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Evaluation of the Influence of Tool Coatings on the Machinability of the Ti6Al4V Alloy Using Gray Relational Analysis

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ABSTRACT

The article presents the research on turning the titanium alloy Ti6Al4V with uncoated carbide blades and physically coated with PVD and chemically CVD. By examining the processed surfaces using the contact method, it was found that the chemically applied coating allows one to obtain the best 3D roughness. Using finishing cutting parameters and CVD-coated blades, it is possible to obtain a surface with a roughness of *Sq* at the level of 0.7 μm and *Sz* 2 μm. Cutting force tests have shown that applying coatings to the cutting blade increases the total cutting force by approximately 20%. Additionally, on the basis of microscopic observations, it was found that thermal and adhesive wear occurs on the surfaces of coated blades. Tool coatings have no influence on the shape of the chips produced. The grey relational analysis performed showed that the best turning results for the Ti6Al4V alloy are obtained when using an uncoated HX insert with a feed of 0.08 mm/rev and a cutting speed of 70 m/min. The results of this analysis also indicate that the tested blades, which are not recommended for the machining of superalloys, should not be used to turn the Ti6Al4V alloy.

Keywords: titanium, cutting capabilities of tools, tool coatings, surface roughness, cutting force.

INTRODUCTION

The use of titanium alloys is very wide. Their properties, and in particular their excellent strength-to-weight ratio or corrosion resistance, mean that titanium alloys are used for the manufacture of elements for means of transport, mainly aircrafts, helicopters as well as machine components in the food and chemical industries [1–3]. Titanium alloys are also the main constituent material of orthopaedic implants [4–6]. They are encountered in structures exposed to seawater [7]. The requirements for such items are very high, so the dominant method of processing titanium alloys, especially in the last stage of technological and manufacturing processes, should be machining. Unfortunately, due to the low thermal conductivity of titanium alloys, their high hardness and strength, the low value of the longitudinal elastic modulus and the high tendency to strengthen by crushing, as well as their high chemical reactivity, titanium alloys are classified as materials that are difficult to machine [6, 8, 9].

The greatest problems that occur in the machining of titanium alloys are: heat concentration on the cutting edge and the surface of the blades, high cutting forces, changes in the material structure of the cutting blades and the surface layers of the machined elements and large deformations in the machined objects, especially thin-walled ones [10, 11]. Accelerated cutting blade wear makes the machining efficiency of titanium alloys low. Attempts are being made to increase it by using various methods to reduce the cutting temperature and the friction of chips against the rake surface of the blades. Classical flood cooling minimises diffusion and adhesion wear, as well as reduced adhesion of the chips to the blade rake surface [6, 12]. Even better results are obtained when the coolant is applied under high pressure [13]. The chip-to-tool contact length is then reduced and the chips are broken more effectively.

Blade life is increased by 75% compared to flood-cooling machining. Therefore, cutting speeds can be doubled. In addition, the cutting temperature is reduced more effectively [6]. The effectiveness of this cooling of the cutting zone in terms of surface roughness is inconclusive [6, 14]. For environmental reasons, flood cooling is increasingly being replaced by minimum quantity cooling and lubrication (MQL). Compared to machining without liquid, MQL allows reducing the roughness of the machined surface [15], the wear of the cutting blades [16, 17], the energy intensity of the process [18] or the cutting forces [19]. Liquids used in systems for minimal lubrication of the cutting zone are very often ecological, which is an additional advantage. An even more environmentally friendly and effective cooling method during titanium machining is cryogenic machining [20]. However, the widespread use of this method is limited by difficulties in practical application. Increased machinability of titanium alloys is also attempted by assisting cutting with ultrasound [21]. Another equally effective technology is the cutting of titanium with simultaneous laser action [22]. An interesting solution that reduces the thermal loads on the cutting blades is the microtexturing of their rake face [23, 24]. For example, the use of microtexturing of the WC-10Ni3Al carbide blades resulted in a lower thermal wear on these tools than on the WC-8Co carbide tools. Furthermore, it has been observed that microtexturing on the rake face can lower the cutting temperature and therefore reduce tool wear, as microtexture acts as a lubricant reservoir and facilitates penetration of lubricant during the cutting process [25].

The machinability of titanium alloys also depends on the material used for the cutting blades. Attempts are being made to machine these materials with cermet [26] or ceramic [27] tools. The conventional Ti_6Al_4V alloy, as well as the one obtained using SLM methods, can be machined without cooling fluids with polycrystalline diamond blades [28]. It is generally known that the life of cutting tools can be increased by using tool coatings. This also applies to the machining of titanium alloys. Cemented carbides are most often coated, both chemically and physically. Many researchers have tested the possibility of using different coatings on cutting tools when machining titanium alloys. The TiSiAlN coating, with its high hardness and excellent wear resistance, was found to significantly improve the life of the cutting tool when the Ti_6Al_4V alloy was machined [29]. Even conventional coatings, such as TiAlN, TiSiN, and AlTiN, provide excellent wear and oxidation resistance [30, 31]. These coatings also have a lower friction coefficient due to their anti-adhesive properties [15]. The durability of cutting blades is especially increased by coatings with chromium [32]. However, attention should be paid to the selection of cutting parameters because the effectiveness of tool coatings can decrease at elevated cutting speeds since at higher cutting speeds the arising stresses exceed the yield strength of the coating [33]. The effectiveness of tool coatings increases when machining under cooling conditions [34]. The blade wear mechanisms then change, and abrasive wear is significantly reduced [35]. Self-lubricating coatings offer great hope to increase the productivity and efficiency of titanium alloy machining. They provide excellent wear and oxidation resistance as a result of the generation of lubricating phases at elevated temperatures [36]. For example, the TiSiVN coating, through the low friction lubricating phases generated during the machining process, results in reduced friction at the chip-to-tool interface, resulting in reduced tool wear [37]. Data from the literature clearly indicate that titanium alloys are difficult to machine. The possibilities for improving their machinability are related to coatings, cooling and the correct choice of cutting parameters. The appropriate selection of cutting conditions is very complex. Therefore, in addition to the attempts to develop new technologies for the machining of titanium alloys, it is necessary to use tools to analyse the results of research to identify the best solution. Such a tool is undoubtedly grey relational analysis (GRA) used to select the best machining conditions in the cutting of composites [38], heat-resistant alloys [39] or titanium alloys [40, 41], as well as, for example, optimal tribological parameters for metal composites [42].

Due to the great importance of tool coatings in the cutting of titanium alloys, as well as the ambiguous degree of their impact on the machining efficiency, the aim of the research was to determine the effectiveness of tool coatings in turning the Ti6Al4V alloy. Since tool companies offer a wide range of coated and uncoated tools, both first choice and complementary ones for titanium machining, it was decided to test unified, catalogue tools.

RESEARCH METODOLOGY

Machining material

The material used in the study was the two-phase titanium alloy Ti6Al4V, also referred to in western, and especially American, nomenclature as Grade 5 alloy. According to many sources [43, 44], this is the most popular titanium alloy used in the construction of machines. This is due to the properties generally attributed to titanium alloys, such as high relative strength, corrosion resistance or maintaining strength at elevated temperatures, as well as the individual properties of this alloy, presented in Table 1. The data in the table are from certificates provided by the material manufacturer.

Cutting tools

Four folding turning knives with replaceable cutting inserts were selected for the study. It was considered that the inserts should be intended for machining titanium alloys, i.e. material group S, according to PN-ISO 513:1999. However, in order to increase the scope of the study, it was decided to use one more tool, with any coating, intended for machining a material group other than group S. Each of the selected cutting inserts was characterised by the same geometry, size and rhombic shape. Such inserts are referred to as CCMT 09T3 04, according to PN-ISO 1832–1998. Other information about the selected inserts has been collected and presented in Table 2. One uncoated blade, 2 chemically coated (CVD) and 1 physically coated (PVD) inserts were tested. For easier reference in the text of the article, they will be referred to by the designation defining the carbide substrate and coating or lack thereof used by the tool manufacturer.

Test conditions

When planning the experiment, it was decided to carry out the experiment according to a determined complete plan. This involved taking strictly defined input values, which were the cutting speed v_c and the tool feed f. When planning the experiment, it was decided to take two cutting speeds and five feeds as independent variables. Following the recommendations of the manufacturer of the cutting inserts used, cutting speeds v_c of 30 and 70 m/min and feeds of 0.08, 0.13, 0.17, 0.21 and 0.27 mm/rev were selected. The remaining machining parameter, which was the depth of cut a_p, remained constant throughout the experiment and was 0.5 mm. This value is typical for finishing, which aims to give the surface the best possible quality. Adopting such a value for the a_p parameter, therefore, widened the range of possible output variables to include surface roughness.

Research equipment

The tests were carried out without the use of cutting fluids on a CNC TUR560MN lathe. Cutting forces were measured using a measuring track (Fig.1), which included a piezoelectric force meter 9257A from Kistler, an electrical signal amplifier type 5011 and a Digital Phosphor Oscilloscope TDS 5054B from Tektronix. Roughness measurements were carried out with a SURFTEST SV-3200 profilographometer (Fig. 2) with an X-axis

Table 1. Material properties of the machined Ti6Al4V alloy

Density g/cm^3	Yield strength 0.2 Rp 0.2 [MPa]	Tensile strength Rm [MPa]	Young modulus [GPa]
4.42	880	950	114
Elongation [%]	Impact strength J/cm^2	Hardness HRC	Poisson ratio
14	122	36	0.342

Table 2. Cutting inserts used in tests

Lp.	Identificaton	Chip breaker	Destination		Coating		
			First choice	Second choice	Type	Structure	Colour
1	HX	F2	S	M i K	–	–	Silver
2	CP200	F2	S i M	P i K	PVD	(Ti, Al)N + TiN	Bright-yellow
3	TH1500	F1	S	K	CVD	Ti(C, N)+ Al_2O_3	Black
4	TP40	F2	P i M	–	CVD	TiC/Ti(C, N) +TiN	Golden-yellow

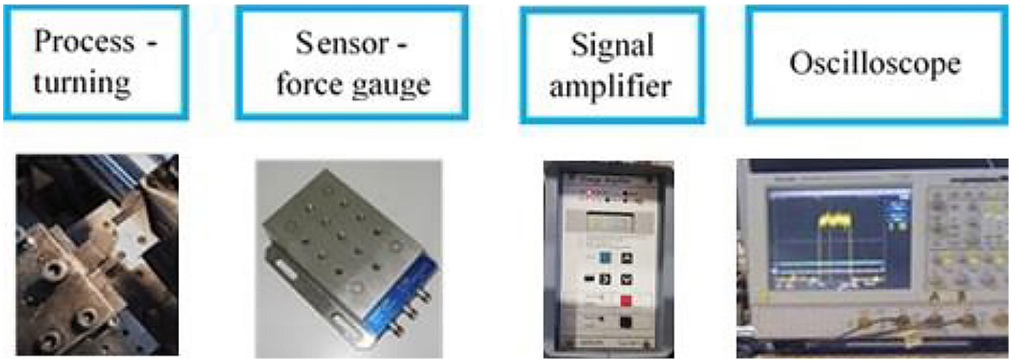

Figure 1. Track for measuring cutting forces

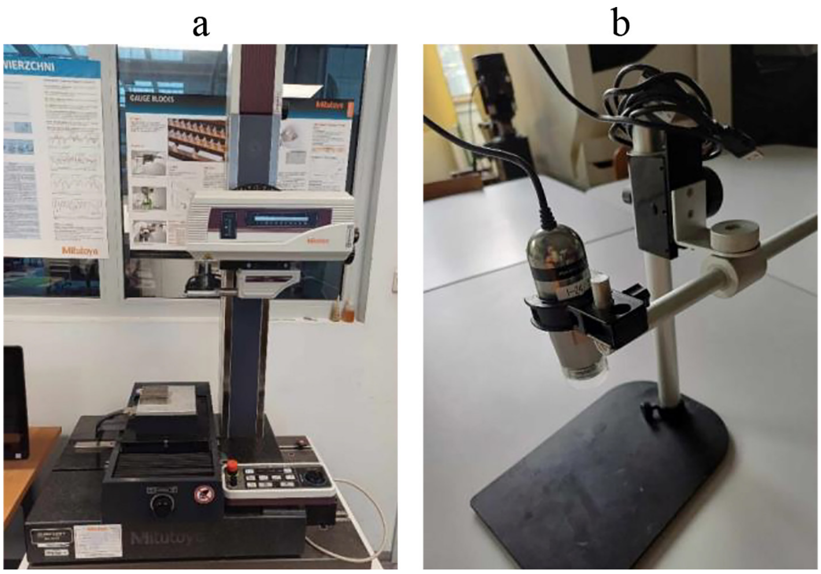

Figure 2. SURFTEST SV – 3200 profilographometer (a), Dino Lite Capture 2.0 microscope (b)

measuring range of 100 mm, a tip pitch of 800 µm, and an additional Y-axis positioning table for 3D surface topography. The device had a measuring tip in the form of a diamond needle with a cone rounding radius of 2 µm and a cone angle of 60°. The profilographometer used has built-in FORMTRACEPACK roughness measurement and McCube Ultimate 3D surface analysis software. The inserts after cutting tests were observed with a Dino Lite Capture 2.0 microscope (Fig. 2).

RESULTS AND DISCUSSION

Surface roughness

Three measurements of each surface were made. The measured surfaces were subjected to a procedure including: extraction of a 0.95 × 0.95 mm section from the measured surface (to eliminate possible measurement errors at the border of the area under examination), levelling the surface using the least-squares method, removing the shape by a polynomial of degree two, and filtering of the signal (separation of the waviness profile from the roughness). Roughness was separated from waviness by a Gaussian filter. The limiting wavelength λc for the Gauss filter was 250 µm. The programme then calculated a number of roughness parameters according to PN-EN ISO 25178-2:2022. The Sq and Sz parameters were selected for analysis. Tables 3 and 4 summarise the results of 3D roughness measurements, whereas Figures 3 and 4 show graphs of the dependence of selected roughness parameters on the feed. Trend lines have been introduced in the charts. It was decided to present the results in such a way as to minimise the influence of single roughness peaks, which may distort the results for the *Sz* parameter, especially in the case of 3D measurements. To standardise the way of presenting the results, trend lines were

Table 3. *Sq* parameter measurement results

Cutting parameters		HX	CP200	TH1500	TP40
v_c	*f*	*Sq*			
m/min	mm/rev	µm			
30	0.08	0.98	1.24	0.75	0.68
30	0.13	1.69	2.02	1.24	1.44
30	0.17	2.01	2.51	1.73	1.74
30	0.21	2.2	2.69	2.03	1.95
30	0.27	2.3	2.72	2.18	2.2
70	0.08	0.94	1.4	0.79	0.63
70	0.13	1.61	2.2	0.75	1.17
70	0.17	1.97	2.82	0.84	1.61
70	0.21	2.11	2.97	1.03	1.79
70	0.27	2.26	2.71	1.57	1.81

Table 4. *Sz* parameter measurement results

Cutting parameters		HX	CP200	TH1500	TP40
v_c	*f*	*Sz*			
m/min	mm/rev	µm			
30	0.08	4.95	5.65	4.27	3.65
30	0.13	7.88	7.13	4.87	5.70
30	0.17	8.26	11.10	7.90	8.40
30	0.21	7.94	10.20	8.32	8.20
30	0.27	9.50	11.20	9.96	11.40
70	0.08	5.10	7.13	4.77	3.31
70	0.13	7.26	8.16	3.22	5.36
70	0.17	7.07	10.08	5.08	7.24
70	0.21	7.84	13.30	5.46	9.44
70	0.27	9.72	11.80	9.08	8.42

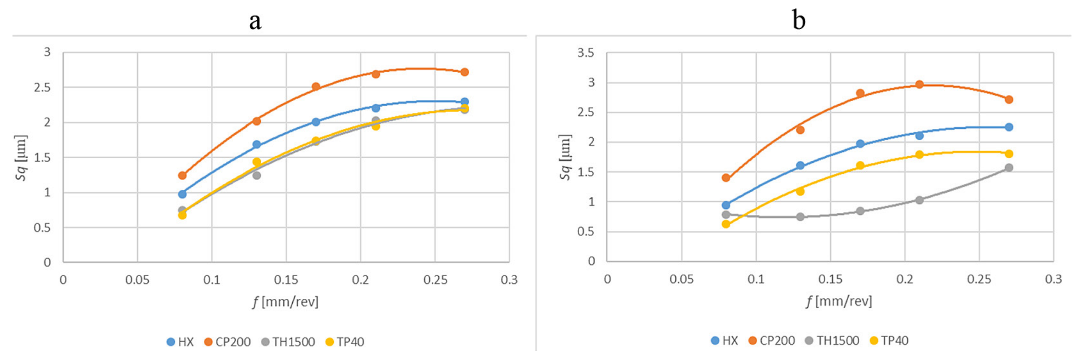

Figure 3. Roughness parameter Sq as a function of feed after turning of Ti6Al4V alloy with the tested inserts at cutting speeds of 30/min (a) and 70 m/min (b)

also introduced for the *Sq* parameter. The value of the R^2 coefficient for the trend in the *Sq* parameter is at the level of 99%. However, in the case of the *Sz* parameter, the R^2 coefficient ranges from 82 to 95%.

When analysing the results in Table 3 and Figure 3, it can be seen that the clearly worst quality of the machined surface expressed by the *Sq* parameter was obtained after turning with the PVD-coated CP200 insert. For v_c = 30 m/min, the difference between the results for this tool and the other three inserts was averaged 37%. For a higher cutting speed, the CP200 results averaged

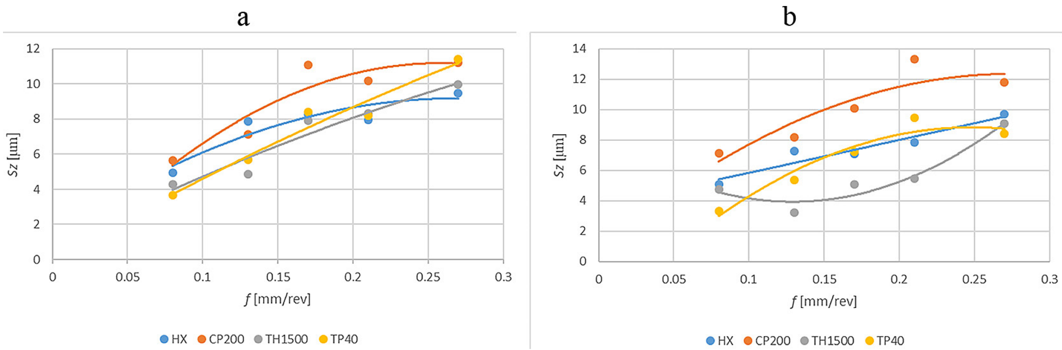

Figure 4. Roughness parameter *Sz* as a function of feed after turning of the Ti6Al4V alloy with the tested inserts at cutting speeds of 30/min (a) and 70 m/min (b)

76% more than the rest of the tools. A slightly worse surface finish was obtained with the uncoated HX insert tool. In this case, the values of the *Sq* parameter oscillated between 1 and 2.3 µm. For all five feeds at a cutting speed of 30 m/min, the results of the *Sq* parameter for roughness obtained with this tool were approximately 22% lower than those of the CP200 insert. Increasing the cutting speed increased this difference to about 38%. The smallest differences between the *Sq* measurement results can be seen at the highest feed for both set cutting speeds. Clearly, the best results were obtained with the chemically coated TH1500 and TP40 tools. After cutting at a lower cutting speed, the surface roughness *Sq* generated by them is very similar over the entire range of adopted feeds. The greatest difference can be observed at a feed rate of 0.13 mm/rev – it is 14%. For the remaining feeds, the discrepancy between the results is approximately 4%. At higher speed, the *Sq* values for these inserts deviate significantly to the detriment of the TP40 tool. The difference in results is particularly visible in the range of 0.13–0.21 mm/rev. The effect of feed on the obtained values of the *Sq* parameter is consistent with predictions based on surface engineering theory. Surface roughness *Sq* for most of the cases studied increases with feed. Only after turning with a TH1500 insert at a cutting speed of 70 m/min and feeds in the range of 0.08–0.17 mm/rev, a surface with a comparable *Sq* value was obtained. This allows, without analysing other machinability indicators, to optimistically predict the possibility of machining with this tool with greater efficiency owing to the increase in feed without deterioration of the machined surface. When analysing the values of the roughness parameter *Sz* (Table 4 and Fig. 4), one can notice their convergence with the measurement results of the *Sq* parameter. By far, the highest values of maximum roughness were obtained after turning with an insert with a physically applied coating. However, the differences in relation to the surfaces generated by other inserts are smaller and amount to 23% for lower cutting speed and 56% for higher cutting speed, respectively. Among the remaining tools, there is no one that would provide the lowest values of the *Sz* parameter in all cutting conditions tested. For a speed of 30 m/min and feeds of 0.08–0.13 mm/rev, the best results are achieved with an insert that is not directly recommended for machining superalloys, i.e., TP40. By increasing the feed to 0.21 mm/rev, requires the selection of a TH1500 insert, and for even higher feeds, an insert without coating. The uncoated HX insert guarantees the lowest values of the *Sz* parameter when turning at a speed of 70 m/min and feed in the range of 0.13–0.21 mm/rev. Using feeds lower and higher than this range, lower *Sz* values can be obtained by machining the Ti6Al4V alloy with a TP40 blade. The influence of the feed on the *Sz* parameter is the same as in the case of *Sq*, i.e. its value increases with the increase in feed. On the other hand, a greater impact of cutting speed was observed on the *Sz* values than on the previously considered *Sq*. This especially applies to the surfaces generated with CVD coated inserts. The HX insert without any coating was characterised by the greatest stability of results, regardless of cutting speed, followed by the CP200 tool with a PVD coating. The explanation for this condition can be found in the faster wear of tools with chemical vapour deposition coatings, which influenced the instability of the entire process, especially the ratio and dynamics of the cutting force components, and, as a result, the quality of the machined surface. By verifying the results of surface roughness measurements with available literature sources, it is possible to determine the correctness of the experiment. Several research studies have presented the same effect of tool coatings on the geometric structure of the surface of the Ti6Al4V alloy. In [45], a plate with a CVD TiCN + Al_2O_3 + TiN coating produced a surface with lower roughness than an analogous tool with a PVD TiAlN layer in the vc range of 60 and 90 m/min. However, as the authors of the paper pointed out, the problem was the faster wear of the CVD coating on the tool, which resulted in an increase in the process instability with the cutting distance. In the paper [46] describing the influence of the lubrication conditions of the cutting zone and the type of tool coating on the technological effects, the same observations were made. The CVD-coated TM4000 insert provided the lowest *Ra* values in each of the lubrication strategies tested, i.e., dry machining, MQL and conventional tool pouring. The average surface roughness made with this plate was approximately 14% lower than the result obtained with the TS2000 tool with a PVD coating in the v_c range of 67–114 m/min.

Cutting forces

The next output values of the experiment were the components of the total cutting force *F*. They are three forces, distributed in the Cartesian coordinate system, acting in characteristic machining directions. These directions are determined by the cutting speed v_c, feed *f*, and the straight line perpendicular to the machined surface. Hence, they are referred to as the main cutting force *Fc*, the feed force *Ff* and the thrust force *Fp*, respectively. All three, together with their resultant, constitute auxiliary indicators of the machinability of materials and indicators describing the cutting ability of tools. The total cutting force calculated from its components was selected for further analysis. The total cutting force values are shown in Table 5, and the comparison of these measurements is shown in the chart (Fig. 5). The value of the coefficient of determination R^2 for fitting the trend line for the force *F* is greater than 99%. When analysing the values from Table 5, it can be

Table 5. Results of measurements and calculations of the cutting force *F*

Cutting parameters		HX	CP200	TH1500	TP40
v_c	*f*	*F*			
m/min	mm/obr	N			
30	0.08	114.5	131.1	131.8	128.9
30	0.13	171.6	177.2	180.9	192.8
30	0.17	176.2	177.6	179.3	183.9
30	0.21	216	237.1	247.5	260.3
30	0.27	284.7	289.1	295.5	302.5
70	0.08	132.4	139.3	143.8	152.6
70	0.13	145	163.4	175.8	190.7
70	0.17	209	206.9	211.4	216.9
70	0.21	240.7	232.3	246.2	237.3
70	0.27	285.6	281	284.5	287.1

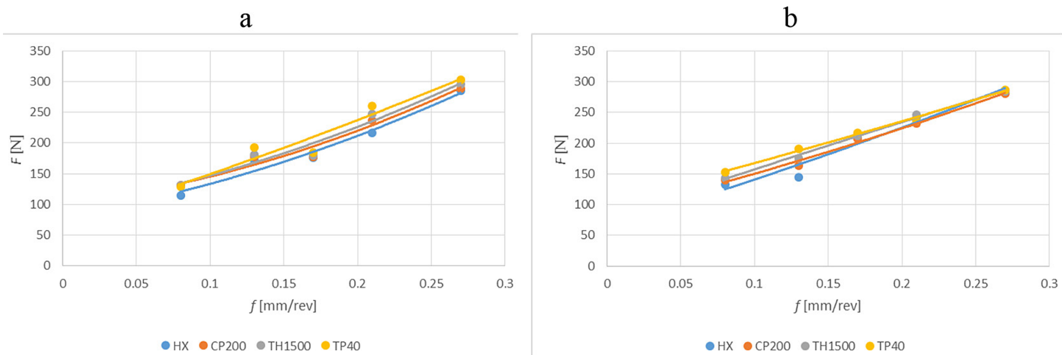

Figure 5. Cutting force *F* as a function of feed after turning at a cutting speed of 30/min (a) and 70 m/min (b) of the Ti6Al4V alloy with the tested blades

concluded that of all independent variables, the feed has the greatest influence on the value of the total cutting force. The smallest force value *F* was achieved with its lowest value when turning with a cutting speed of 30 m/min with the HX tool. However, the influence of the application and type of coating on the value of the cutting force is quite ambiguous. At the lower cutting speed used, the forces generated by all four inserts were similar, with a slight advantage for the uncoated HX insert in the first three feeds. The increase in feed resulted in a slight increase in the differences between the results for individual inserts. Within the entire range of feeds, the lowest force values were measured when machining with an uncoated HX insert, and the highest when turning with an TP40 insert. The largest difference between the results for these tools was observed at a feed of 0.21 mm/rev, it was approximately 20%. Increasing the cutting speed to 70 m/min resulted in equalisation of the results recorded for each insert. The greatest difference can be seen when turning with a 0.13 mm/rev feed, for which a force of 31% greater was recorded when turning with a TP40 insert than when turning with an uncoated HX insert. At the lowest feed used, the difference was less pronounced and amounted to only 16% between these tools. When comparing the influence of cutting speed on the measured force, it can be seen that its increase resulted in a reduction in force of only 4% on average.

Summarising the analysis of the resulting total cutting force, it can be concluded that there is no significant impact of tool coatings on the force values when turning the Ti6Al4V titanium alloy. Machining with the uncoated insert generated lower forces acting on the blade than cutting with the inserts coated with both types of coating, i.e. CVD and PVD. Perhaps the application of coatings dulled the edge of the inserts, which resulted in increased specific cutting pressure. The highest cutting forces occur when machining with a CVD-coated TP 40 insert. The explanation for this situation can be found in the fact that it is not the first-choice tool for machining the material group of superalloys and titanium alloys.

Chips

Chips are an important indicator of machinability and, because their unfavourable shape has a large negative impact on the cutting process and may indirectly affect other indicators such as the quality of the machined surface or tool life. The shape of the chips is classified and assessed according to the PN-ISO 3685 standard. Photos of selected chips are shown in Figures 6–9.

In all experimental tests, an unfavourable chip shape was observed, which can be classified as open screw or conical in the long or tangled variety. When analysing in more detail, it was observed that when turning with a cutting speed of 30 m/min, the value of the applied feed had the greatest impact on the shape of the chip, followed by the coating and the type of chip breaker on the rake face of the insert. As the feed increases from 0.08 to 0.27 mm/rev, it can be seen that the chip becomes stiffer and the pitch of the chip twist helix decreases. This is due to the increase in the cross section of the cut layer and, therefore, its lower susceptibility to plastic deformation when flowing from the rake face of the tool. In the case of the first two feeds, i.e. 0.08 and 0.13 mm/rev, the chip created during machining

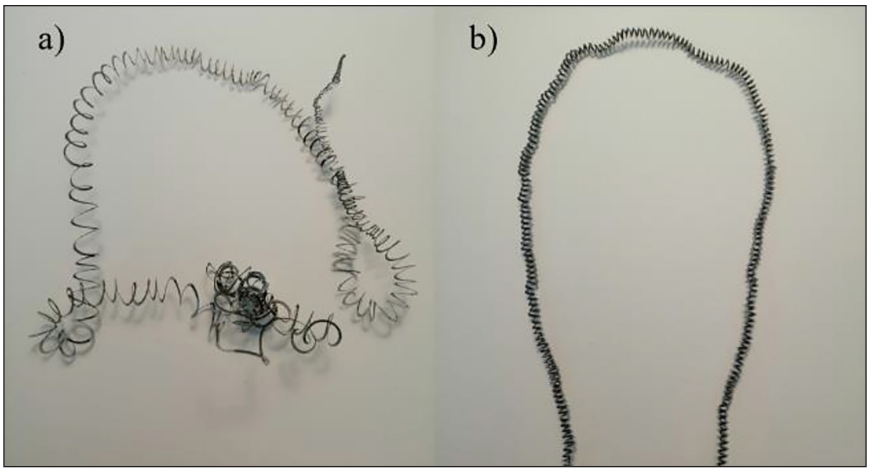

Figure 6. Chip from turning with CP200 insert with v_c 30 m/min and *f*, a) 0.08 mm/rev, b) 0.27 mm/rev

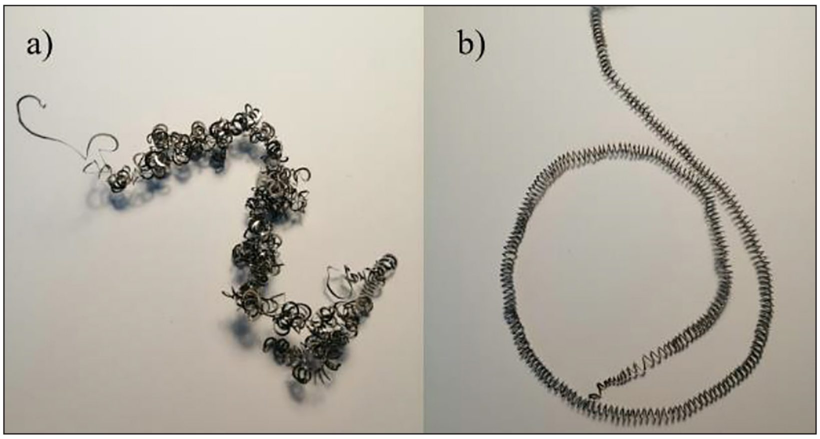

Figure 7. Chip from turning with CP200 insert with v_c 70 m/min and *f*, a) 0.08 mm/rev, b) 0.27 mm/rev

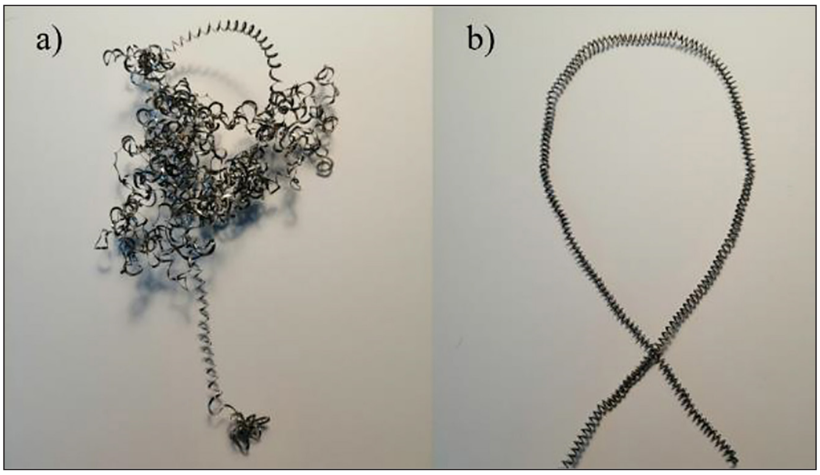

Figure 8. Chip from turning with TH1500 insert with v_c 70 m/min and *f*, a) 0.08 mm/rev, b) 0.27 mm/rev

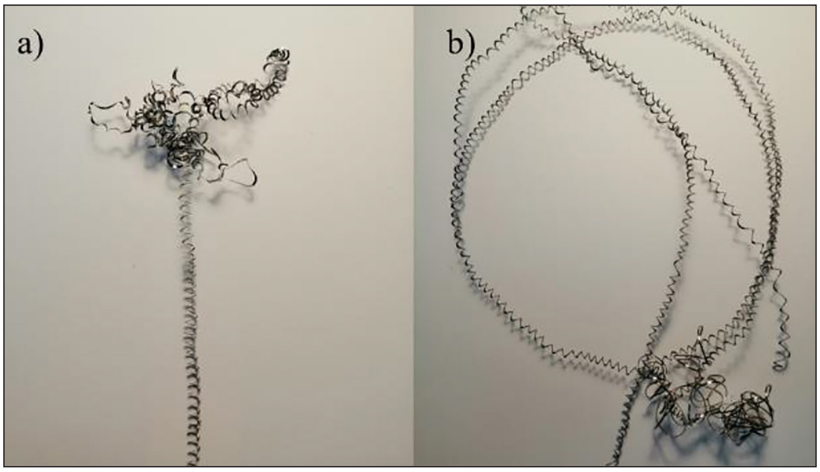

Figure 9. Chip from turning with TP40 insert with v_c 70 m/min and *f*, a) 0.08 mm/rev, b) 0.27 mm/rev

with each insert had a partially tangled form with a large diameter and a helical pitch. Above this range of feed, the HX and TH1500 inserts generated increasingly straight and more stable chips, which unfortunately did not break into shorter fragments. However, it was noticeable during turning that the chips made with these tools could be easily removed from the cutting zone quite quickly without the risk of damaging the already made surface. Only when machining at maximum feed with these inserts did the chips break into shorter sections. In the case of the TH1500 insert, these were fragments about 20 mm long, and for the HX insert, about 100 mm long. In contrast, the extent of partial entanglement of the chips made with CP200 and TP40 tools was one feed value higher. Additionally, the chips created when cutting with these two inserts had a more open shape, with a diameter almost three times larger than in the case of the TH1550 and HX inserts. Increasing the feed during turning with these tools resulted in a reduction in chip twist, but disturbances in chip flow were noticeable, especially in the case of turning with the CP200 insert. At maximum feed, only the chips made with the TP40 insert were fragmented into sections of approximately 70 mm. When turning with the CP200 insert, a continuous chip was created at this feed (Fig. 6). The reason for the different structure and lower stability of chip formation with the last two inserts can be found in the increased influence of heat on the process of shaping them. Symptoms of high temperature can be seen on the surfaces of these tools, so this can be considered as a confirmation of this thesis.

Increasing the cutting speed to 70 m/min did not significantly affect the shapes of the chips created. They remained open screw-shaped or conical. The increase in v_c influenced the appearance of long chips in the tangled variety, produced using HX and TH1500 inserts. In their case, chip entanglement occurred only at the lowest feed. When turning with CP200 and TP40 tool, the feed range is much wider, in which the chip partially entangled around the tool. In the case of CP200, a straight and untangled form of the chip was created only at f = 0.21 mm/rev. The TP40 insert fared much worse, because a partially untangled chip was created only at the maximum feed of 0.27 mm/rev. Moreover, at the end of cutting with this feed, the chip structure changed to a very tangled ribbon form. Machining at a higher speed resulted in no short chips being created with any tool, as was the case during machining at a lower cutting speed.

Tool wear

Figures 10 and 11 show photos of the inserts after a series of experimental tests. Figure 10 shows the corners after turning the Ti_6Al_4V alloy at a cutting speed of 30 m/min, while in Figure 11 it shows the corners at a higher speed, i.e. 70 m/min. Each of the observed inserts covered the same cutting distance, which means that the inserts in Figure 10 worked longer, but at a lower cutting speed and were exposed to less wear.

When analysing the photos of the inserts used during machining at a cutting speed of 30 m/min, it can be clearly stated that the blade wear is low

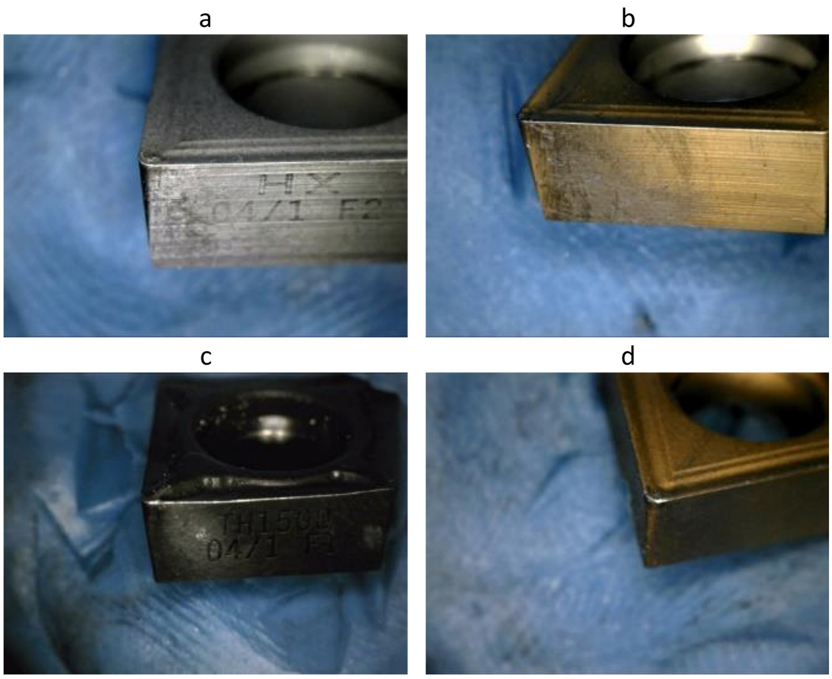

Figure 10. Photos of inserts after turning tests of the Ti_6Al_4V alloy at a cutting speed of 30/min; a) HX uncoated tool; b) CP200 tool with (Ti, Al) N + TiN coating; c) TH1500 tool with Ti(C, N) + Al_2O_3 coating; d) TP40 tool with TiC/Ti(C,N) + TiN coating

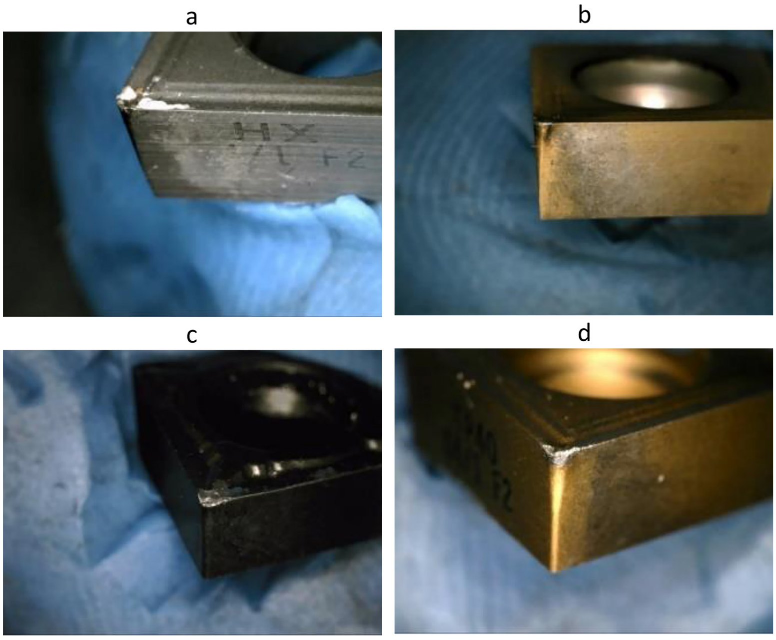

Figure 11. Photos of inserts after turning tests of the Ti_6Al_4V alloy at a cutting speed of 70/min; a) HX uncoated tool; b) CP200 tool with (Ti, Al) N+TiN coating; c) TH1500 tool with Ti(C,N) + Al_2O_3 coating; d) TP40 tool with TiC/Ti(C,N) + TiN coating

and its dominant mechanism was the abrasion mainly on the rake surface right at the nose of the inserts. In the case of HX, CP200 and TP40 tools with F2 chipbreaker, one can see a small worn groove on the rake face caused by the chip sliding along it. However, the TH1500 insert showed, in a similar place, only slight abrasion of the coating from the surface of the F1 chipbreaker. An interesting phenomenon was that more signs of wear could be observed on coated tools than on the HX insert. For example, on the CP200 insert, one can see microcracks perpendicular to the cutting edge, indicating a high thermal load on the tool. On the TH1500 blade, one may notice chipping or scratches that indicate the beginning of crater wear. When the TP40 insert is observed, slight burns and thermal deformation of the corner can be recognised.

In the case of each of the tested cutting inserts, both coated and uncoated, increasing the cutting speed resulted in an increase in the wear intensity. The greatest wear of the uncoated HX insert was observed around the corner and on the rake face (Figure 11a). The chipping of the cutting edge in the corner area and the worn areas on the rake surface in the form of a groove are clearly visible. Moreover, on the rake face traces of a build-up edge are noticeable. Wear bands on the flank face are also visible, but their size is smaller than on the rake face. The previously observed wear mechanism on the CP200 insert not only increased but also extended to the flank face (Figure 11b). Moreover, just below the corner of the insert, the effects of oxidation of the coating material can be seen in the form of dark fields, which also limit the area of the probably heat-deformed corner. A similar intensification of tool wear mechanisms occurred in the case of the TH1500 blade (Figure 11c). Increasing the cutting speed led to the breakage of a fragment of the corner of this insert. In the area between the cutting edge and the chip breaker, a clear detachment of the coating layer from the surface of the carbide substrate can also be observed. The TP40 insert also suffered stress wear. In the photo (Figure 11d), one can see a fragment of the corner broken off at an angle to the rake surface. Moreover, on its active cutting edge, one can notice a form of built-up edge or tool material upset during thermal deformation

To summarise the observations, turning with a lower cutting speed resulted mainly in abrasion of the tool surface, and in inserts with coatings, additionally in thermal wear. Increasing v_c intensified the wear of the blades, which was to be expected, but also showed a very different effect of the coatings on their durability. The symptoms of high temperatures only on inserts with coatings can be explained by the concentration of very large amounts of thermal energy in the cutting zone, which was not dispersed due to the thermal barrier created by these coatings. The lower thermal wear observed on the insert without the coating indicates more efficient heat dissipation by the sintered carbide material to the surroundings and the holder material. When PVD and CVD tool coatings and their influence on tool life are compared, it can be concluded that the first type gives a chance for longer blade operation without reaching the tool-life criterion. The tendency of CVD coatings to mechanical damage was observed, regardless of whether the insert was intended for the machining group S material or not. The blunting of TH1500 and TP40 inserts at a cutting speed of 70 m/min actually eliminates the possibility of working with such parameters in industrial conditions, where cutting distance is much longer than that used in the experiment. Moreover, observations of each insert make it clear that the coatings consisting of TiN or even painted make it easier to check the condition of the tool. They contrast with the silver colour of sintered carbide.

SELECTION OF THE BEST MACHINING CONDITIONS FOR THE TI_6AL_4V ALLOY

The research is complemented by the selection of a set of cutting parameters and a tool that will ensure the best possible quality of the surface produced with the highest process efficiency. For this purpose, the GRA method was used. The parameters analysed included feed and cutting speed, and roughness parameters Sq and Sa, as well as the values of the components of the total cutting force as indicators. It was not decided to use the data on chip shape and blade wear mechanisms because the observations of these indicators were only qualitative and not quantitative. Moreover, the difference in chip shape was so small that it would not significantly change the analysis results. The selected set of analysed data allowed indicating the machining parameters that ensure the highest cutting efficiency, surface quality, and the lowest cutting resistance.

To perform GRA, the data had to be normalised. In the case of feed and cutting speed, a relationship was adopted according to the rule - the higher their values, the better, because the higher the volumetric cutting efficiency. Therefore, Equation 1 was used to normalise their values.

$$x_i^* = \frac{x_i^0(k) - min\, x_i^0(k)}{max\, x_i^0(k) - min\, x_i^0(k)} \tag{1}$$

Equation 2 was used to normalise the results of the *Sq*, *Sz* parameters and cutting force components. This is due to the principle that the lower the surface roughness and cutting forces and the specific cutting pressure, the better.

$$x_i^* = \frac{max\, x_i^0(k) - x_i^0(k)}{max\, x_i^0(k) - min\, x_i^0(k)} \tag{2}$$

The value x_i* determined in formulas 1 and 2 is the normalised value of each of the analysed parameters. The values max $x_i^0(k)$ and min $x_i^0(k)$ are the largest and smallest values from the set of the considered variable, $x_i^0(k)$ is the value of each subsequent analysed parameter. The result of normalisation is a set of numbers contained in a closed interval from zero to one. However, for the data normalised according to formula 1, the largest initial value corresponds to the value 1 and the smallest to 0. In the case of data for which formula 2 was used, this relationship is reversed, i.e., the lowest values of the roughness and force parameters have the value 1 and the highest value was 0. The next stage of the analysis was to determine the deviation coefficient of the parameter in question. For this purpose, formula 3 was used, where the value 1 is the largest value in the normalised set of a given parameter.

$$\Delta_{0i}(k) = |1 - x_i^*| \tag{3}$$

In the next step, using formula 4, the grey coefficient r_{0i} (k) was determined.

$$r_{0i}(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(k) + \zeta\Delta_{max}} \tag{4}$$

In formula 4, Δ_{min} is the smallest value in the designated set of the deviation coefficient of a given parameter, that is, the value 0 and Δ_{max} is the largest value from the set of deviation coefficients, for previously normalised data it always takes the value 1. Coefficient ζ is a characteristic variable; most often, it has the value 0.5 in order to average the values of the determined grey ratio. Δ_{0i} (k) is the coefficient of deviation determined for each subsequent value of the normalised data set.

The final stage of GRA analysis is to determine the grey level of the set of analysed data. Its value is the arithmetic mean of the grey ratios corresponding to the same machining conditions. The formula by which the grey level was determined for each of the forty data sets is presented in Equation 5.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} r_{0i}(k) \tag{5}$$

Table 6 shows the final result of the analysis. The higher the grey level value, the closer the

Table 6. Grey level of efficiency and surface quality of the tool and cutting parameters in turning of the Ti6Al4V alloy

Cuttng parameters		HX	CP200	TH1500	TP40
v_c	f	Grey level γ			
m/min	mm/obr				
30	0.08	0.73	0.69	0.67	0.72
30	0.13	0.61	0.58	0.64	0.54
30	0.17	0.62	0.58	0.52	0.51
30	0.21	0.61	0.53	0.51	0.51
30	0.27	0.61	0.57	0.54	0.54
70	0.08	0.8	0.72	0.73	0.75
70	0.13	0.75	0.66	0.73	0.56
70	0.17	0.68	0.63	0.68	0.52
70	0.21	0.67	0.63	0.66	0.53
70	0.27	0.69	0.67	0.64	0.57

analysed set of parameters is to ensuring the best process efficiency and the quality of the surface produced and the lowest cutting forces.

GRA data show that the best turning results for the Ti_6Al_4V alloy are obtained when using an uncoated HX insert with a feed of 0.08 mm/rev and a cutting speed of 70 m/min. Another, although less effective solution is turning with the same insert and changing the feed to a higher value of 0.13 mm/rev or at a lower speed and minimum feed. The other inserts could provide similar process efficiency when cutting with a higher v_c and the lowest feed. GRA analysis also showed that the worst technological effects combined with efficiency are obtained by selecting a TP40 coated insert, which is not the first choice for the machining of titanium alloys.

CONCLUSIONS

The results of tests on turning the Ti6Al4V alloy with uncoated blades and coated with both PVD and CVD methods show that:

- Regardless of the cutting speed, the best surface quality expressed by the roughness parameters Sq and Sz was obtained after machining with inserts with a CVD coating, then with an uncoated blade, and the worst with an insert with a PVD coating. As the feed rate increased, the difference between the surface roughness after turning with an uncoated blade and CVD-coated blades decreased.
- The coated tools were exposed to more wear mechanisms than the uncoated HX tool. In the case of the latter, only abrasive wear was observed on the rake face. Tools with coatings, apart from the abrasive mechanism, also showed symptoms of thermal and adhesive wear. Additionally, on CVD-coated inserts, one may notice chipping and cracking of the corner and cutting edge. This could be caused, firstly, by the low thermal conductivity of titanium, and, on the other hand, by the coating acting as a thermal barrier, which caused a large amount of heat to accumulate around the cutting edge and corner.
- The effect of blade coating on the values of the total cutting force components was unfavourable. The total cutting force when turning with an uncoated insert was the lowest, especially at low feeds. Such results could be partially related to the fact that the wear of coated plates, especially those using the CVD method, was higher.
- The chip produced by turning with all four inserts was mainly unfavourable. In most cases, they took the form of long tangled or long straight open or conical helical chips. The transition from one form to another occurred after the feed was increased. A more favourable chip shape in the form of shorter sections of several centimetres was achieved at maximum feeds and lower cutting speeds with CVD-coated and uncoated inserts turning. The type of chip breaker did not affect the shape and length of the chips.
- Grey relational analysis confirmed that the worst technological effects combined with the efficiency of the turning process are obtained by selecting the TP40 insert, which is not the first choice for machining materials from the S group. Furthermore, this analysis

showed a certain superiority of the uncoated blade. Therefore, the use of such blades while carefully monitoring the degree of their wear guarantees the most effective machining of the Ti6Al4V alloy.

The research results presented in this work increase the knowledge about the machinability of the Ti6Al4V alloy and the applicability of cutting blades in the machining of this material. The results confirm that it is very difficult to choose a blade that will provide the best quality of the machined surface, will be the most durable and will generate the lowest cutting forces. To select the optimal blade, statistical analyses such as grey relational analysis or another type of analysis should be used, especially when differentiating the importance of the measured indicators. Many technologists are wary of using uncoated blades. The work shows that these blades can be used successfully to machine the Ti6Al4V alloy, combined with the selection of cutting parameters that ensure the lowest wear. In the next stage, the research presented in this work should be extended to include a wider range of cutting parameters, more detailed tests of blade wear, and the cutting distance should be increased to examine the effect of cutting time on wear, forces and surface roughness.

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