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THE INFLUENCE OF CUTTING FLUID AND DIAMOND-LIKE CARBON COATING ON CUTTING TOOL WEAR

Key words: diamond-like carbon coating (DLC), cutting tools wear, friction, turning.

Abstract: The aim of the research was to determine the effect of coolant on the wear of tools made of cemented carbides without a coating and with a diamond-like coating DLC type a-C:H and the quality of workpiece surface. The a-C:H coating was obtained by plasma-assisted chemical vapour deposition PACVD. Identification of the elements included in the cutting tool before and after turning was performed using a scanning electron microscope equipped with an EDS X-ray microanalyser. The face turning was carried out using a numerically controlled lathe. Turning were made without using cutting fluid ("dry") and using a non-toxic cutting fluid containing zinc aspartate. After turning, the wear of cutting tools was measured using a stereoscopic inspection microscope, and the surface texture of the workpieces was examined with an optical profilometer. The research discussed in this article contributed to the development of production thanks to the comparison of materials used for cutting tools for metalworking, as well as in the search for more and more durable cutting tools for extending durability of cutting tools, improving the quality of treated surfaces and reducing machining costs. During the machining process with the cutting fluid aspartate, layers of zinc compounds were formed, which reduced the coefficient of friction and tool wear.

Wpływ chłodziwa i powłoki diamentopodobnej na zużycie narzędzi skrawających

Słowa kluczowe: powłoka diamentopodobna (DLC), zużycie narzędzi, tarcie, toczenie.

Streszczenie: W artykule przedstawiono realizację i wyniki badań, których celem było określenie wpływu chłodziwa na zużycie narzędzi z węglików spiekanych bez powłoki oraz narzędzi z węglików spiekanych z naniesioną powłoką diamentopodobną DLC typu a-C:H. Oceniono również jakość obrobionej powierzchni detalu. Powłokę a-C:H uzyskano techniką chemicznego osadzania z fazy gazowej wspomaganej plazmą PACVD. Identyfikację pierwiastków wchodzących w skład narzędzi przed i po toczeniu wykonano przy użyciu skaningowego mikroskopu elektronowego wyposażonego w mikroanalizator rentgenowski EDS. Toczenie poprzeczne przeprowadzono za pomocą tokarki sterowanej numerycznie. Wykonano toczenie poprzeczne bez użycia chłodziwa – „na sucho" oraz z zastosowaniem nietoksycznego chłodziwa zawierającego asparaginian cynku. Po toczeniu zmierzono zużycie narzędzi skrawających stereoskopowym mikroskopem inspekcyjnym, a teksturę powierzchni obrabianych przedmiotów zbadano profilometrem optycznym. Badania polegały na porównaniu materiałów stosowanych na narzędzia skrawające do obróbki metali, a także na poszukiwaniu coraz to wytrzymalszych, wpływających na przedłużenie trwałości narzędzi, poprawiających jakość obrabianych powierzchni oraz na zmniejszeniu kosztów obróbki. Podczas obróbki skrawaniem z użyciem chłodziwa zawierającego asparaginian cynku powstały warstwy związków cynku, które wpłynęły na zmniejszenie współczynnika tarcia oraz zużycia narzędzia.

Introduction

One of the most frequently used methods of forming products is machining [1], which consists in removing material with the use of cutting tools [1–3]. The method is used in almost all production technologies [1]. During the machining process, tools are subjected to high loads arising during the chip formation process, as well as resistance to motion occurring between the tool and the workpiece. In addition, heat is generated during the deformation of materials and friction, which can cause the tool and chips to overheat and partial overheating of the machined workpieces. The contact surfaces are usually clean and very chemically active; therefore, complex physico-chemical processes take place on them [1, 4, 5]. That is why tools should be made of hard and durable materials that reduce the adhesion of the cutting tool material to the workpiece material.

Carbides are a common material used to produce cutting tools [6, 7]. Cemented carbides are multiphase composite materials manufactured by powder metallurgy consisting of one or more hard phases and a metallic bonding phase [8]. They are characterized by exceptionally high hardness, wear resistance, and excellent strength [6]. One of the drawbacks is their brittleness [6, 7].

In order to improve the mechanical, physico-chemical and technological properties of cemented carbide elements, surface layers can be applied to them. In recent years, there has been a rapid development of research on thin diamond-like carbon coatings applied using chemical vapour deposition (CVD) and physical vapour deposition (PVD) methods. They are widely used in various branches of industry due to their excellent tribological properties (low friction, anti-wear properties), stability and corrosion resistance, high hardness and thermal stability [9–14].

Some coatings have self-lubricating properties and can be subjected to the process of dry machining without the use of cutting fluids. This method is used to avoid problems associated with the use of cutting fluids, such as environmental pollution when disposing of used, hazardous components in fluids used in machining. This form of machining is used in most cutting operations, such as turning or milling of steel, steel alloys and cast iron. Sreejith [15] examined the cutting parameters when machining a relatively soft 6061 aluminium alloy under various machining conditions. He conducted experiments on dry turning, turning with a minimum amount of cutting fluid, and with a large amount of cutting fluid. The results showed that, at high cutting speeds, a good quality of the surface can be achieved even in dry machining conditions. Diniz and Micaroni [16], on the other hand, conducted tests during dry turning and turning with the use of cutting fluids at variable cutting speeds, feed rates, and tool radii. The objective of their research was to determine the best parameter during dry machining. They found that it was necessary to increase the radius of the tool's cutting edge and reduce the cutting speed in order to obtain a good quality surface finish without excessive tool wear. They studied tool durability while improving the surface roughness of the workpiece and energy consumption. Although the use of cutting fluids can improve tool durability, dry machining results in lower energy consumption and better surface finish.

Scientists have developed many techniques to reduce or eliminate the use of cutting fluids. This can be achieved by improving the properties of the cutting tool by, for example, applying a coating to it or developing new tool geometries. Advanced tool materials with a lower coefficient of friction, high hardness, good oxidation resistance, and high temperature resistance can significantly help in dry machining applications. This led to the introduction of advanced materials for the production of cutting tools such as regular boron nitride, cubic polycrystalline boron nitride, polycrystalline diamond, ceramic tools and others [17, 18].

Cutting fluids are also used to reduce tool wear and improve the surface quality of workpieces. They perform many directional functions, such as cooling, lubrication, a reduction in the friction coefficient, improvement in the surface condition, the transportation of chips from the machining zone, temporary protection of the product against corrosion, the extension of tool life, an improvement in the quality of manufactured products and the effectiveness of the machining process, a reduction in cutting force, and a reduction in workpiece deformation [19].

Mineral oil-based machining fluids are often used in machining operations. Statistics show that the costs of purchasing, preparing, maintaining, and removing cutting fluids account for a large share of the total production costs. In addition, global trends favour the environmental and health protection measures. They have contributed to scientific research towards safe/environmentally friendly production. Therefore, dry machining is becoming increasingly common, where the machining makes it possible to use a minimum amount of cutting fluids (Minimum Quantity Lubrication – MQL) as well as use non-toxic and biodegradable cutting fluids [18].

In this paper, the results of experimental studies carried out during dry turning and with a non-toxic cutting fluid containing zinc aspartate and tools made of carbide without and with a diamond-like carbon coating were compared.

1. Test materials

1.1. Tools and Workpiece

The following cemented carbide tools were used for facing: uncoated tools and tools with a a-C:H diamond-like carbon coating. The choice of these tools was dictated by the fact that carbide cutting tools are commonly used in machining. The chemical composition of SM25 cemented carbide is presented in Table 1.

Table 1. Composition of sm25 cemented carbide

Carbide/element	WC	TiC + TaC + NbC	Co
Share, %	69.5	21	9.5

Table 2. The characteristics of a-c:h coating

Microhardness, HV 0.025	Thickness, µm	Coefficient of friction	Coating process temperature, °C	Coating operating temperature max., °C	Colour
2000–4000	1.02	0.05–0.15	160–300	350	black

Table 3. Composition of c45 steel

Element	C	Mn	Si	P	S	Cu	Cr	Ni	Mo	W	V	Cu
Share, %	0.42–0.5	0.5–0.8	0.1–0.4	max 0.4	max 0.4	max 0.3	max 0.3	max 0.3	max 0.1	–	–	max 0.3

The a-C:H coating was obtained by plasma assisted chemical vapour deposition (PACVD). The PACVD process is a CVD process that is supported by glow discharge plasma. This method allows producing thin, hard surface layers, and layers with desired properties, e.g., protective, anticorrosive, and tribological [13]. Compared to CVD, the PACVD method is more effective in the initial phase of nucleation of the diamond structures. This process can produce a cleaner layer of high hardness, thermal conductivity, chemical inertia, as well as electrical and optical properties similar to diamond [20]. In the PACVD process, the pulsed glow discharge occurs at low pressure, resulting in higher internal energy, which allows the process temperature to be reduced from 300°C to 700°C. The process parameters must be carefully selected to match the substrate and coating materials to achieve good adhesion. There are many ways to achieve this, e.g., by changing the composition and partial pressure of the gas, as well as the glow discharge parameters. These control variables ultimately determine stoichiometry, the ratio of sp3 to sp2 bonds, the hardness of the layer, and the functional properties. When depositing ~1 µm/h, the PACVD layers have a dense column structure with a smooth surface that eliminates the need for final polishing [21].

The a-C:H coating has been applied to cemented carbide cutting tools. The properties of a diamond-like carbon coating are shown in Table 2.

The workpiece was a 38 mm diameter shaft made of C45 steel. It is unalloyed, quality steel for quenching and tempering, difficult-to-weld, and its chemical composition is presented in Table 3. C45 steel is used for medium duty machine and device components. Products made of this steel can be surface hardened to a hardness of 50–60 HRC.

1.2. Machining Fluid

An environmentally neutral cutting fluid based on DEMI demineralised water containing a biodegradable polymer – zinc aspartate was used in the tests. A 9% concentration of cutting fluid was used in the tests.

Table 4. Parameters of the demineralised water at 25°C

pH	Conductivity, mS/cm	Maximum resistivity, MΩ – cm
5.0–7.2	$5.5^{-10}\cdot 10^{-5}$ (1.42 µS/cm)	18.2

Table 5. Properties of the cutting fluid containing zinc aspartate

Colour	Scent	pH	Density, g/cm^3	Water solubility
from orange to red	peculiar	9.2–9.7	1.20–1.25	soluble

This fluid contains, primarily the following:

- Alkanolamine borate – 60%.
- Biodegradable oligomer based on zinc poly(aspartic acid) (PASP) – 30%.
- Demineralised water.

The parameters of demineralised water are presented in Table 4.

Zinc poly-asparaginates are the basis for the biostability of the cutting fluid. The physical and chemical characteristics of the cutting fluid containing zinc aspartate are presented in Table 5.

2. Research methodology

The aim of the study was to compare uncoated cemented carbide cutting tools with cemented carbide cutting tools to which a a-C:H diamond-like carbon coating was applied.

2.1. Scanning Microscopy SEM/EDS

The elements forming the cutting tools made of cemented carbides with and without a-C:H coating were observed and identified with the use of a Phenom XL scanning electron microscope with an EDS microanalyser.

2.2. Turning Process

The turning process was performed on a CTX 310 ECO CNC lathe, located in the Conventional Machining Laboratory at the Kielce University of Technology. It is a DMG Gildemeister compact lathe controlled by the Sinumerika 810 system. Facing was performed both “dry” and with the use of a cutting fluid containing zinc aspartate. Table 6 presents the basic parameters of the turning process.

Table 6. Parameters of the turning process

Rotational speed, n, m/min	Turning diameter, d, mm	Cutting speed v_c, m/min.	Feed per revolution, f, mm/rev	Cutting depth, ap, mm
1,257–3,000	38–15.92	150	0.2	0.5
3,000	15.92–0	150–0	0.2	0.5

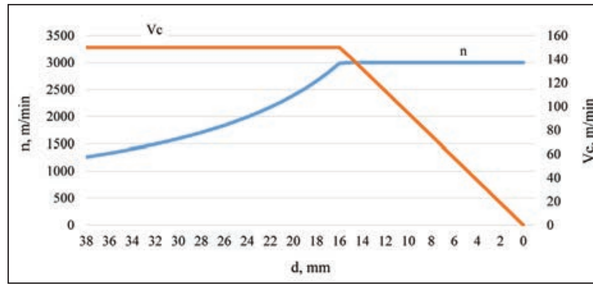

Fig. 1. Dependence of rotational speed and cutting speed on the turning diameter for cemented carbide tools without and with a-C: H coating

Facing was performed, during which 100 passages were made. After machining, the tool and the machined material were tested. The graph in Figure 1 shows the dependence of rotational speed and cutting speed on the turning diameter.

2.3. Geometric Structure of the Surface

The geometric structure of the surfaces of the elements after the turning process was analysed using a Leica DCM8 optical profilometer. In addition, an SX80 stereoscopic inspection microscope was used to observe the wear of the cutting tools after turning.

3. Results and discussions

3.1. Scanning Microscopy SEM/EDS

Figure 2 presents a photograph of the surface microstructure and an analysis of the chemical composition of the elements in the micro-area of the cemented carbide cutting tool.

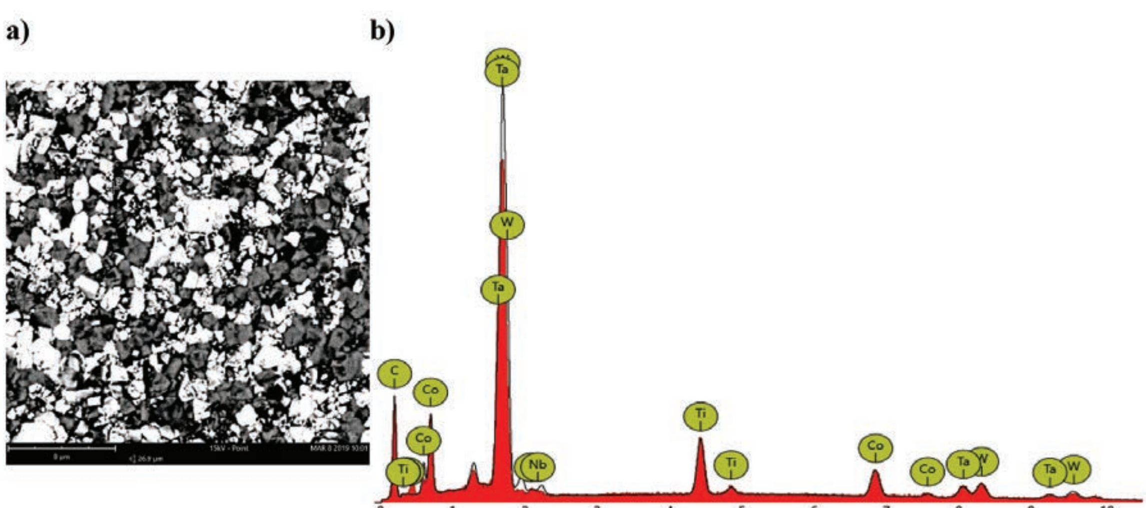

Fig. 2. SEM image: a) surface morphology, b) characteristic spectrum (EDS) in a micro-area for a cemented carbide insert

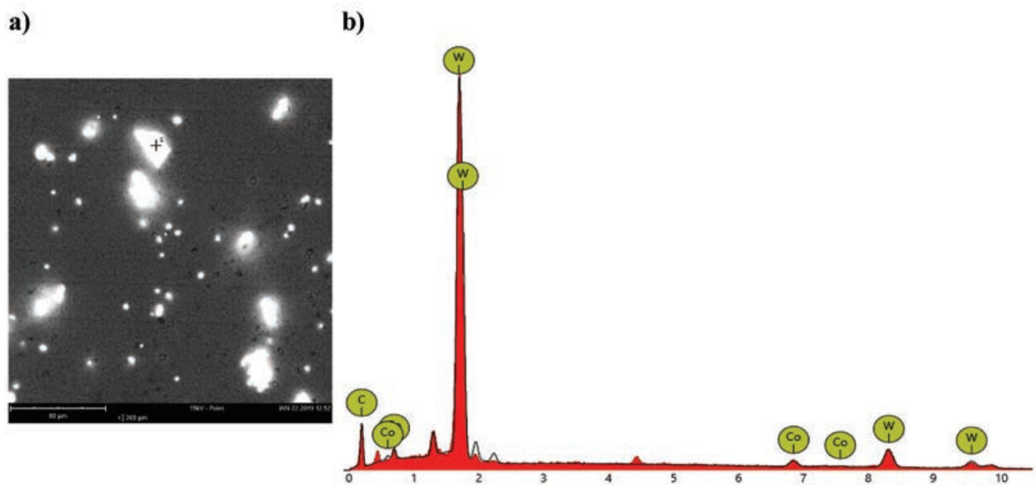

Fig. 3. SEM image: a) surface morphology, b) characteristic spectrum (EDS) in a micro-area for a diamond-*coated* cemented carbide insert

Figure 2a presents the microstructure of the cemented carbide tool surface. It has been observed that it has a rather heterogeneous surface with lighter and darker areas visible. The results of the point analysis of the chemical composition of the tool (Figure 2b) showed a tungsten mass content of 51.58%, tantalum – 32.02%, cobalt – 4.16%, titanium – 3.28, niobium – 0.38%, and the rest was carbon – 8.59%.

Figure 3 presents a photograph of the surface microstructure and an analysis of the composition of the elements in the micro-area of the cemented carbide cutting tool with coating a-C:H.

The microstructure of the a-C:H coating surface (Figure 3a) shows that the coating has a fairly homogeneous surface, although lighter areas are visible. 1.44% cobalt content was identified in these areas. Tungsten content was also recorded at the level of 92.54% of mass. The remaining 6.02% was carbon. In the analysed micro-area, no carcinogenic elements such as titanium, tantalum, or niobium were identified.

3.2. Geometric Structure of the Surface

Photographs of cutting tools were taken using a SX80 stereoscopic inspection microscope, and with the use of the inspection microscope software, measurements of average VB_B and maximum VB_Bmax widths of wear bands on the contact surface were taken according to PN-ISO 3685 [22]. Figure 4 summarises the obtained values of VB_B and VB_Bmax parameters.

The lowest mean value of the width of the band of abrasive wear on the contact surface (VB_B) was observed for uncoated cemented carbide tools, both in case of dry turning and with the use of a cutting fluid. In turn the smallest value of the maximum width of the band of abrasive wear on the contact surface (VB_Bmax) was obtained after dry turning using cemented carbide tools with a-C:H coating (Figure 4b).

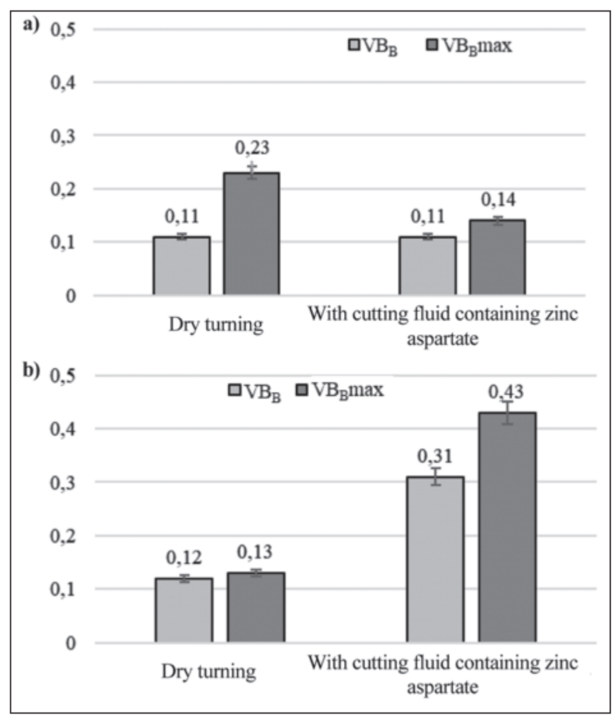

Fig. 4. Wear of the cutting tools made of cemented carbides after turning: a) without coating, b) with a-C:H coating

Comparing uncoated cemented carbide tools with a-C:H coated cemented carbide tools after dry turning, the tool diamond-like carbon coating was better. The VB_B value was slightly higher, and the VB_Bmax value was almost 50% lower. However, after turning using a cutting fluid, the consumption was about 3 times lower for uncoated cemented carbide tools than for those coated with a-C:H. A-C:H coated cemented carbide tools are more effective in dry turning than turning with the use of a cutting fluid. This is due to the self-lubricating property of the diamond-like carbon coating. Such tools do not require lubrication and can be used for dry machining. Uncoated cemented carbide tools, on the other hand, work better when used with cutting fluids. The use of a cutting fluid resulted in a reduction in the VB_Bmax value by about 1.6 times.

Topography and surface profiles of the workpieces after dry turning and with the use of zinc aspartate were observed in the place where the cutting speed was the highest (Figures 5–8).

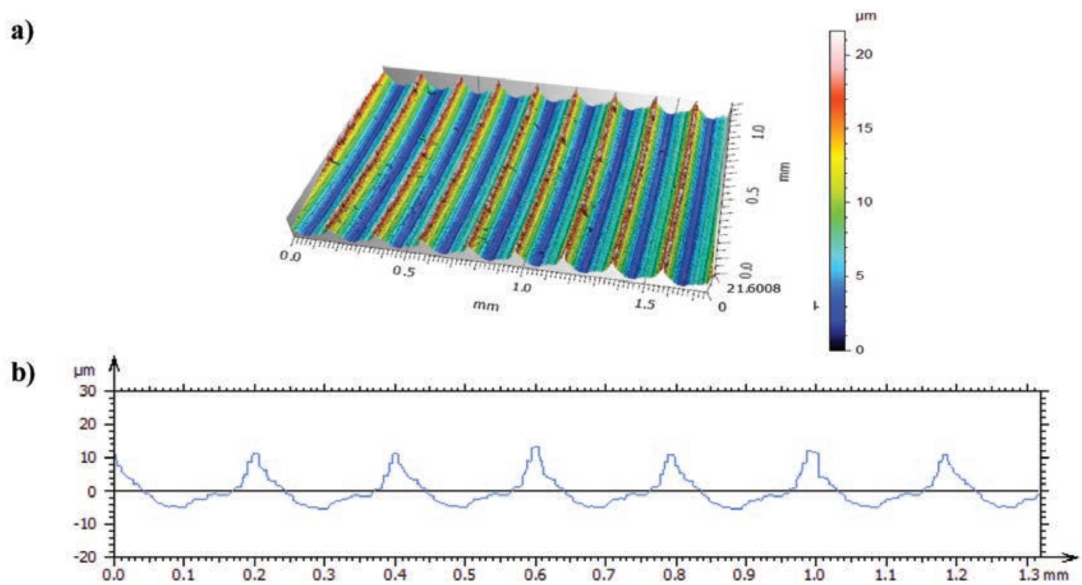

Fig. 5. Surface texture of the edge of the workpiece after dry turning with a cemented carbide cutting tool: a) isometric view, b) primary profile

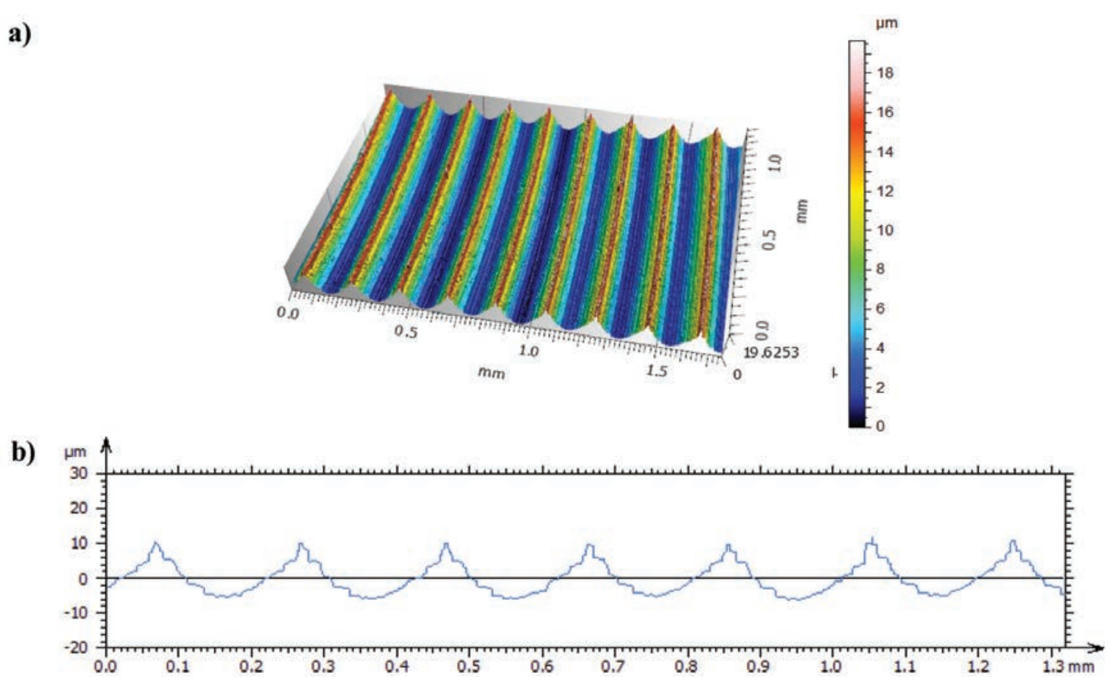

Fig. 6. Surface texture of the edge of the workpiece after dry turning with cemented carbide cutting tool with a-C:H coating: a) isometric view, b) primary profile

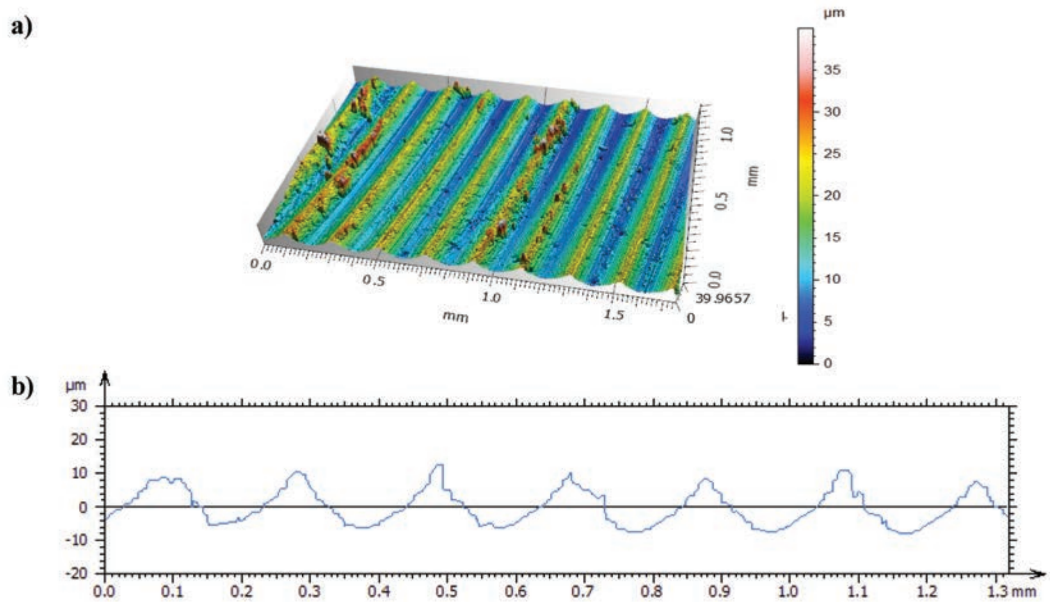

Fig. 7. Surface texture of the edge of the workpiece after turning with cutting fluid containing zinc aspartate with a cemented carbide cutting tool: a) isometric view, b) primary profile

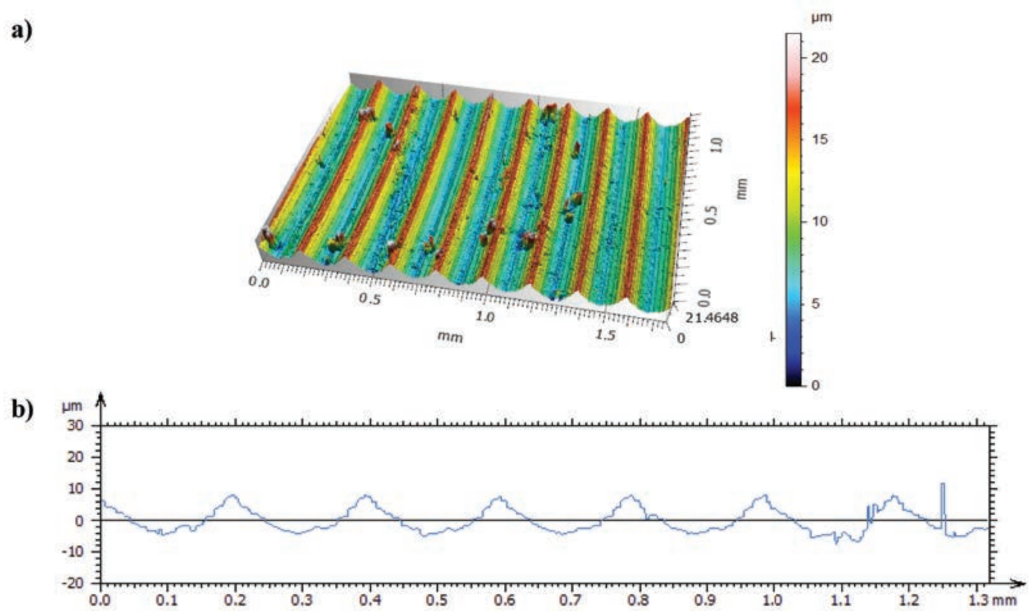

Fig. 8. Surface texture of the edge of the workpiece after turning with cutting fluid containing zinc aspartate with a cemented carbide with a-C:H coating cutting tool: a) isometric view, b) primary profile

The carried-out analyses indicate that the lowest elevations and the shallowest recesses were formed on the workpiece after turning using a-C:H coated cemented carbide cutting tools with a cutting fluid containing zinc aspartate. The parallel tool passages (feed rate: 0.2 mm per revolution) are clearly visible on all workpieces. After dry machining and machining using a cutting fluid with an uncoated cemented carbide tool and after machining using a cutting fluid with an a-C:H coated cemented carbide tool, a few disturbances were observed. Peaks are clearly visible, and a few elevations could have been formed when the particles of the workpiece material transferred with the chip adhered to the workpiece.

Table 7 presents the parameters of the geometric structure of the surface of machined materials produced after dry turning and machining with a cutting fluid containing zinc aspartate.

When comparing the values of surface roughness parameters on the edge of the machined workpieces after the dry turning process and turning with a cutting fluid containing zinc aspartate, the following observations were made:

- The lowest values of Sa, Sq, Sp and Sz were observed for the cemented carbide tool with a-C:H coating after turning with a cutting fluid.
- The lowest Sv value was recorded for the cemented carbide tool after dry turning.
- The lowest Ssk and Sku values were observed for cemented carbide tools with a-C:H coating after dry turning.

Table 7. Surface texture parameters obtained for the discs after turning

Surface roughness parameters			"Dry" turning		With a cutting fluid	
			Made of cemented carbide	Made of cemented carbide with a-C:H coating	Made of cemented carbide	Made of cemented carbide with a-C:H coating
Sa	µm	Arithmetic mean of the height of the area	3.81	3.72	4.6	3.15
Sq	µm	Root mean square height of the surface	4.85	4.39	5.62	3.66
Sp	µm	Maximum height of the area peak	29.55	12.79	25.53	11.52
Sv	µm	Maximum height of the surface recess	8.25	6.84	14.44	9.95
Sz	µm	Maximum area height	37.79	19.63	39.97	21.46
Ssk	–	Surface asymmetry	1.46	0.60	0.75	0.66
Sku	–	Surface kurtosis	5.80	2.34	3.43	2.36

The amplitude parameters of Ssk and Sku are sensitive to characteristic elevations and recesses as well as defects. A positive value of the Ssk parameter indicates elevations with sharpened geometry. Whereas, the Sku parameter (kurtosis) is a measure of the smoothness of the distribution curve of ordinates, which is also called the coefficient of concentration. For the normal ordinates distribution, Sku = 3.

3.3. Scanning Microscopy SEM/EDS

Figures 9–10 present SEM images of traces of tool wear after machining with cutting fluids and a point analysis of the elemental composition.

On tools made of cemented carbides without and with a-C:H coating applied at selected points on the build-up after turning with a cutting fluid, in addition to

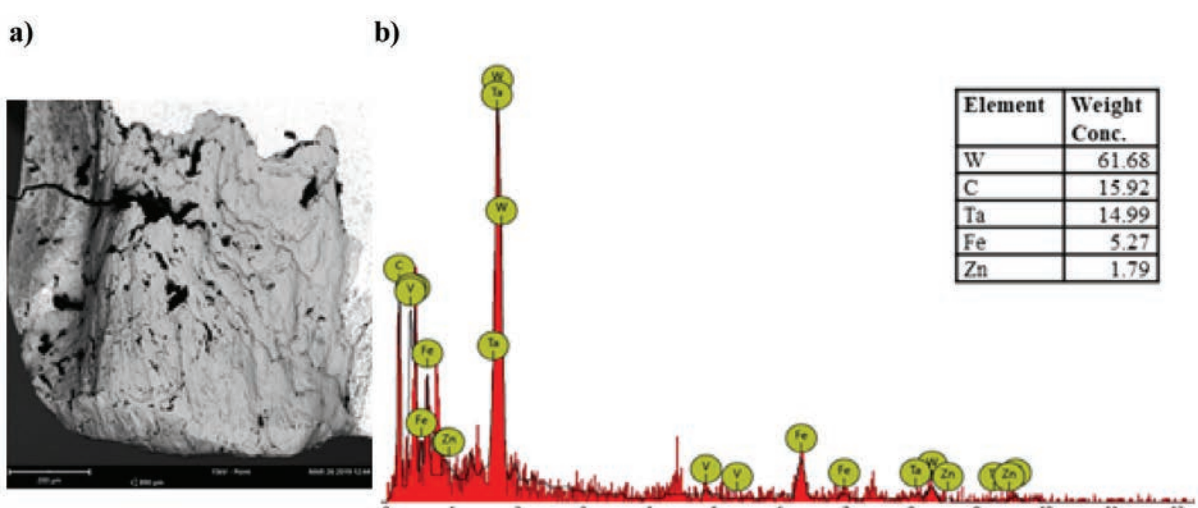

Fig. 9. 1SEM analysis of the tool wear made of cemented carbides after turning with cutting fluid containing zinc aspartate: a) image of the wear track and b) X-ray energy spectrum

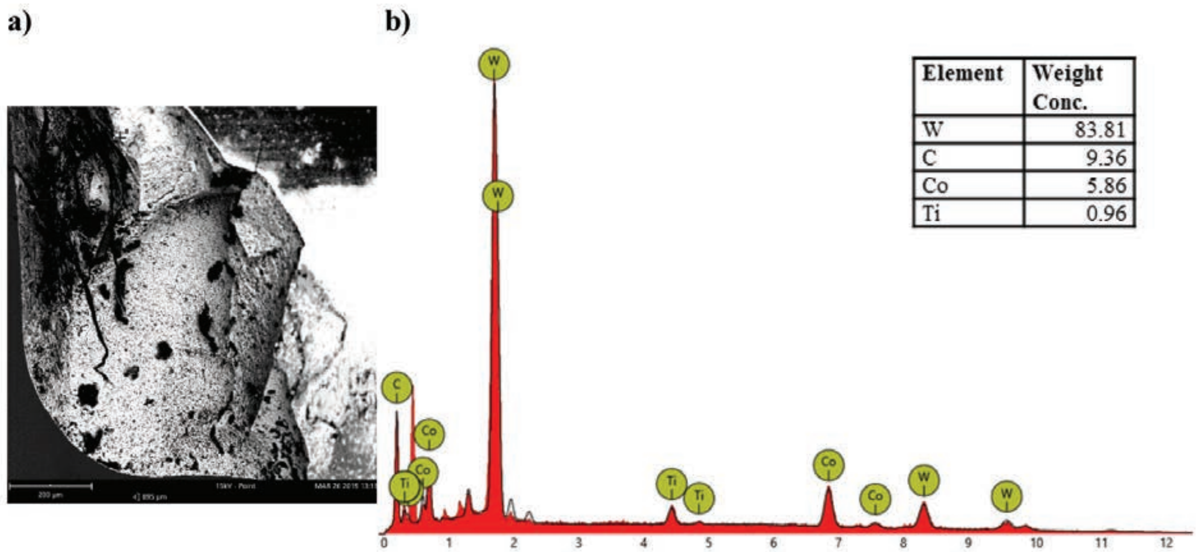

Fig. 10. SEM analysis of the tool wear made of cemented carbides with a-C:H coating after turning with cutting fluid containing zinc aspartate: a) image of the wear track and b) X-ray energy spectrum

the elements coming from the tool material, an additional element coming from the workpiece, i.e. iron, was observed. A local transfer of material from the workpiece occurred. Thus, adhesion of the tool material to the workpiece material and the process of their selective transfer took place. Iron from the workpiece was not identified on a-C:H coated cemented carbide tools. The presence of elements such as titanium and cobalt from the substrate, i.e. cemented carbide, was observed.

Moreover, after turning with uncoated cemented cutting tools with a cutting fluid containing zinc aspartate, the presence of zinc from the cutting fluid was also registered. This indicates that a layer of zinc compounds was formed there, reducing the coefficient of friction and the wear of the tool.

Conclusions

The tests carried out in this study are in line with current trends in the search for increasingly durable materials that will prolong use, ensure savings and eliminate downtime during production.

The lowest values of the width of the band of abrasive wear on the contact surface (VB_B) was obtained after facing using cemented carbide tools with a cutting fluid containing zinc aspartate as well as dry machining. On the other hand, the lowest value of the maximum width of the band of abrasive wear on the contact surface (VB_Bmax) was obtained after dry turning with a-C:H coated cemented carbide tools. Thus, due to its self-lubricating properties, the a-C:H coating perfectly fulfils its anti-wear function during dry machining.

The best parameters of the geometric structure of the surface, i.e. the lowest elevations Sz and the shallowest recesses Sv, were characterized by the details after turning using an a-C:H coated cemented carbide tool with a cutting fluid.

After turning, build-up was formed on the tools. In the case of machining using an uncoated cemented carbide tool with a cutting fluid, a local transfer of material from the workpiece occurred and layers of zinc compounds were formed. These layers contributed to the reduction of the coefficient of friction and wear of the tool.

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