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REVIEW ON MACHINABILITY OF TITANIUM ALLOYS: THE PROCESS PERSPECTIVE

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Abstract. Titanium alloys are widely used in the engineering field, namely in the aerospace, automotive and biomedical parts, because of their high specific strength and exceptional corrosion resistance. However, the machinability of titanium alloys is difficult due to their low thermal conductivity and elastic modulus, high hardness at elevated temperature, and high chemical reactivity. This article reviews the state of the art of machinability of titanium alloys, and focuses on the analysis of the process details, namely the especial techniques for cutting improvement, machining forces, chip formation and cutting temperature. The influence of titanium properties on the machinability is also highlighted. Particular attention is given to the turning process of Ti-6Al-4V alloy. The conclusions presented at the end highlight some current trends, disagreement, and research needs.

1. INTRODUCTION

Because of their high specific strength and exceptional corrosion resistance, titanium alloys are widely used in the engineering field, namely in the aerospace, automotive and biomedical parts [1,2]. In many applications, these materials replace steels and aluminum alloys, which usually results in weight and/or space saving, increase of system efficiency by rising the service temperature, and removal of need of protective coatings that should be used in steels.

According to Childs [3], the most common metal shaping technology includes turning, milling and drilling. On the other hand, the fabricated parts for high tech industries require, generally, high dimensional accuracy and good surface integrity, being the machining an essential production process for reaching these requirements [4]. However, machining titanium alloys is not easy [5]. The low thermal conductivity, low elastic modulus, maintenance of high hardness at elevated temperatures, and high chemical reactivity are the main factors for low machinability of those alloys. These factors may results in rapid tool wear, low material removal rate, and degradation of surface integrity of machined parts [6-8].

Several strategies have been used with some success in the development of machinability of titanium alloys and other materials, namely the optimization of cutting parameters [1,9], chip breaking [10,11], tool vibration [7,12], cryogenic cooling [13], high pressure coolant [14,15], and others.

Numerous literatures have been dedicated, fully or partially, to the state of the art of titanium machining, including books [16-19], thesis [14] and review papers [2,20-22], among others. However, new applications and machining technologies for titanium alloys are continuously being developed by

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Table 1. Thermal conductivity (k) of titanium and its alloys versus temperature [3].

Temperature [°C]		0	200	400	600	800
k [W/m.K]	Pure-Ti	22	21	21	21	-
	α / α+β / β	5.5-8.0	8.0-12.0	10.0-17.0	12.5-21.0	15.0-25.0

Table 2. Selected properties of Ti-6Al-4V alloy in its two main metallurgical conditions [27,66,67].

Material	*TS* [MPa]	*YS* [MPa]	*E* [GPa]	*H* [HV]	*k* [W/m.K]	β-Transus [°C]
Ti-6Al-4V (annealed bar)	895	825	110	340	7.3	995
Ti-6Al-4V (solution + age bar)	1035	965	-	360	7.5	995

TS – Tensile Strength; *YS* – Yield Strength; *E* – Elastic modulus; *H* – Hardness; *k* – Thermal conductivity.

worldwide researchers. Therefore, additional literatures are always needed.

Because the machining process involves many variables, a comprehensive review is complex. This article focuses on the turning process of the classic alloy Ti-6Al-4V, with especial attention to the cutting techniques, machining forces, chip formation and cutting temperatures. The influences of titanium properties on machinability are also highlighted.

The main conclusions, presented at the end, underline some current trends, divergences and needs for research.

2. MACHINABILITY VERSUS TITANIUM PROPERTIES

2.1. Overview

The thermal conductivity of titanium materials is relatively low when compared with that of steel (about 60 – 30 W/mK) and aluminum alloys (about 170 – 200 W/mK at 0 °C and 220 – 240 W/m.K at 600 °C) [23]. In addition, the thermal conductivity of titanium alloys varies significantly with temperature change, but not for pure titanium, which remain around 21 W/mK (Table 1).

Considering the properties provided in Table 2, especially the tensile strength (*TS*) and hardness (*H*), one can infer that the Ti-6Al-4V alloy in the annealed condition requires less machining power than the same alloy in the solution and aged condition. But with regard to thermal conductivity the last seems to be easier to machine because higher thermal conductivity generally results in lower cutting temperature. Besides, the referred table provides information on the β-transus temperatures, which is a central point of metallurgical transformation that can cause changes on the mechanical properties, distortion and residual stresses in the workpiece under cutting process.

Fig. 1 provides information on variation of Ti-6Al-4V alloy properties with temperature. Any of these properties vary significantly with temperature. The increase of thermal conductivity *k* (Fig. 1a) [24], and decrease of hardness *H* (Fig. 1b) [25] and ultimate tensile strength *UTS* (Fig. 1d) [26] with increasing temperature seem to be beneficial for machining, in terms of heat removal rate and magnitude of cutting force, respectively. But the decrease of elastic modulus *E* (Fig. 1c) [27] results in more susceptibility for workpiece deflection and vibration during machining and is, therefore, not desirable.

2.2. Influences of titanium properties on machinability

Titanium and its alloys present low machinability due to their low thermal conductivity, high reactivity, low elastic modulus, high hardness and strength at elevated temperature, and peculiar work hardening features. Table 3 summarizes the influence of titanium properties on its machinability.

3. ESPECIAL TECHNIQUES TO IMPROVE MACHINABILITY

3.1. Overview

The main problems inherent to cutting process result, among other factors, from excessive temperature at the chip-tool interface. The application of large

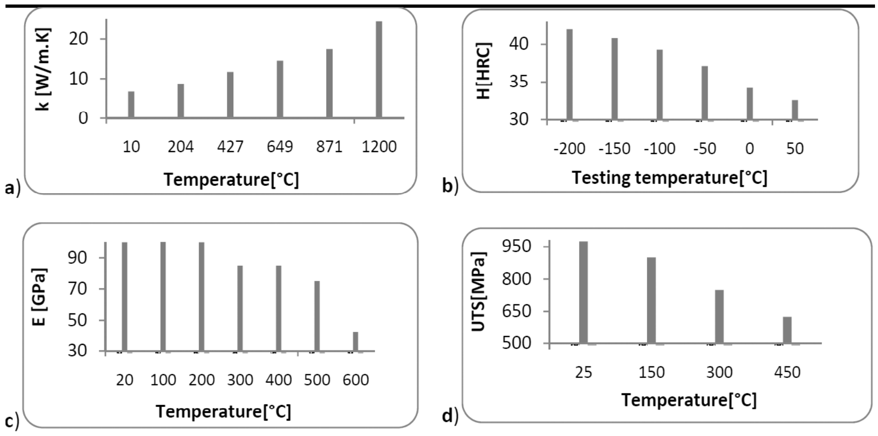


Fig. 1. Influence of temperature on the properties of Ti-6Al-4V alloy. *k* - Thermal conductivity; *H* – hardness; *E* – elastic modulus; *UTS* – ultimate tensile strength, data from [24-26].

Table 3. Summary on the influence of titanium properties on its machinability.

Property	Description	Ref.
Thermal conductivity	Low thermal conductivity causes concentration of heat on the tool cutting edge and face, influencing negatively the tool life.	[16]
Chemical reactivity	Reactivity with common gases such as oxygen, hydrogen and nitrogen leads to formation of oxides, hydrides and nitrides, respectively. These phases cause embritlement and decrease of the fatigue strength of the alloy.	[66,67]
	Surface hardening by formation of hard solid solution due to internal diffusion of oxygen and nitrogen cause decrease of the fatigue strengh of machined surface and increase of tool wear.	[16,67]
	Reactivity with cutting tool material causes galling, smearing and chipping of the workpiece surface and rapid tool wear.	
Elastic modulus	Low elastic modulus allows deflection of slender workpiece under tool pressure, inducing chatter and tolerance problems.	[16,68]
Hardness and strengh	The high temperature strengh and hardness of titanium alloys require high cutting forces which results in deformation on the cutting tool during cutting process.	[21]
	High dynamic shear strengh during cutting process induces abrasive saw-tooth edges, generating tool notching.	
Work hardening	The peculiar work hardening of titanium alloys causes absence of built-up edge in front of the cutting tool and increase of the shearing angle, which in turn induces a thin chip to contact a relatively small area in the cutting face, resulting in high bearing loads per unit area. The high bearing stress, combined with the friction between the chip and bearing area causes a significant heat raises in a very small area of the cutting tool and production of cratering close to the cutting edge, resulting in rapid tool breakdown.However, the formation of built-up edge is referred to be detrimental for tool coating.	[67,69]

amount of cutting fluids reduces the cutting temperature but results in environmental pollution and fluids saving problems. The use of new cutting tools made from advanced materials, and better combination of cutting parameters contributed to a significant but limited development of machining process, particularly in the case of titanium and its alloys. So, especial techniques for improving machinability have been developed and tested by several researchers.

Table 4. Summary on the main techniques employed for cutting process improvement.

Technique	Description	Ref.
Dry cutting	Dry cutting minimizes environmental pollution, health risk for machine operator and thermal shock in interrupted cutting. But the absence of cutting fluids causes more limitation in the cutting speed and may results in high cutting temperature, rapid tool wear, and degradation of workpiece surface integrity.	[70-73]
Dry electrostatic cooling	This technique involves injection of ionized gas with ozone molecular in the cutting zone, which is cheap, ecological, and proved to reduce tool wear and increase tool life.	[74,75]
Flood cooling	With this method the coolant is delivered with a low pressure pump and flooded in general cutting area, which is effective when machining at low cutting speed.	[21,62,76]
Minimum quantity lubrication	This technique is based on directing a little amount of water and soluble oil to the cutting edge, which allows reducing the temperature, surface roughness, and cost. Disadvantage of this technique include health hazard as a result of mist generation. The use of vegetable oils is better than mineral oils in terms of cost, health, safety and environment. The performance can be enhanced by using chip evacuation system. New researches are needed, including optimization of air-oil moisture ratio and coolant pressure.	[21,73,77]
Water vapor	The use of water vapor is not only an economical, environmentally compatible, and health friend lubrication technique for machining, but also reduce cutting force and extend tool life. Water removes heat 2.5 times faster than oil do and is encouraging when mixed with soluble oils because this last provides better lubrication.	[28,64,78]
High pressure coolant	With this technique the cutting fluids is supplied under high pressure and very close to the critical point on the secondary shear zone, which allows high cutting speed, adequate cooling, and excellent chip breakability and removal, but the equipment is expensive. The application of this technique results in segmented chips, lower cutting force, better tool life and acceptable surface finish.	[21,28,61, 76,79]
Cryogenic cooling	Cryogenic cooling is based on directing a cutting fluid, usually liquid nitrogen, under pressure and at low temperature, into the cutting zone, and is an efficient way to maintain the cutting temperature well below the softening temperature of the tool material. This technique increase tool life, don't cause environment pollution, and improve productivity through the use of higher feed rate.The application of cryogenic coolant in metal cutting has received special attention recently as liquid nitrogen is a secure, clean, non-toxic, and easy to disposal coolant that can significantly improve tool life.	[13,21,25, 28,42, 43,80]
Cold-air	Cold-air method use compressed refrigerated gas with small amount of oil, which is directed to the cutting zone. Mixing air with oil gives better performance.	[28,81-83]
Solid lubricants	In the form of dry powder, the graphite and molybdenum disulphide are the most common materials used as solid lubricants. Performance of solid lubricants is better at higher cutting speed. Elimination of environmental pollution and capacity to lower the cutting temperature are encouraging the use of these lubricants.	[28]
Hot machining	This technique consists in pre-heating the workpiece in order to minimize the required cutting forces, improve surface finish and	[84-88]

	increase tool life. Pre-heating methods includes high frequency induction, laser beam, and others.	
Rotary tooling	It is based on the use of round insert rotating around itself, and driven externally or by the cutting force effect. Continuous rotation minimizes the tool wear due to continuous change of specific solicited position on the cutting edge.	[21,38,80, 89-91]
Chip breaker	In this case, chips are broken into smaller pieces by using inserts with chip breaking geometries, or by using other methods such as oscillating CNC toolpaths, etc. Broken chips facilitate its handling and evacuation.	[11,76,92,93]
Ramping	This technique is based on the continuous tool-workpiece shifting in order to change the respective contact length, which results in wear distribution on a larger area and, therefore, preventing notch wear.	[80]

3.2. Techniques

Table 4 provides some descriptions on especial techniques techniques for machining improvement. The majority of them use especial cooling/lubrication methods in order to reduce temperature and friction at the tool-chip interface, while dropping cost and increasing productivity by saving cutting fluids, improving material removal rate, tool life and surface integrity, and reducing environmental pollution.

As stated by Sharma et al. [28], all types of cooling techniques give good results with the majority of tool materials, especially with coated and uncoated carbides, and PCBN, being the vegetable oils proposed by some researchers as good coolant in cutting process. In addition, the referred paper also underlines that the performance of coconut oil as coolant is encouraging at lower cutting speeds, and indicates that the other types of vegetable oil should also be verified for their suitability as coolants in the turning process.

4. MACHINING FORCES

4.1. Overview

The components of resultant force in machining process, especially the main cutting (tangential) force, is one of the main parameters providing information on machinability of materials. The machining force components are influenced by several factors such as cutting speed, feed rate, depth of cut, cutting fluids, tool geometry, and others, besides the properties of the material being machined [29,30]. The forces, in turn, influence cutting temperature, tool wear and life, workpiece surface integrity, machining dynamics, dimension of the machine-tool organs, machining power, and others [31,32]. Therefore, knowledge on magnitude and evolution of machining force components is essential to characterize machinability of materials.

In the real cutting processes, which are generally oblique (3D), the resultant force acting on the cutting tool can be decomposed into three mutually perpendicular components, which in the case of turning process can be named as tangential or main cutting force, axial thrust force, and radial thrust force (depth force). Thrust force can also be referred as feed force when it has the feed direction. Usually, for simplification purpose, researchers assume orthogonal (2D) model in the cutting process modeling. In this case, the cutting edge is perpendicular to the plan defined by the directions of tool feed and cutting edge.

On the other hand, each component of resultant force is a mix of static and cyclic (dynamic) forces, being the cyclic forces characterized by amplitudes and frequencies and may results from chip segmentation [33], among other factors.

4.2. Dynamic forces versus cutting parameters

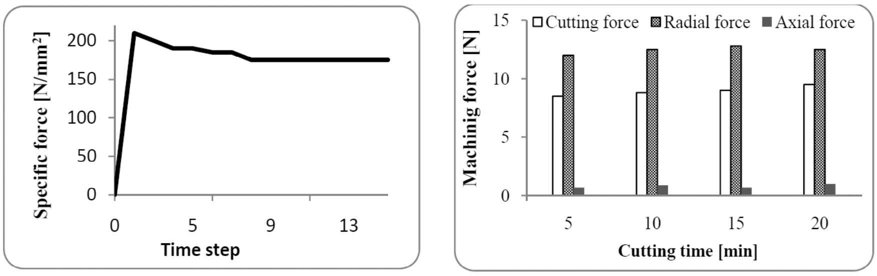
In cutting process, instability is always present in a major or minor extent. According to Kopac et al. [34], the real time variation of uncut chip area and depth of cut, the irregularities of workpiece geometry as a result of early process stages, and the change of feed rate and effective lead angle along the tool path, produce large dynamic force variations. Table 5 summarizes the effect of cutting parameters on dynamic force behavior during cutting process.

4.3. Static forces versus cutting parameters

Fig. 2 provides information on the static force variation with cutting time. This force generally

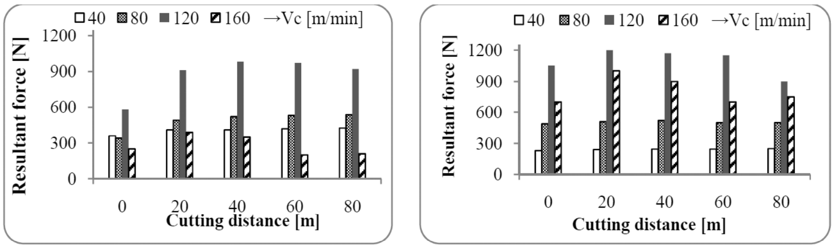
Table 5. Influence of cutting parameters on dynamic force behavior in machining process.

Parameter	Influence	Ref.
Cutting speed	Increasing of cutting speed caused a linear increase of dynamic force frequency, but the respective amplitude changed inversely during dry turning of Ti-6Al-4V alloy.	[33]
	Higher cutting speed resulted in lower dynamic force amplitude, while turning a medium carbon steel with carbide insert. As cutting speed increases, friction is reduced and strain rate increases, which is followed by force decrease leading to a more stable process.	[94]
Feed rate	Both amplitude and frequency increased and decreased randomly with increasing feed rate, while dry turning Ti-6Al-4V alloy. Decrease of cyclic force frequency with increasing feed rate result from the augment of chip segment spacing. For high cutting speed, larger feed rate is necessary to eliminate low-frequency vibration. The force fluctuation at low feed rates resulted from low chip stiffness caused by the combination of low *elastic modulus* of titanium and high cutting temperature, but can be eliminated by increasing the feed rate or changing the tool entry angle.	[33]
	During the first few seconds of the medium carbon steel turning, which is the initial stage of tool wear, the dynamic force signals indicate wider dynamic amplitude for higher feed rate.	[94]
Dept of cut	Results of dry turning of Ti-6Al-4V alloy showed that the amplitude of force fluctuation increased linearly as the depth of cut increases, but no significant change occurred in the frequency.	[33]
	During the turning of Ti-6Al-4V alloy, vibration increased with increasing depth of cut up to 0.8 mm and then decreased. The jump of vibrations for titanium alloy is probably caused by friction phenomenon and low Young's modulus compared to steel. Also, it was described that the proper cutting depth for titanium alloy may be a very small value or a value bigger than some critical one, being this behavior not observed in other compared materials, namely the stainless and construction steels.	[40]
Friction	Experimental results of diamond turning of aluminum single crystals indicated that the periodicity of the fluctuation in cutting forces depends on the frictional condition during cutting, being the proposed model also applicable to polycrystalline materials in which there is a strong crystallographic texture. Cyclic cutting forces are found to include two patterns, one with higher amplitude (major) and other with lower amplitude (minor). As friction increases, the magnitude of the major pattern is found to increase accordingly, while that of the minor pattern appears to be unchanged. The power spectral densities of the cutting force were found to increase as the coefficient of friction increases.	[95]
Tool wear	It seems that the dynamic behavior of different force signals is affected by type, location and configuration of the wear mode.	[94]
Chip	Simulation of high speed dry machining of Ti-6Al-4V alloy showed that the cutting force fluctuation can be caused by chip segmentation. The chip segmentation frequency increased with increasing rake angle but the degree of segmentation becomes weaker and the amplitude of cutting force fluctuation decreased.	[96]
Microstructure	The experimental results concerning the diamond face turning of aluminum single crystal indicated that the periodicity of the fluctuation in cutting forces depends on the crystallographic orientation of materials being cut.	[95]
Machine	Random frequency components with a low power spectral density can be caused by the spray of coolant and fine vibration of the machine.	[95]



a) b)

Fig. 2. Machining forces versus cutting time: a) typical evolution profile obtained from turning simulation of Ti-6Al-4V alloy, replotted from [35]; b) Evolution of steady state (average) values during dry turning of CP-Ti with PCD insert at cutting speed of 60 m/min and rake angle of 5°, replotted from [52].



a) Tool: WC (6% Co, 94% balance)

b) Tool: WC-Co (6% Co, 4.5-4.9% TiC + TaC, WC)

Fig. 3. Machining force versus cutting distance, for different cutting speed, during the turning process of Ti-6Al-4V alloy with two cemented carbide tools, data from [39].

increases linearly from zero to a peak value, then decreases and finally approaches gradually to a steady value (Fig. 2a). This steady state value is the average force usually measured in the cutting tests [35,36]. According to Fig. 2b, the force components tend to increase with cutting time, although not very pronounced. Other aspect is that the cutting component is lower than the axial and radial components, which is not the common occurrence.

Results of other authors [37], concerning the turning of an $\alpha+\beta$ alloy, show a decrease of cutting force as the cutting progresses, and finally increase with increasing cutting time, being the decrease attributed to the occurrence of geometric adaptation of the cutting edge with the workpiece surface after the phase of run-in wear of the cutting edge. According to the authors, the time for occurrence of increase of cutting force can be considered as a criterion for tool life. Results of Lei and Liu [38] obtained from high speed turning of Ti-6Al-4V alloy with rotary tool (round-shaped uncoated tungsten carbide insert) demonstrate that all three machining force components increased with cutting time, being this growth attributed to the tool wear.

Considering the results presented in the Figs. 3a and 3b, the resultant forces, for any cutting speed, tend generally to increase initially and then decrease with increasing cutting distance, for both the cutting tools. Wang et al. [39] explained that these increase are caused by tool wear, while the decrease result from reduction in depth of cut due to severe tool wear.

The depth of cut, feed rate and rake angle influence the machining force evolution (Fig. 4). Both cutting and thrust forces increase with increasing depth of cut (Fig. 4a). Results of Rusinek [40] obtained from turning of the Ti-6Al-4V alloy show similar trends, being the forces (in MPa) changed from about 100 to 820 (feed force), 250 to 1000 (thrust force), and 280 to 1420 (cutting force), when the depth of cut increased from 0.4 mm to 3.0 mm.

The increase of feed rate also results in increasing machining force components, but seems to have much less influence than the depth of cut (Fig. 4b). Results of Ozel et al. [36] and Barry et al. [29], also regarding the turning process of Ti-6Al-4V alloy, present similar trends in terms of force evolution with increasing feed rate. However, the increase of rake angle results in decrease of the cutting forces (Fig. 4c).

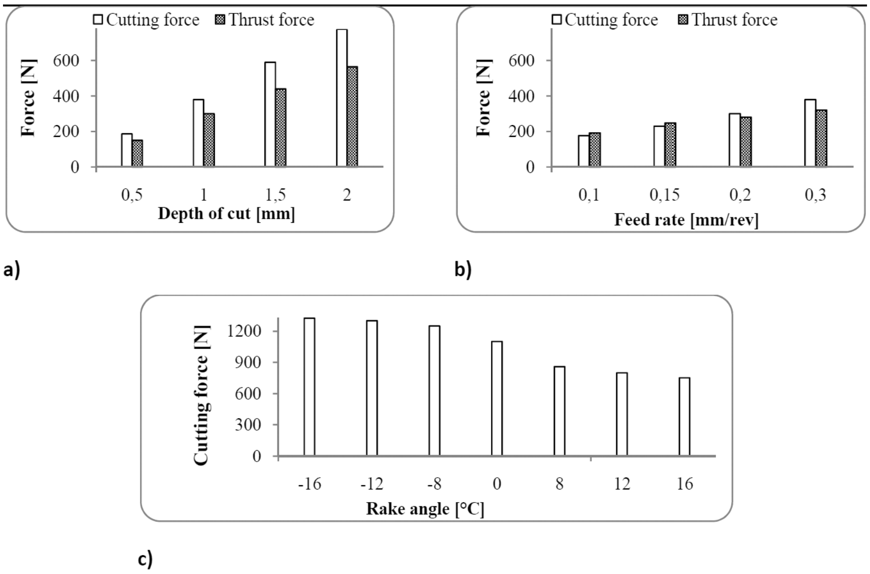


Fig. 4. Machining forces versus depth of cut (a) [64] and feed rate (b) [64] during orthogonal dry turning of Ti-6Al-4V alloy with uncoated carbide insert (ISO K10), feed = 0.2 mm/rev, speed = 50 m/min, and versus rake angle (c) [35], obtained from simulation of orthogonal turning of Ti-6Al-4V with cemented carbide, cutting speed = 300 m/min, and feed rate = 0.3 mm/rev.

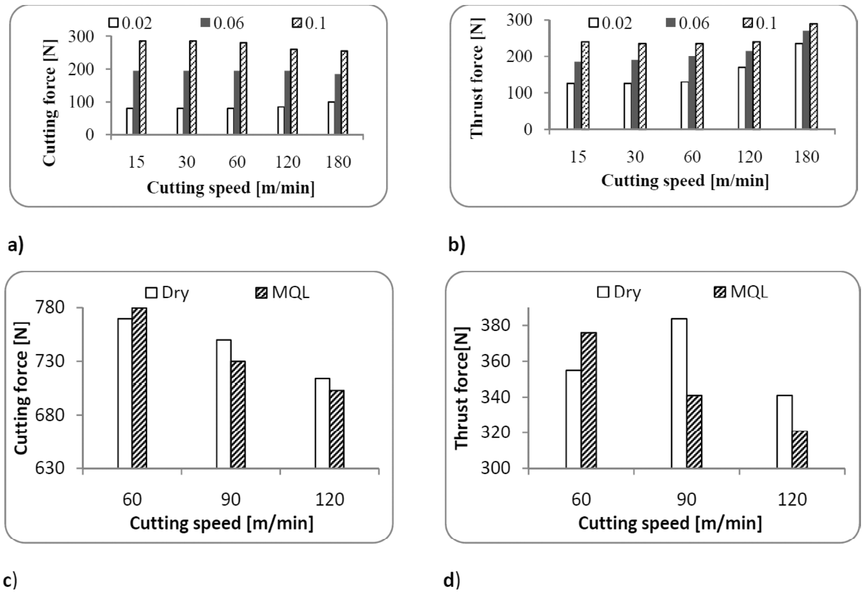
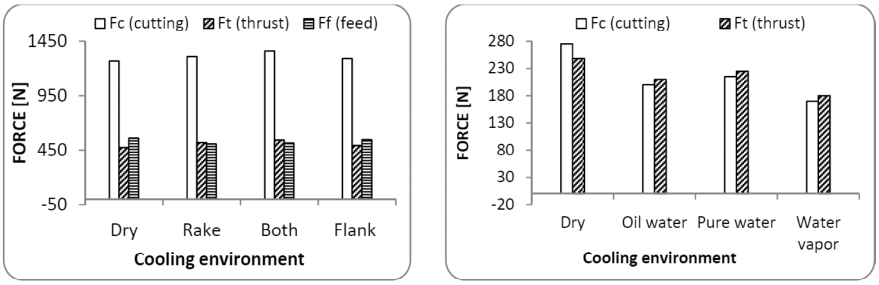


Fig. 5. Influence of cutting speed on cutting force (a, c) and thrust force (b, d) during the turning process of Ti-6Al-4V alloy, for various feed rates (0.02, 0.06 and 0.1 mm/rev) and cutting environments: (a, b) with uncoated P10/P20 carbide tool, depth of cut = 1.1 mm, rake angle = -6°; (c, d) with uncoated carbide insert. Dry – Dry cutting; MQL – Minimum Quantity Lubrication [29,41].

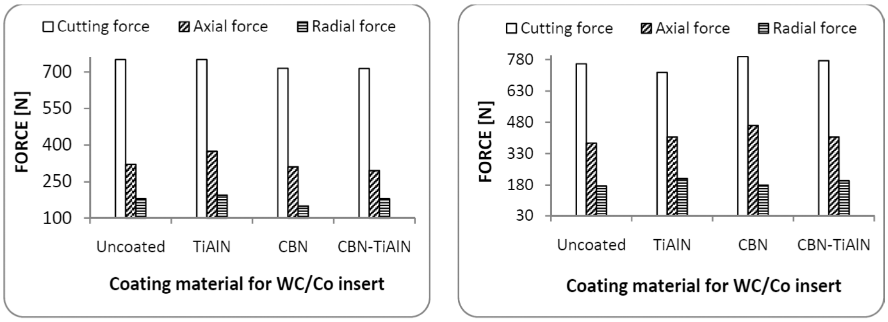
Cutting speed can have little (Figs. 5a and 5b) [29] or great (Fig. 5c and 5d) [41] influence on the evolution of machining force components, according to the results of several authors [29, 41]. As the cutting speed increases, the cutting force tends to growth smoothly, showing the thrust force opposite behavior, but these evolutions are not significantly affected by feed rate (Figs. 5a and 5b). Other results (Figs. 5b and 5c) show that the machining forces decrease significantly with increasing cutting speed, both in dry machining or with application of minimum lubrication (MQL), except for thrust force in dry cutting process, which first increases and then decreases (Fig. 5d).

The comparison between dry and cryogenic cutting (Fig. 6a) demonstrates that the later process does not affect significantly the machining force components, either using the rake nozzle (Rake),



a) b)

Fig. 6. Influence of cooling fluids on machining force during turning process of Ti-6Al-4V alloy: a) oblique cutting with uncoated insert (equivalent to ISO K05-K20), cutting speed = 90 m/min, depth of cut = 1.27 mm, feed rate = 0.254 mm/rev; fluid = liquid nitrogen; rake flow = 0.625 l/min, flank flow = 0.53 l/min, rake and flank flow = 0.814 l/min [30]; b) orthogonal cutting with uncoated carbide insert (ISO K10), feed= 0.1 mm/rev, depth of cut = 1 mm, speed = 50 m/min, data from [64].



a) b)

Fig. 7. Influence of insert coating on machining force during longitudinal turning of Ti-6Al-4V alloy with tungsten carbide tool, feed = 0.1 mm/rev, depth of cut = 2 mm, and: a) cutting speed = 50 m/min, b) cutting speed = 100 m/min, data from [36].

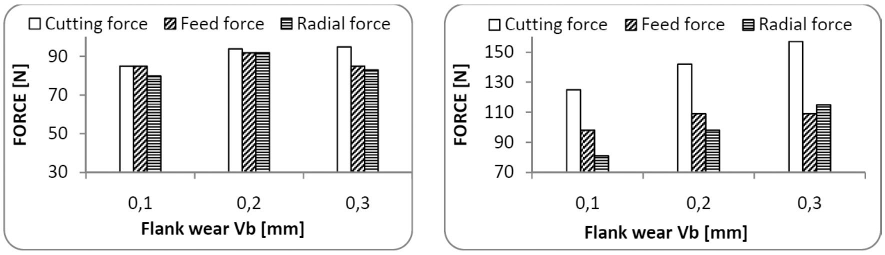
flank nozzle (Flank) or nozzles in both locations (Both), but the feed force decreased slightly for all cryogenic cooling options. According to Hong et al. [30], the feed force (in MPa) reduced from 560 in dry cutting to 507 (Rake), 547 (Flank), and 516 (Both). On the other hands, the cutting force tends to increase from dry to cryogenic cutting and this behavior was attributed by the authors to the hardening of work material under cryogenic temperature. However, the lower temperature makes the material less sticky, reducing the frictional force inherent in the cutting process [30].

Unlike the one found by Hong et al., the results of Bermingham et al. [42] showed that, in turning of Ti-6Al-4V alloy, the main cutting force decreased with the application of cryogenic coolant, due to lubrication on the flank face, but the thrust force increased, while no significant change in feed force was observed. Also it was observed that the friction coefficient in the rake face/chip interface did not reduce and, in some cases, increased with the use of cryogenic coolant.

Also, Sun et al. [43] compared the machining forces obtained during dry and compressed air turning of Ti–6Al–4V alloy, and the results indicate that, at start of cutting, the forces in dry condition are smaller than those in compressed air and in cryogenic compressed air cooling, but increase rapidly during machining and reaches the highest values for long cutting lengths of 31 m at a cutting speed of 200 m/min. In addition, the effect of cryogenic compressed air on the cutting force diminishes with the increase of cutting speed and feed rate.

Results of application of oil water, pure water and water vapor as cutting fluids (Fig. 6b) demonstrate that the later fluid is more effective in reduction of both cutting and thrust forces.

Wang et al. [41] concluded that, in continuous turning process, the dry cutting is successful only at lower cutting speed and feed rate, the minimum quantity lubrication (MQL) and flood cooling have similar cooling and lubrication ability, but at higher cutting speed and high feed rate, MQL seems to be more effective than flood cooling as a result of its



a) b)

Fig. 8. Evolution of cutting forces with flank wear during dry turning process of Ti-6Al-4V alloy with cubic boron nitride (CBN), cutting speed = 180 m/min, depth of cut = 0.5 mm, and [65]: a) feed rate 0.05 = mm/rev, b) feed rate 0.25 mm/rev.

better lubrication ability. These authors also concluded that, in interrupted cutting, the MQL is more effective than both dry and flood cooling cutting.

According to the results provided in the Fig. 7, the tool materials affect the machining force components only moderately. For cutting speed of 50 m/min, the cutting inserts coated with cBN and cBN + TiAlN conducted to slightly lower cutting forces (Fig. 7a), but these coatings resulted in slightly higher cutting forces at 100 m/min cutting speed (Fig. 7b). In addition, the highest thrust force occurred for cBN coating at higher cutting speed (Fig. 7b). Özel et al. [36] argue that the deposition of coatings (cBN and TiAlN) results in larger tool edge radius, which in turn causes force increase at higher cutting speed, because in this condition the effect of larger edge radius become the dominant mechanism on force. So, these authors claim that the reduction of cutting edge radius by modifying the edge preparation of inserts coated with cBN or TiAlN may be beneficial.

The plotted results provided in Fig. 8 illustrate the influence of flank wear on the evolution of machining force magnitude, for two different feed rates. For a feed rate of 0.05 mm/rev (Fig. 8a), the force components tend to increase and then decrease with increasing flank wear, except for the cutting force which did not decreased. For higher feed rate of 0.25 mm/rev (Fig. 8b) all forces always increased with increasing flank wear.

On the other hand, Lei and Liu [38] showed that the components of machining force may increase with cutting time and attributed this increase to the tool wear as well stated that the increase in tool wear results in more contact area between the workpiece and the tool, principally in the plane normal to the thrust force component. Because of that, this force grows faster and surpasses the cutting force at a certain time. As mentioned before, other authors [39] found that the resultant machining force increases initially with increasing cutting distance due to tool wear, and then decreases as a result of reduction in depth of cut due to severe tool wear.

The discrepancies observed in the influence of tool wear on cutting forces can be due to differences in cutting conditions such as geometry or material of the cutting tool.

In a study of turning a cylindrical bars made from Ti-6Al-4V and the new developped Ti54M alloy with uncoated carbide tool inserts and conventional cooling, higher specific cutting and feed force values were found for Ti-6Al-4V alloy [44].

Experimental results on orthogonal turning of Ti–6Al–4V alloy, performed by Wyen and Wegener [45], showed that the variation of feed forces is more sensitive than cutting forces to a change in cutting edge radius. These authors also found that the plugging forces can significantly contribute to the total forces in a cutting process. In addition, the experimental data indicates that plugging forces exist even for ideal sharp tools, the coefficient of friction is influenced by both cutting edge radius and cutting speed, and the influence of cutting speed on feed force is non-linear and depends on the cutting edge radius.

Result of FEM modeling and simulation of dry cutting Ti–6Al–4V alloy shows that when friction coefficient increases from 0.3 to 1, the highest temperature migrates from the tool tip to the end of rake face/chip interface, which leads to a decrease of the feed force, but without affecting the amplitude of cutting force [46].

5. CHIP FORMATION

5.1. Overview

The cutting processes usually lead to the production of large amount of chips that must be handled efficiently. In addition, chip formation affects machining forces, cutting temperature, tool life, and workpiece surface integrity. Therefore, it is important to understand the cutting conditions that result in chips that are easy to handle and minimize the negative effects on the cutting tool and workpiece surface. The formation of adiabatic shear bands is the most studied feature when analyzing the chip development during cutting of titanium alloys [44].

5.2. Chip morphology and formation mechanism

Chip morphology can be analyzed by cross-sectioning, polishing, etching with solution of 4% nitric acid in ethyl alcohol, and observation under a microscope SEM [32]. Chip morphology can also be predicted by modeling and simulation process, although the predictions are not always accurate. For example, according to the conclusions of Calamaz et al. [47], in a study where they used a cutting speed of 60 m/min and feed rate of 0.1 mm/rev for turning the Ti-6Al-4V alloy, the chips obtained from simulation were continuous while in the real cutting process the chips were segmented.

Chip morphology may be divided basically into continuous and discontinuous. Continuous chips, also named ‘uniform shear chips’ [29] or ‘flow chips’ [32] are those that does not break apart but continues to curl around itself during machining. Ductile metals tend to create continuous chips. Continuous chips are desirable for good surface finish but may result in handling and evacuation problems [48].

Regarding the discontinuous chips, different words have also been used in its designation, especially ‘saw-tooth chip’, ‘serrated chip’ [49] and ‘segmented chip’ [50, 51]. Daymi et al. [32] define segmented chips as continuous chips in which the shear zones appear aperiodically and the chip thickness varies with time.

Segmented chips present intense shear bands dividing itself into segments [35], so can easily break apart from the workpiece into separate pieces, consequently sample to eliminate, ideal for automated cutting operations [35] and, according to Bayoumi and Xie [50], suitable for good workpiece surface integrity, which seems not to agree with Groover et al. [48] who underline that the continuous chips are desirable for good surface finish. Chip segmentation by shear localization is an important process observed in a certain range of cutting speeds, being this phenomenon desirable in reducing the cutting forces level as a result of chip evacuation improvement, according to Daymi [32] and Bayoumi [50]. Prediction of cutting conditions that leads to serrated chips is very helpful in the context of increasing the production rate and decreasing the machining cost [50]. However, Sun et al. [33] referred that discontinuous chips cause cyclic forces and tool vibrations. Segmented chips are commonly observed when cutting titanium and its alloys because these materials have low thermal conductivity [52].

However, the mechanism of chip formation is still not completely understood, although shear instability and crack initiation and growth are the two main theories supporting this phenomenon [49]. In the case of machining titanium alloys, the mechanism is generally accepted to be based on thermo-plastic instability (also called adiabatic shear) within the primary shear zone, which occurs when the rate of thermal softening exceeds the rate of strain hardening [29]. In these alloys, the metallurgical transformation of α-phase (hexagonal close package) to β-phase (cubic body centered) during cutting process is also considered to foment the adiabatic shear because this last structure presents larger number of slip systems [29]. At low cutting speeds, initiation and propagation of crack is a mechanism of chip formation supported by some authors. The crack may start from the tool tip and propagates to the free surface of workpiece, or start from free surface and propagate toward the tool tip [53,54].

5.3. Evolution of chip morphology

Chip morphology may change greatly with the cutting parameters. For example, there is a critical cutting speed for which the chip changes from continuous to a segmented. Komanduri et al. [55] predicted the critical cutting speed for shear localization in cutting Ti-6Al-4V alloy and found a value of 9 m/min. In addition, serrated chips can change from aperiodic to periodic with increasing cutting speed and/or feed rate (undeformed chip thickness) [29].

Orthogonal turning of Ti-6Al-4V alloy showed that, in the range of cutting speeds between 0.01 and 21 m/s, the chip is serrated but remains continuous, and the segments is attached to each other, but for cutting speeds greater than 21 m/s the chip is discontinuous and fragmented in small pieces [56]. In machining of pure Ti, no serrated chip was produced, and the authors speculated that the continuous chips observed can be attributed to the lower cutting temperature that occurred from using a small depth of cut, feed, and cutting speed [52]. Barry et al. [29] also predicted that if the values of depth of cut are small enough (in the order of

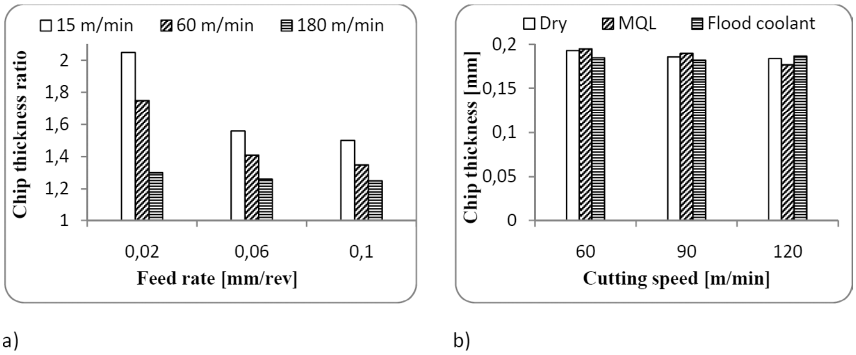


Fig. 9. Influence of cutting parameters on chip evolution: chip thickness ratio versus feed rate and cutting speed (a) [29]; chip thickness versus cutting speed and cutting fluids (b) [41].

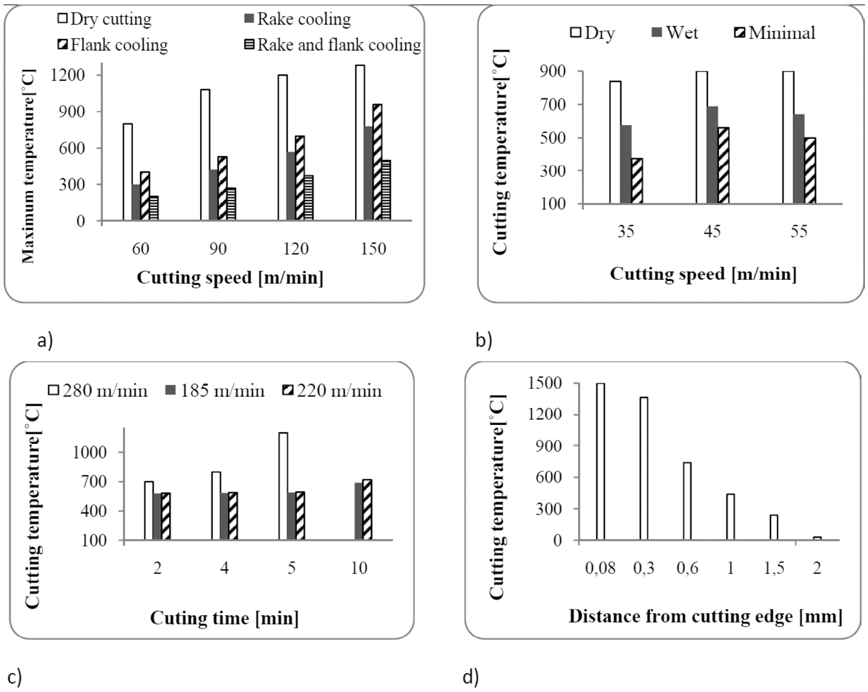


Fig. 10. Evolution of cutting temperature during turning process of Ti-6Al-4V alloy [28, 37, 62, 63].

microns), then continuous chips can be formed in machining Ti-6Al-4V alloy.

According to Bayoumi et al. [50], there is a critical value of chip load at which shear banding is observed, and the frequency of its formation increases with an increase in feed rate and/or a decrease in cutting speed. These authors also underline that there are different critical cutting conditions necessary to form serrated chips, which for Ti-6Al-4Valloy is a chip load of 0.004, and that different materials have different strain-hardening capacities and, consequently, need different cutting conditions for thermal softening exceed this capacity.

Finite element simulation carried out by Xie et al., regarding the turning of Ti-6Al-4V alloy, show that the shear banding angle increase with increasing rake angle, changing from 36° to 55° in the practical rake angle variation from -16° to 20° [35].

On the other hand, results of Molinari et al. [56] obtained from machining Ti-6Al-4V alloy show that the shear band width decreases with increasing cutting speed, the frequency of chip segmentation increases with increasing cutting speed, and the distance between adiabatic shear band decreases with increasing cutting speed.

Turning process of Ti-6Al-4V alloy with cryogenic coolant produced longer serrated chips than those produced in dry turning, as a result of shorter tool–chip contact in first case, meaning that a chip is formed with a smaller curving radius, which may prevent the chip from fracturing on the chip breaker [42]. In addition, the increase of feed rate and decrease of depth of cut resulted in thicker chips, greater distance between serrations and smaller shear band angle.

According to other study, the tendency to form a segmented chip is higher in cryogenic compressed air cutting than in compressed air and in dry cutting, but only within the ranges of speed and feed that cause chip transitions from continuous to segmented [43]. Moreover, the effect of cryogenic compressed air on the chip formation diminishes with increase in cutting speed and feed rate.

Fig. 9 displays graphically the evolution of chip thickness with cutting parameters. The thickness ratio decreases significantly with increasing feed rate and with increasing cutting speed, and its dependence on the cutting speed decreases with increasing feed rate (Fig. 9a). However, with regard to thickness, the influences of cutting speed and cutting environment seem to be negligible (Fig. 9b).

Another feature of the machining of Ti-6Al-4V alloy is the occurrence of welding between the chips and the cutting tool, which increase with increasing cutting speed, being the fracture of the weld considered to be the dominant cause of acoustic emission [29]. The application of high-pressure water jet improves chip breaking and removal and practically no adhesion between the chip and tool occurs [57].

6. CUTTING TEMPERATURE

6.1. Overview

In machining process, the cutting energy is mostly transformed into heat and eliminated through the chips but some of this energy increases the temperature of the tool and workpiece. High cutting temperature, which can easily reach 1000 °C for Ti-6Al-4V alloy [25], results from high cutting force and/or low thermal conductivity of the workpiece material, as is the case of titanium. High cutting temperature decreases tool life, degrades workpiece surface integrity, and can also results in low cutting accuracy due to thermal expansion of the tool and workpiece [58,59]. High chemical reactivity of titanium at elevated temperature intensifies the referred problems. Therefore, low cutting temperature is essential for better machinability.

The main source of energy that is converted into heat is the plastic deformation at shear zone, friction in the interfaces tool/chip and tool/workpiece. During the cutting process, high temperatures are generated near the tool cutting edge, and these temperatures affect greatly the tool wear rate. These temperatures, whose maximum value occurs along the tool rake face at some distance from the cutting edge [28], can be estimated from measure of the thermal electromotive force of tool-workpiece thermocouple during cutting process [58].

Different coolants and techniques have been used in cutting process. Common cutting fluids may be divided into three main categories such as neat cutting oils, water-soluble fluids and gases. Other authors [13] provide description details on these fluids. On the other hand, the main cooling-lubrication techniques includes Emulsion flood cooling [25], Minimum quantity lubrication [28], Cryogenic cooling [25], Compressed air and vapor jets [28,60], High pressure coolant [61], Solid coolants and lubricants [28], and Allied cooling [28].

Currently, the relatively soft materials are dry machined but after increasing success of minimum quantity lubrication application in hard materials, such as titanium alloys, there is a tendency for using air jet assisted cutting and dry cutting for these materials [60].

6.2. Evolution of cutting temperature

Fig. 10 provides information on evolution of the cutting temperature during cutting process. For all cutting environments (Fig. 10a) [62], significant increase in cutting temperature occurred (about 300 to 500 °C) when cutting speed is varied from 60 to 150 m/min. This Figure also shows that the rake cooling is better than flank cooling, but simultaneous cooling in both locations is the most effective. Increase of cutting speed from 35 to 55 m/min (Fig. 10b) [28] causes little influence on the evolution of cutting temperature, which suggests that in this range of cutting speed occurred a certain balance between the amount of heat generated by cutting process and the heat extracted from the cutting zone. It seems that the wet and minimum lubrication/cooling techniques are very effective in the friction reduction and/or heat extraction because significant reduction in the cutting temperature occurred, according to the data of Fig. 10b.

No considerable change in the cutting temperature is observed in cutting during 2 to 10 min, according to the Fig. 10c [37], except for cutting speed of 280 m/min for which a significant increase was observed after 5 min of cutting. This behavior suggests that at cutting speed of 280 m/min the rate of heat generation is too high, so not possible to be balanced by the rate of heat extraction. Cutting temperature varies greatly with the distance from the cutting edge, as shown in the Fig. 10d [63]. The decrease of the rate of heat generation with increasing distance from the cutting edge seems to be the main reason for this behavior.

7. CONCLUSIONS

Generally it is accepted that the titanium properties, including high strength at elevated temperature, low elastic modulus, high chemical reactivity and low thermal conductivity influence negatively the machinability of titanium-based materials, and the latter two seem to be the most degrading factors. However, very little or no studies exists on quantification of these influences. For example, there is a need of study on relationship between the cutting parameters, the induced workpiece deflexion and chatter, and the dynamic cutting forces generated. Also, there is a lack of research on quantification of chemical reactivity between titanium and tool material, and on the relationship between cutting parameters and workpiece hardening. Most of the investigations carried out on the machinability of titanium alloys were based on different cutting conditions, which make it difficult to compare results from different authors.

Built-up edge

Some authors consider the absence of built-up edge during cutting titanium alloy undesirable because it results in rapid tool breakdown, but others defend that the presence of built-up edge is detrimental for example for tool coating. Thus, more research is needed to clarify this point.

Cutting techniques

Several techniques for improving the machinability have been studied by worldwide researchers and the published reports show that the majority of them present considerable improvements in the cutting process, but there is a lack of work that compare these techniques and determine the conditions under which each of them is most advantageous. In general, there is a trend to use environment-friendly fluids, including water vapor, air and other gases in order to improve the machinability and ensure green cutting.

Cutting forces

The results provided by authors regarding the evolution of machining force components with cutting variables and environments seems not to agree in some cases, probably due to differences in the cutting conditions, thus more studies need to be carried out in order to get clarification. For example, some results show that the application of cryogenic cooling causes increase of the cutting force due to hardening of work material under low temperature, while others indicate that the cutting force decreases due to the lubricating effect.

Chip formation

Though the mechanism of chip formation is not yet well understood, for titanium alloys is generally accepted that it is based on thermo-plastic instability and the adiabatic shear banding seems to be the most studied feature. Concerning the effect of the type of chip on surface finish of machined pieces, no agreement was reached yet. Some authors admit that the continuous chip is favorable to good surface finish as opposed to others that consider segmented chip desirable for better surface integrity, so much more studies need to be performed in this field.

Cutting temperature

Cutting temperature is mainly influenced by the cutting speed, but its influence is not linear. Significant increase in the cutting temperature may occur during the machining of titanium alloys if no cooling technique is used, but at the start of cutting the cooling fluids may have negligible influence. For some cutting speed ranges, which depends on the cutting conditions, the increase of cutting speed results in great increase of cutting temperature, probably as a result of too much heat generation rate that cannot be balanced by the rate of heat extraction from the cutting zone. It seems there is a lack of studies on the relationship between the cutting conditions, rate of heat generation and extraction, and evolution of cutting temperature.

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