Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia CIRP 1 (2012) 202 – 207

www.elsevier.com/locate/procedia

5th CIRP Conference on High Performance Cutting 2012

Machining behaviour of Ti-6Al-4V and Ti-5553 alloys in interrupted cutting with PVD coated cemented carbide

Asier Ugarte[a, b], Rachid M'Saoubi[a]*, Ainhara Garay [b], P.J. Arrazola[b]

[a]R&D Materials and Technology DevelopmentProcesses, Seco Tools AB, Fagersta, SE-73782, Sweden
[b]Manufacturing Department, Faculty of Engineering, Mondragon University, Mondragon, Spain
* Corresponding author. Tel.: +46 22340668; fax: +46 22371860.E-mail address: rachid.msaoubi@secotools.com.

Abstract

Machining behaviour of Ti-5553, Ti-6Al-4V mill-annealed (MA) and Ti-6Al-4V solution treated and aged (STA) alloys was studied in different interrupted cutting operations using PVD coated cemented carbide tools. Single tooth face milling was employed to study the wear behaviour and tool life of the coated tools that were further inspected using scanning electron microscopy. The results indicated that a poor machinability was observed for Ti-5553 when compared to Ti-6Al-4V (STA) and Ti-6Al-4V (MA). This was found to correlate reasonably well with an increase of work material adhesion severity on the cutting tool that resulted in an increased chipping and led to catastrophic tool failure. Series of orthogonal interrupted cutting tests were performed subsequently to investigate the role of work material and cutting data on the chip formation, mechanical loads and frictional conditions at the tool-chip contact. A detailed analysis of the chip segmentation characteristics of the different Ti alloys is provided and the results are employed in different analytical models to assess the shear strain, strain rate and segmentation frequency. Finally, a comparison of Ti-5553 and Ti-6-4 (MA) in interrupted turning is presented where the differences in terms of cutting temperature are discussed.

Keywords: Machining; Interrupted cutting, Titanium alloys; Ti-6Al-4V; Ti-5553.

1. Introduction

Titanium alloys such as Ti-6Al-4V are generally regarded as difficult to machine materials because of inherent properties such as (i) low thermal conductivity giving rise to high temperatures at the tool-chip and tool-work interfaces, (ii) the development of plastic instability and the formation of adiabatic shear bands [1] causing high dynamic loads and tool vibration [2], (iii) a high chemical reactivity with many cutting tool materials causing rapid chemical wear by diffusion [3-5].

The cutting temperatures when machining titanium alloys are considerably higher than for carbon steel [6] and these are concentrated in a small are near the tool edge due to the shorter contact length causing higher stresses and premature tool failure. Such characteristic behaviour of titanium alloys makes them also more sensitive to changes in tool micro-geometry that is likely to affect the frictional conditions at the tool-chip interface [7].

The development of new near β Titanium alloys such as Ti-5553, displaying a high strength and fracture toughness makes them very attractive for advanced structural and landing gear applications in aircrafts. However its superior properties makes this material more difficult to machine than Ti-6Al-4V as reported in a recent machinability study in turning [8].

The development of adequate tooling and machining strategies for such alloys requires a good understanding of the thermal, mechanical and microstructural aspects involved in the chip formation process. Hence, the motive of the present investigation is a contribution in this direction where, accordingly, the cutting characteristics of Ti-5553 are compared to those of Ti-6Al-4V alloys in different interrupted cutting operations using PVD coated cemented carbide tools. In particular, the role of work material and

 http://dx.doi.org/10.1016/j.procir.2012.04.035

cutting data on the chip formation, thermo-mechanical loads and frictional conditions at the tool-chip contact are investigated.

2. Experimental

The work materials used in the metal cutting tests were Ti-6Al-4V (Ti 6-4) and Ti-5Al-5V-5Mo-3Cr (Ti-5553) alloys and were provided in the form of plates with different treatments, respectively Mill Annealed (Ti 6-4 MA), Solution Treated and Aged (Ti 6-4 STA and Ti-5553). The mechanical properties and hardness of the work materials are listed in Table 1. The cutting tools consisted of PVD coated (TiAlN-TiN) cemented carbide inserts (ISO TPUN160308 Seco grade F40M, edge radius 15 mm, rake angle 0°) and the milling cutter was R220.17-0040-16 (40 mm diameter).

Material	$Rp_{0.2}$ (MPa)	R_m (MPa)	Elongation (%)	Hardness $Hv_{0.1}$
Ti 6-4 MA	931	1014	14	351
Ti 6-4 STA	1055	1145	15	370
Ti-5553	1170	1290	6	417

Table 1. Mechanical properties and hardness of the titanium alloys.

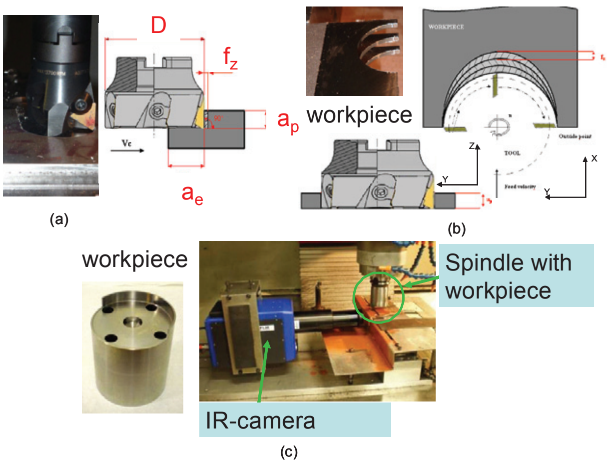

Fig. 1. Schematics of the different machining tests- (a) single tooth face milling- (b) orthogonal milling- (c) interrupted cutting.

Fig. 1 details the schematics of the different set-ups for the metal cutting experiments and the corresponding cutting data is listed in Table 2.

The single tooth face milling and orthogonal milling tests were carried out on a MORI SEIKI SV-500 CNC vertical milling machine equipped with a rotating Kistler dynamometer for force measurement. Additionally, interrupted cutting and Infrared temperature measurement were performed on cylindrical workpiece specimens using a CNC LAGUN milling machine using a FLIR Thermal Imaging system (InSb detector 320 x 256, bandwidth 3.97- 4.01 µm, spatial resolution: 10 µm). The temperature measurements were restricted to Ti-6-4 MA and Ti-5553 only since these were both available in the form of bars specimens.

Tool wear during single tooth face milling was measured at regular time intervals using a standard toolmaker microscope. The wear tests were stopped when tool life criterion was reached, either flank wear VB=0.3 mm or severe edge chipping and tool fracture. The inserts were further examined in the scanning electron microscope (SEM). Cutting forces and chips were collected during the orthogonal milling experiments.

Operation	Material	vc (m/min)	fz (mm/tooth)
Face Milling	Ti 6-4 MA	40-70-100	0.15
	Ti 6-4 STA	40-70-100	0.15
	Ti-5553	25; 40	0.15
Orthogonal Milling	Ti 6-4 MA	40-70-100	0.1-0.15-0.2
	Ti 6-4 STA	40-70-100	0.1-0.15-0.2
	Ti-5553	25; 40	0.15
Interrupted Cutting	Ti 6-4 MA	40-70	0.15
	Ti-5553	25; 40	0.15

Table 2. Cutting data used in the different machining experiments.

3. Results and discussion

3.1. Tool wear tests

Fig. 1 displays the tool wear curves obtained for the different work materials during the single tooth face milling operation. At vc= 40 m/min, a regular increase of flank wear with cutting time is observed for both Ti 6-4 variants (MA, STA) reaching a tool life of 30 and 26 minutes respectively. The machinability of Ti-5553 at the same cutting speed was extremely poor as the cutting tool suffered catastrophic failure after only 2 minutes. In the latter, a reduction of cutting speed to vc=25 min resulted in a more regular increase of flank wear with cutting time where a tool life of 13 min could be achieved.

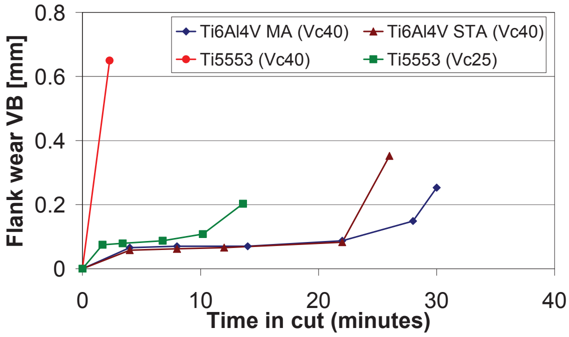

Fig. 2. Tool wear curves obtained from the face milling tests (vc=40m/min, fz=0.15 mm/tooth, ap=2 mm).

A closer examination of the tool wear scars in SEM (Figs. 3-5) reveals the presence of and adhesive layer of the work material on the tool surface already after a short cutting time (1 min.). The adhesion severity seems to be more pronounced for Ti-5553 than for the other Ti 6-4 alloys. An EDS analysis of the adhesive layers (Fig.6) reveals the presence of chemical elements typical from the work material (Ti, Al, V) an also the presence of small carbon peak suggesting that a Titanium carbide layer has most likely formed on the cutting tool in the regions where the PVD coating was removed and Cemented carbide was substrate exposed. The formation of TiC layer on WC-Co cemented carbide has also been reported in previous studies [4, 9]. The severe adhesive wear mechanisms involved in cutting of the Ti alloys is responsible for the fracture of the edge resulting from carbide pull out.

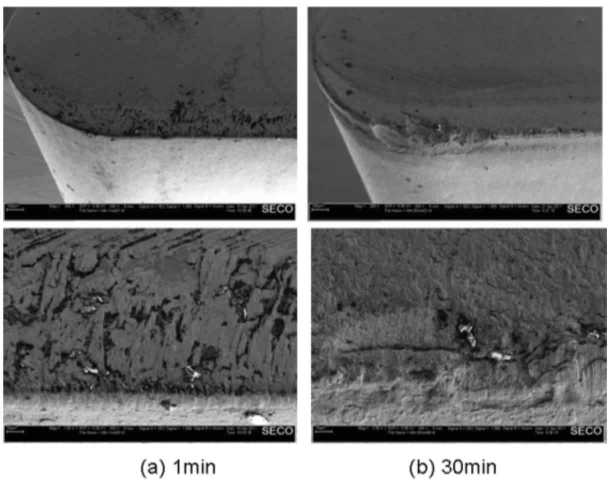

Fig. 3. SEM view of the worn insert after milling Ti 6-4 MA (vc=40m/min, fz=0.15 mm/tooth, ap=2 mm)

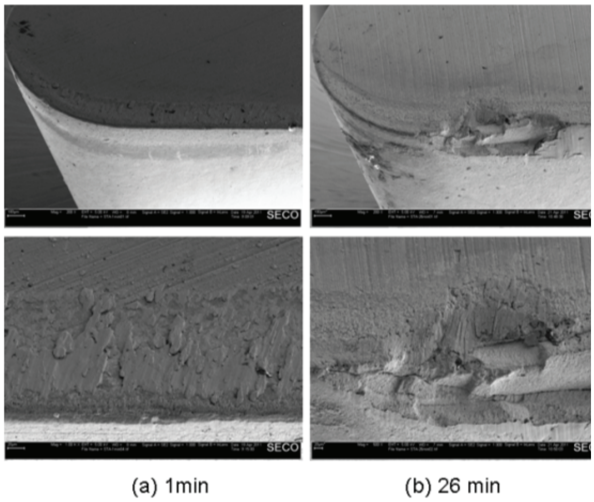

Fig. 4. SEM view of the worn insert after milling Ti 6-4 STA (vc=40m/min, fz=0.15 mm/tooth, ap=2 mm)

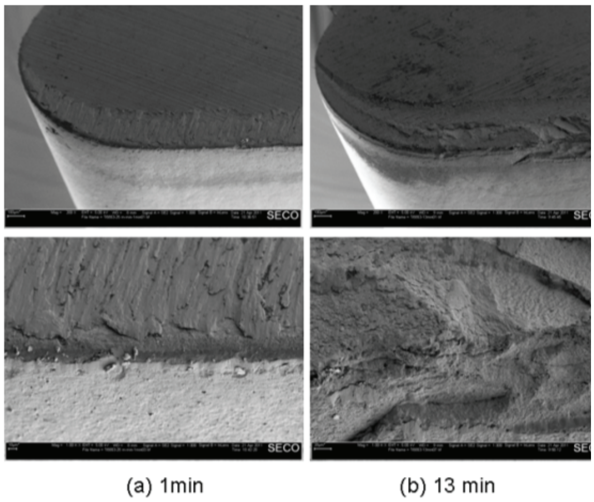

Fig. 5. SEM view of the worn insert after milling Ti-5553 (vc=25m/min, fz=0.15 mm/tooth, ap=2 mm)

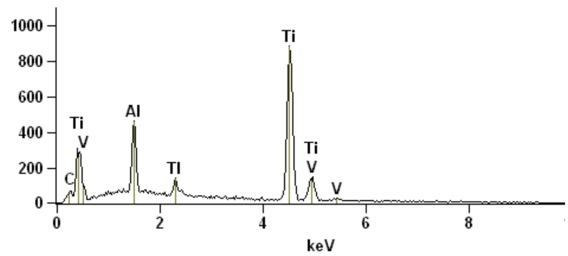

Fig. 6. EDS analysis of the rake surface showing evidence of work material adhesion (Material Ti-5553)

3.2. Cutting forces

Fig. 7 shows the cutting forces (tangential Ft and radial Fr components) obtained during the orthogonal milling experiments where one milling cycle characteristic from the force signal was extracted. The results indicate that Ti-5553 produces the highest cutting forces. In the case of Ti 6-4 alloys, MA and STA treatments seem to have a marginal effect on the cutting forces.

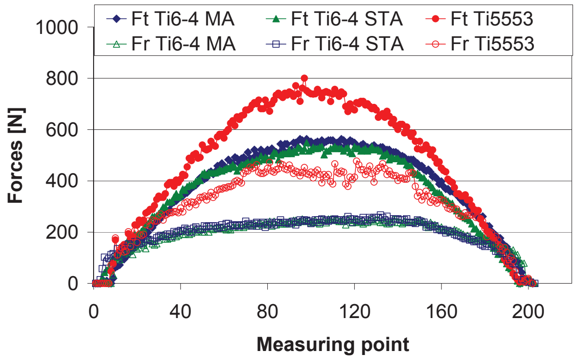

Fig. 7. Typical force signal obtained from one orthogonal milling cycle (vc=40m/min, fz=0.15 mm/tooth., ap=2 mm)

The effect of feed per tooth and cutting speed on the milling forces was further investigated in the context of Ti 6-4 alloys where maximum tangential (Ft) and radial (Fr) forces were extracted from the analysis of 10 milling cycles. The results showed that an increase in feed per tooth from 0.1 to 0.2 mm (Fig. 8) resulted in a systematic increase of both tangential and radial force components. An increase in cutting speed from 40 to 100 m/min seems to have very little effect on the tangential forces while an increase in the radial forces is generally observed (Fig. 9).

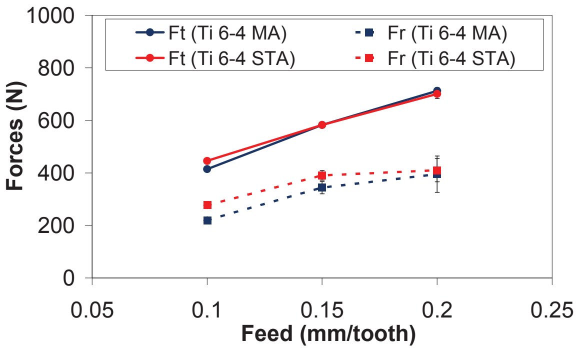

Fig. 8. Effect of cutting speed on maximum cutting forces

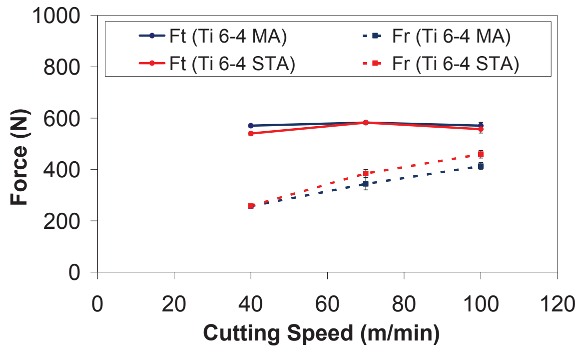

Fig. 9. Effect of cutting speed on maximum cutting forces

3.3. Chip studies

A metallographic analysis of the chip specimens produced during the orthogonal milling experiments was carried out in order to study the variations in chip morphology between the different work materials.

An example of this can be seen in Fig. 10 where typical "shear-localized" or "segmented" chips are observed in the different Ti alloys. The shear bands are generally much thinner for Ti-5553 than for Ti 6-4 alloys suggesting a more intense adiabatic shear in this material.

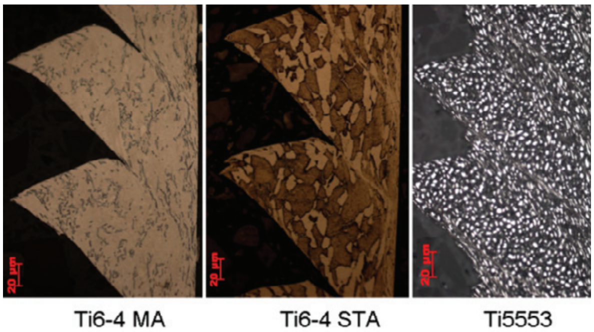

Fig. 10. Chip morphology (vc=40m/min, fz=0.15 mm/rev., ap=2 mm)

The corresponding chip segmentation frequency $f_{seg.}$ was determined using the following equation:

$$f_{seg.} = \frac{v_c \cdot f}{H \cdot L} \qquad (1)$$

where v_c is the cutting speed, f the feed, H the maximum height of the segment and L the segment lamella spacing.

A comparison of the different work materials at vc=40 m/min indicates that Ti-5553 displays the highest segmentation frequency (4,7 kHz), followed by Ti 6-4 STA (4,2 kHz) and Ti 6-4 MA (3,6 kHz).

The differences in segmentation frequency between the different work materials results in a variation of the dynamic loads on the cutting tool material. The higher segmentation frequency and resulting dynamic loads observed for Ti-5553 appear to be consistent with the poorer machinability observed for this material when compared to Ti-6-4 MA and Ti 6-4 STA. A further analysis of the effect of cutting conditions on segmentation frequency in the Ti-6-4 alloys indicate that this parameter increases with cutting speeds while it decreases with feed rate.

In order to determine the plastic shear and strain and strain rate in the shear bands, the analytical model developed of He et al. [10] was employed. The results are shown in Table 3 and indicate that Ti-5553 remarkably higher strain and strain rate than the Ti-6-4 alloys Ti 6-4 alloys.

Work material	Shear strain	Shear strain rate [$10^3 s^{-1}$]
Ti -6-4 M.A	7.0	53. 9
Ti-6-4 STA	6.2	63. 6
Ti-5553	21.1	121.3

Table 3. Effect of work material on shear strain, strain rate (vc= 40m/min, fz=0.15 mm/tooth, ap=2 mm)

Fig. 11 show the effect of cutting parameters on the shear strain and strain rate for Ti 6-4 alloys and the results indicate an increase of these with both cutting speed and feed rate. The STA variant displays also higher shear strain and strain rate than the MA variant.

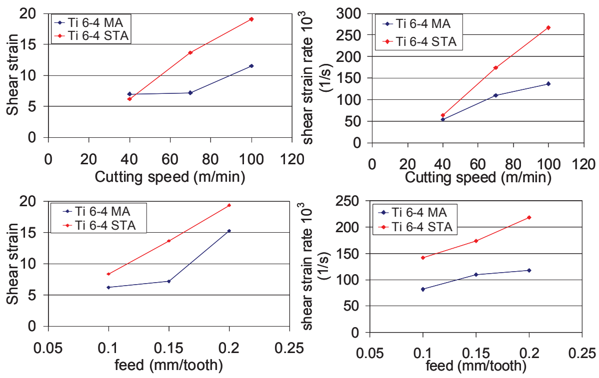

Fig. 11. Shear strain and strain rate in the shear localized bands within the chip

3.4. Frictional conditions at tool-chip contact

An analysis of the cutting forces contributing to chip forming process only was performed based on an approach develop by Albrecht [11] and further applied by Wyen and Wegener in Titanium 6-4 [7]. From such analysis, the average friction (τ) and normal (σ) stresses acting on tool surface can thus be determined.

Fig. 12 displays the variation of σ and τ at different angular positions during a milling cycle where an angle of 90° corresponds to the maximum uncut chip thickness. The results indicate that higher stresses are observed for Ti-5553 while the stresses obtained for Ti-6-4 MA and Ti 6-4 STA are comparable.

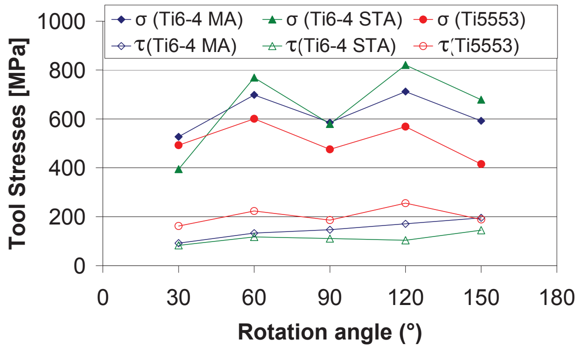

Fig. 12. Average tool stress on rake face (vc=40m/min, fz=0.15 mm/tooth, ap=2 mm)

Fig. 13 displays the average tool-chip friction coefficient obtained on the tool rake face for the different materials. Here again, larger friction coefficient is observed for the Ti-5553 material confirming also the more severe adhesive contact observed in the SEM study of the tool inserts.

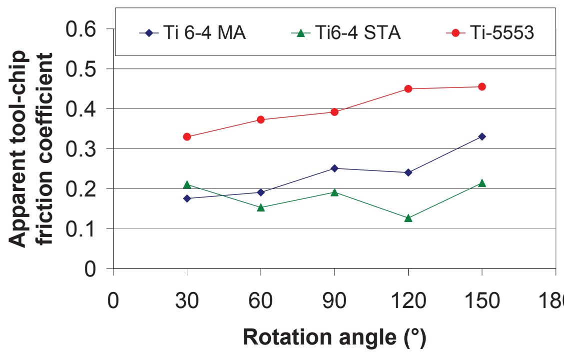

Fig. 13. Apparent tool-chip friction coefficient (vc=40m/min, fz=0.15 mm/rev., ap=2 mm).

3.5. Tool temperature

Typical view of the experimental tool temperature distribution obtained during interrupted cutting of Ti-6-4 MA and Ti-5553 at a cutting speed of 40 m/min and feed rate of 0.15 mm/rev is shown in Fig. 14. The maximum temperature is located further away from tool edge on the rake surface. A difference of approximately 80ºC in maximum rake temperature is observed between Ti-5553 (~630°C) and Ti-6-4

(~550°C). Such difference is likely to affect the tendency for tool-work material adhesion which is found more severe for Ti-5553 than for Ti-6-4 alloys.

Fig. 15 shows the variation of maximum tool temperature for the work materials as a function of the cutting parameters. An increase in temperature with increasing cutting speed is generally recorded, but a small increase in temperature is observed for Ti-5553 as compared to Ti-6-4. Moreover for Ti-555.3 at vc= 25m/min, f=0.1mm/rev., temperature is higher than the one obtained for Ti-6-4 at Ti 6-4 at vc= 40 m/min, f= 0.15mm/rev.

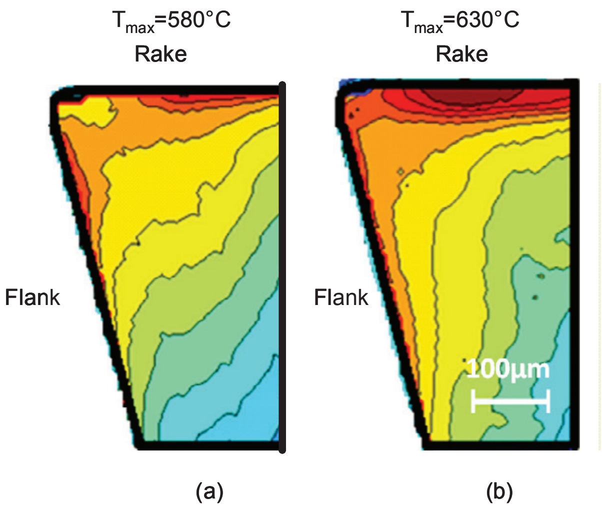

Fig. 14. Temperature on the tool during interrupted cutting. (a) Ti 6-4, (b) Ti-5553.

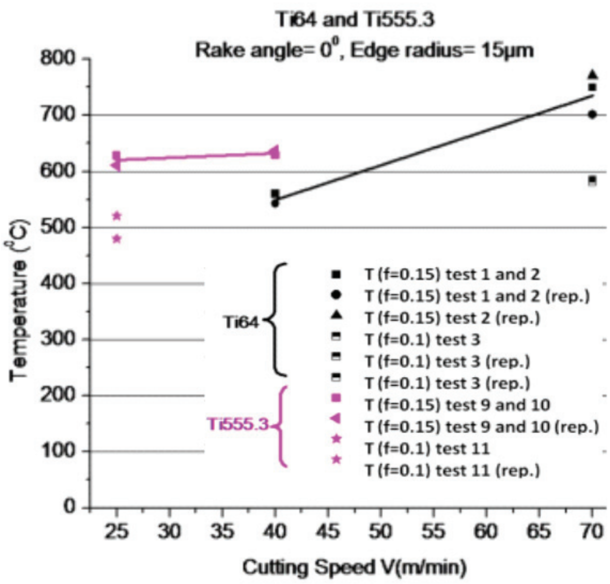

Fig. 15. Variation of tool temperature with the cutting parameters (speed, feed) in Ti 6-4 MA and Ti-5553.

4. Conclusion

The machining properties of Ti-5553 and Ti-6-4 alloys were investigated in different interrupted cutting operations and the results indicated systematically a lower machinability of Ti-5553. This was attributed mainly to a combination of high dynamic loads as a result from a higher chip segmentation frequency, higher cutting temperatures and an increased adhesion tendency of the work material on the tool surface.

Acknowledgements

The present project was carried out within the respective programs of student internship from Seco Tools AB (Sweden) and Mondragon University (Spain) and we are thankful to them.

References

[1] R. Komanduri, B.F. Turkovich, New observations on the mechanism of chip formation when machining titanium alloys, Wear (1981); 69:179–188.
[2] S. Sun, M. Brandt, M.S. Dargusch, Characteristics of cutting forces and chip formation in machining of titanium alloys, International Journal of machine Tools & Manufacture (2009);49:561-658.
[3] P.D. Hartung, B.M. Kramer, Tool wear in machining titanium, Ann. CIRP (1982), 31 (1):75-80
[4] Wang, M., Zhang, Y., Diffusion wear in milling titanium alloys, Mater. Sci. Technol. (1988); 4:548-553.
[5] A. Jawaid, S. Sharif, S. Koksal, Evaluation of wear mechanisms of coated carbide tools when face milling titanium alloy, Journal of Materials Processing Technology (2000); 99:266-274.
[6] M. Armendia, A. Garay, A. Villar, M. A. Davies, P. J. Arrazola, High bandwith temperature measurement in interrupted cutting of difficult to machine materials, CIRP Annals - Manufacturing Technology (2010); 59/1:97-100.
[7] C.-F. Wyen, K. Wegener, Influence of cutting edge radius on cutting forces in machining titanium, CIRP Annals – manufacturing Technology (2010); 59:93-96.
[8] P.-J. Arrazola, A. Garay, L.-M. Iriarte, M. Armendia, S. Marya, F. Le Maitre, Machinability of titanium alloys (Ti6Al4V and Ti555.3), Journal of materials Processing technology (2009); 209:2223-2230.
[9] Ikuta, A.; Shinozaki, K.; Masuda, H.; Yamane, Y.; Kuroki, H.; Fukaya, Y.; Consideration of the adhesion mechanism of Ti alloys using a cemented carbide tool during the cutting process Journal of Materials Processing Technology (2002); 127:251-255.
[10] N. He, T. C. Lee, W. S. Lau, S. K. Chan, Assessment of deformation of a shear localized chip in high speed machining, Journal of Materials Processing Technology (2002);129:101-104.
[11] P. Albrecht, New Developments in the Theory of the Metal-Cutting process, Part I. The Ploughing Process in metal Cutting, ASME Journal of Engineering for Industry (1960); 81:348-358.