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Investigation of the Titanium Alloy Turning Process with Prime A Tools under High-Pressure Cooling Conditions

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When turning titanium alloys, it is difficult to ensure the required quality with maximum machining efficiency. A typical problem in the turning process of titanium alloys is to achieve effective breaking and removal of chips from the machining zone. The combination of the new construction of cutting tools and machining methods in the machining of titanium alloys increases the efficiency of the machining. For this reason, the use of tools typical for the Prime Turning method in combination with the high-pressure cooling (HPC) method was analysed. The longitudinal turning of the Ti6Al4V ELI titanium alloy was performed using Sandvik Coromant grade 1115 carbide tools. An increase in the pressure of the cutting fluid to p = 70 bar was used. Measurements of the components of the total cutting force for finishing machining with variable cutting parameters in the range of: feed rates f = <0.1;0.4> mm/rev, cutting depth a_p = <0.25;1.0> mm and cutting speed v_c = <40;80> m/min were performed. It has been shown that the values of cutting force are mainly dependent on the feed and the depth of cut. An analysis of the forms of chips obtained is presented. The dependence of the applied cutting parameters on the value of the chip breakage coefficient C_{ch} was determined. The method of searching for the maximum efficiency of the turning process was determined, taking into account the desired value of the chip breakage coefficient.

Keywords: turning, titanium alloy, cutting forces, chip form, chip breakage index

Highlights

- *Using the carbide cutting insert CP-A1104-L5 and the HPC method is an effective means of improving productivity in the turning process of the Ti6Al4V ELI titanium alloy.*
- *The cutting parameters have a significant impact on the values of the components of the total cutting force and the chip breakage index.*
- *It is possible to increase the efficiency of the machining process by maintaining the required chip form.*

0 INTRODUCTION

The optimization of existing titanium alloy machining processes and the use of new machining techniques enable the achievement of the expected efficiency and quality of machining at low cost [1]. This is particularly significant for the machining of expensive materials or demanding materials. Titanium alloys, next to nickel alloys and heat-resistant steels, are difficult-to-cut materials. This is due to the specific mechanical and chemical properties that characterize this group of materials [2] and [3].

Due to their high strength, corrosion resistance and inertness, titanium alloys are most often used by the automotive, aerospace, chemical and medical industries [4]. On-going research broadens knowledge in the field of machining titanium alloys. The area of research described in the literature concerns the influence of cutting parameters on the roughness of the machined surface and the determination of the value of forces or temperature in the cutting zone [5]. Another important issue is the process of breaking chips during machining and the use of calculation methods that enable the simulation of cutting processes [6] and [7]. Accelerated wear of cutting tools due to high temperatures in the cutting zone and stress concentration at the edge of the cutting insert are also frequently analysed issues [1] and [8].

The machinability of titanium alloys can be increased as a result of the use or combination of different techniques and machining methods. For example, the use of various cooling methods in the cutting processes of titanium alloys yields measurable results. The literature describes the results of research on machining under dry cutting conditions, with minimal quantity or high pressure of the cutting fluid, as well as cryo-machining [8] to [12].

Increasing the efficiency of the titanium alloy machining process can be achieved using the high-pressure cooling (HPC) method. Currently, the pressure range recommended by cutting tool manufacturers to work with titanium alloys is 50 bar to 300 bar. This method allows faster heat dissipation and lower temperatures in the cutting zone. Compared to typical cooling, this results in a longer cutting tool life of up to 15 times. HPC machining greatly supports the chip-breaking process and chip removal outside the machining zone [4] and [10]. This is particularly important for turning and drilling processes [13].

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In the case of turning titanium alloys under HPC conditions, the selection of tool materials is important. Palanisamy et al. [15] described the results of experimental studies on the machining of inserts made of cemented carbide. The authors showed that HPC machining increases tool life by almost three times compared to conventional cooling. Furthermore, they showed that the mechanical effect of the liquid jet on the chips supports the process of breaking and removing chips from the cutting zone. HPC machining has been shown to produce short, segmented chips. In turn, Ezugwu et al. [16] analysed the machinability of titanium alloys under conventional and high-pressure cooling conditions with tools made of cemented carbides and coated with various coatings. They also demonstrated reduced cutting tool wear under HPC machining conditions. Da Silva et al. [17] analysed the mechanism of tool wear during high-speed machining of titanium alloys. They showed that tool life decreased with increasing cutting speed, and increased productivity was achieved during high-pressure cooling. In turn, Stolf et al. [18] analysed the method of tool wear due to tool-chip contact conditions during HPC machining of the Ti6Al4V alloy. They found that the coolant pressure and the maximum wear on the flank surface are inversely proportional. This is due to the effect on the process of abrasion of heat acting on the surface of the cutting tool application. The authors also pointed out that HPC machining has a positive effect on lowering the temperature of the tool and on the chip breakage process. Kaminski and Alvelid [19] showed that high coolant pressure causes fluid to enter the slip zone, reducing friction and temperature. In addition, the high-pressure cutting fluid stream reduces the chip winding radius and shortens the contact time between the tool and the chips.

In turn, Liang et al. [20] performed Ti6Al4V surface integrity tests at different cooling pressures and injection positions of cutting fluid. The researchers examined three injection positions, i.e., only injection in the rake face, only in the flank face, and injection in both rake/flank face directions. They observed that compared to dry cutting and HPC conditions, 3D surface roughness parameters were reduced during high-pressure jet-assisted machining. Masek et al. [21] analysed the influence of the direction of liquid supply to the cutting zone during polycrystalline diamond (PCD) machining. Their study showed that double cooling is strongly recommended when machining titanium alloys, both on the rake surface and on the flank surface, and the results showed that the appropriate HPC intensity was around 60 bar. This results in an increase in the efficiency of the chip-breaking process with reduced tool wear. Çolak [22] optimized the HPC machining process using genetic algorithms due to the desired surface roughness. Surface roughness and chip breaking were selected as optimisation criteria due to their importance for the finishing turning process.

One of the recently developed concepts for increasing the efficiency of the machining process is the so-called Prime Turning method. This concept takes into account the changed geometry of the cutting tool. These cutting inserts have three edges for longitudinal, face and profiling turning. This ensures efficient use of the edges and a longer tool life. Krajčoviech et al. wrote about the use of this type of tool for steel machining [23]. The authors showed that the depth of cut has the most significant impact on the values of cutting forces.

According to a review of the literature presented, researchers investigated various HPC strategies with the common goal of reducing tool wear or increasing process efficiency. However, the impact of machining efficiency of various cutting conditions is connected with different cutting parameter values and tool geometry, methods of cutting liquid delivery, etc. Furthermore, analysis of the quality of the cutting process could be realized from different points of view. In this regard, there are still few analyses that take chip forms into account. Due to the problems described above for obtaining effective machining of titanium alloys, Ti6Al4V ELI alloy turning tests were carried out under conditions of feeding the cutting fluid with increased pressure and using Prime A turning tools. The experimental research plan took into account three variables, i.e., feed, depth, and cutting speed. During the experiments, the processes of cutting forces were recorded, microscopic analysis of the chip form was carried out and the chip breakage coefficient was determined. The concept of maximising machining efficiency is presented, taking into account the favourable form of the chips.

1 METHODS

The experimental research plan was developed according to the Taguchi method [24] for three variables, i.e., feed f, depth of cut a_p and cutting speed v_c. The 16th test systems were designated. For statistical analysis, every group of the experimental run was done three times, for a total of 48 trials (16×3 runs). Table 1 shows the assumed ranges of cutting data values. The values of the cutting parameters are within the range of cutting parameters recommended by the tool manufacturer for turning titanium alloys.

Table 1. *The variables values in the research plan*

No.	Coded parameter	Real parameter	Value			
1	A	f [mm/rev]	0.1	0.2	0.3	0.4
2	B	a_p [mm]	0.25	0.50	0.75	1.0
3	C	v_c [m/min]	40			80

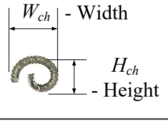
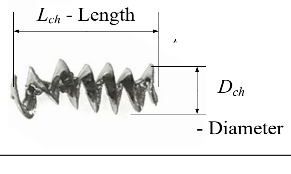
The signal-to-noise (S/N) ratio analysis strategy was adopted as "the lowest-best" according to Eq. (1) **[24]**.

$$S/N = -10 \cdot \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right). \tag{1}$$

A modified classification and characteristics of the chips presented by Fang et al. **[25]** and Lee et al. **[26]** were adopted. The aim of the modification was to adapt the classification of chips to practical industrial use. In general, chips can be described using words and numbers. In practice, a typical approach is to characterize chips using language terms such as "good", "weak", etc.

The authors of the paper presented a concept in which there are four different types of chip shapes, i.e., arch/bulky, spiral/circular, helical/tubular and ribbon. For each chip type, two main dimensional characteristics of the chips were assigned, which in turn were converted into numerical values. These values can be used to classify and determine the chip breakage coefficient **[27]**. During the investigation, the analysis of the form of the chips and their classification and evaluation were carried out. Only two forms of chips obtained during machining tests were observed, i.e., arc/bulky and helical/tubular type chips. For these types of chips, the dimensional characteristics were adopted according to Table 2.

Table 2. *Dimensional features of chips obtained during cutting tests*

Group	Chip index characterization
Arc/Bulky	
Helical/Tubular	

Based on the dimensions of the measured chip, the chip breakage coefficient C_{ch} was determined according to Eqs. (2) to (4). In the investigation, a simplified method of chip classification was adopted, according to which the chip breakage index C_{ch} takes values from 0 to 1 and is described by Eq. (2). Lower C_{ch} values represent better chip breakability.

$$C_{ch}(Dim) = \begin{cases} 0.01 \cdot Dim_{ch} & \text{if } 0 < Dim_{ch} < Dim_{ch\_limit2} \\ 1 & \text{if } Dim_{ch} \geq Dim_{ch\_limit2} \end{cases}, \tag{2}$$

where

- $Dim_{ch\_limit1} \leq 5$ mm;
  correct chips ($0 < C_{ch} \leq 0.2$);
- $Dim_{ch\_limit\,1} > 5$ mm and $Dim_{ch\_limit\,2} \leq 20$ mm;
  acceptable chips ($0.2 < C_{ch} < 1.0$);
- $Dim_{ch\_limit\,2} > 20$ mm;
  unfavourable chips (C_{ch} = const. = 1.0).

Where Dim_{ch} were described for arc/bulky chips by Eq. (3) and for helical/tubular chips by Eq. (4):

$$Dim_{ch} = \overline{W_{ch}} + \overline{H_{ch}}, \tag{3}$$

$$Dim_{ch} = \overline{L_{ch}} + \overline{D_{ch}}. \tag{4}$$

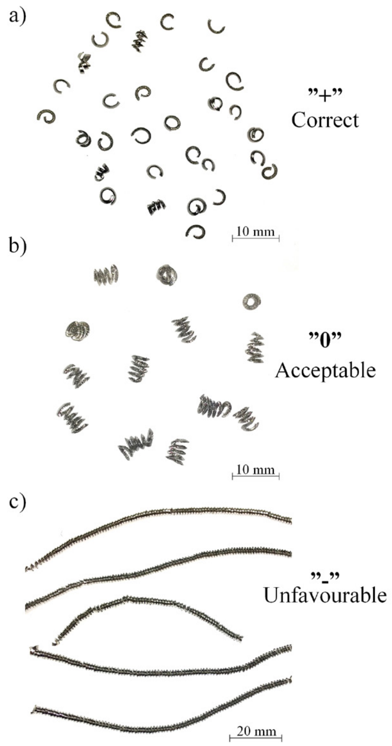


Fig. 1. Sample of chips photographs for parameters:
a) f = 0.4 mm/rev, a_p = 0.50 mm, v_c = 40 m/min,
b) f = 0.4 mm/rev, a_p = 0.75 mm, v_c = 80 m/min, and
c) f = 0.1 mm/rev, a_p = 1.00 mm, v_c = 40 m/min

The main criterion for the assessment of chip form was the chip dimensions, i.e., length and height for arc chips or length and spiral diameters for tubular chips. A three-stage assessment of the chip form was assumed, i.e., correct chips up to 5 mm, acceptable chips up to 5 mm to 20 mm and incorrect chips over 20 mm. The following markings were adopted when assessing the form of chips: "+" chips correct (good); "–" chips unfavourable (poor); "0" chips acceptable (fair). Example photographs of chips are shown in Fig. 1.

2 EXPERIMENTAL

Ti6Al4V-ELI (extra low interstitials) titanium alloy contains less oxygen, nitrogen, carbon, and iron than a typical Ti6Al4V alloy. This improves the ductility and resistance to cracking of the material, which means that this alloy is used in dentistry and medicine, for example, for orthopaedic implants [27]. The material to be processed was a shaft with a diameter of Dc = 50 mm. The mechanical properties of the alloy were as follows: tensile strength = 902 MPa, hardness = 29 HRc, elongation 13 %, Yield $\text{strength}_{0.2\%}$ = 815 MPa. Chemical composition ware: Al 6.1 %, V 4.13 %, Fe 0.05 %, O 0.1 %, N 0.01 %, C < 0.01 %, H 0.003 % and Ti remainder.

The longitudinal turning process was analysed under conditions of coolant supply with increased pressure. The cutting fluid was fed to the rake face by the cutting tool through the tool holder nozzle.

In cutting tests, cutting inserts of type Prime A turning (Fig. 2) type CP-A1104-L5 grade 1115 and the tool holder QS-CP-30AR-2020-11C from Sandvik Coromant were used. The value of the corner radius of the cutting insert was r_ε = 0.4 mm. A new cutting edge was used in each machining test. The impact of cutting-edge wear was not analysed. A constant cutting liquid pressure of p = 70 bar was used, and Blaser's 10 % Blasocut 2000 universal emulsion was used as the cutting fluid. The selected cutting parameters were within the range of finishing titanium alloys. The tests were carried out on a conventional lathe, equipped with a 150 bar pressure high-pressure plunger pump.

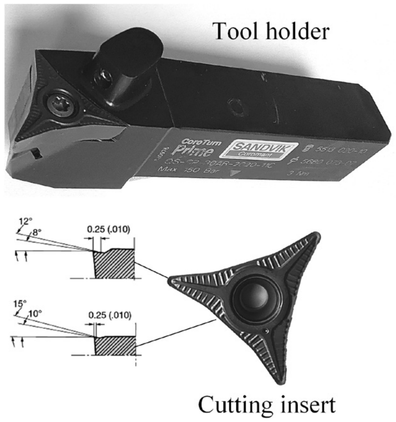


Fig. 2. Cutting tool Prime A

During the research, measurements of the components of the total cutting force and microscopic measurements of the chip dimensions were carried out. To record and analyse the components of the cutting forces, a measuring track system consisting of a 9257B dynamometer and a Kistler 5070B amplifier was used. Chip analysis was carried out using a Keyence VHX-7000 type 3D microscope with dedicated measurement software.

Table 3. *Test results for measurements of cutting force F_c and chip breakage coefficient C_{ch}*

No	A	B	C	f [mm/rev]	a_p [mm]	v_c [m/min]	F_{c_mean} [N]	S/N_{Fc}	C_{ch_mean}	S/N_{Cch}
1	1	1	1	0.1	1.00	40	255.4	–48.2	1.00	0.0
2	1	2	1	0.1	0.75	40	208.7	–46.4	0.17	15.2
3	1	3	2	0.1	0.50	80	140.0	–42.9	0.07	22.9
4	1	4	2	0.1	0.25	80	68.2	–36.7	0.05	26.6
5	2	1	1	0.2	1.00	40	462.3	–53.3	0.41	7.5
6	2	2	1	0.2	0.75	40	395.3	–52.0	0.13	17.6
7	2	3	2	0.2	0.50	80	210.6	–46.5	0.07	23.2
8	2	4	2	0.2	0.25	80	122.0	–41.7	0.05	26.4
9	3	1	2	0.3	1.00	80	610.0	–55.7	0.42	7.4
10	3	2	2	0.3	0.75	80	445.9	–53.0	0.14	17.2
11	3	3	1	0.3	0.50	40	285.4	–49.1	0.05	25.2
12	3	4	1	0.3	0.25	40	152.3	–43.7	0.04	27.3
13	4	1	2	0.4	1.00	80	776.0	–57.8	0.20	14.0
14	4	2	2	0.4	0.75	80	545.0	–54.7	0.10	19.6
15	4	3	1	0.4	0.50	40	351.2	–50.9	0.06	24.8
16	4	4	1	0.4	0.25	40	184.1	-45.3	0.05	25.9

3 RESULTS

In accordance with the adopted research plan, measurements of the components of the total cutting force and geometrical dimensions of the chips obtained were made. The influence of the assumed variables, i.e., feed values f [mm/rev] and depth a_p [mm] and cutting speed v_c [m/min] on the values of components of the total cutting force, i.e., main cutting force F_c [N], feed force F_f [N] and resistive F_p [N] was analysed. Table 3 presents the results of the average values of the cutting force F_{c_mean}, and the chip breakage coefficient C_{ch_mean} and the values of the *SN* parameter obtained in individual test systems. Tables 4 and 5 present a statistical analysis of the results.

Figs. 3 and 4 show the influence of individual variables on the average value of the main cutting force F_c and the values of the chip breakage coefficient C_{ch}.

4 DISCUSSION

The analysis of the measurement results showed a linear dependence of the values of all components of the total cutting force on the assumed values of the

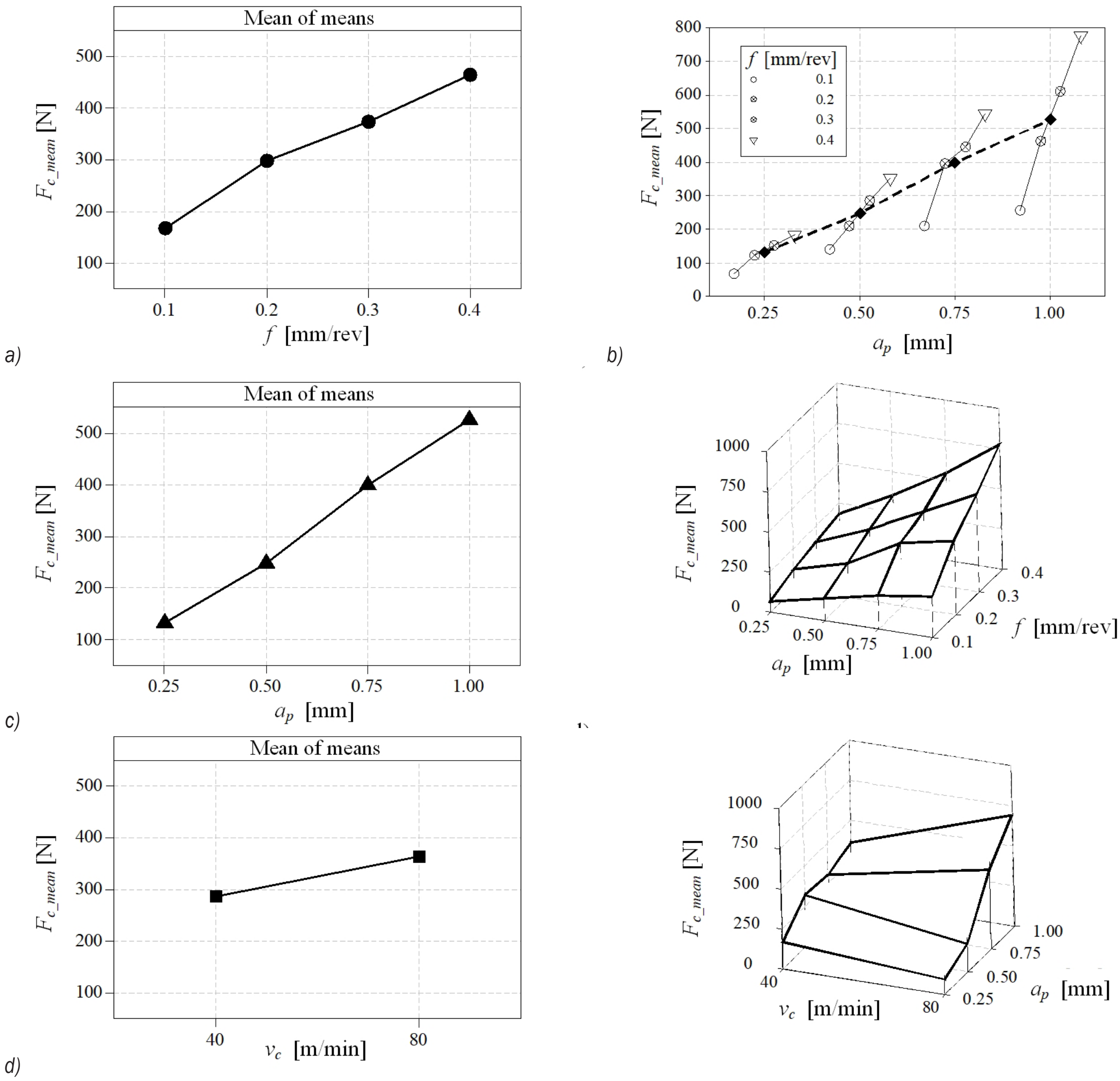


Fig. 3. *Influence of the analysed cutting parameters on the mean values of the cutting force F_c; a) each parameter in separate graphs: feed f, depth of cut a_p and cutting speed v_c; b) only depth of cut a_p; c) only depth of cut a_p and feed f; and d) only cutting speed v_c and feed f*

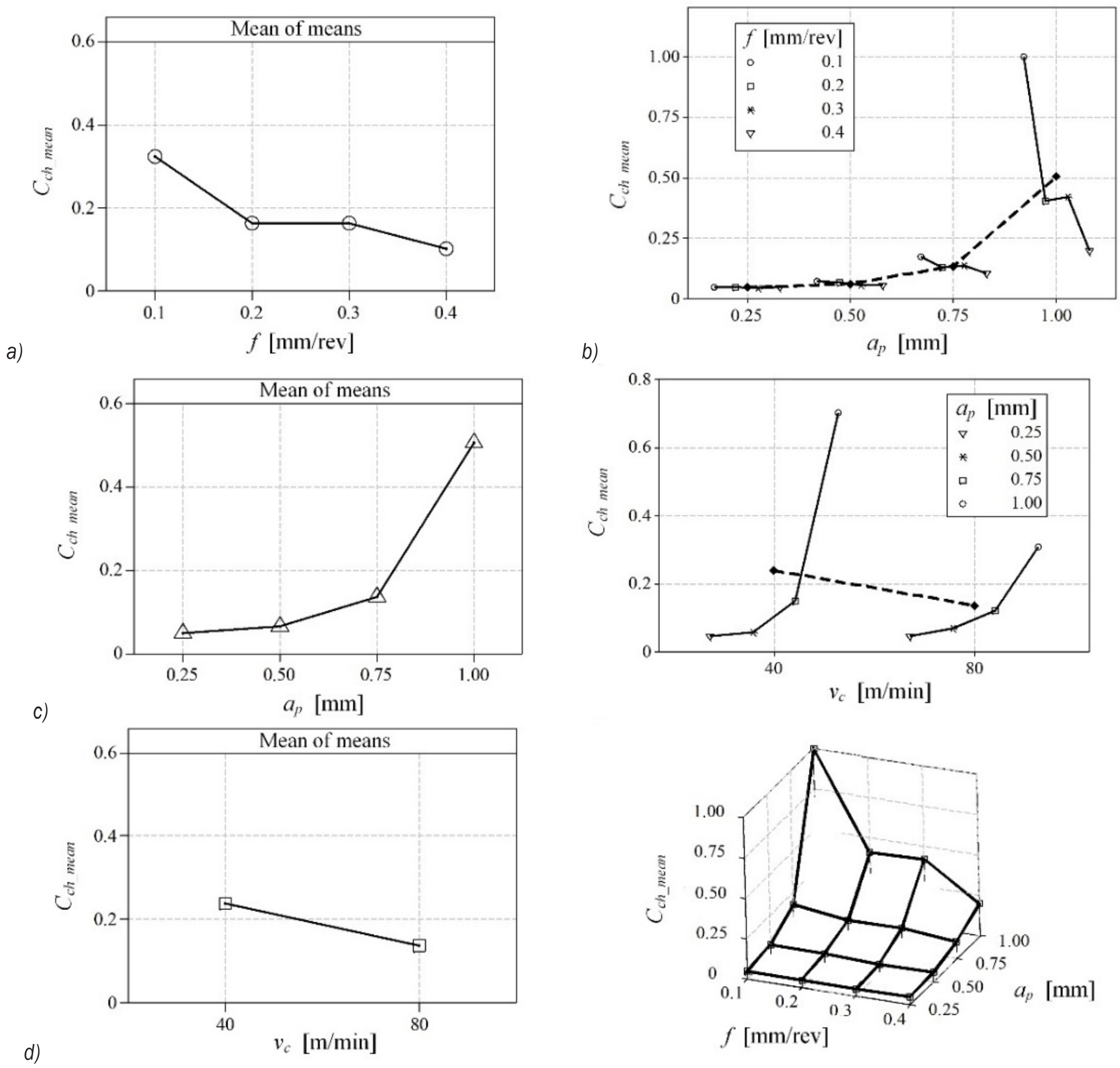


Fig. 4. *Influence of the analysed cutting parameters on the mean values of the chip breakability index C_{ch}; a) each parameter in separate graphs: feed f, depth of cut a_p and cutting speed v_c; b) only depth of cut a_p; and c) only cutting speed v_c; and d) only feed f and depth of cut a_p*

cutting parameters during the HPC turning of the titanium alloy Ti6Al4V ELI.

The most significant factors (Fig. 3) on the value of the cutting force F_c were depth of cut a_p and feed f. The depth of cut contributed 58 % and the feed rate contributed 30 % in the F_c response of the cutting force during the machining of the alloy. This was due to the increase in the cross section of the cut layer, which required the cutting process to use higher cutting forces. A fourfold increase in feed value or cutting depth results in about a fourfold increase in the average cutting force. In turn, a twofold increase in cutting speed, that is, from v_c = 40 m/min to v_c = 80 m/min, resulted in an increase (by about 50 N) in the average cutting force F_c. For cutting speed v_c = 80 m/min, an increase in the intensity of increase in cutting forces was observed, both as a function of depth of cut a_p and feed f (Fig. 3c and d).

The analysis of the data obtained showed that the chip form and average values of the chip breakage coefficient in the longitudinal turning process are significantly influenced by the tested cutting parameters (Fig. 4a), with the cutting depth a_p most significantly. The depth of cut contributed 70 % in chip breakage coefficient C_{ch} responses during the turning of the tested alloy. The cutting speed v_c and

Table 4. *Analysis of variance for mean values for cutting force F_c*

Source	DF	SeqSS	AdjSS	AdjMS	F	P	% Contribution
f	3	188287	188287	62762	18.96	0.001	30
a_p	3	357200	357200	119067	35.96	0.000	58
v_c	1	24255	24255	24255	7.33	0.027	12
Residual Error	8	26486	26486	3311			
Total	15	596228					

Table 5. Analysis of variance for mean values for chip breakability index C_{ch}

Source	DF	SeqSS	AdjSS	AdjMS	F	P	% Contribution
f	3	0.107	0.107	0.036	1.36	0.323	14
a_p	3	0.558	0.558	0.186	7.09	0.012	70
v_c	1	0.042	0.042	0.042	1.61	0.240	16
Residual Error	8	0.210	0.210	0.026			
Total	15	0.917					

the feed rate f contributed, respectively, 16 % and 14 %.

In this case, the correct and acceptable form of chips results from the simultaneous action of the pressure of the cutting fluid and the shape of the chip groove on the rake surface of the insert. For increasing depth of cut and feed values, the chip groove is filled with the chip material to a greater degree. The chip winding radius is also reduced (more short arc chips). The pressure of the cutting fluid additionally supports the process of chip winding and cracking. The chip-cracking process may also be supported by the impact of the chip formed against the unfinished surface of the workpiece or the flank surface of the cutting insert.

In contrast, increasing values of depth of cut cause a much faster increase in the average values of the chip breakage coefficient C_{ch} (Fig. 4b). An increase in the depth of cut value causes an increase in the width of the created chip. The chip strength are increased. The pressure of the cutting fluid may not be sufficient to initiate the chip cracking process.

The determined regression equations $F_c(f,a_p,v_c)$ and $C_{ch}(f,a_p,v_c)$ are shown below.

$$F_c\left(f,a_p,v_c\right) = -366 + 964\cdot f + 534\cdot a_p + 1.95\cdot v_c, \quad (5)$$

$$C_{ch}\left(f,a_p,v_c\right) = 0.711 - 1.899\cdot f - 1.192\cdot a_p - 0.00257\cdot v_c + 2.479\cdot f^2 + 1.418\cdot a_p^2. \quad (6)$$

A confirmatory test was performed to verify the predicted values compared to the experimental values. The results obtained (Table 6) showed a good precision of the predicted cutting force values and the classification of chips based on the chip breakability index C_{ch}.

It was also observed that for the cutting speed v_c = 80 m/min, lower values of the C_{ch} coefficient and thus a more correct form of chips were obtained (Fig. 4c). The unacceptable form of chips (Fig. 4d) was obtained for low feed values (e.g., f = 0.1 mm/min) and large depth of cut values (e.g., a_p = 1.0 mm). It is a prerequisite to look for an increase in the efficiency of the machining process, taking into account the correct form of the chips. This is particularly important for the finishing machining titanium alloys.

Analysing the results obtained, it can be concluded that increased machining efficiency should be sought by selecting higher values of depth or cutting speed. It is well-known that the feed value has a significant and negative effect on the surface roughness. Therefore, for finishing machining, it may be difficult to increase productivity by increasing feed value.

An example illustrating the method is shown in Fig. 5. In the analysed case, $F_c \leq 200$ N and $C_{ch} \leq 0.2$ (correct form of chips) were adopted as limiting criteria to not exceed the cutting force value. The cutting force diagrams F_c and C_{ch} were determined on the basis of the regression equations presented in Eqs. (5) and (6). The material removal rate Q_v was established according to Eq. (7):

$$Q_v\left(f,a_p,v_c\right) = f\cdot a_p\cdot v_c \quad [\text{cm}^3/\text{min}]. \quad (7)$$

Taking into account the limiting criteria, it can be noted that the adoption of a higher cutting speed value (i.e., v_c = 80 m/min) results in an increase in the material removal rate, from Q_v = 4 cm³/min to Q_v = 6.2 cm³/min, which is an increase of more than 50 % in efficiency. Despite the reduction in depth of

Table 6. *Results for confirmation test*

No	F_{c_mean} [N]	$F_{c\_anticipated}$ [N]	F_c percentage error [%]	C_{ch_mean}	Chips class.	$C_{ch\_mean\_anticipated}$	Anticip. chips class.
1	255.4	342.4	34.1	1.00	unfavo.	0.67	accept..
2	208.7	208.9	0.1	0.17	correct	0.35	accept.
3	140.0	153.4	9.6	0.07	correct	0.10	correct
4	68.2	19.9	70.8	0.05	correct	0.13	correct
5	462.3	438.8	5.1	0.41	accept.	0.55	accept.
6	395.3	305.3	22.8	0.13	correct	0.23	accept.
7	210.6	249.8	18.6	0.07	correct	0.00	correct
8	122.0	116.3	4.7	0.05	correct	0.02	correct
9	610.0	613.2	0.5	0.42	accept.	0.38	accept.
10	445.9	479.7	7.6	0.14	correct	0.06	correct
11	285.4	268.2	6.0	0.05	correct	0.02	correct
12	152.3	134.7	11.6	0.04	correct	0.05	correct
13	776.0	709.6	8.6	0.20	correct	0.37	accept.
14	545.0	576.1	5.7	0.10	correct	0.05	correct
15	351.2	364.6	3.8	0.06	correct	0.00	correct
16	184.1	231.1	25.5	0.05	correct	0.04	correct

cut a_p resulting from the limitation of the permissible value of the cutting force F_c.

It should be noted that an increase in the cutting speed may accelerate the wear of the cutting tools. This may result in higher manufacturing costs. The presented method does not take into account the tool life of the cutting edge.

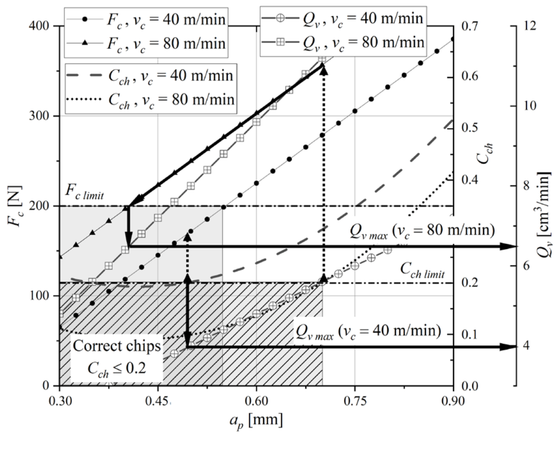


Fig. 5. *Method of searching for an increase in material removal rate Q_v*

5 CONCLUSIONS

The purpose of the experimental research was to analyse the machinability of the Ti6Al4V ELI titanium alloy with Prime A turning tools made of cemented carbides under machining conditions with increased pressure of the cutting fluid. The main area of analysis was to determine the influence of the cutting parameters (f, a_p, v_c) on the values of the cutting forces, as well as the chip breakage coefficient C_{ch} and the form of the chips. The results of the analysis showed that:

- the values of the cutting force F_c depend linearly on the cutting parameters adopted. According to the statistical analysis, the cutting depth a_p was the most significant parameter, followed by feed f, which affects the cutting force. The cutting speed v_c affected the mean cutting force to a much lesser extent.
- the cutting depth a_p was the most significant parameter which affects the chip breakability index C_{ch}. The obtained form of chips (correct, acceptable, and incorrect) depends on the range of cutting parameters used. On average, for the tested ranges of cutting parameter values, a correct chip form was obtained for: $a_p \leq 0.75$ mm, $f \geq 0.2$ mm/rev. A higher cutting speed value, that is, for v_c = 80 m/min, reduced the chip breakage coefficient value.
- obtaining a correct form of chips in the finishing turning of titanium alloy Ti6Al4V under HPC machining conditions depends on the synergistic impact of factors such as the values of cutting parameters, the shape and degree of filling of the chip breaker on the rake face, as well as the pressure of the cutting fluid. Under these

conditions, it is possible to increase the machining efficiency by selecting the cutting speed. In the case presented, the increase in the material removal rate Q_v of the machining was more than 50 %.

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