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RESEARCH

Influence of Combined Hard and Fine Machining on the Surface Properties of Cemented Carbides

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A B S T R A C T

As a result of recent developments in cold forging cemented carbides are increasingly used as tool materials. Due to their high hardness only electrical discharge machining (EDM) and grinding are suitable for tool machining. The structure of tool surface has significant influence on dominating failure mechanisms wear and fatigue. For improvement of tribological conditions the surface is polished in a finale processing step. The result of hard and fine machining is a specific combination of coarse and fine structure which is determined by processing parameters. The different surface structures lead to a particular tool behavior in forming process. This paper aims to show the influence of combined hard and fine machining on the surface properties of cemented carbides.

1. INTRODUCTION

The worldwide supply with manifold industrial goods requires superior manufacturing techniques. In the field of steel products cold forging has gained importance for the last sixty years [1]. Cold forging enables an economical production of precise components of high strength. The tool determines both accuracy and efficiency of forming process. Consequently it takes a key role in the forming process.

Tool manufacturing belongs to the main challenges in cold forging. As application of tools is cost-intensive, industry aims both increasing tool life and cost-effective tool production [1]. The ongoing trend in using work piece materials with high yield stresses in combination with additional strain hardening leads to high tool stresses during the forming process. As a result of this development cemented carbides are increasingly used as tool materials in cold forging. However, the high process-stresses limit the tool life by initiating fatigue and wear [2]. While wear is often the result of high friction between work piece and tool, fatigue is caused by cyclic loads [3]. In many cases fatigue has its origin in surface defects. Because tool surface has a significant influence on both failure mechanisms the manufacturing process of tools requires consideration of machined material.

Cemented carbides are composed of mainly a hard and brittle carbide phase and a ductile binder phase. The composite is characterized by high hardness, high compressive strength but low tensile strength. For application of cemented carbide as die material high pre-stressing is mandatory. With that the outstanding high wear resistance of cemented carbide as tool material can be used. As a consequence of high hardness cemented carbides can only be hard machined by grinding or electrical discharge machining (EDM).

EDM and grinding generate different and specific coarse surface structures which can include grooves or craters. Since cemented carbides reveal high sensitiveness to tensile strains superposed by cyclic loads, these surface defects have to be removed by a final polishing step to avoid early tool failure [4].

The result of combined hard and fine machining is a combination of coarse and fine structure, which is determined by the processing parameters of different machining steps. The generated various surfaces lead to different tool behaviour in forming process. The scope of the present study is to investigate and to describe the correlation between manufacturing process, surface properties and tool behavior in a quantitative way.

2. EXPERIMENTAL SETUP

For the investigations simple cylindrical specimen geometry was chosen in order to limit the efforts of the sintering process of powder-metallurgical blank as well as to facilitate separation of cylindrical bars because of large number of required samples.

The specimens have a diameter of 12 mm and a height of 10 mm. Blind holes with a diameter of 8 mm were machined comparatively by EDM and grinding. The geometry guaranties high accessibility for the different characterization methods. While in tool making roughing strategies remove the major part of work piece material to achieve the pre-shape, pre-finishing and finishing strategies create the final shape and determine the surface topography. As investigations focus on surface characterization of forming tools a pre-finishing and finishing strategy were chosen for both methods of hard machining.

The different strategies were evaluated in terms of removal rates and resulting specific surface topography which is characterized by roughness measurements. It is expected that pre-finishing leads to high removal rates and rough surface topography. In contrast, finishing strategies will lead to low removal rates and reduced surface roughness resulting in a better surface quality. Because hard machining does not achieve surface qualities required in cold forging-industry, the generated coarse structure has to be removed by fine machining in terms of polishing in order to improve tribological conditions of surfaces [5].

Specimens

The specimens are made of G55 which represents the current standard in forming technology. The cemented carbide is mainly used for active tool components such as die or punch. G55 is cemented carbide containing tungsten carbide (WC) and cobalt (Co). In general, cemented carbides are characterized by high hardness and metallic behavior like electrical and thermical conductivity.

The hard WC-grains are cemented by the Co-binder phase, thus the composite combines advantages of hard WC with ductility of Co. The Co-fraction of commercial qualities is between 3 and 30 wt% [6]. Since the high hardness is accompanied by brittleness, the tensile loads during cold forging require sufficient fracture toughness. Consequently, for cold forging-tools usually high Co-cemented carbides are applied. The material characteristics of G55 are given in Table 1.

Table 1. Material characteristics of cemented carbide G55 [7].

Type	Co (wt.%)	WC (wt.%)	Density (g/cm^3)	Hardness HV30	Bending strength (N/mm^2)	Compressive strength (N/mm^2)	Grain size (µm)
G55	27.0	73.0	12.95	860	3000	3000	2.5

Table 2. EDM parameters.

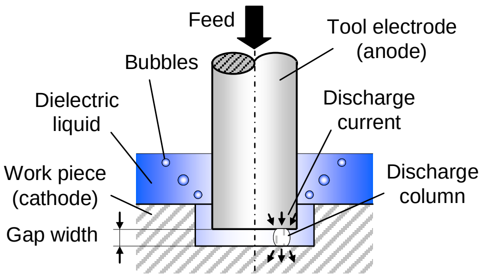
Strategy	Peak current (A)	Pulse duration (µs)	Discharge voltage (V)	Pulse interval (µs)
Pre-finishing	48	3.2	-80	100
Finishing	0.5	1.6	-200	1.6

Table 3. Grinding parameters.

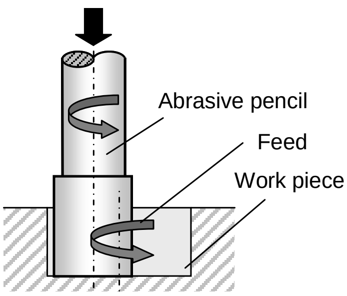
Strategy	Grain size D (µm)	Revolutions per minute (1/min)	Feed (mm/min)	In-feed (µm/1)
Pre-finishing	91	10000	800	5.4
Finishing	46	10000	600	2.0

Hard Machining

EDM enables machining of materials regardless to their hardness. The only requirement is conductivity of material to be machined. Consequently, EDM is suitable for tool manufacturing of cemented carbides. Electro erosion uses controlled discharges for achieving precision machining [8]. Pulsed arc discharges emerge in the gap between tool electrode and work piece (Fig. 1).



(a) EDM process [9].



(b) Grinding process.

Fig. 1. Characteristics of hard machining methods.

The working gap is filled with a hydro carbonic dielectric liquid in order to enable a small gap size to realize precise machining. On the opposite, the minimal gap size is limited by the requirements of a stable process. The discharge is caused by a high ignition voltage at the point of shortest distance between work piece and tool electrode. This principle guarantees the high accuracy of EDM [9]. The arc discharge is accompanied by the formation of a channel of plasma. The induced heat partially melts and evaporates the surface of work piece and electrode. The final material removal of cemented carbides is mainly achieved by thermal shock and dissolving of WC-grains by removal of binder phase [10]. The EDM was done on a sinking-machine "Roboform 350 µ" of the company AGIE CHARMILLES. Copper rods with a diameter of 8 mm were used as electrodes since copper is the industrial standard for finishing of cemented carbides. As mentioned above, the study considers two EDM strategies: pre-finishing and finishing (Table 2). While pre-finishing is characterized by high discharge currents and longer pulse durations, finishing is accompanied by lower discharge energies.

Material removal via grinding can only be achieved by an abrasive with hardness higher than that of cemented carbide. According to industry standard diamond was used for the investigations. A huge number of abrasive grains form geometrical undefined cutting edges which chip the base material [11]. The reference geometry was machined via internal cylindrical grinding with an abrasive pencil of diameter 5 mm (Fig. 1) on an "Ultrasonic 20 linear" grinding machine of the company SAUER. Within grinding of cemented carbide material separation is accompanied by initiation and expansion of micro cracks as well as generation of thermal stresses since most of induced mechanical energy is converted into heat [12]. To prevent heat generation a coolant is used. Within the study two grinding strategies are considered (Table 3). While the step with grain size D91 is a pre-finishing strategy, grain size of D46 is typically used for finishing.

Fine Machining

To produce a surface that is applicable for tools in cold forging the hard machined surfaces were polished. Standard in industry is manually controlled polishing [13]. Consequently, the worker determines polishing time by visual evaluation. An arbour made of wood brings the polishing compound in contact with rotating work piece surface (Fig. 2). Within polishing process material removal is achieved by mechanical effects similar to grinding process [12]. As hard machining methods and strategies led to different roughness values, several grain sizes of diamond (25 µm, 15 µm, 7 µm) have been used.

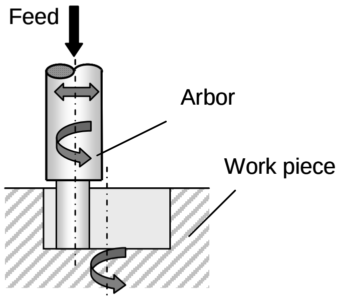


Fig. 2. Principle of polishing process.

Roughness measurement

Roughness was measured by tactile stylus measurement according to ISO 3274 [14]. Centre line average roughness Ra and averaged roughness height Rz were chosen for the analysis since they replace the worldwide standard in industrial roughness measurement. Even though, Ra and Rz are only 2D values, they are suitable for getting a first overview of roughness.

Topography analysis methods

For investigation of topography various methods are applicable. Surfaces of specimens have been investigated by confocal and scanning electron microscopy. For confocal microscopy an objective with a 10x magnification resulting in a measuring field of 1.6 mm x 1.6 mm is used. In addition to confocal microscopy hard and fine machined surfaces have been investigated by scanning electron microscopy (SEM) to visualize surface defects.

3. SURFACE CHARACTERIZATION

Machining Results

The results of hard machining are given in Table 4. Grinding achieves higher removal rates and better surface qualities in comparison to EDM. As expected, for both machining methods removal rates and roughness values of pre-finishing are higher. In EDM this is caused by higher discharge energies which remove higher amounts of material per discharge. Within grinding coarser abrasive grains in combination with higher feed result in higher removal rates and roughness. As a consequence, tool geometries of low complexity should be machined by grinding as cost-effectiveness is higher and roughness is lower compared to EDM. Depending on the aimed machining results a compromise between removal rates and roughness has to be found within one hard machining method to achieve an optimal combination for high cost-effectiveness and surface quality. In cold forging tools are stressed by cyclic loads which can result in critical peak stresses. Especially high roughness and surface defects can lead to such stress peaks. To avoid early tool failure, surface damages such as grooves or craters induced by hard machining have to be removed during final fine machining. In order to prevent notch stresses as well as to improve tribological conditions during cold forging, an Rz value of 0.5 µm is required [6]. EDM achieves a minimal Rz value of 4.172 µm. Thus ED-machined surfaces have to be fine machined. Pre-finishing strategy of grinding leads to an Rz value of 0.972 µm which is also above the required limit. Thus pre-finished surface needs a final finishing step. Even tough, finishing already achieves an Rz value below 0.5 µm, the surface has to be polished as grooves appear on the surface (Fig. 10).

Table 4. Results of hard machining.

Hard machining	Strategy	Removal rate (mm^3/min)	Ra (µm)	Rz (µm)
EDM	Pre-finishing	1.126	2.302	13.866
	Finishing	0.045	0.628	4.172
Grinding	Pre-finishing	7.617	0.153	0.972
	Finishing	2.082	0.050	0.402

Table 5. Results of fine machining.

Hard machining	Strategy	Polishing time (min) for grain size D (μm)			Total time (min)	Polishing depth (μm)	Ra (μm)	Rz (μm)
		25	15	7				
EDM	Pre-finishing	10	4.0	4.4	18.4	36	0.053	0.339
	Finishing	-	4.7	3.6	8.3	6	0.037	0.258
Grinding	Pre-finishing	-	3.5	3.2	6.7	6	0.042	0.282
	Finishing	-	2.3	3.3	5.6	4	0.049	0.310

Table 5. shows the results of polishing with the associated grain sizes and polishing times. The rough ED-machined surfaces lead to longer polishing times as more material has to be removed. Within one method of hard machining pre-finishing requires longer polishing times since pre-finished surfaces are rougher than finished ones. The results reveal that polishing removes the surface topography caused by hard machining since polishing depths are deeper than the Rz value of hard machined surfaces. After fine machining all surfaces have surface roughness Rz below 0.5 μm. The values range from 0.258 μm to 0.339 μm. Low Rz value of polished surface makes clear that obtained roughness profile has a plane appearance which is favourable for cold forging-process. All in all, the results reveal, the lower the roughness of hard machining the shorter is the following polishing process.

Topography

Results of confocal microscopy of ED-machined surfaces are given in Figs. 3 and 4 EDM generates craters on the surface. These dimples have a kind of "cornflake"-shape. The craters are positioned side by side and overlap each other. Together they result in a chaotic surface topography [9], where no preferential direction can be detected. The chaotic outcome of process can be explained by chaos theory. Even though, chaos develops deterministically the result is chaotic. This means that forecast of movement of discharge location is impossible since initial conditions of the system influence the subsequent events dramatically. The distribution of craters induced by pre-finishing proves this theory (Fig. 3). Pre-finishing strategy causes craters larger in size compared to finishing as higher discharge energies induce more heat into work piece.

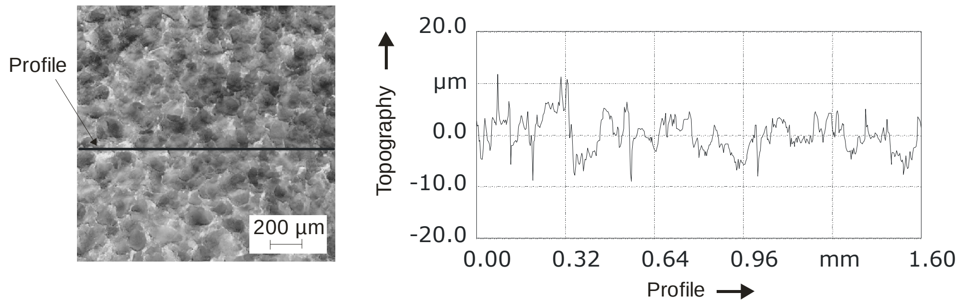


Fig. 3. Topography generated by pre-finishing (EDM).

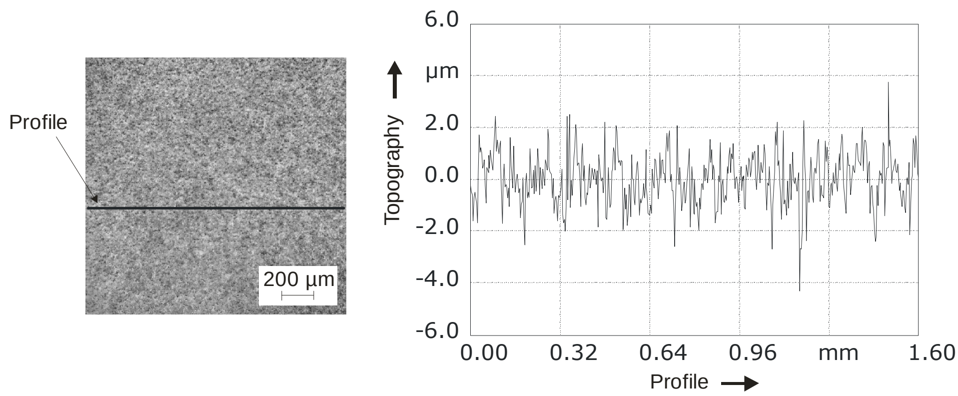


Fig. 4. Topography generated by finishing (EDM).

The roughness profile of pre-finished surface forms a distinct asperity characterized by high peaks and deep valleys. The distance between the highest peak and the deepest valley amounts to approximately 20 µm. In contrast, finishing results in a flatter roughness profile formed by many small craters. The corresponding maximum distance amounts to approximately 8 µm. Since cost intensive polishing has to remove asperity caused by EDM, shallow craters as obtainable in finishing are preferred. With that, the amount of material which has to be removed can be limited.

The SEM analysis (Figs. 5 and 6) confirm the results of confocal microscopy. The figures show the typical structure of ED-machined surfaces characterized by overlapping craters without any preferential direction. The pre-finished surface clearly reveals the typical “cornflake”-shape of craters. As can be seen in Figs. 5 and 6 with high magnification, both EDM strategies induce micro-cracks. This phenomenon can be explained by thermal influence. The electrical discharge and the accompanied plasma channel induce high temperatures in the surface layer which partially melt and evaporate the surface. At the end of a discharge the top layer rapidly cools down. This quenching process results in tensile stresses in the top layer because of material contraction. At points of highest stresses micro-cracks occur. Since pre-finishing strategies lead to higher thermal stresses than finishing, the related higher tensile stresses cause larger cracks. If these surface damages are not fully removed by a finale fine machining step, these remaining micro-cracks result in high notch stresses during cold forging- process. Often these cracks are the reason for tool failure as they initiate fatigue under cyclic loads.

In contrast to EDM, grinding leads to a regular structure characterized by furrows (Figs. 7. and 8.). The induced preferential direction is the result of rotational movement of bounded abrasives. Compared to EDM the roughness profile has a flat appearance. The distance between highest peak and deepest valley amounts approximately 1 µm for both grinding strategies. As topography of both strategies has a similar appearance a visual distinction of pre-finished and finished surface via confocal microscopy is difficult. If surface profile generated by grinding is not fully removed by fine machining, the remaining furrows can influence the material flow during later forming-process. In this context, furrows perpendicular to material flow impede the material flow and can lead to high notch stresses. While blockage of the material flow leads to increased forming forces in combination with higher tool stresses, high notch stresses reduce tool life under cyclic loads by causing fatigue.

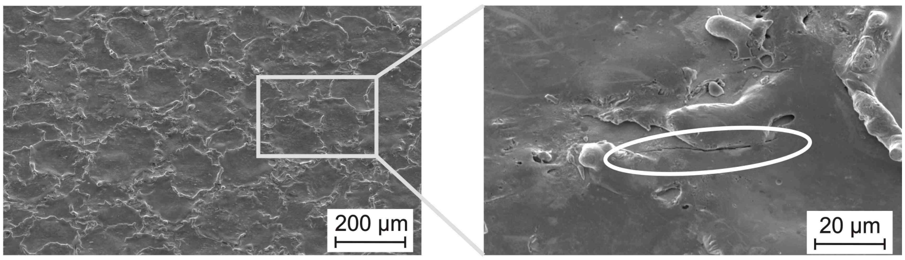


Fig. 5. Topography and micro-cracks generated by pre-finishing (EDM).

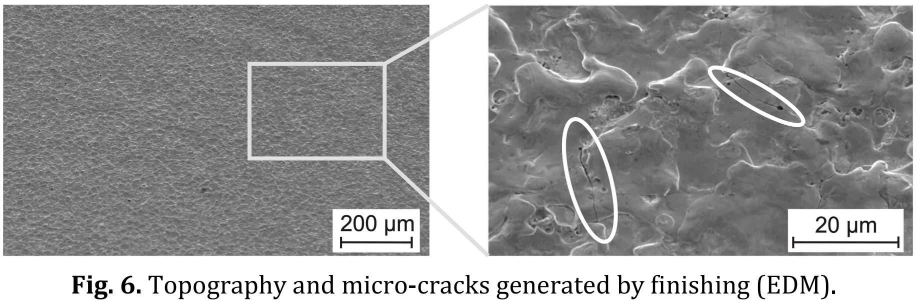


Fig. 6. Topography and micro-cracks generated by finishing (EDM).

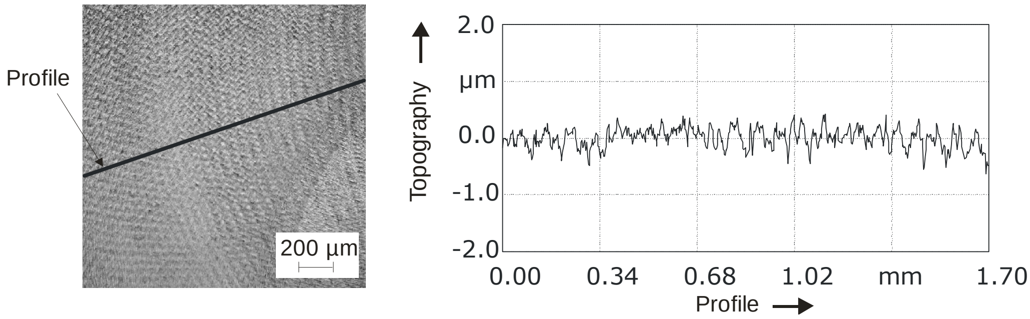


Fig. 7. Topography generated by pre-finishing (grinding).

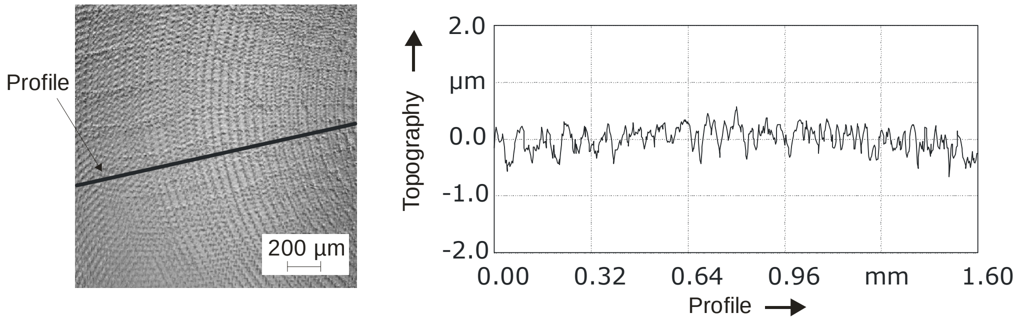


Fig. 8. Topography generated by finishing (grinding).

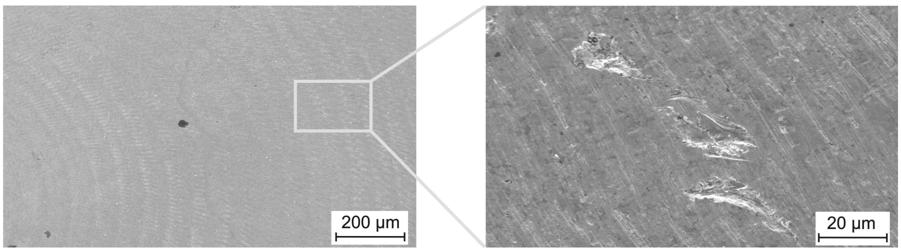


Fig. 9. Topography and surface defects generated by pre-finishing (grinding).

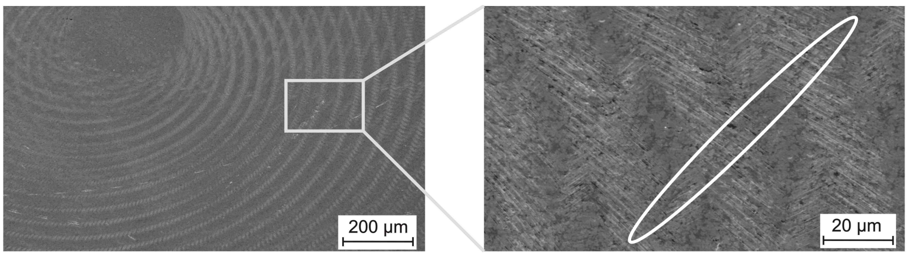


Fig. 10. Topography and surface defects generated by finishing (grinding).

Even though roughness values of grinded surfaces are almost suitable for tool surfaces, surface defects still can be detected. Results of SEM show surface damages induced by pre-finishing (Fig. 9). The surface reveals large notches in the top layer which cause high notch stresses during forming process. To avoid premature tool failure these defects have to be removed by finishing process. Also, finished surfaces include small surface defects in form of grinding grooves which have to be removed by polishing (Fig. 10). The dark regions between furrows reveal already high smoothness as the ground material can be seen. The "fishbone"-structure of the finished surface has its origin in superposition of rotation of abrasive pencil and the circumferential feeding movement of the pencil.

Compared to EDM and grinding, polishing leads to lowest roughness values. Figs. 11 and 12 show the surfaces after final polishing step with a grain size of 7 µm. The polished surface is superposed by a waviness structure. As polishing is manually controlled, removing of roughness is accompanied by creation of waviness because it is difficult for the worker to estimate the polished depth precisely. The pre-finished (EDM) surface has the highest roughness after hard machining process. Since a lot material has to be removed to achieve sufficient surface roughness, pre-finished surface reveals a distinctive waviness. The surface after finishing (EDM) is characterized by low roughness combined with low waviness as less material compared to pre-finishing has to be removed. Achieved asperity reveals that polishing is able to remove high roughness cause by hard machining. This will lead to improved tribological conditions during cold forging-process. Since the surfaces of combined grinding and polishing have a similar appearance to Fig. 12, they are not shown separately.

Figure 13 shows exemplarily the result for the polished surface which was pre-finished by EDM since all surfaces have a similar appearance regardless of hard machining process. The various polishing steps with its different grain sizes down to 7 µm result in a fine surface. Since the roughness produced by hard machining is fully removed, no influences of hard machining can be detected. The figure with high magnification already shows the structure of base material. The WC-grains (bright particles) are surrounded by the Co-binder (dark phase). As the detected grooves reveal a longish shape, they can only result from fine machining. EDM defects would have an irregular shape. The detected little damages might be the result of coarser grain size of former polishing steps. The achieved surface topography represents the current standard of tools applied in cold forging.

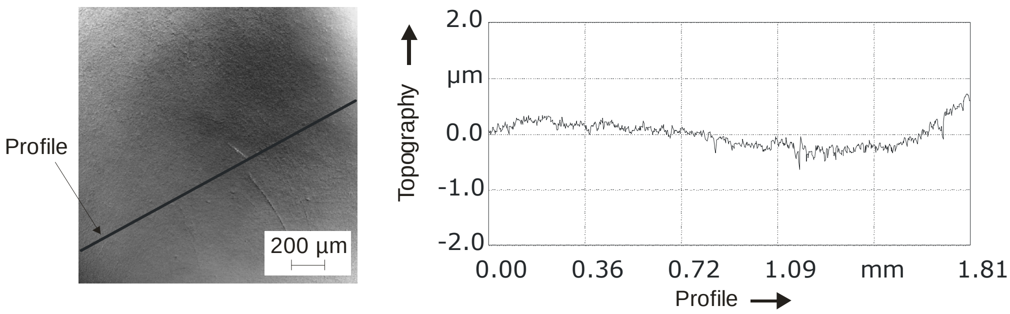


Fig. 11. Topography of polished surface hard machined by pre-finishing (EDM).

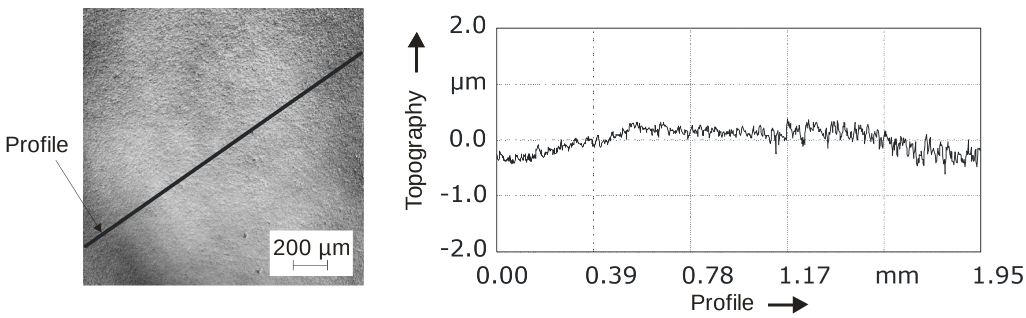


Fig. 12. Topography of polished surface hard machined by finishing (EDM).

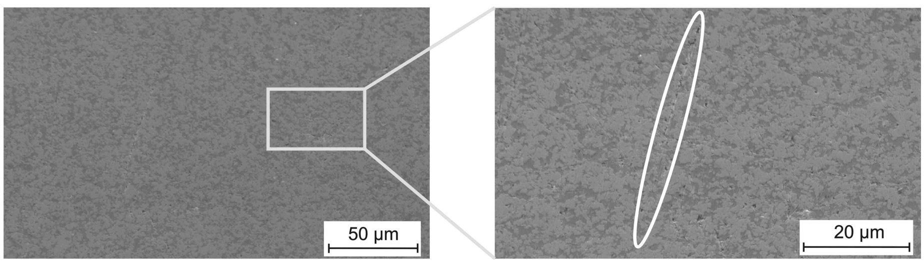


Fig. 13. Topography of polished surface hard machined by pre-finishing (EDM).

4. CONCLUSIONS

Manufacturing forming tools made of cemented carbide requires a combination of hard and fine machining. While hard machining generates the shape of tool, fine machining reduces roughness and removes surface defects to achieve the required surface topography. Due to high hardness of cemented carbide hard machining can only be done by EDM or grinding. EDM generates a surface structure characterized by craters which are positioned side by side and overlap each other. The resulting topography includes micro-cracks induced by thermal influence of EDM-process. In comparison, grinding leads to a straightened surface structure which is characterized by regular furrows. The grinding process is accompanied by grooves in the top layer. Grinding achieves higher removal rates and lower surface roughness compared to EDM. In contrast, EDM enables precise machining of complex geometries. Both machining methods reveal that hard machined surfaces are not sufficient for application in cold forging. To improve surface topography, cost intensive polishing has to remove micro-cracks and grooves. Results reveal, the higher the roughness caused by hard machining the longer is the required time of polishing since more material has to be removed. As polished surfaces do not reveal any defects caused by hard machining, further investigations of cross sections of specimens will analyze the depths of the effects resulting from hard machining. This will enable recommendations of required polishing depth to achieve suitable surface qualities and reduced polishing effort.

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