Durability and tool wear investigation of HSSE-PM milling cutters within long-term tests

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ABSTRACT

Tool durability is an important parameter in the evaluation of the performance of the cutting tools and inserts. It is directly connected with tool wear that significantly affects the quality of the workpiece. Only from an understanding of the nature behind the machining process in given conditions (a combination of cutting parameters, machined material, tool characteristics including its material, etc.), a tool wear mechanism can be identified and consequently estimate the tool life and its durability.

The article deals with a durability ofthe milling cutters produced from the high-speed steel via powder metallurgy (HSS-PM) and coated by AlTiN coat. Effects of a varying combination of cutting speed and depth of cut to tool wear and surface roughness had been also investigated within the long-term tests. Conventional milling was selected as a technology to test the durability of HSSE-PM shank milling cutters at which the steel 1.4301 (AISI 304, DIN 1.4301) as a material that is very difficult to cut was machined without a coolant. Within the research, the tool wears in several points on a cutting edge were evaluated, while several types of tool wear have been identified. Achieved data were statistically processed and based on them the development of the tool wear of individual milling cutters in time has been processed as well as a dependency of the tool wear on cutting speed and cutting depth has been plotted. The accompanying phenomenon of tool wear increasing is a deteriorated quality of surface roughness and change in a chip formation. The average values of surface roughness Ra relative to machining time achieved by milling cutters working at a specific depth of cut were also assessed. The pictures of the chips approved that along with tool wear increasing the chip becomes thinner with larger rugged relief.

Keywords: Long-term test HSS-PM steel Durability Wear Milling

1. Introduction

A cutting process is still part of many products, components and parts production. The tendency to reduce the main technological time of the machining is the reaction to the market requests that force on the manufacturers to look for the starting points for two basic requirements in high competition as are the production price reduction and the quality preserve or increasing. These demands are connected with the fact that the operation of each cutting tool is limited. Over time, the tool loses its cutting ability (sharpness) until it reaches the stage when it is no longer usable (it is blunted). The cutting ability is based on the measure of how long a tool is able to work at the given quality of a workpiece surface. This can be useful when comparing materials that have similar properties and power consumptions, but one is more abrasive and thus decreases the tool durability. Tool durability is an important parameter in evaluation of the performance of the cutting tools and inserts. It is directly connected with tool wear that significantly affects the quality of the workpiece.

The nature of tool wear, unfortunately, is not yet clear enough, in spite of numerous investigations. Although various theories and assumption have been introduced to explain the wear mechanism, the complexity of the processes in the cutting zone hampers the formulation of a sound theory of cutting tool wear. Therefore, the tool life and tool durability cannot be predicted from only a few studies and many studies have to be done in order to understand the behaviour of tool wear mechanism, to predict when tool wear occurs and the period time of tool life itself. Only from the understanding of the nature behind the machining process in given conditions (a combination of cutting parameters, machined material, tool characteristics including its material, etc.), a tool wear mechanism can be identified and consequently estimate the tool life and its durability.

The objective of the article is to study the cutting properties of HSS tools prepared via powder metallurgy. Authors have tried to demonstrate the capabilities and limitations of this type of high-speed steels as a material of cutting tools at the machining a material that is difficult to cut.

2. State of the art

At each contact of the geometrically specified cutting edge with the material to be machined occurs to their interaction and the cutting wedge is thus exposed to a strain due to the contact of the tool face with the material being cut off, due to the contact of the tool flank with machined surface, due to a friction originated on the face or flank surfaces of the tool and due to the thermal load caused by the thermal field that results from the transformation of the deformation energy when cutting the chip. These types of stresses on the cutting wedge represent resistance to the relative movements exerted by the tool against the workpiece. The external manifestation of this resistance on the cutting wedge is the dimensional changes on the face and back surfaces of the tool, as well as on the radius of the cutting edge and the radius of a tool corner round, which are due to the material loss or due to deformation. This cause that after a certain period of machining, the tool starts to show different types of wear. A predetermined amount of the tool wear is then so-called a tool wear criterion. So, in this context, the durability of the cutting tools can be defined as the cutting time for which the tool wear criterion is achieved. The result of external wear is an increase in cutting forces, a deterioration of the roughness of the machined surface, an increase in the heat generated in the cutting zone and a change in the dimensional tolerances of the produced dimensions **[1]**.

In the case of cutting tools, three types of wear zone can be observed: the initial wear zone, the normal wear zone and zone of accelerated wear (zone of critical wear). Depending on what physical causes cause the wear, it can be spoken of following types of wear: abrasive (abrasive), adhesive, chemically diffuse, oxidative. It should be noted, however, that also other external manifestations of a straining appear on the cutting wedge, which leads to its damage, can be recognized. These include plastic deformation of the cutting wedge and the formation of cracks on the cutting wedge **[2]**.

Zetek & Zetkova **[3]** stated that there are several variables in the cutting process, which need to be in balance to be the best durability of a tool achieved. They are normal and shear stresses along with material, tool geometry, technological and thermal conditions, etc. The researchers Lin **[4]**, as well as Ko **[5]** with their colleagues have found out that the minimal tool wear occurs at the lowest friction coefficient using optimal cutting speed, taking into account the fact that the values of normal and shear stresses, which appear in a contact area, change during the machining. It is also related to tribological processes occurring in the cutting area as an outcome of chemical and thermal impacts **[6-8]**.

Researcher Wagner with his colleagues **[9]** studied conditions of the tool wear. They have found out that the process of tool wear is divided into several phases, which are related not only to the cutting process but also to the chip formation. Heat transfer and temperature in the cutting zone along with attrition between the cutting tool and removed material affect the built-up emergence and its growth rate, what has a great impact on the tool wear and subsequently also on the quality of a machined surface **[10]**. It has been found that the greatest impact on the durability of the cutting tool has a cutting speed, a smaller feed rate and the least impact on durability has the cutting depth **[11,12]**.

At present, the greatest effort is being made in the field of cutting tools to improve the machining properties of existing cutting materials or newly developed tool materials. The material of a tool needs to have a specific set of attributes such as temperature ability, strength, hardness and thermal conductivity, but one of the most important properties of tool durability is its wear resistance. The selection of material for a suitable tool depends on the work conditions, which affect the method of the tool wear **[13]**. More recent studies **[14-16]** highlight that the low-content Cubic Boron Nitride (CBN) tool is superior to a high-content CBN tool in terms of tool wear and surface integrity for intermittent hard turning. On the other hand, according to **[17]**, the most versatile tool material is sintered carbides (SC) that have sufficient hardness (approximately 2000 HV), toughness and bending strength (approximately 1200-2000 Nmm^{-2}). The tools from SC can work effectively at cutting speeds from 100 to 300 $mmin^{-1}$. However, when it is necessary to machine at low cutting speeds and in cases, where cutting forces vary in both amplitude and frequency, the cutting properties of modern high-speed steels (HSS) compete the sintered carbide, even in some cases, they exceed them. **[18,19]** In general, a tool steel grade is delivered by the manufacturer in its as-annealed state; after proper heat treatment, it can achieve hardness values up to 65 HRC, according to the requirements of each particular application. In many cases, these requirements could be further augmented, demanding thus, the enhancement of the components' surface properties, mainly, its wear, fatigue and corrosion/oxi-dation resistance **[20]**.

The high-speed steels (HSS) can be produced by melt metallurgy and powder metallurgy. High-speed steels (HSS) are preferably applied in threading, broaching, drilling, milling, reaming and sawing. Powder metallurgy (PM) technology makes it possible to apply larger percentages of alloying elements, which results in a further improvement in properties. Compared to conventional casting metallurgy, powder metallurgy allows the production of tools with increased machinability, better dimensional control during heat treatment and increased cutting performance. The main advantage of powder metallurgy is the much greater compositional flexibility that makes it possible to create types of steels that cannot be produced by casting metallurgy. PM HSS has a uniform fine-grained microstructure with fine isotropic and evenly distributed carbides, (mostly having a higher carbide content) resulting in increased durability **[21]**. The timeliness and suitability of HSS application are also manifested in the milling of difficult-to-machine materials such as stainless steels, nickel alloys, and titanium alloys. Machining these currently technically attractive materials is a complex issue. Titanium alloys and stainless steels conduct heat very poorly, and all three materials can form a sintered layer during machining that adversely affects not only the quality of the next machined surface but also the durability of the cutting tools. The interoperation of the high temperatures generated in the cutting zone and the high specific pressures reduces the tool life. One way to minimize these adverse effects is to machine these materials under conditions ensuring that the strain rate does not exceed the rate of cold hardening. Another advantage of HSS and HSS-PM milling cutters is the possibility to work with a high axial depth of cut, but the stability of the cutting process has to be maintained **[22-24]**.

Basic principles and physical phenomena (plastic deformation, friction, heat transfe, etc.) occurring in a cutting zone have been studied by many researchers for a long time. Many experiments have been done to analyse relations and interactions between the cutting tool and a workpiece. It has been proved that there is a direct relationship between surface roughness of the machined part and the tool wear **[25-27]**. But the manufacturing industry, the surface has to be within certain limits of roughness. Therefore, measuring surface roughness is vital for quality control of machining workpiece. Surface quality after machining and tool durability become in this way very important indicators of machining efficiency.

Although there are many other studies related to the tool durability, to the parameters that affect it and to the tool wear appearances such as e.g. **[28-32]**, it is still challenging to understand the nature of the HSS-PM as a tool material. To know its advantages or disadvantages can improve product quality, productivity and so also the entire efficiency of the manufacturing process.

The article aims to study the HSS-PM tools durability at the machining of steel 1.4301 that is a material that is difficult to cut. The next partial goals of the long-term tests have been also to investigate the effects of a varying combination of cutting speed and depth of cut on the tool wear and surface roughness, as well as to study a change in the chip formation as the accompanying phenomenon of the tool wear.

The study is an original contribution to the HSS-PM tool wear and tool durability research because, in spite of the studying many works in this topic, authors haveńt found the presented combination of cutting conditions (milling technology, tool and machined materials, cutting parameters, etc.). The know-how can help the producer to set up conditions in real practice to be the production more effective and so a company more competitive.

3. Materials and methods

3.1. Materials

3.1.1. Tool material

During the experimental research, the milling cutters from HSS prepared via powder metallurgy were tested. The preliminary tests confirmed the chemical composition of HSS-PM consistent with ISO (AISI) standard according to which the steel contains 1.3% of C, 1.4% of Cr, 6.4% of W, 5% of Mo and 3% of V. This HSS-PM is characterized by homogeneous microstructure, higher shape stability and higher durability for machining titanium alloys **[33]**.

The cutters were coated in layer 1-4 µm by AlTiN coat that is suitable for the dry machining. The friction coefficient of this coat is 0.7 and the hardness is 3000-3500 HV. The tool overhanging was the same 50 mm at all experiments.

3.1.2. Machined material

The chromium-nickel steel EN X5CrNi18-10 (DIN 1.4301, AISI 304) was selected as a machined material within the research. It is widely used due to its excellent intergranular corrosion resistance, good deformability, good deep drawability and weldability. Chemical composition of the steel is presented in **Table 1**.

The yield stress $R_{e0,2}$ and maximum strength stress Rm of the steel have been verified at the beginning of investigation within preliminary tests. The measured values were in the range of $R_{e0,2} = 268 \div 271$ MPa and $R_m = 570 \div 572$ MPa that correspond to the producer declaration and to the material list. The chemical composition of the 1.4301 steel is in **Table 1**.

Due to the increasing requirements to minimize the environmental burden of machining and due to obtaining more obvious test results, machining was carried out without cutting fluids (Dry Machining).

Table 1 Chemical composition of EN X5CrNi18-10 (DIN 1.4301, AISI 304) steel.

Steel	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Ni (%)	Mo (%)	Co (%)	N (%)
EN X5CrNi18-10	0.029	0.47	1.87	0.03	0.024	18.26	8.31	0.27	0.078	0.048

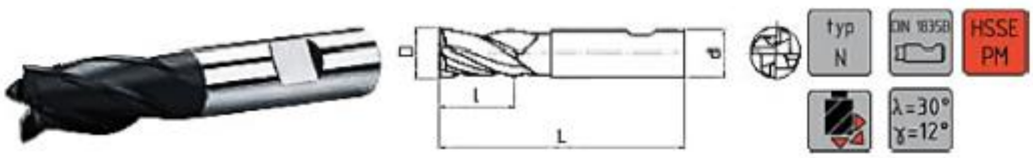


Fig. 1. Milling cutter from high-speed steel HSSE-PM used within the experiments.

3.2. Methods

3.2.1. Machining conditions

Conventional milling was selected as a technology to test the durability of tools made of HSS-PM. It is a machining technology that is characterized by the rotational working movement of a multi-edge cutting tool with a specific geometry that intermittently enters and outgoings from the contact area and removes the varying thickness of the material being machined. These specifics have been taken into account when selecting the cutting material, cutting tool, and cutting conditions.

The CNC machine Pinnacle VMC 650 was used for the up milling (conventional). HSSE-PM shank milling cutter (**Fig. 1**) of ZPS-FN a.s. Zlin producer with following characteristics: ϕ d = 8 mm, ϕ = 10 mm, l =

38 mm, L = 88 mm, corner radius rε = 0.3 mm, rake ϒ = 12° and helix angle λ = 30° were used at the experiments.

The long-term tests were carried out in the following way:

- The steel AISI 304 (DIN 1.4301) was machined without a coolant.
- Clamping of the workpiece was carried out in such a way to be a zero point that was set on the CNC milling machine, maintained at every tool change.
- The tool was inserted into the collet and clamped in a tool holder with a Morse taper.
- The overhanging of the tool was always checked with a perpendicular measure device made for this purpose.

The tool position relative to a workpiece during the experiments is shown in **Fig. 2**.

Initial cutting conditions for the milling cutters numbers 1÷3 were selected based on the recommendations of the HSS-PM producer and based on the tool catalogue of Guhring KG company **[34]**. They were: cutting speed v_c = 30 mmin^{-1}, cutting depth a_p = 12 mm and feed per tooth f_z = 0.012÷ 0.02 mm. However, in given conditions at authors workplace, the machining process was very unstable (followed by vibrations), so these results were not be taken into account at a tool wear evaluation and the conditions for other tools (no. 4÷14) were modified, they are presented in **Table 2**. At all measures, the feed per tooth has been set up to the same value f_z = 0.012 mm.

3.2.2. Measuring & evaluation conditions

Properties of cutting materials are evaluated within the durability tests which are usually divided into two main categories: shortterm and long-term tests. In practice, short-term durability tests are used more frequently due to the time saving and economy. They are often used for input checks of workpiece materials, respectively for fast comparing the durability of a tested cutting tool with an etalon. A long-term experiment is an experimental procedure that runs through a long period of time, in order to test a hypothesis or observe a phenomenon that takes place at an extremely slow rate **[35]**. Long-term cutting tool life testing in machining is defined by international standard ISO 3685-E-77-05-15 **[36]**.

In this experimental study, the tool wear, tool durability and the quality of surface roughness were evaluated within the long-term tests. Since the tools worked at different axial cutting depths, it resulted in a need to measure and classify wear at several points on the cutting edge. The wear of the cutting tool was evaluated according to predetermined criteria based on STN ISO 8688-2 (Milling durability testing). The wear was measured using a metallographic microscope NJC 160 at 40- and 100-times magnification. The tool wear values were then recorded using a 1.3-megapixel Moticam 1000 USB camera and evaluated using the appropriate Motic Images Plus 2.0 software. To measure the surface roughness, the roughness measuring device Mitutoyo SJ 400 was used, by means of which the average roughness *Ra* (the arithmetic average of the absolute values of the profile heights over the investigated length) has been gauged. The microgeometry of the machined surface has been copied by means of a standard stylus.

The active part of cutting edge was divided into the sections according to the ISO 8688 standard as it is shown in **Fig. 3**, while **Table 3** interprets the distances from the corner of individual points, where the wear was evaluated.

Fig. 2. The tool position relative to a workpiece during experiments.

Table 2 Cutting conditions.

Tool number	Spindle revolutions [min^{-1}]	Cutting speed v_c [$mmin^{-1}$]	Axial depth of cut a_p [mm]	Feed v_f [$mmmin^{-1}$]
4	500	12.56	8	24
5	500	12.56	8	24
6	550	13.82	8	26.4
7	660	16.6	8	31.68
8	792	19.9	8	38
9	550	13.82	12	26.4
10	792	19.9	12	38
11	660	16.6	18	31.68
12	550	13.82	18	26.4
13	660	16.6	12	31.68
14	792	19.9	18	38

The photos capturing the wear during testing were used to make protocols describing the progress and the wear appearance of individual tools at specific time intervals. Each measurement of the wear was carried out at least three times. The measured values were subjected to error testing based on the Grubbs test criterion. From the measured values the average value was calculated and it was subsequently noted in the evaluation protocol and it was also used to compile graphical dependencies of the wear on time.

3.2.3. Statistical evaluation

The statistical evaluation of the dependence of durability on cutting speed and axial depth was based on the Taylor equation of durability **[37]**

$$T = \frac{C_{Tv}}{v^m \times a_p^{X_T} \times f^{Y_T}} \quad (1)$$

where T is tool durability [min], C_T is a constant, v_C is cutting speed [m/s], a_p is cutting depth [mm], *f* is feed per revolution [mm] and m, X_T, Y_T are constant exponents.

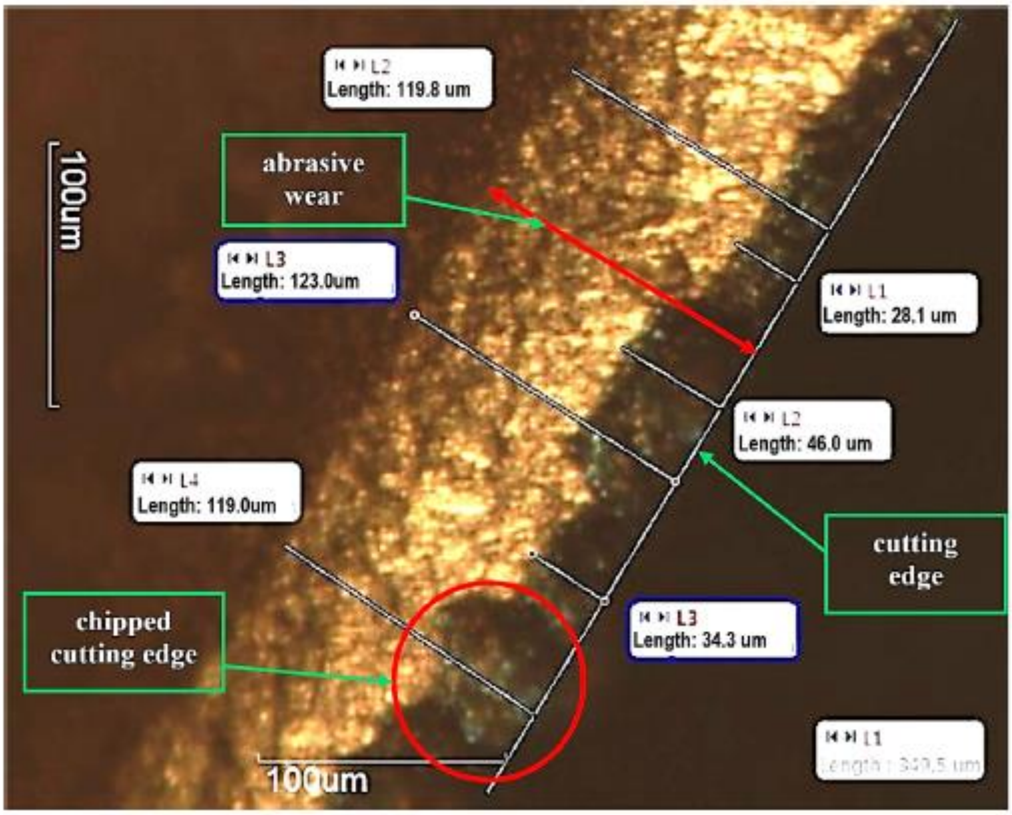


Fig. 3. An example of tool wear evaluation.

Table 3 Positions of individual points on the cutting edge specified for the tool wear evaluation.

Tool number	Distance from the corner [mm]				
	Position I.	Position II.	Position III.	Position IV.	Position V.
4, 5, 6, 7, 8	1 ÷ 2.5	3.5 ÷ 5	6 ÷ 7.5		
9, 10, 13	1.5 ÷ 3	4.5 ÷ 6	7.5 ÷ 9	10,5 ÷ 12	
11, 12, 14	1.5 ÷ 3	4.5 ÷ 6	7.5 ÷ 9	10.5 ÷ 12	13.5 ÷ 15

In this study, the dependence T = $f(v, a_p)$ was investigated for constant feed per teeth f_z = 0.012 mm, or feed per revolution f = 0.012 mm. A regression analysis, more precisely the finite method of matrix inversion **[38]**, was used as a tool for specification of the target variable based on the knowledge of other quantities.

To obtain the values of the vector b = [b_0, b_1, b_2] determining the main unknowns, the matrix X was defined with elements x_{0i} = log 10, x_{1i} = log v_i and x_{2i} = log a_{pi}, where x_{0i} represents a fictive variable

$$y = X \times b. \tag{2}$$

The vector of coefficients b = [b_0, b_1, b_2] was calculated according to the Eq. (3)

$$b = [X^T X]^{-1} \times X^T \times y. \tag{3}$$

Data processing results into a function describing the dependence T = $f(v, a_p)$ and the Fisher-Snedecor testing criterion **[39]** was used to verify the adequacy of the approximation quality of the regression function

$$F = \frac{s_y^2}{s_r^2}, \text{ while } \quad F > F_{0,05}(f_1, f_2), \tag{4}$$

where s_y^2 is a dispersion of measured durability values and s_r^2 is residual dispersion.

4. Results and discussion

4.1. Tool wear identification

Tool wear is the change of shape of the tool from its original shape, loss of tool material and it influences cutting power, machining quality, tool life and machining costs. When tool wear reaches a certain value, increasing cutting force, vibration and rise of cutting temperature cause surface integrity deterioration and dimensional error. At the identification of the causes of the types of wear, it was necessary to take into account the specific factors involving the experimental conditions. As it has been already noticed, the up (conventional) milling was applied within the experiments. At this type of milling, the cutting begins from zero thickness of a cut layer, where the corner of a cutting wedge and the part of cutting edge marked I. **(Table 3)** are in the contact area with the machined material as the first, so they are the most loaded. These loaded parts of the cutting wedge had to overcome the resistance of the material to deformation. At the same time, the compression of the machined material under the cutting edge in the initial phase of cut is the most intensive, therefore, along with the effect of high temperatures and friction, also the most intensive wear comes into existence. This initial adverse phase of up milling has also negative influence on the hardening of machined material, what can cause a problem at the next passing of shank mill, where the tooth of cutter begins to cut the hardened material, whose structure is created by martensite. The consequence of this phenomena is a higher cyclic loading of the cutting wedge **[40]**.

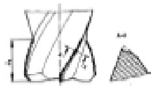
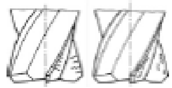
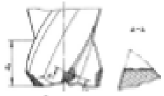
It is also necessary to consider that the cutter is pushed away from the cut area, which can cause a surface waviness. The used cutter mill can be so secondary excited, so the cutting wedges are exposed to the cyclic loading and relaxation due to changes in the cross-section of cutting chips. At the excessive wear of the tool corner, there were observed uncut deformed rests of material on the machined material.

Based on the STN ISO 8688-2 (Milling Durability Test that defines the basic appearances of damage), the following types of tool damage with associated codes presented in **Table 4** have been identified. The examples of captured wears that really appeared at on the tested milling cutters are presented in **Fig. 4**.

Chipping of the cutting edge has been probably caused by cyclic load peaks at which the cutting material particles begin to separate from the cutting wedge. This type of wear is typical for intermittent cuts and it has occurred at all tested milling cutters. It should be noted that the radial depth of cut was 0.5 mm and the mean thickness of the cut-off layer was even smaller, so it is necessary to take into the account shifting the area of maximum pressure stresses from a place on the cutting wedge, where the crater would be otherwise created, to the places closer to the cutting edge. Specific wear with cracks on the cutting edge and on the tool flank is a form of fatigue wear and it is probably caused by thermal shocks.

The pictures have shown that the highest tool wear values were generated at the tips of the cutting wedges and in the section designated as location I. This was a fatigue fracture at the tip of the cutting wedges and uneven wear of the back surface caused by abrasion. In some cases, besides the abrasive wear on the flank surface, it was also observed the markedly delimited surface, at which by the influence of elastoplastic zone under the flank surface of the cutter, it has occurred to a removing of deposited AlTiN coat could occur.

Table 4 Types of tool damage with associated codes.

wear code	Wear description	
1	uniform flank wear	
2	non-uniform flank wear	
3	uniform chipping of the cutting edge	
4	non-uniform chipping of the cutting edge	
5	specific wear (cracks on both the tool face and the tool flank oriented approximately perpendicular or parallel to the major cutting edge)	
6	tool tip/cutting wedge wear	
7	irregular cracks (appear on the tool face and on the tool flank that are irregularly oriented)	

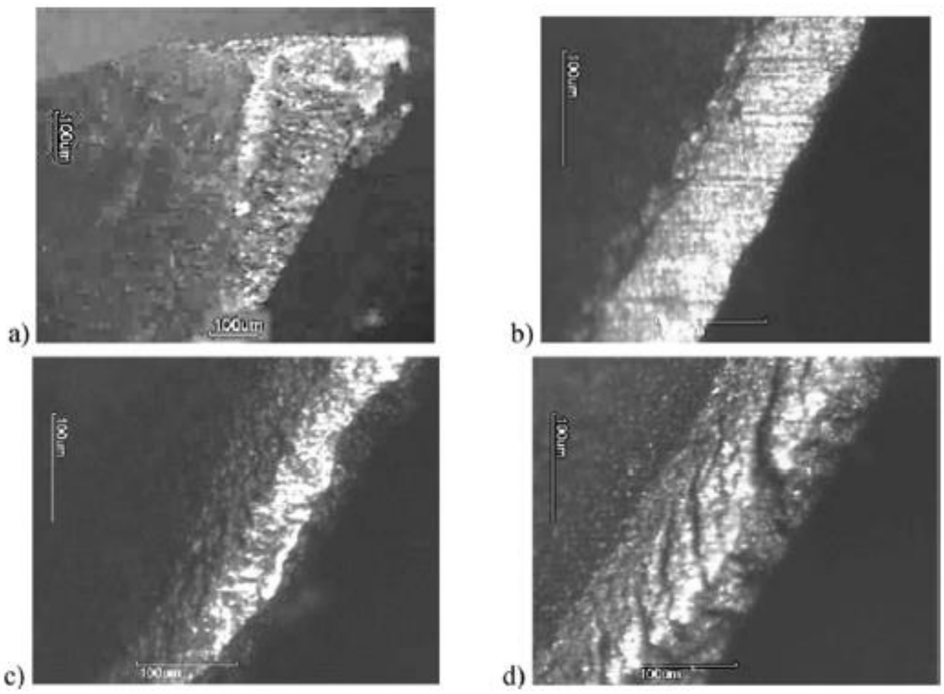


Fig. 4. The examples of the tool wear, (a) fatigue failure of the cutting wedge - cutter no. 13 after 10 transitions; (b) uniform chipping of the cutting edge - cutter no. 6 after 12 transitions, position IV.; (c) non-uniform chipping of the cutting edge - cutter no. 7 after 6 transitions, position II.; (d) specific wear including cracks on cutting edge - cutter no. 11 after 4 transitions, position III.

Table 5 Example of extract from the tool wear report recorded for milling cutter no. 4.

Tool no. 4		2 transitions		6 transitions		12 transitions	
Tooth no.	Wear position	Wear types	Average values [μm]	Wear types	Average values [μm]	Wear types	Average values [μm]
1.	I.	6/2/4	148/43/25	6/1/4	214/67/20	6/2/4	266/83/28
	II.	5/1	63/46	5/1/4	67/43–18	5/1/4	84/37/12
	III.	1	13	1	19	1	18
2.	I.	6/2	202/38	6/2/4	161/111/18	6/1/4	276/95/15
	II.	5/1	68/44	5/2	79/27	5/1/4	100/62/18
	III.	1	14	1	25	1	21
3.	I.	6/2/4	161/59/17	6/2/4	245/79/27	6/1/4	229/99/17
	II.	5/1,4	65/49,22	5/2	75/51	5/2/4	88/42/14
	III.	1	17	1	16	1	18
4.	I.	6/2/4	114/58/25	6/2/4	214/65/18	6/1/4	264/88/16
	II.	5/2/4	68/48/16	5/1	80/51	5/1/4	102/57/18
	III.	1/4	18/11			1	22

4.2. Durability evaluation

The values of tool wear obtained within their identification for each milling cutter were noted in the protocols, where for every tooth of the tool were stated the types of wear (by means of wear codes specified in **Table 4**), wear position and average values. Example of extract from the tool wear report recorded for milling cutter no. 4 is shown in **Table 5**.

After the first observations of tool wear, it could be stated that in some cases the most intense wear occurred in the area of cutting wedge and in other cases in the area of the cutting edge or tool flank. Based on **[32,41,42]** two values were selected as the criteria of a tool durability: maximum value of VB = 300 µm - as the maximum wear in the cutting wedge and value of VB = 100 µm - as the average value of tool wear in the area of cutting edge. The dependencies of tool wear on time are shown in **Figs. 5 and 6**, while figures in the left side (a) represent dependencies for milling cutters no. 4÷8 working at cutting depth a_p = 8 mm and figures in the right side (b) represent dependencies for milling cutters 9÷14.

It can be seen from **Figs. 5 and 6** that the tools achieved tool wear criteria with a different intensity.

As expected, the shortest durability had milling cutter no. 14, which reached VB = 100 µm in 18 min. This cutter operated at the highest cutting depth a_p = 18 mm and at the maximum experimental cutting speed of v_c = 19.9 $mmin^{-1}$. Milling cutters no. 8, 11 and 12 achieved the critical wear of VB = 100 µm in the range of 21÷24 min. The fact that the cutter no. 8 was operating at the highest cutting speed, but with the lowest testing cutting depth a_p = 8 mm, indicates that wear in the cutting-edge area is more affected by the cutting speed than by the cutting depth. For all of the above milling cutters, the dependencies have a steep character. On the other hand, the longest durability achieved milling cutters no. 4 and 9, while the milling cutter no. 4 worked under the lowest experimental conditions (depth of cut a_p = 8 mm and cutting speed v_c = 12.56 $mmin^{-1}$), but cutter no. 9 pointed out that a suitable combination of cutting parameters (in this case, ap = 12 mm and vc = 13.8 mmin-1) can significantly affect tool durability.

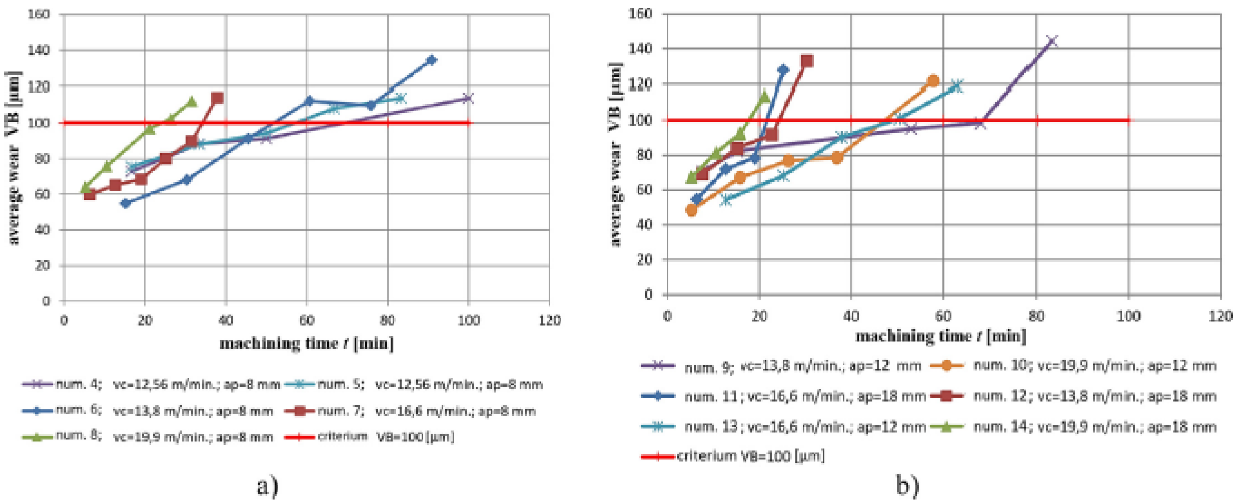


Fig. 5. Average tool wear in cutting edge area, (a) milling cutters no. 4-8, (b) milling cutters no. 9-14.

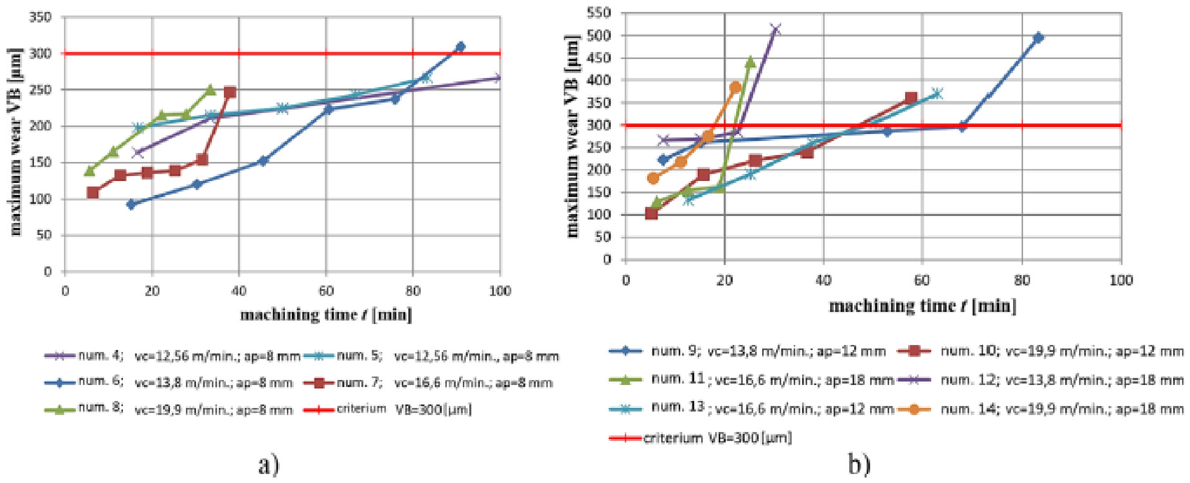


Fig. 6. Maximum tool wear in cutting wedge area, (a) milling cutters no. 4-8, (b) milling cutters no. 9-14.

From the dependencies presented in **Fig. 6** follow that the tool life for almost all milling cutters working at a cutting depth a_p = 8 mm (with the exception of milling cutter no. 6) was shorter than time, at which the tools reached the criterion VB = 300 µm specified for cutting wedge. The lowest wear intensity and longest durability had again the milling cutter no. 4 operating at the minimal experimental values of a_p = 8 mm and v_c = 12.56 $mmin^{-1}$. The durability of cutter no. 6, which as the only milling cutter working at a_p = 8 mm exceeded the specified wear criterion VB = 300 µm and which operated at a cutting speed of v_c = 13.8 $mmin^{-1}$, was 88 min. From the tools that were working with a higher cutting depth, the highest durability (68 min) has achieved milling cutter no. 9. On the contrary, the highest wear intensity and the shortest durability had milling cutter no. 14, similar to the evaluation of the cutting-edge wear in Fig. 5.

The measured data were statistically processed. The resulting form of the function describing the dependence T = $f(v, a_p)$ is given by Eq. **(5)** on a logarithmic scale and by Eq. **(6)** on a natural scale.

$$\log\hat{T} = 3,7286 - 1,2239\log v - 0,6501\log a_p \tag{5}$$

$$\hat{T} = 5353,034 \times v^{-1,2239} \times a_p^{-0,6501} \,[\mathrm{min}] \tag{6}$$

The adequacy of the approximation quality of the regression function was verified, the Fisher-Snedecor testing criterion $F > F_{0,05}(f_1, f_2)$ was met, as F = 3833 and the value of $F_{0,05}$ is 3347.

Based on achieved values and their statistical processing, the dependency of tool durability T of HSS-PM milling cutters on cutting speed vc and on axial cutting depth ap was prepared and it is presented in **Fig. 7**.

4.3. The surface roughness of machined material evaluation

The first sign of tool wear is a deteriorated quality of a machined surface. Products with low surface roughness improve the functional ability and reliability of machine systems. Surface roughness influences the major properties of products such as fatigue strength, creep life, corrosion resistance, and wear resistance. In the engineering aspect, these properties should be improved by controlling the surface roughness of components in the manufacturing stage **[43-45]**. Within the research, the roughness of the machined surface was also evaluated in order to determine the consequences of tool wear as an initial manifestation of its impaired ability to machine.

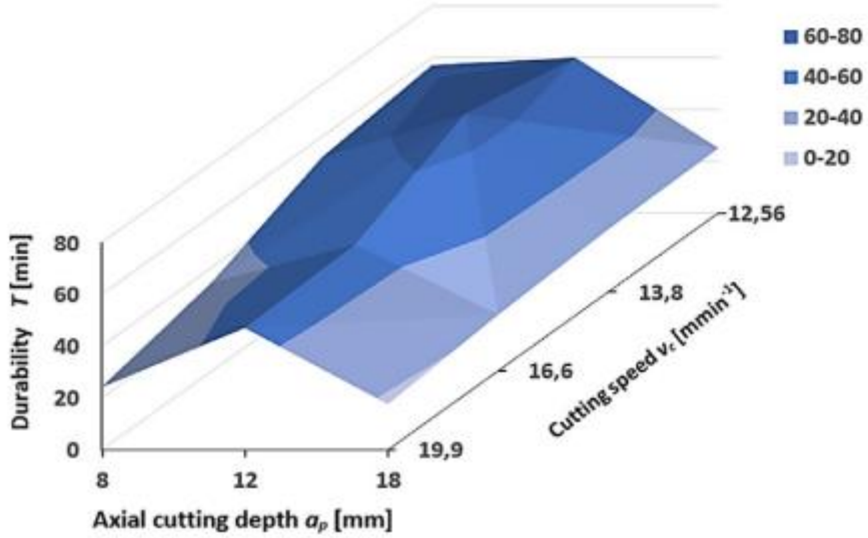


Fig. 7. The dependency of durability on axial cutting depth ap and cutting speed v_c.

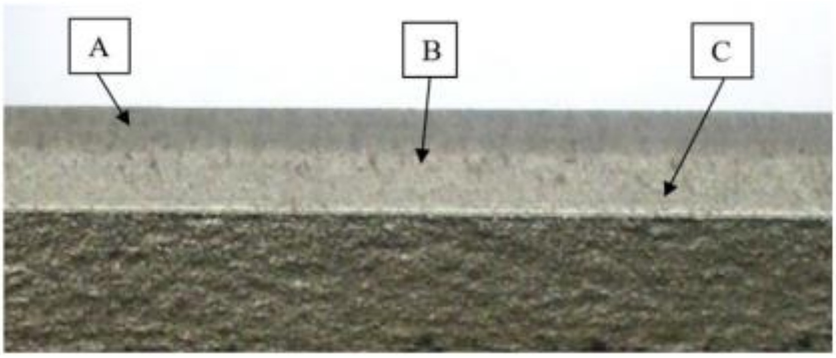


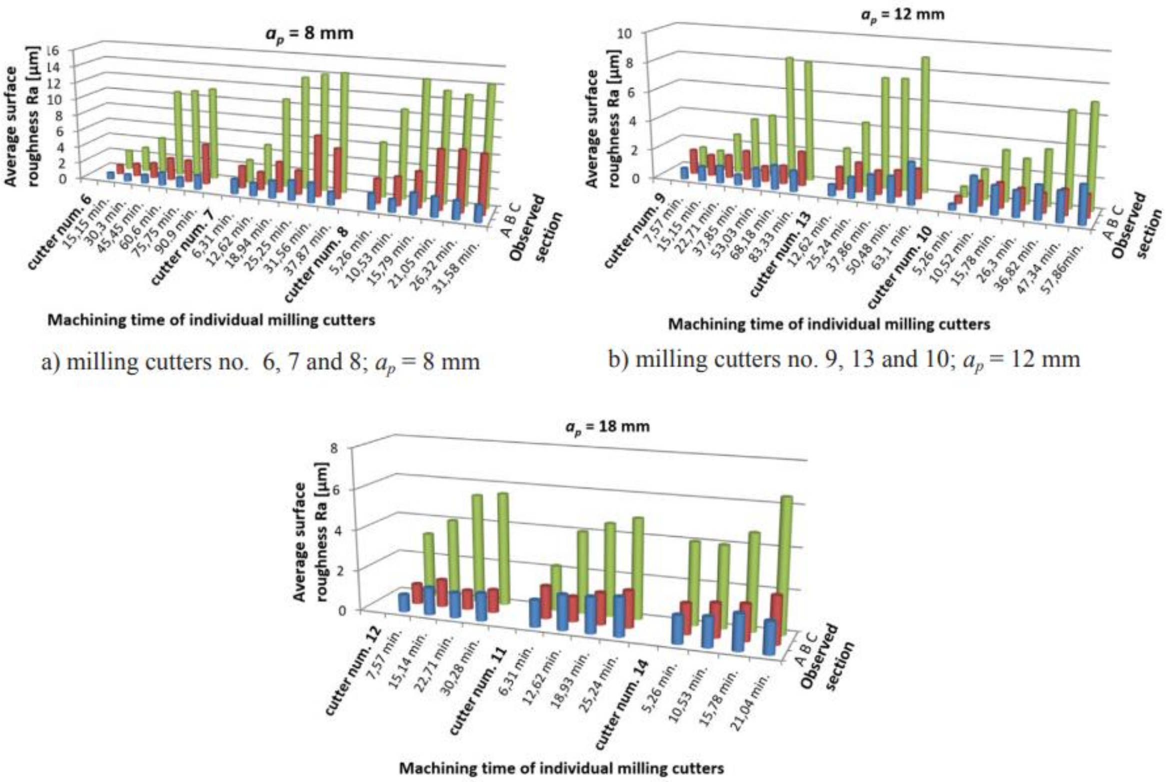
Fig. 8. Position of the sections for the surface roughness measuring.

The surface roughness measuring was carried out in three sections (marked A, B, C in **Fig. 8**) of the machined profile to be possible to provide an overview of the character of machined surface and to be possible to evaluate an originated microgeometry relative to the wear of cutting edge.

Six measurements were taken at each of the three sections of the machined surface. Subsequently, the measured values were subjected to Grubbs gross error testing. After meeting the test criterion, the arithmetical mean was calculated from the measured values, which was then used to generate the bar charts for individual cutting depth and for the milling cutters worked at this specific axial depth of cut. They are presented in **Fig. 9.**

It is clear from the above graphical dependencies that Ra values were highest in the measured section C for all milling cutters. It was a section of the machined surface formed by the cutting edge just behind the tip of the cutting wedges, i.e. the section of the cutting edge showing the highest wear values. In some dependencies, an increase and decrease in *Ra* values over time may be observed, which could be due to:

- build-up - if there is a build-up on the cutting edge, the geometry of the cutting wedge changes and the cutting width changesaccordingly;
- the place of measurement of the Ra parameter - since the parameter was not measured at the same location on the section under evaluation.



a) milling cutters no. 6, 7 and 8; $a_p = 8$ mm

b) milling cutters no. 9, 13 and 10; $a_p = 12$ mm

c) milling cutters no. 12, 11 and 14; $a_p = 18$ mm

Fig. 9. Surface roughness values Ra relative to machining time achieved by individual milling cutters at specific cutting depth

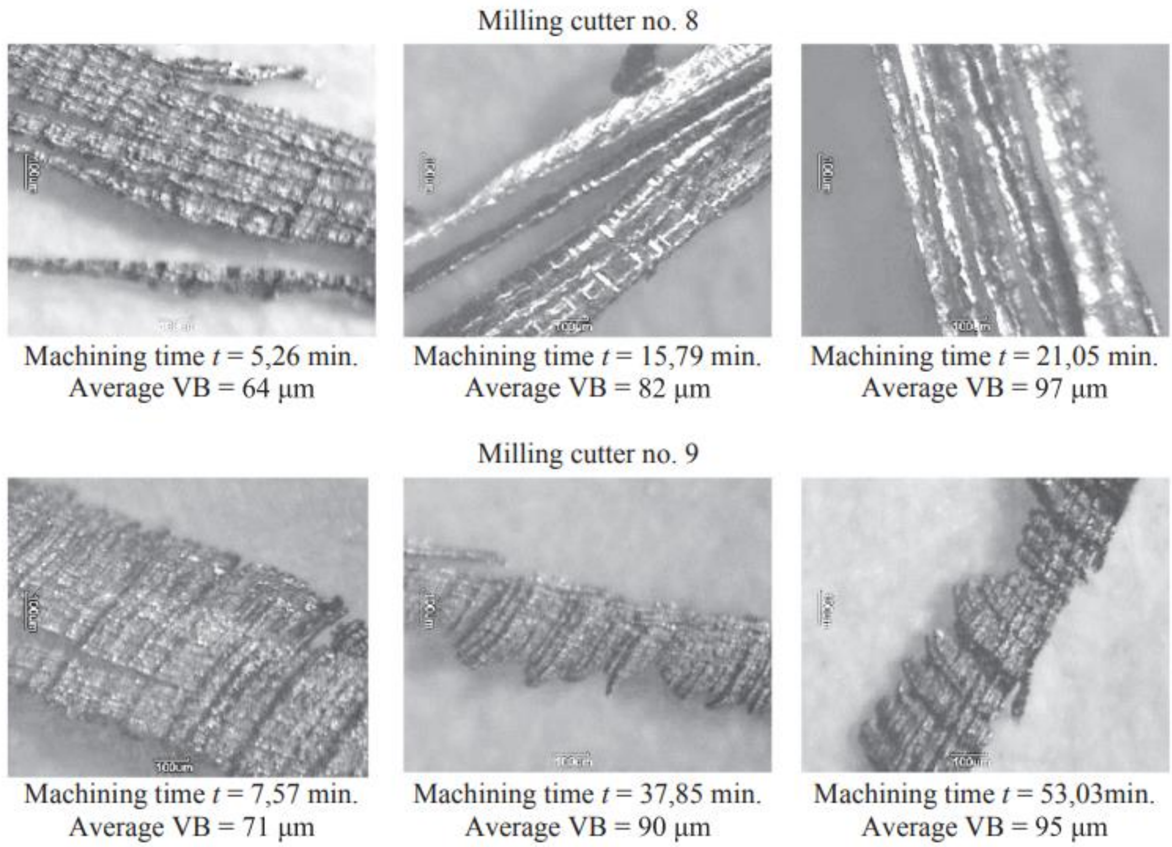


Fig. 10. Changes in the chip shapes during machining with milling cutters no. 8 and 9.

As wear increases, the reduced yield strength and steel ductility have fully begun to occur, so the worn cutting edge has not been able to properly cut the material. The material had been getting to pluck out more and more. Just before the end of machining, a “dandruff" texture was observed on the machined surface. This texture of the machined surface is characterized as the longitudinal surface irregularity measured in the direction of the cutting speed vector. This texture is due to a decrease in the clearance angle of the main flank surface as a result of wear. There was a change in the round radius of the cutting edge and, at low cutting depths, the material was pressed under the cutting wedge. So, the dandruff formation was caused by an elastic and plastic deformation when the material was in contact with the tool flank.

As it was mentioned above, during machining the formation of a built-up edge was observed in the section I. This phenomenon caused a change in the rake and clearance angles of the cutter as well as a change in the radius of cutting edge. Increasing the radius of cutting edge subsequently made it difficult to cut the material. The occurrence of an increase could also have a negative effect on the strengthening of the subsurface layer of the machined surface. Continuously deteriorating cutting conditions and increased vibration are also documented by photographs of the resulting chip. With the increase of tool wear, the chip became thinner with greater rugged relief as it is shown in **Fig. 10**.

5. Conclusions

Until today, a major gap exists between the current understandings of tool wear and the ultimate goal of tool wear research. Tool wear phenomenon still not fully understood since many of investigation and case study shown many contradictory results. While many studies conducted had proven that cutting speed is the most influential machining parameters that determine the tool wear rate, the less study regarding the effect on feed rate and depth of cut to tool wear rate have been investigated.

To evaluate machining properties of high-speed steel HSSE-PM produced via powder metallurgy, the tool durability depending on both cutting speed and cutting depth was investigated within the experimental tests.

Observation of wear appearances showed that the most intensive wear of the cutters occurred in the area of the wedge tip. The wearing course along the cutting edge towards the cylindrical shank had a decreasing character. In addition to abrasive wear on the flank surfaces, irregular cracks, cutting edge chipping and fatigue fracture were also observed. All of these signs of wear significantly worsened the cutting conditions, which was reflected in the roughness values of the machined surface and the chip shape.

Based on the achieved results, it can be concluded that the combination of cutting speed v_c = 13.82 $mmin^{-1}$ and axial depth of cut a_p = 12 mm has proven to be the best in terms of durability for the HSS-PM milling cutter working in given conditions. Even the combination of all cutting speeds with the axial depth of cut noted above proves to be most appropriate in comparison with other cutting conditions. The effect of increasing cutting speed on reducing tool durability has been also confirmed.

An accompanying phenomenon of the wear increasing is the surface quality decreasing. The measures showed that average surface roughness *Ra* was highest in the section of the machined surface formed by the cutting edge just behind the tip of the cutting wedges, i.e. the section of the cutting edge showing the highest wear values. Continuously deteriorating cutting conditions and increased vibration appeared also in the changes of a resulting chip because with the increase of tool wear, the chip became thinner with greater rugged relief.

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