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The geometric surface structure of hardened powder tool steels after finish turning using coated and uncoated PCBN cutting tools

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ABSTRACT

Purpose: The work aimed to determine the possibility of replacing the grinding operation of Vanadis 4 Extra Super Clean and Vanadis 23 Extra Super Clean powder steels with a turning operation using PCBN cutting tools available on the market.

Design/methodology/approach: The paper presents test results of the geometric surface structure of tempered steels such as powder steel (Vanadis 4 Extra SuperClean, Vanadis 23 SuperClean) and alloy steel (Sverker 21) after finish turning with coated and uncoated regular boron nitride (PCBN) cutting tools. Selected roughness parameters, 3D topographies, depth and degree of material strengthening, as well as residual stresses on machined surfaces, were studied and analysed.

Findings: An analysis of the machined surfaces of Van4 and Van23 powder steels indicates that the lowest values of both roughness parameters were obtained after machining with TiAlN-coated blades. The conducted analysis has revealed a strengthening of the surface layer of all machined surfaces, regardless of the type of machined material and the type of tool. The surface parameters of Van23 powder steel were similar to the ones obtained after the grinding operation, after machining with each type of tested blade. Van4 and Van23 powder steel surfaces examined had the highest compressive stresses among all turned surfaces.

Research limitations/implications: The research should be extended to include commercially available powder materials and coated tools.

Practical implications: It is possible to obtain a surface layer with properties corresponding to the grinding process in the turning process. Research has shown the possibility of replacing the grinding process with turning. Such a solution is only possible for the tested materials when using a PCBN blade with a TiAlN coating. It does not cause a reduction in the parameters of the surface layer.

Originality/value: The analysis carried out showed many advantages of using coated tools for turning a given group of materials, such as, i.e. lower values of the key roughness parameters of the machined surfaces or the absence of adverse phenomena on the machined surfaces (side flow, material sticking) which adversely affect the functional properties of the surfaces after machining.

Keywords: Powder metallurgy, Coatings, Machining, PCBN, Tempered steel

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PROPERTIES

1. Introduction

Environmentally friendly technologies have gained popularity and are increasingly used in machine parts manufacturing. Aspects related to the ecology in its broadest sense affecting decisions on the selection of optimal production methods concern both issues related to the energy efficiency of the process and minimising the amount of waste generated during the process, which directly affects the cost efficiency of the production process [1]. Powder metallurgy is an intensively developing field of production [2] and is used, among others, in the aviation, medicine [3], automotive, tool [4,5] and machinery industries. Lower energy requirements and the generation of small amounts of waste make its use profitable compared with conventional semi-finished product manufacturing techniques [6], and it is in line with accepted global ecological trends. Powder metallurgy enables using both conventional [7], additive, and hybrid technologies to produce products using metal powders, their alloys, and ceramics [8].

In recent years, there has been a gradually growing interest in using powder tool steels in various industries, primarily due to the well-defined chemical composition and high degree of purity of the materials [9]. According to Erden et al. [10], P/M steels have better microstructure properties than conventional steels due to a more uniform and homogeneous distribution of carbides in the material matrix and their finer grain size. P/M steels are also increasingly used because of their high mechanical strength and wear resistance.

The problem with workpieces made of sintered steel is their low machinability. Machinability is a complex concept defined as a set of measurable quantitative and qualitative parameters, the analysis of which tells about the broadly understood machinability of a material.

The low machinability of P/M steels, compared to that of forgings [11], causes faster wear of cutting tools, resulting in lower machining economic efficiency of the group of materials. The two most commonly discussed aspects of the poor machinability of powder steels relate to their low thermal conductivity due to the porosity of the structure, as well as the repetitive micro impacts of the cutting tool on the workpiece material – the lack of continuity of the structure results in a “quasi-interrupted” cutting action. Low thermal conductivity of the workpiece material results in higher temperatures in the cutting zone, affecting the cutting tool and leading to its faster wear. In turn, microimpacts of the cutting tool on the workpiece material may contribute to the formation of cracks in the applied protective coating and its faster abrasive wear, increasing the final cost of production of finished parts [12]. According to Salak et al. [13], it is one of the reasons for the still low popularity of the materials in industry. However, the described “quasi-interrupted” cutting may contribute to obtaining favourable chip shapes compared to machining conventional materials.

The aspects referred to above make it necessary to use tools with extremely high hardness parameters and resistance to abrasive wear for machining P/M steels. They primarily include polycrystalline cubic boron nitride (PCBN) cutting tools, which exhibit very high operability due to their high strength, oxidation resistance [14], good thermal conductivity and resistance to temperatures as high as 1500°C [15]. They are also chemically inert to iron and its alloys and chemically stable at high temperatures [16], which enables their use in high-performance machining of P/M steels. PCBN tools are divided into two groups, namely the so-called BL group, with a low percentage of boron nitride (CBN) in the cutting tool material (40-70%), and the so-called HL group, with a high percentage of CBN, above 70%.

The machining of “hard” materials, i.e. having a hardness above 45 HRC according to [17], is performed with dedicated cutting tools, which include those made of PCBN. The machining of “hard” materials results, among other things, in a reduction of preparation and manufacturing time and an increase in machining efficiency, which translates into measurable economic benefits. Moreover, the benefits are further increased by the fact that there is no need to use cutting fluids during machining, which affects the pro-environmental aspects of the type of machining [18].

The cutting tool market offers both coated and uncoated cutting inserts. The most common coatings commercially used on cutting tools for steel machining, including in the hardened state, are TiN, TiAlN, and, less commonly, Ti (C,N) applied to cutting tools by physical vapour deposition (PVD). Compared to uncoated tools, coated tools perform better in terms of overall machining efficiency as they are more resistant to wear, especially crater and abrasive wear, as well as to the destructive effects of high temperatures in the cutting zone. Such property is particularly important when using the tools while machining hardened or tempered materials where the temperature at the interface between the cutting edge and the machined workpiece considerably exceeds 800°C [19]. Compared to uncoated CBN cutting tools, TiN and TiA coated cutting tools were characterised by 30 (for TiN coatings) to even 40% (for TiAlN coatings) longer tool life. The property is directly related to the oxidation resistance of these coatings – the beginning of the oxidation process of titanium nitride (TiN) occurs at a temperature of about 400°C. The TiAlN coating, which is an alumina-enhanced TiN coating, oxidises at temperatures above 600°C, thus providing greater resistance to chemical degradation by oxidation.

Using protective coatings (PVD and CVD) on cutting tools allows for more efficient machining of P/M steels [20]. Coated tools, compared to uncoated ones, are characterised by better resistance to mechanical and thermal loads; they reduce friction between the tool and the chip and increase the wear resistance of the cutting tool over wide temperature ranges [21]. According to Fernandez-Abia et al. [22], the thickness, thermal properties, residual stresses, and adhesion of CVD and PVD coatings are different, which is a direct result of the technology of their application on cutting tools. Compared to CVD, PVD coatings provide higher wear resistance due to their high hardness. They are also characterised by compressive stresses that provide greater cutting-edge strength and increase overall tool reliability [23].

The issue of analysing the effect of the type of cutting tools and their condition after turning powder steels is topical. Still, the number of research and test results available in the literature is relatively low because the material group in question has been used in industry for a short time. Studies on the machinability of hardened powder steels (high-speed PN SW7M and special Hoganas OB1 powder steels) with uncoated PCBN tools were carried out by M'Saoubi et al. [24], among others. They showed that increasing the feed rate had the greatest effect on the condition of the machined parts and the wear of the cutting tools during the finish turning process. The results also showed that the tool geometry determined by the tip rounding radius of the cutting tool – r_ε – had no significant effect on the surface roughness after machining.

Comparative studies of selected surface layer properties after grinding and finish turning of "Vanadis® 8 SuperClean" sintered tool steel improved to the hardness of 64 ±1 HRC were presented in Tobola et al. [25]. In both cases, the obtained values of the examined parameters of the machined surfaces (among others *Sa*, *Smr*) were comparable. Moreover, a higher % wear resistance of about 40% was observed for the surface after turning.

Comparative studies of the influence of the binder type on the wear of BL cutting tools during machining of, among others, "Vanadis 4E" powder steel improved to 60 HRC hardness were presented in [26]. The MC carbides contained in the microstructure of this material resulted in the dominance of abrasive and diffusive wear of the tested tools.

The study aimed to determine the technological feasibility of replacing the grinding operation of tempered Vanadis 4 Extra Super Clean and Vanadis 23 Extra Super Clean powder steels with turning operation using commercially available PCBN cutting tools. The paper describes the effect of TiN and TiAlN antiwear coatings applied to PCBN cutting tools on the geometric surface structure of the studied powder steels. The analysis carried out showed many advantages of using coated tools for turning a given group of materials, such as i.e. lower values of the key roughness parameters of the machined surfaces or the absence of adverse phenomena on the machined surfaces (side flow, material sticking) which adversely affect the functional properties of the surfaces after machining.

2. Research tools, materials and methods

High-carbon tool steels were selected for testing:

- Vanadis® 4 Extra SuperClean powder steel (hereinafter: Van4);
- Vanadis® 23 SuperClean powder steel (hereinafter: Van23);
- Sverker® 21 alloy steel (hereinafter: Sv21).

The chemical composition of research steels is shown in Table 1.

Table 1.
The chemical composition of research steels

Material chemical composition, %wt.							
	C	Si	Mn	Cr	Mo	V	W
Van4	1.4	0.4	0.4	4.7	3.5	3.7	-
Van23	1.28	-	-	4.2	5.0	3.1	6.4
Sv21	1.55	0.3	0.4	11.3	0.8	0.8	-

Samples in the form of rolls with the following dimensions: $\varnothing$ = 50 mm, l = 20 mm were subjected to the quenching and tempering process (quenching with subsequent low tempering), which ensured the hardness of the samples of 60±2 HRC. The steel manufacturer carried out the heat treatment – Uddeholm in order to obtain the preferred properties. The structure of both powder steels obtained is characterised by fine carbides evenly distributed in the matrix (Fig. 1a, b). The structure of Sv21 alloy steel (Fig. 1c) is characterised by the occurrence of large primary carbides and fine secondary carbides formed during tempering, the microhardness of which is up to three times higher than the hardness of the martensitic matrix of the material [27].

The machining was performed using the CTX 510 machining centre with the following cutting parameters: v_c = 160 m/min, a_p = 0.2 mm, f = 0.075 mm/rev. The PDJNR2020K11 holder knife was used in the research (κ_r = 93°, α_o = 6°, γ_o = -6°) with DNGA 110408 replaceable inserts (r_ε = 0.8 mm). The research adopted cutting inserts from leading tool manufacturers preferred for machining such a material group. The assumption was made to provide an answer as to which of the cutting inserts available on the market could obtain a favourable condition of the surface layer, allowing the elimination of the grinding process. The material of the cutting tools is presented in Table 2.

Grinding with aluminium oxide (elektrocorundum 99A) wheels with resinous bonds was carried out on an SWA 25 roller grinder.

A JEOL JSM-6400 scanning microscope was used for metallographic examination. The machined surfaces and cutting tools surfaces were assessed on the three-axis optical measurement system Alicona Infinite SL coupled with the IF-Laboratory measurement module.

A ZWICK ZHV10 microhardness tester was used to test the depth and degree of material reinforcement. HV 0.05 microhardness was measured by keeping the distance between the impressions in each direction of no less than 3 of the impression diagonal.

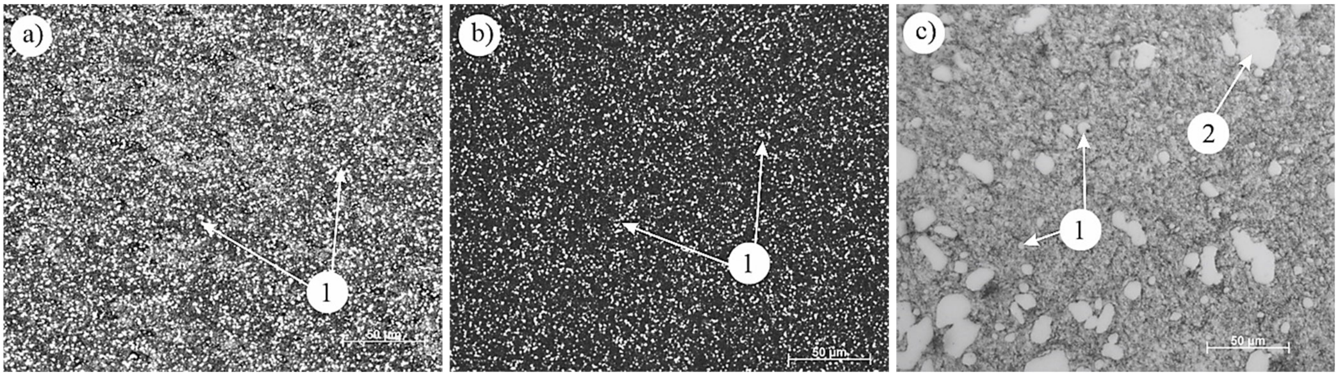

Fig. 1. The structure of the materials used in research (magnification 200x) where: a) Van4, b) Van 23, c) Sv21, 1 – primary carbides, 2 – secondary carbides

Table 2.
Characteristics of the cutting blades adopted for the test

Tool type	T1	T2	T3
Machining type	Continuous and slightly interrupted machining	Continuous machining	Continuous machining
PCBN structure	60% CBN in a ceramic binder	50% CBN in a ceramic binder	50% CBN in a ceramic binder
Coating type	NONE	TiN (PVD)	TiAlN (PVD)
Coating thickness	-	1-4 µm	2-4 µm
Coating hardness	-	2100–2600 HV	2400-2800 HV
Chamfer	BN = 0.1 mm GB = 20°	BN = 0.1 mm GB = 30°	BN = 0.13 mm GB = 25°
Cutting edge radius**	21.7 µm	17.17 µm	25.26 µm
where: BN: chamfer width, GB: chamfer angle; ** – average of 3 measurements			

The residual stress tests on the machined surfaces were performed in the X (perpendicular) and Y (parallel to the roll axis) directions using a Proto XRD x-ray diffractometer using chromium radiation (Fe $2\theta=156,4°$) in Łukasiewicz Research Network - Institute of Non-Ferrous Metals.

Machining was performed without cooling and lubrication, using a new cutting tool to machine each sample.

3. Results and discussion

The geometric structure of the machined surfaces was analysed by comparing the values of the key roughness parameters: *Ra* – arithmetical mean height and *Rz* – maximum height of profile.

Figure 2 shows the measurement results of selected roughness parameters *Ra* and *Rz* after machining for all processed materials and tools. Figure 3 shows an example of surface topography results and actual machined material images.

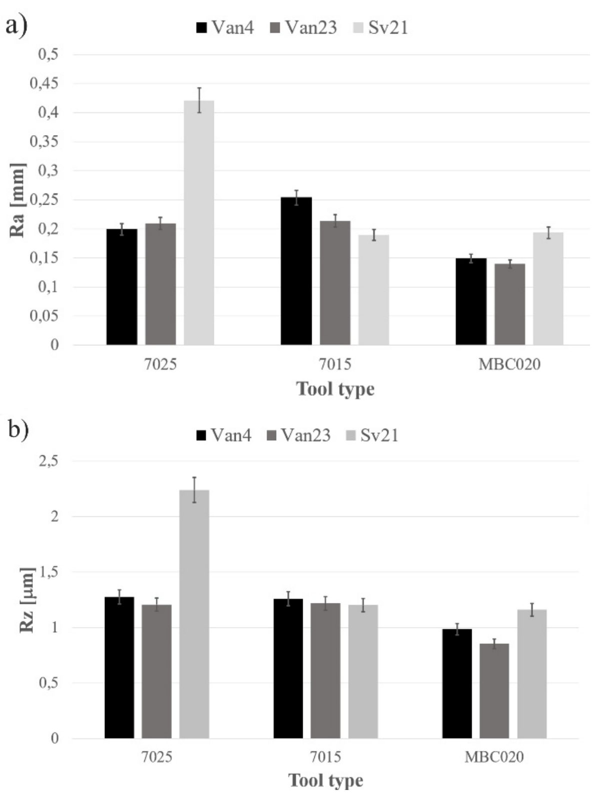

Fig. 2. Measurement results of selected roughness parameters of machined surfaces, where: a) Ra parameter, b) Rz parameter

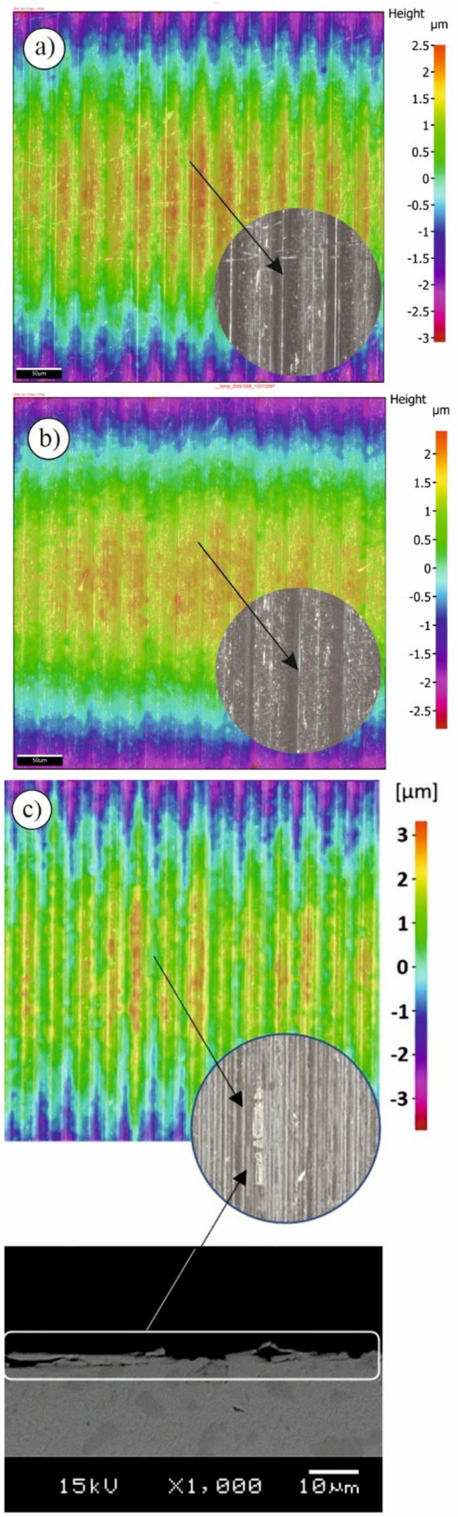

Fig. 3. Examples of surface topography test results, where: a) Van4 – T3 tool; b) Van 23 – T3 tool; c) Sv21 – T1 tool, 1 – material side flow, mag. x200

The analysis of the *Ra* roughness parameter of the tested samples showed that:

- for Van4 powder steel, the lowest influence of the type of cutting tool on the values of the analysed parameter was obtained,
- for Van23 powder steel, the lowest values of the analysed parameter were obtained for surfaces machined with TiAlN-coated T3 cutting tools. In contrast, the highest values were obtained for surfaces machined with uncoated T1 cutting tools.
- for Sv21 powder steel, the lowest values of the analysed parameter were obtained for surfaces machined with TiN-coated T2 cutting tools. In contrast, the highest values were obtained for surfaces machined with uncoated T1 cutting tools.

Ra parameter values obtained for both powder sheets of steel are similar to the surface roughness of the ground parts used as punches and stamping die in the toolmaking industry (*Ra* ~ 0.2-0.3 µm).

The analysis of the *Rz* roughness parameter of the tested samples showed that:

- for both powder steels (V4, V23), the lowest values of the analysed parameter were obtained for surfaces machined with TiAlN-coated T3 cutting tools. In contrast, the highest values were obtained for surfaces machined with uncoated T2 cutting tools.
- For SV21 alloy steel, similar to the *Ra* parameter, the lowest values of the *Rz* parameter were obtained for surfaces machined with TiN-coated T2 cutting tools. In contrast, the highest values were obtained for surfaces machined with uncoated T1 cutting tools.

An analysis of the condition of a surface machined with an uncoated T1 blade on Sv21 alloy steel shows that the most probable reason for the highest value of the examined roughness parameters of the material after machining with T1 blades is the phenomenon of lateral flow, as shown in Fig. 3c. It is manifested by the fraying of the ridges of the bumps in the region of the feed marks and by the outward furrowing of the processed material. The phenomenon may be directly related to the uneven distribution and large size of carbides in the structure of the material (Fig. 1c) and the simultaneous lack of a coating on the cutting edge. It may have affected the mechanism that removes heat from the cutting zone and transfers a smaller amount to the cutting blade. Such conditions promote the plasticisation of the material and often result in the occurrence of the phenomenon. Minor scratches are noticeable on all machined surfaces due to the impact of the chip created by cutting. Besides, no machining effects that could negatively affect their operational parameters were observed on the tested surfaces machined from both Van4 and Van23 powder steel.

Figures 4 and 5 show the results of microhardness and the degree of strengthening of the material depending on the type of cutting tool. The results were compared with measurements of the surface microhardness obtained after the finishing grinding process to *Ra* ~ 0.2-0.3 µm.

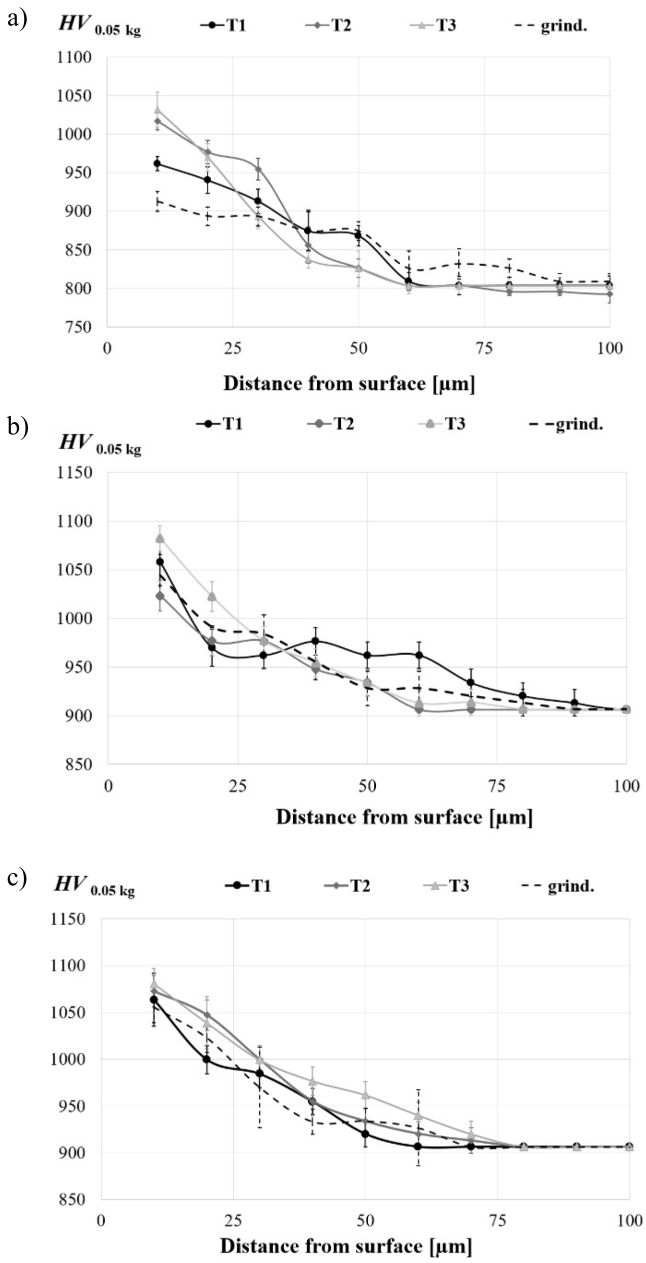

Fig. 4. Results of material microhardness measurements, where: a) Van4, b) Van23, c) Sv21

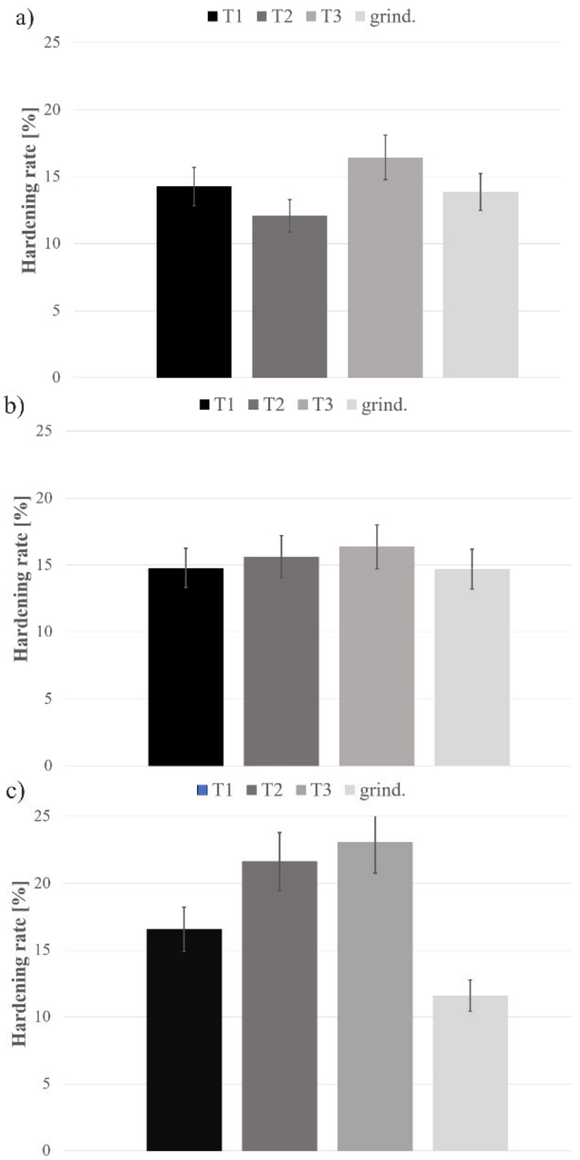

Fig. 5. The degree of material strengthening depending on the type of tool, where: a) Van4, b) Van23, c) Sv21

The analysis of the obtained results indicates a similar strengthening of both powder steels after turning all cutting tools used in the tests. The greatest changes in material microhardness occurred at the surface layer depth of about 50 µm from the outer surface. For all cases analysed, the hardness of the material core was reached at a depth of about 75-100 µm from the outer edge boundary of the machined material. After grinding, the lowest degree of material strengthening was obtained for Sv21 alloy steel. For both powder steels, the degree of strengthening after turning differed slightly from the strengthening obtained after the grinding process. The surface layers of Sv21 alloy steel samples machined with all types of the tested cutting blades displayed a higher degree of micro-hardness and reinforcement than a ground sample of the given material. It can be explained by the phenomenon of the changes in structure that occur in the material during cutting. Microscopic examination has revealed a so-called "dark layer", 30-40 µm thick, which indicates tempering of the material below the strengthened (hardened) surface of the sample. An example of both phenomena for a surface machined with an uncoated T1 blade rev is shown in Figure 6.

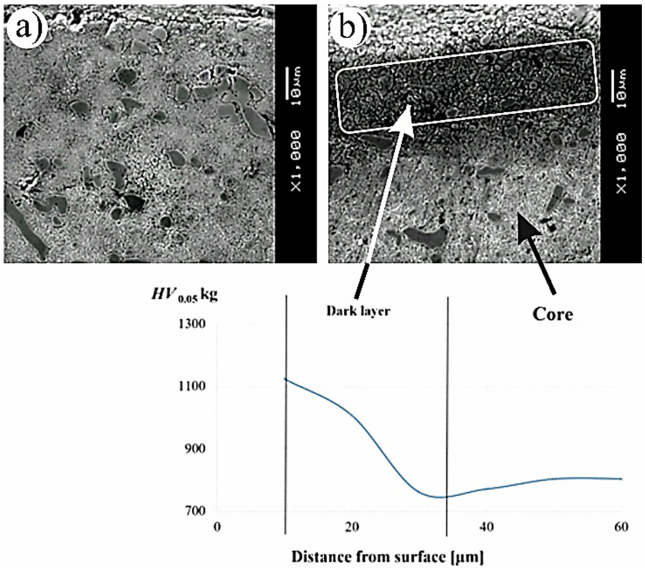

Fig. 6. Changes in the structure of SV21 alloy steel following the turning process after machining with T1 cutting tool: a) before machining and b) after machining

The processing of the tested materials resulted in compressive stresses on both turned and ground surfaces. They were created as a result of the impact of the cutting edge on the processed material, softened by the action of high temperatures in the cutting zone. Figure 7 shows the test results of residual stress on the machined surfaces at a depth of 20 µm in X and Y directions, depending on the cutting tool type. The results were compared with the residual stress obtained after the finished grinding process to *Ra* ~ 0.2-0.3 µm.

The tested materials are characterised by negative stresses (compressive stresses) in both directions. An exception is a sample made of Sv21 alloy steel, machined with the uncoated tool T1, the only one with tensile stress in the X direction. The most probable cause of this situation is the material side flow phenomenon observed on the surface of the sample, an example of which is shown in Figure 3c. In such a case, the processed material was not separated but "pushed" out of the cutting zone due to plasticisation, leaving tensile stresses within the defect.

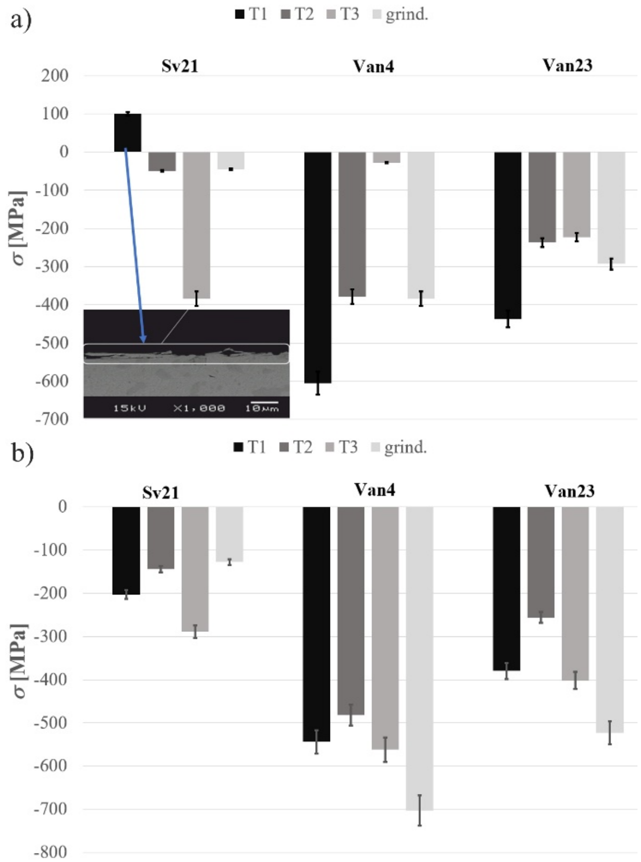

Fig. 7. Results of residual stress measurements at a depth of 20 µm in X (a) and Y (b) direction relative to the surface

The analysis showed that a negative stress value was obtained in the Y-axis direction for all surfaces. The highest negative stress value in that direction was obtained for Van4 powder steel after machining with all tested cutting tools, while the lowest value was obtained for all machined surfaces of SV21 alloy steel. It can be explained by the phenomenon of the transformations occurring in the material during cutting, an example of which is illustrated in Figure 7. The highest stresses characterise the machined surfaces of both powder steels studied, and in the nanoscale, the machining of this type of material is considered as quasi-interrupted machining. Microimpacts of the material having, as in the case of powder steels, a hard weld result in higher deformations of the surface layer compared to continuous machining. Attention should be paid to the different cutting-edge radius values of the cutting tools tested and the different geometry of the protective shear used. The differences result in different deformation of the material and its strengthening during cutting, leaving different stress values in the surface layers of the machined materials.

4. Conclusions

The results of this work can be summarised as follows:

1. The highest values of *Ra* and *Rz* roughness parameters were obtained after machining Sv21 alloy steel with uncoated T1 tools, while the lowest values were obtained after machining with TiN-coated T2 blades. An analysis of the machined surfaces of Van4 and Van23 powder steels indicates that the lowest values of both roughness parameters were obtained after machining with TiAlN-coated T3 blades. *Ra* parameter was 33-56% lower than surfaces machined with uncoated T1 blades and 30-53% lower than those machined with TiN-coated T2 blades. *Rz* parameter, on the other hand, was 29-49% lower compared to surfaces processed with uncoated T1 blades and 23-45% lower compared to surfaces treated with T2 blades.
2. The surface of Sv21 alloy steel machined with an uncoated T1 blade showed the phenomenon of material side flow that directly influenced the highest roughness values of these surfaces. The phenomenon did not occur on surfaces machined with TiN-coated T2 and TiAlN-coated T3 blades. This may indicate that the temperature in the cutting zone was generated below the plasticisation temperature of the machined material, which prevented the occurrence of the described phenomenon.
3. The conducted analysis has revealed a strengthening of the surface layer of all machined surfaces, regardless of the type of machined material and the type of tool. For all examined samples, core hardness was achieved at a depth of approximately 100 µm from the external border of the machined material. The microhardness distribution and the degree of strengthening of Van4 powder steel were similar to the results obtained after grinding operations after machining with uncoated T1 blades. The surface parameters of Van23 powder steel were similar to the ones obtained after the grinding operation, after machining with each type of tested blade.
4. Van4 and Van23 powder steel surfaces examined had the highest compressive stresses among all turned surfaces. The most probable reason behind this is the different deformation mechanisms of a porous material compared to a solid one, leaving different compressive stresses in the surface layers of the treated materials.

It is possible to obtain a surface layer with properties corresponding to the grinding process in the turning process. Such a solution is possible for the tested materials only with a PCBN blade with a TiAlN coating. It does not reduce the parameters of the surface layer. Research has shown the possibility of replacing the grinding process with turning. However, as research has shown, the phenomena occurring during processing may result in forming a surface layer with different parameters for materials with different chemical compositions. Therefore, individually selected tools and coating for the processed material are necessary.

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