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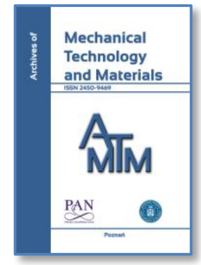

WEAR ANALYSIS OF CEMENTED CARBIDE DURING TURNING OF CAST IRON CONSIDERING ECONOMICAL MACHINING SPEED

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A B S T R A C T

The purpose of this paper is to find economical machining speed during turning of grooves for piston rings with various feeds. In the first part of the paper, literature analysis concerning durability of cutting tools is presented. Next, the wear of cemented carbide cutting tools during turning of cast iron is researched. The research has been done for seven cutting tools. During conducted turning trials, angular speed has been altered from n=530rev/min to n=710rev/min and feeds from f=0.007mm/rev to f=0.105mm/rev. On the basis of Taylor's equation, which relates cutting speed to tool life, the economical cutting speed is established with the application of two various methods.

1. INTRODUCTION

Wear of a cutting tool is a change in its geometry, material loss and loss of cutting properties, that result from the operation of the tool. Wear of a cutting tool is caused by tribological processes, which take place between the cutting tool and processed material. This is compounded by the impact of chemical and thermal interactions [3,10]

In many branches of industry requirements for cost and efficiency, regarding new construction materials are growing. Most efforts to achieve these requirements revolve around finding new materials with similar strength but lower density or increasing the strength of traditional material by means of alloys or heat treatment. The choice depends on parameters such as mechanical and thermal stresses and also on boundary conditions such as the cost of production, recycling or machinability. Materials made of cast iron offer high flexibility in shaping and relatively low production costs [4,5].

An example of a wear-resistant material is hardened austempered ductile iron (ADI), which has been tested in the paper [5].

Cast iron is very often machined with cemented carbide tools coated with coatings which cause an increase in hardness, reduction of adhesion, increase of resistance to high temperatures as well as reduction of coefficient of friction.

Cutting tools made of cemented carbide used in machining of grey iron have been investigated in the study [2]. Due to their high wear resistance and toughness, cemented carbides are applied to machining of metal, especially the cast iron [13].

The purpose of the study [7] is to determine the coated carbides tool life and the tool point surface topography. The results of the wear occurring on both tool points were compared with the width of the flank wear in relation to the period of the steady-state wear of the tool point. Occurrences of various mechanisms have been proven, such as abrasive wear and adhesion wear. Where machining without the use of a cooling lubricant occurred, longer tool life has been

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determined as well as greater resistance to abrasive wear of the tools which were coated with Al_2O_3.

Cast iron is very often machined with cemented carbide tools coated with coatings which cause an increase in hardness, reduction of adhesion, increase of resistance to high temperatures, as well as reduction of coefficient of friction.

In the paper [15], a comparison of tool life of sintered carbide (with TiAlN coating) and cubic boron nitride (CBN) ball end mills was presented. Experiments were carried out on hardened steel. The research revealed that in certain range of cutting speed the tool life reached for sintered carbide can be higher than that obtained for cubic boron nitride tool.

Durability of tools of different materials are also addressed in the article [8] where the comparison of the tool life and wear of the wedges made of SiAlON and whisker ceramics during the precise turning at different cutting parameters was presented.

Wojciechowski S. and Twardowski P. [14] concentrate on the analysis of tool's vibrations generated during the ball end milling process, including the influence of progressing tool wear. Their research revealed that vibrations generated in a stable milling process are strongly affected by the tool wear width on the flank face.

Investigations in laser-assisted machining have shown that under certain conditions, it also reduces the tool wear [6, 11]. Laser-assisted machining has been considered as an alternative for hard-to-wear materials such as metallic alloys and ceramics. This paper presents the results of research conducted on laser-assisted machining of one such hard-to-wear material, high chromium white cast iron. Results show that laser-assisted machining causes more frequent shearing of material, less uniform surface formation, and the heat penetration increases as the distance between laser spot and tool increases. It also leads to the reduction in cutting forces with expected improvement in tool life [9].

Researches on durability of tools are carried out not only in order to increase the quality of processed material or to gain higher efficiency of the cutting process, but also to make full use of tool life and reduce the cost of the process. Due to substantial costs of the replacement of tools, full use of cutting tools has always been a problem [1].

Analysis of the wear of cutting tools is necessary in order to establish economical machining speed.

Economical machining speed is the value of cutting speed which preserves the following relation: minimum cost per unit – maximum tool life.

2. EXPERIMENTAL DETAILS

2.1. Research and objective range

The workpiece processed was a ductile iron sleeve. Ductile iron is obtained by adding spheroidizators, most often magnesium or cerium; adding these chemical elements to grey iron which has clotting tendencies, increases surface tension. In accordance with the norm PN-EN:2000 ductile iron is classified according to its mechanical properties (tab. 1).

Table 1. The mechanical properties of ductile iron [12]

Symbol of ductile iron	Mechanical properties			Hardness, HB	Structure
	R_m [MPa]	$R_{p0,2}$ [MPA]	A [%]		
EN-GJS-350-22	350	220	22	≤160	Ferritic
EN-GJS-400-18	400	250	18	130÷175	
EN-GJS-400-15	400	250	15	135÷180	
EN-GJS-450-10	450	310	10	160÷210	
EN-GJS-500-7	500	320	7	170÷230	Ferritic-perlitic
EN-GJS-600-3	600	370	3	190÷270	
EN-GJS-700-2	700	420	2	225÷305	Perlitic
EN-GJS-800-2	800	480	2	245÷335	Perlitic, bainite or tempered martensite
EN-GJS-900-2	900	600	2	270÷360	

The cutting tool was cemented carbide in the form of a cutting insert (fig. 1) mechanically clamped in a holder (fig. 2).

The analysis was conducted on a universal lathe TUR 560E. During the tests the wear of cutting edges for different turning parameters was measured (tab. 2), where t_s is machining time for one path l= 5mm.

Fig. 1. Cutting insert

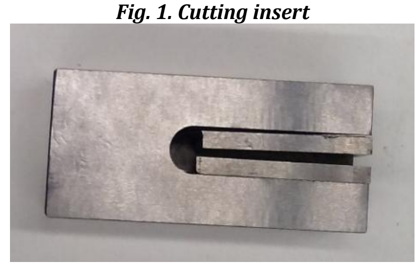

Fig. 2. Cutting insert-holder

Table 2. Turning parameters

Cutting tool no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
n [rev/min]	530	530	710	710	710	530	710
D [mm]	86	76	76	76	87.5	87.5	87.5
v_c [m/min]	143	126.5	169.4	169.4	195.2	145.7	195.2
f [mm/rev]	0.047	0.13	0.3	0.097	0.02	0.077	0.047
t_s [min]	0.5	0.2	0.067	0.18	1	0.33	0.32
a_p[mm]	1.0						

2.2. Research method

During the tests, the flank wear – specified by means of indicator VB_B– *was measured* on all tested cutting inserts*.* The measurements were carried out after a different number of passes, which were dependant on the intensity of wear. Indicator VB_B was measured by means of a workshop microscope with a scale of 0.01mm, as shown in Figure 3.

The pictures of the face and flank surfaces for each cutting tool were made by means of a stereoscopic microscope Discovery ZEISS V12.

In order to determine the durability of the tool, the critical tool wear has been selected. In the study it has been assumed that the cutting tool is blunt, when it reaches the following wear value: $VB_B \geq 0.2$mm.

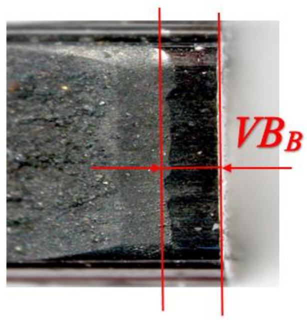

Fig. 3. Diagram presenting wear on the flank face

The results of the analysis on the wear of cutting inserts allow to determine cutting tool life time T for the adopted criterion*.*

After determining the cutting tool life time T*,* coefficients C_T, s and u from Taylor's equation (1) can be determined:

$$T = \frac{C_T}{v_c^s f^u a_p^e} \qquad (1)$$

where:

T - cutting tool life [min],

C_T - constant depending on the total processing conditions and factors, not included the equation,

v_c– cutting speed[m/min],

a_p- cutting depth [mm],

f - feed [mm/rev],

s, u, e - exponents defining the intensity of the impact of: cutting speed v_c, cutting depth a_p and feed f*.*

In this study, the coefficients have been determined with the use of:

- Excel programme
- system of equations.

The first method of determining the coefficients is to use Excel, in which it is possible to present logarithmically the relation between the cutting speed or feed and durability. Power function, the same as in Taylor's equation, has been used for the description of the variables. The programme automatically generates the equation together with *u, s,* C_T values.

Determination of the coefficients using the system of equations consists of substituting the value of the cutting speed, tool life and feed into Taylor's equation. As a result, the system of three equations with three unknowns has been found (2):

$$\begin{aligned} T_1 \cdot v_{c1}^s \cdot f_1^u &= C_{T1} \\ T_2 \cdot v_{c2}^s \cdot f_2^u &= C_{T2} \\ T_3 \cdot v_{c3}^s \cdot f_3^u &= C_{T3} \end{aligned} \qquad (2)$$

The above system of equations was calculated by means of using the following determinants:

$$\begin{aligned} T_1 \cdot v_{c1}^s \cdot f_1^u &= C_T \\ T_2 \cdot v_{c2}^s \cdot f_2^u &= C_T \\ T_3 \cdot v_{c3}^s \cdot f_3^u &= C_T \end{aligned} \qquad (3)$$

$$\begin{aligned} T_1 v_{c1}^s f_1^u &= T_2 v_{c2}^s f_2^u \\ T_1 v_{c1}^s f_1^u &= T_3 v_{c3}^s f_3^u \end{aligned} \qquad (4)$$

$$\begin{aligned} \ln(T_1 v_{c1}^s f_1^u) &= \ln(T_2 v_{c2}^s f_2^u) \\ \ln(T_1 v_{c1}^s f_1^u) &= \ln(T_3 v_{c3}^s f_3^u) \end{aligned} \qquad (5)$$

$$\begin{aligned} \ln T_1 + s \ln v_{c1} + u \ln f_1 &= \ln T_2 + s \ln v_{c2} + u \ln f_2 \\ \ln T_1 + s \ln v_{c1} + u \ln f_1 &= \ln T_3 + s \ln v_{c3} + u \ln f_3 \end{aligned} \qquad (6)$$

$$\begin{aligned} (\ln v_{c1} - \ln v_{c2})s + (\ln f_1 - \ln f_2)u &= \ln T_2 - \ln T_1 \\ \ln v_{c1} - \ln v_{c3})s + (\ln f_1 - \ln f_3 \ u &= \ln T_3 - \ln T_1 \end{aligned} \qquad (7)$$

$$s = \frac{W_s}{W} = \frac{\begin{matrix} \ln T_2 - \ln T_1 & \ln f_1 - \ln f_2 \\ \ln T_3 - \ln T_1 & \ln f_1 - \ln f_3 \end{matrix}}{\begin{matrix} \ln v_{c1} - \ln v_{c2} & \ln f_1 - \ln f_2 \\ \ln v_{c1} - \ln v_{c3} & \ln f_1 - \ln f_3 \end{matrix}} \qquad (8)$$

$$u = \frac{W_u}{W} = \frac{\begin{matrix} \ln v_{c1} - \ln v_{c2} & \ln T_2 - \ln T_1 \\ \ln v_{c1} - \ln v_{c3} & \ln T_3 - \ln T_1 \end{matrix}}{\begin{matrix} \ln v_{c1} - \ln v_{c2} & \ln f_1 - \ln f_2 \\ \ln v_{c1} - \ln v_{c3} & \ln f_1 - \ln f_3 \end{matrix}} \qquad (9)$$

$$C_T = T \cdot {v_c}^s \cdot f^u \qquad (10)$$

Economical machining speed was determined using the following formula (11):

$$v_e = \frac{C_T}{T_e}^{m} = \sqrt[s]{\frac{C_T}{\tau(s-1)\ t_z + \frac{K_N}{K_o}}}\ [m/min] \qquad (11)$$

For the coefficient τ, which in the formula defines the participation of the cutting time t_s in the machine time t_m, the value τ = 1 was set. The time of the tool change was selected as t_z=1 min.

In order to find economical machining speed it is also necessary to determine the cost of the machine tool workstation K_o and tool costs K_N. Determination of these costs is possible by means of a calculation conducted by taking into account all the factors which affect these amounts. In a laboratory environment, in which the tests were carried out, due to the lack of detailed data it is difficult to carry out this type of analysis. For this reason the following values were adopted for K_o and K_N:

$$K_o = 40PLN/h$$

$$K_o = 0.67PLN/min$$

$$K_N = 20PLN/h$$

$$K_N = 0.33PLN/h$$

3. RESULTS AND DISCUSSION

Figures 6 ÷ 10 are graphs presenting cutting tool wear specified by indicator VB_B in a function of cutting time. Two photographs showing the face and flank surfaces have been taken for the given tools. The photographs were taken after the cutting tool had reached the predetermined criterion of dulling, and in the case of insert7 after finishing machining.

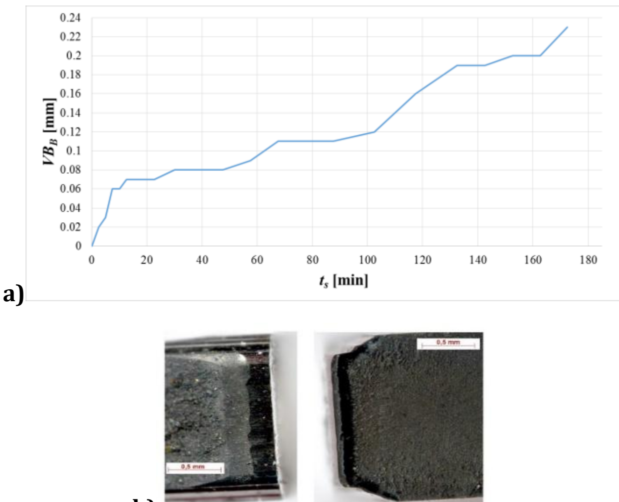

Fig. 6. a) Tool wear in cutting time function, b) image of the face and flank surfaces for insert no. 1

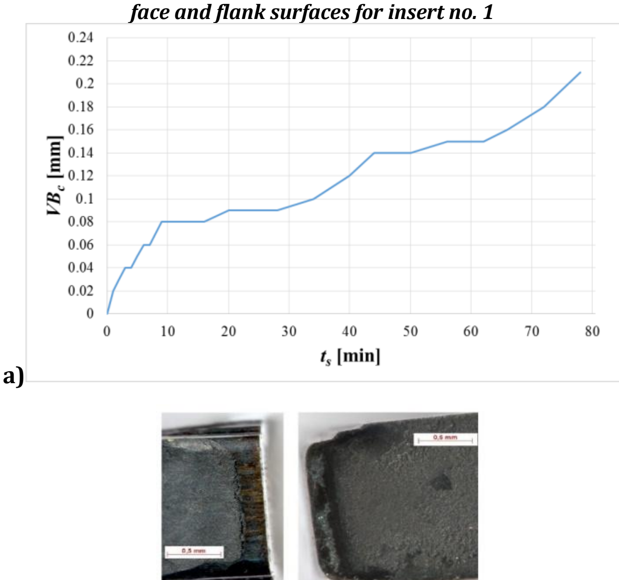

Fig. 7. a) Tool wear in cutting time function, b) image of the face and flank surfaces for insert no. 2

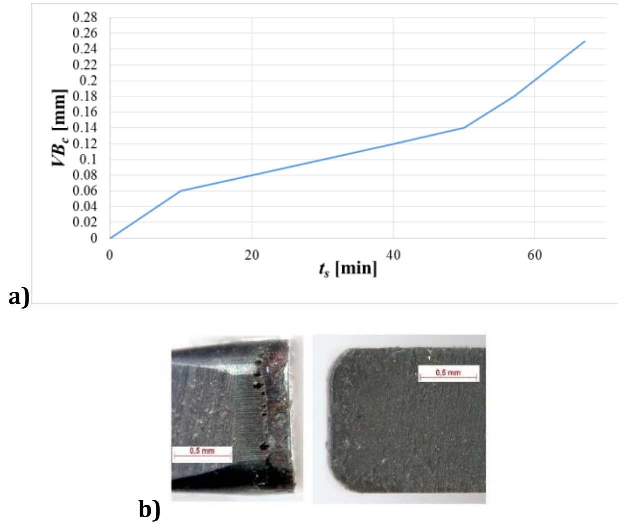

Fig. 8. a) Tool wear in cutting time function, b) image of the face and flank surfaces for insert no. 5

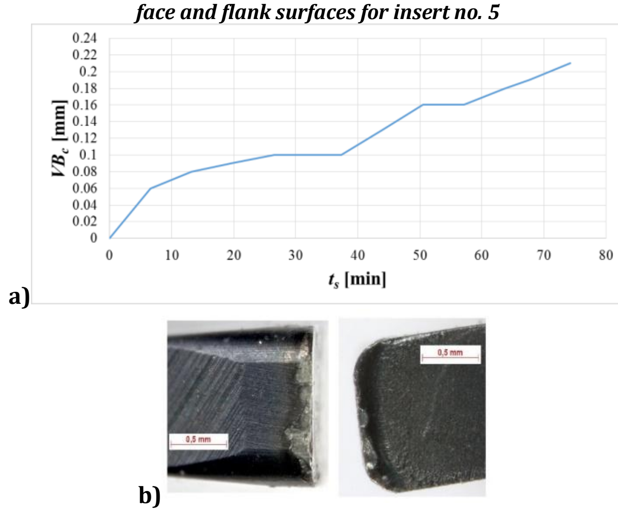

Fig. 9. a) Tool wear in cutting time function, b) image of the face and flank surfaces for insert no. 6

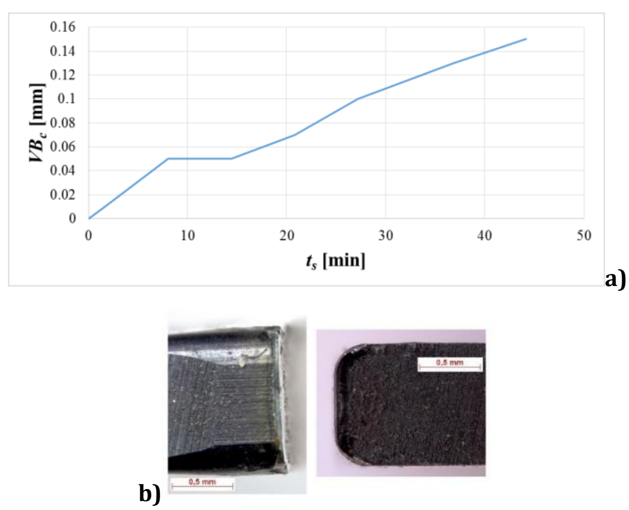

Fig. 10. a) Tool wear in cutting time function, b) image of the face and flank surfaces for insert no. 7

The graphs show that with the increased rotational speed *n* and feed *f,* the wear of the tool is greater. On each set of cutting inserts mechanical wear in the form of cracks, or chipping, which are particularly visible on the rake face, can be observed. In the inserts 3 and 4 the catastrophic tool chipping has been observed because of too high parameters (fig. 11).

Fig. 11. Inserts 3 and 4

The comparison of tool life under rotation speed *n* shows the influence of feed onto the tool life (fig. 12). At the speed *n*=530 rev/min, insert no. 1 had the highest durability. Insert no. 1 cut with the lowest feed rate *f*=0.02 mm/rev. In the case of the other two inserts the applied feed was greater, which resulted in lower tool life.

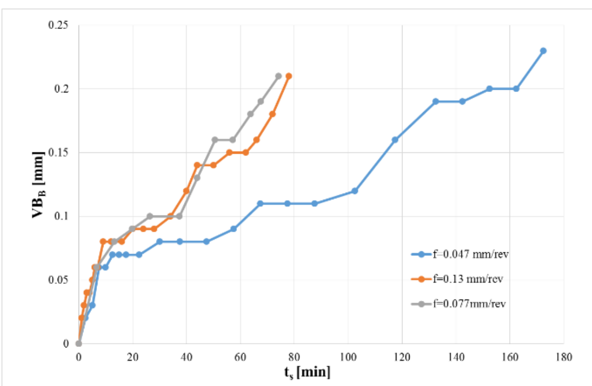

Fig. 12. Comparison of wear for speed n=530 rev/min

A similar analysis as in Figure 12 was carried out for the remaining cutting speeds. The results are shown in figures 13÷17.

These diagrams show the values of searched C_T, *s* and *u,* determined by using Excel software.

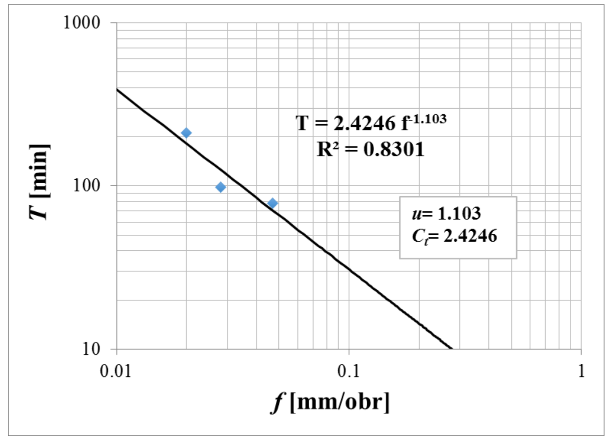

Fig. 13. Relation between feed and tool life for v_c=126 m/min

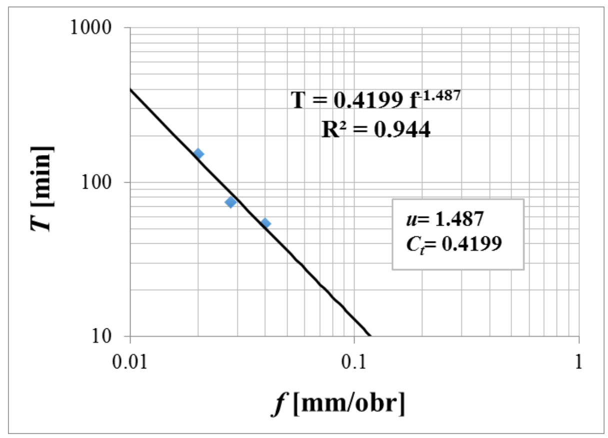

Fig. 14. Relation between feed and tool life for v_c=143 m/min

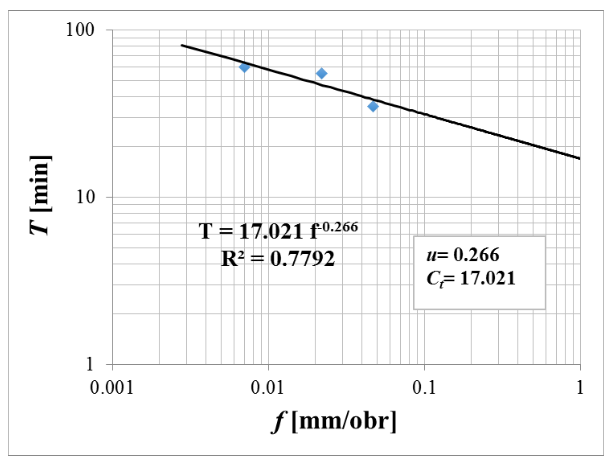

Fig. 15. Relation between feed and tool life for v_c=195 m/min

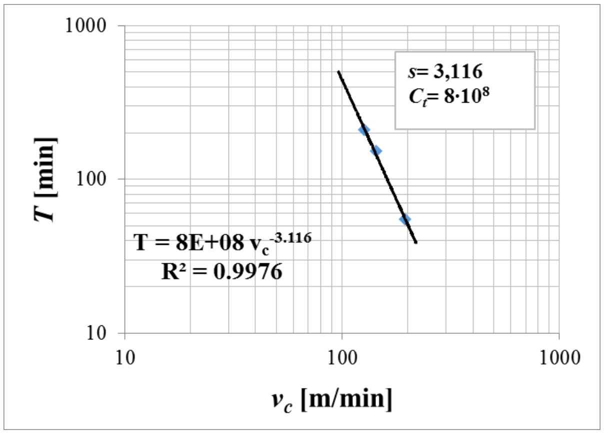

Fig. 16. The relation between cutting speed and tool life f=0.02 mm/rev

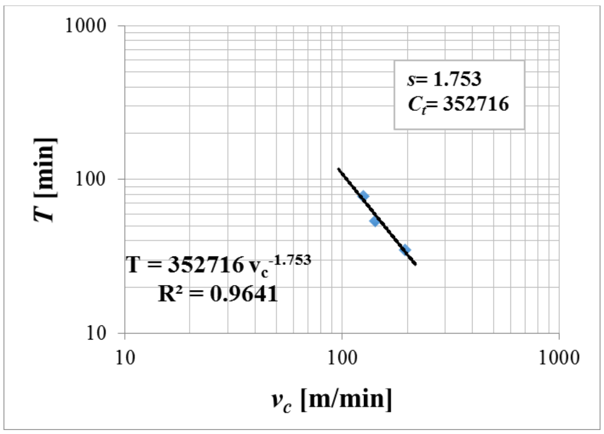

Fig. 17. The relation between cutting speed and tool life f=0.047 mm/rev

The second method used to determine the indicators: C_T, s and u is the algebraic method.

The values of searched variables after substituting in the equation (2) in the case of various variants are given below.

1	2
$78 \cdot 126^s \cdot 0.047^u = C_T$ $74 \cdot 143^s \cdot 0.028^u = C_T$ $35 \cdot 195^s \cdot 0.047^u = C_T$	$152.5 \cdot 143^s \cdot 0.02^u = C_T$ $60 \cdot 195^s \cdot 0.007^u = C_T$ $55 \cdot 195^s \cdot 0.022^u = C_T$
$s = 1.8347$ $u = 0.3465$ $C_T = 192986.2422$	$s = 3.2652$ $u = 0.0757$ $C_T = 1236690555$
3	4
$152.5 \cdot 143^s \cdot 0.02^u = C_T$ $74 \cdot 143^s \cdot 0.028^u = C_T$ $55 \cdot 195^s \cdot 0.022^u = C_T$	$60 \cdot 195^s \cdot 0.007^u = C_T$ $74 \cdot 143^s \cdot 0.028^u = C_T$ $35 \cdot 195^s \cdot 0.047^u = C_T$
$s = 2.6264$ $u = 0$ $C_T = 69830381.14$	$s = 1.9414$ $u = 0.6190$ $C_T = 77649.76$

To verify the method of determining exponents s, u, a comparison of the results obtained by using Excel and results of algebraic calculations has been carried out. Differences between the results for the exponent s are illustrated in Figure 18. Despite different methods of determination, the results vary slightly. The difference in the determined value between Excel and algebraic calculations is around 0.15.

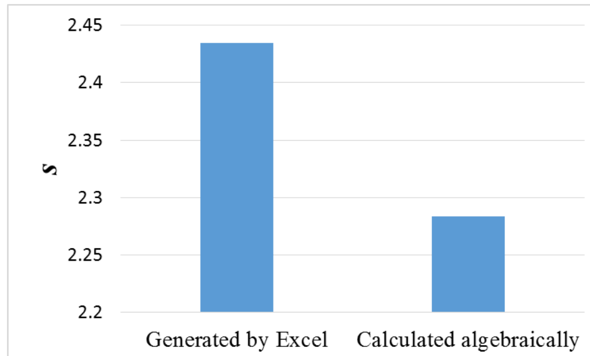

Fig. 18. Comparison of the value of exponent s generated by Excel and calculated algebraically

However, in the case of coefficient u the difference between the different methods of calculating is greater and amounts to 0.6 (fig. 19).

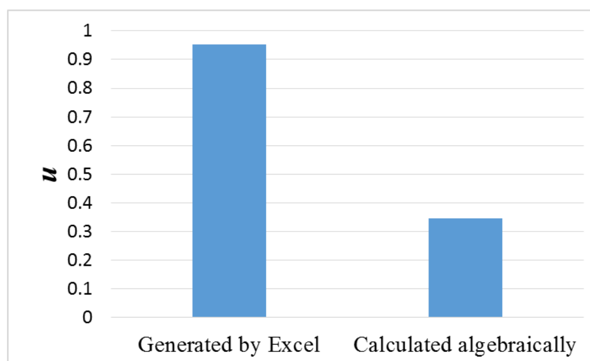

Fig. 19. Comparison of the value of exponent u generated by Excel and calculated algebraically

Since the different values of exponents: s, u and constant C_T have been obtained depending on the applied method, the economical machining speed was counted with the use of several variants. Subsequently, on the basis of the obtained values a mean value of economic cutting speed was calculated. Each of the cases is based on the constants generated by Excel and on the constants determined by algebraic method.

Table 3 presents the results of economic machining speed calculations in the case of the tool durability determination method analysed in the paper. Based on the calculated cutting speeds depending on the value of s, C_T, a mean value has been established, which is considered as the final value.

Table 3. Economical machining speed for different values of s and C_T

1 generated by Excel	$s = 3.116$ $C_T = 8 \cdot 10^8$
	$v_e = 497.66 m/min$
	$s = 1.753$ $C_T = 352716$
	v_e =1366.47m/min
2 determined algebraically	$s = 2.6264$ $C_T = 69830381.14$
	$v_e = 692.53 m/min$
	$s = 1.9414$ $C_T = 77649.76$
	$v_e = 277.58 m/min$
mean value	$\boldsymbol{v_e = 708.56 m/min}$

It can be stated that the comparison of economical machining speed did not bring a clear result for applied coefficients s and C_T, since the calculated machining speeds are different (Figure 20). The difference between each of the pairs of the results is substantial and economic machining speed amounts to approximately 868 m/min and 414 m/min in the case of Excel programme and algebraic calculations respectively.

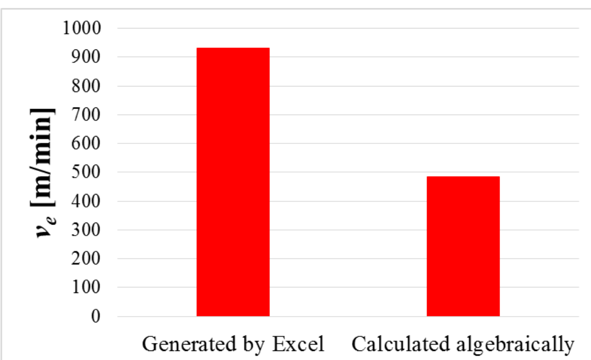

Fig. 20. Comparison of the value of economical machining speed v_e

The economical machining speed v_e= 708.56 m/min indicates that speeds to be selected should be greater than those on which the calculation of exponents s and u and constant C_T were based, i.e. speeds above 200 m/min. Obtained economical machining speeds do not fall within the range of tested values that ranged from v_c = 126 m/min to v_c = 195 m/min.

4. CONCLUSIONS

The following conclusions are drawn as a result of the research:

- Conducted research as well as the values of tool life, established using approximation, attest to the fact that with the increase in cutting speed and feed, the tool life decreases.
- The main cause of cutting tools wear observed in the microscopic images was abrasive wear of the rake and flank surfaces.
- The selection of economic machining speed determination method significantly affects the obtained values. The calculated values differ from each other.
- By averaging the obtained values of economical machining speed, the result of v_e= 708.56 m/min is received, which indicates that speeds to be selected should be greater than the speeds on which the calculation of exponents s and u and constant C_T were based, i.e. speeds above 200 m/min.
- Obtained economical machining speeds do not fall within the range of tested values that ranged from v_c = 126 m/min to v_c = 195 m/min.

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