TOOL WEAR AND SURFACE ROUGHNESS EVALUATION OF THE REAMING PROCESS FOR THE 15-5 PRECIPITATION HARDENING STAINLESS STEEL

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Abstract. *This paper presents the results of the reaming process for two types of the 15-PH stainless steel. This paper also presents a comparison between several cutting conditions, aiming to define the best relation between cutting speed and feed per teeth for a solid carbide multi tooth reaming tool. It was observed that the feed rate is the main aspect for a reasonable chip formation due to the preciptation hardening profile that usually provides a poor chip formation condition. The tool wear was related with the roughness profile and it was possible to conclude that the wear for the reaming process is strictly concentrated at the flank surface and no chipping can be measured before the total collapse of the tool when the chip is not correctly extracted from the hole. The hole preparation was performed in order to submit the reamer to a industrial common condition for a H7 quality profile. The aging heat treatment showed to be worst for the tool wear, however it proved to be reliable for the chip formation. All the cutting condition can be considered as "severe" and the tool perfomance is acceptable for this type of material.*

Keywords*: Reaming; Tool Wear; Cutting conditions; stainless steel; surface roughness*

1. INTRODUCTION

The reaming process is widely used to produce holes with surface and cylindrical specifications under 0,8 μRa and H7 standard level respectively. The reaming technology is related with drilling and milling at the same time but the cutting parameters are specifically for this kind of operation. A reamer cuts in the same direction that a drill and sometimes it´s sharped like a solid mill cutter.

The tool is the reamer and this can be solid, interchangeable, single-teeth, multi-tooth and the majority of the applications are rotary tools and static workpiece.

A very important cutting condition for the reaming process is the feed rate. The feed rate will conduct with good accordance to the hole specifications and also will provide the stability of the process, specially in those applications which the chip is not well removed from the cutting region because of the workpiece material high ductility. This condition is easily observed during the reaming process of all types of stainless steel.

It´s common to observe at the machine shop a programming error during the reaming process specification. This error is to decrease the feed per teeth of the process. This is an erroneous idea because as soon as the feed is decreased, the chip formation won´t offer a regular chip flowing out of the cutting interface and this will provide not only the surface roughness damage but also a chip constraining. Once the chip is not removed it clearly affects the hole quality and unfortunately damage the tool.

The reaming process is usually applied with coolant and the coolant composition must be strictly related with lubricity and heat extraction capacity of the cutting fluid. Even tough the reamer cuts a narrow width of the material, the surface friction along the reamer guides and cylindrical body also affects the heat generation and the fluid is about to reduce this negative effect.

Nowadays the reamer technology provides internal coolant reamers and special multilayer cover that increase the tool life and performance.

It´s common to say that the precipitation hardening stainless steel series is one of the most difficult material to be machined. The strain hardening profile offered by this austenitic series increases the material resistance along the machining process. All the deformation at the cutting interface is suggested to become chip during the chip formation but for this type of material this condition reflects onto the workpiece, increasing the mechanical resistance of the material and consequently damaging the tool.

The wear behavior of the reamer is concentrated at the entrance of the tool. Flank wear is observed in most of the applications.

This paper presents results during the reamer process of the 15-5 Ph stainless steel. All the details of the machining process are presented at 3. An overview of the reaming technology and metallurgical aspects of the workpiece material can be seen at 2. The results observed at 4 are an extract from the trials proceeded following 3.

2. BIBLIOGRAPHIC REVIEW

2.1. The reaming technology

The reamer is a tool oriented for finishing operation and it depends strictly from the previous drilled hole surface roughness and alignment. The reamer is supposed to cut a small part of the hole material volume (round 3,5%). The development of special drills to produce the previous hole became an enough condition to the use one single finish reamer instead of two tools.

Some special features of the reamer are the unequal angular tooth distribution and the feed rate to be applied in this process. A rotary tool like a reamer must be centered in other to avoid incomplete cut along the hole and the unequal distribution of the teeth is concerned to offer it, Acacio (2008a).

Another geometrical consideration is the flute geometry. This geometry is related with material ductility and hole type. As soon as the workpiece material ductility increases the flute angle is suggested to be positive in other to extract the chip from the hole with lower attrition between the reamed hole and the tool. Lower ductility of the workpiece material tolerates neutral flute angle.

The feed rate for the reamer operation is also an important aspect of the tool design and cutting parameters. Despite the fact a reamers cuts a narrow chip it increases the specific cutting pressure and this condition leads to quality problems because of the vibration.

Ferraresi (1972) suggests for the reamer design a combination of lead angles in other increase the reaming stabilility. Nowadays this stability is also increased by the use os guides along the flutes and shaper and wear resistant cover, Acacio (2007b).

Figure 1 presents the general characteristics of a reamer, following Acacio (2008a) and Ferraresi (1972) and figure 2 presents the lead angle combination according to Ferraresi (1972).

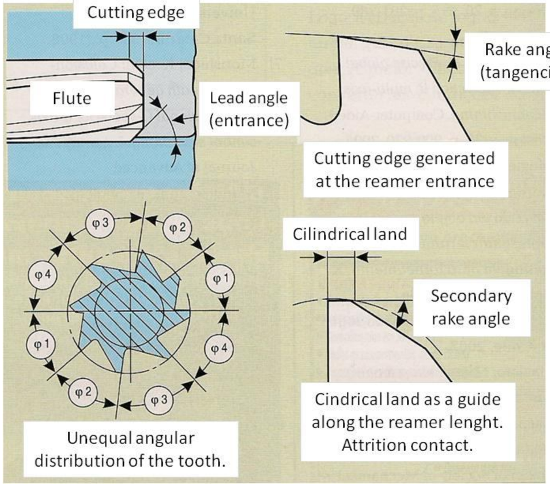


Figure 1. Reamer characteristics according to Acacio (2008a) and Ferraresi (1972).

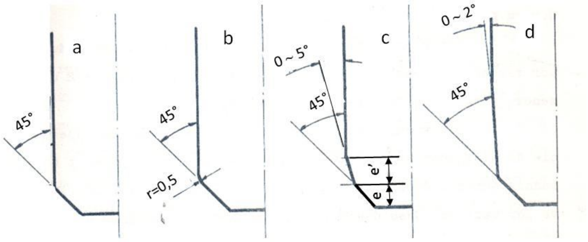


Figure 2. (a) Regular lead angle. (b) Regular and honed edge. (c) Double chamfer. (d) Double chamfer aligned with the flute. According to Ferraresi (1972).

The cutting parameters area calculated normally using the well know equations, according to Guhring (2007) and the cutting speed is also tabled like the other machining process.

The cutting tool material for a reamer must be harder than tougher because of the concentrated heat generation that occurs at the entrance of the tool. K10 ISO grade is the common material for producing reamers and the covers must be controlled in order to not to change the tool diameter.

Acacio (2007b) observed the reaming operation for titanium and concluded that during the reamer operation the cutting edge will accommodate during the first set of holes. This idea is also observed during the reaming operation for ductile and hard materials. At this stage, the vibration is also observed and the cutting edge is being naturally honed by the machining process. After this stage, the tool is ready for the operation providing better surface finish.

2.2. The 15-5 precipitation hardening stainless steel

This is a martensitic, precipitation hardening, chromium-nickel-copper stainless steel. The main applications of this material are: aircraft components, fabricated parts in high pressure corrosive environments including valves, shafts, fasteners, fittings and gears.

It´s a very sensitive material because of the precipitation hardening profile. The table 1 presents the mechanical properties as function of solution heat treatment temperature. This grade of stainless steel is also produced by ESR or VAR foundry process. Table 2 presents the chemical composition.

Table 1. Mechanical properties as a function of the solution heat treating temperature, according UNS 15500.

Solution temperature	*Tensile Strenght*	*Elongation (%)*		*Reduction of area (%)*		*Hardness*	
(F)	(MPa)	Min		Min		(HB)	
		Long.	Trans	Long.	Trans	Min	Max
900	1310	10	6	35	20	388	444
1000	1172	10	7	38	25	375	429
1025	1069	12	8	45	32	331	401
1050	1000	13	9	45	33	311	375
1100	965	14	10	45	34	302	363
1150	931	16	11	50	35	277	352

Table 2. Chemical composition, according UNS 15500.

C	Mn	P	S	Si	Cr		Ni		Cu		Cb + Ta	
0,07 max	1,0 max	0,04 max	0,03 max	1 max	14 min	15 max	3,5 min	5,5 max	2,5 min	4,5 max	0,15 min	0,45 max

The elasticity modulus is about 200 GPa. The precipitation hardening (PH) profile is a hardening mechanism also called age hardening or dispersion hardening. The central idea of this characteristic is to provide fine particles of controlled impurities phases which constrain the movement of dislocation or defects in the crystal´s lattice. Since the dislocation are the main aspect in the plasticity behavior, this constrains serves to harden the material. The solution heat treating involves the formation of single-phase via solid solution.

2.3. The 15-5 stainless steel machinability

Trent (1984) considered the austenitic stainless steel as more difficult material to machine than carbon or low alloy steels. This profile is related with the amount of Ni and Cr in the alloy. Trent (1989) considers the intermediate phases formation (the precipitation behavior cited above) as the explanation for the wear mechanism of this grade of stainless steel.

Krabbe (2006) reviewed the literature about stainless steel and following Trent (1989) concludes that adhesion followed by chipping are the main wear mechanisms for this grade of material. Braghini apud Krabbe (2006) and Acacio (2007b) also concluded that the use of lubrication decreases the tool life during milling operation. Figure 3 presents the wear of a cutting tool related with adhesion and followed by abrasion, according to Acacio (2008c).

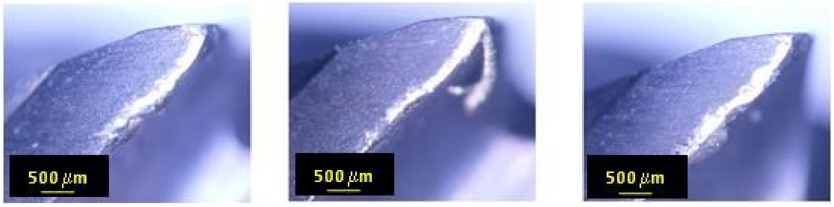


Figure 3. Wear pattern for machining 15-5 Ph stainless steel. The lightening area along the cutting edge shows the adhesion behavior. It´s also observed a notch at the end of the cutting depth, after Acacio (2008c).

It´s possible to conclude about stainless steel machinability that as more as the nickel and chromium amounts increase, the machinability grade decreases until we overcome the steel classification that finds its end at the beginning of nickel base super alloy, like Inconel and many others.

By the same way that happens with low and medium steel alloys, the manipulation of sulphur, manganese, phosphorous and silicon provide better machinability grade because of the decrease of rupture limit and elasticity modulus. According to Bain and Paxton (1966) the following chemical coumpounds influence mechanical behavior as follows:

- Carbon (C): Increase hardenability and carbide formation. Decrease machinability;
- Manganese (Mn):Moderate contribution to hardenability. Increase machinability;
- Phosphorus (P): Corrosion resistance. Increase machinability.
- Sulfur (S): Decrease strength. Increase machinability.
- Silicon (Si): Moderate contribution to hardenability.
- Copper (Cu): Increase electrical properties associated with heat.
- Nickel (Ni):Increase adhesion and corrosion resistance. Decrease machinability;
- Chrome (Cr): Increase hot hardness resistance. Increase corrosion resistance. Decrease machinability;
- Cobalt (Co): Increases creep temperature and accelerates carbide forming.
- Tantalum (Ta):Increase abrasion behavior by forming interstitial hard particles (carbides).

Figure 4 synthesizes the idea of chemical compounds influences on steel, according to Bain and Paxton (1966).

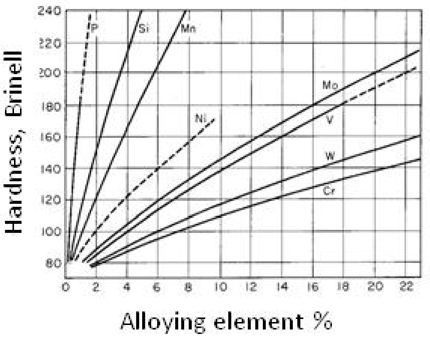


Figure 4. Influence of the chemical elements on hardness, according to Bain and Paxton (1966).

3. EXPERIMENTAL PROCEDURE

3.1. Materials and equipments

A reaming operation has been executed under several cutting conditions. The details for this operation are listed below.

Machine: Okuma MC-V4020 vertical milling center (14,7 Kw).

Cutting tool: 11,7 mm solid carbide reamer. The details for the reamer are presented at table 3.

Table 3. Cutting tool specification.

Tool	*N° of Tooth*	*γ axial*	*γ radial*	*Substrate*	*Cover layer*	*Supplier*
Solid carbide reamer	6	0º		WC+C K10	TiAlN	Guhring

Figure 5. Solid carbide reamer used on the trials

Material Sample: Two types of 15-5 precipitation hardening stainless steel. The details for the samples are listed at table 2. The solution treatment occurred at 1025 F for all the submitted samples.

Table 2. Material sample specification.

Material Type	*Heat treatment*	*% Weight Sulphur*	*Hardness*
704 – SE	Solution annealing and aged	10 PPM	363
656 – SE	Solution annealing and aged	45 PPM	363

Measurement: Olympus optical microscope Bx60M with 20, 50 100, 200 e 500X magnification.
Fixture set-up: Figure 6 presents the fixture system.

Figure 6. (a) Material sample fixture. (b) Hydraulic fixture for the tool.

Coolant / Lubrication: Semi synthetic emulsion of 10,5% made with BIO G 1017 – Micro Química.

3.2. Experimental routine

Table 3 presents the experimental planning for the reaming operation. The reamed holes depth were 54mm. All the holes were produced in a previous hole of 11mm diameter made with a solid carbide drill hold in a hydraulic tool holder. The drilled holes were cleaned up before the beginning of the reaming process in order to avoid the chip jam inside the produced holes.

The sequence of holes was produced without observing the wear and this were only observed at the end of the investigation. The machine strategy for operations, drilling and reaming were both without pecking cycle.

Table 3. Experimental planning for the reaming operation

Experiment n°	*Material*	*Cutting speed (m/min)*	*Feed per teeth (mm/teeth)*
1	704 - SE	90	0,2
2		180	0,2
3		270	0,2
4		90	0,4
5		270	0,4
6	656 - SE	90	0,2
7		180	0,2
8		270	0,2
9		90	0,3
10		270	0,3

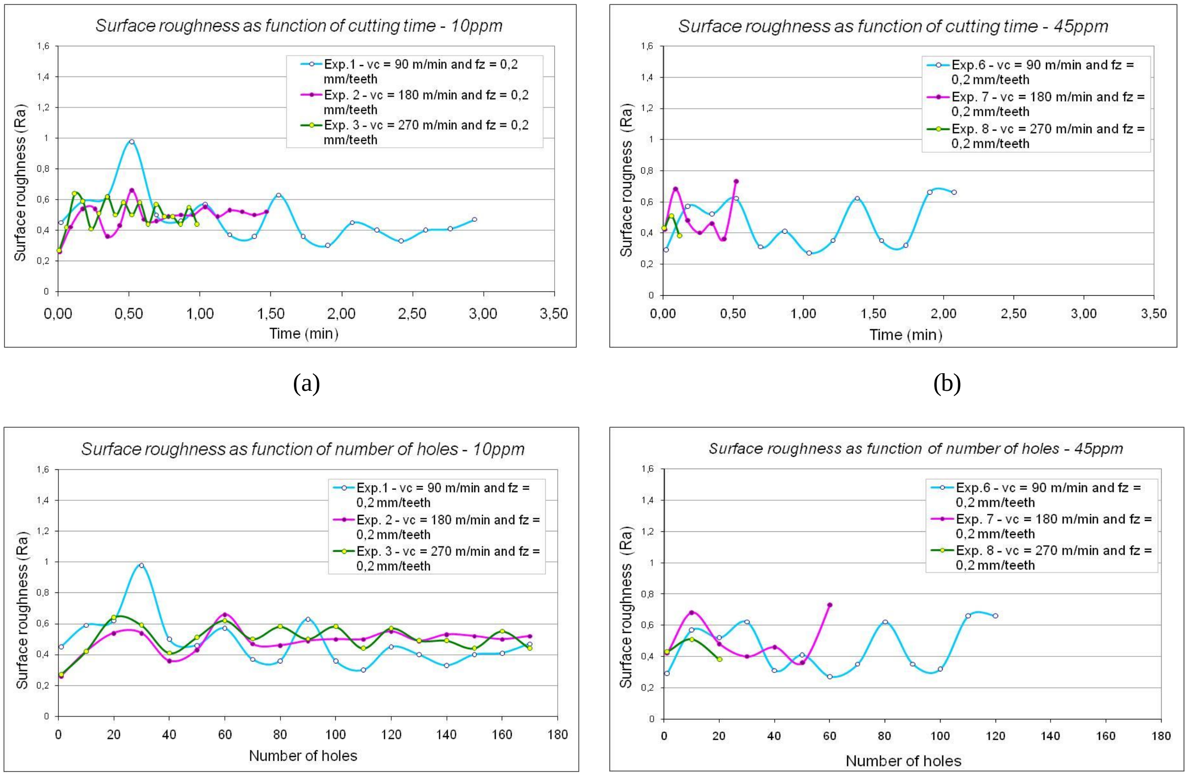
The sequence of the experiments followed exactly the table 3. The wear criteria applied was composed by the analysis of the two aspects: (first criteria) a limited number of reamed holes (170 holes for each experiment) or (second criteria) the tool brakeage along the reaming sequence from the first up to the last reamed hole. The sequence of reamed holes was produced without measuring the flank or the rake face wear. These were only observed at the end of the investigation with the use of optical microscopy. The machine strategy for the operations of drilling and reaming were both without pecking cycle.

One important aspect that was only observed during the first trial of experiment 9 is that an uncontrolled strain hardening profile was observed, and the table 3 that had been previously compiled with the same feed per teeth values for both materials was corrected in order to provide a reasonable tool life observation. The experiment 9 with 0,4 mm/teeth was performed three times and the reamer has broken out at the first hole. This condition led us to conclude the table 3 that was applied in this investigation.

4. RESULTS AND DISCUSSION

4.1. Surface roughness

The figures below present the surface roughness as a function of accumulative cutting time and number of holes for the two types of steel.



(a) (b)

(c) (d)

Figure 7. Surface roughness as a function of accumulated cutting time (a,b) and accumulated number of holes (c,d).

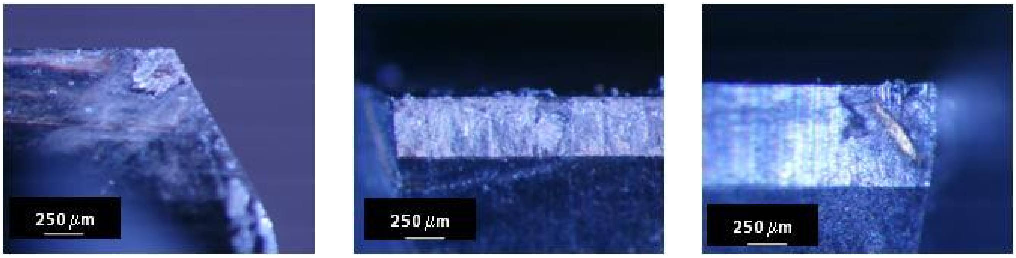
It´s possible to observe at figures 7-(a) and 7-(b) that an increase in sulfur amount from 10 ppm to 45 ppm conducted to a decrease in tool life. From figures 7-(c) it is possible to observe that at the begging of hole sequence the surface roughness presented a higher fluctuation and a lower cutting speed (90m/min) seems to be the best cutting condition. All the information at figure 7 was performed with 0,2 mm/teeth.

The severe number of holes reduction observed at figure 7-(d), compared to figure 7-(c) is related with tool breakage. The higher amount of sulfur decreased the chip formation characteristic and this aspect conducted to continuous chip curled on the tool shank. The figure 8 presents the unfavorable chip curled on the tool shank.

(a) (b)

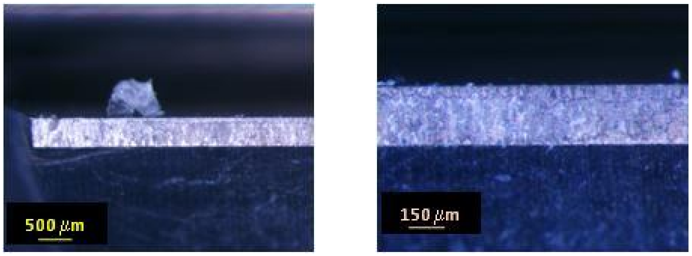
Figure 8. Curled chip on the tool shank (a) and hole obstructed (b).

It was observed during the trials that an increase in the feed per teeth could be a solution for the chip obstruction and tool breakage. The figures 9 and 10 present the tool wear for those conditions where no breakage occurred.



(a) (b) (c)

Figure 9. Tool wear related with the tool nose. Figure 9-(a) presents the rake face. Figure 9-(b) presents the secondary clearance face. Figure 9-(c) presents the primary clearance face and the major cutting edge.



(a) (b)

Figure 10. Tool wear related with minor cutting edge - reamer guide. Figure 10-(a) complete contact length. Figure 10-(b) presents the outer region of the guide.

It was observed at figures 9 and 10 that the tool wear is strictly related with adhesion and consequently pull out the adhered material. This behavior is controlled and no chipping or notching was observed. When the tool broke, no previous wear was measured but after the relation of curled chip and the tool wear it is possible to conclude that the tool grinding profile was changed by two reasons: the adhesion behavior of the material and the inadequate relation between cutting speed and feed per teeth. This inadequate relation conducts to curled chip without good evacuation.

Adhesion can be observed at all of the detailed figures (a,b and c) at figure 9. The lighting region indicates nickel welding. The figure 10 presents also a change in wear mechanism: adhesion and abrasion. No chipping was also observed at this region but a different profile of the wear can be seen at the outer region of the tool minor edge, according to figure 10 (b)

The usual practice of reaming leads to a common misunderstanding and the feed per teeth is wrongly decreased in order to increase the surface roughness quality. By the other hand the chip is badly formed and the tool breakage consequently occurs.

Acacio (2008c) observed adhesion profile not only at stainless steel but also nickel base super alloys and concluded that the adhesion is always followed by notching and abrasion. No notching was observed but a scratched profile was observed and this can be related to the pulling out behavior of carbides probably found at the material matrix. Figure 11 presents the scratched after adhered surface suggested. This fact conducted to the feed per teeth manipulation once the results above were discussed. These results are discussed after figure 12.

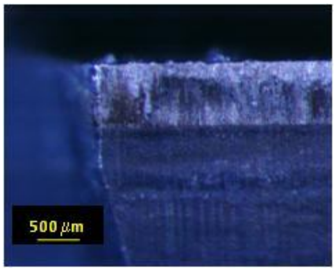
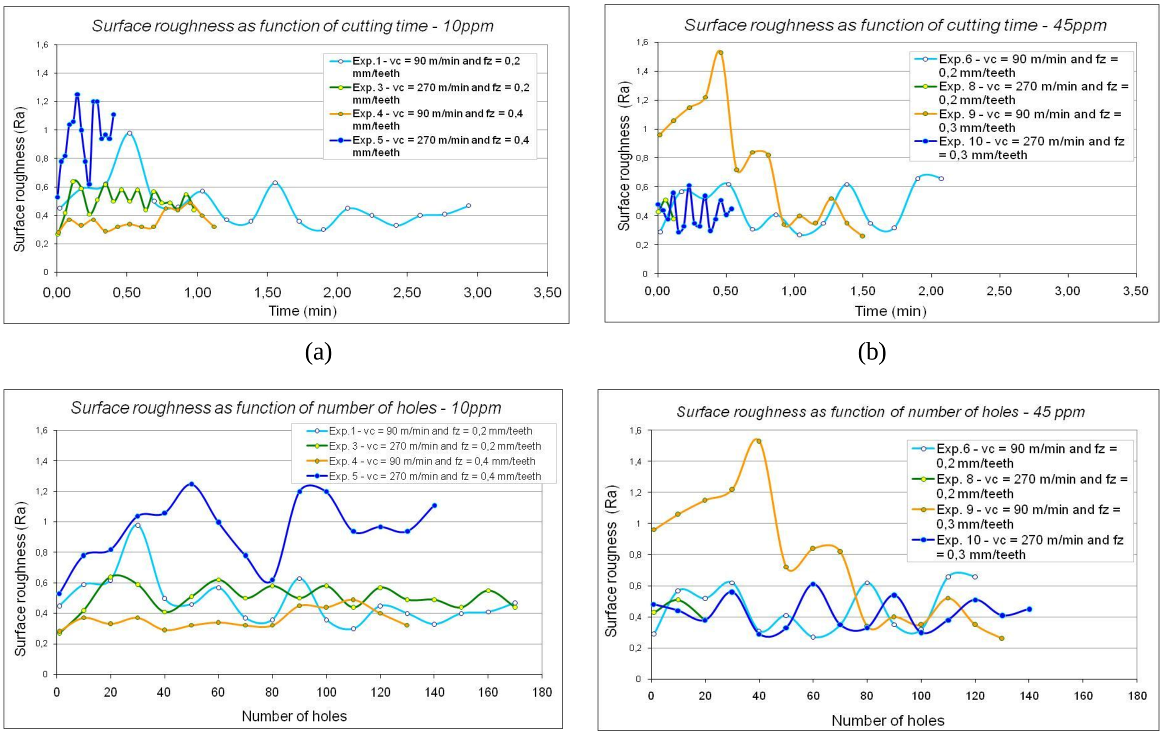


Figure 11. Adhesion followed by scratching suggested by Acacio (2008c).



(a)

(b)

(c)

(d)

Figure 12 . Surface roughness as a function of accumulated cutting time (a,b) and accumulated number of holes (c,d).

It was possible to observe at figures 12-(a) and 12-(b) that no tendency can be outlined for the roughness profile along all the hole sequence performed. By the other hand, according to figure 7, the beginning of the trials shows a higher fluctuation and all the surface roughness average is under 0,6 μRa. During the trials, it was also possible to observe that an increase of 100% in the feed per teeth was not possible for the 45ppm material. This condition was concluded after a set of tool breakage at the first reamed hole. The explanation for this situation is related with strain hardening profile of the material. It means that even with a higher amount of sulfur, which should increase machinabilility, the strain hardening profile plays an important hole in the reaming process.

Acacio (2008c) concluded better machinability for a higher amount of sulfur for milling but this tendency can not be expanded for reaming.

The wear profile under higher feed per teeth condition provided a notch at the primary clearance face just below the major cutting edge. It is also possible to conclude about the tool wear that the adhesion behavior increased with the feed per teeth increase and the adhesion was also predominate at the guides. Figures 13 and 14 conclude the wear behavior under higher feed per teeth condition.

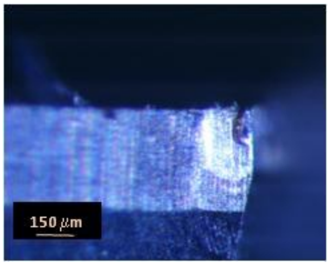


Figure 13 . Notch at the major cutting edge with the use of higher feed per teeth (0,4 mm/teeth).

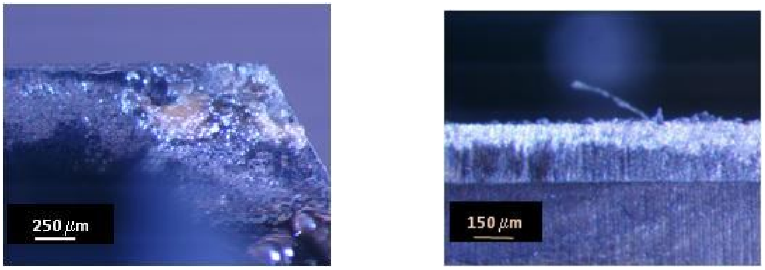


Figure 14 . Higher adhesion behavior with the use of higher feed per teeth (0,4 mm/teeth).

5. CONCLUSIONS

The following ideas are the conclusion of the investigation presented above:

- The reamer technology suggested above is reasonable for machining PH - stainless steel und 0,6µRa for every combination of cutting speed from 90 to 270 m/min and feed per teeth from 0,2 to 0,3 mm/teeth;
- The adhesion is the predominant wear mechanism followed by abrasion for every cutting condition cited above;
- At higher feed rate the adhesion increases and notch wear becomes a tendency;
- The precipitation hardening profile assured to the 15-5 Ph stainless steel is observed at higher feed rate (0,4 to 0,6 mm/teeth);
- Fluctuation of the roughness at the begging of the trail sequence was observed and it may be related with a cutting edge natural honing which occurs at the cutting edge up to the moment of machining stabilization;
- The curled chip on the tool shank leads to the tool breakage;
- Differently from the results observed by Acacio (2008c), a higher amount of sulfur didn´t conduct to a better chip evacuation as observed in milling;

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