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CBN and PCD micro face milling of hardened tool steel for surface texture generation in the lower nanometer range

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Abstract
Cubic boron nitride and polycrystalline diamond micro milling tools offer new possibilities to push the limits of achievable surface roughness in milling of hardened steel towards values in the lower nanometer range and thus, towards the optical surface quality range. In the presented study, micro face milling of hardened X40Cr14 tool steel was performed employing an ultra-precision milling machine. Pre-machined surfaces of 1 x 1 mm² area were stepwise face milled with CBN and PCD milling tools. For CBN milling, a 2-flute end micro mill with a tool diameter of Ø = 0.2 mm was used. The PCD milling tool was ball-shaped with a ball radius of 50 µm and a tool diameter of Ø = 0.1 mm. A 3D optical profiler was used to measure the surface texture. The quality of the milled areas was analysed based on several roughness parameters according to the ISO 25178-2 standard and compared both with the initial ground surface and a mechanically polished sample of the same steel. An arithmetical mean height less than 10 nm could be achieved with the CBN micro milling tool. Combined CBN and PCD milling resulted in an arithmetical mean of 7 nm. Milling marks from previous CBN face milling could be removed by PCD milling and reduced to a minimum, proving PCD milling to be efficient to generate low textured surfaces. Conclusively, the reported results show that smooth, texture-low surfaces can be manufactured in hardened steel by stepwise CBN and PCD milling, which may be of certain interest for several fields such as precision mold making.

Keywords: Cubic boron nitride (CBN), face milling, roughness, super finishing

1. Introduction

Steel parts with surface qualities comprising roughness in the lower nanometer range and minimal or any texture are essential for various applications in precision and micro engineering.

On macro-scaled parts or individual part features, smooth and texture-low surfaces are usually generated by mechanical polishing as a finishing step in manufacturing. In contrast, this method is rather uncapable in terms of accuracy and scalability for polishing steel precision components or features of dimensions in the upper micro-scale, which is dimensionally in the range of 1000 µm down to 100 nm [1].

This also affects the design and manufacturing of mold inserts used to mold glass or plastic micro components. Qualitatively, a finished (50 nm ≥ Sa ≥ 10 nm) or even mirror polished (Sa ≤ 10 nm) surface roughness [2] for the mold insert is typically demanded by the molding process or else the later function of the molded part. Commonly applied materials for mold inserts are non-ferrous, nickel-based metals [3, 4], since for these materials the required surface qualities can be achieved by ultra-precision machining using monocrystalline diamond (MCD) tools. MCD tools are, in turn, not applicable to machine ferrous materials due to carbon uptake and thus, blunting of the tool. In spite of this fact, hardened steel still may be a preferable material choice over non-ferrous materials due to material processing, long-term durability and economic reasons.

Technological solutions to achieve the above mentioned surface qualities on micro-scaled features for steel are precision polishing which sophisticated tools [5], abrasive jet machining [6] or shear-thickening polishing [7]. However, these advanced technologies are potentially still limited in their industrial applicability or bring the need of additional machinery.

Recent advancements in cutting tool manufacturing have facilitated the miniaturization of cubic boron nitride (CBN) and polycrystalline diamond (PCD) cutting tools suitable for micro hard milling [8]. The application of these tools follows a stepwise procedure. Hardened steel is pre-processed with conventional processes and then successively machined with a CBN tool and a PCD tool. This procedure is advantageous because the entire surface preparation of features can be conducted in one clamping. Recent studies investigated the effect of different machine setups and processing parameters on the surface integrity [9, 10]. The results revealed promising advancements in the generation of mirror polished-like, low roughness surfaces on steel comparable to surface qualities only achieved by mechanical polishing. However, an in-depth study on obtainable surface qualities has not yet been conducted to the authors knowledge. This kind of analysis is enabled by surface roughness measurement in accordance with the ISO 25178 standard series.

In this study, hardened and ground mold tool steel was micro face milled with CBN and PCD micro milling tools. As distinct from other studies, this study focuses on the evaluation of surface roughness and texture of hardened steel in CBN and PCD machining. The analysis of the differently manufactured surfaces was conducted by means of several areal surface texture parameters as standardised in the ISO 25178-2 standard. The initial ground surface as well as the surface of a mechanically polished sample were considered as a reference. The achieved results clearly demonstrate the capabilities of CBN and PCD hard machining in terms of surface quality.

2. Methodology

The methodology used for micro face milling and measuring the surfaces in this study was as described in the following.

2.1. Materials and micro face milling experimental methods

Conventional tool steel X40Cr14 ESR (Meusburger Georg GmbH & Co KG, Wolfurt, Austria) was chosen as sample material due to its importance in mold making. Cuboid-shaped samples with a size of 20 x 20 x 10 mm³ were pre-machined by milling. Subsequently, the samples were hardened and tempered to a hardness of 52 HRC. After the thermal treatment, the planar surfaces were surface ground to achieve a sufficient parallelism of the surfaces. Finally, geometric features with a respective height of 1 mm and an area of 1 x 1 mm², which served as test fields for CBN und PCD milling, were milled into the samples. The ground surface texture represented the initial condition for the upcoming micro milling operations. The design of the sample used in this study for the micro face milling operations is shown in Figure 1.

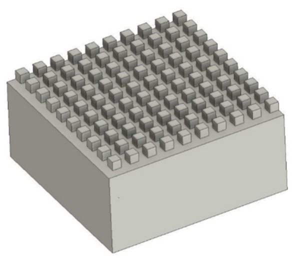

Figure 1. Sample design used for micro face milling

Micro face milling with CBN and PCD micro milling tools was conducted with an ultra precision milling machine KUGLER Micromaster 5X-L (Kugler GmbH, Salem, Germany).

For CBN, a 2-flute micro end mill (NS TOOL Co., Ltd., Tokyo, Japan) with a tool diameter of Ø = 0.2 mm was used. A ball-shaped PCD micro mill (NS TOOL Co., Ltd., Tokyo, Japan) with a ball radius of 50 µm and a tool diameter of Ø = 0.1 mm was used for the finishing of the previously CBN face milled surfaces. The milling parameters were experimentally determined in advance. CBN micro face milling of the ground surfaces was performed with a spindle speed $n = 50\ 000\ min^{-1}$ and a feed per tooth $f_z = 2$ µm/tooth. The axial and radial depth of cut was set to $a_p = 3$ µm and $a_e = 30$ µm. In total, 36 fields were micro face milled in perpendicular direction to the grinding marks.

PCD micro milling with the ball-shaped tool was conducted on previously CBN micro face milled surfaces in one clamping operation. A spindle speed $n = 45\ 000\ min^{-1}$, a feed rate f = 50 mm/min and an axial and radial depth of cut of both 1 µm were set as cutting parameters. Again, 36 fields were machined. UNILUBE 2032 (Unilube AG, Berg TG, Switzerland) was used in all milling operations as cutting fluid.

Figure 2. shows the two milling tools used in this study prior to the micro face milling experiments. The images were taken using the scanning electron microscope unit of a FEI Helios NanoLab 600 (FEI Company, Hillsboro, USA) FIB-SEM.

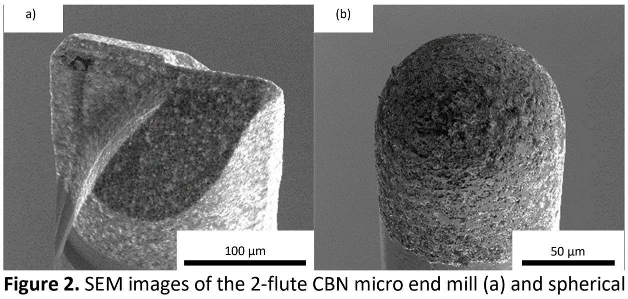

Figure 2. SEM images of the 2-flute CBN micro end mill (a) and spherical PCD ball end mill (b) used in this study

A cylindrical mechanically polished sample made of the same tool steel served as a reference for the surface texture analysis. The steel was first processed equally to the samples used for the milling operations and then mechanically polished by an industrial mold polisher.

2.2. Surface analysis

For a qualitative analysis of the surfaces, a 3D digital microscope Hirox RH-2000 (Hirox Co., Ltd., Tokyo, Japan) was used to acquire images of the respective surfaces in the ground, CBN micro face milled, PCD micro face milled and polished condition. All surfaces were captured under the same lighting conditions.

The areal surface texture measurement of the processed steel surfaces was conducted using a 3D optical profiler ZYGO Nexview NX2 (Zygo Corporation, Middlefield, USA) equipped with a 50x-magnification objective (numerical aperture 0.55, field of view 0.17 x 0.17 mm²). The measurement data processing followed by the surface texture analysis was performed with the instrument-specific software ZYGO Mx. In accordance with the ISO 25178-2, a scale-limited (S-L) surface has to be obtained by data processing for the characterisation of the areal surface roughness. In this study, the data processing was conducted as briefly described in the following.

First, a Gaussian spline filter with a nesting indice $N_{is} = 0.0005$ mm was set as S-Filter to obtain the primary surface. Second, a plane form removal filter was applied as F-operator. Last, a Gaussian spline filter with a nesting indice N_{ic} equivalent to the respective x-/y-side lengths of the evaluation area cropped out from the primary area was applied. Since the measurement of smooth surfaces is susceptible to errors, a spike clip was applied on the S-L surfaces acquired for the CBN and PCD processed and polished surfaces.

For an initial surface texture analysis, all micro face milled feature surfaces were measured. For the generated data, a S-L surface (Nis = 0.0005 mm, F-operator plane, $N_{ic} = 0.15$ mm) was obtained. The areal arithmetic mean height Sa [nm] was evaluated for an area of 150 x 150 µm².

The three features with the lowest Sa values were considered for the in-depth analysis of surface texture evolution in CBN and PCD micro face milling compared to the ground surface condition and to the surface of the reference steel sample. For this further analysis, the measurement of three ground surfaces, the three CBN and PCD processed and the polished steel surfaces was repeated in stitch measurement operation for a measurement field size of 1 x 1 mm². A S-L surface (Nis = 0.0005 mm, F-operator plane, $N_{ic} = 0.5$ mm) was obtained for an evaluation area of 500 x 500 µm².

Finally, the areal surface texture was evaluated by means of the following parameters given in the ISO 25178-2 standard:

- Height parameters: arithmetical mean height Sa [nm], root mean square height Sq [nm], maximum height Sz [nm], kurtosis Sku [-], skewness Ssk [-]
- Functional parameter: core surface height Sk [nm]
- Spatial parameters: texture aspect ratio Str [-], texture direction Std [°]
- Hybrid parameters: root mean square of the surface gradient Sdq [µm/mm], developed interfacial area ratio Sdr [-]

3. Results and discussion

The generated surfaces were first analysed by means of the exemplary microscope images in Figure 3., which show the ground (a), CBN micro face milled (b) and PCD micro face milled (c) surface condition in comparison to the polished reference sample (d). The coordinate system indicates the directions needed for the detailed surface texture analysis. The evaluation

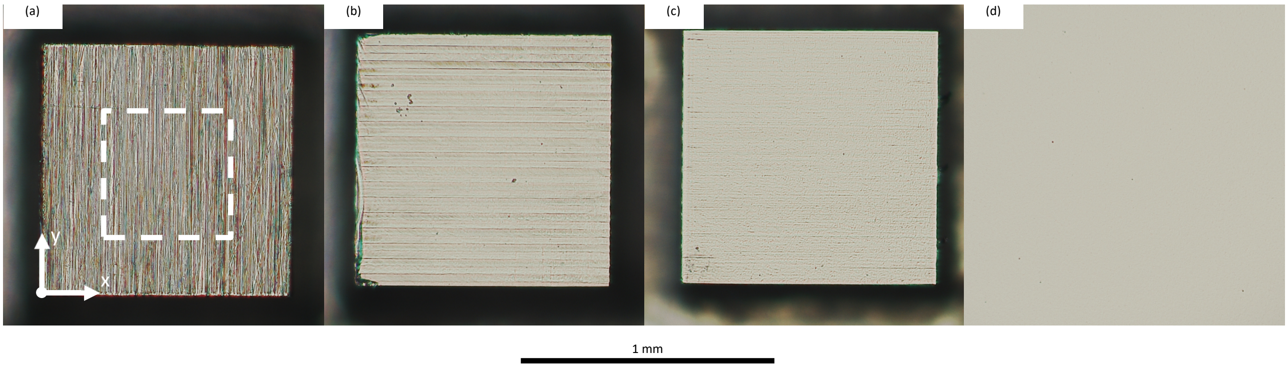

Figure 3. Microscope images of a ground (a), CBN micro face milled (b), PCD micro face milled (c) and polished (d) surface condition in this study

Table 1. Surface texture of face ground, CBN micro face milled and PCD micro face milled X40Cr14 ESR tool steel in comparison to a polished X40Cr14 ESR tool steel reference sample for an evaluated area of 500 x 500 µm²

Sample condition	Sa [nm]	Sq [nm]	Sz [nm]	Sku [-]	Ssk [-]	Sk [nm]	Str [-]	Std [°]	Sdq [µm/mm]	Sdr [-]
Face ground	151 ± 3	193 ± 1	1912 ± 544	4.04 ± 0.60	-0.80 ± 0.27	462 ± 53	0.03 ± 0.01	179.50 ± 0.01	189.065 ± 23.78	1.9239 ± 0.48
CBN micro face milled	12 ± 1	15 ± 2	121 ± 14	3.38 ± 0.44	-0.02 ± 0.19	36 ± 4	0.04 ± 0.02	89.96 ± 0.01	15.371 ± 2.335	0.0131 ± 0.0036
PCD micro face milled	8 ± 1	10 ± 1	77 ± 6	3.13 ± 0.11	0.19 ± 0.10	24 ± 2	0.05 ± 0.03	89.90 ± 0.11	5.499 ± 1.670	0.0017 ± 0.0009
Polished (ref.)	2	3	17	2.92	0.18	7	0.78	90.40	2.802	0.0004

area of 500 x 500 µm² applied for this analysis is indicated by a dashed line rectangle, which is exemplarily highlighted atop of the image of the ground surface.

All surfaces to be evaluated in this study appear to a large extent to be homogenous over the 1 x 1 mm² test field. The ground surface shows a typical appearance marked by parallel machining marks in the y-direction. Compared to the ground surface, CBN face milling decreases the number of residual marks and smoothens the surface. Parallel machining marks in the x-direction with a distance corresponding well with the radial depth of cut of a_e = 30 µm remain clearly visible. Furthermore, individual concentric milling marks, which result from the cutting edge of the turning milling tool, can be spotted. One must point out to the reader that ambient reflections can be seen in scattered light. At the same time, the marks of two consecutive milling paths are spaced close enough to deflect incident light under a certain incident angle. Compared to the CBN machined condition, the PCD micro face milled surface is less textured. The milling marks resulting from the radial depth of cut are pronounced to a minimum, but have not fully disappeared. Concentric milling marks are hardly traceable. Since the used spherical PCD micro milling tool does not have a defined cutting edge, the results of PCD machining implicit a burnishing of the texture generated by CBN micro face milling. In comparison, the polished steel sample shows a typical smooth, isotropic textured surface with hardly any defects.

For an evaluation area of 150 x 150 µm², the arithmetical mean heights are Sa = 140 ± 24 nm, Sa = 9 ± 1 nm and Sa = 7 ± 1 nm for the ground, the CBN machined and the PCD machined condition, respectively. The arithmetical mean height of the polished reference surface is Sa = 2 nm. In this respect, the polished sample has the best surface and was assessed to be applicable as a reference in this study.

These results already imply that surfaces with roughness in the lower nm-range as well as low texture and thus, a mirror polished-like surface quality can be manufactured by stepwise CBN and PCD micro face milling. On the other side, more texture parameters such as spatial parameters are needed to be considered for a more specific analysis of the surface characteristics.

The results of the in-depth surface texture analysis for an evaluation area of 500 x 500 µm² are given in Table 1. The four surface processing conditions are compared by means of the individual parameters.

Again, the arithmetical mean height, as the probably most frequently used measure to quantify roughness in manufacturing, was evaluated for the larger evaluation area. The ground surfaces are with Sa = 151 ± 3 nm within a typical range for precision flat grinding. The smoothing of the steel surface as determined in the qualitative analysis is also reflected in the quantitative data. The resulting Sa is reduced by a factor of around 12.5 times to an average Sa of 12 ± 1 nm. In correspondence with the surface quality classification stated in [2], a finished close to mirror polished-like surface quality has been achieved. A mirror polished-like surface finish is achievable with PCD micro face milling. However, its effect on the resulting arithmetical mean height is for Sa = 8 ± 1 nm relatively low. The polished reference sample exhibited the lowest Sa = 2 nm which is in correspondence with existing literature. The decrease in surface roughness height for the different surface conditions is also recognizable by means of the root mean square height Sq, which is more relevant in optics manufacturing. In general, the root mean square heights are slightly higher than the arithmetical mean height.

This evolution in surface roughness can also be imagined from the maximum height Sz, which is in fact 8 to 12 times the Sa-value of the respective surface conditions. With respect to the higher axial depth of cuts in milling compared to the Sz value of the ground surface, one can determine that the entire surface zone must have been removed and that the Sz of the CBN and PCD micro face milled surfaces is related to the residual tooling marks and thus, the generated texture. However, it must also be noted that Sz may be generally influenced by surface defects, contamination as well as measurement noise, which is particularly reflected in a higher relative standard deviation, especially for the ground surface. A spike clip was not considered here.

The kurtosis Sku describes the sharpness of the surface height distribution with a Sku-value of 3 for a Gaussian distributed topography. In flat grinding, a rather sharp valley-like topography of Sku = 4.04 ± 0.60 is generated due to the penetration of the surface by single grains embedded in the grinding disc matrix. Based on a mean kurtosis value of Sku = 3.38 ± 0.44, CBN micro face milling can generate approximately uniform surfaces. A further harmonization of the surface height distribution through PCD machining can be deduced from the respective Sku = 3.13 ± 0.11. The surface height of the polished reference sample surface is nearly normally distributed, which is in good agreement with previously made statements on the texture.

The distribution of the height is described by the skewness Ssk with symmetry characterised by a mean value of 0. The ground surface height is deviated above the mean. In contrast the skewness of the CBN micro face milled surface is approximated to the mean with a Ssk = -0.02 ± 0.19, indicating that for the chosen milling parameters a homogenously distributed texture height is achieved. The PCD micro face milled surface and the polished surface is slightly negatively skewed by about the same amount.

The core height Sk is defined as the characteristic S-L surface excluded from core-protruding hills and dales. Sk is therefore more robust to errors and presents a reliable alternative to the maximum height Sz. Supported by the presented data of Sk = 462 ± 53 nm (ground surface) and Sk = 36 ± 4 nm, the core surface of a pre-machined surface is significantly reduced and less deviated after CBN face micro milling. Through a further removal of individual surface asperities in the form of milling marks by the PCD burnishing, the core surface is further reduced to Sk = 24 ± 2 nm. The lowest core surface is Sk =7 nm, which was determined for the reference steel sample.

The strength of a texture is analysed by its aspect ratio Str. As for the ground, CBN micro face milled and PCD micro face milled surfaces, the Str values are close to 0. An anisotropic texture can be derived for these surface conditions, which may be explained with the parallel spaced machining marks resulting from the specific cutting direction. In polishing, the material removal of asperities by loose grains is non-directional and results in a higher isotropy of surfaces. In fact, the surface of the polished reference sample is with Str = 0.78 above the threshold of 0.5 and therefore exhibits strong isotropy.

The texture direction Std of the surfaces is measured in the Zygo Mx software relative to the y-axis, as indicated in Figure 3. a). The qualitatively distinct texture directions of the ground, CBN and PCD milled surfaces, as shown in Figure 3. a) – c), are well supported by the quantitative Std-values. With respect to the beforementioned statement on the isotropy of the polished surface, the issued value of Std = 90.40° might be at first unexpected. However, in the Zygo Mx software the Std-value is calculated only by the most dominant lay, which in the presented case was almost perpendicular to the y-axis.

The hybrid parameters mean square of the surface gradient Sdq and the developed interfacial area ratio Sdr are useful to describe the steepness of surface roughness and its interfacial area ratio towards an ideally flat surface. Both the Sdq and the Sdr are particularly higher for the ground and thus, rougher surface. For the qualitatively smoothened surfaces by CBN and PCD micro face milling as well as polishing, the Sdq and Sdr are less pronounced, which also quantifies the smoothing of the surface. Especially for the PCD machined surfaces, the Sdq and Sdr are slightly small with values of Sdq = 5.5± 17 µm/mm and Sdr ≤ 0.01 %. The latter result may be of interest in the scenario of mold making for the molding of liquid-transferring parts, since the developed interfacial area ratio is useful to determine the corrected contact angle in wetting.

5. Conclusion

In this study, the texture of hardened tool steel surfaces generated by stepwise CBN and PCD micro face milling were analysed and compared with a typically ground surface as well as a polished reference surface. The aim of this study was not to investigate the effects of certain CBN and PCD milling parameters, but to present what surface qualities can be practically achieved for a best-practice milling parameter setup.

First, for a S-L surface with a size of 150 x 150 µm² an arithmetical mean height Sa less than 10 nm for the CBN and PCD hard surfaces was generated, which can be qualitatively classified as mirror polished-like finished.

An in-depth surface assessment by means of further parameters standardised in the ISO 25178-2 demonstrated for an evaluation area of 500 x 500 µm² that CBN and PCD micro face milling is highly capable to generate surfaces of low height (proven by means of Sa, Sq, Sz and Sk) with a uniform (proven by means of Sku) and nearly symmetrical (proven by means of Ssk) topography and a comparably high smoothness (proven by Sdq and Sdr), but still with a strong isotropy (proven by Str and Std) compared to polished steel. The findings show that hardened steel components with a surface roughness in the lower nm-range but defined texture can be manufactured, which is not only relevant in the field of precision mold making.

In conclusion, stepwise CBN and PCD micro milling presents an alternative to advanced polishing technologies for hardened steel parts with complex geometry.

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