Surface roughness analysis after machining of direct laser deposited tungsten carbide

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Abstract. In this paper, an experimental surface roughness analysis in machining of tungsten carbide is presented. The tungsten carbide was received using direct laser deposition technology (DLD). Experiments carried out included milling of tungsten carbide samples using monolithic torus cubic boron nitride (CBN) tool and grinding with the diamond cup wheel. The effect of machining method on the generated surface topography was analysed. The 3D surface topographies were measured using optical surface profiler. The research revealed, that surface roughness generated after the machining of tungsten carbide is affected by feed per tooth (f_z) value related to kinematic-geometric projection only in a minor extent. The main factor affecting machined surface roughness is the occurrence of micro grooves and protuberances on the machined surface, as well as other phenomena connected, inter alia, with the mechanism for material removal.

1. Introduction

Tungsten carbide is a material applied mainly in the cutting tools or moulds and dies industries. This field of application is attributed to tungsten carbide's excellent physicochemical properties such as, superior strength, high hardness, high fracture toughness, and high abrasion wear-resistance. However, these unique properties can cause substantial difficulties during machining process, which can result in low machinability. Therefore, machining of tungsten carbide requires the knowledge about the physical effects of the process, as well as appropriate selection of machining method and cutting conditions, enabling desired technological effects. The primary objective of post-process machining of tungsten carbide is to achieve satisfactory geometric and physical properties of its surface texture.

The most popular finishing method of tungsten carbides manufactured by powder metallurgy technology is grinding with the diamond and CBN (cubic boron nitride) wheels. However, in order to produce optical components made of cemented carbide (e.g. spherical mirrors) the profile quality requires a low surface roughness, stringent form accuracy on the submicron scale, as well as a low amount of surface damage [1]. Traditional grinding with the diamond wheels can cause machining-induced cracks and damages to the material. To remove these cracks and damage the ultraprecision grinding can be applied [2, 3]. This kind of process is conducted on the ultraprecision CNC grinding machines, with three – axes movements, and micro-system to deterministically generate, fine, and pre-polish surface. Apart of grinding, recently are seen tendencies to cutting (mainly turning and milling) brittle materials such as, tungsten carbide and reaction-bonded silicon carbide (RB-SiC) by a

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superhard CBN (cubic boron nitride) and PCD (polycrystalline diamond) cutters in cutting conditions assuring ductile cutting [4, 5]. This technique of cutting can be achieved when uncut chip thicknesses are extremely low and a quotient of the tool cutting edge inclination angle to uncut chip thickness is greater than unity (r_n/h>1). In milling process of tungsten carbide by CBN tools, the transition from ductile to brittle cutting occurs at critical depth of cut equal to approx. 5 μm. Therefore, machining with very low cutting conditions is feasible only on ultraprecision machine tools with high rigidity, what is substantial limitation of this technique.

The most popular method for producing tungsten carbide components is by powder metallurgy technology. Nonetheless, for individual, small quantity production or product prototyping this method is too costly and time consuming. The alternative to powder metallurgy, which can be applied to manufacturing of tungsten carbide parts, is Direct Laser Deposition (DLD) technology. This kind of process can be used to quickly produce metallic powder prototypes by a layer manufacturing method [6, 7]. The primary objective of DLD technology is the regeneration of machine parts or machine parts manufacturing with the improved surface layer properties, e.g. higher corrosion, erosion and abrasion resistance. Direct Laser Deposition is an extension of the laser cladding process, which enables three dimensional fully-dense prototype building by cladding consecutive layers on top of one another [8]. Unfortunately parts produced by DLD technology (i.a. tungsten carbide) has an unsatisfactory geometric accuracy as well as surface roughness and requires some post-process machining to finish them to required tolerances [9].

From the previous own – research [10, 11] it is resulting, that machining of direct laser deposited tungsten carbide is feasible and significantly increases surface quality (see Fig. 1).

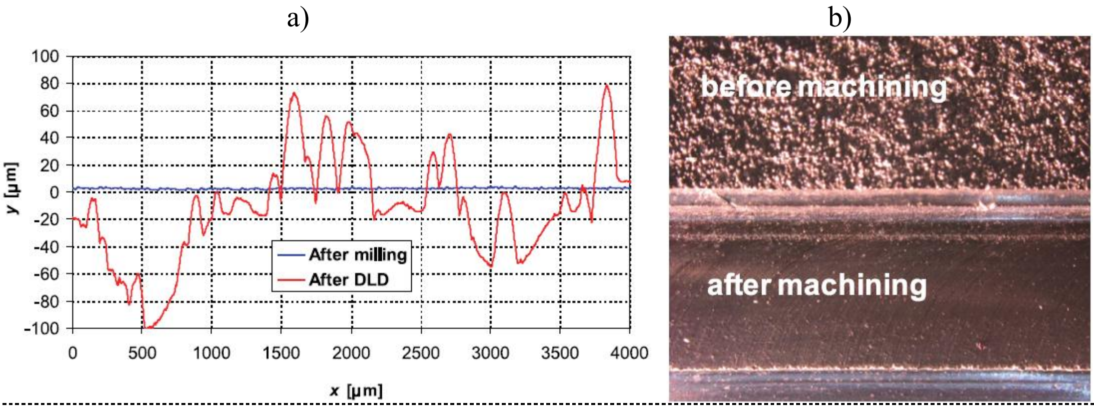


Figure 1. Surface texture of direct laser deposited tungsten carbide: a) 2D surface profile, b) image of surface [12].

However the problem of surface texture generation during machining of direct laser deposited tungsten carbide is still insufficiently examined. Therefore, in this paper the analysis of surface topographies after machining of tungsten carbide is presented. The investigations have also focused on the comparison of surface topographies generated after finish milling and grinding.

2. Research range and method

2.1. Finish milling process

Tungsten carbide received employing direct laser deposition technology DLD (fig. 2) was used as the machined workpiece in this study. The sample was machined during symmetrical face milling process (radial depth of cut – $a_e = D$) with the application of 2-toothed cubic boron nitride monolithic torus end mil (fig. 3). Tool diameter was D = 12 mm, corner radius was r_ε = 0.5 mm, cutting edge inclination angle was $\lambda_s = 0^0$ and the radius of tool arc cutting edge was r_n = 4μm. The cutting tests were conducted in face milling conditions on 5-axis DECKEL MAHO model DMU 60monoBLOCK milling centre.

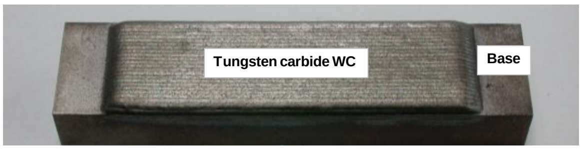


Figure 2. The view of the machined sample.

Figure 3. CBN torus end mill applied in the research.

Surface texture of the tungsten carbide manufactured with the application of the DLD technology is very often characterized by the occurrence of asperities which height usually exceeds 100 µm (see – fig. 1). In order to finish this kind of surface, series of face milling tests with low axial depths of cut a_p and feeds f_z were carried out. During the first pass, cutter was in contact with the highest asperity of the machined sample (see fig. 4). Subsequently, series of passes (number of passes – i = 10) with the constant machining allowance in the tool's axial direction were conducted. Cutting parameters applied in the milling experiments are presented in table 1.

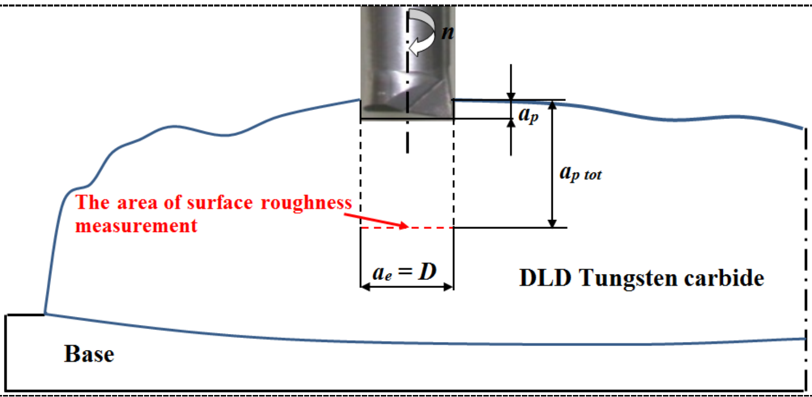


Figure 4. The scheme of face milling process.

Table 1. Cutting conditions applied in the finish milling.

a_e [mm]	a_p [mm]	i	$a_{p\ tot}$ [mm]	f_z[mm/tooth]	n [rev/min]	v_c [m/min]	v_f [mm/min]
12	0.02	10	0.2	0.01	1804	68	36

2.2. Grinding process

Tungsten carbide samples were also grounded during plane grinding process without coolant. The FUM SPC 20B grinding machine was applied. A metal – bond diamond cup wheel with a diameter of 200 mm was used in grinding. The grinding set – up is shown in figure 5. The selected grinding process included two phases, i.e. stock removal and spark out. During the stock removal part axial depth of grinding a_p was selected as 2 µm. Subsequently, sample was sparked out. The number of spark out passes was equalled to 30. These two phases of grinding process were repeated for 100 times in order to finish sample's surface and to obtain total grinding allowance $a_{p\ tot}$ equalled to 200 µm. The detailed grinding conditions are presented in table 2.

Figure 5. The set – up of plane grinding process.

Table 2. Cutting conditions applied in the grinding.

a_p [µm]	$a_{p\ tot}$[µm]	n [rev/min]	v_c [m/s]	v_f [mm/min]
2	200	2400	25	5000

2.3. Surface topography measurement

The 3D surface topographies were measured using optical surface profiler Veeco NT 1100 (see fig. 6). The area of surface roughness measurement is presented in figure 4. The measurements were made with 5x and 20x magnification. During the measurement with 5x magnification the scanning area was equalled to 0.9 mm x 1.2 mm and the distance of vertical points was 1.65 µm. The measurements with 20x magnification were carried out with the scanning area equalled to 0.23 mm x 0.3 mm and the distance of vertical points 0.41 µm.

Figure 6. The optical surface profiler Veeco NT 1100.

As a result of 3D measurements, surface topography charts were received. On the basis of surface topography charts the 2D and 3D surface roughness parameters (*Ra*, *Rz*, *Sa*, *Sz*) were calculated and the Power Density Spectra (PDS) were evaluated using Veeco Vision 32 software.

3. Research results and analysis

Figures 7 and 8 depict namely surface topography and surface roughness parameters of the tungsten carbide sample after manufacturing with direct laser deposition technology (DLD).

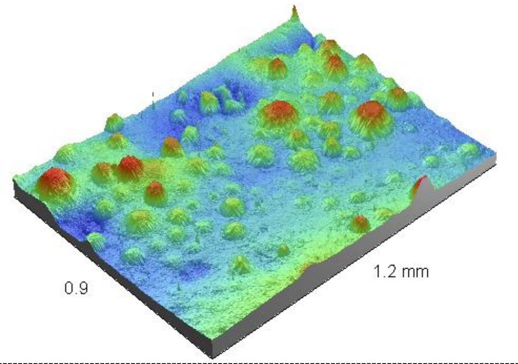


Figure 7. The surface topography of tungsten carbide after manufacturing with DLD technology.

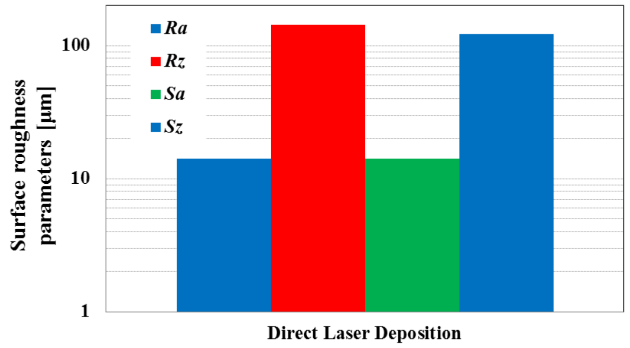


Figure 8. The surface roughness parameters of tungsten carbide after manufacturing with DLD technology.

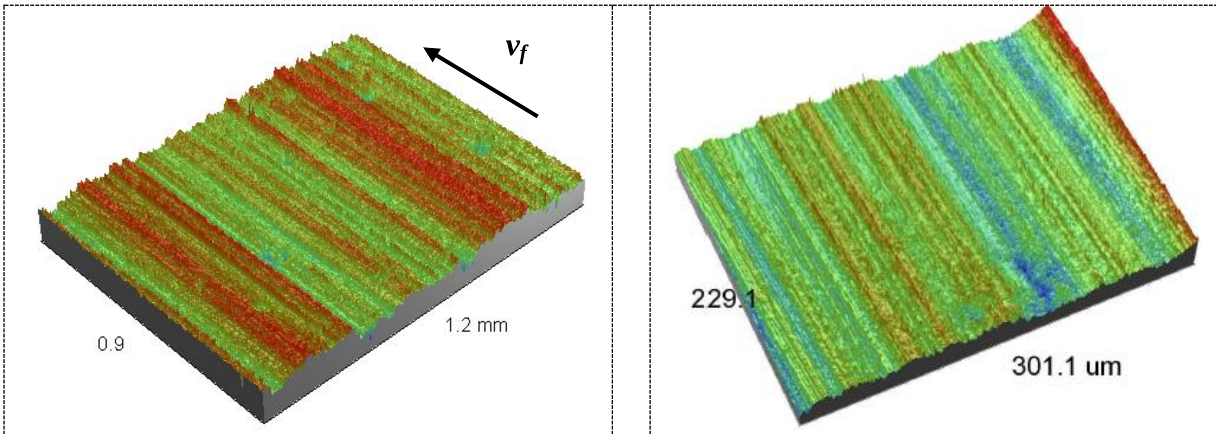
It can be seen, that tungsten carbide's surface (after DLD process) is rough and characterized by the occurrence of irregularities which height usually exceeds 100 µm (see fig. 8). This kind of surface is typical for the materials manufactured by the layer manufacturing methods and requires some post-process machining. Nevertheless these protruding irregularities are remarkably hampering machining by the generation of the sudden cutting force oscillations [12], which as a result can cause cutting edge chipping during milling or fracture of grinding wheels.

The figures 9 and 10 present surface topographies of tungsten carbide samples after grinding and milling. Surface topography after grinding reveals the occurrence of irregularities orientation perpendicular to the feed motion vector v_f. This phenomenon is probably resulting from the projection of the grinding wheel grains into the workpiece. In case of milled sample, the orientation of surface irregularities stays in agreement with the kinematic – geometric projection of cutter into the workpiece. The distance between the irregularities is approximately equal to feed per tooth f_z value, what is especially seen on the sample measured with the 20-fold magnification. It was also observed, that independently of machining method some micro grooves and protuberances on the machined surfaces can be found (fig. 11). Their height very often exceeds 5 µm and thus have direct influence on the machined surface topography. These irregularities are probably resulting from the material discontinuities formed during direct laser deposition process. However this problem requires further studies.

The figure 12 depicts the comparison of surface roughness parameters generated after grinding and milling of tungsten carbide samples. It can be seen that all investigated parameters (*Ra*, *Rz*, *Sa*, *Sz*) have lower values after finish milling using CBN torus mill in comparison to those obtained after grinding. It means that finish milling of hard tungsten carbide parts can be applied as an alternative to grinding process.

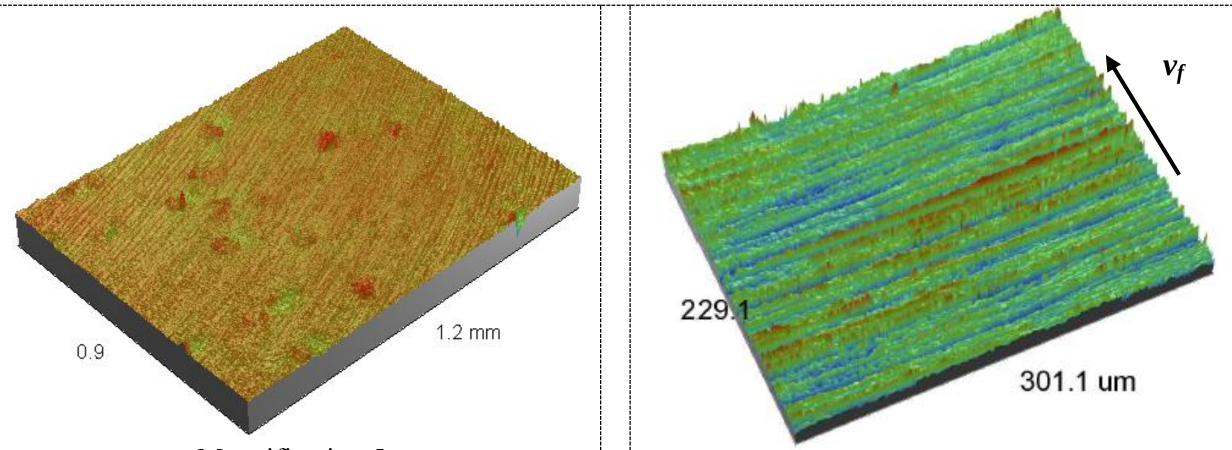
It was also observed, that the value of surface roughness height after milling (described by the *Rz* and *Sz* parameters) exceeds 4 µm, whereas its theoretic value *Rzt*, resulting from kinematic model is scarcely equal to 0.002 µm. This means that surface roughness generation during milling is dependent on the kinematic – geometric projection only in the minor extent. One of the factors, substantially affecting surface roughness height is the presence of previously discussed micro grooves and protuberances on the machined surface. This observation is also confirmed by the power density spectra (Fig. 13, 14) which represent wavelengths of surface irregularities generated during machining. Surface topographies don't consist of wavelengths related to the feed per tooth (f_z = 0.01

mm) or feed per revolution (f = 0.02 mm) values, which occurrence is related to the kinematic-geometric projection of cutter into the workpiece.



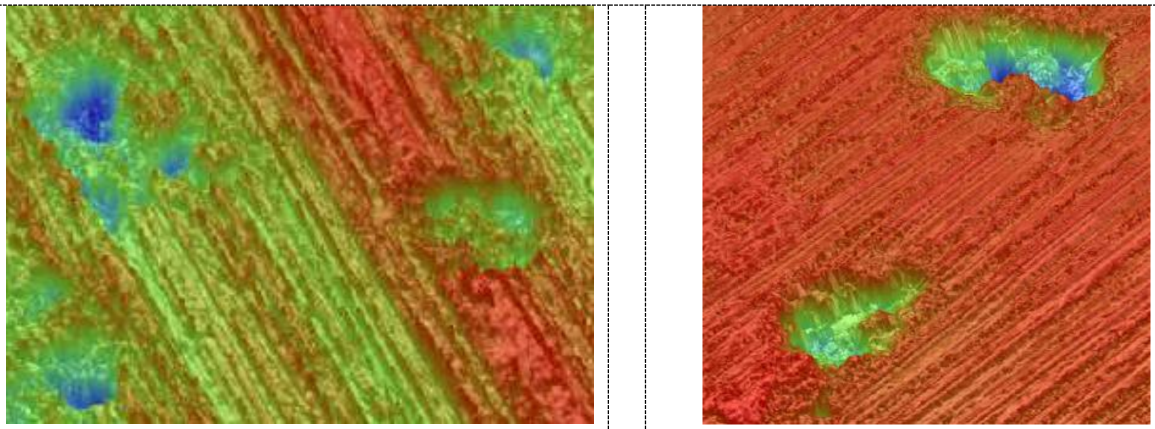
Magnification 5x Magnification 20x

Figure 9. The surface topography of tungsten carbide after grinding.



Magnification 5x Magnification 20x

Figure 10. The surface topography of tungsten carbide after finish milling.



After grinding After milling

Figure 11. The images of micro grooves observed on the machined surface.

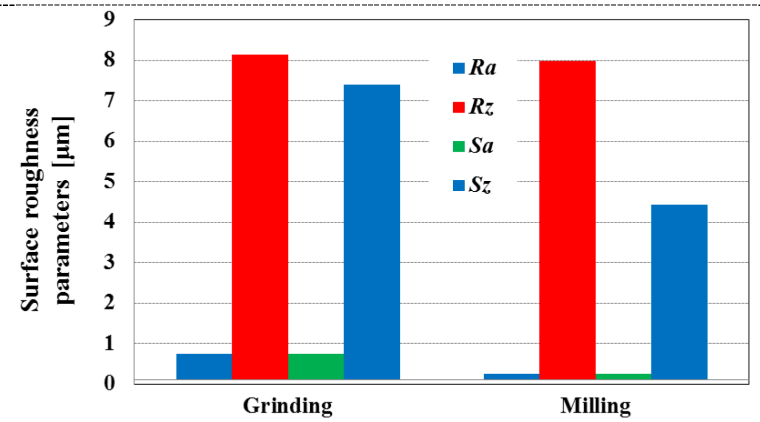


Figure 12. The comparison of surface roughness parameters generated after grinding and milling of tungsten carbide samples.

Instead of these constituents, surface topography consists of wavelengths within the range of 0.05 mm to 0.15 mm. This means that surface topography is affected by the micro grooves and protuberances on the machined surface, as well as the other phenomena (e.g. plastic and elastic deformations of work material, cutting edge notch, variation of the temperature in the cutting zone and some random factors). Surface topography after grinding (Fig. 14) consists also of many wavelengths, which means that it has a random character.

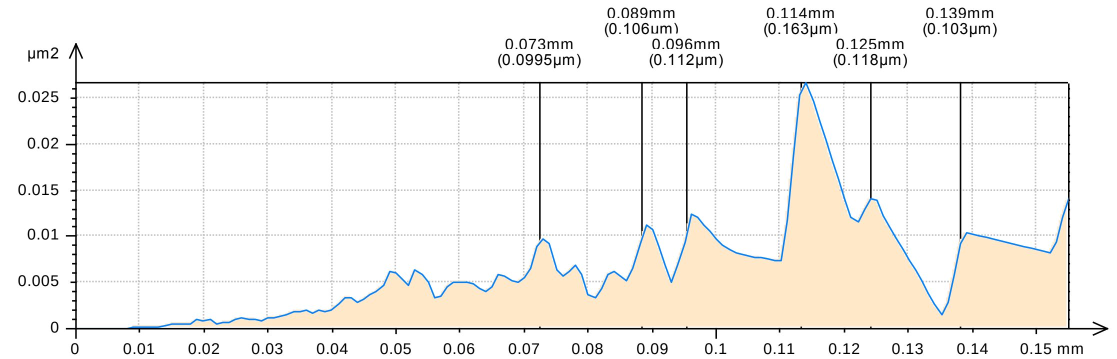


Figure 13. Power density spectrum chart of surface topography after milling.

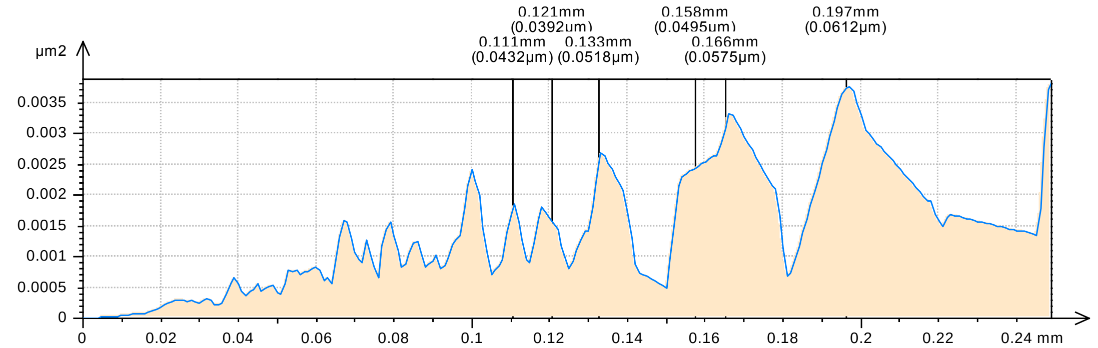


Figure 14. Power density spectrum chart of surface topography after grinding.

4. Conclusions

The investigation revealed, that surface topographies after milling and grinding have different irregularities orientation. These distinctions are resulting from the different milling and grinding kinematics. In case of grinding, irregularities are oriented perpendicularly to the feed motion vector v_f, whereas after milling they stay in agreement with the kinematic – geometric model (the distance between the irregularities is approximately equal to feed per tooth f_z value). Nevertheless, power density spectrum analysis reveals, that surface roughness generation during milling is dependent on the kinematic – geometric projection only in the minor extent.

It was also observed that independently of machining method some micro grooves and protuberances on the machined surfaces can be found. Their height very often exceeds 5 μm and thus have direct influence on the machined surface topography.

It can be seen that all investigated parameters (*Ra*, *Rz*, *Sa*, *Sz*) have lower values after finish milling using CBN torus mill in comparison to those obtained after grinding. It means that finish milling of hard tungsten carbide parts can be applied as an alternative to grinding process. Nevertheless it should be carried out on rigid machine tools and with very low depths of cut and feeds, ensuring moderate tool wear.

5. References

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