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Specific cutting force in dry turning of Ti6Al4V ELI using different grades of carbide inserts

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ABSTRACT

This paper presents the results of experimental studies on the influence of the turning process parameters on the values of specific cutting force k_c. with the use of different grades of carbide inserts. Three variables were analyzed, i.e. cutting speeds v_c, depth of cut a_p and feed f, for dry turning of the difficult-to-cut titanium alloy Ti6Al4V ELI. In the cutting tests, two types of inserts were used and made of two different grades of cemented carbides, ie, H13A and 1115. To determine the specific cutting force (SCF), a measuring system was used to trace and record the circumferential cutting force F_c. According to the adopted research plan, a total of 36 test systems were determined, on the basis of which the values of the k_c coefficient were determined. The significance of the influence of the machining parameters on the SCF values was analyzed. The tests showed that the specific cutting force k_c depends primarily on the cross-sectional area of the cutting layer, that is, directly on the feed value and depth of cut. Furthermore, it has been shown that turning with coated inserts results in a lower specific cutting force, which can directly translate into an increase in tool life. The mean value of the k_c coefficient for the use of a cutting insert without coating differed from a cutting insert with a coating of 282.7 MPa (1952.2 MPa compared to 2234.9 MPa). Furthermore, a higher tendency for surface hardening and built-up edge was observed in the cutting tests for uncoated tool turning. The obtained results allowed to present the recommended ranges of machining parameters for dry turning of the processed material. The presented results can provide practical guidelines for the selection of cutting parameters for the machine industry and contribute to the reduction of costs and the negative impact on the environment of machining with the use of cutting fluids. The obtained research results were analyzed and concluded according to the Taguchi method. Based on the desirability function and the response surface methodology, cutting speed v_c = 80 m/min, depth of cut a_p = 1.0 mm and feed f = 0.2 mm/rev were selected as optimal machining factors.

Keywords: specific cutting force, turning, Ti6Al4V Eli, dry machining.

INTRODUCTION

Knowing the specific cutting force value plays a key role in the process of selecting optimal machining conditions and designing cutting tools. This is particularly important when machining materials named superalloys, such as titanium alloys, and materials under demanding machining conditions, such as dry turning. The selection of tools and cutting parameters is a complex process that must be carefully considered and requires many factors to be taken into account. Algorithms for selecting cutting tools and parameters such as feed, cutting speed, and depth of cut recommend taking into account the hardness of the material and the specific cutting force (k_c) value for the type of material being processed. The value of a specific cutting force is essential to estimate the power requirement or cutting force in the turning process. Due to the high complexity of the algorithms, various optimization methods and tools have been developed, especially in the field of turning machining. In this respect, the machining of superalloys, such as nickel-based and titanium-based alloys, places extremely high demands.

The Ti6Al4V ELI titanium alloy is a very frequently used alloy in the aerospace, automotive, and biomedical industries due to its favourable properties, in particular the strength-to-weight ratio, excellent corrosion resistance and biocompatibility [1]. Nevertheless, these very attributes also lead to its designation as a material difficult-to-cut. The progressive development of materials science and metallurgy improves the properties of these alloys but, at the same time, makes them more difficult to process [1, 2]. In this respect, the difficulty of machining lies in the difficulty of obtaining the appropriate value of a specific criterion, such as a sufficiently long tool life of inserts, the desired short chip form, or maximising the material removal rate or achieving a certain quality of the machined surface [2, 3]. It is also worth noting that in the field of optimization of cutting processes, a dynamic development and application of various methods of mathematical analysis is observed [4], such as Pareto, Taguchi, RSM methods, as well as artificial neural networks or genetic algorithms [5, 6].

Current cutting data selection procedures also take into account environmental factors and carbon footprint calculations. Therefore, there is an increasing interest of both manufacturers and users of cutting tools in minimizing or completely eliminating the application of cooling and lubricating fluids in cutting processes. Many authors have conducted research on dry cutting or under conditions of minimal feeding of cutting fluids and have proven that while maintaining the required accuracy and economic efficiency, it is possible to machine with a reduced environmental load [7]. Another way to protect the environment is to optimize the execution of cutting processes due to the amount of energy required to carry out the processes. For example, the authors [8] described a method of reducing the power requirement for cutting titanium alloys, taking into account the form of chips [9, 10].

When cutting titanium alloys, the temperature in the cutting zone, especially on the cutting edge and the formed chip, can increase significantly if one of the methods of delivering the cutting fluid is not used [2]. The low thermal conductivity of Ti6Al4V alloys causes a concentration of heat on the cutting edge of the tool, which has a negative effect on tool life [1]. In addition, the low thermal conductivity of this material does not allow heat generated during machining to be dissipated from the cutting edge, causing intense deformation and accelerated tool wear [3]. It has been observed that, depending on the material of the tool, up to 50% of the heat generated during machining can be transferred to the cutting tool [11]. In addition, high temperatures at the cutting edge and excessive plastic deformation lead to higher cutting forces [3]. This contributes to the characteristic wear patterns of tools such as notching, flank wear, crater wear, chipping, and catastrophic damage [12]. Other research results [13] show that the variety of oxides generated on the rake face and the oxide layer formed on the contact surface of the tool and chip affect the cutting tool life. Another problem with turning alloys are the long, unfavorable form of the chips and residual stresses [14]. Machining of various titanium alloys is also problematic for other cutting methods such as drilling or milling [15].

Advances in tool materials and coatings for cutting tools have reduced the use of cooling and lubricating fluids in cutting processes. In recent years, the use of tools equipped with ceramic and cubic boron nitride (CBN) inserts has been constantly increasing [16, 17]. Various methods of delivering fluids to the cutting zone have also become popular, such as MQL (minimum quantity lubrication), HPC (high pressure coolant), or cryogenic cooling, which is clean and environmentally friendly [18]. The results indicate that cryogenic cooling gives the best results in the machining of titanium alloys. It enables high metal removal rates by using higher feed rates. In addition, tool life is significantly increased because the cryogenic fluid can penetrate the cutting zone more efficiently [19].

The temperature in the cutting zone could also be effectively reduced by MQL machining. The authors [20] carried out the process of turning the Ti-6Al-4V alloy using PVD coated cermet turning inserts, with a cutting environment of a mixture of low temperature air and mist based on vegetable oil. The authors found that this method of cooling the cutting zone reduced the average cutting temperature by 26.6% and 17.5% compared to dry machining at cutting speeds of 90 and 150 m/min, respectively.

Likewise, the high-pressure cutting fluid cools the cutting zone, enabling high cutting speeds and excellent brittleness and chip evacuation. This technique results in favorable chip form, lower cutting force, better tool life, and acceptable surface finish [20]. The authors [21] found that using polycrystalline diamond inserts, tool life was improved by at least 250% compared to wet cooling, and cutting forces are significantly reduced in a high pressure cooling environment. On the other hand, the authors [22] showed that when the Ti6Al4V alloy is machining with PCD tools, the limiting cutting speed is 300 m/min and the optimal liquid pressure was 80 bar.

Dry machining of titanium alloys has not been widely investigated so far because these materials are still considered difficult to cut. The authors [23] conducted tests on turning the Ti6Al4V alloy with dry uncoated cemented carbides and found that it is possible to use these tools for work under conditions that are more stringent than those specified by the manufacturer. On the other hand, the authors [24] investigated the surface integrity of the Ti-6Al-4V-ELI alloy during dry carbide-coated machining and showed that the surface roughness value recorded for cemented carbide tools was lower at high feed rates. Furthermore, it was found that the surface roughness values are more influenced by the feed speed and corner radius. A white layer or a plastically deformed layer was found during machining at a cutting speed of 95 m/min, a feed rate of 0.35 mm/rev and a depth of cut of 0.1 mm and at the end of the tool life.

The cutting speed has the most significant impact on tool life, and the increased cutting speed resulted in an increase in the frequency of dynamic forces during turning of the Ti 6Al-4V alloy [25]. They observed that the vibration increased with increasing the depth of cut to 0.8 mm and then decreased, and the vibration spike is perhaps due to friction and the low Young's modulus. The authors [26] studied the turning of the Ti-6Al-4V alloy using coated tungsten carbide inserts and found that the cutting speed and the depth of cut are significant cutting parameters that affect the cutting force. The Ti-6Al-4V alloy turning process using PVD-coated cemented carbide was carried out by [27], the percentage effects of the cutting speed were 25.51%, 8.6%, and 7.2% on the output parameters of the cutting temperature, surface roughness, and cutting force, respectively. During dry and wet machining of titanium alloy Ti-6Al-4V using uncoated cemented carbide inserts, it was observed that surface roughness and energy consumption were reduced due to increased cutting speed and material removal rate [28].

Experimental turning studies of the PVD-coated tool (with TiAlN coating) to machining Ti-6Al-4V ELI alloy by [29] have shown that the feed rate is the most important factor affecting the surface roughness, and the cutting force is strongly dependent on the feed rate. In this case, the optimal cutting data were a cutting speed of 67 m/min and a feed rate of 0.08 mm/rev. In turn, the authors [30] showed that tools with multiple TiAlN + AlCrN coatings showed an increase in tool life of up to 15% compared to uncoated and single-coated tools, with an improvement in surface roughness ranging from 30 to 45% depending on the cutting speed. In turn, the authors [31] showed that the CrN coating has unique micromechanical properties and tribological adaptive characteristics that minimize BUE formation and significantly improve tool performance when machining the Ti6Al4V alloy.

During dry turning of titanium alloys, the specific cutting force is influenced by many factors such as tool geometry, cutting parameters, and machining conditions. The presented research analyzes the effect of cutting parameters on the specific cutting force k_c when the Ti6Al4V ELI alloy was turned in dry conditions using inserts made of two different types of cemented carbides. The main aim and novelty of the described research was to determine the optimal and effective cutting parameters settings and efficient utilization of carbide insert grades for eco friendly dry turning of theTi6Al4V Eli titanium alloy.

A novelty in the research was to establish the effective range of cutting data with coated and non-coated cutting inserts made of different grades of cemented carbide and the expansion of knowledge about the ecological and cost-effective machining of titanium alloys. The results of the research contributed to the development of a repository of technical knowledge and optimization of dry turning of the Ti6Al4V ELI alloy.

EXPERIMENTAL SETUP

The material that was subjected to turning tests was the Ti6Al4V ELI titanium alloy and the workpiece was in the form of a cylinder with a diameter of Ø40 mm. This material is classified as a difficult-to-cut superalloy and is a variant of the popular and widely used Ti6Al4V titanium alloy. The ELI "Extra Low Interstitial" designation indicates a reduced content of chemical elements such as oxygen, nitrogen and iron in relation to the Ti6Al4V alloy. This change in chemical composition has a positive effect on the physicochemical properties of the tested material. Table 1 contains the chemical composition and mechanical properties and the chemical composition of the material tested.

It is a material with a density much lower than steel, yet the mechanical strength is at the level of specialized alloy steels such as: 20MnCr5 or 42CrMoS4. In addition, this alloy is characterized by a high strength-to-weight ratio, high fatigue strength, and fracture toughness. The reason for achieving very good mechanical properties is the microstructure that combines the alpha and beta phases. The properties of the Ti6Al4V ELI alloy make it most commonly used in the aerospace and medical industries. For example, this material is used in the production of highly stressed components that require high reliability, such as aircraft wing mounts, in the production of high-temperature parts such as aircraft engine turbine blades, or in the production of components subject to fatigue wear, such as aircraft landing gear. In the medical industry, Ti6Al4V ELI alloy is eagerly used due to its low reactivity with human tissues, corrosion resistance, and due to its mechanical properties imitating the behavior of human bone, e.g., hip and knee implants, and dental implantology [32, 33].

Two Sandvik Coromant inserts were used in the study, CNGG120404-SGF and CNMG120404-SF. The inserts were made of grade 1115 sintered carbides with a TiAlN + TiAlN coating and H13A without coating. The cutting inserts selected for testing are dedicated to the machining of difficult-to-cut alloys. They are characterized by high wear resistance, which is important when machining titanium, which is an abrasive and can quickly wear tools. They can be used in dry machining due to their good temperature resistance in the cutting zone and low thermal conductivity coefficient. The geometry of the inserts with a tool angle of 80º also provides adequate strength and resistance to the loads occurring in the machining of titanium alloys. The values of the cutting data in the turning tests were selected for the ranges characterizing the finishing machining. Figure 1 shows the cutting zone with cutting tools and an example of the recorded courses of the cutting forces components.

The Kistler measuring system with a type 9257B force gauge and a type 5070A signal amplifier was used to measure the components of the total cutting force, including the circumferential cutting force F_c. DynoWare from Kistler and Origin from OriginLab Corporation were used to record and analyze cutting forces. The measurements were recorded at a frequency of 1000 Hz and the minimum recording time for each measurement was 10 seconds.

The experimental research plan was developed in the MiniTab software according to the Taguchi method. Cutting parameters such as cutting speed v_c, feed f, and cutting depth a_p were assumed to be variable parameters. Table 2 shows the values adopted in the research plan. The cutting speed varied at two levels, while the depth of cut and the feed rate varied at three levels. The values of the cutting parameters used in the cutting tests were within the range recommended by the cutting tool manufacturer. The mean value of the cutting force components was determined from five measurements for each test system. Table 3 presents the research plan with the coded and real values of the parameters used in the experimental tests.

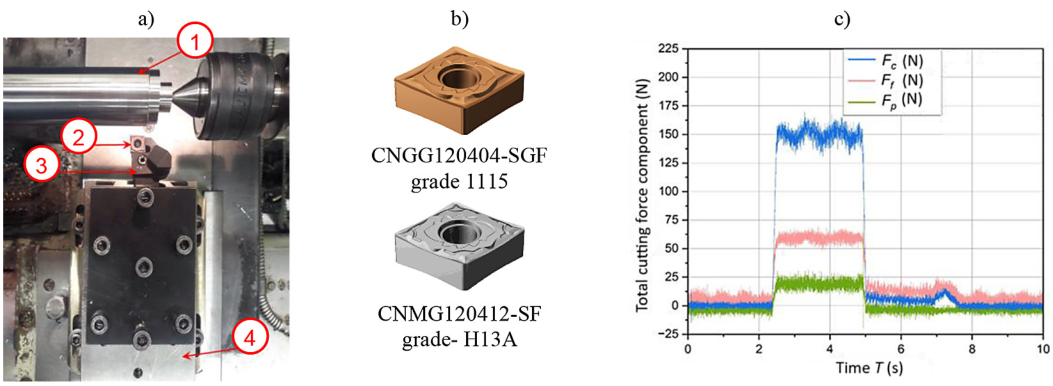

Figure 1. Test stand and example of the results of the recorded cutting force measurement (a) machining zone where: 1 – workpiece, 2 – cutting insert, 3 – PCLNR 2020K12 toolholder, 4 – Kistler 9257B dynamometer (b) cutting inserts, (c) example of the recorded cutting force components for v_c = 40 m/min, a_p = 1.0 mm, f = 0.08 mm/rev

The *S/N* ratio analysis strategy was adopted as 'the lowest-the best' according to the formula (1) [34].

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

To perform the statistical analysis of the research results, a general model of the matching function described by the mathematical formula (2) was adopted:

$$Y_1 = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3 \quad (2)$$

where: Y_1 the estimated response, x_1- x_3 the logarithmic transformations of the variables i.e. cutting speed v_c, feed f and depth of cut a_p, 'b' v the estimates of the corresponding parameters.

The specific cutting force k_c is defined as the ratio of the main cutting force F_c to the cross-section area of the cutting layer A_D (formula 3)

$$k_c = \frac{F_c}{A_D} = \frac{F_c}{f \cdot a_p}\ (\text{N/mm}^2) \quad (3)$$

RESULTS

The influence of cutting parameters and two types of cutting insert material was investigated on the specific cutting force k_c values in dry turning of the Ti6Al4V ELI titanium alloy. To design the experiment for each cutting insert, the Taguchi L18 test plan was used. The response surface methodology (RSM) was also used to establish the relationship between factors, that is, the turning parameters and the SCF values. The most important machining parameter influencing the cutting SCF value was obtained using the analysis of variance (ANOVA). The impact of the factors analyzed on the mean SCF values was presented graphically in charts. A model of mathematical functions that allows to estimate the value of the SCF coefficient was also presented. Finally, a graphical comparison of the use of inserts made of two different carbide grades is presented.

A summary of the results of the specific cutting force measurements obtained for the adopted research plan is presented in Table 4. The average values of the specific cutting force k_c and the values of the signal-to-noise ratio (S/N) for both tested inserts, i.e., made of carbide grades 1115 and H13A, are presented.

The mean values of the SCF coefficient k_c obtained from the tests of the coated tool made of sintered carbide grade 1115 are in the range $k_c \in (1681.7 \div 2456.1)$ MPa. The average value of k_c obtained from all systems in the test plan is 1952.2MPa. The lowest mean value of the k_c coefficient was obtained for the test system no. 18, corresponding to the highest values of the machining parameters, that is, the highest efficiency of the chip discharge amount. In this case, the lowest value of the S/N coefficient was obtained, while the highest mean value of the k_c coefficient was obtained for the test system no. 1, for which the lowest values of the cutting parameters were used, which corresponds to the lowest efficiency of the machining. This means that roughing (high removal rates) has a low cutting force, while finishing has a high cutting force. Analyzing the angle of inclination of the graphs, it can be concluded that the depth of cut has a greater impact on the value of k_c in the range $a_p \in (0.25 \div 0.5)$ mm than in the range $a_p \in (0.5 \div 1.0)$ mm. Analogously considering the influence of the feed value f, it can be said that in the range $f \in (0.08 \div 0.15)$ mm/rev the influence on the values of k_c is slightly greater than in the case of $f \in (0.15 \div 0.2)$ mm/rev.

In the case of an uncoated tool made of H13A grade, a higher proportion of vibrations in the recorded waveforms and higher values of cutting forces were observed, which resulted in an increase in the SCF values. The probable cause is the lack of coating of the insert, which means that the cemented carbide comes into direct contact with the titanium alloy during cutting. In addition, the adhesive properties of the workpiece material can contribute to built-up edge development of the tool, which can cause vibration. A gradual upward trend was also observed in the course of the cutting forces. Most likely, the reason for this was the phenomenon

Table 1. Mechanical properties and chemical composition of the Ti6Al4V Eli alloy

Mechanical properties		Chemical composition (%)	
Tensil strenght	902 MPa	Al	6.10
Yield Strength 0.2%	815 MPa	V	4.13
Elongation	13%	Fe	0.05
Reduct. of area	49%	C	< 0.01
Hardness	29 HRC	N	0.01
Density	4.43 g/cm³	O	0.10
Poisson number	0.342	H	0.003
Melting point	1650 °C	Ti	Remainder

Table 2. Values of variable parameters in the research plan

No.	Coded parameter	Real parameter	Value		
			Min		Max
1	A	v_c (m/min)	40		80
2	B	a_p (mm)	0.25	0.50	1.00
3	C	f (mm/rev)	0.08	0.15	0.20
4	Cemented carbide		1115		H13A

Table 3. Research plan with real values

No.	Coded value			Real value		
	A	B	C	v_c (mm/min)	a_p (mm)	f (mm/rev)
1	1	1	1	40	0.25	0.08
2	1	1	2	40	0.25	0.15
3	1	1	3	40	0.25	0.20
4	1	2	1	40	0.50	0.08
5	1	2	2	40	0.50	0.15
6	1	2	3	40	0.50	0.20
7	1	3	1	40	1.00	0.08
8	1	3	2	40	1.00	0.15
9	1	3	3	40	1.00	0.20
10	2	1	1	80	0.25	0.08
11	2	1	2	80	0.25	0.15
12	2	1	3	80	0.25	0.20
13	2	2	1	80	0.50	0.08
14	2	2	2	80	0.50	0.15
15	2	2	3	80	0.50	0.20
16	2	3	1	80	1.00	0.08
17	2	3	2	80	1.00	0.15
18	2	3	3	80	1.00	0.20

of surface hardening. The dry treatment used has created favorable conditions for this process, which primarily requires an appropriate temperature value in the cutting zone. The values of the k_c coefficient in the case of using a cutting insert made of grade H13A were in the range of k_c∈(1902.1÷2731.4) MPa. The average value of k_c for all test systems was 2234.9MPa. Similarly to the coated insert, the lowest value k_c was obtained for measurement no. 18. Also, the highest k_c value was reached for the first research system.

Figure 2 shows a graphical presentation characterizing the influence of variable factors on the SFC coefficient values for the two types of analyzed tool materials.

The analysis of the results showed an insignificant effect of the cutting parameters on the values of the k_c index when turning the titanium alloy Ti6Al4V Eli. For the turning of the titanium alloy tested, the factors that significantly influenced the values of the k_c index were the feed f and the depth of cut a_p. The cutting speed v_c had a much smaller effect on the SCF values and did not exceed 10%. Therefore, to minimize the SCF coefficient, it is necessary mainly to strive to increase the feed values and the depth of cut.

Figures 3a and 3b show a graphical comparison of the changes in the mean value of the k_c coefficient depending on the cutting parameters for both tested inserts. Differences in the mean values of the k_c coefficient are shown in Figure 3c. The average difference in values was 282.7 MPa, with higher values obtained for the uncoated tool of H13A grade. In both cases of the tools tested, a decrease in the value of the k_c coefficient was observed as the values of the cutting parameters increased. This is also confirmed by the determined linear trend patterns presented on the Figure 3d.

Table 4. Summary of results for two types of inserts (1115 and H13A grade)

No.	v_c (m/min)	a_p (mm)	f (mm/rev)	*1115*		*H13A*	
				k_{c1_mean} (N/mm²)	S/N_1	k_{c2_mean} (N/mm²)	S/N_2
1	40	0.25	0.08	2456.1	-67.8	2731.4	-68.7
2	40	0.25	0.15	2141.2	-66.6	2382.7	-67.6
3	40	0.25	0.20	2090.2	-66.4	2277.2	-67.2
4	40	0.50	0.08	2043.1	-66.2	2485.2	-67.9
5	40	0.50	0.15	1990.6	-66.0	2184.8	-66.8
6	40	0.50	0.20	1802.1	-65.1	2064.6	-66.3
7	40	1.00	0.08	1950.1	-65.8	2184.4	-66.8
8	40	1.00	0.15	1849.2	-65.3	2030.7	-66.2
9	40	1.00	0.20	1737.7	-64.8	1981.0	-65.9
10	80	0.25	0.08	2070.7	-66.3	2731.4	-68.7
11	80	0.25	0.15	1965.0	-65.9	2372.8	-67.5
12	80	0.25	0.20	1957.2	-65.8	2106.2	-66.5
13	80	0.50	0.08	1988.6	-66.0	2532.5	-68.1
14	80	0.50	0.15	1877.4	-65.5	2176.7	-66.8
15	80	0.50	0.20	1806.4	-65.1	1959.2	-65.9
16	80	1.00	0.08	1930.4	-65.7	2166.0	-66.7
17	80	1.00	0.15	1801.4	-65.1	1959.2	-65.8
18	80	1.00	0.20	1681.7	-64.5	1902.1	-65.6

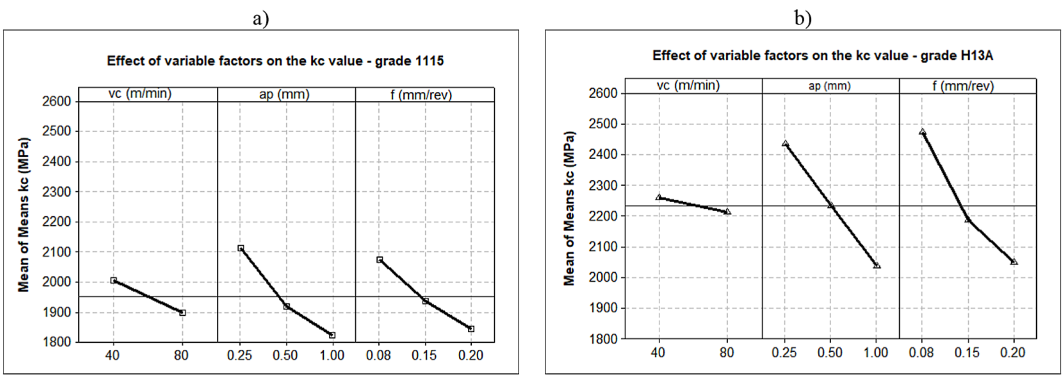

Figure 2. Main effects plot for specific cutting force k_c for (a) 1115 and (b) H13A grade

The ANOVA results for the SCF values, considering coated and uncoated carbide tools, respectively, are presented in Tables 5 and 6. The interaction effect of the cutting parameter variables had a negligible effect, therefore, linear factors were selected for the analysis of the results. Based on the results obtained from the analysis, the depth of the cut a_p showed a significant effect on the SCF values, with the contribution of the coated carbide insert of 48.4%. In turn, in the case of the uncoated insert, the feed value f had the most substantial effect, accounting for 50.3%. The results of the ANOVA showed a ranking of the significance of the parameters $a_p - f - v_c$ and $f - a_p - v_c$ for inserts 1115 and H13A, respectively. High fit factor values of R^2 = 87.7 and R^2 = 93.5 were obtained for both inserts, coated and uncoated, respectively.

The precision of the SCF values for the mathematical model obtained for the matching function presented in Table 7 was determined based on the absolute error (AE%) between the experimental and predicted results. Equation 4 was used to calculate the absolute error (AE%) of the results.

$$AE = \left(\frac{k_{c\_exp.} - k_{c\_pred.}}{k_{c\_exp.}}\right) \cdot 100\ (\%) \qquad (4)$$

According to the results in Table 7, the average AE value for coated and uncoated carbide inserts, taking into account the SCF values, is 2.3% and 2.26%, respectively. On this basis, it can be assumed that the mathematical model presented can calculate the expected value with high probability.

For comparison purposes, additional models of the SCF function were developed using linear regression. The mathematical models determined for coated and uncoated carbide inserts are given in Equations 5 and 6, respectively. The coefficient of determination (R^2) showing the precision of the models proposed in this case for 1115 and

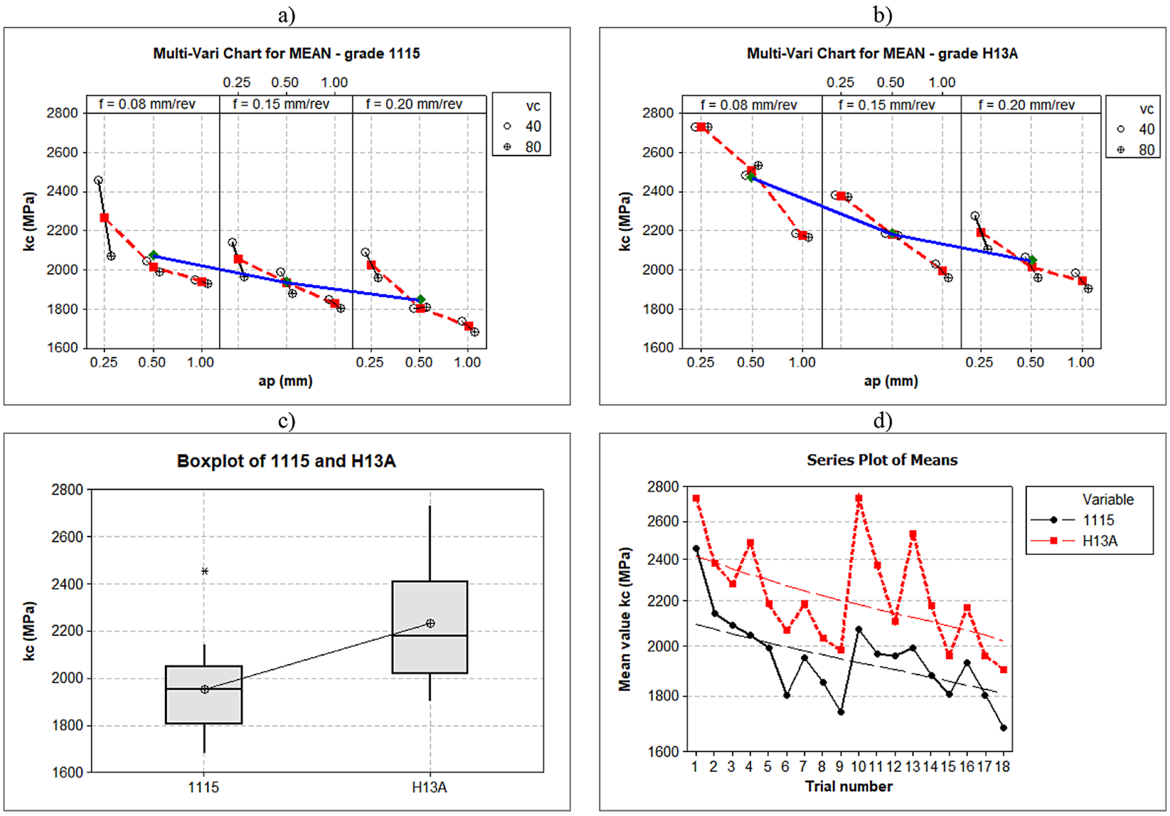

Figure 3. Effect of variables on the values of the k_c coefficient. Turning process with grade 1115(a) and H13A (b), comparison of mean values (c) and trends in trial numbers (d)

Table 5. ANOVA results for grade 1115

No.	Source	DF	Seq SS	Adj SS	Adj MS	F-value	P-value	Cont.
1	v_c (m/min)	1	53530	53530	53530	9.72	0.009	10.0%
2	a_p (mm)	2	259825	259825	129913	23.59	0.000	48.4%
3	f (mm/rev)	2	156901	156901	78451	14.25	0.001	29.3%
4	Residual error	12	66081	66081	5507			12.3%
5	Total	17	536338					100.0%

Table 6. ANOVA results for grade H13A

No.	Source	DF	Seq SS	Adj SS	Adj MS	F-value	P-value	Cont.
1	v_c (m/min)	1	9613	9613	9613	1.58	0.232	0.9%
2	a_p (mm)	2	471398	471398	235699	38.83	0.000	42.3%
3	f (mm/rev)	2	560771	560771	280386	46.19	0.001	50.3%
4	Residual error	12	72843	72843	6070	6070		6.5%
5	Total	17	1114626					100.0%

H13A grade carbide cutting tools was calculated as 80.6 and 91.1, respectively.

$$k_{c_{1115}} = 2573 - 2.73 \cdot v_c - 356 \cdot a_p - 1701 \cdot f \text{ (N/mm}^2\text{)} \quad (5)$$

$$k_{c_{H13A}} = 3070 - 1.16 \cdot v_c - 509 \cdot a_p - 3191 \cdot f \text{ (N/mm}^2\text{)} \quad (6)$$

Very important, especially from a practical point of view, is optimization of the machining parameters to obtain the minimum SCF value. Therefore, the optimal parameter values for turning the Ti6Al4V ELI alloy determined by the Taguchi method were additionally verified by the response surface methodology (RSM). Figure 4 shows the optimization plot for the cutting parameters to obtain the minimum SCF value.

Table 7. Results for confirmation tests with absolute error (*AE* %) for experimental and predicted results

No.	v_c (m/min)	a_p (mm)	f (mm/rev)	k_{c1} (N/mm²)	$k_{c1\_pred.}$ (N/mm²)	*AE* (%)	k_{c2} (N/mm²)	$k_{c2\_pred.}$ (N/mm²)	*AE* (%)
1	40	0.25	0.80	2456.1	2288.9	6.8%	2731.4	2693.7	1.4%
2	40	0.25	0.15	2141.2	2153.2	0.6%	2382.7	2406.3	1.0%
3	40	0.25	0.20	2090.2	2061.6	1.4%	2277.2	2270.2	0.3%
4	40	0.50	0.80	2043.1	2093.6	2.5%	2485.2	2493.9	0.3%
5	40	0.50	0.15	1990.6	1957.9	1.6%	2184.8	2206.6	1.0%
6	40	0.50	0.20	1802.1	1866.3	3.6%	2064.6	2070.4	0.3%
7	40	1.00	0.80	1950.1	2000.6	2.6%	2184.4	2297.3	5.2%
8	40	1.00	0.15	1849.2	1864.9	0.8%	2030.7	2010.0	1.0%
9	40	1.00	0.20	1737.7	1773.4	2.1%	1981.0	1873.8	5.4%
10	80	0.25	0.80	2070.7	2179.8	5.3%	2731.4	2647.4	3.1%
11	80	0.25	0.15	1965.0	2044.1	4.0%	2372.8	2360.1	0.5%
12	80	0.25	0.20	1957.2	1952.6	0.2%	2106.2	2224.0	5.6%
13	80	0.50	0.80	1988.6	1984.5	0.2%	2532.5	2447.7	3.4%
14	80	0.50	0.15	1877.4	1848.8	1.5%	2176.7	2160.4	0.8%
15	80	0.50	0.20	1806.4	1757.2	2.7%	1959.2	2024.2	3.3%
16	80	1.00	0.80	1930.4	1891.6	2.0%	2166.0	2251.0	3.9%
17	80	1.00	0.15	1801.4	1755.8	2.5%	1959.2	1963.7	0.2%
18	80	1.00	0.20	1681.7	1664.3	1.0%	1902.1	1827.6	3.9%

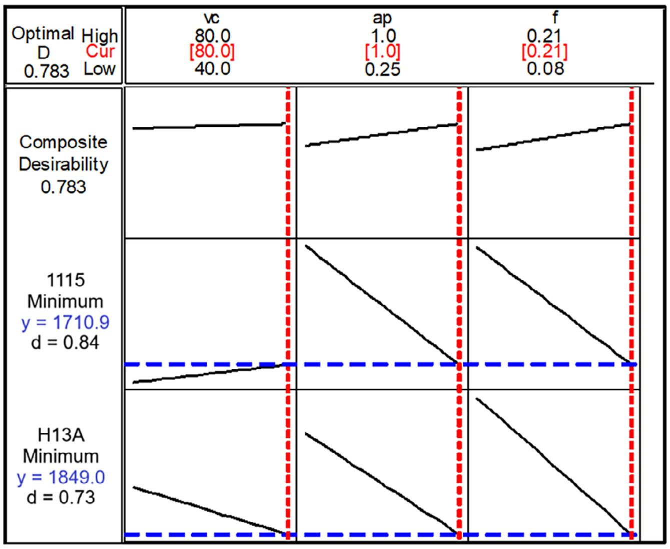

Figure 4. Response surface methodology optimizer graf for coated and uncoated inserts

The accuracy of optimized parameters was calculated by the value of the composite desirability (*D*) indicates. For both insert grades, a composite desirability of 0.7–0.8 indicates well-optimized responses. According to Figure 4, the optimal cutting parameters for minimizing the specific cutting force are: a_p = 1.0 mm, v_c = 80 m/min and f = 0.21 mm/rev. The resulting cutting data values are the same as those obtained by the Taguchi method. The minimum specific cutting force k_c = 1710 MPa using coated carbide insert and k_c = 1849 MPa using uncoated insert are obtained considering the optimum machining parameters.

CONCLUSIONS

The following conclusions can be made on the basis of the results obtained and the analyses carried out to determine the value of the specific cutting force in the longitudinal dry turning process (using carbide grades 1115 and H13A) of the Ti6Al4V Eli titanium alloy samples:

1. The specific cutting force k_c depends primarily on the feed and depth of cut, i.E. On the cross-sectional area of the cutting layer. The anova results show the dominant impact of feed and depth of cut over the k_c coefficient in both inserts (i.E. Grade 1115 and h13a). The contribution effect of the feed rate and depth of cut on k_c value for coated and uncoated insert is approximately 50%. The cutting speed has an insignificant effect on the response.
2. Analysis showed that the recommended cutting parameters for turning under dry conditions of the ti6al4v eli titanium alloy, allowing the lowest values of the specific cutting force coefficient k_c, were: v_c = 80 m/min, f = 0.2 Mm/rev and a_p = 1.0 Mm.
3. The k_c coefficient values for both tested inserts depend on the type of machining. For the range of finishing parameters, the k_c values are the largest, and for roughing, they are the smallest. The mathematical models presented in the article allow to determine the scf value as a function of cutting parameters.
4. Turning with coated inserts results in lower specific cutting forces (on average by about 280 mpa), and therefore longer tool life and lower load on the machine tool units.
5. At certain values of the machining parameters during turning under dry conditions with the use of a cemented carbide cutting insert without an external coating, the titanium alloy Ti6Al4V Eli shows a tendency to surface hardening and built-up edge.

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