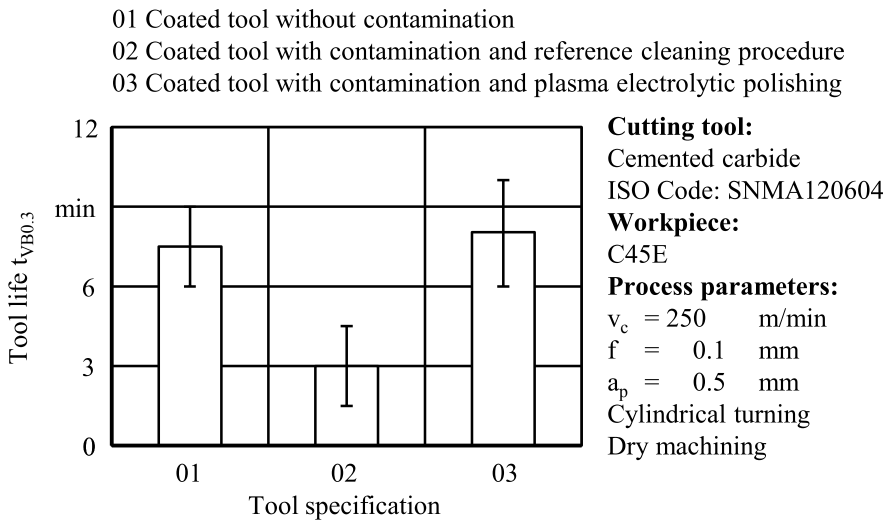

Fig. 7. Comparison of tool life $t_{VB0.3}$ [IWF].

The insufficient coating adhesion leads to excessive wear on the flank face, see Fig. 8b. By using the PEP-process the average tool life could be extended to $t_{VB0.3}$ = 8 min. Fig. 8c shows the reduction of flank wear at the cutting edge. However, uneven wear along the cutting edge is ascertainable due to local coating defects.

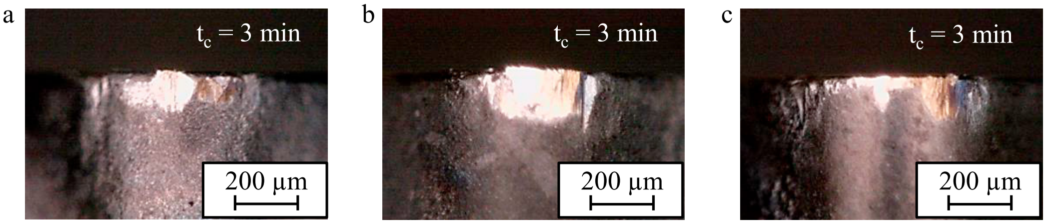

Fig. 8. Flank wear VB coated tools; (a) coated without contamination; (b) coated after contamination and reference cleaning procedure; (c) coated after contamination and plasma electrolytic polishing [IWF].

4. Conclusion and outlook

The following conclusions can be drawn from these results:

- A successful cleaning of cutting tools with an alternative innovative cleaning process using environmentally harmless electrolytes is possible.
- The cleaning performance by using plasma electrolytic polishing was increased compared to conventional processes.
- Even with a higher degree of contamination comparable results were achieved.
- Tool microgeometry is not influenced by the PEP-process.
- In contrast to conventional cleaning-baths a shortening in the process chain is possible
- PEP reduces the quantity of required media significantly.
- The substitution of existing wet-chemical cleaning processes with PEP is imaginable.

In the further project progression, the correlation between the machining tests and the coating adhesion will be examined in detail. The cleaning potential of further ecological cleaning procedures as well as the impact of complex tool geometries, such as shank milling and drilling tools, are also being investigated.

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