INFLUENCE OF THE EXTERNAL THREADING PROCESS AT HIGH SPEED CUTTING ON TURNING OF DENTAL IMPLANTS

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Abstract. *This work evaluated the effect of cutting speed on machinability and surface integrity of titanium dental implants (ASTM F67 degree 4). Chip formation, tool wear, workpiece microhardness and thread surface quality were investigated. TiNAl coated carbide tools and abundant cutting fluid were used in external threading process (CNC lathe). The results indicated alterations on workpiece microhardness generated by different cutting speeds. The chip formation depended on cutting speed reaching the segmentation for higher cutting speed. Images obtained by Scanning Electron Microscopy (SEM) revealed that increase on cutting speed was prejudicial for thread surface quality and threading tool due to wear and adherence. The cutting temperature estimated by a thermadynamic model reached 1283°C.*

Keywords*: dental implants, high speed cutting, external threading, surface integrity, machinability.*

1. INTRODUCTION

The wide use of titanium and its alloys reflects its good physical and mechanical properties in service. The high ratio between strength and weight is one of the most valuable characteristics in its industrial selection. Non-alloyed titanium is commonly used where there are strong corrosive agents and the need for fatigue strength (Wang, 2000).

Although this material's excellent applications characteristics, Shaw (1984) classifies titanium as a low machinability material, because of the high temperatures achieved in cutting and poor deformation and shear metallurgical characteristics in machining.

In medical use, commercially pure titanium, generally used in dental implants manufacturing, can be classified according to ASTM F67 standard in four degrees of purity in its chemical composition. The increasing use of titanium and its alloys in implants manufacturing, either orthodontic or orthopedic ones, are due to the simultaneous presence of the excellent biocompatibility (already proved by Williams, 1981), the high mechanical and corrosion strength, and relative low density of these materials.

The osseointegration rate of the implants is directly related to their surface quality. Several researches show that surface roughness affects the bone integration ratio e the bio-mechanical fastening (Gemelli *et al*, 2007). In the case of the dental implants, the machining process responsible for the generation of the thread fillet is the most influent agent in the surface quality and in the sub-surface integrity.

This paper presents a quantitative and qualitative evaluation of the surface integrity of titanium dental implants by microhardness measures and thread fillets' images obtained by SEM. Besides that, the machinability is evaluated when studying the chip formation mechanism, the tool wear and cutting temperature determination.

2. MATERIALS AND METHODS

Performed by "IMPLALIFE – Medical-Dental Products Industry", the manufacture of specimen (commercial dental implants), with dimensions of ∅5 x 15 mm and external thread M5 x 0.8 mm, has been done with Titanium ASTM F67 degree 4, machined with a turning machine CNC STAR®, model SR-20RII, with power of 2.2 kW. The machining was used external thread tool ISCAR® 16 ER 0.80 ISO IC 908 (coated carbide with TiNAl) and cutting fluid ECOCUT 910 (FUCHS®) in abundance. Cutting parameters are show in Tab. 1.

Table 1. Cutting parameters used to manufacture the specimens.

Cutting speed [m/min]	pitch [mm/rot]	Depth of cut [µm] **
19 and 70	0.8 *	100

** Thread with double entry.*
*** Deph of cutting applied in each pitch of the thread.*

The metallographic preparation of specimens began with the slitting of the samples, using a diamond abrasive disk and application of lubricating and coolant fluid in abundance. After sectioning, the specimens were built-in in polyester resin, sanding with sizes 320, 400, 600, 1000 and 1500, and polished with alumina 0.03 µm. The measures of microhardness were performed in a Carl Zeiss® microscope, model Neophot 21. The applied load was 20 gf for 15 s. The Figure 1 shows the schematic drawing of the regions where the measurements of microhardness were made.

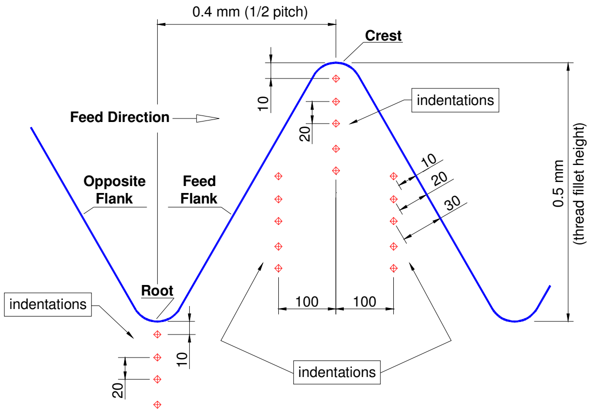


Figure 1. Schematic drawing of distances of indentations [µm].

The cutting temperature at primary and secondary shear zones was calculated on the basis of specific cutting energy. In accordance with Ferraresi (1970), considering that 90% of mechanical energy is converted into thermal energy, the cutting temperature (Tc) could be estimated by solving Eq. (1) which is derived from the First Law of Thermodynamic:

$$u=\rho\int_{T_i}^{T_c}C(T)dT \tag{1}$$

where µ [J/m3] is specific cutting energy, ρ [kg/m3] is workpiece specific mass, Ti [°C] is initial temperature before threading, Tc [°C] is cutting temperature at primary and secondary shear zones during threading and C [kJ/kg·K] is specific heat. To extract the cutting temperature (Tc) the specific heat was fitted by an exponential curve (R2 = 0.920) along to cutting temperature variation. Specific mass and specific heat range were obtained for the threaded workpiece material from Incropera and DeWitt (1992). Specific cutting energy was considered from Rodrigues (2005). Finally, the segmentation of chips was determined by Eq. (2):

$$G_s=100\left(\frac{H-h}{H}\right) \tag{2}$$

where Gs [%] is chip segmentation degree, H [µm] is the chip maximum thickness and h [µm] is the ligament length in chip shear bands.

3. RESULTS AND DISCUSSION

It's showed below the measurements of microhardness and visual characterization of threaded profiles into three major regions: crest, root and sides of the threads lead. The average deviation statistical measures associated with the microhardness was ± 1.8%, considering a confidence interval of 95% and one reply (two specimens for each cutting conditions).

3.1 Microhardness and visual characterization of thread crest

Microhardness measurements of the crest f the thread were made as illustrated in Fig. 1. The decrease levels of microhardness with increasing depth below the surface screw is shown in Fig. 2.

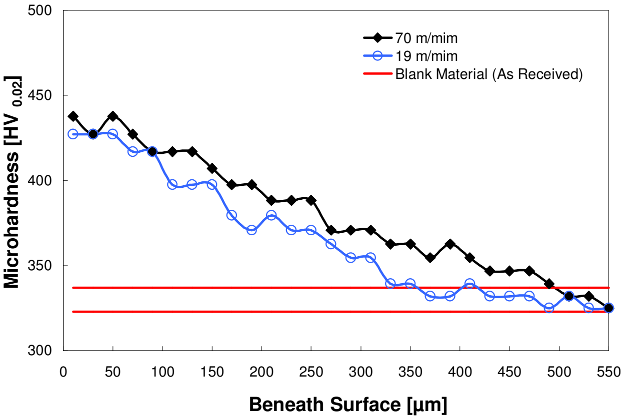
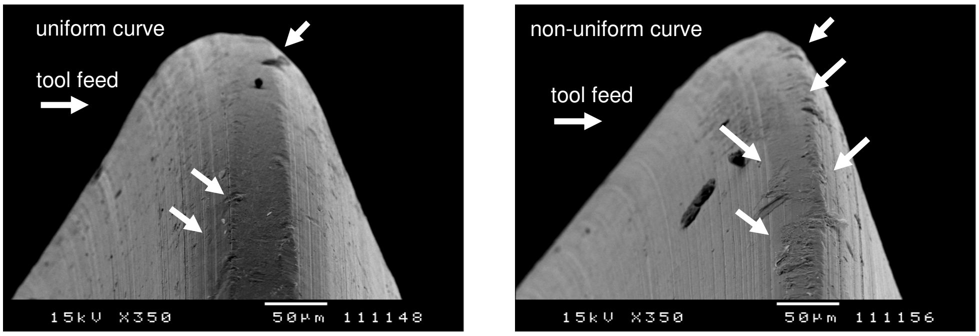
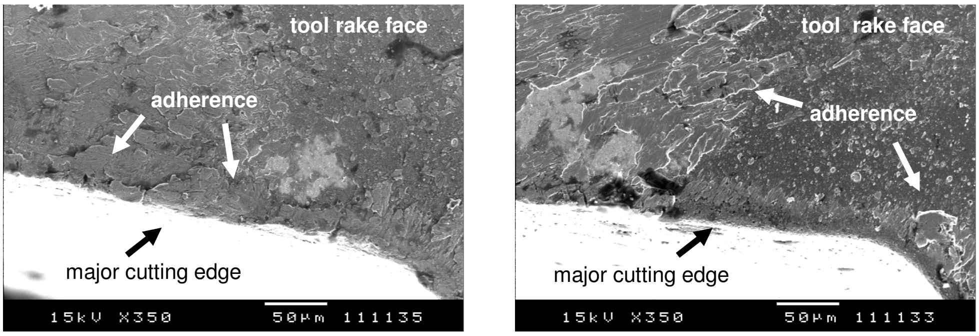


Figure 2. Microhardness profile in thread crest.

Notice that the cutting speed increase of 19 to 70 m/min promoted an increase about 160 µm in hardened layer by the treading process, taking as reference the range of microhardness of the material in the raw state. The lowest cutting speed reached a layer cold worked of 330 µm, while the higher cutting speed reached 490 µm. Both profiles of microhardness showed a gradient about 0.2 HV/µm, which reached an average level of threaded surface microhardness of 430 HV, in other words, 27% higher than the raw material. It is observed that the curve resulting from the higher cutting speed always presents higher levels (about 10 HV), regardless of the depth measure. This behavior of the microhardness in the subsurface threaded can be explained by the hardening of the material (cold work) given the increase in the level and rate of deformation resulting from the increase of cutting speed. Figure 3 shows images obtained by SEM of the surface quality of the thread crest and its relationship with the rake face of the cutting tool.



(a) v_c = 19 m/min (b) v_c = 70 m/min



(c) v_c = 19 m/min (d) v_c = 70 m/min

Figure 3. Images from SEM of thread crest root (a, b) and tool (c, d).

Looking to Fig. 3a, it is observed that the thread machined with the cutting speed of 19 m/min showed a more uniform profile in the radius of rounding of the crest, with few points of pullout of the material of the piece. The thread machined with the cutting speed of 70 m/min, shown in Fig. 3b, exhibited a profile of rounding the crest more irregular (deformed toward the direction of feed of the tool), containing various micro-regions of pullout and flow of material. This behavior is related to the small volume of material in the crest and the high mechanical strength at high temperatures before increasing the cutting speed. Under these conditions, the material has no time to exercise their plasticity and small fractures pieces are removed with the chips. The ductility of titanium is 60% lower than the structural steels. Even with the irregularity in the rounding of the crest of the thread, which was more pullout and lateral flow of material by increasing the feed speed, the greater the cutting speed has a better finishing by the reduction of deformations and radial grooves. The irregularity in the rounding of the thread crest maybe can influence the threading process into the bone given the greater torsion, but this may be not prejudice the dental implant functionability.

Figure 3c shows that there was no significant deposition of pieces material on the major cutting edge and the rake face of tool by using low cutting speed, these converging results to the microhardness and quality of thread for this condition of machining. However, the speed of 70 m/min, it's possible to see a lot of material joined in the regions of the tool that are responsible for the machining the flank and the crest of the profile of the thread (Fig. 3d). In this case, the high temperature at tool-chip interface and low thermal diffusivity of titanium (about 50% lower than that of structural steels) favored the process of adhesion of material on the cutting tool.

3.2 Microhardness and characterization of thread root

Other critical region related to the bone-integration and mechanical loads of dental implant is the thread root. Similarly to thread crest, Fig. 4 shows the decrease of microhardness with the increase in depth beneath thread surface.

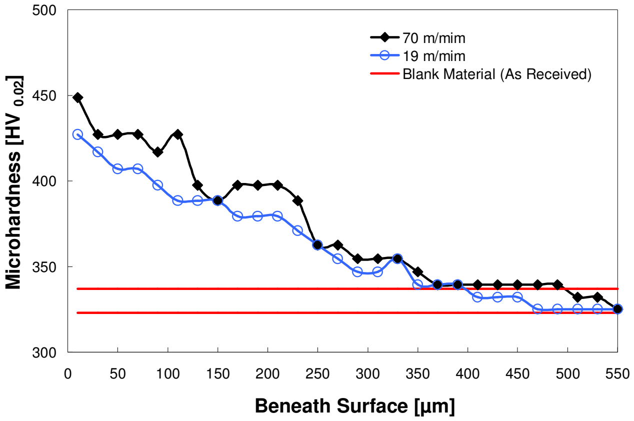
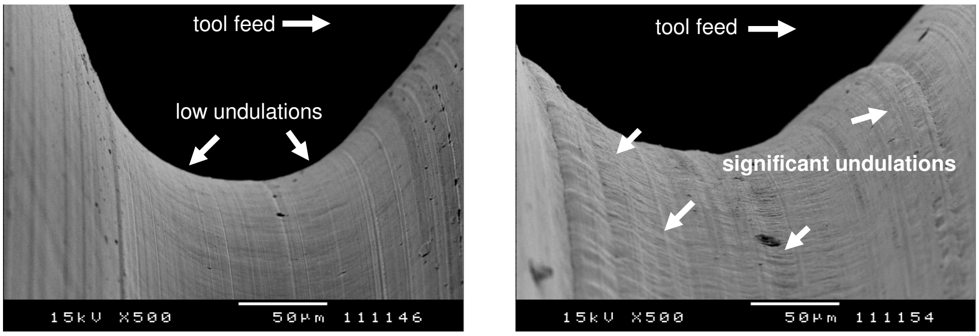
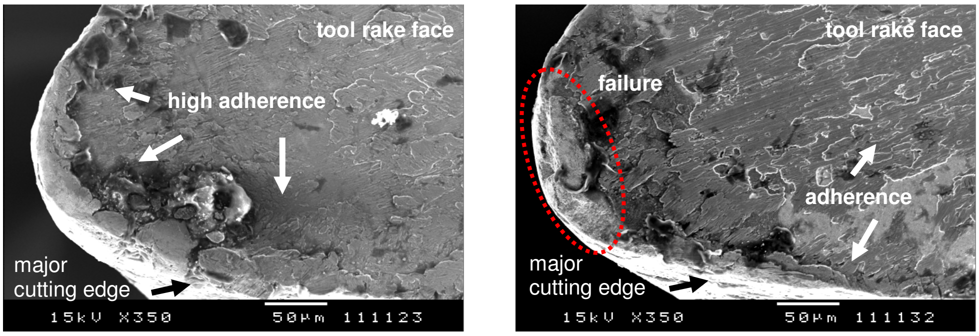


Figure 4. Microhardness profile in thread root.

It can be seen that the high speed cutting caused an increase of 100 µm approximately in hardened layer when the measurements are compared to the blank material. The lower cutting speed reached a hardened depth of 390 µm, while 70 m/min cutting speed attained 490 µm. The microhardness profiles presented also a medium gradient about 0.2 HV/µm, reaching nominal values in the thread surface of 450 HV against 427 HV from 19 m/min cutting speed. It is possible to note that microhardness levels related to the high-speed cutting are greater than that from lower cutting speed, except for the depths of 150 and 250 µm. This difference decreases when depth beneath thread surface increases. Analogue to thread crest, the microhardness behavior in thread root indicates that hardening due to higher strain rate is the main factor influencing on surface integrity. Images from SEM of thread root surface and their relation with the tool rake face are shown in Fig. 5.



(a) v_c = 19 m/min (b) v_c = 70 m/min



(c) v_c = 19 m/min (d) v_c = 70 m/min

Figure 5. Images from SEM of thread root (a, b) and tool (c, d).

The Fig. 5a reveals that thread screw machined at 19 m/min presented a more uniform profile in the root region with few undulations and vibration marks. The thread root performed at high speed cutting exhibits high irregularity degree, evidenced by excessive vibrations and significant undulations (Fig. 5b). Figure 5c demonstrates that lower cutting speed caused a sensitive adherence of workpiece material over tool edge, without affecting the thread root surface quality. However, it is possible verify that high speed cutting caused significant adherence over tool rake face and wear located on tool tip radius (Fig. 5d). Probably the high cutting speed and vibration can have worn the tool and produced the irregularities in the thread root. This phenomenon was helped by confinement of tool tip radius in the thread root.

3.3 Microhardness and visual characterization of thread flanks

Microhardness presented distinct patterns for the fillets lateral surfaces of the thread. The surface placed in the feed direction, named tool entry, indicates that the cold work of the thread fillets' sub-surface reached the extension of, approximately, 230 µm for the higher cutting speed and 250 µm for the lower cutting speed (Fig. 6a). This shows that the cutting speed wasn't significant determinant in the extension of the hardened layer. The microhardness gradient was on average of 0.40 HV/µm for both cutting speeds, but the lower amplitudes of microhardness were generated by the cutting speed of 19m/min up to the depth of 150 µm. Below this value, the microhardness gradients may be considered similar. In the same way of the previous results, the higher cutting speed led to a hardening on the flank surface of the thread.

The surface opposite to the feed direction, named tool exit, presented an inverse behavior in the thread sub-surface (Fig. 6b). Between 20 and 160 µm depth beneath the surface, the lower cutting speed caused a higher hardening, achieving an increase of up to 40 HV. Besides that, the microhardness gradient for the cutting speed of 70m/min was 70% higher than the one of the lower speed (0.80 against 0.47 HV/ µm). However, in the machined surface, the cutting speed of 70m/min generated the higher values of microhardness again, showing the same levels of the thread's lateral surface on the feed direction. The extension of the cold worked layer was similar to the sub-surface on the feed direction, reaching 200 µm to the higher cutting speed and 250 µm to the lower speed. Taking the raw material as reference, the increasing of the microhardness for both surfaces of the thread's fillets reached 30% and achieved an average level of 440 HV in the threaded surface. These results as similar to the thread root's ones, what shows that the root and the flanks of thread's fillet are the most request during the threading process.

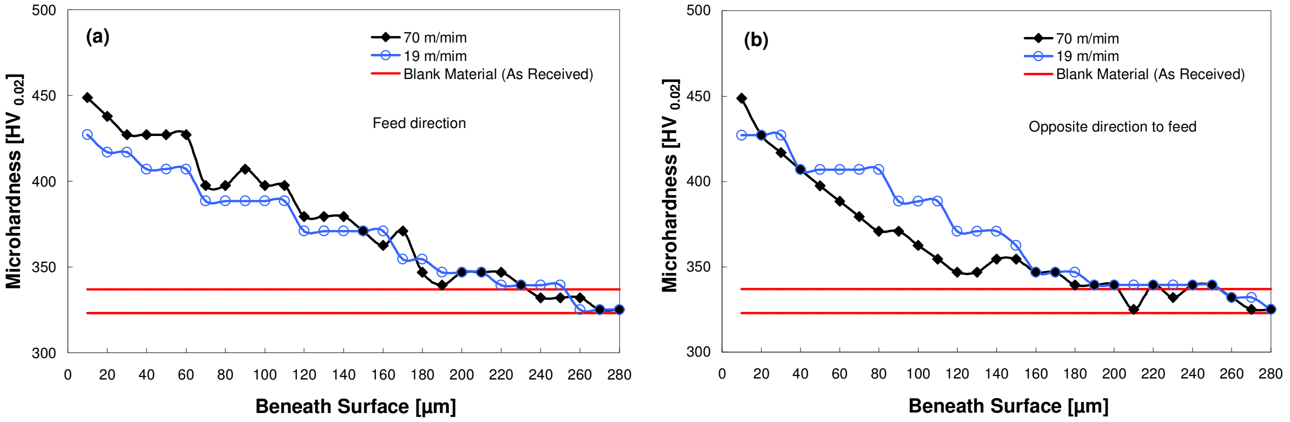
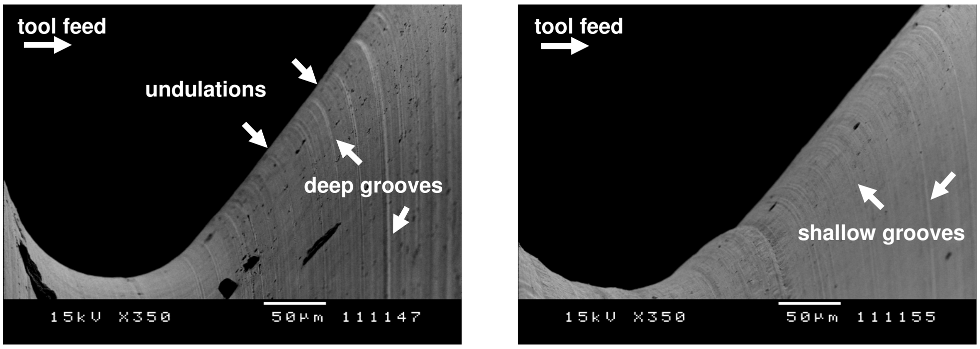


Figure 6. Microhardness profile in thread flanks in feed direction (a) and opposite direction to feed (b).

As regards the quality of the flank surfaces of the thread's fillets, it can be seen that the employee of the higher cutting speed resulted in a smaller quantity of grooves and lower levels of undulations. This behavior happened on the both flank of the fillets, being that referring to the feed direction shown on the Fig. 7b. For the cutting speed of 19m/min, however, the undulations marks and the grooves were significant (Fig. 7a). This behavior of the quality of the threaded surfaces is related to the cutting speed and to the tool performance, as shown on the Images 5c and 5d. When employing the lower cutting speed, there was adherence of the workpieces material in the edges of the tool, increasing the upsetting of the adhered material against the machined surface. For the higher cutting speed, the adherence level in the tool edges wasn't significant and didn't harm the quality of the thread's flanks.

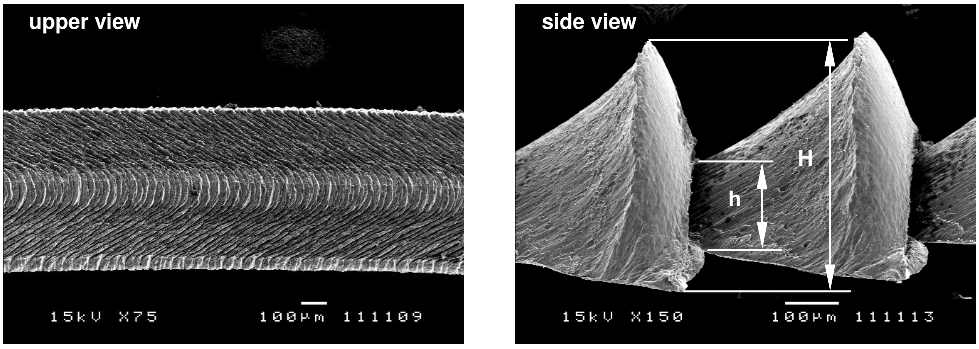


(a) v_c = 19 m/min

(b) v_c = 70 m/min

Figure 7. Images from SEM of thread flank (feed direction).

The Fig. 8 shows images of the generated chips in the threading process. It can be seen that the cutting speed was decisive on the chip formation mechanism, therefore, about the shape, both were band chips, but, about the type, the lower cutting speed generated continuous chips, whereas segmented chips were generated for the higher cutting speed. The band chips are characterized by the overlap of the flakes, not been possible to differentiate them even with microscopy and the segmented chips are determined in the machining under high cutting speeds of materials with poor thermal properties, such as titanium. In these conditions, the localized deformation occurs in intense ways on the shear bands of the chips and the flakes are disposed totally free of deformation of the microstructure. The formation mechanism is ruled by the balance in adiabatic conditions between the cold work ratio due to the mechanical action of the cut and the ratio of softening caused by the thermal effect in the primary shear zone.



(a) v_c = 19 m/min (b) v_c = 70 m/min

Figure 8. Chip (a) continuous and (b) segmented provided in threading.

Aiming relate the chip formation mechanism to the results of machinability and surface integrity of the machined material, the average segmentation ratio of the chips generated under high cutting speed was measured, Eq. (2), and the cutting temperature was estimated, as shown in Eq. (1). The segmentation ratio reached 63%, which is equivalent to a percentage of ligaments between the flakes of just 37% (Fig. 8b). Despite of the threading process resulted in an elevated chip segmentation ratio, it can be seen that this effect not contributed in the process, once the higher level of material adhered on the tool and to the low surface quality of the threaded surfaces. Commonly, segmented chips tends to decrease the cutting force and increase the cutting ratio, promoting the shear of the material and the surface finish. The cutting temperature, estimated by the procedures above described , reached the interval between 987 and 1283°C, signaling that the machining generated a temperature above the material's homologous temperature (977°C), independent of the cutting speed adopted. This fact indicates that the deformation ratio played the major role in the threading process, what means, in the tool wear, in the increasing of microhardness of the threaded surface and in the surface finish of the thread fillets.

4. CONCLUSIONS

The main conclusions of the study are outlined below:

- The cutting speed for the operation of external thread in commercially pure titanium affects the machinability and surface integrity of the piece. The process of thread caused an increase in surface microhardness of approximately 30% compared to the raw material provided 'as received', with a statistical deviation of 1.8% and reliability of 95%;

- The higher the cutting speed, the higher the microhardness on the surface and the deepest layer is cold work. The thread at high speed cutting increased by 5.4% in the surface microhardness and increased by up to 48% in the subsurface layer threaded hardened, both in comparison to the cutting speed. The gradients of microhardness were similar, except on the lateral surface of the fillets in the direction opposite to the advancement of the tool, where the high speed cutting increased the gradient by 70%;

- There was adhesion of material piece of the tool, independent of speed cutting employed, being located on the edge for low speed and distributed on the rake face for high speed cutting;

- The quality surface of the thread depends on the cutting speed, with the performance of the tool and the mechanical properties and thermal-physical of titanium. The machining at high cutting speed caused tearing of the material and plastic deformation of the crest of the thread towards the feed direction, increased vibration and waves in the root, and reduction of undulations and grooves in the thread flanks;

- The cutting temperature calculated in primary shear zone has a range above the homologous temperature of the material, indicating mainly that the rate of deformation, beyond the level of deformation, was decisive in the behavior of the microhardness, surface quality of the thread, the performance tool and mechanism of chips formation.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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