TOOL LIFE AND MACHINED SURFACE DAMAGE ON TITANIUM ALLOY MILLING USING DIFFERENT COOLING-LUBRICATION CONDITIONS

Armando Ítalo Sette Antonialli, antonialli@ufscar.br
Materials Engineering Department, Center of Exact Sciences and Technology, Federal University of São Carlos,
ZIP 13565-905, São Carlos, São Paulo, Brazil; Phone number 55-16-33518513; Fax number: 55-16- 3361-5404

Anselmo Eduardo Diniz, anselmo@fem.unicamp.br
Henrique Kull Neto, henriquekiill@yahoo.com.br
Manufacturing Engineering Department, Faculty of Mechanical Engineering, State University of Campinas, PO Box 6122,
ZIP 13083-860, Campinas, São Paulo, Brazil; Phone number 55-19-35213290; Fax number: 55-19-32893722

Abstract. *Titanium alloys are key materials for the aerospace industry due to their excellent corrosion resistance, thermal and mechanical properties. However, they present poor machinability, especially because of their high chemical reactivity with most cutting tool materials at elevated temperatures and their low thermal conductivity, which provides higher cutting temperatures in cutting zone and makes that heat generated is concentrated at cutting tool, hence accelerating tool wear, compared to those. Therefore, water-based cutting fluids are usually employed in order to extend tool life by attenuating tool overheat, in such a way machining processes can be more productive, and also to avoid undesirable damages on the machined surface, as titanium components for aerospace applications cannot present any kind of defect. Nevertheless, it is well known that this kind of cutting fluids may cause thermal cracks or coating delamination on tool cutting edge, and so shorter tool life, in case of processes involving interrupted cutting, like milling. The aim of this work is to verify if other cooling-lubrication conditions can be successfully applied on titanium alloy finish milling. Four cooling-lubrication conditions were tested: dry, compressed air, minimum quantity lubrication (MQL) and water-based flood coolant. Output variables analyzed were tool life and its main wear mechanisms and machined surface roughness, microhardness and grain deformation. Results showed that either dry cutting or cutting with compressed air or MQL provided longer tool life than when flood coolant was applied, probably because of the intense thermal shock generated over the tool in this last condition. In terms of surface roughness, either dry cutting or cutting with MQL did not present good results. In addition to that grain deformation, an unrecorded inclusion precipitation lead by machining was possibly found when dry cutting. Cutting using compressed air seems to be the best cooling-lubrication condition for titanium alloy finish milling among tested choices.*

Keywords*: Milling, titanium alloys, cooling environments, surface integrity*

1. INTRODUCTION

Heat-resistant alloys, with high melting points are, nowadays, the most employed materials on the aerospace industry. Called as superalloys, they can be dismembered upon four categories: nickel, iron, cobalt and titanium based alloys (Ezugwu, 2004). These materials can maintain excellent chemical and mechanical properties even on high temperatures, characteristic that justifies their application on aeroengine components (Ezugwu, 2005).

In the case of titanium alloys, their excellent strength-to-weight ratio allied to high corrosion resistance and good hot mechanical properties led them to a growing and extensive application on airplanes and spaceships since the middle of XX century, although the high cost implicated on their obtainment (Silva and Mei, 2006). Outstanding prices for titanium alloys can be justified by its complex extraction from its ores (for example, from rutile, TiO_2), the high temperatures on casting besides, of course, commerce demand. However, their production is increasing, and most of the components made of them are machined, due to several project requirements typical of the aerospace industry that cannot be satisfied by forming (Ribeiro *et al.*, 2003). Here, another point that enhances the high price of these components: the poor machinability of titanium alloys.

According to Yang and Liu (1999) and Ezugwu and Wang (1997) difficulties on titanium machining can be mainly attributed to its high chemical affinity to all known tool materials, low thermal conductivity, hot mechanical properties and low Young modulus.

First of all, titanium alloys are poor heat conductors. Ti-6Al-4V, the major employed grade, presents thermal conductivity k = 7 W/m.K at room temperature (Lampman, 1990), lower than half of 314 stainless steel, k = 17.5 W/m.K (Washko and Aggen, 1990), and near seven times less than AISI 1045 steel, k = 50 W/m.K (Metals Handbook, 1990) on the same condition. That way, heat generated during machining is barely dissipated through workpiece and chip, but concentrated on the tool cutting edge, which loses hardness and mechanical resistance, been susceptible to plastic deformation and rapid wear (Ezugwu *et al.*, 2003).

Titanium's capability to maintain its mechanical properties even on high temperatures is one of the main reasons for being a key material to the aerospace industry. On the other hand, it also impairs machinability, because it hampers plastic deformation during chip formation (Machado and Wallbank, 1990).

Beyond the high temperatures generated over the cutting edge, titanium alloys exhibit strong chemical affinity to all known tool materials. This scenario provides intense workpiece material adhesion over the tool followed by particles pullout (attrition), often triggered by a diffusion mechanism, or tool collapse (Rahman *et al.*, 2003).

Besides that, titanium alloys present low Young modulus, which is responsible for workpiece excessive elastic deformation on machining. According to Boyer *et al.* (1994), even 0.8 % strain can be elastically settled down, what difficulties good finishing achievement, especially when thin walls are been made (López de Lacalle *et al.*, 2000). When it deals about milling processes, low Young modulus is responsible for intense cutting thickness fluctuation, leading to chatter vibration and then early tool flank wear with microchipping occurrence (Ezugwu and Wang, 1997). This situation harms titanium machined surface quality not only by roughness increasing, but even by microstructure damage (Che-Haron and Jawaid, 2005). Sharman *et al.* (2001) identified the depth of cut and cooling-lubrication condition as being the main influence variables over surface crack initiation and surface microhardness variation.

It is well known that the use of cutting fluids on machining process means costs raise and possible health and ecological impacts. However, is it possible to avoid them when cutting a refractory material like a titanium alloy?

The main goal of this work is to test cooling-lubrication alternatives on titanium alloy milling, than water-based cutting fluid, and their impact over tool life and surface integrity. Besides dry cut, minimum quantity lubrication (MQL) technique and pressurized air were experienced, supported on the results obtained by Hassan and Yao (2004) and Barnett-Ritcey (2005) respectively.

2. MATERIALS AND METHODS

2.1. Equipments

The experiments were carried out in a 3-axis Mori Seiki SV-40 vertical machining center (22 kW power and 12 000 rpm maximum rotation spindle) equipped with a GE Fanuc MSC-518 CNC.

Tool wear evolution during the tests was monitored using a Leica stereo-microscope with 50x maximum magnification and the software ImageJ 1.40c. After machining trials, tools were taken to a scanning electron microscope (SEM) Jeol JXA-840A, which provides higher magnifications, besides having an energy dispersive x-ray spectrometer (EDS) resource, that allows chemical elements over the tool to be identified an so, wear mechanisms to be understood or, at least, speculated.

During the experiments, surface roughness was monitored using a portable roughness profiler Mitutoyo SJ-201P. Besides that, specimens of the machined surfaces were taken from the workpiece at the end of tool life, in order to achieve information about surface integrity. Microhardness was measured using a Buehler microdurometer for Vickers hardness test with a 200 gf for 15 s load, following ASTM (2008). For metallography study, samples were prepared using sandpaper and then polished, etched with Kroll reagent (3 % HF, 6 % HNO_3), and photographed by an optical microscope Leica DM ILM.

2.2. Materials

Workpiece material was a recrystallized plate of Ti-6Al-4V alloy, the most employed among all titanium alloys. Tests were done using an indexable insert milling cutter of 25 mm maximum diameter (maker's code R300-025T12-10M), with three rounded shape cemented tungsten carbide inserts (maker's code R300-1032M-MM) coated with a TiAlN/TiN multilayer (GC2030, or ISO HC S25 grade), recommended for finishing and semi-finishing operations.

Cutting fluids used in this work were a water miscible vegetable-based oil (Vasco 1000 ®) 10 % brix applied tool externally at 45 l/min, and a straight vegetable-based oil (Vascomill 42 ®) applied at a minimum quantity lubrication (MQL) flow of 30 ml/h and 0.6 MPa.

2.3. Experimental Planning

In order to compare different cooling-lubrication environments for titanium alloy milling, a fixed effect model for level randomized planning was designed. Cooling-lubrication input levels were: dry, pressurized air (0.6 MPa), MQL and flood. Response variables analyzed were tool life and tool wear mechanisms, besides surface roughness, microhardness and grain deformation for the machined surface.

2.4. Experimental Procedures

Cutting parameters used in all the experiments are shown on Tab. 1, where v_c is cutting speed, f_z feed per tooth, a_e radial depth of cut, and a_p axial depth of cut. As it can be seen, typical finish milling parameters were applied.

Table 1. Cutting speed parameters (based on Sandvik Coromant, 2007)

v_c [m/min]	f_z [mm/tooth]	a_e [mm]	a_p [mm]
65	0.2	14.5	0.5

The end of tool life, and also the end of an experiment, was determined by maximum flank wear of 0.2 mm (actually a low value for industrial purposes, chosen to avoid waste of workpiece material) or maximum cutting time of 100 min. In order to provide an acceptable statistic confidence level, all experiments were replied. Several average surface roughness (R_a) measurements were done along each tool life.

Semi-quantitative analysis for chemical elements provided by the EDS resource of the SEM on flank face of inserts was useful to indentify whether there was or not presence of coating (Ti, Al), tool substrate (W, Co) and/or workpiece material (Ti, Al, V) adhered to it.

Microhardness measurements were done along the section of the specimens from 100 to 900 µm above machined surface. Therefore, it was possible to verify whether different cooling-lubrication conditions affect microhardness variation of the workpiece.

Metallography samples were analyzed restricted to a band of 100 µm below machined surface in order to infer grain deformation and other particularities owing to cooling-lubrication condition.

3. RESULTS AND DISCUSSION

Results for average tool life among run trials for all tested conditions are shown on Fig.1.

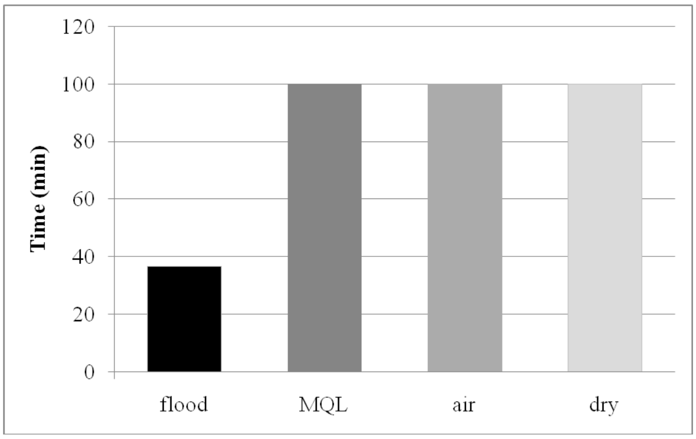


Figure 1. Tool life as a function of cooling-lubrication condition

It is clear that flood coolant was the worst condition in terms of tool life, less than half of what was attained on MQL, pressurized air or dry cut, which reached the top limit allowed for test time (100 min).

A possible reason for that is the unavoidable thermal shock over the tool provided by the water-miscible fluid. Inside the cut, the cutting edge reaches very high temperatures because of the titanium alloy low thermal conductivity and then, when it exits the workpiece in each revolution, the contact with the emulsion decreases its temperature abruptly, what may lead to thermal cracks on tool cutting edge or even coating delamination and so, to short tool life (Diniz *et al.*, 2006). In the case of the other cooling-lubrication conditions, as no water is present, the cooling effect of the fluid (either air or MQL) makes the tool temperature variation negligible.

This result contradicts what Antonialli and Diniz (2008) gathered for the rough milling of this same titanium alloy, case in which emulsion provided the best tool life result. In this work, the use of water-based fluid proved to be disadvantageous for tool life, and so it can be concluded that high cooling capacity may be advantageous when it deals about large material removal rates, but not when finishing parameters are being used.

Figure 2 contains SEM pictures of the worn tools in each experiment, in which different regions of the cutting edge are pointed and identified.

No considerable differences can be noticed among flood (Fig. 2 (a)), MQL (Fig. 2 (b)) and air (Fig. 2 (c)) conditions, in which attrition – or adhesion of workpiece followed by tool's particles removal – seems to be the main wear mechanism, as irregularities along the cutting edge are clearly visible. One point of distinction on tool used on flood test (Fig. 2 (a)) is the presence of oxide, commonly found when it deals about water miscible fluids, although no indication of thermal crack is noticed, what would be expected. In this experiment, tool wear is a little bigger than in the other conditions, as it was the only situation in which 0.2 mm was reached.

On the other hand, for dry cut, as tool edge shows smooth appearance, diffusion wear may be occurring. This difference may be attributed to the higher resulting temperatures when no cutting fluid is being applied, an ideal scenario for atoms transference from workpiece to tool and vice versa. Here, it is important to remember that titanium alloys exhibit strong chemical affinity to all known tool materials, what stimulates diffusion.

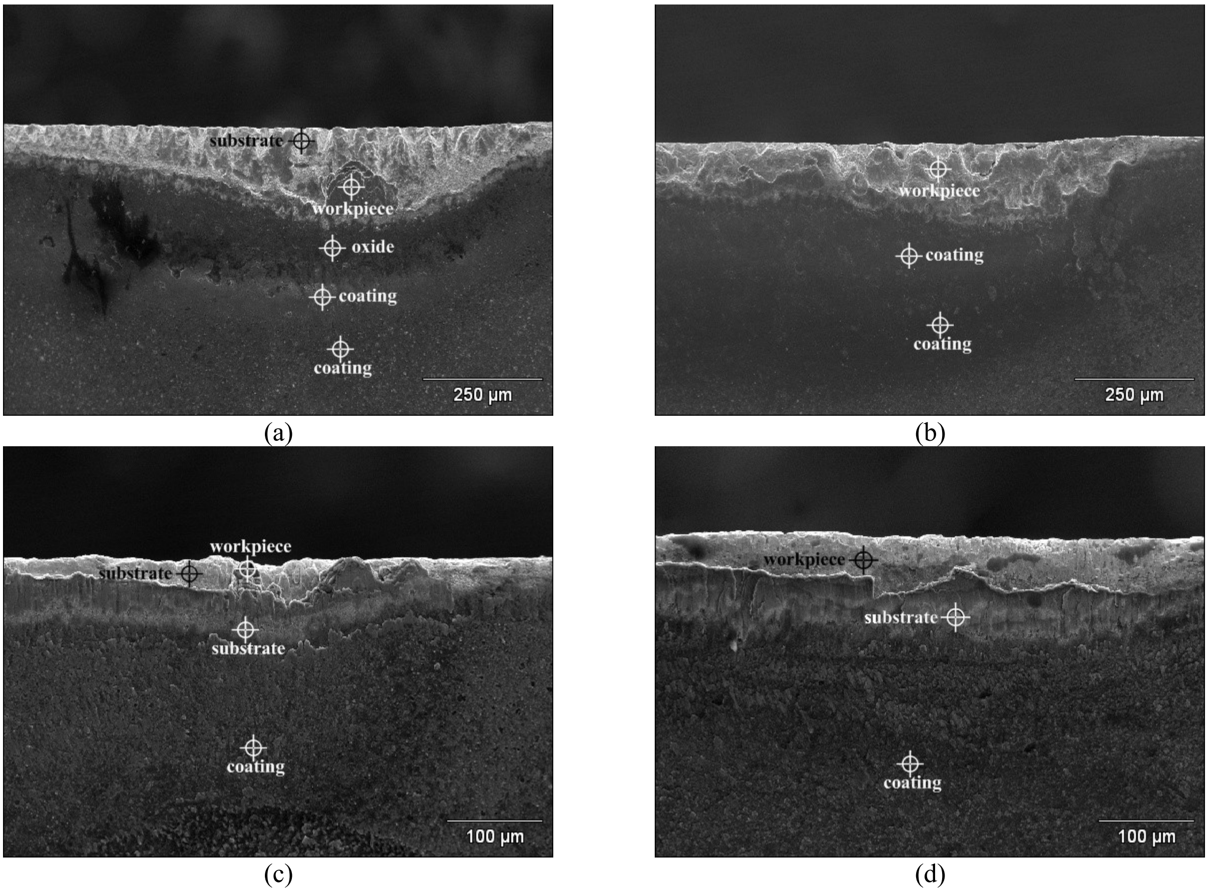


Figure 2. SEM pictures of worn tools as a function of cooling-lubrication condition:
(a) flood, (b) MQL, (c) air and (d) dry

Average surface roughness (R_a) acquired on the experiments is plotted on Fig.2, where the error bars describe standard deviation around the average.

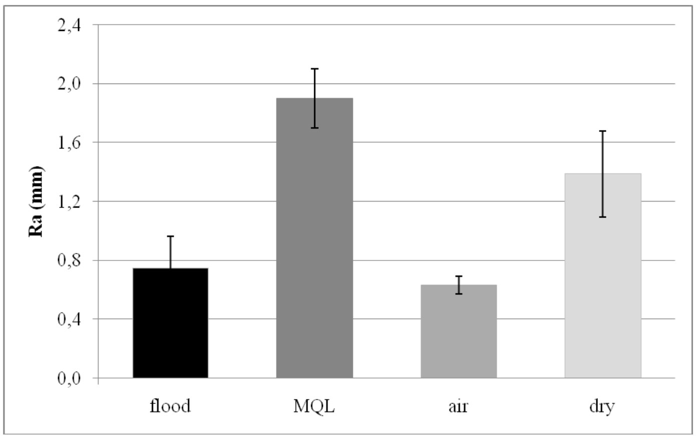


Figure 3. Surface roughness as a function of cooling-lubrication condition

Differently from tool life results, flood and pressurized air exhibited better results for surface roughness – $R_a < 0.8$ µm – than the other cooling-lubrication conditions. Dry cut presented R_a near 1.5 µm, what can be attributed to the lack of lubricity between tool and workpiece in this experiment, which impairs shearing and increases cutting temperature and cutting forces, leading to some kind of vibration. MQL cooling-lubrication was even worse: almost 2.0 μm of average roughness, a non-expected result for a condition that is usually effective in terms of lubricity. Disparity between this bad result presented by MQL and the good result obtained with pressurized air can be explained by a relative inefficiency of vegetable-based oils when it deals about low cutting speeds – like 65 m/min used in these experiments – situation in which mineral-based oils could have perform better.

Microhardness results along workpiece specimen section for all experiments are shown on Fig. 4.

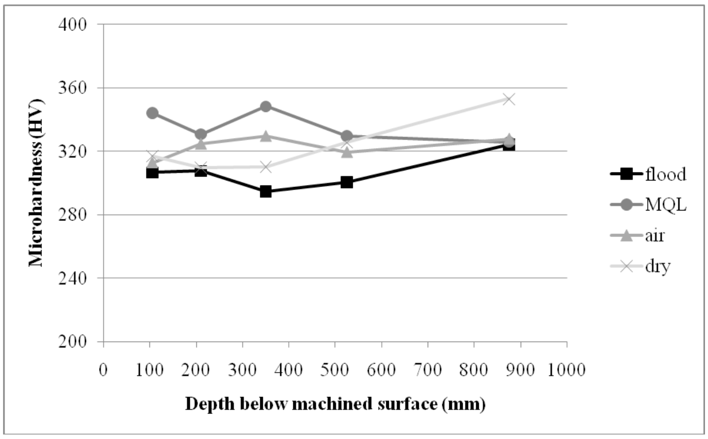


Figure 4. Microhardness depth profile as a function of cooling-lubrication condition

It seems that no relevant difference can be stated among cooling-lubrication conditions in terms of microhardness from 100 to 900 μm below machined surface, as measured values are not too far from each other – always between 300 and 350 HV, which is close to 349 HV found by Boyer *et al.* (1994) for annealed Ti-6Al-4V. Although, it cannot be observed that no variation was occurring, because microhardness may be higher closer to the surface (less than 100 μm of distance), as verified by Mantle and Aspinwall (2001).

Figure 5 contains photographs of the section of the metallographic samples for each cooling-lubrication condition tested. The upper region of the pictures corresponds to the machined surface, and the bottom part, to a line 100 μm below it.

Showing equiaxial grains constituted of α-phase (lighter), along with β-phase (darker) on their boundaries (although they are not very well defined), Fig. 5 (a) illustrates a typical metallography of recrystallized Ti-6Al-4V, which was obtained on flood condition. No grain deformation is found because of the emulsion high cooling capability.

On the other side, when no cutting fluid is applied (Fig. 5 (d)), microstructure damage is clearly noticed, as grains seem not to be equiaxial anymore, but severely aligned to an almost normal direction from the machined surface, effect of the stresses generated on milling and also of the excessive heat imposed and restricted – because of the titanium alloy low thermal conductivity – to this area right beneath the cut, as the workpiece is not cooled in this condition.

Besides that, some kind of heterogeneity (dark points) appears inside the grain, which can be pitting points, pores or inclusions.

Knowing the high corrosion resistance presented by titanium alloys, it is not presumed that the etching would lead to pits like these, whose appearance, after all, would be lighter.

Pores occurrence would also be weird in a rolled plate processed following the high exact requirements of the aerospace industry.

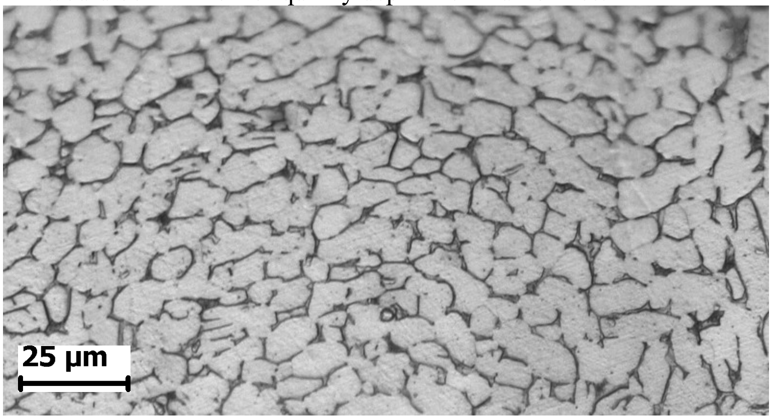
Therefore, it is likely that the heat produced by tool-workpiece and tool-chip rubbing, besides chip strain, may have promoted the age hardening of a thin zone through beta phase precipitation, since heat is not dissipated by an efficient cooling condition, but tied in this layer, as titanium presents low thermal conductivity.

It was not found in literature any citation about the occurrence of this phenomenon. For instance, it is not possible to ensure that this phase transformation is really happening, since it would be necessary a focused analysis of these inclusions on SEM and EDS besides hardness measurements restricted to that machined surface.

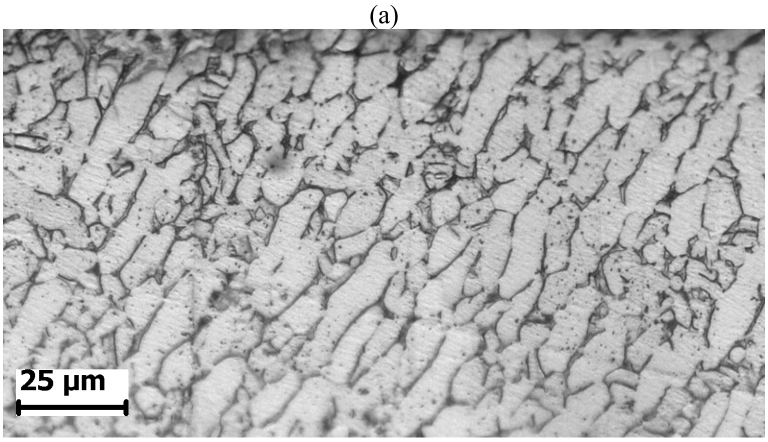
On the other cooling-lubrication conditions, MQL (Fig. 5 (b)) and pressurized air (Fig. 5 (c)), grain deformation is also noticed, although not as well pronounced as on dry cut, since these tests provide some cooling of the workpiece anyway. Likewise, precipitates can be seen again, but in a much less applicable quantity, what reinforces the hypothesis that that thin layer is really age hardening when dry cutting.

As grain deformation and this possible precipitation hardening may be found restricted to a 0.1 mm band right below the machined surface, results indicate no evidence of smashing surface damage ocurrence, especially in the cases of MQL and pressurized air, in which grains' distortion and inclusions precipitation is scanty.

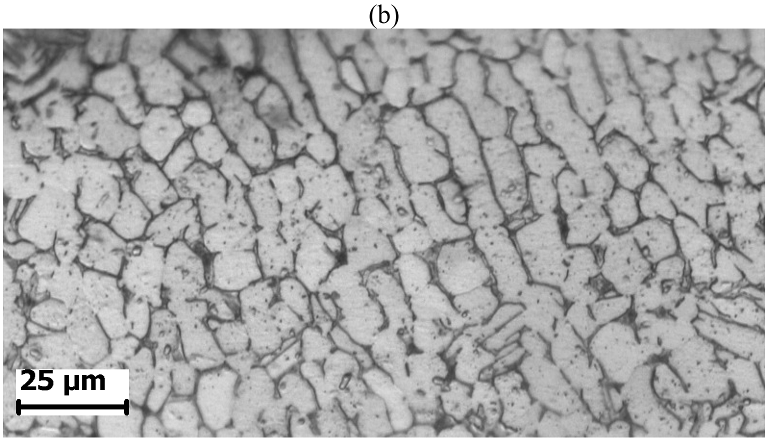
Although, as aerospace industry criterions are very tough, these phenomena could cause titanium alloy machined components rejection, what would be a matter for quality department authorities.



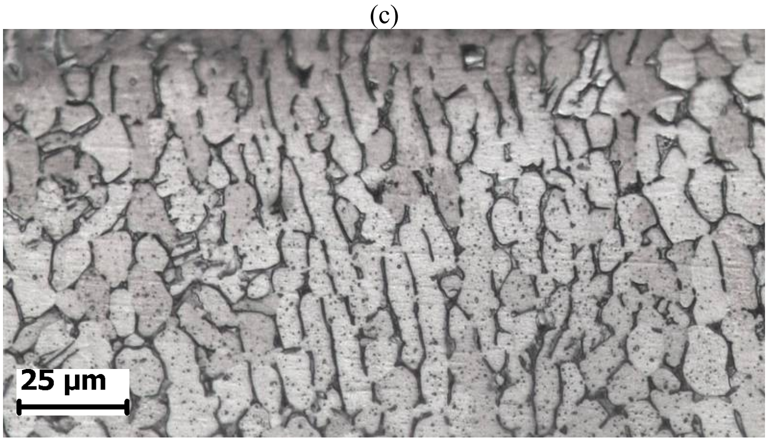
(a)



(b)



(c)



(d)

Figure 5. Metallography as a function of cooling-lubrication condition
(a) flood, (b) MQL, (c) air and (d) dry

4. CONCLUSIONS

After results analysis and discussion, the following conclusions can be pointed:

- On the finish milling of Ti-6Al-4V titanium alloy, either MQL, pressurized air or dry cut provided much longer tool life than that obtained when flood water miscible cutting fluid was used. The main reason for that may be the intense thermal shock to which tool is susceptible in this last condition, as it reaches very high temperatures inside the cut – specially because of titanium's low thermal conductivity – and, outside the workpiece, is quenched by the cutting fluid;
- Attrition seems to be the preponderant tool wear mechanism, as adhesion of workpiece material over the tool cutting edge is notable in all conditions tested. However, when dry cut is employed, diffusion wear is also remarkable, probably because of the higher temperatures reached in this situation;
- In terms of machined surface roughness, only pressurized air achieved results as good as flood condition, while dry cut and MQL were not well succeeded, probably because difficulties on lubricity maintenance between tool and workpiece;
- Worthy evidences point out that the excessive heat generated on dry cut may be promoting an unwilled aging heat treatment, what, in a manufacturing environment, would or would not cause machined component rejection, depending on quality judicious applied.

5. ACKNOWLEDGEMENTS

The authors would like to express thanks to Blaser Swisslube, Embraer, and Sandvik Coromant for cutting fluids, titanium plate and tools supply respectively.

Also thanks to PIBIC/CNPq for the scholarship granted.

6. REFERENCES

Antonialli, A.Í.S., Diniz, A.E., 2008, "Utilização de óleo integral no fresamento de liga de titânio aeronáutica", Anais do Congresso Usinagem 2008, São Paulo, Brazil, pp. 1-16.

ASTM, 2008, E 384 – 08a: "Standard Test Method for Microindentation Hardness of Materials", West Conshohocken, USA, 33 p.

Barnett-Ritcey, D., 2005, "High speed milling of titanium and γ-titanium aluminide: an experimental investigation", PhD Thesis, McMaster University, Hamilton, Canada, 222 p.

Boyer, R.R., Welsch, G., Collings, E.W., 1994, "Materials properties handbook: titanium alloys", ASM International, Materials Park, USA, 1176 p.

Che-Haron, C.H. and Jawaid, A., 2005, "The effect of machining on surface integrity of titanium alloy Ti-6%Al-4%V", Journal of Materials Processing Technology, Vol. 166, No. 2, pp. 188-192.

Diniz, A.E, Marcondes, F.C, Coppini, N.L., 2006, "Tecnologia da usinagem dos materiais", Artliber Editora, S.Paulo, Brazil, 254 p.

Ezugwu, E.O. and Wang, Z.M., 1997, "Titanium alloys and their machinability - a review", Journal of Materials Processing Technology, Vol. 68, No. 3, pp. 262-274.

Ezugwu, E.O., 2004, "High Speed Machining of Aero-Engine Alloys", Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 26, No. 1, pp. 1-11.

Ezugwu, E.O., 2005, "Key improvements in the machining of difficult-to-cut aerospace superalloys", International Journal of Machine Tools and Manufacture, Vol. 45, No. 12-13, pp.1353-1367.

Ezugwu, E.O., Bonney, J. and Yamane, Y., 2003, "An overview of the machinability of aeroengine alloys", Journal of Materials Processing Technology, Vol. 134, No. 2, pp. 233-253.

Hassan, A., Yao, Z.Q., 2004, "Minimum lubrication milling of titanium alloys", Materials Science Forum, Vol. 471-472, pp. 87-91.

Lampman, S., 1990, Wrought Titanium and Titanium Alloys, In: "Metals Handbook", ASM International, Materials Park, USA, Vol. 2, pp. 592-633.

López de Lacalle, L.N., Perez, J., Llorente, J.I. and SANCHEZ, J.A., 2000, "Advanced cutting conditions for the milling of aeronautical alloys", Journal of Materials Processing Technology, Vol. 100, No. 1, pp. 1-11.

Machado, Á.R., Wallbank, J. , 1990, "Machining of titanium and its alloys: A review", Proceedings of the Institution of Mechanical Engineers, Vol. B204, No. 1, pp. 53-60.

Mantle, A.L, Aspinwall, D.K, 2001, "Surface integrity of a high speed milled gamma titanium aluminide", Journal of Materials Processing Technology, Vol. 118, No. 1-3, pp. 143-150.

Metals Handbook, 1990, "Physical Properties of Carbon and Low-Alloy Steels", ASM International, Materials Park, USA, Vol. 1, pp. 195-199.

Rahman, M., Wong, Y.S. and Zareena, A.R., 2003, "Machinability of titanium alloys", JSME International Journal, Vol. 46, No. 1, pp. 107-115.

Ribeiro, M.V., Moreira, M.R.V. and Ferreira, J.R., 2003, "Optimization of titanium alloy (6Al-4V) machining", Journal of Materials Processing Technology, Vol. 143-144, No. 1, pp. 458-463.

Sandvik Coromant, 2007, "Main Catalog", Sandviken, 1157 p.

Sharman, A.R.C., Aspinwall, D.K., Dewes, R.C., Bowen, P., 2001, "Workpiece surface integrity considerations when finish turning gamma titanium aluminide", Wear, Vol. 249, No.5-6, pp. 473-481.

Silva, A.L.V.daC. and Mei, P.R., 2006, Aços ferramenta, inoxidáveis e ligas especiais, In: "Aços e ligas especiais", Ed. Edgard Blücher, S.Paulo, Brazil, chap. 7, pp. 363-473.

Washko, S.D. and Aggen, G., 1990, Wrought Stainless Steels, In: "Metals Handbook", ASM International, Materials Park, USA, Vol. 1, pp. 841-907.

Yang, X. and Liu, C.R., 1999, "Machining Titanium and its Alloys", Machining Science and Technology, Vol. 3, No. 1, pp. 107-139.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.