Influence of Cutting Environments on Surface Integrity and Power Consumption of Austenitic Stainless Steel

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Abstract

Surface roughness is a result of the cutting parameters such as: cutting speed, feed per tooth and the axial depth of cut, also the tool's geometry, tool's wear vibrations, etc. Moreover, the surface finish influences mechanical properties such as fatigue behaviour, wear, corrosion, lubrication and electrical conductivity and the combination of cutting parameters influence the power consumption during the machining process affecting the environment. The research reported herein is focused mainly on searching for an optimum combination of cutting parameters to obtain a low value of surface roughness and minimize energy consumption when milling an austenitic stainless steel in different cutting environments. The experiments were conducted on a Siemens 840D Bridgeport Vertical Machining Centre 610XP2. The selection of this workpiece material was based on it's widely applications in cutlery, surgical instruments, industrial equipment and in the automotive and aerospace industry due to its high corrosion resistance and high strength characteristics. The results show that the dry cutting environment is the best option in terms of power consumption and surface roughness values to conduct the milling of an austenitic stainless steel under the selected cutting parameters.

1. INTRODUCTION

Metal machining processes generates heat due to tool friction, increasing tool wear and as a consequence reducing the tool life. Despite the fact that the use of cutting fluids benefits the cutting process as they remove heat more rapidly, some conventional cutting fluids are ineffective in controlling the high cutting temperature and the rapid tool wear as well as knowing how they deteriorate the environment. Due to the fact of pollution caused by cutting fluids in terms of recycling, disposal, works health issues, etc. the use of dry machining has increase in the workshops, however it can lead to reduce tool life and poor part quality. In order to avoid these problems flood-cooling methods can be used to enable efficient cutting of metals.

In order to lead to a conscious, clean and eco-friendly environment cryogenic cooling has showed great benefits as there is no need to recycle and/or disposal the cutting fluids. Based on the theory of cryogenic hardening, the field of cryogenics cutting (below -180 ^{o}C) advanced during the World War II when scientist found that besides contributing to an eco-environment, metals showed excellent wear resistance at frozen stage, better surface finish and improved tool life when comparing it to a dry cutting process The cooling process usually uses liquid nitrogen as is a fluid which can cause rapid freezing, it absorbs the heat from the cutting process and it becomes part of the air as it evaporates into nitrogen gas (79% of the air is composed by nitrogen). Other fluids commonly used are liquid helium and liquid CO_2. (Paul et al 2001).

Researchers Hong and Broomer in 2000 conducted a cryogenic study when machining 304 stainless steel at V= 3.05 - 3.82 m/s. They concluded that despites the benefits of an eco-friendly environment when using cryogenic machining, the liquid nitrogen produced an increased on the cutting forces and a reduced of tool life when machining this steel. However the process improved when injecting a small amount of liquid nitrogen to the chip-tool interface. In 2008 Khan and Ahmed, compared the effects on tool life when using conventional cooling and cryogenic cooling when turning 304 stainless steel, where the results showed an increase of tool life of more than four times when using cryogenic cooling, also it was found to be more effective at higher cutting speeds.

Advantages of cryogenic machining over dry machining were also studied by Kalyan et al 2008. In this case they studied the tool wear and the cutting forces generated during the cryogenic turning of 202 stainless steel. Their experiments showed an advantage of using cryogenic machining over dry machining as a decrease of 37% of the tool flank wear and 14.83% of the cutting forces were obtained.

In 2011, Nalbant and Yildiz, studied the effect of cryogenic cooling when milling in different directions a 304 stainless steel. In their studies they did not observe an advantage of using cryogenic machining against dry machining as they obtained almost 8% of increase on the cutting forces when using cryogenic machining. Also it was highlighted that conventional milling yield the best results in terms of tool failure under both type of machining processes.

Bermingham et al. in 2011 studied the tool life, the cutting forces and the chip morphology when cryogenic turning titanium, Ti-6Al-4V. They concluded that a better tool performance was obtained when using cryogenic coolant and the main cutting forces decreased with this application. Also cryogenic coolant produced changes to the chip morphology and tool-chip contact length. Despite not having a significant effect on the chips thickness and the distance between serrations it appeared that this process has an effect on the tool-chip contact length and the primary shear band angle.

The influence of cryogenic cooling on surface integrity was studied by Umbrello et al in 2012. In their studies an AISI 52100 steel was turned with cubic boron nitride tools with chamfered and horned geometries. The results showed that cryogenic machining offers a potential benefit for surface integrity (improved of the surface roughness) enhancement for improved product life.

Depending on materials mechanical, physical and chemical properties they are easier or more difficult to machine. The stainless steel has been defined as a difficult-to-machine ferrous alloy (Shokrani A et al, 2012), basically due to its low thermal conductivity, where the heat generated during the cutting process concentrates in the cutting zone producing diffusion as main tool wear mechanisms as well as Built Up Edge (BUE) formation, this last increases the machining instability producing chipping on the cutting edge and poor surface quality.

With regards quantities of coolant, special attention should be given as a large amount can have a negative effect on the machinability and tool life by unfavourable cooling, which prevents heat softening of the workpiece material (Astakhov,V.P. 2006).

Based on all these reviews, the aim of this research is to study the optimal combination of cutting parameters for a low power consumption and low value of surface roughness when face milling a 303 austenitic stainless steel in different cutting environments such as: dry, flood coolant and cryogenic.

2. EXPERIMENTAL PROCEDURE

The importance in conducting this experiment is the contribution in the manufacturing field towards the eco-friendly machining of difficult-to-cut materials, through the application of different environments; as well as the possibilities of reducing power consumption and surface roughness based on an optimal combination of cutting parameters.

2.1. Workpiece material

303 annealed stainless steel bars of 65mm diameter and 120 mm length were pre-machined to 120 x 55 x 32 mm^3 as show in Figure 1.

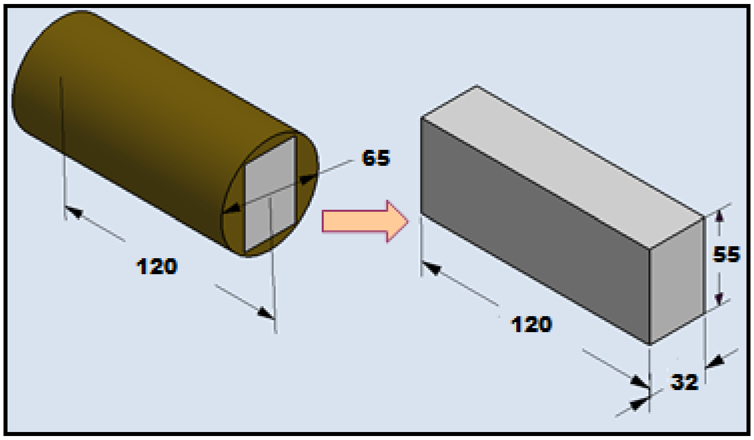


Figure 1: Scheme of the workpiece geometry used in this study (units in mm).

Table 1 and Table 2 show the chemical composition and the mechanical properties of this 303 stainless steel respectively.

Table 1: Chemical composition of 303 stainless steel bars used for the experiments

%C	***%Cr***	***%Fe***	***%Mn***	***%Mo***	***%Ni***	***%P***	***%Si***	***%S***
<=0.15	18.0	69.0	<=2.0	<=0.6	9.0	<=0.2	<=1.0	>=0.15

Table 2: Mechanical properties 303 stainless steel bars used for the experiments

BHN	***σu (MPa)***	***σy (MPa)***
160	620	240

2.2. Tool characteristics

A coated end mill and tool holder of $Ø_{Tool}$= 14 mm with 3 flutes was used for the climbing milling experiments, with the following code Guhring GTN 03872. This type of tool is recommended for the machining of stainless steel under different cutting environment. Figure 2 shows a scheme of the tool geometry.

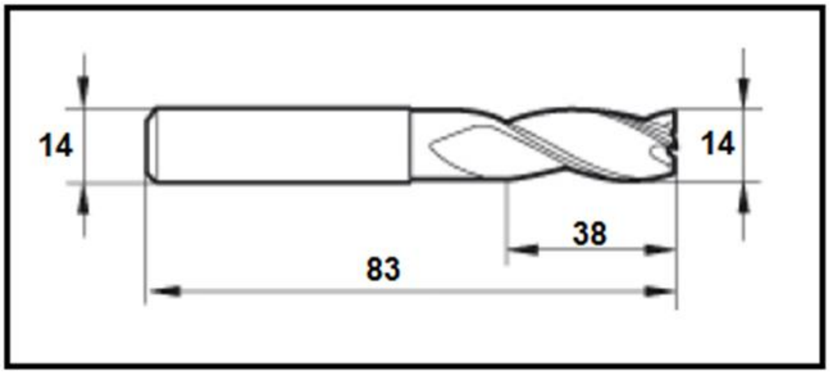


Figure 2. Scheme of the tool geometry

2.3 Cutting parameters and machining process.

Dry, Flood Coolant and Cryogenic (liquid nitrogen) were selected as cutting environment and the cutting speed and feed per tooth were the cutting parameters chosen for the study, since from previous research it was observed that these variables had the most influence on the surface roughness. Selected cutting parameters are shown in table 3.

Table .3: Experiments cutting conditions

Trial	Environment	V $[m/min]$	F $[mm/min]$	fz $[mm/*\ tooth]$	ap $[mm]$	ae $[mm]$
1	Dry	105	480.0	0.0670	3	11
2		157	717.6	0.0670	3	11
3		157	535.5	0.0500	3	11
4		157	364.0	0.0335	3	11
5	Flood Coolant	105	480.0	0.0670	3	11
6		157	717.6	0.0670	3	11
7		157	535.5	0.0500	3	11
8		157	364.0	0.0335	3	11
9	Cryogenic	105	480.0	0.0670	3	11
10		157	717.6	0.0670	3	11
11		157	535.5	0.0500	3	11
12		157	364.0	0.0335	3	11

Due to the restriction on the amount of material, the machining process was conducted based on the workpiece dimensions (120 x 55 x 32) and considering two trials per block, one in each side of the block. Five passes with ae = 11mm were used to cover the width of the workpiece (55 mm). In order to guarantee that the vice was holding enough material, only a maximum depth of 18 mm could be reached, so three passes with ap = 3 mm each were used to cover a 9 mm depth for a trial on side A and 9 mm depth for the trial on side B. By taking into account these two factors the total length of cut is 1800 mm (120 x 5 x 3) per trial. Once side A was machined the block was turned over and a new setup of experiments was conducted for side B. Figure 3 shows a scheme of the cutting process.

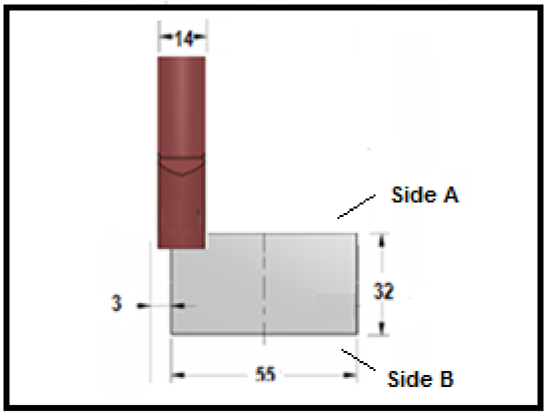


Figure 3. Scheme of the cutting process.

For the cryogenic machining the liquid nitrogen was delivered through a special nozzle designed for previous research and located close to the tool-workpiece interface (Dhokia et al 2012). A schematic setup of the cooling system is shown in Figure 4.

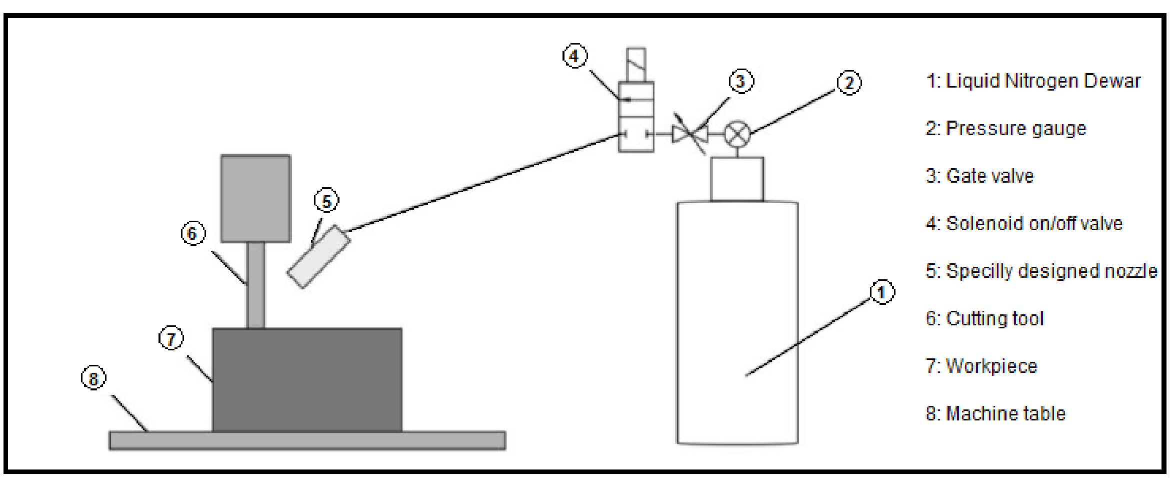


Figure 4. Schematic setup for cryogenic machining (Dhokia et al 2012)

2.4 Equipment characteristics

A Siemens 840D Bridgeport Vertical Machining centre 610XP2 with a maximum spindle speed of 8000 rpm was used for the face milling operations. The tests were conducted under three different cutting environments, dry, flood coolant and cryogenic (liquid nitrogen). Since the cutting length is small (L=1800 mm) the tool wear is not considered as a criterion that will affect the result of the cutting process.

2.5 Power consumption analysis

In order to consider in the future the cost of cutting techniques and energy efficient process planning, the power consumption was registered using a Hioki 3169-20 Power Hitester. The collection data was fixed to a frequency of 50 Hz with 1 second interval.

2.6. Surface Integrity

2.6.1 Roughness measurements

The surface roughness was measured across the direction of the machined surface lay (feed direction) using a non-contact white lamp profilometer ProScan 2000. The roughness average value of each specimen was determined by measuring five points, located in the centre of the specimen, where maximum and minimum values were neglected. The idea of measuring the roughness at the workpiece centre was in order to make sure that the obtained values of surface roughness were not affected by possible vibrations due to the impact of the tool entering the workpiece. Then an average of these three values was used to represent the surface roughness value of the specimen (Ra). Also the 2D surface roughness profile and 3D surface were obtained.

2.6.2 Microstructure analysis

The samples were prepared for metallographic study in order to analyse the microstructure of each sample machined under different cutting conditions. The samples were etched with a solution of $1HNO_3 3 + 1HCl + 1H_2O$ for a period of 2 min. Figure 5 shows a scheme of the samples preparation

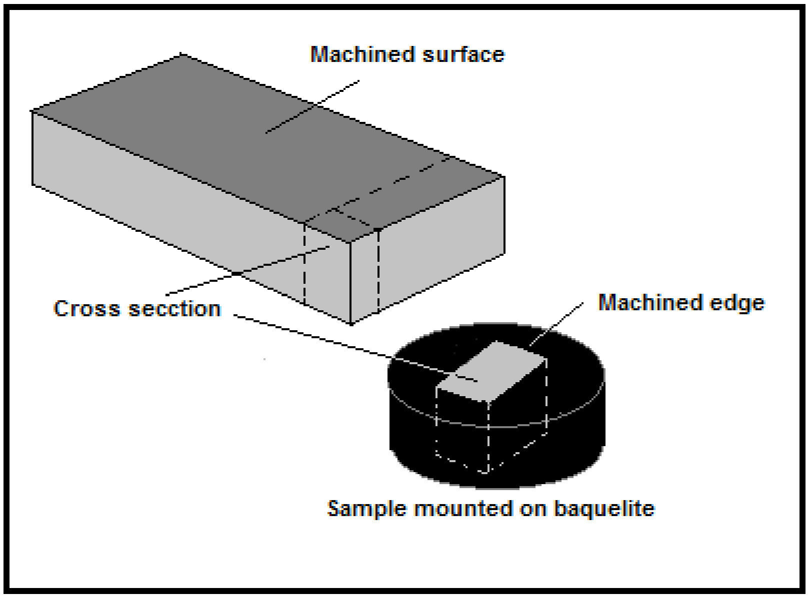


Figure 5. Scheme of metallographic preparation

2.6.3 Microhardness tests

In order to analyse possible changes in hardness below the machined surface, Vickers microhardness tests were conducted in each sample using a LECO M400 hardness equipment using a load of 50 g for a period of 15 s.

2.7. Chip studies

Once each trial was conducted the chips were collected in order to compare their appearance, morphology, etc. A Jeol JSM6060LV was used for SEM images. Also a Sartorius analytic scale with an accuracy of 0.0001 g was used to weigh the chips.

2.8. Material Removal Rate

The material removal rate was calculated for each of the trial in order to obtain the optimal combination of cutting parameters for the highest MRR without compromising the power consumption and surface roughness. In this case equation 1 was used.

$$MRR = (ap * ae * F)/1000 \quad (1)$$

Where:

MRR: cm^3/min

ap; mm

ae: mm

F: mm/min

3. RESULTS AND DISCUSSION

Once experiments were concluded the following results were obtained.

Table 4 show the average power consumption, the average surface roughness and the material removal rate obtained for the 303 stainless steel machined under different cutting conditions.

Table 4. Average power consumption, average surface roughness and material removal rate obtained for the 303 stainless steel machined under different cutting conditions.

Trial	Environment	V $[m/min]$	fz $[mm/\ tooth]$	ap $[mm]$	ae $[mm]$	$P*$ $[W]$	$Ra*$ $[\mu m]$	MRR $[cm^3/min]$
1	Dry	105	0.0670	3	11	260	1.290	15.84
2		157	0.0670	3	11	259	0.945	23.68
3		157	0.0500	3	11	250	0.841	17.67
4		157	0.0335	3	11	249	0.710	12.02
5	Flood coolant	105	0.0670	3	11	269	1.234	15.84
6*		157	0.0670	3	11		-	23.68
7		157	0.0500	3	11	271	0.871	17.67
8		157	0.0335	3	11	268	0.759	12.02
9	Cryogenic	105	0.0670	3	11	1510	1.180	15.84
10		157	0.0670	3	11	1710	1.229	23.68
11		157	0.0500	3	11	1600	0.974	17.67
12		157	0.0335	3	11	1500	0.932	12.02

*No results are show for trial 6 due to technical problems during the execution

3.1. Power consumption analysis

As previously mentioned, while the machining process was conducted the power consumption was registered. Table 4 reports the average power consumption for each trial during the machining operation which takes into account the cutting time and dead time.

3.1.1. Influence of the cutting speed on the average power consumption

Figure 6 show the influence of the cutting speed on the average power consumption for 303 stainless steel machined under different cutting conditions. As observed it seems that the cutting speed has a neglected effect on the power consumption under the studied cutting conditions when using a dry cutting environment. However, the situation is different when cutting in a cryogenic environment where it can be observed that the average power consumption increased when the cutting speed was increased. In this case an increase of 50% of the cutting speed (from 105 m/min to 157 m/min) produced an increase of 13% of the average power consumption (from 1510 W to 1710 W). This result is in agreement with previous research (Patel, 2012)

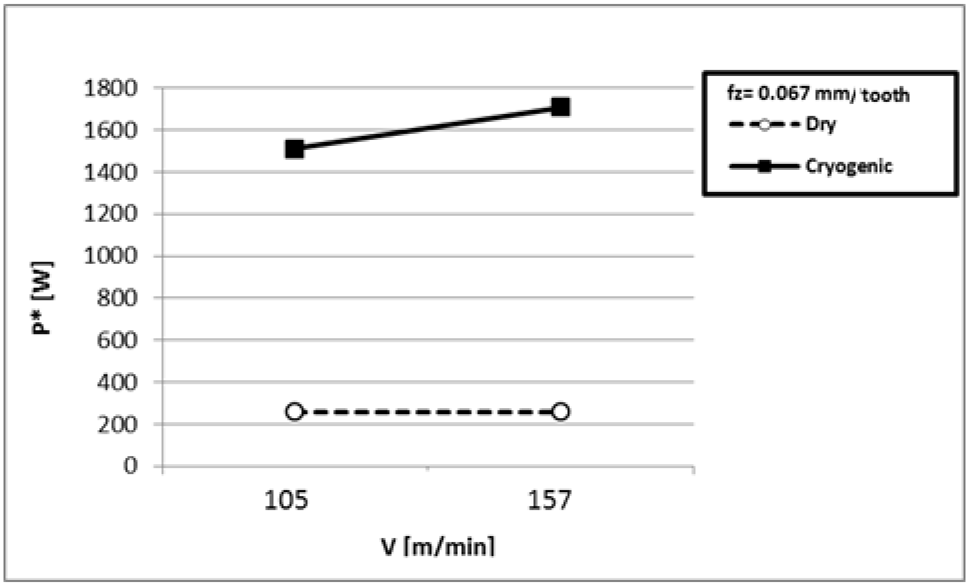


Figure 6. Influence of the cutting speed on the average power consumption for 303 stainless steel machined with fz= 0.067 $mm/tooth$, ap= 3 mm and ae= 11 mm.

3.1.2. Influence of the feed on the average power consumption

Figure 7 show the influence of the feed per tooth on the average power consumption for 303 stainless steel machined under different cutting conditions.

When analysing Figure 7 it is observed that once again in a dry and flood coolant environment the feed per tooth seems to have a neglected effect on the power consumption when working under the established experimental condition, however, when using the cryogenic environment it is observed that the average power consumption increases when increasing the feed per tooth. In this case an increase of 100% of the feed per tooth (from 0.0335 $mm/\ tooth$ to 0.0670 $mm/\ tooth$) produced an increase of 14% on the power consumption when cryogenic machining and 4% when using a dry environment. This result is in agreement with previous research (Palter, 2012).

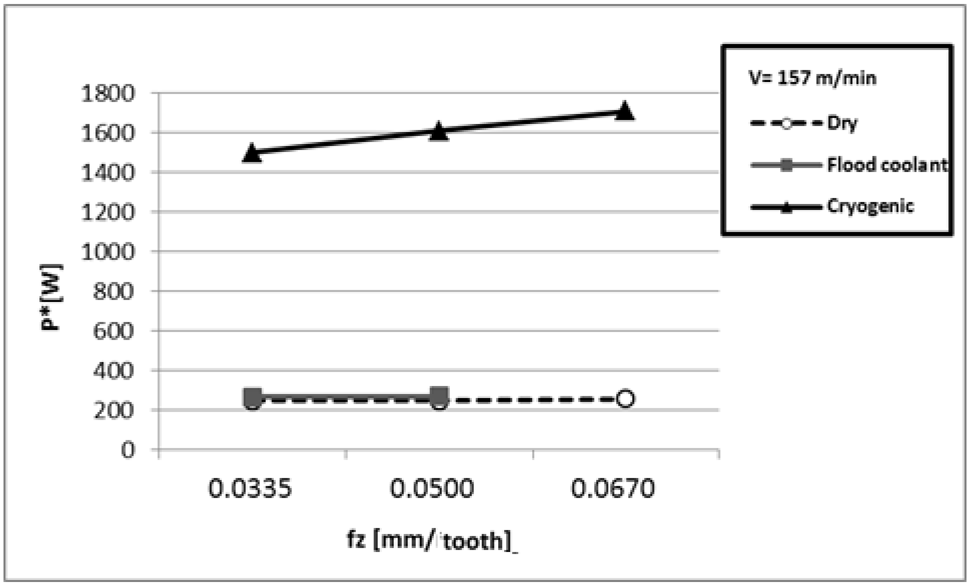


Figure 7. Influence of the feed per tooth on the average power consumption for 303 stainless steel machined with V=157 m/min, ap = 3 mm and ae = 11 mm.

The fact that the power consumption of the machine tool becomes so high when using a cryogenic environment when compared to the dry and flood coolant environment is probably due to a possible increase on the materials hardness as an effect of using super cold liquid nitrogen. This result is in agreement with previous research (Shokrani et al, 2012).

3.2. Surface Integrity

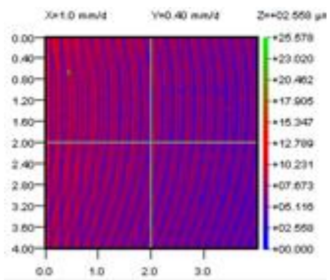
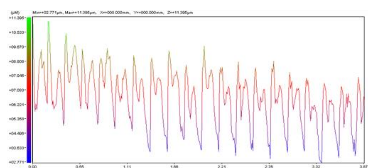
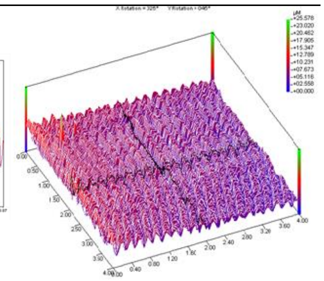
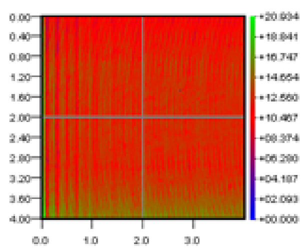
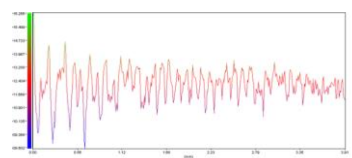
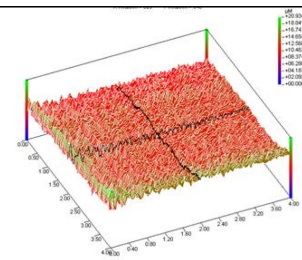
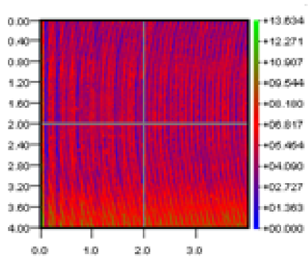
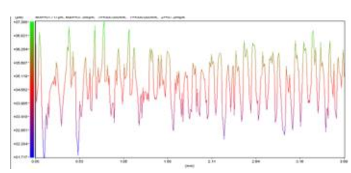
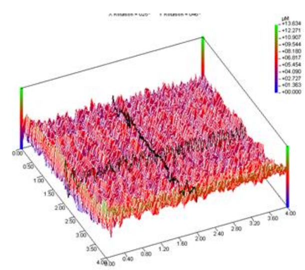
3.2.1. Surface Roughness

Once the milling process was conducted the surface roughness was measured and the average roughness is reported in table 4. It must be highlighted that in general a difference of 20% was obtained between the minimum and the maximum value of surface roughness measured on the machined surface under the same cutting conditions.

Table 5 show few examples of the average surface roughness, plan view, 2D profiles and 3D surface for 303 stainless steel bars machined under different cutting conditions.

As observed from Table 5 the plan view, shows the normal trail left by the cutting tool on the machined surface, with clear defined feed marks, the 2D surface roughness profile obtained for each trial show a harmonic function, with any kind of irregularity that could lead to an imperfection on the machined surface. In general all the results indicate that apparently no defect on the tool (such as wear) or high enough vibrations were presented during the milling process.

Table 5. Average surface roughness, plan view, 2D profiles and 3D surface for few 303 stainless steel bars machined under different cutting conditions

Trial		$Ra*$ $[\mu m]$	Plan View	2D profile	3D surface
1	Dry	1.290			
8	Flood coolant	0.759			
12	Cryogenic	0.932			

3.2.1.1. Influence of the cutting speed on the surface roughness

In Figure 8 the influence of the cutting speed on the surface roughness for 303 stainless steel machined under different cutting environments can be observed.

When analysing the results for a dry cutting environment it can be observed that an increase of 50% of the cutting speed (from 105 m/min to 157 m/min) produced a decrease of 37% on the surface roughness (from 1.290 μm to 0.945 μm). This result is probably due to the fact that an increase of the cutting speed probably produces a suppression of built-up-edge formation in this range of cutting speed. In addition, an increase of cutting speed produces an increase of temperature in the cutting zone, this fact makes the material softener, the metal machines more plastically and consequently the efforts necessary for machining the workpiece decrease.

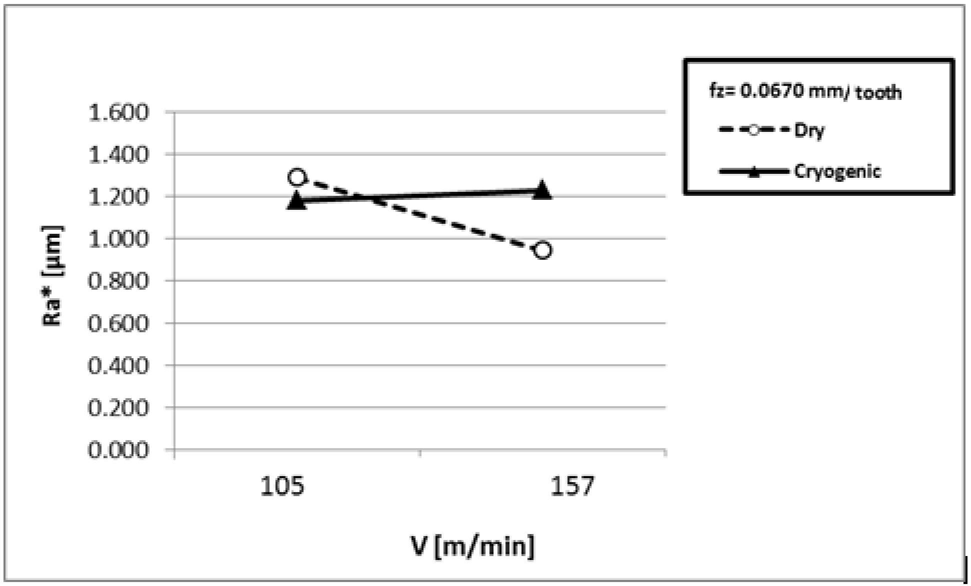


Figure 8. Influence of the cutting speed on the surface roughness for 303 stainless steel machined with fz=0.067 $mm/tooth$, ap = 3 mm and ae = 11 mm.

When analysing the results corresponding to a cryogenic cutting environment it can be observed that an increase of 50% of the cutting speed (from 105 m/min to 157 m/min) produced an increase of 4% on the surface roughness (from 1.180 μm to 1.229 μm), as previously mentioned probably due to a possible increase on the materials hardness as an effect of using super cold liquid nitrogen (Shokrani et al, 2012). As the increased in roughness was so small (4%), we can consider a neglected influence of the cutting speed when machining in a cryogenic environment under this cutting speed and feed per tooth under study as a difference of almost 20% between the minimum and the maximum value of roughness was obtained when measuring the roughness of each trial. Results obtained in cryogenic environment obtained higher values of roughness when compared with dry machining as well as an increased of roughness when increasing the cutting speed from 250 m/min (Yakup and Muammer 2008)

3.2.1.2. Influence of the feed rate on the surface roughness

In Figure 9 the influence of the feed per tooth on the surface roughness for 303 stainless steel machined under specific cutting conditions can be observed. When analysing Figure 9 the surface roughness increases when increasing the feed per tooth. This result is in agreement with previous research and is probably due to the fact that as the feed is increased the thickness of the chip also increases resulting in an increase of cutting forces. (Muñoz-Escalona and Maropoulos, 2010, Shokrani et al 2012, Sureh Kumar Reddy, 2008)

We can also observe that in general an increase of 100% of the feed per tooth from 0.0335 $mm/tooth$ to 0.067 $mm/tooth$ produced a general increased of 32% on the surface roughness when using either a dry or a cryogenic environment.

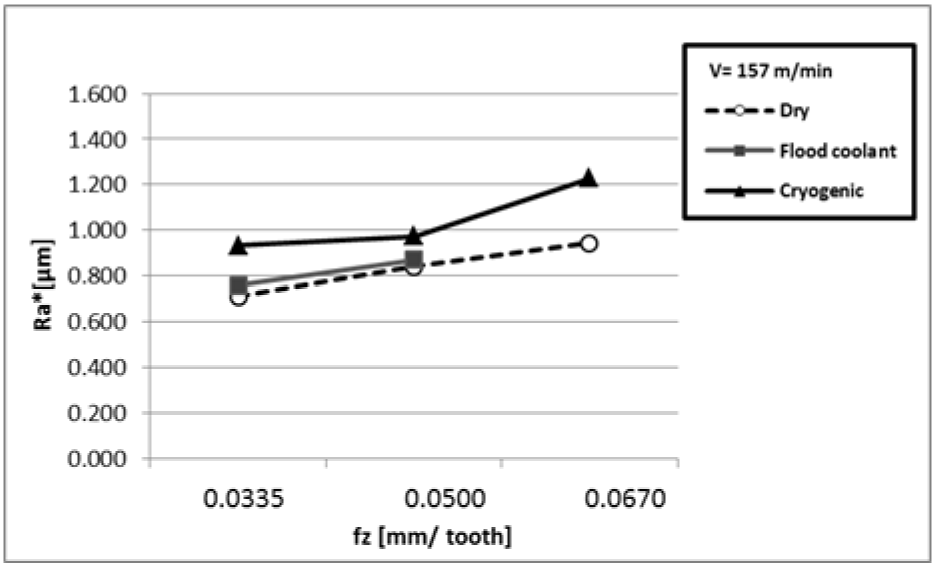


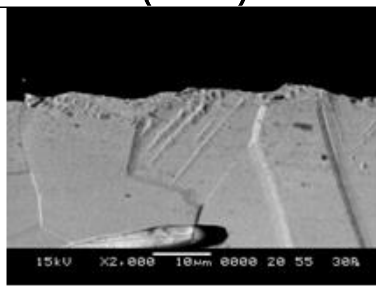
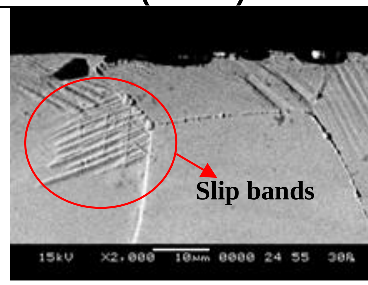
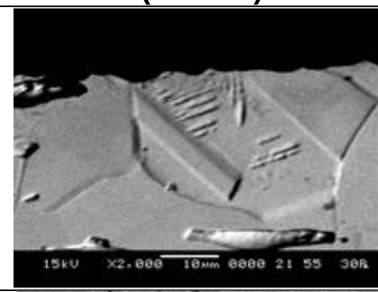
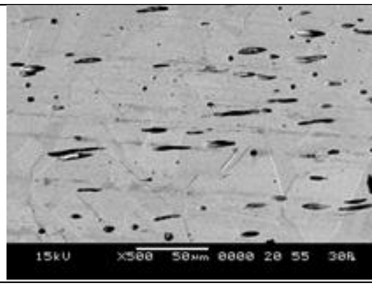
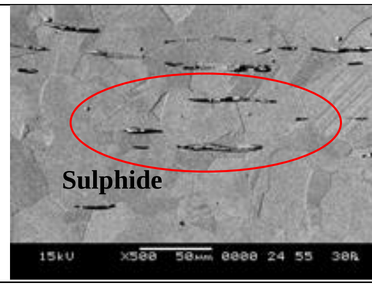
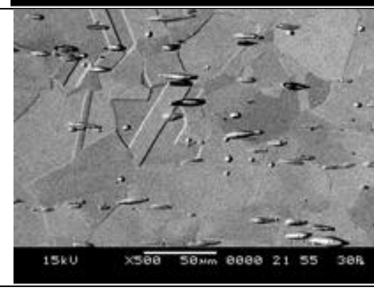
Figure 9. Influence of the feed per tooth on the surface roughness for 303 stainless steel machined in different environments with V=157 m/min, ap = 3 mm and ae = 11 mm

3.2.2. Microstructure analysis

Once surface roughness measurements were conducted trials from dry and cryogenic environment were selected for microstructure analysis and the results are shown in Table 6. Table 6 shows SEM images of few trials showing the microstructure below the machined surface and at the centre of the specimen.

As observed all the specimens showed elongated black spots and the EDAX analysis revealed that these correspond to the presence of sulphur as reported in Figure 10 EDAX image. This was expected as sulphur is added to this type of steel in order to improve their machinability as they tend to work harden very fast. All the samples revealed a normal equiaxed twinned austenitic grain structure as well as some slip bands just above the machined surface of specimens cut in dry and cryogenic environment. The formation of these slip bands is probably due to the plastic strain caused by the machining process when removing the material.

Table 6. SEM images of microstructure 303 stainless steel obtained by side milling under different cutting conditions

	Dry $V = 105\ m/min$, $fz = 0.0670\ mm/tooth$ **(Trial 1)**	**Dry** $V = 157\ m/min$, $fz = 0.050\ mm/tooth$ **(Trial 3)**	**Cryogenic** $V = 157\ m/min$, $fz = 0.050\ mm/tooth$ **(Trial 11)**
Machined surface			
Centre of the specimen			

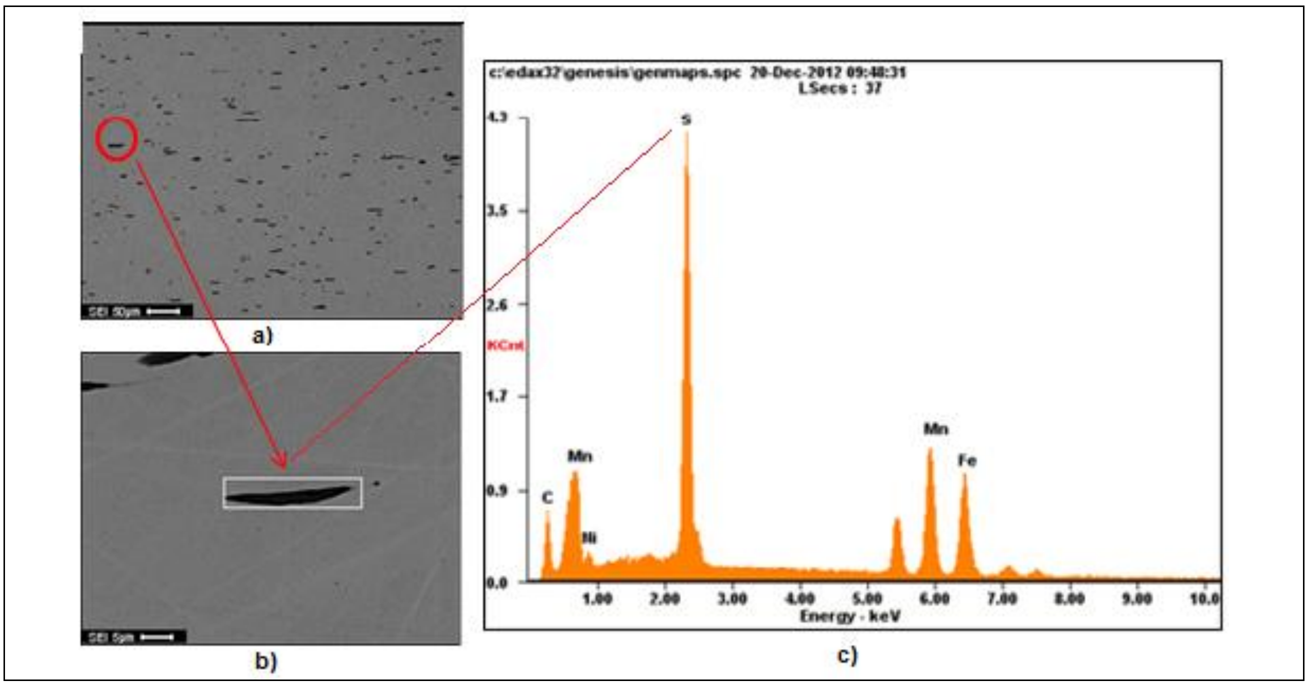


Figure 10. a) Microstructure of 303 Stainless steel 50X b) Detail of elongated black spot and c) EDAX analysis

3.2.3. Microhardness studies

In order to analyze possible changes in hardness especially below the machined surface, Vickers microhardness tests were conducted in each sample using a LECO M400 hardness equipment using a load of 50 g for a period of 15 s.

Figure 11 and 12 show the changes in microhardness from the machined surface towards the center of the specimen. The material bulk reported a value of 170 HV. As observed all the trials reported a higher value of hardness below the machined surface, between 20 μm – 40 μm and the hardness started to stabilize at around 100 μm from the machined surface.

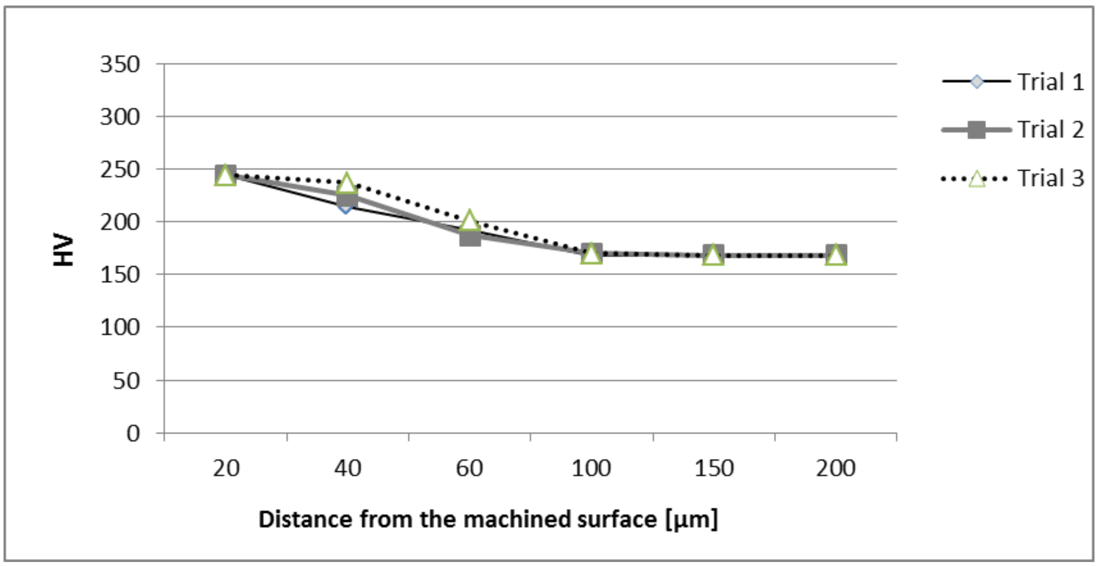


Figure 11. Vicker hardness vs Distance from the machined surface for samples machined in a dry cutting environment under different cutting conditions.

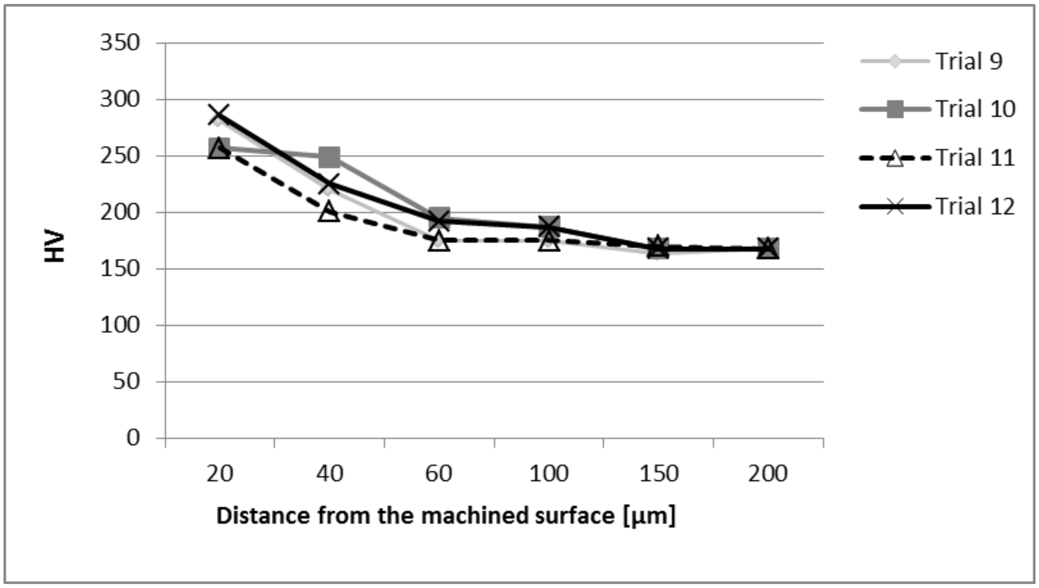


Figure 12. Vicker hardness vs Distance from the machined surface for samples machined in a cryogenic cutting environment under different cutting conditions

Figure 13 shows the changes in hardness from the machined surface towards the center of the specimen of samples machined in dry and cryogenic environment under the same cutting conditions.

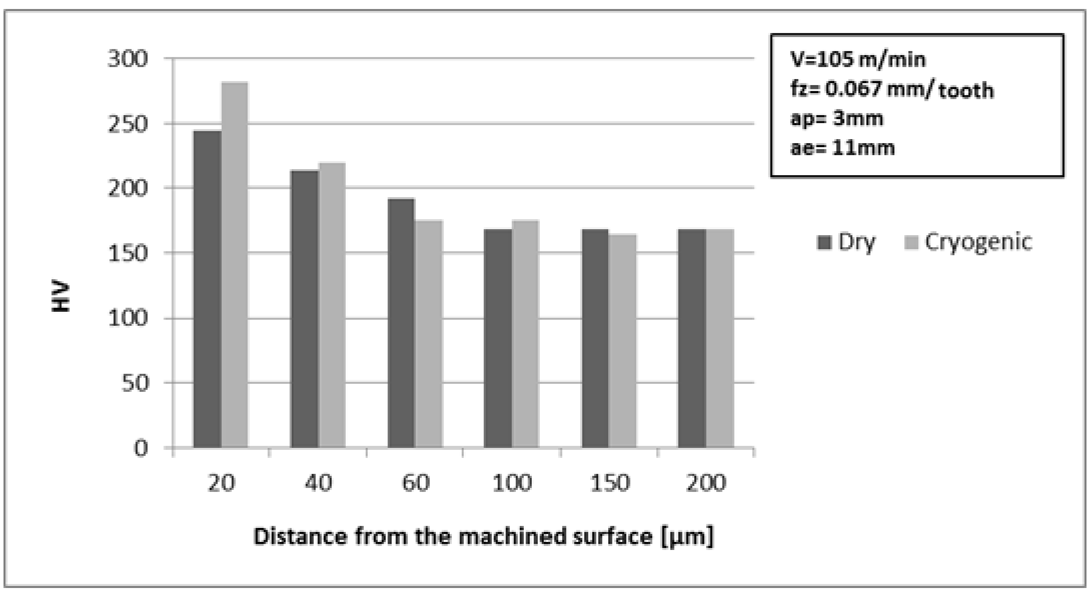


Figure 13. Vickers Hardness vs Distance from the machined surface for samples cut in dry and cryogenic environment under the same cutting conditions.

As observed when analyzing this figure 10, specimen machined in a cryogenic environment achieved higher values of hardness below the machined surface compared to specimen machined in a dry environment. This is probably due to strain hardness during the cutting process been more noticeable in the cryogenic environment due to a decrease of the cutting temperature. In the case of the dry environment probably the increase of temperature helped to soften the material easing the removal of material.

3.4. Chip studies

All the chips were collected after each cutting process and the results are observed in table 7. When analysing the chips it was observed that all the chips were short. The chips obtained from dry machining presented a yellow appearance while cryogenic chips presented a white appearance, this is probably due to the difference in temperature between each environment.

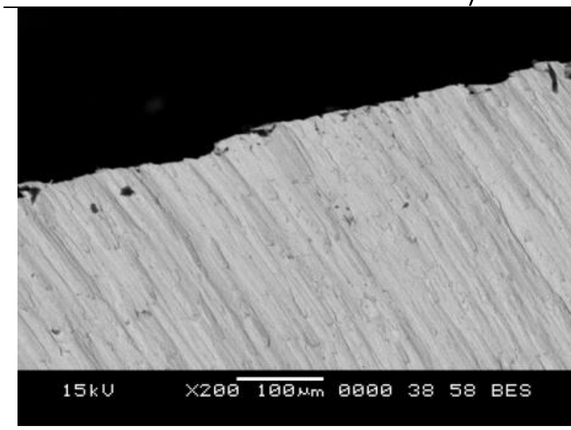
Table 7. Example of 303 stainless steel chips obtained when milling in dry and cryogenic cutting environment under different cutting conditions

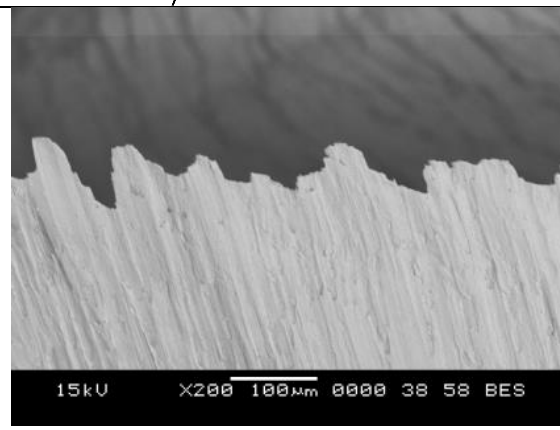
	
X20	***X20***
Dry environment	**Cryogenic environment**
V*= 105 *m/min, fz*= 0.0670 *mm/tooth	***V*= 157 *m/min, fz*= 0.050*mm/tooth***
(Trial 1)	**(Trial 11)**

The chip cross section morphology was analyzed using a JEOL JSM6060LV SEM .Table 8 show these images.

As observed when comparing chips obtained in dry and cryogenic environment, cut under the same cutting conditions (trial 1 and trial 9 respectively) it can be observed a serrated formation when using a cryogenic environment, like if the chips were torn from the workpiece material. This is probably due to an increase of hardness due to the cryogenic environment. The increase of hardness produces an increase of the cutting forces. This result matches with the power consumption results, where a 600% of increase of this value was observed when using a cryogenic environment compared to the dry environment. This result is in agree with previous research (Patwari et.al 2010)

Table 8. SEM images of 303 stainless steel chips at magnification of X200 obtained from chip cross section -side milling in dry and cryogenic cutting environment at V=105 m/min and fz=0.067 $mm/tooth$



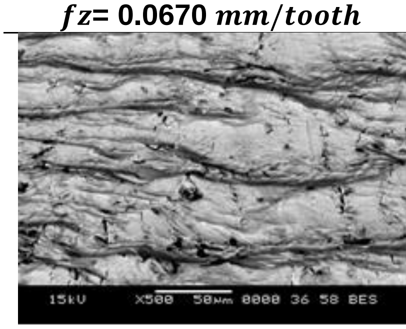


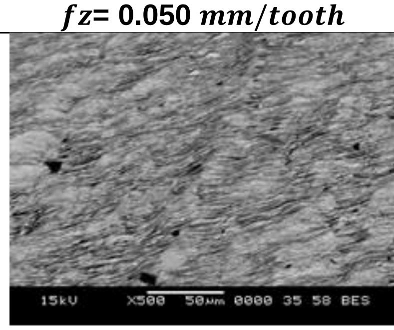
Trial 1	***Trial 9***

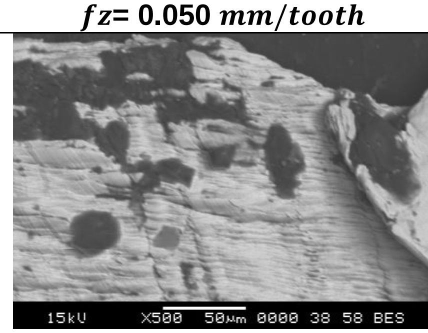
Chips were also unfolded and the results are shown in Table 9. It must be highlighted that three attempts were made to unfold the chips and the results showed that the chips obtained from a dry environment could be unfold easily and 100%, however this was not the case for the chips obtained from a cryogenic environment were in the case of trial 9 they were impossible to unfold and for trial 11 chips tend to fracture making them impossible to unfold 100%.

Table 9. SEM images of unfolded 303 stainless steel chips obtained by side milling under different cutting conditions

Dry. Trial 1 V= **105** m/min, fz= **0.0670** $mm/tooth$	**Dry. Trial 3** V= **157** m/min, fz= **0.050** $mm/tooth$	**Cryogenic. Trial 11** V= **157** m/min, fz= **0.050** $mm/tooth$







Note: Trial 9 (cryogenic) is not shown as the chip was impossible to unfold

As observed from Table 9, a bigger separation between shear planes is observed in trial 1 when compared with trial 3 where a difference of 25% of the feed per tooth was used.

Finally the chips were weighed and in general all the values kept constant for the same cutting conditions. Table 10 shows these results. Also it can be mentioned that a decrease of 25% of the feed per tooth (fz= 0.067 $mm/tooth$ to fz=0.05 $mm/tooth$) produced a decrease of 25% of the chip weight from 0.0162 g to 0.0127 g.

Table 10. Average weight of 303 stainless steel chips milled under different cutting conditions.

Trial	Environment	V $[m/min]$	fz $[mm/\ tooth]$	ap $[mm]$	ae $[mm]$	W $[g]$
1	Dry	105	0.0670	3	11	0.0162
9	Cryogenic	105	0.0670	3	11	0.0159
3	Dry	157	0.0500	3	11	0.0127
11	Cryogenic	157	0.0500	3	11	0.0127

3.3. Material Removal Rate, MRR

As known the MRR increases proportional to the increase of cutting speed and feed per tooth. When analysing Figure 14, which illustrates the results given by Table 4, it is observed that the combination of cutting parameters used for trials 2, 6 and 10 achieved the highest material removal rate. This represents a 49% increased of MRR when compared to trials 1, 5 and 9 which cutting speed is 50% lower, but also a 97% of increase in MRR when compared to trial 4, 8 and 12 which feed per tooth is 50% smaller. So it is observed that the feed rate has 100% more influence on the MRR when compared to the cutting speed parameter.

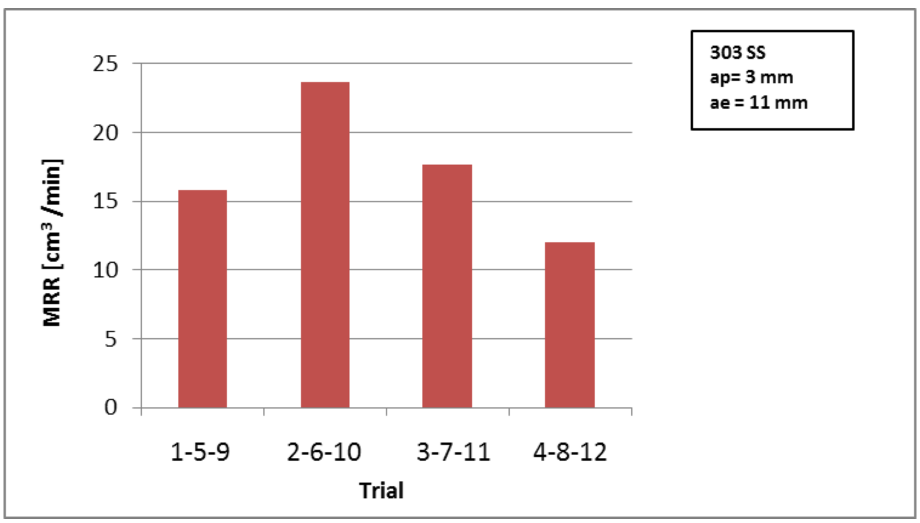


Figure 14. Material Removal Rate for 303 stainless steel under different cutting conditions

An increase on the MRR means more material can be cut in a shorter time and this is achieved by increasing the cutting speed and the feed rate. To do this in an economical way depends on many areas related to metal cutting namely the machine tool, the cutting tool, the cutting fluid and the materials. With regards machine tools, it is necessary to increase the power and accuracy. The increase of power to remove more material in a shorter time increases the heat generation near the cutting edge of the tool, and the power consumed in metal cutting is largely converted into heat. This heat is dissipated by the four systems processing the material: the cutting tool, the workpiece, the chip formed and the cutting fluid, (Bacci 1999)

3.3.1. Influence of the Material Removal Rate on the Power consumption and the Surface Roughness

Figure 15 and 16 show the influence of the material removal rate on the average power consumption and surface roughness respectively when face milling 303 stainless steel under different cutting environment

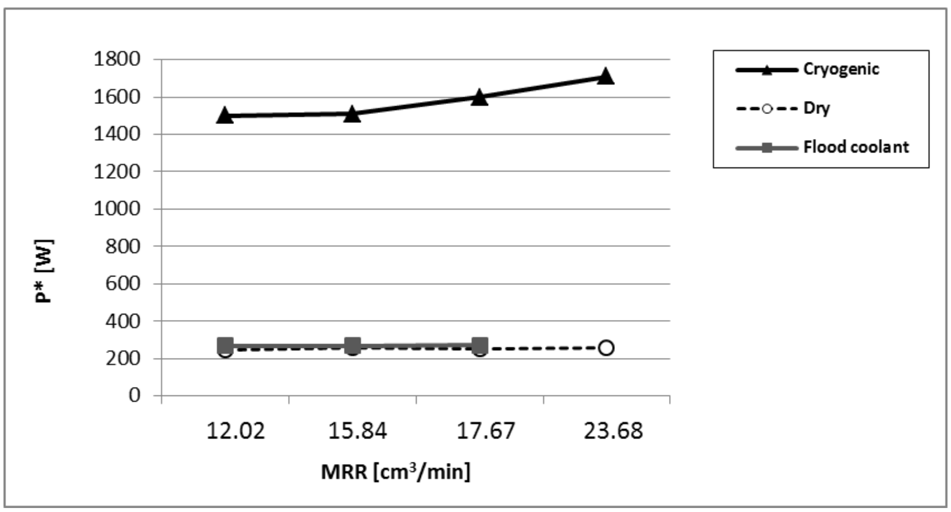


Figure 15. Influence of the material removal rate on the power consumption when machining in different cutting environments

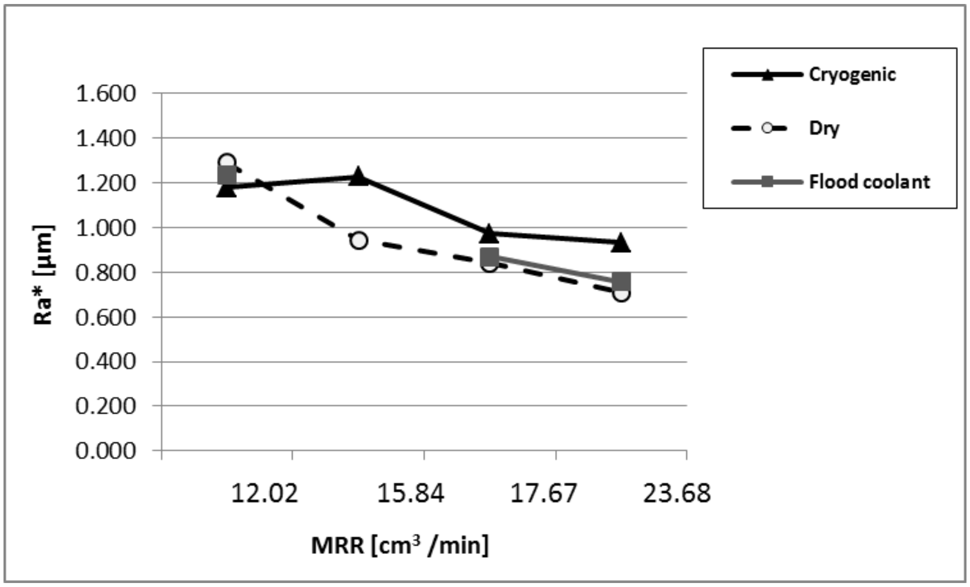


Figure 16. Influence of the material removal rate on the surface roughness when machining in different cutting environments

As observed from figure 15 as the material removal increases the power consumption increases as the cutting forces are increased, been more noticeable when cutting in a cryogenic environment. When analysing Figure 16 as the material removal increase the surface roughness improves achieving better results when using a dry cutting environment.

4. CONCLUSIONS

- After analyzing the results of 303 stainless steel machined under different cutting environments it can be concluded that under the specified cutting parameters the dry environment is more suitable for the machining process as the surface roughness, power consumption and materials microhardness achieved the lowest results.
- A proper combination of cutting parameters can achieve low values of power consumption and surface roughness instead of changing the cutting parameters individually
- Overall the optimal combination of cutting parameters are V= 157 m/min and fz = 0.050 $mm/tooth$ (corresponding to Trial 3, dry environment.) as a low value of power consumption, surface roughness and microhardness was obtained as well as a high MRR

- It was observed an increase of 15% of the microhardness near the machined surface when using a cryogenic environment compared to the dry environment.

- There were no noticeable changes on microhardness when changing the cutting speed or the feed per tooth, however all the specimens hardness started to stabilized at 100 μm from the machined surface

- The power consumption was increased in almost 600% when using a cryogenic environment compared to dry and flood coolant when machining under the same cutting conditions

-Chips obtained from a cryogenic environment presented a more serrated shape in the cross sectional area when compared to chips from a dry environment

5. FUTURE RESEARCH

Authors would like to extend this research by analysing the consequences of cutting environments together with cutting parameters on the residual stresses generated during the milling operation.

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