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MECHANISM AND KINETICS OF PCBN TOOL WEAR DURING FACE MILLING OF HARDENED STEEL

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Abstract. *This article presents the results of a study on the wear behavior of cutting tools equipped with polycrystalline cubic boron nitride (PCBN) inserts in the machining of 4Kh5MFS hardened steel with a high hardness of 62 HRC. A key property of 4Kh5MFS steel is its ability to be hardened uniformly without losing hardness throughout the depth of the workpiece, and to maintain its strength level under high temperatures and mechanical loading. Laboratory experiments were carried out on vertical milling machines – DMU 80 eVo Deckel Maho and HAAS VF-2SSYT-NG – using a Seco Tools face mill with a built-in inclination angle of −6°, fitted with six cutting inserts at negative angles of −20° and −25°. Four types of Seco Tools inserts were employed: Group BH (CBN200, CH3505, DBS900) and Group BL (DCS500). The study focuses on comparing the performance of PCBN tools in BL and BH groups, which differ in composition, microstructure, and resistance to shock and high temperatures. Group BH inserts exhibit higher fracture toughness and strength, making them generally recommended for operations involving considerable dynamic loading. The wear rate of PCBN tools, especially at high cutting speeds, is largely determined by the mechanical, chemical, and adhesive interactions in the cutting zone, driven by tribological reactions between the cutting and workpiece materials. By means of energy-dispersive X-ray (EDX) microscopy, the worn areas of the cutting inserts were scanned to identify the wear mechanism, measure the width of the worn notch, and detect any chemical element adhesion that occurred as a result of interactions between the workpiece and the cutting insert over time. Based on the research findings and subsequent analysis, characteristic wear stages for each PCBN tool group were established, along with recommended cutting conditions that provide the best balance between machining efficiency and tool life. The practical significance of this study lies in the development of guidelines for selecting the appropriate type of PCBN tool (BL or BH) depending on thermal and mechanical loading conditions and the required surface quality.*

Key words: *hardened steel, face milling, wear mechanism, diffusion wear, cubic boron nitride, BL and BH groups.*

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1. INTRODUCTION

Face milling of hardened steels is one of the key technological processes in modern machine building, particularly in the manufacture of dies, moulds and cutting tools. Hardened steels, particularly 4X5MFS, are characterised by high hardness (60–62 HRC) and wear resistance, which makes them difficult to machine. Traditionally, such materials are finished by grinding, which ensures high surface quality but is inefficient and requires significant resources. In this regard, there is a need to introduce alternative high-performance processing methods, such as face milling.

Polycrystalline cubic boron nitride (PCBN) is one of the most common materials for cutting tools used for machining hardened steels. Tools equipped with PCNB are characterised by high hardness, thermal stability and wear resistance, which ensures the stability of the cutting process, reduction of cutting forces and high quality machined surfaces [10, 11, 12]. However, the wear process of tools made of PCNB, especially in milling conditions at high cutting speeds, is complex and depends on many factors, such as chemical composition of PCNB, tool geometry, cutting modes, and the presence of wear-resistant coatings [16, 17].

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An important task is to study the mechanisms and kinetics of wear of cutting inserts made of PCNB of different groups (BL and BH) when machining hardened steels, which will help determine the conditions under which minimal tool wear, stability of the cutting process and high quality of the machined surface are ensured.

The objective of the article is to determine the mechanism and kinetics of wear of BL and BH group CBN cutting inserts during face milling of 4X5MFS hardened steel, to assess the influence of tool geometry and cutting modes on the wear pattern, tool life and machined surface quality.

2. EXPERIMENTAL METHODS

For laboratory studies of the wear mechanism, hardened steel 4X5MFS of hardness 62 HRC was used. The steel is alloyed with elements such as Cr, V, Mo, which increases heat resistance and toughness. An important property of 4Kh5MFS steel is its ability to harden qualitatively and evenly, without changing its hardness to the full depth of the workpiece, and to maintain its strength level under high temperatures and mechanical stress. The hardened steels were machined by face milling on a 5-coordinate vertical milling machine DMU 80 eVo Deckel Maho (Fig. 1 a) and a 3-coordinate vertical milling machine HAAS VF-2SSYT-NG (Fig. 1 b).

Figure 1. Machine tool equipment:
a) DMU 80 eVo Deckel Maho b) HAAS VF-2SSYT-NG

A workpiece of hardened steel 4X5MFS with dimensions of 200*200*120 was processed by face milling on a HAAS VF-2SSYT-NG machine (Fig. 2). The wear of the cutting inserts made of BCNB of the BL and BH groups during face milling of hardened steel 4X5MFS was studied for different cutting periods – 8, 16 and 24 minutes. Under the same cutting conditions (cutting speed – v = 120 m/min; feed rate – f = 0.125 mm/tooth; depth of cut – t = 0.5), inserts with different PCNB content were used (CBN200, CH3505, DBS900 - BH group ~ 90%; DSC500 – BL group ~ 50%).

Figure 2. Machining of hardened steel 4X5MFS by face milling on the machine HAAS VF-2SSYT-NG

Figure 3 a shows the SECOTOOLS face milling cutter used in the present research, with a diameter of 63 mm (6 cutting elements) and a built-in 6° inclination angle.

SECOTOOLS cutting inserts (Fig. 2.b) made of BHA of the BL and BH groups with negative chamfer angles: DBS900 (chamfer 25°), CBN 200 (chamfer 20°), CH3505 (chamfer 20°), DCS500 (chamfer 25°) with a wedge clamping mechanism.

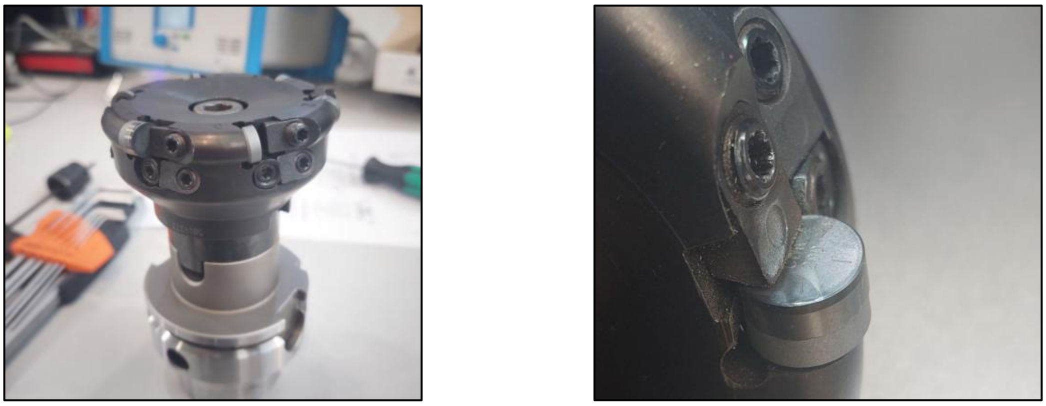


Figure 3. Cutting tools: a) SECOTOOLS face milling cutter
b) SECOTOOLS CBN200 insert made of PCBN of BH grade with a 20° chamfer

The electron microscopic studies of the worn samples were performed using a ZEISS EVO 50XVP scanning electron microscope (manufactured by CARL ZEISS, Germany) with an INCA450 energy dispersive X-ray spectrum analyser equipped with an INCAPentaFETx3 detector and an HKL CHANNEL-5 system for diffraction of reflected electrons (manufactured by OXFORD) (Fig. 4).

Figure 4. ZEISS EVO 50XVP electron microscope

Using a KEYENCE VR-6000 3D profiler (Fig. 5), the worn areas of the insert surface were scanned and obtained after 8 min, 16 min, and 24 min of cutting, and the width of the worn hole was measured.

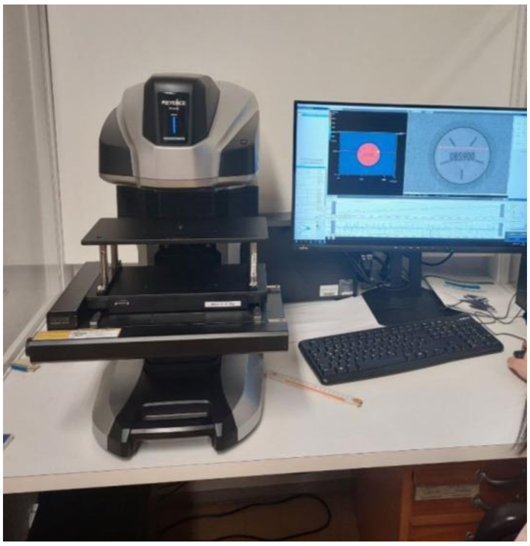


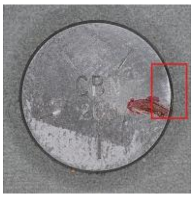
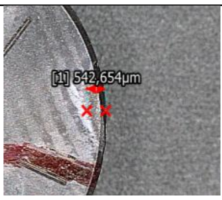
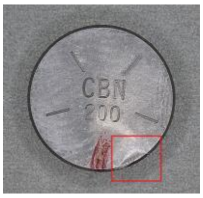
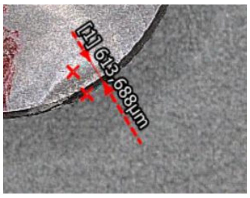
Figure 5. 3D profilometer KEYENCE VR-6000

3. RESULTS AND DISCUSSION

A CBN200 insert (CBN content 90%, chamfer width 0.2 mm with an angle of 20°) was used to process the workpiece for 8 min, 16 min, and 24 min, and after that the 3D profilometer was used to image the worn surface and measure the length of the worn hole (μm). The images of the worn areas of the CBN200 insert for different time periods (8, 16, 24 min) are shown in Table 1.

Table 1

Images of the worn area of the CBN200 insert after 8, 16, 24 min of cutting

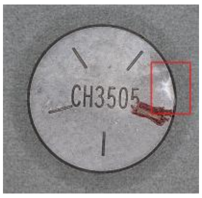
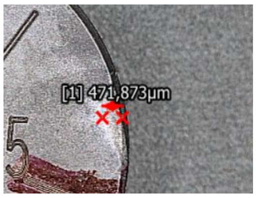
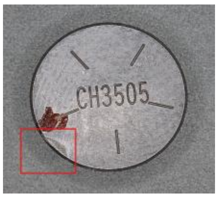
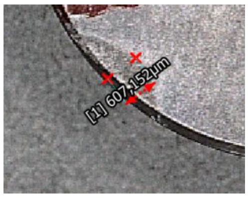
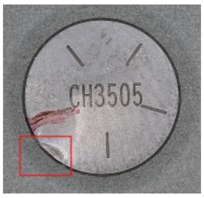
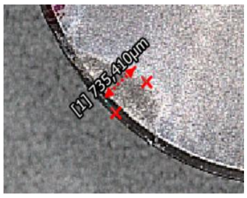
	Insert	Cutting time	Image of the insert surface	Worn areas of the insert
1	**CBN200**	8 min		
2		16 min		
3		24 min		

Based on the results obtained, the width of the worn insert surface was 393.2 µm at 8 min, 542.7 µm at 16 min, and 613.7 µm at 24 min. The wear pattern for different cutting periods is shown in Fig. 6.

The second type of insert CH3505 (CBN content – 90%, chamfer width – 0.2 mm with an angle of 20°) was used for machining of hardened steel for 8 min, 16 min, 24 min, and the length of the insert wear hole was measured using a 3D profilometer. Images of the worn areas of the insert after cutting at different time periods are shown in Table 2.

Table 2

Images of the worn area of the CH3505 insert after 8, 16, 24 min of cutting

	Insert	Cutting time	Image of the insert surface	Worn areas of the insert
1		8 min		
2	**CH3505**	16 min		
3		24 min		

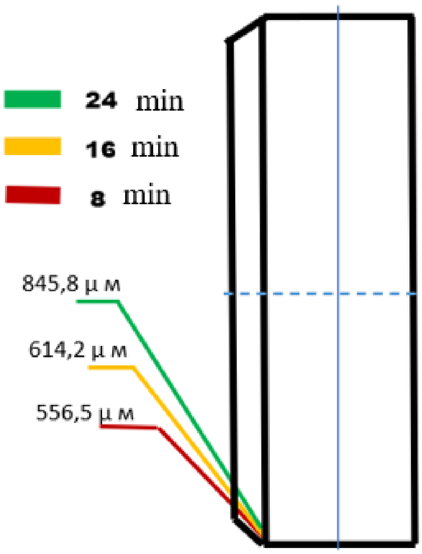


Figure 6. Wear pattern of a CBN200 cutting insert over a different time periods

Based on the results obtained, the width of the worn surface of the insert was 471.9 µm at 8 min, 607.2 µm at 16 min, and 735.4 µm at 24 min. The wear pattern for different cutting periods is shown in Fig. 7.

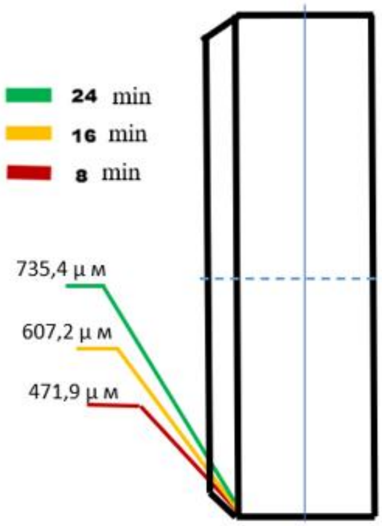


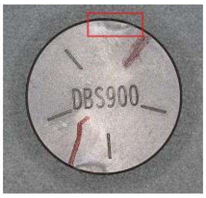
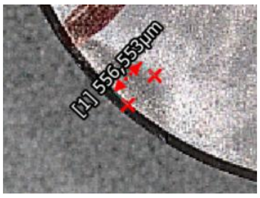
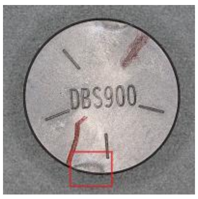
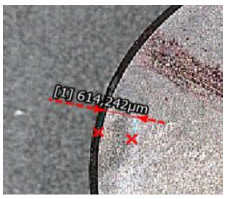
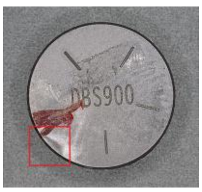
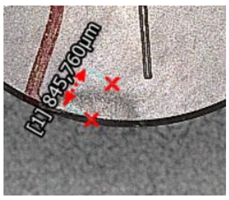
Figure 7. Wear pattern of the CH3505 cutting insert over different time periods

The third type of insert was used by the DBS900 in machining hardened steel for 8 min, 16 min, and 24 min, and the length of the wear hole of the insert was measured with a 3D profilometer. Images of the worn areas of the insert after cutting at different time periods are shown in Table 3.

Based on the results obtained, the width of the worn surface of the insert was 556.6 µm at 8 min, 614.2 µm at 16 min, and 845.8 µm at 24 min. The wear pattern for different cutting periods is shown in Figure 8.

Table 3

Images of the worn area of the DBS900 insert after 8, 16, 24 min of cutting

	Insert	Cutting time	Image of the insert surface	Worn areas of the insert
1	**DBS900**	8 min		
2		18 min		
3		24 min		

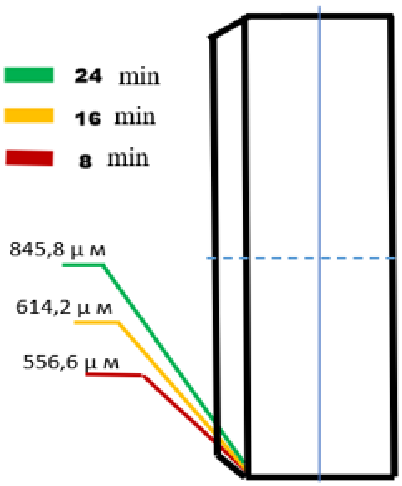
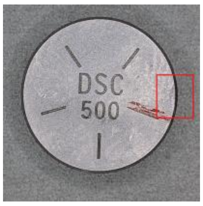
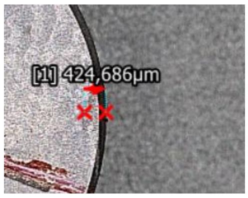
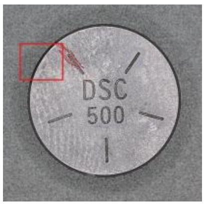
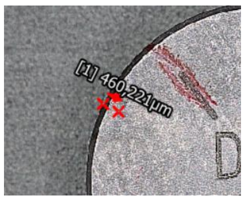
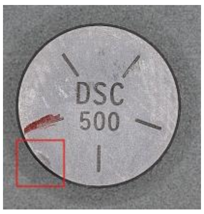
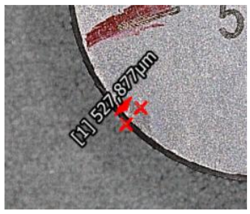


Figure 8. Wear pattern of the DBS900 cutting insert over different time periods

The last type of insert, the DCS500, was used for machining of hardened steel for 8 min, 16 min, and 24 min, and the length of the worn hole of the insert was measured with a 3D profilometer. Images of the worn areas of the insert after cutting at different time periods are shown in Table 4.

Table 4

Image of the worn area of the DCS500 insert after 8, 16, 24 min of cutting

	Insert	Cutting time	Image of the insert surface	Worn areas of the insert
1	DCS500	8 min		
2		16 min		
3		24 min		

Based on the results obtained, the width of the worn surface of the insert was 424.7 μm at 8 min, 460.2 μm at 16 min, and 527.9 μm at 24 min. The wear pattern for different cutting periods is shown in Fig. 9.

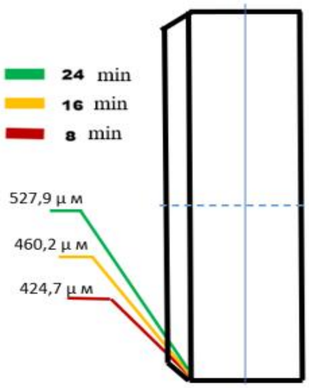


Figure 9. Wear pattern of the DCS500 cutting insert over different time periods

Figure 10 shows the width of the worn area of all the inserts (CBN200, CH3505, DBS900, DCS500) depending on the cutting time (8, 16, 24 min).

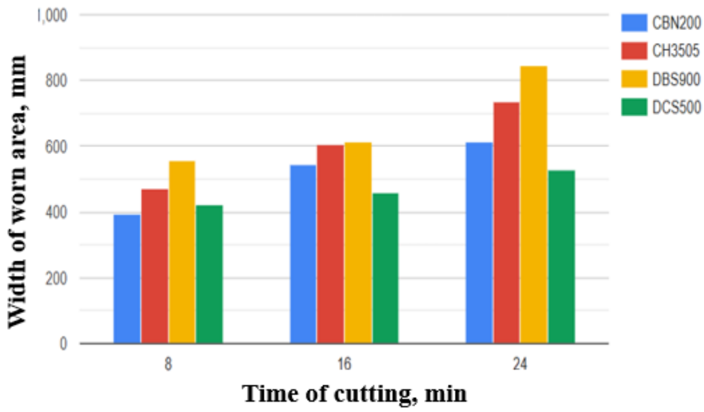


Figure 10. Dependence of the width of the worn area of the cutting inserts on the time of cutting

Figure 10 shows that at 24 min, all insert types had a maximum width of wear area compared to 8 and 16 min. The highest wear at 8, 16, and 24 min was recorded when cutting with the DBS900 insert (556.6 μm, 614.2 μm, and 845.8 μm).

Microscopic studies of the wear of cutting inserts. The worn areas of the cutting insert after 24 minutes of cutting (cutting depth 0.5 mm, feed 0.125 mm/tooth, cutting speed 120 m/min) were examined under a microscope at a magnification of up to 100X and an image of the structure of the worn area of the insert was obtained.

CBN200 insert. Image of the surface structure of the CBN200 insert (Fig. 11).

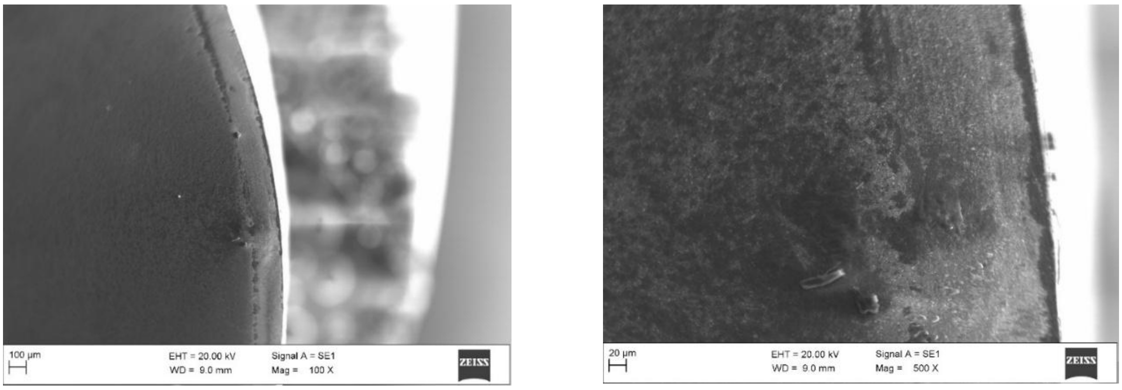


Figure 11. Image of the worn area of the CBN200 insert after 24 min of cutting

The X-ray phase composition of the surface of the cutting inserts was studied by micro-X-ray spectral analysis, where it was found that the predominant wear mechanism is diffusion. The analysis shows that, in addition to CNB, the insert samples contain adhesions of chemical elements from a 4X5MFS hardened steel workpiece. Fragments of adhering elements are distributed into spectra (areas) on the cutting insert. The distributed spectra on the cutting insert are shown in Fig. 12. For detailed analysis, the spectrum closest to the cutting edge of the CBN200 insert was selected (spectrum 15).

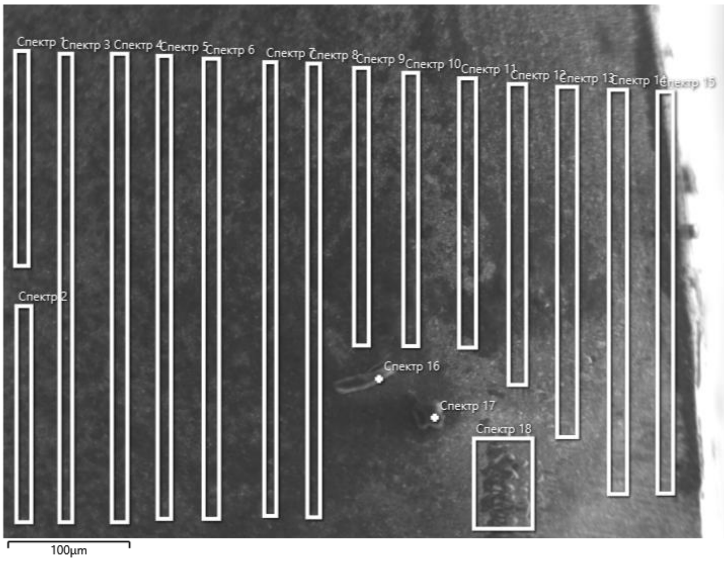


Figure 12. Distribution of adhesion spectra on a CBN200 cutting insert

The distribution of elemental adhesions on the spectrum 15 of the CBN200 cutting insert is shown in Fig. 13. The figure shows that the highest content of chemical elements on the insert is the adhesion of W, C, N, B, Al, Co. It can be concluded that W, C, Co are adhesions of chemical elements from the workpiece, and N, B, Co are adhesions from the tool due to the chemical interaction of the workpiece and the tool during cutting.

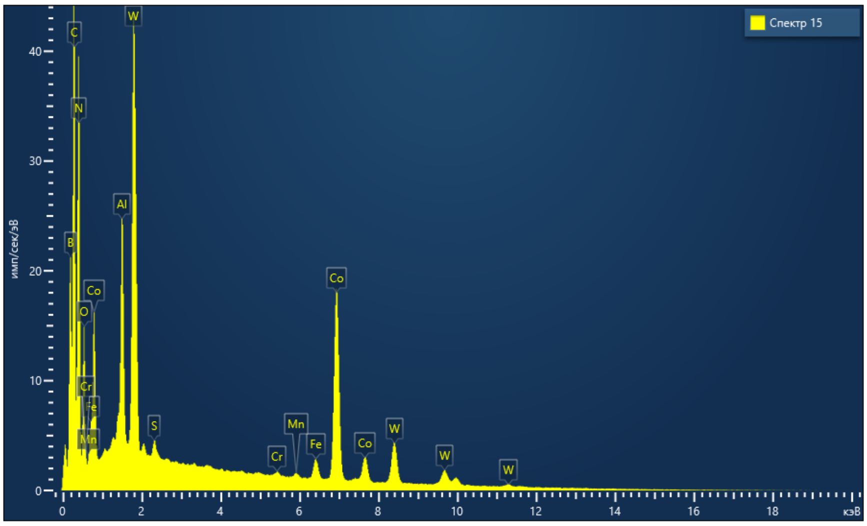


Figure 13. Content of chemical elements in the scope of adhesions on the CBN200 cutting insert

4. CONCLUSIONS

The carried out research has confirmed the high efficiency of using a tool made of PCBN for face milling of hardened steel 4X5MFS with a hardness of 62 HRC. It was found that tools of the BH group (CBN200, CH3505, DBS900), due to such properties as impact resistance and fracture toughness, are more suitable for machining under conditions of increased dynamic loads, while the BL group (DCS500) shows more uniform wear (at 8 min – 424.7 μm, 16 min – 460.2 μm, 24 min – 527.9 μm), but can lose hardness faster due to inefficient heat dissipation.

It has been determined that:

- The main mechanism of wear of cutting inserts is diffusion wear, which occurs due to high temperature, intense contact pressure, and chemical activity of alloyed elements in hardened steel.
- The processes of interaction between the tool and the material being processed in the cutting zone significantly affect the formation and wear rate of the CBN200 cutting insert chamfer, which was confirmed by energy dispersive X-ray microscopy of the worn areas of the inserts where the adhesion of chemical elements was detected. The highest content of chemical elements on the plate: W, C, N, B, Al, Co, where W, C, Co are chemical elements adhering from the workpiece, and N, B, Co are adhering from the tool due to chemical interaction between the workpiece and the tool during cutting.

Based on the obtained experimental data, the characteristic stages of wear for each group of PCBN were determined, and the recommended cutting conditions (CBN200 insert, cutting speed – 120 m/min, cutting depth – 0.5 mm, feed – 0.125 mm/tooth) were established to ensure an appropriate ratio between efficiency and tool life.

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МЕХАНІЗМ ТА КІНЕТИКА ЗНОШУВАННЯ ІНСТРУМЕНТУ З ПКНБ ПРИ ТОРЦЕВОМУ ФРЕЗЕРУВАННІ ЗАГАРТОВАНОЇ СТАЛІ

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Резюме. *Представлено результати досліджень зношуваності інструменту, оснащеного різальними пластинами з полікристалічного кубічного нітриду бору (ПКНБ) при обробці загартованої сталі 4Х5МФС високої твердості (62 HRC). Важливою властивістю сталі 4Х5МФС є здатність якісно та рівномірно загартовуватися, не змінюючи твердість на всю глибину заготовки і в подальшому не змінювати свій рівень міцності під дією високих температур в умовах механічного навантаження. Лабораторні дослідження проведено на вертикально-фрезерних верстатах: DMU 80 eVo Deckel Maho, HAAS VF-2SSYT-NG, а інструмент, зокрема торцева фреза фірми SECOTOOLS, обрано з вбудованим кутом нахилу -6° з різальними пластинами у кількості 6 ножів з від'ємними кутами -20° і -25°. Різальні пластини використовувалися теж марки SECOTOOLS чотирьох типів: група ВН – CBN200, CH3505, DBS900, група BL – DCS500. Зосереджено увагу на порівнянні характеристик інструменту, що оснащений ПКНБ групи BL і ВН, які відрізняються за складом, мікроструктурою та властивостями ударо- і жаростійкості. Пластини групи ВН мають більш високу в'язкість руйнування, є міцнішими, тому оснащені ними інструменти зазвичай рекомендуються для обробки і значним динамічним навантаженням. Інтенсивність зношування інструментів із ПКНБ, особливо при високих швидкостях різання, залежить від закономірностей протікання механічних, хімічних та адгезійних процесів у контактній зоні різання внаслідок трибологічних реакцій взаємодії між інструментальним та оброблюваним матеріалами. За допомогою енергодисперсійної рентгенівської мікроскопії відскановано зношені ділянки різальної пластини, що дозволило встановити механізм зношування, ширину зношеної лунки та налипанння хімічних елементів, що виникли при взаємодії оброблюваного матеріалу з різальною пластиною в зоні різання за різний період часу. На основі проведених досліджень й аналізу результатів визначено характерні стадії зношування кожної групи інструменту із ПКНБ, а також встановлено раціональні режими різання для забезпечення кращого співвідношення між ефективністю й терміном служби інструменту. Практична значущість дослідження полягає у формуванні рекомендацій щодо вибору типу інструменту із ПКНБ (BL чи ВН) залежно від теплових і механічних навантажень та заданої якості оброблюваної поверхні.*

Ключові слова: *загартована сталь, торцеве фрезерування, механізм зношування, дифузійне зношування, кубічний нітрид бору, група BL і ВН.*

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