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Analysis of surface roughness parameters achieved by hard turning with the use of PCBN tools

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Abstract. The turning of hardened steels has been applied in many cases in production. Currently, the most important problem is concerned with the properties of the surface finish. This paper investigates the effect on surface finish in a continuous dry turning of hardened steel when using polycrystalline cubic boron nitride tools. The surface profiles (2D arrangement) and surface topography (3D arrangement), generated during the hard turning operation on an EN 41Cr4 low chromium alloy steel, heat treated to the hardness of 58 HRC, were evaluated. This paper introduces the multiparameter characterization of the surface when cutting with different tool materials.

Key words: surface roughness, hard turning, PCBN tools.

1. INTRODUCTION

The main applications of hard turning are finishing processes, which are characterized by a high level of accuracy in terms of the form and size, and high quality of surface finish and surface integrity in workpieces [1].

Hard turning can provide high accuracy for many hard parts. However, the accuracy of the surface finish is difficult to preserve, because its properties are influenced not only by the process parameters (highly controlled), but also by the variation of the cutting tool geometry and tool edge microgeometry during the cutting process [2]. Moreover, hard turning can influence the workpiece surface microstructure by generating undesirable residual stresses and brittle, “white layer”, which reduces fatigue life of turned surfaces [3].

Hard machining has become possible by using a range of advanced cutting materials such as polycrystalline cubic boron nitride (PCBN). A low depth of cut, small feed rate and large cutting edge radius are typical by hard turning with

PCBN tools. The cutting tool can produce a predictable surface finish, but still the cutting tool geometry is one of the critical process parameters [4,5].

In this study, finish turning tests were carried out using a hardened low chromium steel and cutting inserts (coated and uncoated PCBN tools). The assessment of surface features in both 2D and 3D arrangement are presented in relation to their being produced by coated and uncoated tools.

2. EXPERIMENTAL PROCEDURE

The main aim of this study was the assessment of the surface finish, produced during the process of turning with coated and uncoated PCBN tools. Turning tests were performed on a high rigidity NEF 400 lathe. Bars of low chromium alloy steel, equivalent to EN41Cr4, hardened to 58 HRC, were used. They were 90 mm long with an external diameter of 26 mm.

The cutting tool material used in research was Sandvik polycrystalline cubic boron nitride – CB20 and 7020. The inserts conformed to the ISO code TNGA 160408 S1020 and the tool holder to DTGNR 2525 M 16. Triangular inserts with the same nose radius of 0.8 mm were used. Cutting conditions were selected according to the recommendations provided by cutting tool's manufacturers. The cutting speed was kept at 165 m/min with feed rate of 0.15 mm/rev. Five independent experiments were performed for each cutting tool material.

After each turning test, the surface finish was measured in 2D and 3D arrangements. Two-dimensional data were obtained using the contact technique. A set of the 2D roughness parameters was determined by performing simple roughness measurements using a Taylor Hobson CLI 2000 instrument. 2D surface data were taken along the whole pitch-surface generator and repeated five times in different cross-sections. For roughness parameters the cut-off was set as 0.8 mm with the Gaussian filter.

In addition, 3D measurements were carried out by means of the Talysurf CCI 6000 profilometer. The three-dimensional topographic maps of the machined surfaces were produced using the interferometry technique. 3D data were also taken along the pitch-surface generator but they were collected in five different time points of five sampling lengths. The data were levelled, shape was removed and then parameters were calculated with the Gaussian filter (cut-off was 0.8 mm) [6,7].

In consequence of the measurements, the analysis of the geometrical structure of the surface was done using both profiles and 3D topographies of the surface.

3. RESULTS AND DISCUSSION

3.1. Tool geometry and wear

For cutting tests, uncoated and coated (with a TiN layer, 1 μm thick) inserts were selected. The geometry of both wedges was similar (chamfer normal rake angle $\gamma_n = -20°$, chamfer width 0.1 mm, honing edge radius 0.03 mm). The cutting edge inclination angle of the insert was $\lambda_s = -6°$, whilst the normal rake angle was $\gamma_n = -6°$.

Wedges underwent an analysis in the initial phase of their work, when the tool nose was still coated with the TiN layer. The cutting time was 18 s, which corresponded to the length of the cut of 48 m. After this time, the wedge's durability was not distorted and the wear rate was insignificant, occurring only on the main flank. Figure 1 presents a view of the flank. In the case of the CB20 cutting tool material the wedge's wear was almost unnoticeable. For the 7020 wedge, the wear is outlined by the changeability of material properties in scanning electron microscopy images. Nonetheless, the change in tool geometry is visible only in the areas where the tool edge is rounded.

3.2. Machined surface

Theoretical research on surface roughness focuses on the kinematic-geometrical mapping of the tool nose. Cutting takes place through a part of the rounded tool nose. The radius of the tool nose determines an almost flat stretch parallel to the surface of a length similar to the value of the feed rate.

The theoretical roughness [8], calculated for cutting conditions, is estimated to be 0.807 μm in both cases. The measured roughness, however, is higher than the theoretical value. The reason for this phenomenon is the minimal irremovable layer of the cut material, when cutting with technical edges featuring a non-zero edge radius (Fig. 2a).

Figure 2 shows a field of forces on the cutting edge rounding. It is clear that if the thickness of the cut material is less than the minimum (Fig. 2b, point 1), the

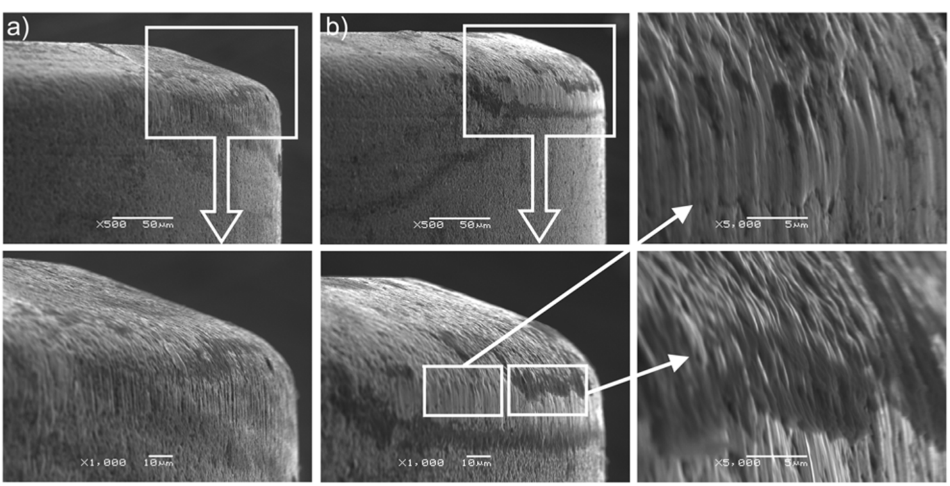


Fig. 1. Tool flank wear for CB20 (a) and 7020 (b) cutting tool material.

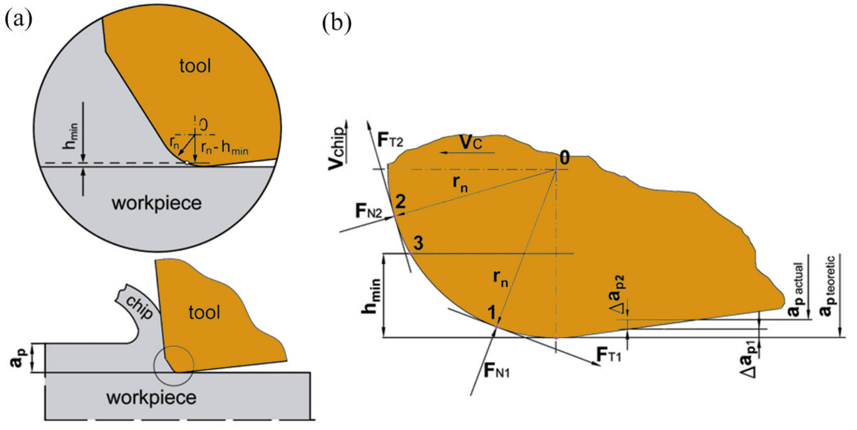


Fig. 2. (a) Model of orthogonal cutting, (b) force field on the rounding of the cutting edge [8].

tangent forces counted on the edge rounding may only have a sense consistent with the direction of the flow of the work material around the rounding.

If we assume that the tool moves, then the relative movements influence the sense of normal and tangential forces on the edge rounding. To allow simultaneous movement of both of the elements toward the flank and rake faces, there must be a point (Fig. 2, point 3) of the separation of the cut layer. Corresponding to this point, the thickness of the cut layer is called the minimum thickness.

During turning, the layer located below the minimum value (h_{min}) moves under the lowest point on the edge, and hence is subjected to very strong plastic deformations. The dimension after the passing of the tool is, therefore, the depth difference between the surface of the base (theoretical value of a_p) and the newly formed cut surface after the passage of the tool (actual value of a_p). This dimension represents two elements: the residual, plastically deformed thickness of cut (Δa_{p1}), and the deeper located part of the material (Δa_{p1}), which elastically returns after the tool pass. It is difficult to estimate the actual value of the depth of cut, different from the theoretical depth, because its value is largely determined by the properties of the workpiece material.

When the edge is unable to remove the material then it is deformed or removed through microcutting, scratching or ploughing. During microcutting, the side flow is detected in the machined material through exposition of the unevenness in the cutting edge, which goes into the material, cuts its parts off during relative movement, piles them up and tears them off. Scratches appear in the machined material because of the protruding element of unevenness of the cutting edge. The phenomenon of scratching is a transitional stage. Ploughing describes the indenting projection of the cutting edge into the machined material and plastic expression of a furrow in it during the relative movement. The material ploughed from the furrow causes repulsion of the material from the wedge in the opposite direction to the feed. Chip material flows in a direction perpendicular to that of the usual chip flow during machining of the hardened steel. This material sticks to the new machined surface and causes a deterioration of the machined surface quality, even if the surface roughness is kept within the desired tolerance. In addition, the adhered material is hard and abrasive, such that it wears any surface that comes into contact with the machined surface.

Figure 3 presents the image of the machined surface, produced in turning with PCBN tools. For optical images, the machined surface after turning was illuminated to expose its features. Both surfaces revealed ridges with side flow. They were perfectly visible both on optical and SEM images as a light, unequal ribbons set parallel along the traces.

The images are a confirmation of the results obtained by Kishawy and Elbestawi [9] and others [10–13]. The presence of the side flow along the ridges is very intensive and material flow is visible also between ridges. In Fig. 3 the burrs, as the result of side flow, are visible for both tools but for CB20 the burrs created on ridges are rarer and more substantial. Similar results for coated/uncoated tools were obtained in [12]. In this research the side flow for uncoated inserts was also more intensive. The phenomenon was explained by a better tribological behaviour of the TiN layer in contact with the cut material. Explanation to that can also be the fact that more heat is conducted into the workpiece when a coated tool is used [14].

The development of the machined surface demonstrates very different mechanisms when considering coated and uncoated wedges. Description is more qualitative when images are concerned. To describe it more quantitative, the surface measurements were performed. In this way further considerations concern the analysis of the machined surface topography in 2D and 3D arrangements.

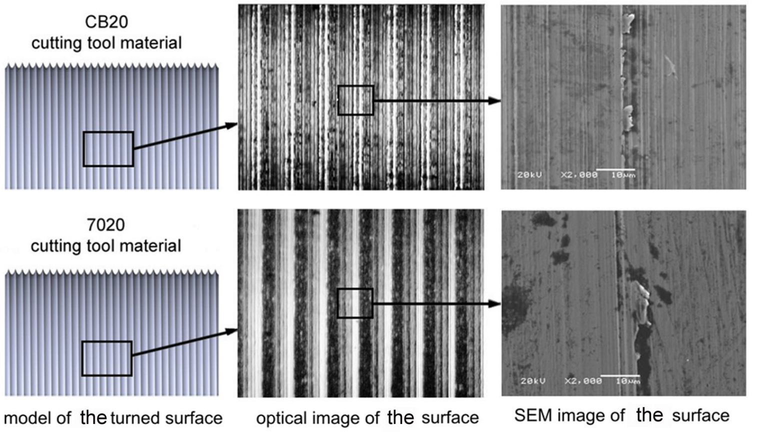


Fig. 3. Optical and SEM images of the machined surface.

3.3. Surface roughness – 2D analysis

Four components of the surface texture can be distinguished in a machined surface profile, namely: form, waviness, roughness and microroughness (Figs. 4, 5).

The wavelength of the form as a component of the surface finish is similar to the wavelength of the object. The deviation of the measured form from the theoretical one demonstrates the rigour-dimensional form-machining but it needs to be removed in order to analyse the surface texture. The surface texture component, varying along the horizontal direction, is called waviness when the changes are slow, and roughness when changes are more rapid.

Roughness is decisive for the visual aspect of the texture, friction and wear. The finest component of the surface texture, composed of high frequencies, is the microroughness. This component is usually very low in energy and is omitted when roughness is evaluated.

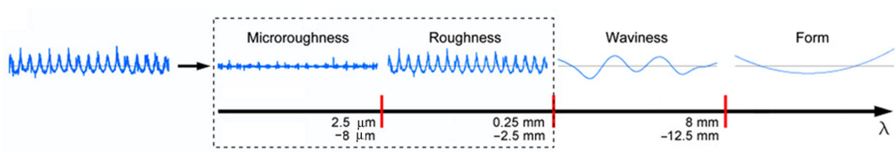


Fig. 4. Components of the surface profile.

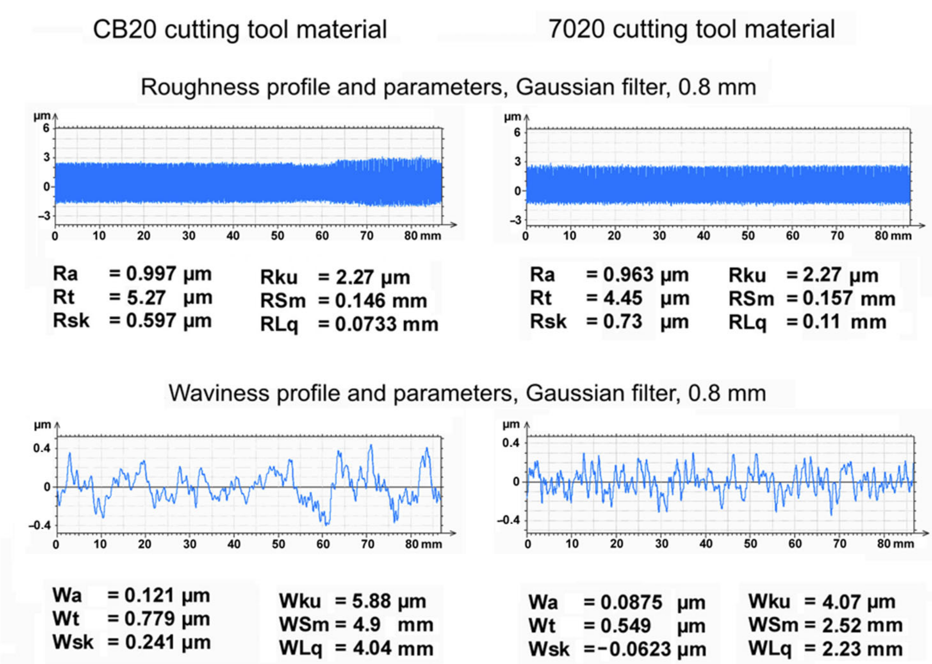


Fig. 5. Machined surface roughness and waviness profiles and parameters.

Due to the repeatability of the profile at the distance of the feed rate's value in terms of roughness, part of the profile of a feed rate length can be distinguished in such a way that the 'outline of the wedge' – the basic shape of unevenness – is obtained. By comparing the proportions in height of the unevenness with length of the basic shape of unevenness (5 μm of height to 150 μm of length of the feed rate) it can be noticed that it is a tiny, almost flat part of the wedge, which is printed on the surface and remains unchanged for a long time, despite the change of the wedge's geometry on the main flank and rake face.

An analysis of the roughness profiles, created by the CB20 and 7020 cutting tools, highlights the differences (Fig. 6). The initial phase of cutting is very similar; parameters are almost identical. This observation is the confirmation of the results obtained in [15–17], where it was stated that the machined surface features are mainly determined by the cutting parameters and tool geometry. Tool wear becomes important for surface generation when it changes the geometry of the tool. Nevertheless, minor changes in the cutting tool geometry (difficult to measure [18] and barely observable) influenced the surface roughness profile for the CB20 cutting tool material. The parameter Rt increased more than 1 μm so that the averaged value for the whole profile was equal to 5.27 μm. For the 7020 cutting tool material the removal of the TiN layer did not influence the machined surface – statistical profile parameters are almost identical.

An analysis of the surface waviness profile demonstrates significant differences for all the parameters. Differences in this case emerge from the difficulties in cutting with a negative rake angle and a large and developed cutting edge.

3.4. Surface roughness – 3D analysis

Traditional surface finish analysis consists mainly of studying the surface texture, consisting of roughness and waviness (Fig. 7). This implies that the other components of the relief (form and microroughness) have been removed.

The relief of an object, measured using a surface finish measurement instrument, can be separated into different components. The notion of wavelength comes from optics and signal processing. The smaller the wavelength, the more altitude variations the surface contains on the same horizontal distance. Topography parameters are calculated according to the ISO 12781 standard, on the basis of a surface levelled by the least square method and then low-pass filtered with a cut-off of 0.8 mm.

An analysis of the topography, displayed in Fig. 8, demonstrates a very smooth surface in both cases. The ridges after the tool pass are almost identical for the same surface and quite dissimilar when considering different cutting tool materials. The range of the height is approximate, though it is smaller for the surface shaped by the coated wedge. The differences are barely noticeable for most of the amplitude, area and volume, and spatial parameters. Therefore their description is omitted.

Observing the contour maps of the surface and the layout of the unevenness one can see differences. The concentration of lines and points on the contour map is

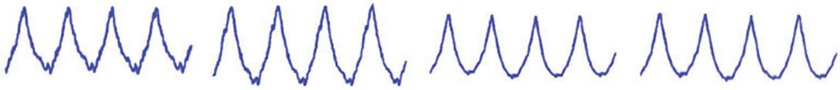
	CB20		7020	
	Time, s			
	0	18	0	18
				
Ra, µm	0.95	1.23	0.957	0.952
Rt, µm	4.29	5.44	4.1	4.12
Rmr, %	13.1	12.8	12.3	11.9
Rsm, mm	0.148	0.156	0.152	0.152

Fig. 6. Machined surface roughness profile.

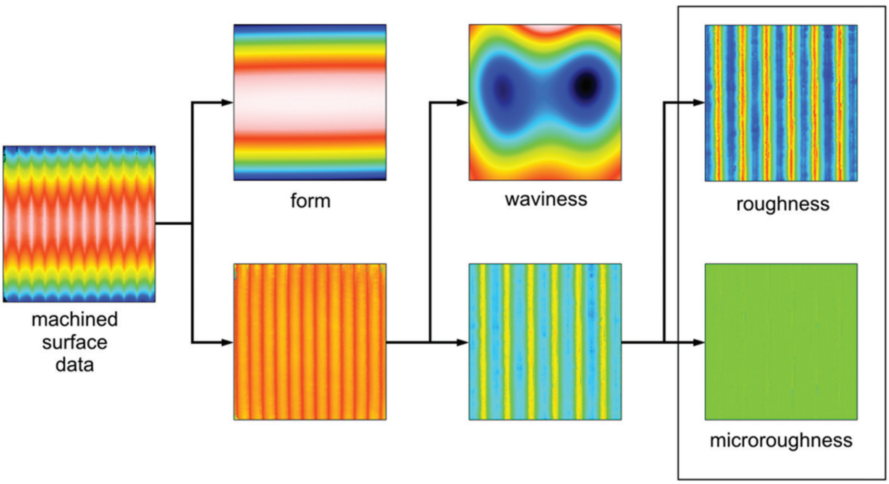


Fig. 7. Components of surface 3D data.

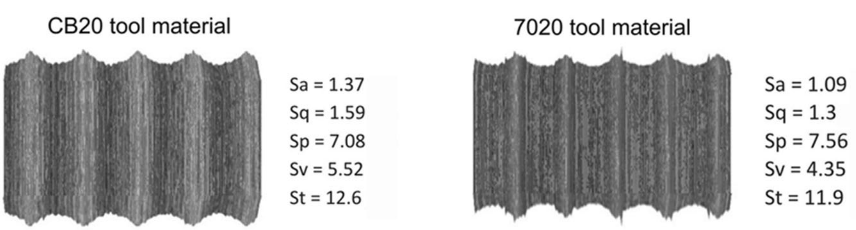
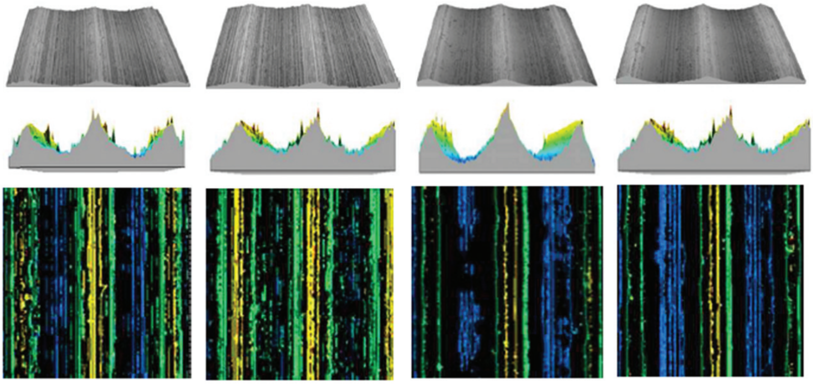


Fig. 8. Parameters of the machined surface in 3D arrangement (in µm).



	CB20		7020	
	Time, s			
	0	18	0	18
Smmr, $\mu m^3/\mu m^2$	3.69	4.35	2.99	2.86
Sds, pks/mm^2	319 799	380 241	143 142	143 158
Sdq, µm/µm	1.06	1.3	0.48	0.47
Ssc, 1/µm	3.82	4.37	2.77	2.59
Sdr, %	33.1	47.8	9.41	8.95

Fig. 9. Parameters of the machined surface topography.

different. Greater randomness of the surface is visible especially in case of the surface, created by the uncoated wedge, more developed without the covering. To describe the visible differences more clearly, several parameters were chosen (Fig. 9).

Mean material volume ratio (Smmr) was selected as the first parameter. This parameter describes the total volume of material of the surface, obtained by measuring the space between an imaginary horizontal plane at the minimum altitude of the surface and the points of the surface. The higher value of Smmr for the CB20 cutting tool material (>3 $\mu m^3/\mu m^2$) indicates that in this case the material volume was subjected to higher wear.

The density of summits in the eight-point neighbourhood (Sds), and root-mean-square slope (Sdq) were selected for the reason that they are able to describe the susceptibility to abrasive wear. The values of the parameters for uncoated tools are nearly twice of those of the coated. These and subsequent parameters confirm the greater complexity of the machined surface for the CB20 as opposed to the 7020.

The arithmetic mean summit curvature (Ssc) shows the mean form of the peaks, either pointed or rounded, according to the mean value of the curvature of the surface at these points. The value of Ssc for the CB20 cutting tool material is greater, and increases with the cutting time.

The developed interfacial area ratio (Sdr) describes the complexity of the surface, thanks to the comparison of the curvilinear surface and the support surface. A completely flat surface has a Sdr about 0%. The Sdr for the CB20 cutting tool material equals 33.1%, whereas this is only 9.41% for the 7020 cutting tool material. Machined surface for CB20 cutting tool is three times greater. For the 7020 cutting tool material the machined surface complexity stays with time, on the same level with a tendency of becoming even smaller. For the CB20 cutting tool material the complexity is so large that it seems that the whole surface in microroughness scale is ragged. The tendency is for the surface to be even rougher with time and tool wear.

4. CONCLUSIONS

Based on the experimental results, 2D and 3D parameters of the surface, produced by hard tuning with PCBN coated and uncoated tools, were selected and analysed.

Hard turning with PCBN tools can produce a very smooth and uniform surface. Deterioration of this surface is caused by the side flow. This phenomenon, described by several researchers, is quite significant when the machined surface is to be the surface finish. Then, the hard and rough burrs on the ridges and between them can deteriorate the surface and its exploitation efficiency.

Describing machined surface with parameters, taken from surface measurements in 2D and 3D arrangements, makes possible the quantitative analysis of the geometrical features of the surface.

In 2D arrangement the machined surface was measured along the pitch-surface generator for the whole time of cutting. The changes were not significant in both cases. For the CB20 cutting tool material, the amplitude parameters increased on average for 20% (Fig. 6).

In 3D arrangements the character of the machined surface was better distinguished than in 2D arrangements. The complexity of the textures for both surfaces was described by five different parameters. 3D images and adequate contour maps of the surfaces, generated by hard turning, allow distinguishing mixed-anisotropic textures when the random part of the generated surface was significantly greater for the CB20 cutting tool material.

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Pinnakaredusparameetrite analüüs PCBN-lõikeriistadega rasktreimisel

Anna Zawada-Tomkiewicz

Karastatud teraste treimist kasutatakse tootmises palju. Tänapäeval on selle kõige olulisemaks probleemiks pinnakareduse parameetrite määramine. Antud töös uuriti viimistleva pinnatöötluse mõju karastatud terase jahutuseta pidevtreimisel PCBN- (polükristalliline kuubiline boornitriid) lõikeriistadega. Analüüsiti kõvaduseni 58 HRC kuumtöödeldud madallegeeritud kroomterase EN 41Cr4 rasktreimisel saadud pinnaprofiili (2D) ja pinna topograafiat (3D). Artiklis on esitatud pinna mitmeparameetrilise kirjelduse metoodika erinevate lõikeriistamaterjalidega töötlemisel.