



Milling a Titanium Alloy Using Different Machining Parameters: A Comparative Study on Tool Wear, Tool Life and Performance

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Abstract. The machining process is still quite relevant in the manufacturing industry, being employed in the production of high-precision and quality parts for a wide variety of industries, for instance, the aerospace and aircraft industries. The components produced for these industries are usually comprised of high-performance alloys, such as titanium alloys. However, there are some problems associated with the machining of titanium alloys. Therefore, new strategies, tools and sets of parameters are being used for the machining of these alloys, trying to correct problems associated with production quality and tool-life. In the present work, milling tests are conducted on a Ti6Al4V titanium alloy, using different machining strategies, mainly focused on the variation of the cut's radial depth. The employed tools consist of 16 mm diameter mills, coated with TiAlN. After the machining, the tools are subjected to optical and scanning electron microscopy, in order to quantify the tool flank wear and the developed tool wear mechanisms for each of the used cutting conditions. The machined surface quality and machining time for each of the conditions are also analyzed. This work aims to expand the knowledge on the machining of these alloys, offering viable solutions that can be adopted in the future, when it is intended to optimize tool life and performance for the machining of titanium alloys.

Keywords: Milling · Titanium · Machining strategy · Tool wear · Tool life

1 Introduction

Machining remains the most used process to produce high-quality and precision parts for a wide variety of industry sectors, with turning and milling being the most employed machining processes to produce these kinds of parts [1]. The machining industry has shown considerable growth in the past few years, being projected to keep growing, due to the expansion of its sectors. With this increasing need for high-quality and tight-tolerance parts, the need to improve and optimize already existing machining processes also grows, either by the implementation of novel tool geometries or tool coatings [2].

This also happens because of the monitorization and control of the cutting forces that are developed during the machining process itself [3], as these provide valuable information regarding process stability and tool condition. Due to its application in the aerospace and aeronautical industry sectors, titanium machining is still a very popular research topic, with researchers aiming to develop new strategies for the machining of these alloys, as well as studying and optimizing already existing processes to produce titanium parts [4]. The use of the Taguchi method for the optimization of machining processes is quite well documented [1] and, for titanium machining, the same rule applies. Recent studies employ this method to determine optimal machining parameters for the machining of these alloys, while studying the influence of each parameter on the machining process itself [5]. Regarding the development of new titanium machining strategies, recently there is an emphasis on sustainability. As such, new cooling methods [6] are being developed in the machining of these alloys [7], which study the influence of these strategies on the quality of the produced parts, process' stability, developed cutting forces [8–10] and tool-wear sustained during the machining of these alloys. Regarding recent improvements/developments made in titanium machining, there has been a focus on the study and development of new coatings [11] aimed to reduce the developed cutting forces and, consequently, improving production quality and tool-life [12]. Ziberov et al. [13] evaluated the wear of TiAlN and DLC (Diamond Like Carbon) coated tools for micro-milling operations of Ti6Al4V titanium alloy under dry and flooded cooling conditions. The authors concluded that the main wear times consisted of the rounding of the tool's edge and the built-up edge for all the tested tools. The wear values and tool-life were compared between the two mentioned coatings, as well as with uncoated WC-Co (Tungsten carbide with cobalt binder) tools. It was concluded that the DLC tools exhibited better tool-life and performance under dry and flood cooling conditions when compared to TiAlN and uncoated tools. Furthermore, TiAlN coated tools were deemed unsuited for dry machining of this alloy. There have been also made developments regarding the optimization and use of cooling methods for the improvement of production quality and tool-life. The hybrid MQL (Minimum quantity lubrication) + Cryogenic cooling has been employed successfully in the machining of Ti6Al4V titanium alloy, reporting an improvement in surface finish and tool-life [14]. Yang et al. [15] developed a new synthetic water-based cutting fluid for the machining of titanium alloys, testing this fluid in tapping, milling, and drilling operations, after which compared the developed cutting forces with commercially available emulsions. The authors reported lower cutting forces for all the analyzed operations and even registered an improvement in machined surface roughness for milling operations. In addition, for drilling operations, it was concluded that the cutting forces dropped drastically when conducted using the developed cutting fluid.

As seen from the studies presented above, the study of titanium machining is still quite popular and relevant, focusing on the development and improvement of machining strategies and, thus, improving production quality, productivity, and tool-life. In the present study, the machining performance and tool-wear of TiAlN coated milling tools using different parameters are presented, offering a final comparison based on production quality, productivity, and tool-wear.

2 Materials and Methods

In the present section, all the materials and methods used for the conduction of this work are presented.

2.1 Materials

Regarding the machined material, a block of Ti6Al4V titanium alloy was employed. The tools had to produce the part shown in Fig. 1.

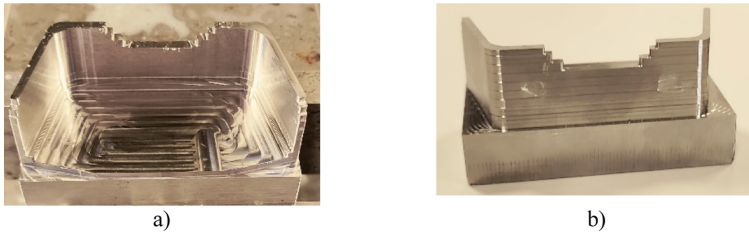


Fig. 1. Desired format of the workpiece (Ti6Al4V alloy): (a) back view, (b) front view.

One type of tool was tested in this work, namely a four-fluted end-mill. The tool's substrate is the cemented carbide WC-Co grade 6110, provided by INOVATOOLS, S.A. (Leiria, Portugal). This cemented carbide grade presents micro-grain with about $0.3 \mu\text{m}$ and uses 6% Co (wt.) as a binder. The tools possess a diameter of 16 mm, having a cutting length of 36 mm and a total length of 92 mm. These tools were coated with PVD (physical vapor deposition) TiAlN coatings and deposited by a CemeCom CC800/9ML PVD Unbalanced Magnetron Sputtering equipment provided with four target holders. The deposition parameters of the TiAlN coating, are: deposition time of 200 min; $\text{Ar}^+ + \text{Kr} + \text{N}_2$ reactor gases; 4 TiAl (40:60 ratio) targets; pressure of 580 mPa; temperature of 450°C ; bias voltage of -110 V ; target current density of 20 A/cm^2 ; and holder rotational speed of 1 rpm.

2.2 Methods

As for the analyses that were performed, the tool coating was characterized, evaluating its thickness and mechanical properties. The thickness measurements were performed using a FEI QUANTA 400 FEG scanning electron microscope (SEM), provided with an EDAX Genesis Energy Dispersive X-Ray Spectroscopy microanalysis system. The coating's hardness and Young's Modulus was assessed using a NanoTest Micro Materials equipment, provided with a Vickers diamond indenter. The normal load selected to perform these tests was 15 mN and the dwell time used to avoid creep phenomenon of the sample was 30 s.

Regarding the machining tests, these were performed in a HAAS VF2 CNC milling center, capable of reaching 10,000 rpm and having a maximum power of 20 kW. The strategy and tool path were the same for all the tested tools, varying only in the machining

parameters. The machining tests were performed using a water-miscible cutting fluid projected externally (5% oil in water). Furthermore, a set of parameters was chosen, considering the optimal values for machining operations that were suggested by the tool substrates provider. In the present work, the impact of the radial depth of cut was studied on the production quality, machining time and tool wear sustained by the end-mills. The machining parameters can be observed in Table 1, where there is a variation of 25% in radial depth of cut in relation to a base value of 1.6 mm, corresponding to the T100AE tools (tested with 100% a_e (radial depth of cut) value). A total of three tools per set of parameters was analyzed, producing a total of 9 machined parts (1 for each tool).

Table 1. Machining parameters and tool references for the conducted tests

Tool Ref.	Vc (m/min)	fz (mm/tooth)	N (rpm)	a_p – axial depth of cut (mm)	a_e – radial depth of cut (mm)
T75AE	79.92	0.0645	1590	32	1.2
T100AE	79.92	0.0645	1590	32	1.6
T125AE	79.92	0.0645	1590	32	2.0

After the machining, the tools were collected and cleaned for a posterior SEM analysis, to quantify and characterize their wear, by identifying the main wear mechanisms and performing flank wear (VB) measurements on all the tested tools, according to the ISO 8688-2:1986 standard. This analysis was carried out using the same SEM equipment mentioned above. The machined surface quality of the titanium parts was also evaluated, through the conduction of surface roughness measurements, using a MAHR PERTHOMETER M2 profilometer, following the standard procedure described in DIN EN ISO 4288/ASME b461. For the surface roughness analysis, the Arithmetic Mean Roughness (Ra), mean roughness depth (Rz), and maximum roughness (Rmax) was considered. The R profile was also analyzed, to identify any sharp peak in the surface roughness values and other phenomena.

3 Results and Discussion

Regarding the evaluated TiAlN coating, it had an average thickness of 1.875 μm , and a hardness and Young's modulus values of, 22.7 GPa and 309 GPa, respectively.

As for the machining time, as expected it was noticed a relevant reduction for higher values of radial depth of cut. The total machining times were registered for each test conducted for the conditions and are shown in Table 1. For T75AE tools, the machining time was 11:02 min, for T100AE tools it was 9:06 min and, for the T125AE tools, 7:46 min.

The machined surface quality was evaluated using the equipment mentioned in the previous section, by performing several measurements on the machined surface of the machined titanium part. In Fig. 2, the mean Ra values, taken from all the machined parts, are presented for each of the test conditions. As can be seen in the same figure, there

is a significant increase in surface roughness values from the T75AE to the T100AE tested tools (from $0.745 \mu\text{m}$ to $0.987 \mu\text{m}$). However, for the test conditions with higher a_e values, the surface roughness improves slightly, namely to $0.890 \mu\text{m}$.

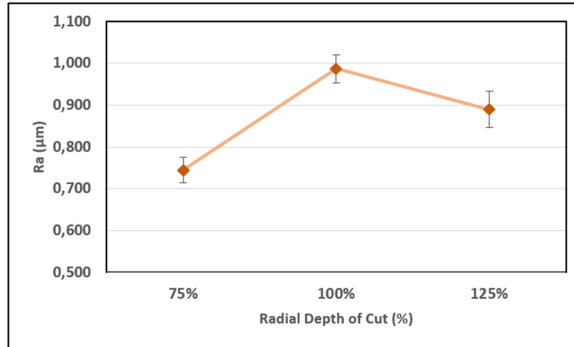


Fig. 2. Average Ra values of the machined surface quality for all test conditions

Regarding the tool wear assessment, the evaluation was performed according to the methods mentioned in the previous section. The VB (flank wear) values were measured for each tested tool for all the test conditions, and its distribution can be observed in Fig. 3.

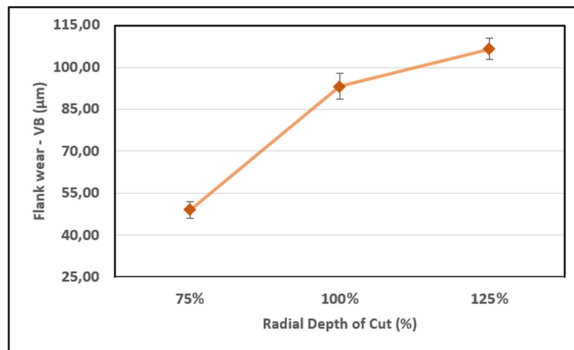


Fig. 3. Average VB (flank wear) values of the tested tools for all test conditions

As observed in Fig. 3, the VB values increase significantly from the T75AE tools to the T100AE ones, as seen for the initial increase in surface roughness values observed in Fig. 2. Notwithstanding, the VB values keep increasing for higher radial depth of cut values, reaching its maximum value for the tools tested at 125% a_e value. In Fig. 4, a comparison between the wear registered for the T75AE and T125AE tools can be observed. This increase in the VB value, however, is not as accentuated as that observed from the T75AE tools to the T100AE. Moreover, these higher VB values did not seem to negatively affect the surface roughness quality, since as observed in Fig. 2, the T125AE

tools produced better results (in terms of machined surface roughness) than the T100AE tools. Nevertheless, the best machined surface quality is achieved by the tools that exhibited the least amount of flank wear.

Regarding wear evaluation, an increase of the rake face wear matching the tool flank wear for the T75AE and T100AE tools was noticed. In spite of this, regarding the sustained rake face wear for the T125AE tools, this was less severe than the one registered for the T100AE tools, despite the T125AE tools presenting more severe flank wear than the latter ones. This can be observed in Fig. 4, where two SEM images of the rake faces of T100AE (Fig. 4 (a)) and T125AE (Fig. 4 (b)) are presented.

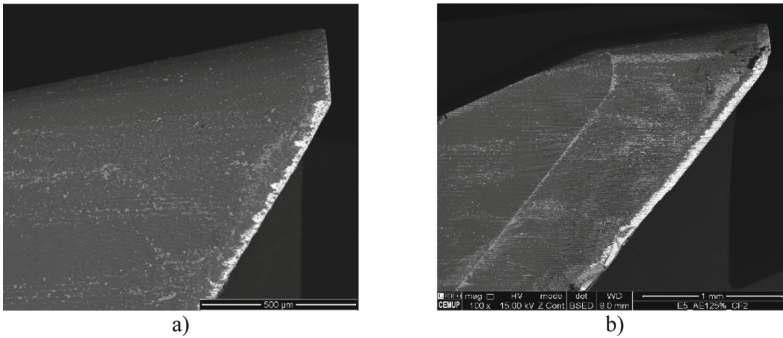


Fig. 4. SEM images of the clearance faces of tools tested at: (a) T75AE; (b) T125AE

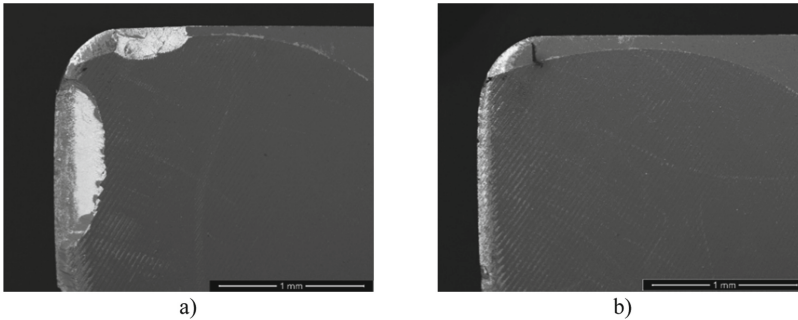


Fig. 5. SEM images of the rake faces of tools tested at: (a) T100AE; (b) T125AE

The fact that the rake faces of the T100AE tools sustained more wear than those tested at T125AE might explain the increase in surface roughness values for the T100AE tools. Regarding the wear observed in Fig. 5, it can be observed more crater wear on the tool tested at 100% radial depth of cut (Fig. 5 (a)), presenting, as well, some adhesive and abrasive damage, the amount of adhesive wear is promoted by abrasive wear, which can explain the deterioration in machined surface quality [6]. For the T125AE tools (Fig. 5 (b)), as well as the T75AE tools, it was noticed that the wear was mainly of the adhesive and abrasive kinds, with some areas of delaminated coating being registered, as well as

some crater wear. However, in terms of severity of sustained rake face wear, this was less severe for T75AE tools, albeit very similar to that registered for T125AE tested tools.

Wear mechanisms observed were primarily adhesion, abrasive wear, coating delamination, cratering and some built-up edge (BUE), registered primarily for tools tested at higher values of radial depth of cut [1, 2]. Material adhesion and adhesive wear were registered under all tested conditions, being higher when increasing a_e values. Abrasive and adhesive wear were observed in all tested tools, being more severe for T100AE tools [6], followed by T125AE tools. Cratering was observed primarily on the rake face of T100AE tools, and also sporadically registered for T75AE and T125AE tools, but in a less severe manner. Coating delamination was more severe on the flanks of T125AE tools, being promoted by the increased material adhesion to tools' surfaces, as well as by the increase in a_e value. The main tool wear mechanisms can be observed in Fig. 6.

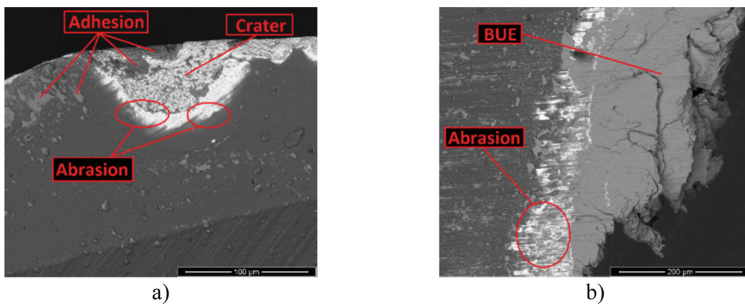


Fig. 6. SEM images of primary wear mechanism, registered in: (a) a T75AE tool's rake face; and (b) a T125AE tool's clearance face

4 Conclusion

In the present work, a comparative study on the influence of the cut's radial depth on the machining time, machined surface quality and tool wear sustained by end-mills used for machining Ti6Al4V titanium alloy is presented, with the following conclusions being drawn: (1) The radial depth of cut influences the machined surface quality productions, with the best quality being obtained using T75AE tools. An increase in this parameter's value will provoke an increase in surface roughness value; (2) It was registered a slight decrease in surface roughness from the T100AE tools to the T125AE tools; (3) T75AE tools exhibited the least flank wear damage. The flank wear values increased for higher values of radial depth of cut; (4) A considerable rake face damage was registered for T100AE tools, with the rake wear sustained by the T75AE and T125AE tools being very similar; (5) The T75AE tools exhibited less overall wear, both in the flank and rake faces; (6) The main wear mechanisms registered in the tools were: adhesive wear, abrasive wear, coating delamination and cratering.

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