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EXPERIMENTAL INVESTIGATION OF CUTTING SPEED EFFECTS ON SURFACE ROUGHNESS AND TOOL WEAR IN TI-6AL-4V MILLING

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Abstract: *The titanium alloy Ti-6Al-4V is a popular choice in the aerospace and medical sectors due to its exceptional mechanical properties, corrosion resistance, and biocompatibility. However, machining this alloy can be challenging due to its high strength and low thermal conductivity, which can result in accelerated tool wear and suboptimal surface quality. This experimental investigation examines the relationship between cutting speed, surface roughness, and tool wear during the milling of Ti-6Al-4V alloy. The selection of an appropriate cutting speed is crucial for enhancing surface finish and prolonging tool life. Experimental findings confirmed that cutting speed significantly influences both surface roughness and tool wear. Higher cutting speeds were associated with increased roughness and accelerated tool wear rates. The study successfully identified an optimal cutting speed that minimizes surface roughness while effectively managing tool wear, contributing to improvements in the overall efficiency of the Ti-6Al-4V alloy milling process.*

Keywords: *cutting speed, depth of cut, tool wear, chip formation, Ti-6Al-4V titanium alloy, surface roughness.*

1. INTRODUCTION

Ti-6Al-4V, a titanium alloy, is highly sought-after in the aerospace, medical, and energy industries due to its remarkable combination of mechanical strength, corrosion resistance, and biocompatibility [1-3]. However, the machining of this alloy is not without its difficulties. Its high tensile strength, coupled with low thermal conductivity and a tendency to work-harden, can pose significant challenges. These material characteristics can result in elevated temperatures within the cutting zone, leading to accelerated tool wear, the generation of continuous chips, and a compromised surface finish on the machined component [4, 5].

Recent research efforts have concentrated on optimizing the machining of titanium alloys, with particular emphasis on understanding how cutting parameters affect surface roughness, tool wear, and cutting forces [6, 7]. Contemporary studies have explored the implementation of advanced cutting techniques, including high-speed milling (HSM) [8, 9] and variable feed milling, to enhance the efficiency of Ti-6Al-4V alloy machining processes [10,11]. Furthermore, there has been a growing interest in developing new coatings and geometries for cutting tools to extend their operational life and minimize wear [12, 13].

"While significant progress has been made in understanding titanium alloy machining, there is still a need for further research to fully elucidate the mechanisms of tool wear and chip formation during the milling of Ti-6Al-4V alloy. Moreover, previous studies have often focused on individual cutting parameters, neglecting the complex interplay between them [14, 15].

This investigation aims to address these gaps by providing a deeper understanding of the relationship between cutting speed, surface roughness, and tool wear in the milling of Ti-6Al-4V. By analyzing the correlation between these critical parameters, this study seeks to contribute to the optimization of the machining process and the enhancement of the quality of finished components.

In contrast to previous research, this study emphasizes a combined analysis of surface roughness and tool wear as a function of cutting speed. Furthermore, it examines chip formation and its influence on the cutting process, adding a novel dimension to the investigation.

The primary goals of this research are:

- To assess the impact of cutting speed on surface roughness during the milling of Ti-6Al-4V alloy.
- To analyze the relationship between cutting speed and tool wear rate.
- To investigate the characteristics of chip formation and its influence on the cutting process.
- To determine the optimal cutting speed that minimizes surface roughness while effectively managing tool wear.

2. RESEARCH METHODOLOGY

To examine the influence of cutting speed on surface roughness and tool wear during the milling of Ti-6Al-4V titanium alloy, a comprehensive experimental investigation was meticulously planned and executed in the following phases.

2.1 Material and cutting tool selection

The experimental trials employed Ti-6Al-4V titanium alloy workpieces, fabricated from hot-rolled plates with dimensions of 60 mm in length, 50 mm in width, and 50 mm in thickness.

"The cutting tool used was a cylindrical milling cutter with indexable carbide inserts, with the cutting geometry specified by the manufacturer (Figure 1)" [17-18]:

- Insert: XNEX080608R-M08 MS2050.
- Holder: Seco R220.96-0080-08-9A.

Fig. 1. Cutting tool selection [16, 19]

2.2 Experimental Planning

The cutting process was the face milling without cooling liquid (dry cutting). The authors have chosen the dry cutting process to increase tool wear speed.

Two experimental factors were identified for investigation: cutting speed (v) and depth of cut (ap).

The cutting speed was varied in two steps, with values of 75 m/min and 100 m/min selected based on the tool manufacturer's guidelines and information from existing literature.

The depth of cut was maintained at a constant value of 0.5 mm for the first set of experiments and then increased to 0.6 mm for the second set.

Other cutting parameters, such as feed per tooth (fz) and cutting width (ae), were kept constant throughout the experiments.

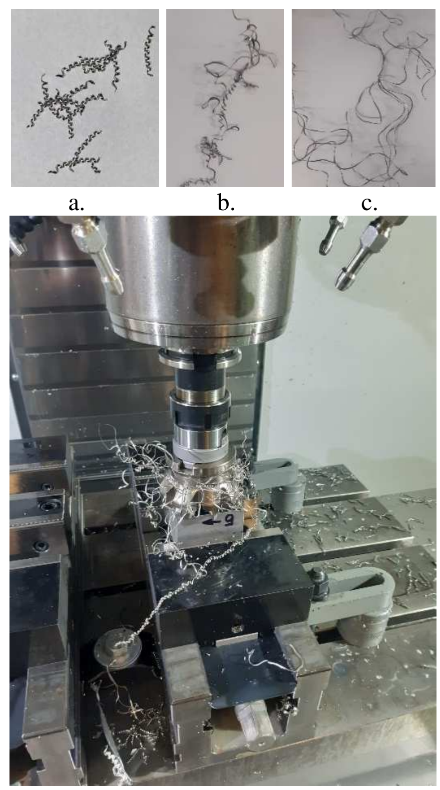


Fig. 2. Chip shape

The number of specimens and the combination of the variation levels of the parameters were deliberately chosen to accelerate the tool insert wear process. The purpose of this approach was to obtain relevant information for the subsequent stages of the research within a reasonable timeframe. We monitored the evolution of the insert wear by observing the shape of the generated chips. A key indicator of the change in the insert's geometry was the transition from helical arc-type chips (fig. 2a) to long (fig. 2b) and very long chips (fig. 2c).

The specific number of machined parts resulted from the continuous execution of the experiment, which was stopped when the shape of the chips indicated a significant change in the insert's geometry, considered technologically unacceptable (the chips began to coil around the cutter) (figure 2). This termination was decided even though the surface roughness (Ra) values did not show significant variations at that point.

Therefore, the selection of the cutting regime and the number of specimens were aimed at capturing the evolution of tool wear, with the shape of the chips serving as the main indicator to determine when changes in the tool's geometry could significantly influence the research results regarding surface quality.

2.3 Sample and Equipment Preparation

The Ti-6Al-4V alloy plates were cut to the dimensions mentioned above and cleaned of impurities. A total of 22 specimens were machined. “The titanium alloy used, with the code TI-6AL-4V, was manufactured according to the AMS 4911 revision R standard” [17].

The chemical composition and mechanical properties of the material are presented in Tables 1 and 2.

Table 1

Chemical Composition of Ti-6Al-4V

Element	AMS 4911 Rev. R (%)	Results (%)
Aluminum (Al)	5.50 - 6.75	6.39 - 6.40
Vanadium (V)	3.50 - 4.50	3.97 - 3.98
Carbon (C)	Max. 0.80	0.025 - 0.026
Iron (Fe)	Max. 0.30	0.14
Oxygen (O)	Max. 0.20	0.182 - 0.192
Nitrogen (N)	Max. 0.05	0.006
Yttrium (Y)	Max. 0.05	< 0.001
Hydrogen (H)	Max. 0.01	< 0.001
Titanium (Ti)	Balance	Balance
Residuals	Max. 0.40	0.069 - 0.070

A HAAS VF2 YT CNC vertical milling center was utilized for the machining operations. The cutting tool was securely mounted within the machine's spindle, and the specified cutting parameters were programmed into the numerical control (NC) system.

Table 2

Mechanical Properties of Ti-6Al-4V

Property	AMS 4911 Rev. R (Minimum Required Values)	Results (Longitudinal Samples)
Yield Strength (ksi)	120	128.6 - 136.9
Tensile Strength (ksi)	130	142 - 147.3
Elongation (%)	10	18.90 - 19.50

2.4 Conducting the Experiments

The face milling experiments were conducted according to the established experimental plan (Figure 3). The cutting process was carefully monitored to ensure its stability and to prevent the occurrence of vibrations or other disruptive factors.

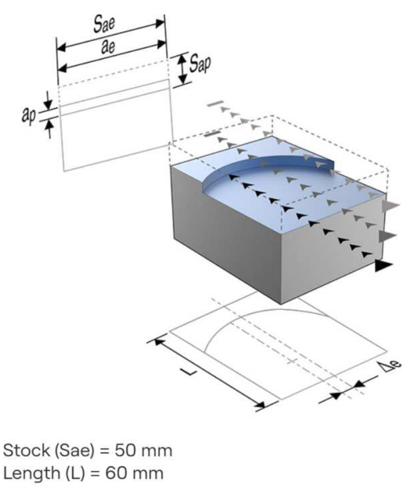


Fig. 3. Face Milling Strategy.

2.5 Surface Roughness Measurement

Surface roughness measurements were performed using a Mitutoyo Surftest SJ-210 profilometer, in accordance with the ISO 21920 standard.

Roughness values were acquired in both the longitudinal and transverse directions, relative to the cutting direction, on each machined surface.

2.6 Data Analysis and Conclusion Formulation

Experimental data were statistically processed using MS Excel software. A comparative analysis was conducted to evaluate the relationship between cutting speed, surface roughness, and tool wear.

Based on the analysis, conclusions were drawn regarding the impact of cutting speed on the quality of the machined surface and the overall durability of the cutting tool.

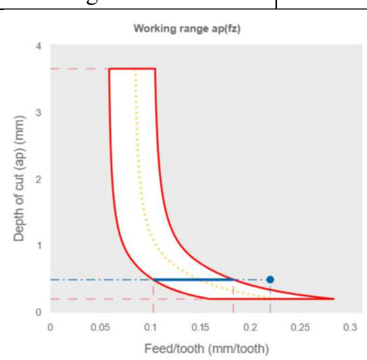
3. EXPERIMENT SETUP

Workpieces 1 through 15 were machined with the cutting parameters shown in Table 3 and Figure 4, using cutting edge 4 of the insert (Figure 5 and Figure 6).

Table 3

Cutting regime used for machining workpieces 1 to 15

Parameter	Value
Number of passes	1
Depth of cut (ap)	0.50 mm
Number of passes (ae)	1
Radial engagement (ae)	50 mm
Radial engagement as % of DC	62.50%
Radial offset (Ae)	0 mm
Feed/tooth	0.220 mm/tooth
Cutting speed	75 m/min
Coolant media	dry
RPM	299 rev/min
Feed speed	592 mm/min
Metal removal rate (Q)	14.7 cm³/min
Average metal removal rate	6.34 cm³/min
Chip thickness (he)	0.0968 mm
Average chip thickness (hm)	0.114 mm
Maximum chip thickness (hex)	0.123 mm
Engagement angle, we	77.5°
Average machine power	0.744 kW
Cutting time	14.2 s



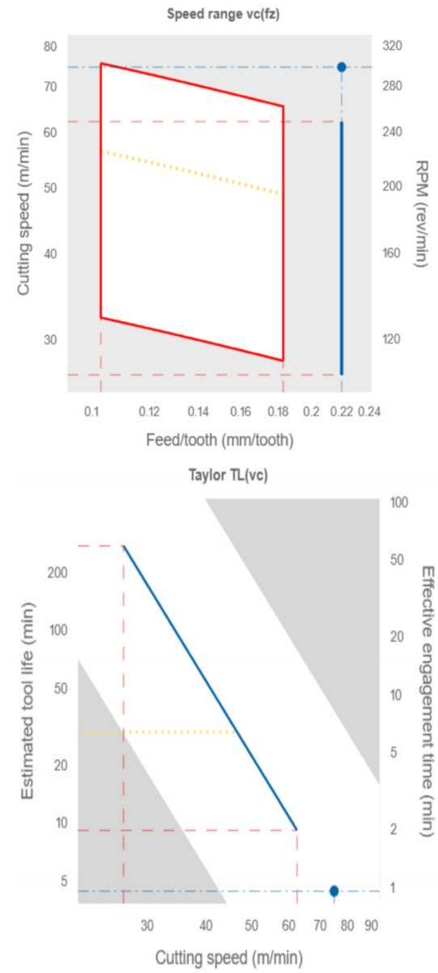


Fig. 4. Graphical illustration of the cutting regime when the cutting speed is 75m/min

Fig. 5. Image of new cutting-edge 4

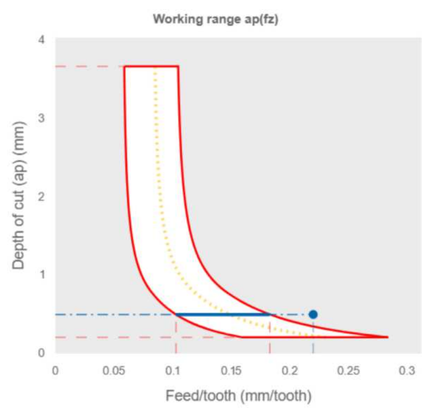
Fig. 6. Image of modified cutting-edge 4

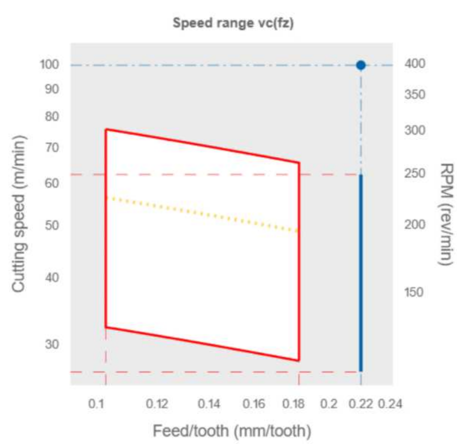
At workpiece number 8, the cutting-edge geometry was modified (Figure 6), and machining continued with the worn insert, having the modified geometry, up to workpiece 15, inclusive, since the surface quality did not undergo significant changes. From workpiece 16 to 19, the machining was carried out with another cutting edge of the same insert - cutting edge 5. The new adopted cutting regime is presented in Table 4 and Figure 7.

Table 4

Cutting regime used for machining workpieces 16 to 19

Parameter	Value
Number of passes	1
Depth of cut (ap)	0.50 mm
Number of passes (ae)	1
Radial engagement (ae)	50 mm
Radial engagement as % of DC	62.50%
Radial offset (Ae)	0 mm
Feed/tooth	0.220 mm/tooth
Cutting speed	100 m/min
Coolant media	dry
RPM	398 rev/min
Feed speed	789 mm/min
Metal removal rate (Q)	19.7 cm³/min
Average metal removal rate	8.45 cm³/min
Chip thickness (he)	0.0968 mm
Average chip thickness (hm)	0.114 mm
Maximum chip thickness (hex)	0.123 mm
Engagement angle, we	77.5°
Cutting time	10.6 s





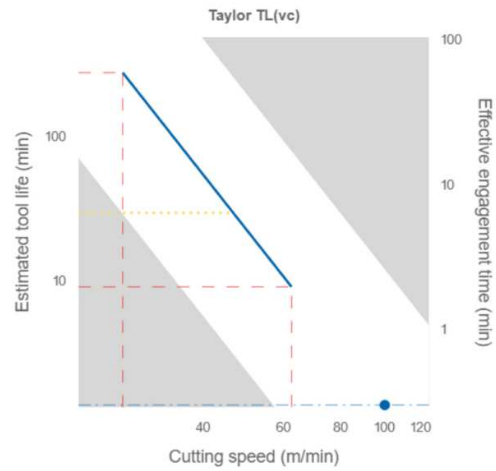


Fig. 7. Graphical illustration of the cutting regime when the cutting speed is 100m/min

Workpieces 16 to 19 were machined using this cutting regime with cutting edge 5 of the insert (Figure 8), until the geometry of the cutting edge was modified, which occurred at workpiece 19 out of the 22 (Figure 9).

Fig. 8. Image of new cutting-edge 5

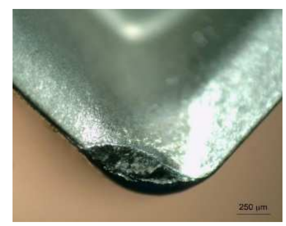


Fig. 9. Image of modified cutting-edge 5

The cutting regime used for machining workpieces 20 to 22 is presented below in Table 5.

Table 5

Cutting regime used for machining workpieces 20 to 22.

Parameter	Value
Number of passes	1
Depth of cut (ap)	0.60 mm
Number of passes (ae)	1
Radial engagement (ae)	50 mm
Radial engagement as % of DC	62.50%
Radial offset (Ae)	0 mm
Feed/tooth	0.220 mm/tooth
Cutting speed	100 m/min
Coolant media	dry
RPM	398 rev/min
Feed speed	788 mm/min

Parameter	Value
Metal removal rate (Q)	23.6 cm³/min
Average metal removal rate	10.1 cm³/min
Chip thickness (he)	0.106 mm
Average chip thickness (hm)	0.125 mm
Maximum chip thickness (hex)	0.135 mm
Engagement angle, we	77.5°
Cutting time	10.7 s

Workpieces 20 to 22 were machined with a new insert. Cutting edge 4 of the new insert was used. It was used until the geometry of the cutting edge was modified.

4. MEASUREMENTS AND DATA COLLECTION

The evaluation of the machined surface quality was performed by measuring the roughness using a profilometer. The measurements were carried out according to the ISO 21920 standard, following the scheme presented in Figure 10 and Figure 11. The roughness was measured longitudinally and transversely along the machining direction, at the beginning and end of each workpiece, as indicated in the figures.

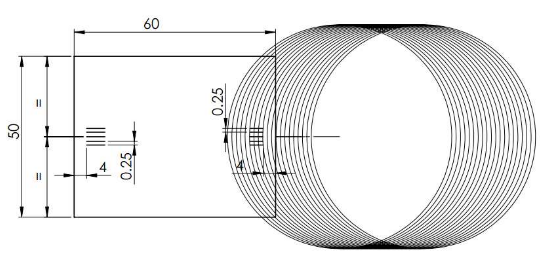


Fig. 10. Ra longitudinal measurement

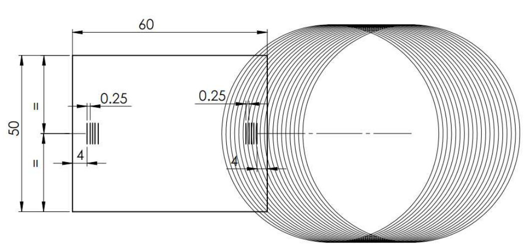


Fig. 11. Ra transverse measurement

For each specimen, 5 roughness measurements were taken at the beginning and end of the workpiece, for a total of 22 specimens. The average values are presented in Table 6 and Table 7.

Table 6

Data collection of Ra longitudinal measurements.

Sample	Ra L beginning	Ra L end	Ra L
1	0.259	0.286	0.273
2	0.271	0.267	0.269
3	0.297	0.207	0.252
4	0.218	0.253	0.235
5	0.270	0.192	0.231
6	0.200	0.210	0.205
7	0.247	0.163	0.205
8	0.224	0.193	0.208
9	0.187	0.176	0.181
10	0.179	0.193	0.186
11	0.194	0.208	0.201
12	0.178	0.255	0.217
13	0.214	0.208	0.211
14	0.232	0.284	0.258
15	0.214	0.183	0.199
16	0.219	0.424	0.321
17	0.363	0.409	0.386
18	0.425	0.307	0.366
19	0.298	0.310	0.304
20	0.392	0.327	0.359
21	0.365	0.323	0.344
22	0.411	0.365	0.388

Table 7

Data collection of Ra transverse measurements.

Sample	Ra T beginning	Ra T end	Ra T
1	0.237	0.2624	0.2497
2	0.2676	0.2482	0.2579
3	0.2152	0.3218	0.2685
4	0.2844	0.2312	0.2578
5	0.2984	0.2214	0.2599
6	0.2146	0.3422	0.2784
7	0.2008	0.2388	0.2198
8	0.3198	0.2244	0.2721
9	0.193	0.2122	0.2026
10	0.2622	0.2736	0.2679
11	0.2088	0.2426	0.2257
12	0.2616	0.1836	0.2226
13	0.2302	0.2108	0.2205
14	0.257	0.2174	0.2372
15	0.213	0.1816	0.1973
16	0.197	0.2456	0.2213
17	0.3302	0.198	0.2641
18	0.3162	0.228	0.2721
19	0.1956	0.1572	0.1764

5. RESULTS AND DISCUSSIONS

This experimental study analyzed the influence of cutting speed on the roughness of Ti-6Al-4V titanium alloy during milling, as well as the impact of tool wear on this parameter.

The collected data, presented in Tables 6 and 7, were analyzed to identify trends and correlations between the parameters studied.

Based on the summary tables of the longitudinal (Ra L) and transverse (Ra T) roughness measurements, the differences presented in the following figures (Figure 12 and Figure 13) can also be observed.

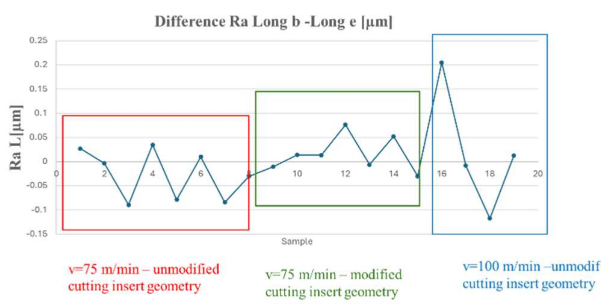


Fig. 12. Differences between longitudinal Ra measurements.

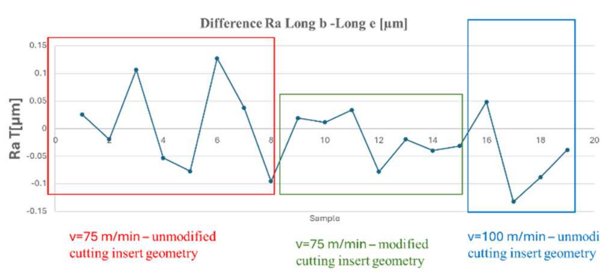


Fig. 13. Differences between transverse Ra measurements.

Examination of the data presented in Table 6 and Figure 12 reveals a trend of increasing surface roughness with higher cutting speeds.

At a cutting speed of 75 m/min, the mean longitudinal roughness (RaL) was measured as 0.239 µm. However, when the cutting speed was increased to 100 m/min, the RaL value rose to 0.344 µm.

This observed increase in surface roughness can be attributed to the elevated temperatures generated within the cutting zone at higher speeds, which can result in more pronounced plastic deformation of the workpiece material and accelerated deterioration of the cutting tool's edge.

An increase in roughness was also observed at the transition from workpiece 7 to workpiece 8, where the tool cutting edge geometry was modified.

For specimens 9-15, machined with the worn cutting edge, the average roughness was lower (0.208 µm) than for specimens 1-7, machined with the new cutting edge (0.239 µm).

This suggests that initial tool wear may have a beneficial effect on surface roughness, probably due to wear in the high stress area.

No clear correlation between temperature and roughness could be established for specimens 1-8.

An analysis of specimens 9-15 revealed a positive correlation between surface roughness and cutting temperature, with roughness increasing as temperature rises.

Conversely, for specimens 20-22, which were machined with a cutting depth of 0.6 mm, a slight decrease in roughness was observed compared to specimens 16-18, machined with a cutting depth of 0.5 mm.

However, this difference was marginal, suggesting that, within the tested range, cutting depth does not have a substantial influence on surface roughness.

When machining specimens 20-22, a trend of decreasing roughness was observed from the beginning to the end of the workpiece.

This trend is not observed in specimens 1-19. The data in Table 7 and Figure 13 show a similar trend for transverse roughness (Ra T).

At a cutting speed of 75 m/min, the average transverse roughness was 0.257 µm, while at a cutting speed of 100 m/min, Ra T increased to 0.241 µm.

An increase in transverse roughness is observed at the transition from workpiece 8 to workpiece 9, like the longitudinal roughness.

For specimens 9-15, machined with the worn cutting edge, the average transverse roughness was lower than for specimens 1-7, machined with the new cutting edge, confirming previous observations regarding the effect of initial wear on roughness.

Although the study did not include direct measurements of tool wear, qualitative observations of chip shape and changes in cutting edge geometry suggest more pronounced wear at higher cutting speeds.

No change in chip shape was observed as a function of chipping speed Only tool wear. With the new cutting-edge machining, the chips were shorter and thicker, while with the worn cutting edge, longer chips were formed (Figure 14).

Fig. 14. Change in chip shape

This change in chip shape influence chip evacuation and increases the risk of accidents, negatively affecting the quality of the machined surface by being scratched by the splinters glued to the cutter.

From a technological point of view, long chips can create additional problems, such as scratching the machined surface, causing accidents, damaging the coolant nozzles, and hindering the automatic tool change.

In the case of the 100 m/min cutting speed, increasing the cutting depth from 0.5 mm (workpieces 16-18) to 0.6 mm (workpieces 20-21) led to an insignificant decrease in roughness along the feed direction, from 0.358 μm to 0.352 μm.

Therefore, in this case, the cutting depth does not significantly influence the surface roughness.

The shape of the chip, i.e. the transition from a short spiral to a long unspiralled / very long chip is a marker of tool tip wear. At this point the geometry of the tool has changed.

6. CONCLUSIONS

In summary, this study has demonstrated that cutting speed plays a crucial role in determining surface roughness when milling Ti-6Al-4V titanium alloy.

Higher cutting speeds tend to increase both longitudinal and transverse surface roughness. Tool wear also contributes to surface roughness, and it was observed that initial wear may have a beneficial effect on surface finish.

Furthermore, chip morphology evolves with cutting speed and tool wear, influencing the final surface quality. Therefore, selecting an appropriate cutting speed is essential for achieving a desirable surface finish and maintaining acceptable tool life.

Within the range of values tested, cutting depth did not significantly affect surface roughness. These findings underscore the complex nature of the Ti-6Al-4V milling process and emphasize the importance of optimizing cutting parameters.

Specifically, cutting speed must be carefully chosen, considering its impact on surface roughness and tool wear.

Further investigation, incorporating quantitative measurements of tool wear, is necessary to establish precise correlations between wear, cutting speed, and surface roughness.

Future research could also explore the effects of other cutting parameters, such as feed rate and depth of cut, on surface roughness and tool wear.

Additionally, the influence of lubrication and cooling strategies on the cutting process warrants further analysis.

Continued research in this area will contribute to the development of optimized machining strategies for Ti-6Al-4V alloy, leading to enhanced product quality and improved manufacturing efficiency.

7. ACKNOWLEDGMENTS

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Studiu experimental privind efectul vitezei de așchiere asupra rugozității și uzurii sculei la frezarea aliajului de titan Ti-6Al-4V

Aliajul de titan Ti-6Al-4V este utilizat pe scară largă în industria aerospațială și medicală datorită proprietăților sale mecanice excelente, rezistenței la coroziune și biocompatibilității. Prelucrarea prin așchiere a acestui aliaj prezintă provocări din cauza rezistenței sale ridicate și a conductivității termice scăzute, care pot duce la uzura rapidă a sculei și la o calitate slabă a suprafeței. Acest studiu experimental investighează efectul vitezei de așchiere asupra rugozității suprafeței și a uzurii sculei la frezarea aliajului Ti-6Al-4V. Viteza de așchiere are un impact semnificativ asupra rugozității suprafeței și a uzurii sculei la frezarea aliajului Ti-6Al-4V. Alegerea unei viteze de așchiere adecvate poate îmbunătăți calitatea suprafeței și poate prelungi durata de viață a sculei. Rezultatele experimentale au arătat că viteza de așchiere influențează atât rugozitatea suprafeței, cât și uzura sculei. La viteze de așchiere mai mari, s-a observat o creștere a rugozității și o uzură mai rapidă a sculei. Studiul a identificat o viteză de așchiere optimă care minimizează rugozitatea și controlează uzura sculei, contribuind la îmbunătățirea eficienței procesului de frezare a aliajului Ti-6Al-4V.

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