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Dry drilling of alloy Ti–6Al–4V

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Abstract

This work is focused on the combined study of the evolution of tool wear, quality of machined holes and surface integrity of work-piece, in the dry drilling of alloy Ti–6Al–4V. Tool wear was studied with optical microscope and SEM–EDS techniques. The quality of machined holes was estimated in terms of geometrical accuracy and burr formation. Surface integrity involves the study of surface roughness, metallurgical alterations and microhardness tests. The end of tool life was reached because of catastrophic failure of the drill, but no significant progressive wear in cutting zone was observed previously. High hole quality was observed even near tool catastrophic failure, evaluated from the point of view of dimensions, surface roughness and burr height. However, microhardness measurements and SEM–EDS analysis of work-piece showed important microstructural changes related with a loss of mechanical properties. Depending on the application of the machined component, the state of the work-piece could be more restrictive than the tool wear, and the end of tool life should be established from the point of view of controlled damage in a work-piece.

Keywords: Dry machining; Ti–6Al–4V; Surface integrity; Tool wear

1. Introduction

Titanium alloys are excellent candidates for high performance applications owing to their high strength to weight ratio and excellent corrosion resistance, maintained even at high temperature [1]. However, titanium alloys are regarded as extremely difficult to cut materials. Tool wear is intense because of high cutting temperature due to low thermal conductivity [2]. In addition, the high chemical reactivity of titanium at high temperature with most of tool materials, produces a strong adhesion of the work-piece to the tool surface, thus leading to chipping and premature tool failure [3]. Thus, the high temperature generated close to the cutting edge of the tool when machining titanium [4], is the principal reason for the rapid wear of the tools.

Additionally, its low heat conductivity increases the temperature at the tool/work-piece interface, thereby also affecting work-piece material adversely. The tendency of titanium alloys to accrue surface damage during machining operations is a disadvantage [5]. Damage appears in the form of heat-affected zones, and residual tensile stresses. Component failure could occur during service as a result of fatigue and stress corrosion [6].

Titanium alloys are generally utilized for parts requiring the greatest reliability and therefore, the surface roughness and any damage to the sub-surface layers must be controlled [7]. The study of Ti alloys machining should be carried out from the point of view of tool wear and surface integrity of a machined work-piece, although surface integrity controls often result in increase manufacturing costs and decreased production rates.

To machine titanium alloys, tool manufacturers recommend hard metal tools, moderate cutting parameters and abundant cutting fluid for cooling, in order to control temperature near the cutting edge [8]. On the other hand dry machining and cooling with ecological cutting fluids have been receiving increasing attention because of ecological impact of conventional cutting fluids [9,10]. Ecological

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machining techniques will be considered as a necessity for manufacturing enterprises in the near future [11].

Dry machining of Ti alloys is extremely difficult because the temperature near the cutting edge, should be controlled in order to guarantee surface integrity of work-piece and to avoid dramatic tool wear. Several authors have published work dealing with cryogenic machining of Ti alloys [12] (LN2 is used as ecological refrigerant), and dry machining of Ti alloys [13,14]. This work has been focused on turning and milling and most of it is developed from the point of view of tool wear, although in some cases damage due to machining was studied [15,16]. Tool wear evolution and damage in a work-piece are strongly related, because tool wear, and so work-piece damage, increase with heat generation. Nevertheless, no work about dry machining of titanium, combining the study of tool wear evolution and damage in work-piece due to cutting process has been found.

This work is focused on the combined study of the evolution of tool wear, machined hole quality and surface integrity of a work-piece in dry drilling of alloy Ti–6Al–4V. The main objective of this paper is to analyse the phenomena associated to these extremely severe condition of machining. Catastrophic tool failure occurred, although tool wear evolution was not pronounced. Significant changes in microstructure of material work-piece were observed, related in scientific literature [15,16] with a loss of mechanical properties. Damage due to machining process could be more restrictive than tool wear, and this fact should be taken into account to establish tool life criterion.

2. Experimental setup

This paper presents the results achieved in drilling operations on a commercial alpha–beta titanium alloy Ti–6Al–4V. Drilling tests were carried out in a B500 KONDIA machining center.

Selected tool was a TiN-coated fine-grain carbide drill ISO K40 recommended by GUHRING to drill alloy Ti–6Al–4V. The composition of the drill is WC–10% Co, the size of the WC particles is smaller than 0.5 μm. The thickness range of the TiN coating is 1.5–3 μm. Geometry of the drill is 6 mm diameter and split-point twist.

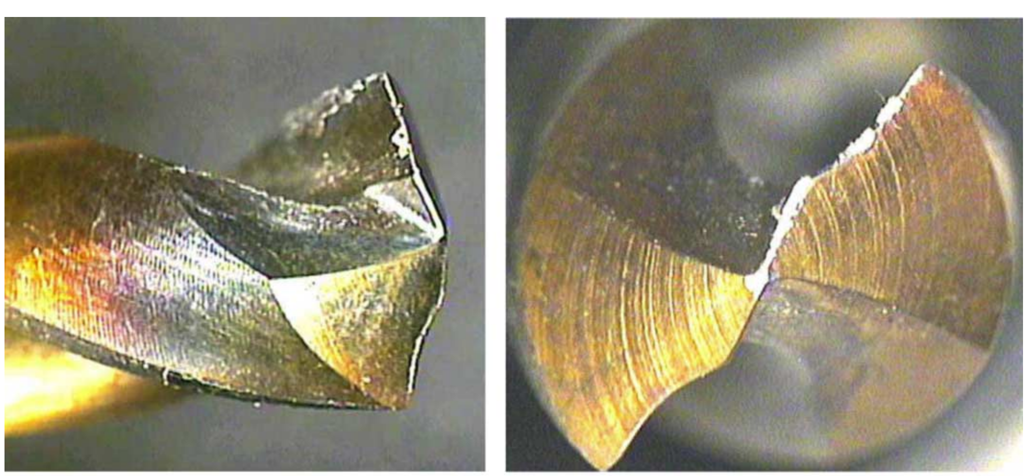
Ti–6Al–4V plates 8 mm thick were used and the distance between holes was 15 mm. Previous dry drilling tests were carried out at peripheral cutting speed ranging between 25 and 65 m/min and feed rate ranging between 0.02 and 0.07 mm/rev, in order to establish appropriate cutting parameters. From these tests cutting speed and feed rate were fixed at 50 m/min and 0.07 mm/rev, respectively.

Surface finish of each drilled hole was measured with a Mitutoyo Surfest SJ-201 type instrument. Average roughness (R_a) was an indicator of surface quality. Burr height was measured with an outside micrometer Mitutoyo with dial indicator of 0.01 mm resolution. Hole diameter was measured with a three point internal micrometer with dial indicator of 0.001 mm resolution.

In order to evaluate tool wear, an OLYMPUS SZ40 optical microscope with a digital camera was used. Tools were tested until catastrophic fracture occurred.

Microstructural changes were evaluated using two methods. Firstly, the observation of microstructures was carried out using a scanning electron microscopy (SEM), Philips XL-30 with an EDSDX4i system. Energy-dispersive X-ray (EDX) allowed further compositional investigation [17]. Secondly, microhardness tests were carried out with a Vickers pyramid indenter, using a HVS-100 ultra-micro-hardness digital tester.

Temperature is the most critical parameter involved in tool wear and material damage. According to Nabhani [18] machining titanium alloys conditions raise local



(a) (b)

Fig. 1. Optical microscope photographs of drill II after the first series of eight holes (condition II, cutting time 0.4 min): (a) side view of the drill, and (b) end view of drill showing material adhesion.

temperatures above 900 °C. Drilling tests were carried out in two different conditions:

- Condition I: the tool and the work-piece were cooled with compressed air after machining each hole. This condition corresponds to drill I.
- Condition II: series of eight holes were machined without pause. The tool was cooled at the end of each series with compressed air. This condition corresponds to drill II.

Condition II was more aggressive that condition I, as the temperature in tool and work-piece, were much more elevated in that condition.

3. Tool wear

Tool wear evolution was analysed in three different stages of condition I and II described previously: initial wear (after eight holes), medium wear (approximately half cutting time corresponding to tool failure) and final wear (cutting time slightly inferior to that corresponding to tool failure).

3.1. Initial wear

Fig. 1(a) and (b), are photographs (obtained in an optical microscope) of drill II after the first series of eight holes (condition II, cutting time 0.4 min). Images show material adhesion in the clearance surface of the tool (specially in cutting edge corners and drill point). However, drill geometry did not present significant changes.

Drill I presented slower wear evolution. Fig. 2(a), shows drill I after machining eight holes (condition I, cutting time 0.4 min). A smaller amount of material work-piece is adhered to the same zones that in the former case (drill point and clearance surface). No significant changes (flank wear, rounding of cutting edge, etc.) are observed in drill geometry.

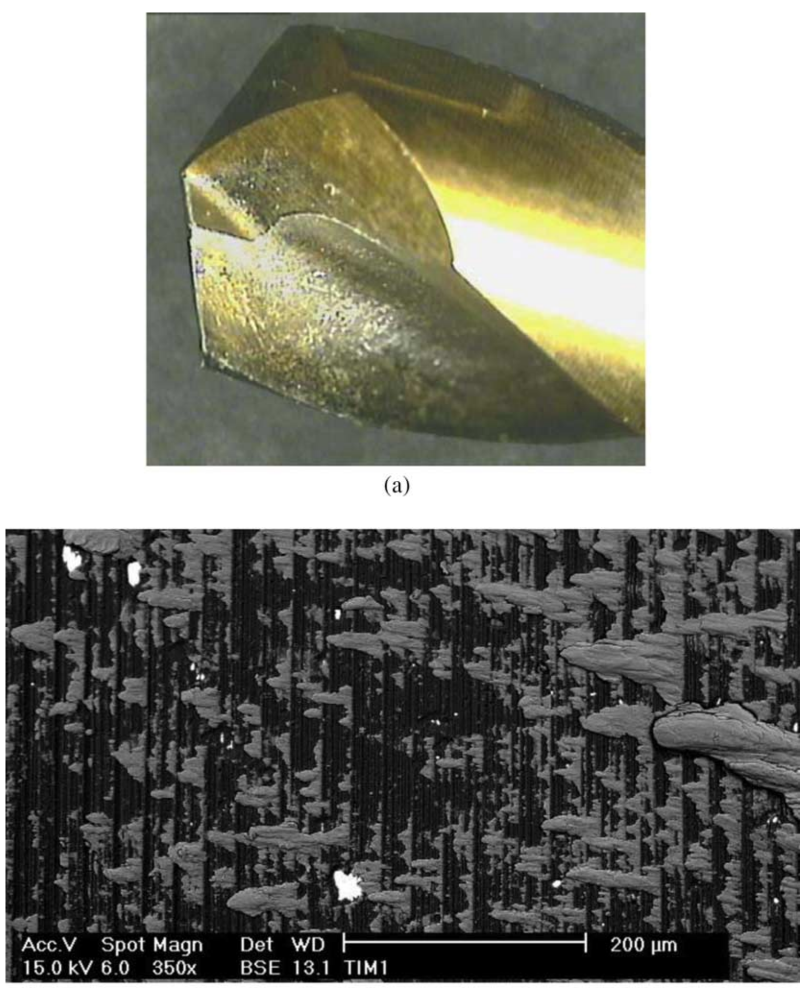


Fig. 2. Initial wear of drill I: (a) optical microscope view of drill I after machining eight holes (condition I, cutting time 0.4 min), and (b) SEM micrograph of rake face of drill I after machining 15 holes (condition I, cutting time 0.8 min).

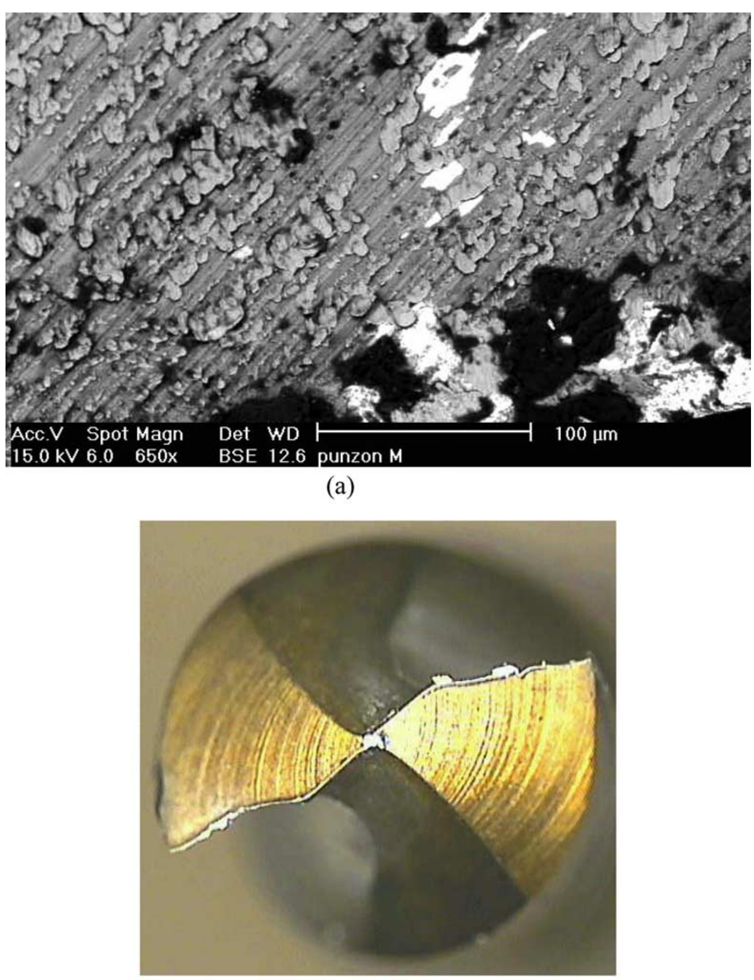
Drill I and II surfaces were analysed with SEM–EDS technique. Fig. 2(b) shows SEM image of rake surface of drill I, after machining 15 holes (cutting time 0.8 min). Zones with different contrast were analysed with EDS technique. Black zone corresponds to the tool coating (TiN), grey zone is material work-piece adhered to the tool and white zone corresponds to tool substrate (22% Co–78% W), due to loss of coating.

3.2. Medium wear

Analysis with optical microscope and SEM–EDS, showed progressive evolution of phenomena described in initial phase of wear. After a significant number of holes both drill I and II presented good state of geometry, and increased loss of coating and material adhesion in rake surface and drill point, more pronounced in drill II.

Fig. 3(a) shows a SEM image of drill II after machining 64 holes (eight series of eight holes, cutting time 3.4 min, being this time approximately half of tool life in this condition). In the EDS analyses of the chemical composition, darker zone corresponds with residue with elevated content of C, light grey is Ti alloy adhered on the tool, dark grey corresponds to tool coating (TiN) and white zone is tool substrate without coating. It is observed a notable increase of work-piece material adhesion and loss of coating in the tool, when compared with initial stage of wear. However, it should be noted that most of TiN coating remains in the drill, being a protective layer against tool wear [7,19].

Fig. 3(b) shows an optical image of drill I after machining 250 holes (condition I, cutting time 13.4 min, being this time approximately half of tool life in this condition). Cutting edges showed a good state of geometry. However, craters in the helical flute of the drill can be observed. Fig. 4 is a photograph of the drill I after machining 80 holes (cutting time 4.3 min). The same mechanism of wear was observed in drill II. As the number of holes machined increased, the size and the amount of craters increased. This tendency was more pronounced in drill I, taking up a surface of 3 mm in the direction of the helix and 1 mm wide. Although the craters do not affect



(a)

(b)

Fig. 3. Medium wear of drill I and drill II: (a) SEM micrograph of rake face of drill II after eight series of eight holes (condition II, cutting time 3.4 min), (b) optical microscope end view of drill I after machining 250 holes (condition I, cutting time 13.4 min).

Fig. 4. Optical microscope view of drill I after machining 80 holes (condition I, cutting time 4.3 min) showing craters in the helical flute.

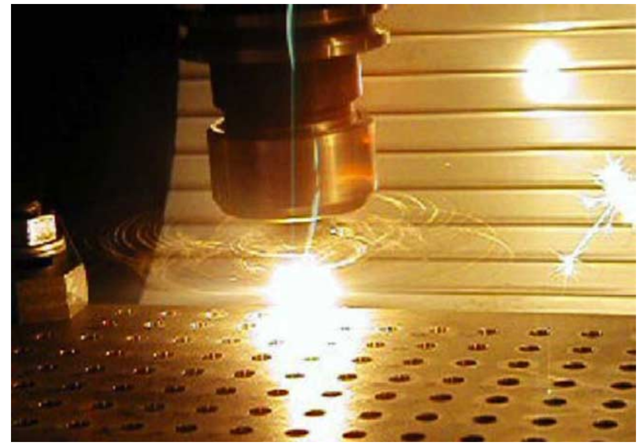


Fig. 5. Drilling test with combustión of the chip corresponding to 14th series with drill II (cutting time 6 min).

the cutting edge geometry, (and apparently, do not affect cutting process), they weaken the tool [20].

Craters are located in a tool zone that reach high temperatures and suffers severe friction during machining. Posterior analysis of the composition of this zone revealed diffusion of work-piece material. The intimate contact between the titanium chip/work-piece and the tool at temperatures above 900 °C provide an ideal environment for diffusion of material atoms across the tool/chip or tool/work-piece interface. The combined action of diffusion and attrition originates the craters.

3.3. Final wear

Cutting edge geometry does not change significantly up to the end of life of the tool. However, as cutting time increased, heat generated in the process increased, due to loss of coating, adhesion of work-piece material and small defects originated at the cutting edge. Tests were carried out in absence of cutting fluid, so high temperature is reached and combustion of chip was observed in some cases. In condition II, small sparks due to weak combustion of the chip appeared after the first series. This tendency increased as the number of holes increased. Since 10th series (cutting time 4 min) the chip began to burn, and since 14th series (cutting time 6 min) chip burned in a more intense way (see Fig. 5). During machining in condition I sparks appeared later (after 70th hole, cutting time 3.8 min). Complete combustion of the chip was observed firstly in hole number 395 (cutting time 21.2 min).

Drill I broke in the corner of one of its cutting edges (this is the zone of the tool that reaches maximum temperature during cutting). However, the rest of the cutting edge and the other edge, do not show significant changes in geometry. Drill failure indicated end of tool life and happened after 455 holes (cutting time 24.5 min, see Fig. 6(a)). Drill II broke after 16 series of eight holes (cutting time 6.9 min). Fig. 6(b) show fracture in drill II located in the corner of one of its cutting edge and extended towards helical flute. This was the zone where diffusion of work-piece material and elevated number of craters weakened the drill.

Fig. 7(a) is an electronic microscope image of the drill II after 128 holes (end of tool life), showing diffusion of material work-piece (dark zone of the image) due to high temperature reached in this zone and the loss of TiN coating. Analysis EDS (Fig. 7(b)) showed chemical composition of light (A) and dark (B) zone. Spectrum A presents peaks of W and Co, corresponding to drill substrate, however, peaks distribution of spectrum B are similar to those corresponding to composition of work-piece material.

SEM–EDS analysis showed diffusion in helical flute of drill. In addition craters due to adhesion and attrition were observed in this zone. The absence of craters in rake surface may be explained because of the tendency of WC/Co grades of cemented carbide to react with the work-piece to form a TiC layer. According to Hartung and Kramer [21] the presence of this layer eliminates the sliding between chip and tool, thus maximising the crater wear resistance [22]. The wear will be limited by the diffusion rate of the tool constituents through this layer. This process of wear is believed to occur at a lower rate compared to that caused by physical motion of the chip under sliding conditions [15].

Brittle fracture of the tool is usually related with instability during machining. Severe thermal and mechanical shocks appear when machining titanium alloys [23] resulting in vibrations due to variable loads. Serious vibrations are often encountered due to the adiabatic shear process by which titanium chips are formed [24]. As tool wear increases dynamic cutting forces increases significantly.

Embrittlement of cutting material (WC+Co) due to diffusion between cemented carbide tools and titanium alloys at the interface in the region of seizure is described in [25]. Carbon atoms from substrate tool diffuse more rapidly than metal atoms (Co and W). In the tool, just below

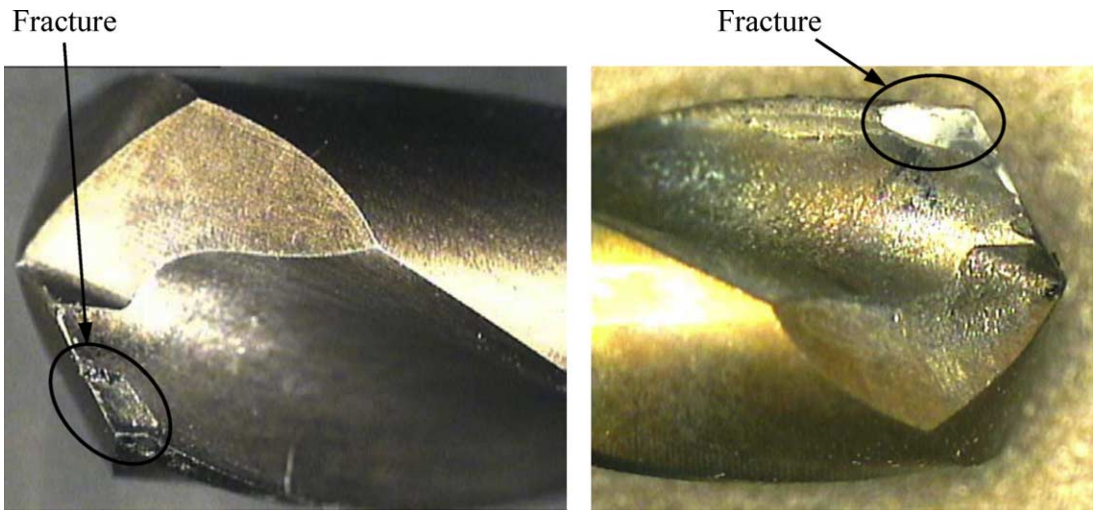


Fig. 6. Optical microscope photographs of catastrophic failure of drill I and drill II: (a) broken drill I after machining 455 holes (condition I, cutting time 24.5 min), and (b) broken drill II after 16th series with drill II (condition II, cutting time 6.9 min).

the surface, there is a carbon deficient region. The tool subsurface region may be embrittled because the carbon content is reduced.

High stress and severe cutting temperatures coupled with the brittleness of the substrate tool due to diffusion, may accelerate the chipping, flaking, cracking, and fracture of the tool [7,14]. Catastrophic failure of the tool occurs without previous significant progressive tool wear.

4. Quality of machined holes and surface integrity

Machining conditions that imply poor cooling in the tool are related with increased tool wear and decreased hole quality and surface integrity. Quality of machined holes was estimated in terms of geometrical accuracy and burr formation. Surface integrity involves the study of surface roughness, metallurgical alterations and microhardness tests.

4.1. Geometrical accuracy

Hole diameter has been measured at 10 points located at different height and orientation. Standard sample deviation of these measurements was always inferior to 0.015 mm. There is concern that the heat generated by the process can lead to thermal expansion of the drill and work-piece that will affect the size and quality of the holes leading to oversized holes [26]. However, diameter measurements were similar in both conditions tested, and no significant changes in diameter were observed neither in condition I nor

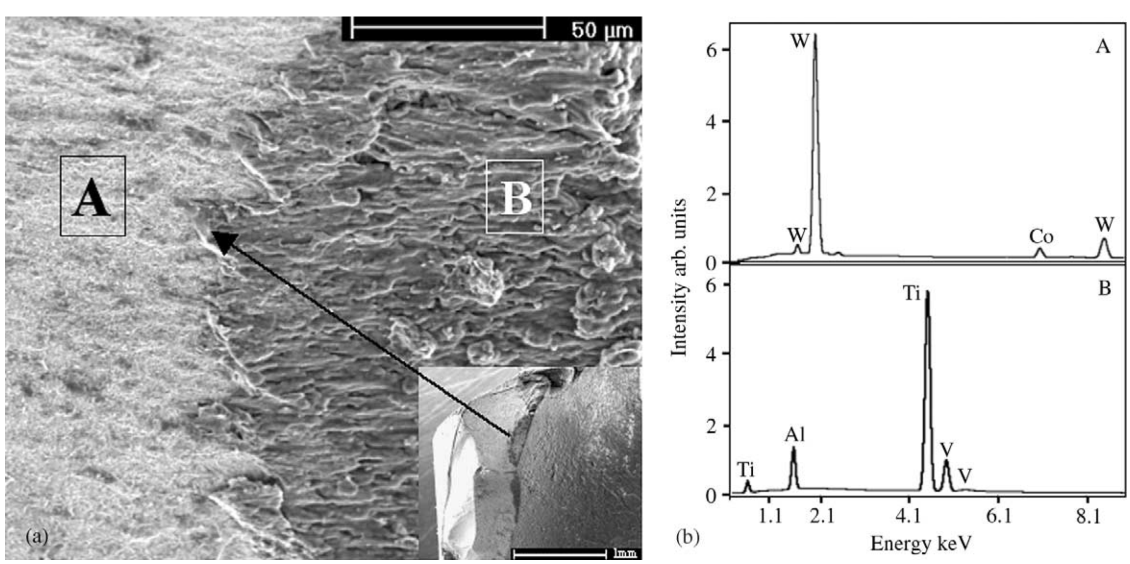


Fig. 7. SEM–EDS analysis of the drill II rake face after 128 holes corresponding to the tool failure: (a) SEM micrograph showing diffusion of material work-piece (dark zone) in the tool. The inset is a close-up of the diffusion region. (b) EDS spectra recorded from regions A (top graph, corresponding to tool substrate) and B (bottom graph, corresponding to work-piece material) in (a).

in condition II as cutting time increased. All diameter measurements ranged from 6.01 to 6.07 mm, and mean values ranged from 6.03 to 6.06 mm. These values correspond to a dimensional tolerance reasonable in drilling operations.

4.2. Burr height

Fig. 8 shows evolution of burr height versus cutting time, corresponding to both conditions I and II (burr height of first and last hole of each series are presented). Burr height increased as cutting time, and so tool wear, increased due to the higher temperatures. Holes machined in condition II (drill II), showed higher burr than those machined with drill I. Burr formation presented more sensibility to heat accumulation than resultant diameter. However, burr height presented moderate values up to tool failure, even in condition II.

4.3. Surface finish

Two surface roughness readings were taken at four positions spaced at 90° intervals around the hole circumference and approximately mid-way down the depth of the hole. The surface roughness of each hole was taken as the maximum value of the eight average roughness (R_a) circumferential readings. Maximum standard deviations of measurements of hole roughness was 0.1 μm. According to ISO standards the evaluation length was set at 4 mm and the cut-off length was fixed at 0.8 mm.

Fig. 9 shows evolution of surface roughness of holes machined with drill I and drill II (roughness of first and last hole of each series are presented) versus cutting time.

In both condition I and II, average roughness (R_a) was approximately 0.7 μm in initial holes. Roughness increased at cutting time corresponding to medium wear of the tool, ranging from 1 to 1.5 μm. Finally, close to tool failure, roughness increased up to 2.5 μm. Roughness values recorded were unstable during the cutting tests (specially in the case of drill II). Good surface quality was obtained up to tool failure, being obtained values of roughness typical in drilling operations.

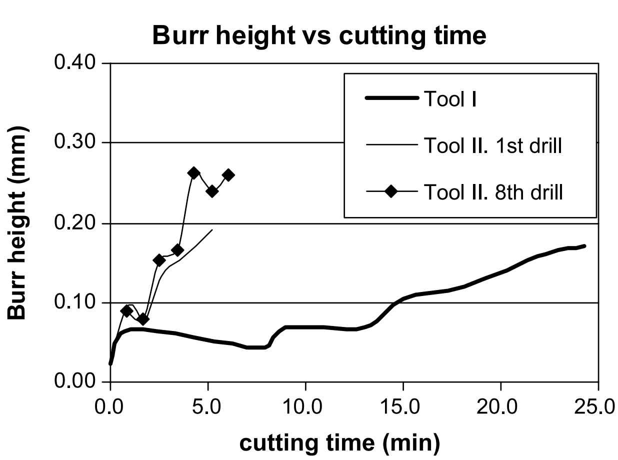


Fig. 8. Burr height versus cutting time for condition I and condition II (first and last hole of each series with tool II are presented).

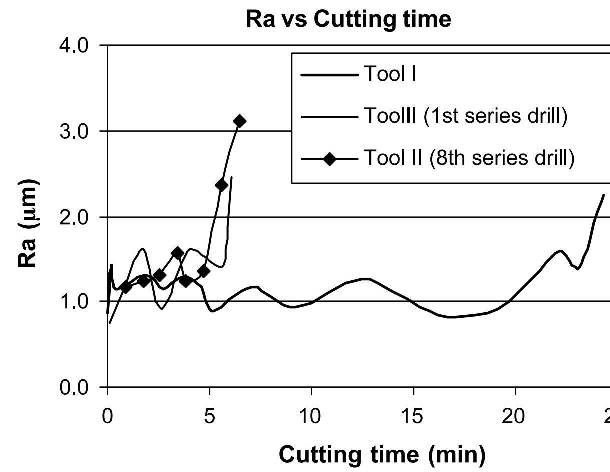


Fig. 9. Surface roughness versus cutting time for condition I and condition II (first and last hole of each series with tool II are presented).

4.4. Microstructural changes

Fatigue behaviour of Ti–6Al–4V is not strongly dependent on surface quality. A wide range of fatigue strengths could be achieved in conventional alpha/beta titanium alloy Ti–6Al–4V, not as a consequence of changes in surface roughness, but because of alterations in surface integrity, as a result of the machining operation [16].

The same qualitative microstructural changes were observed in both condition I and II, but more pronounced in the last condition. Results obtained in condition II are shown in SEM micrograph for a work-piece after 16 series of eight holes (see Fig. 10). The image is a section of a hole

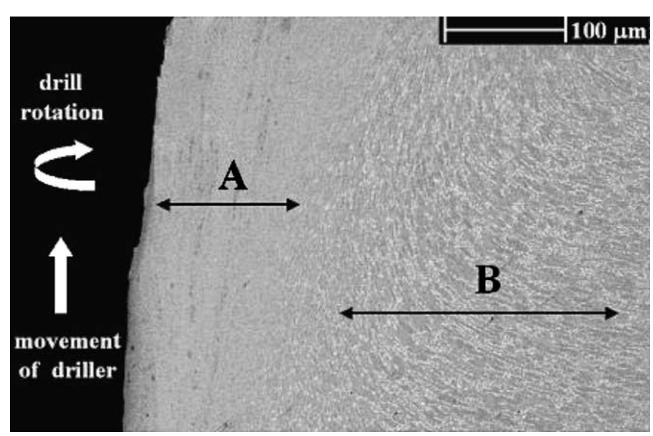


Fig. 10. SEM micrograph of the material work-piece near the surface of the 128th hole machined with drill II. Two regions A and B with different microstructure can be observed: region A, closer to the drill hole surface, with a width of ∼125 μm, corresponds to high temperature; region B, with a width of ∼200 μm, corresponds to medium temperature. The black area is the drill hole.

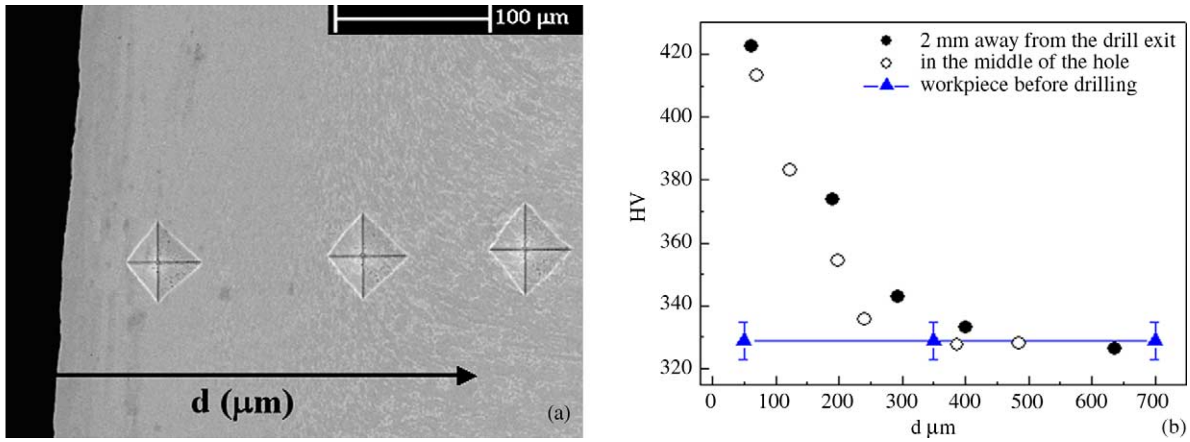


Fig. 11. (a) SEM micrograph showing three microindentation marks on a region approximately 2 mm away from the drill exit, for the 128th hole machined with tool II, (b) contains the microhardness data for two different regions in the same drill hole as (a); black solid circles correspond to the region shown in (a) and open circles to a region close to the middle of the hole; d is the distance measured from the drill hole surface inwards the workpiece; triangles correspond to the microhardness before drilling.

containing the revolution axis of the drill. Two regions A and B with different microstructure can be observed.

Region A, closer to the drill hole surface, with a width of ~125 μm, corresponds to the highest temperature and the most elevated stress. The width of this region is not uniform along the direction of the drill displacement. Variation in width up to 25 μm, is due to higher temperature at the end of the hole (the wider zone) [27]. SEM–EDS analysis showed the absence of light zones corresponding with phase β (with high V content). When titanium alloys are heated in an oxygen or nitrogen-containing ambient, a surface-hardened zone is formed. This layer is referred to as 'alpha case' because oxygen and nitrogen stabilize alpha phase [28]. This is in very good agreement with microhardness observations.

Region B, presents different microstructure because of decrease of temperature with increasing radial distance from the drill hole surface. SEM–EDS analysis allowed to distinguish between two phases, being light zone phase beta and dark zone phase alpha. A strong distortion in microstructure is observed, and the grains are oriented in the direction of the drill displacement. Plastic deformations during machining are caused by mechanical forces from the cutting tool acting upon the work-piece. Additional deformation can occur as a consequence of temperature gradients due to local heating of the machined surface area.

4.5. Microhardness tests

Fig. 11(a) shows marks resulting from microhardness tests in the same specimen obtained from 128th hole machined with drill II. Microhardness (Vickers) was measured in five points (located at a distance d from machined surface ranging from 50 to 600 μm) in two lines perpendicular to the drill displacement direction. First line was approximately in the middle of plate thickness, 4 mm away from the exit of the hole, and second line was 2 mm away from the exit of the hole. Microhardness distribution is shown in Fig. 11(b).

In the zone close to machined surface (distance 75 μm) value of 420 HV was obtained, approximately 30% greater to hardness obtained in material before machining. As distance d to machined surface increases microhardness decreases, reaching values similar to those obtained over material before machining (330 HV) at a distance 500 μm.

The above phenomena, but less pronounced, were observed at shorter cutting time, because prolonged machining with nearly worn tools, produced severe plastic deformation and thicker disturbed layer on the machined surface and the hardness of the disturbed layer of the machined surface increased significantly.

These microstructural changes originated during machining mainly because of elevated temperatures, influences mechanical properties of material, decreasing fatigue and stress corrosion resistance [7,15,16]. As Ti alloys are usually selected for high performance applications, loss of mechanical properties during its service life are an undesirable effect of machining process that should be controlled.

5. Conclusions and future work

This paper is focused on dry drilling of alloy Ti–6Al–4V, studying tool wear evolution, quality of machined holes and surface integrity after machining. Two different drilling conditions were analysed in order to observe the effect of heat accumulation in the drill and work-piece. Condition I, machining with a pause between each hole to cool the drill and the work-piece, and condition II, machining series of eight holes without pause. Moderate cutting parameters were selected defined from preliminary tests.

From obtained results, some conclusions can be summarized.

- Mechanisms of tool wear are similar in both conditions, however, the drill tested in the most severe conditions (series of eight holes machined without pause) broke after a cutting time that was one third the cutting time corresponding to failure of the drill tested under more favourable condition. This fact indicates the importance of establishing tests conditions similar to those imposed during actual industrial process.
- SEM–EDS analysis showed progressive loss of TiN coating of drill and work-piece material adhesion in rake surface. Likewise diffusion of Ti alloy in rake surface and drill helical flute were observed in both conditions tested.
- Attrition in the helical flute combined with diffusion of alloy in the tool resulted in the nucleation and growth of craters with an increasing progression as the cutting time increased.
- In some holes combustion of the chip was observed, the frequency of this phenomenon increased as the cutting time increased.
- The end of tool life was reached because of catastrophic failure of the drill, but no significant progressive wear in cutting zone is observed. Tool embrittlement due to diffusion and severe cutting stresses (both mechanical and thermal) caused tool fracture.
- Hole quality, evaluated from the point of view of dimensions, surface roughness and burr height, is elevated even near tool failure.
- Microhardness measurements and SEM–EDS analysis of the work-piece showed a zone, close to the machined surface, with important microstructural changes. Phase beta was transformed to phase alpha with elevated hardness (an increase of 30% in microhardness was found when compared with the original alloy). The thickness of the affected zone increased, as cutting time increased. Several works dealing with machining of Ti alloys [7,15,16] indicate that observed microstructural changes affect material mechanical behaviour during its service life, specially its fatigue and stress corrosion resistance. Material damage due to machining process could be unacceptable in high performance applications.

Summarizing, selected carbide tool allows to machine in dry conditions, with moderate cutting parameters an elevated number of holes, without an important variation in the drill geometry. Cutting time up to drill failure is specially increased when holes were machined with a pause between each hole to cool the drill. However, depending on the application of the machined component, material damage could be more restrictive than tool wear, and tool life criterion should be established from the point of view of controlled damage in work-piece.

As was explained, the establishment of tool replacement criterion will imply the analysis of mechanical properties of work-piece (fatigue and stress corrosion resistance) in order to evaluate damage due to the influence of machining process.

Surface integrity controls often result in increase manufacturing costs and decreased production rates. The authors are working in the development of a system able to carry out this control in industrial process. As temperature due to machining process is the most important magnitude affecting material damage and tool wear, the development of instrumentation systems to measure temperature in zones close to cutting edge would be an important future work.

Acknowledgements

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References

[1] R.R. Boyer, An overview on the use of titanium in the aerospace industry, Materials Science and Engineering A 213 (1996) 103–114.
[2] A. Molinari, C. Musquar, G. Sutter, Adiabatic shear banding in high speed machining of Ti6Al4V: experiments and modeling, International Journal of Plasticity 18 (2002) 443–459.
[3] L.N. López de Lacalle, J. Pérez, J.I. Llorente, J.A. Sánchez, Advanced cutting conditions for the milling of aeronautical alloys, Journal of Materials Processing Technology 100 (2000) 1–11.
[4] I.J. Polmear, Light alloys: metallurgy of the light metals, London Edward Arnold, 1989.
[5] Machining, Metals Handbooks, ninth ed., vol. 16, ASM International, 1989, pp. 844–847.
[6] A.R. Machado, J. Wallbank, Machining of titanium and its alloys—a review, Proceedings Institution of Mechanical Engineers, Part B: Management and Engineering Manufacture 204 (1) (1994) 53–60.
[7] E.O. Ezugwu, Z.M. Wang, Titanium alloys and their machinability—a review, Journal of Materials Processing Technology 68 (1997) 262–274.
[8] Application guide. Aerospace engine, SANDVIK COROMANT, 1992.
[9] A.E. Diniz, A.J. Oliveira, Optimizing the use of dry cutting in rough turning steel operations, International Journal of Machine Tools and Manufacture 44 (2004) 1061–1067.
[10] M. Sokovic, K. Mijanovic, Ecological aspects of the cutting fluids and its influence on quantifiable parameters of the cutting processes, Journal of Materials Processing Technology 109 (2001) 181–189.
[11] P.S. Sreejith, B.K.A. Ngoi, Dry machining: machining of the future, Journal of Materials Processing Technology 101 (2000) 287–291.
[12] S.Y. Hong, Y. Ding, Cooling approaches and cutting temperatures in cryogenic machining of Ti–6Al–4V, International Journal of Machine Tools and Manufacture 41 (2001) 1417–1437.
[13] S.G. Harris, A.C. Vlasveld, E.D. Doyle, P.J. Dolder, Dry machining—commercial viability through filtered arc vapour deposited coatings, Surface and Coatings Technology 133-134 (2000) 383–388.

[14] A. Jawaid, C.H. Che-Haron, A. Abdullah, Tool wear characteristics in turning of titanium alloy Ti-6246, Journal of Materials Processing Technology 92–93 (1999) 329–334.
[15] C.H. Che-Haron, Tool life and surface integrity in turning titanium alloy, Journal of Materials Processing Technology 118 (2001) 231–237.
[16] D. Novovic, R.C. Dewes, D.K. Aspinwall, W. Voice, P. Bowen, The effect of machined topography and integrity on fatigue life, International Journal of Machine Tools and Manufacture 44 (2004) 125–134.
[17] M.S. Carrilero, R. Bienvenido, J.M. Sánchez, M. Álvarez, A. González, M. Marcos, A SEM and EDS insight into the BUL and BUE differences in the turning processes of AA2024 Al–Cu alloy, International Journal of Machine Tools and Manufacture 42 (2002) 215–220.
[18] F. Nabhani, Machining of aerospace titanium alloys, Robotics and Computer Integrated Manufacturing 17 (2001) 99–106.
[19] P.A. Dearnley, A.N. Grearson, Evaluation of principal wear mechanisms of cemented carbides and ceramics used for machining titanium alloy IMI 318, Materials Science and Technology 2 (1986) 47–58.
[20] T.R. Lin, Cutting behaviour of a TiN-coated carbide drill with curved cutting edges during the high-speed machining of stainless steel, Journal of Materials Processing Technology 127 (2002) 8–16.
[21] P.D. Hartung, B.M. Kramer, Annals of CIRP 31 (1) (1982) 75–80.
[22] T. Wong, W. Kim, P. Kwon, Experimental support for a model-based prediction of tool wear, Wear 257 (7–8) (2004) 790–798.
[23] R. Komanduri, Some clarifications on the mechanics of chip formation when machining titanium alloys, Wear 76 (1982) 15–34.
[24] J. Hua, R. Shivpuri, Prediction of chip morphology and segmentation during the machining of titanium alloys, Journal of Materials Processing Technology 150 (2004) 124–133.
[25] W. Min, Z. Youzhen, Diffusion wear in milling titanium alloys, Materials Science and Technology 4 (1988) 548–553.
[26] M. Bono, J. Hi, The effects of thermal distortions on the diameter and cylindricity of dry drilled holes, International Journal of Machine Tools and Manufacture 41 (2001) 2261–2270.
[27] L. Reissing, R. Völkl, M.J. Mills, U. Glatzel, Investigation of near surface structure in order to determine process-temperatures during different machining processes of Ti6Al4V, Scripta Materialia 50 (2004) 121–126.
[28] M.J. Donachie, Titanium. A Technical Guide, ASM International, 2000, pp. 18–21.