IJME

Int. J. of Applied Mechanics and Engineering, 2024, vol.29, No.3, pp.69-81
DOI: 10.59441/ijame/190057

INVESTIGATION OF COATED AND UNCOATED CARBIDE CUTTING TOOL WEAR IN DRY TURNING OF EN AW 2007 ALUMINUM ALLOY

Kamil Leksycki*[1], Gauravkumar Himmatrao Patil[1,2], Joanna Małecka[3], Cinar Suleyman Cagan[4], Karol Dąbrowski[1]

[1]Faculty of Mechanical Engineering, University of Zielona Góra, Prof. Z. Szafrana Street 4, 65-516 Zielona Gora, POLAND
[2]Machining Department, Lumel Alucast Sp. z o.o., Słubicka Street 1, 65-127 Zielona Gora, POLAND
[3]Faculty of Mechanical Engineering, Faculty of Mechanical Engineering, Opole University of Technology, St. Mikołajczyka Street 5, 45-271 Opole, POLAND
[4]Faculty of Mechanical Engineering, Mersin University, TURKEY
E-mail: k.leksycki@iim.uz.zgora.pl

The automotive, aerospace and marine industries make extensive use of aluminum and its alloys to produce a wide variety of components. This prompts research work related to improving manufacturing processes using these materials. One of the main problems in this area is the durability of cutting tools. This article describes the results of tests on wear of the coated and uncoated carbide cutting tools during turning of EN AW 2007 aluminum alloy. The tests were carried out under dry conditions and at higher cutting speeds. On the face rake, the VB_B indicator (average width of the flank wear) and on the rake face, the *KB* indicator (crater width on the rake face) were evaluated. Only for the uncoated insert, the break-in period, steady-state wear region and intensive wear were observed and the limited alue of the VB_B indicator was obtained after *36* minutes of the tool life. The TiAlN+TiN coated insert, as well as TiCN achieved very short tool life periods of *16* and *24* minutes, respectively. Compared to the uncoated and the TiCN coated insert, a VB_B increase of about *170%* was obtained for the TiAlN+TiN coated insert after *16* minutes. In contrast, an increase in the VB_B of almost *60%* was obtained for the TiCN coated insert after *24* minutes, compared to the uncoated insert. Compared to the uncoated insert, an increase of *12.1%* in the *KB* value was obtained for the TiCN coated insert, and *18.2%* for the TiAlN+TiN coated insert. The main wear mechanism of the tested cutting inserts was the phenomenon of adhesion. Abrasion wear is observed on the surfaces of the TiAlN+TiN and TiCN coated inserts. The TiCN coated insert also showed coating delamination. The build-up edge (BUE) phenomenon is observed on the surfaces of the TiAlN+TiN coated and uncoated inserts.

Key words: tool wear, coated and uncoated inserts, dry turning, EN AW 2007 aluminum alloy.

1. Introduction

Turning process is one of the most widely used machining processes in the manufacturing industry. During the turning process, the workpiece rotates around its axis, while the cutting tool is moved along the material, removing the excess material and giving the workpiece the required shape. During this process, tool wear occurs due to the friction of the cutting tool against the workpiece material, the occurrence of high stresses and the sliding of chips on the rake face of the tool. Tool wear is inevitable and cannot be completely eliminated [1-3].

The cutting tool life during metalworking is a key parameter for evaluating efficiency of the cutting process. During the turning process, especially in the contact area between the tool and the workpiece, high temperatures and high mechanical forces can occur. The consequence is accelerated wear of the cutting edge, which can make it difficult to achieve the expected surface roughness, dimensions and tolerances of the

* To whom correspondence should be addressed

workpiece. This forces the replacement of the tool with a new one and leads to an increase in the cost of the manufactured products [4].

Cutting edge failures can occur prematurely and on a large scale or gradually, leading to the end of the tool life. Tool wear leads to undesirable consequences such as reduced cutting edge strength, increased force and energy consumption, increased cutting temperature, deterioration of the surface quality, loss of part dimensional accuracy and ultimately, loss of productivity. Therefore, it is extremely desirable that the tool wear be minimized and controlled as much as possible [5].

Korkmaz *et al.* [6] investigated cutting tool wear and the mechanisms of its occurrence when turning of AA7075 aluminum alloy. The turning tests were carried out at a constant depth of cut of *1* mm, as well as the cutting speeds of *300*, *450* and *600 m/min* and feed rates of *0.2*, *0.3* and *0.4 mm/rev*. When the cutting speed was doubled and the feed rate was held constant, there was a *44.40%* increase in cutting tool wear. In contrast, there was a *22.78%* increase in cutting tool wear at the constant cutting speed. Gupta *et al.* [7] studied tool life behavior in turning of AA2024-T351 aluminum alloy under dry machining as well as machining with minimum quantity lubrication (MQL), liquid nitrogen (LN_2) and carbon dioxide (CO_2) conditions. Compared to dry and MQL machining, cryogenic conditions provided a reduction in flank wear and nose wear of the cutting tool. It was also found that compared to dry machining, machining with MQL, CO_2 and LN_2 conditions provided significant improvement in cutting tool wear to *15.8%*, *36.8%* and *52.6%*, respectively. Zhang *et al.* [8] investigated cutting tool wear in conventional and ultrasonic elliptical vibration machining of 7050-T7451 aluminum alloy. The material was machined using cutting speed in the range of *600-1800 m/min*, depth of cut of *1.5-3.5 mm*, feed rates of *0.025-0.125 mm/z* and vibration frequencies of *5000-25000 Hz*. Compared to ultrasonic elliptical vibration machining, for conventional machining the tool wear was *3-5* times higher. With conventional machining, tipping, spalling wear and severe adhesive or oxidative wear were observed on the tool surface. In contrast, mild adhesive wear and abrasive wear were observed when ultrasonic elliptical vibration machining was used. Breidenstein *et al.* [9] analyzed wear of the cutting tools produced from natural rocks (flint, lamellar obsidian, quarto). Cutting speed of *1000* and *1500 m/min*, feed rate of *0.1 mm/rev* and depth of cut of *0.5 mm* were used when machining of EN AW 5754 and EN AW 2007 aluminum alloys using dry and flood methods. It was found that the use of rock inserts made it possible to perform the turning process and achieve stable tool life together with low surface roughness. Adhesion and abrasion wear were the main wear mechanisms of the natural rock tools. Gupta *et al.* [10] investigated the geometric features of the cutting tools after turning of AA2024-T351 aluminum alloy. The turning process was carried out under machining with dry, MQL, LN_2 and CO_2 conditions. Tool wear was evaluated in terms of the cutting-edge (VB_C), crater width (KB), crater depth (KT), height of BUE (H_{BUE}) and length of BUE (L_{BUE}). The lowest values of the tested tool wear indicators were observed for LN_2, CO_2, MQL conditions and dry machining, respectively. Musavi *et al.* [11] analyzed wear of the textured and non-textured tungsten carbide cutting inserts during dry and MQL turning of 7075-T6 aluminum alloy. Cutting speed of *100*, *125* and *150 m/min*, feed rates of *0.1*, *0.15* and *0.2 mm/rev* and groove distances of *100*, *200* and *300* µm were used. For the machining conditions tested, reducing groove distance resulted in reduced tool wear. Using high cutting speed, volume of the material penetrating the grooves decreased and the textured tool wear decreased at the same time. Pattnaik *et al.* [12] investigated cutting tool wear in dry turning of pure aluminum. A constant depth of cut of *0.2 mm* was used along with cutting speed of *336*, *426* and *540 m/min* and feed rates of *0.045*, *0.06* and *0.09 mm/rev*. Several cutting tools were tested: $\mathrm{WC\ SPGN}$ and $\mathrm{WC\ SPUN}$ grades, PCD (polycrystalline diamond), $\mathrm{WC+PVD}$ (physical vapor deposition) TiN coating and $\mathrm{WC+Ti(C,N)+Al_2O_3}$ PVD multilayer coatings. The lowest tool wear was observed for PCD and $\mathrm{WC\ SPGN}$ tools. In case of the coated tools, TiN and $\mathrm{WC+Ti(C,N)+Al_2O_3}$ coatings chipped and some aluminum was welded to the tool edge, in addition, the coating was almost completely removed.

In the recent years, a lot of research has been carried out on cutting tool wear during the turning process of aluminum and its alloys using different cutting parameters and cooling conditions. This means that the research in this area is desirable and timely. This is also due to the industry expectations to reduce the production costs, and therefore, to reduce the frequency of the tool replacement (through their appropriate selection) and reduce the machine downtime. In the industry, it is a relatively common practice to replace a cutting tool well before the end of its useful life. Typically, only *50-80%* of the expected tool life is consumed [13].

The aim of the study was to investigate wear of the uncoated and coated carbide cutting tools when turning EN AW 2007 aluminum alloy under dry machining conditions and using higher cutting speed.

2. Methodology of experimental investigations

In the research, turning was carried out on a $\mathrm{CLX}\mathit{350}$ turning center from DMG MORI. A folding tool holder $\mathrm{SVHCL}\mathit{2020}\,\mathrm{K}\mathit{16}$ from Teknik was used as the tool. Three cutting inserts designed for turning aluminum alloys were tested (Fig.1). The first, ISCAR $\mathrm{VCMT}\mathit{160404}-\mathrm{SM\ IC}\mathit{907}$ insert made of solid carbide with a double-layer coating of titanium aluminum nitride (TiAlN) and titanium nitride (TiN) by physical vapor deposition (PVD). The second, ARNO $\mathrm{VCGT}\mathit{160404}\mathrm{FN}-\mathrm{ASF\ AT}\mathit{10}$ insert made of solid carbide with a single layer coating of titanium carbonitride (TiCN) by PVD. A third, uncoated $\mathrm{VCMT}\mathit{160404}-\mathit{14}\ \mathrm{IC}\mathit{20}$ insert from ISCAR made of solid carbide. The geometry of the cutting tools is as follows: tool cutting edge angle $\kappa_r = 107.5^{\circ}$, clearance angle major $\alpha = 7^{\circ}$, insert included angle $\beta = 35^{\circ}$, nose radius $r_{\varepsilon} = 0.4\ mm$.

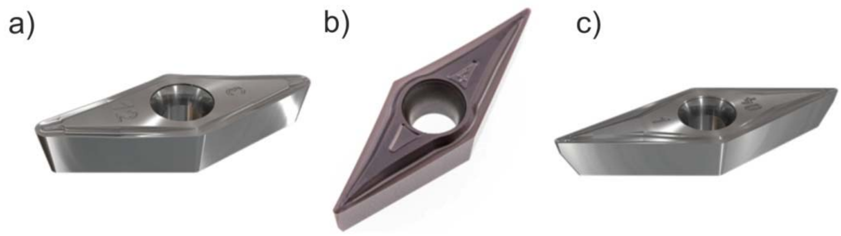

Fig.1. Cutting inserts tested: (a) $\mathrm{VCMT}\mathit{160404}-\mathrm{SM\ IC}\mathit{907}$ with $\mathrm{TiAlN}+\mathrm{TiN}$ double-layer coating, (b) $\mathrm{VCGT}\mathit{160404}\mathrm{FN}-\mathrm{ASF\ AT}\mathit{10}$ with TiCN single layer coating, (c) $\mathrm{VCMT}\mathit{160404}-\mathit{14}\ \mathrm{IC}\mathit{20}$ without coating.

Table 1. Chemical composition of EN AW 2007 alloy, according to DIN EN 573-3.

Chemical composition, %												
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni	Pb	Bi	Sn	Al
0.8	*0.8*	*3.3-4.6*	*0.5-1*	*0.4-1.8*	*0.1*	*0.8*	*0.2*	*0.2*	*0.8-1.5*	*0.2*	*0.2*	Rest

Table 2. Chemical composition of EN AW 2007 alloy, according to DIN EN 573-3.

Mechanical properties			
Hardness (HB)	Yield strength (MPa)	Tensile strength (MPa)	Module of elasticity (GPa)
95	*210-250*	*330-370*	*72.5*

The workpiece material was EN AW 2007 aluminum alloy with the chemical composition and mechanical properties shown in Tabs 1 and 2, respectively. Aluminum alloys, including the alloy under study, are characterized as lightweight materials of good strength, ductility and corrosion resistance as well as electrical and thermal conductivity, which has increased their importance in the aerospace, automotive or biomedical industries. Machinability of aluminum alloys is not as difficult as for stainless steel or titanium alloys. The main problems are related to the generation of continuous chips, which can entangle the tool causing accelerated wear. In turn, high ductility of the aluminum alloys can cause the material to adhere to the surface of the tool, which can increase its cutting temperature and result in shorter tool life [14-16].

The tests were carried out using constant parameters: feed rate (f) of *0.1 mm/rev*, depth of cut (a_p) – *0.8 mm* and higher cutting speed (v_c) – *750 m/min*, which increases productivity of the cutting process. The machining was carried out without the use of coolant and lubricant, thus, under dry machining, as it is friendly to the environment and machine operators, making it desirable for manufacturing companies [17].
Wear tests on the cutting tool were conducted in accordance with ISO 3685:1993. The indicators for determining the amount of the material loss were analyzed (Fig.2). The VB_B indicator (average width of the flank face) was analyzed on the flank face, and the KB indicator (crater width on the rake face) was analyzed on the rake face. The measurements were performed every *4* minutes until a VB_B indicator value of *0.3 mm* was reached. According to the ISO standard, reaching such an indicator value means that the insert should no longer be used for machining. The indicators of cutting tool wear were measured using Dino Lite AM7013MZT Universal Microscope with a resolution of *5* megapixels and DinoCapture software.

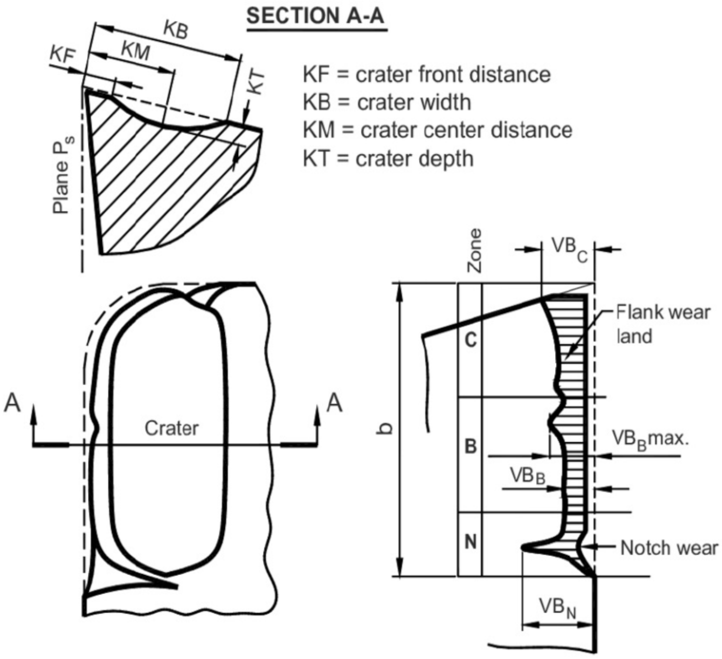

Fig.2. Cutting tool wear indicators according to ISO 3685:1993.

Wear of the inserts were observed using the Scanning Electron Microscope (SEM) from Tescan Vega, which is a *4*th generation instrument. Based on these observations, the wear mechanisms of the analyzed surfaces were evaluated.

3. Results and discussion

Cutting tool wear results in deterioration of the roughness of the machined surface, a change in the dimensions of the machined workpiece, an increase in the vibration and noise levels and an increase in the cutting temperature. Wear of the cutting tool is a process that occurs with varying intensity during its life. The tool wear modes recorded in the turning process are shown in Fig.3.

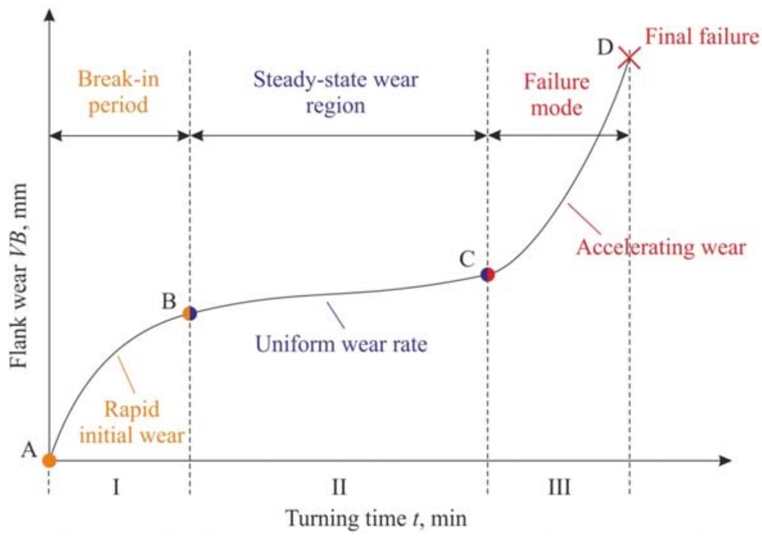

Fig.3. Tool wear modes recorded in the turning process (based on [18-20]).

As shown in Fig.3, there are three typical phases of the cutting edge flank wear [18-20]:

I - The initial, short-lived phase (AB) is caused primarily by lapping the tool surface and removing minor irregularities. During the break-in period, it is important to monitor the tool performance and machining quality to minimize the risk of the tool damage or quality deterioration of the machined parts.

II - The second phase (BC) is characterized by a low increase in the tool wear and usually accounts for about *90%* of the tool's total operating time. In this phase, the cutting process is controlled and predictable and the tool is able to perform its work effectively for a longer period of time without replacement. As the tool maintains high performance with minimal wear, the BC phase is the tool's most desirable period of life for engineers.

III - In the third phase (CD), there is a rapid increase in the wear of the cutting tool. This is due to the increase in cutting forces and temperature resulting from the cutting edge wear. The third phase ends with the tool damage, machine downtime associated with the need to replace the tool and thus, the increase in the production costs.

According to ISO 3685:1996, the durability criterion for the average width of the flank face VB_B is *0.3 mm*, when regular abrasion of the flank face was found in the B zone. For this reason, the VB_B indicator was measured until such a value was reached.

Measured values of the VB_B indicator of the cutting edge wear during turning of EN AW 2007 aluminum alloy using VCMT 160404-SM IC907 insert with $\mathrm{TiAlN+TiN}$ coating are shown in Fig.4, VCGT 160404FN-ASF AT10 insert with TiCN coating in Fig.5 and VCMT 160404-14 IC20 insert without coating in Fig.6.

Flank wear of the cutting edge can cause a sudden deterioration in the quality of the machined surface and reduce the dimensional and shape accuracy of the manufactured parts [21,22]. When turning with the $\mathrm{TiAlN+TiN}$ coated cutting insert, after *4* minutes of operation, the value of average width of the flank wear VB_B increased significantly, reaching *0.134 mm*. This was followed by a very short period of stabilization of the tool work - up to *8* minutes. After this time, the VB_B indicator value increased intensively linearly to reach *0.363 mm* after just *16* minutes. During machining of the TiCN coated insert, a stable increase in the VB_B value was recorded from *4* to *16* minutes, reaching *0.134 mm*. Thereafter, by *24*th minute, the VB_B value increased linearly, reaching *0.304 mm*. During turning with an uncoated insert, a rapid increase in the VB_B indicator value of *0.11 mm* was recorded up to *8*th minute. Then, from *8* to *32* minutes, a stabilization of the tool and a slow increase in the VB_B indicator was observed, which reached *0.22 mm*. After that time, the VB_B value increased significantly to reach *0.318 mm* after *36* minutes. The course of the uncoated insert wear was typical of the tool wear modes observed in the turning process, which is shown in Fig.3.

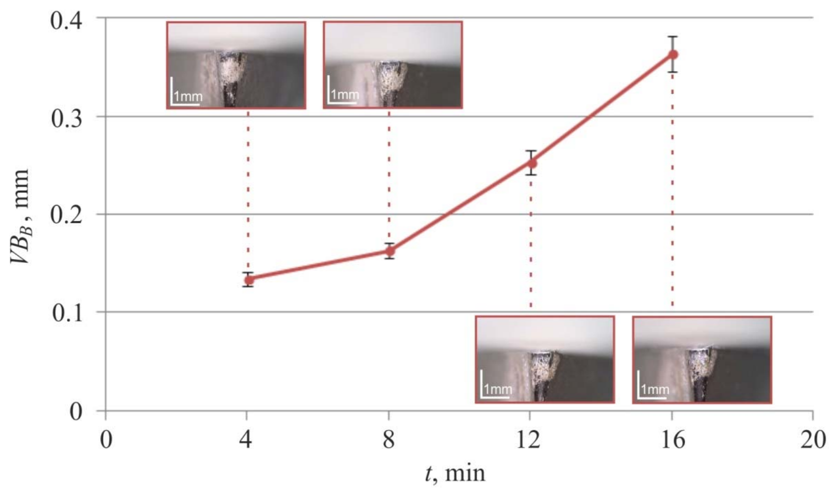

Fig.4. Changes in the VB_B values during life of the $TiAlN + TiN$ coated insert.

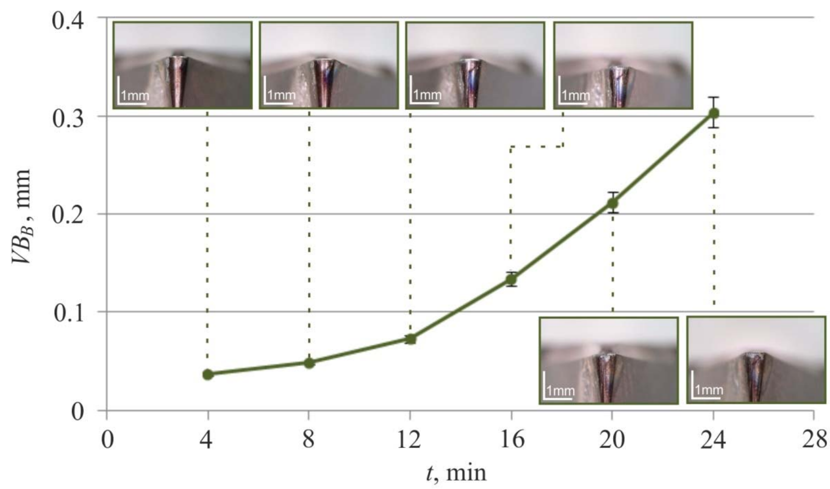

Fig.5. Changes in the VB_B values during life of the TiCN coated insert.

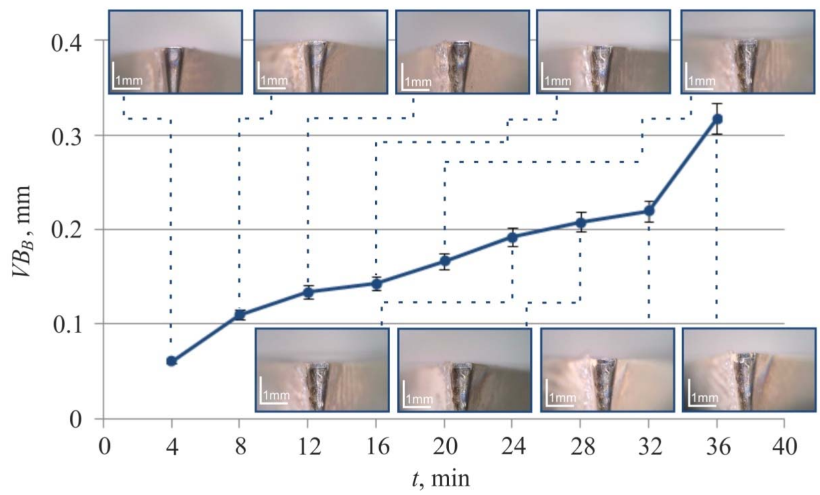

Fig.6. Changes in the VB_B values during life of an uncoated insert.

The summarized changes in the VB_B indicator values during operation of the tested cutting inserts are shown in Fig.7.

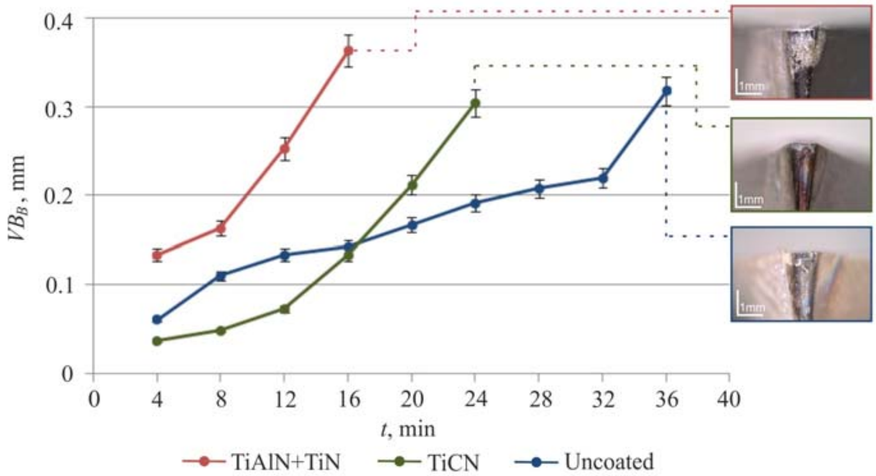

Fig.7. Comparison of changes in the VB_B values during life of the tested cutting inserts.

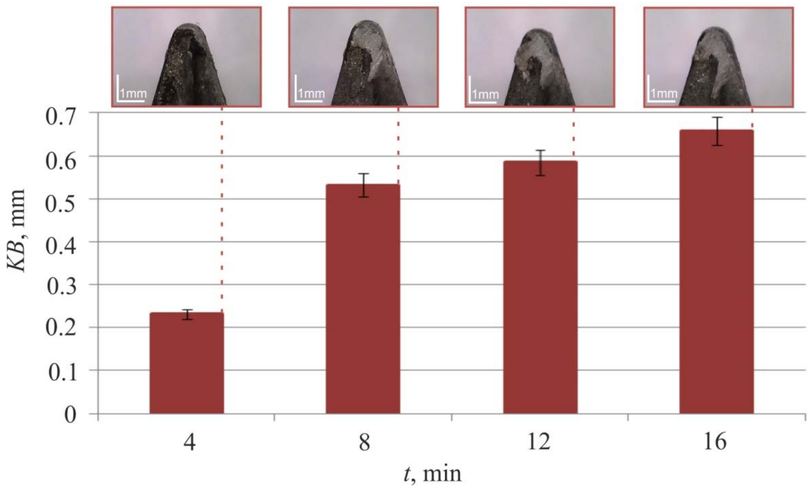

Fig.8. Changes in the KB values during life of the $TiAlN + TiN$ coated insert.

Compared to the uncoated and TiCN coated insert, higher average width of the flank wear VB_B was obtained for the $TiAlN + TiN$ coated insert throughout the working period. After *16* minutes of operation, differences of up to about *170%* are observed. Such significant differences may be due to the fact that when machining aluminum alloy, the resulting chips are welded to the coating of the aluminum-containing insert. The chips welded to the tool increase friction during machining and, at the same time, increase the temperature in the cutting zone, which in turn can cause accelerated wear of the cutting tool [12]. On the other hand, compared to the uncoated insert, smaller VB_B indicator values were obtained for the TiCN coated insert until *16*th minute. After that, the trend was reversed. After *24* minutes, the TiCN coated insert exceeded the limiting value of the VB_B indicator, which was about *60%* higher than the uncoated insert. The uncoated insert reached the limiting value of the VB_B indicator after *36* minutes of operation.

Measured values of the KB indicator of the cutting edge wear during turning of EN AW 2007 aluminum alloy using VCMT 160404-SM IC907 insert with $\mathrm{TiAlN+TiN}$ coating are shown in Fig.8, VCGT 160404FN-ASF AT10 insert with TiCN coating in Fig.9 and VCMT 160404-14 IC20 insert without coating in Fig.10.

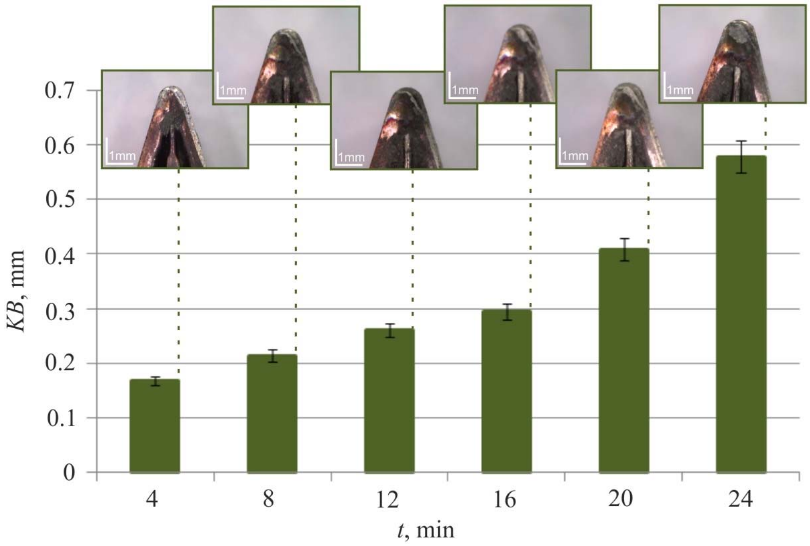

Fig.9. Changes in the KB values during life of the TiCN coated insert.

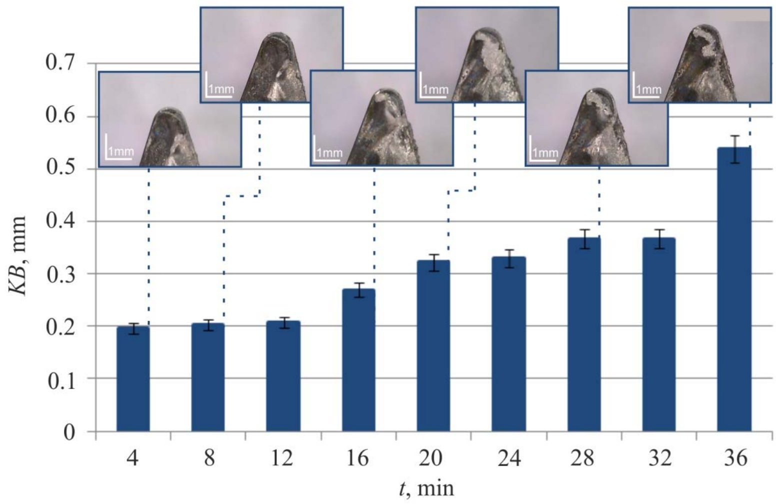

Fig.10. Changes in the KB values during life of an uncoated insert.

Rake face wear occurs at the point of contact between the cutting edge and the chips generated during the cutting process [23]. When turning with the $\mathrm{TiAlN+TiN}$ coated insert, the values of crater width on the rake face KB by *8*th minute of operation increased significantly, reaching *0.632*. Then, by *16*th minute, the KB value increased linearly to finally reach *0.758*. During machining with the use of the TiCN coated insert, a stable increase in the KB value was recorded from *4* to *16* minutes, which reached *0.294 mm*. Then, the KB indicator increased linearly until *24*th minute to finally reach *0.578 mm*. When turning with an uncoated insert, the KB indicator remained constant at around *0.2 mm* until *12*th minute. Then, it gradually increased until *32*nd minute, where the value of *0.367 mm* was obtained. After that, the KB value increased significantly, finally reaching *0.538 mm* at the *36*th minute.

The percentage changes in the KB indicator of the tested cutting inserts at the end of their life are shown in Fig.11.

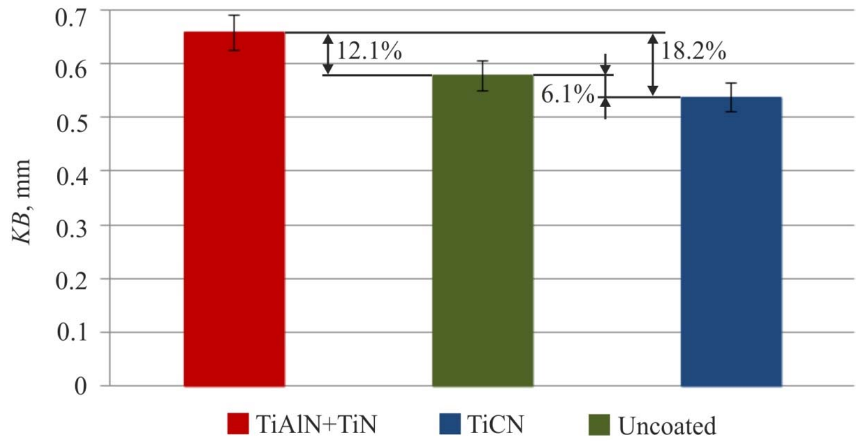

Fig.11. Percentage changes in the KB indicator of the tested cutting inserts at the end of their life.

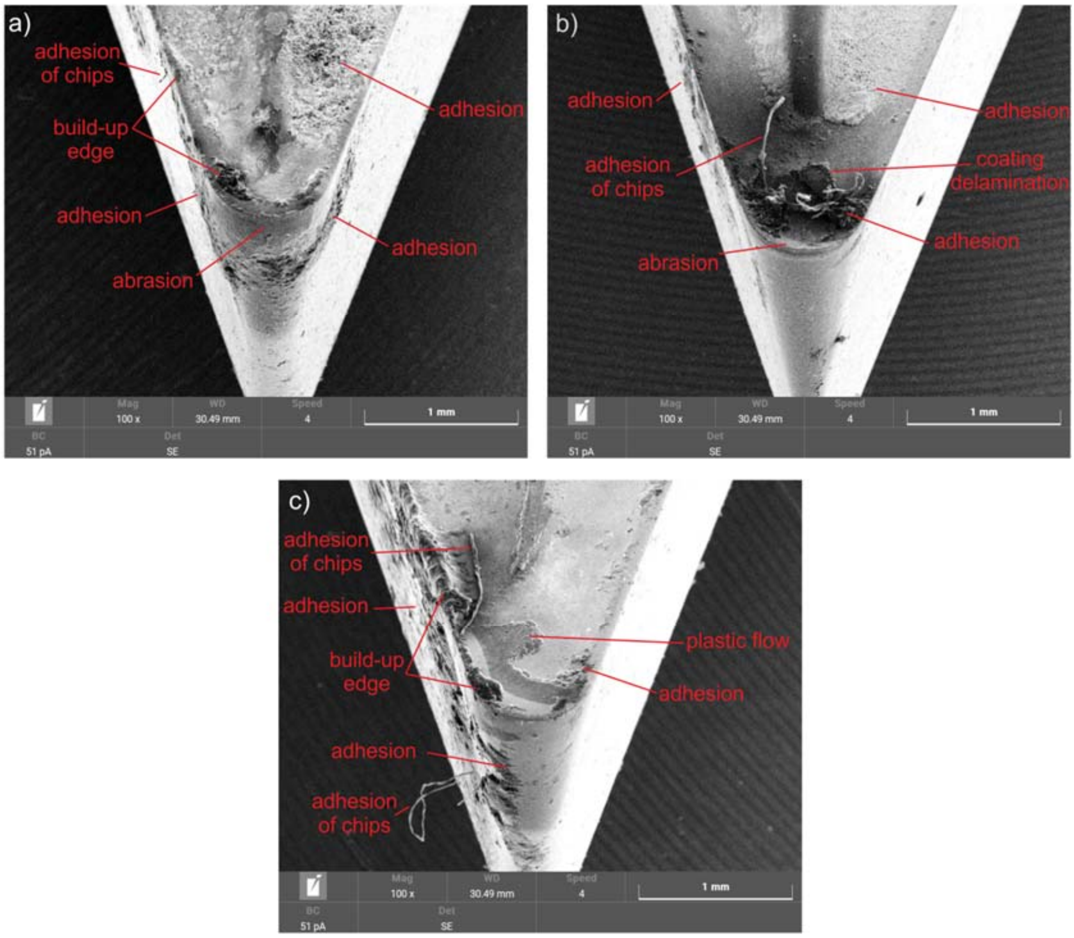

Fig.12. Wear of the cutting insert: (a) VCMT 160404-SM IC907 with TiAlN + TiN double-layer coating, (b) VCGT 160404FN-ASF AT10 with TiCN single layer coating, (c) VCMT 160404-14 IC20 without coating.

Compared to the uncoated insert, a *12.1%* increase in the KB value was obtained for the TiCN coated insert, while an *18.2%* increase was obtained for the $TiAlN + TiN$ coated insert.

The wear of VCMT 160404-SM IC907 insert with $TiAlN + TiN$ coating, VCGT 160404FN-ASF AT10 insert with TiCN coating and VCMT 160404-14 IC20 insert without coating when turning EN AW 2007 aluminum alloy at the end of their life is shown in Fig.12.

An adhesion phenomenon is observed on the surfaces of the tested cutting inserts. It is related to the fact that during dry turning at higher cutting speeds, high amounts of heat are generated in the contact area between the tool and the workpiece. The increase in cutting temperature causes softening of the aluminum alloy and formation of the oxide layers on the workpiece material surfaces and the cutting tool, which leads to adhesion [24]. High temperatures also promotes the formation of a build-up edge, which is observed on the edge of the $TiAlN + TiN$ coated and uncoated cutting edges. Plastic flow is also observed on the surface of the uncoated inserts, which may be related to excessive tool loading and intense plastic deformation of the workpiece material. On the other hand, during dry machining, the tool can also undergo intense abrasion in contact with harder aluminum alloy particles. Abrasion wear is observed on the surfaces of the $TiAlN + TiN$ and TiCN coated inserts. In addition, coating delamination is observed on the surface of TiCN coated tool. The reason for this phenomenon is the intense plastic deformation of the workpiece material, which causes high mechanical loads on the tool and delamination of its coating.

4. Conclusions

The study investigated coated and uncoated carbide cutting tool wear during dry turning of EN AW 2007 aluminum alloy. The tests were realized with a constant feed rate of *0.1 mm/rev*, depth of cut of *0.8 mm* and a higher cutting speed of *750 m/min*. Indicators for determining the amount of material removal were analyzed, namely the average width of flank wear VB_B and crater width on the rake face KB. The worn surfaces of the cutting inserts were also evaluated.

It was found that when turning $TiAlN + TiN$ coated inserts as well as TiCN coated inserts, very short tooling periods were obtained, with no clearly visible lapping or stabilization periods. The coated inserts reached limiting VB_B values after *16* and *24* minutes of work, respectively. During machining with an uncoated insert, the break-in period, steady-state wear region and intensive wear period were observed, and the limiting value of the VB_B indicator was obtained after *36* minutes of life. Compared to the uncoated and TiCN coated insert, an increase in the VB_B value of almost *170%* was obtained for the $TiAlN + TiN$ coated insert after *16* minutes of operation. On the other hand, compared to the uncoated insert, an increase in the VB_B value of almost *60%* was obtained for the TiCN coated insert after *24* minutes.

Analyzing the percentage changes in the KB indicator of the tested cutting inserts at the end of their life, it was found that, compared to the uncoated insert, a *12.1%* increase in its value was obtained for the TiCN coated insert, while an *18.2%* increase was obtained for the $TiAlN + TiN$ coated insert.

The main wear mechanism of the tested cutting inserts was the phenomenon of adhesion. Abrasion wear is observed on the surfaces of the $TiAlN + TiN$ and TiCN coated inserts. TiCN coated insert also showed coating delamination. The build-up edge phenomenon was observed on the surface of the $TiAlN + TiN$ coated and uncoated inserts. The observed phenomena were primarily related to the occurrence of high temperatures in the cutting zone, which caused high loads on the tool and plastic deformation of the workpiece material.

The results showed that when dry turning aluminum alloys at higher cutting speeds, the use of uncoated carbide inserts can provide increased machine tool life.

Nomenclature

a_p – depth of cut

BUE	– build-up edge
CO_2	– carbon dioxide
f	– feed rate
H_{BUE}	– height of build-up edge
KB	– crater width on the rake face
KT	– crater depth
L_{BUE}	– length of build-up edge
LN_2	– liquid nitrogen
MQL	– minimum quantity lubrication
PCD	– polycrystalline diamond
PVD	– physical vapor deposition
r_ε	– nose radius
SEM	– scanning electron microscope
TiAlN	– titanium aluminum nitride
TiCN	– titanium carbonitride
TiN	– titanium nitride
VB_B	– average width of the flank wear
VB_C	– cutting-edge
v_c	– cutting speed
α	– clearance angle major
β	– insert included angle
κ_r	– tool cutting edge angle

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Received: March 18, 2024
Revised: June 13, 2024