The differences in feed force and torque in drilling two similar austenitic stainless steel.

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Abstract. *The austenitic stainless steels represent about 70% of all kind stainless steel produced. The ABNT 304 steel has excellent corrosion resistance the in the environment, high resistance to attack of corrosive agents and keep good tenacity in low temperatures. Unfortunately the heat conduction is about 1/4 that of regular steel, so much of the heat generated during machining is not transferred to the work material or to the chips. It is concentrate on the main cutting edge, and high malleability that indicates softness and tenacity makes chip evacuation difficult due to chip elongation. The work hardening, a phenomenon that occurs near the cutting edge gives poor machinability to the stainless steel. The new stainless steel is Villares 304 UF, with metallurgical control of the inclusions is presented as alternative to ABNT 304. The present work compares the ABNT 304 steel with the new one, measuring the feed force and torque in the drilling process. HSS TiN coated twisted drills had been used in these two different steels with different cutting speeds and feed rates through planned experimentation. The feed force and torque measured were lower in drilling Villares 304 UF. The SEM analysis at tool tip allows explaining the lower cutting force.*

Keywords*. Drilling, austenitic stainless steel, cutting force.*

1. INTRODUCTION

Machining operations such as turning, milling, drilling and grinding are material removal processes that have been widely used in manufacturing since the industrial revolution. Of these processes, drilling is one of the most common machine tool operations in manufacturing. Very frequently drilling is a preliminary operation to reaming, boring or grinding where final finishing and sizing takes place. While very precise work can be done with a drill, it is a roughing operation and the primary items of interest are usually long tool life and high penetration rate. It explains why drilling is the most important metal cutting operations, comprising almost 33% of all metal cutting operations. The drill was designed to produce holes in metal parts quickly and easily. Both cutting edges of a drill operate with variable rake angle, inclination angle, and clearance angle along the cutting edge. The flutes of a drill play the important role of conveying the chips out of the hole and the helix angle of the drill is important in this connection (Shaw, 1986). The selections of tool materials, specifications and types face a large change due to the mass usage of automatic machine tools and a growing level of complexity in the products. (Chen, 2000) There are two unsolved problems in drilling, like in many other cutting processes: tool wear and tool breakage. Due to its complexity, the dynamics of tool wear are not completely understood. After a certain limit, tool wear can cause catastrophic failure of the tool that can cause considerable damage to the workpiece and even to the machine tool set-up. Even if the price of a drill is relatively low, failure can cause an incomparably higher production cost (Ertunc, 2001).

The main advantages of coated drills over the conventional are their good wear resistance, superior edge strength and sharpness, and good surface quality of the processed materials. The coatings are designed to improve the drill performance at a least cost as compared with conventional drills. The successful industrial application of coated drills was generally explained by a combination of good abrasion resistance of the hard coating with a high toughness of the substrate (Konig, 1991).

The complex geometry of the twist drill and its rotary motion cause a helical chip to be formed rather than a spiral chip, as is formed in orthogonal cutting. In addition, because the cutting speed near the drill center is small, becoming zero at the drill tip, material removal does not occur by cutting at the tip. The dominant velocity of the drill in this region is in the feed direction, leading to material being displaced by extrusion rather than by cutting. This important phenomenon is not described in the orthogonal cutting model. Chips are formed during the removal of metal; significant thermal energy is generated by the cutting action and by friction between the tool, the workpiece and the chips; the chips break in irregular ways; tools wear and may eventually break. As a result of the stochastic nature of some of these events, the forces that the cutting tool experiences are not perfectly constant but exhibit some degree of randomness. Although these random processes are present in varying degrees in all machining operations, the magnitude of the fluctuations in a well-designed manufacturing system does not strongly influence the processes or the quality of the final product (Toews, 1998).

1.1. The ABNT 304 austenitic stainless steel

Stainless steels can be applied extensively to fabricate chemical and food processing equipment and machinery parts requiring high corrosion resistance, because of their anti-rust and corrosion resistance properties. From the metallurgical microstructure point of view, stainless steels can be divided into three groups: (1) austenitic, (2) ferritic and (3) martensitic (Chen, 2000).

Stainless steels are normally recognized as difficult materials to machine because of their high toughness, low thermal conductivity and high degree of work hardening. Stainless steels can be regarded as poorly machinable materials because of their high tensile strength leading to high cutting forces and severe tool wear; high work hardening rates and low thermal conductivity leading to wear; high fracture toughness resulting in high temperatures, poor chip breakability and poor surface finish; abrasive carbide particles present in the high alloyed stainless steels causing tool wear; tendency to the built-up edge formation, which contrary to that in conventional steels, is present even at high cutting speeds due to the high fracture toughness and work hardening coefficient of these steels; the presence of the BUE impairs markedly the surface finish (Paro, 2001).

The austenitic stainless steels are more difficult to machine than other alloy steels. Metal cutting operators experience problems with these materials. This is due to several factors, such as the tendency of austenitic stainless steels to work-hardening and its relatively low heat conductivity; approximately 50% of that of carbon steel. Particular problems arise when cutting in a severely work-hardened surface, such as that left by a previous machining operation with a worn tool. The use of a sharp tool and a reasonably high feed rate are two recommendations for prevention of tool damage caused by this work hardening. The work hardening will also contribute to a higher heat generation in the cutting process, which will cause adhesion in terms of more extensive chip-tool interaction. In addition to this, the low thermal conductivity of the steel will increase the temperature and augment the interaction even further. As the temperature becomes higher, the interactive force becomes stronger, resulting from, e.g. adhesion and or interdiffusion between the chip and the tool. A high temperature will promote mechanical wear, such as adhesive wear and chipping in the cutting edge, and chemical wear, such as tool dissolution (Nordin, 2000). Built-up edge (BUE) and irregular wear are often faced in machining operations.

1.2. The V 304 UF austenitic stainless steel

Many attempts have been made to improve the machinability of austenitic stainless steel by adding free-machining elements, such as sulfur, lead, selenium and tellurium. It was reported that controlled oxide inclusions contribute to the improvement of the machinability of these steels, although an early attempt in Japan indicated no remarkable results. In recent years environmental considerations have been forcing industries to take measures to reduce the amount of elements, such as Pb, Se and Te in these steels, which may cause health threats (Akasawa, 2003).

Free cutting austenitic stainless steels with high sulfur content have been developed in order to facilitate cutting operations. Their better machinability is related to the plastic behavior of the sulfides in the flow zone. However, adding this element is detrimental to corrosion resistance and material workability. Consequently, special attention was paid to the development of both calcium and sulfur-controlled austenitic stainless steels. Their addition improves machinability without greatly reducing resistance to corrosion (M'Saoubia, 1999). The use of the sulphurised steel as solution for the improvement of stainless steels machinability has the inconvenient of compromising the corrosion resistance. Many times it is desired higher machinability of the steels like 304 and 316, but these steels cannot be replaced for 303 due to decrease in corrosion resistance. Sometimes the specifications do not allow, as for example, in the market of the food and drink industry.

A new calcium deoxidized free machining austenitic stainless steel has been developed which contains only small amounts of sulphur (less than or equal to 0,1%). The experimental study has shown that the calcium containing low sulphur content free machining austenitic stainless steel has a higher machinability than ordinary austenitic stainless steel, giving a longer tool life, and is characterized by the formation of a golden colored adherent layer on WC-TiC-Co cutting tool. The adhering layer improves the tool life in three ways: it reduces the physical contact between the tool and chip so decreasing abrasive wear; it reduces the physical contact between the tool and the chip thus decreasing adhesive wear; it changes the diffusion model from a dynamic model between tool and chip into a quasi-static diffusion model between tool and adhering layer. As a result, the diffusive wear rate is reduced considerably (Mills, 1997). The main reasons for the improvement in machinability of Ca-S stainless steel are because of the adhering layer formed on the tool surface that protects the tool from abrasive and diffusion wear. Among the factors that influence the formation of the adhering layer, the most important one is the cutting temperature (Tieu, 1998).

Investigations of the adhering layer show the following: the composition of the adhering layer consists of gehlenite inclusions ($CaOAl_2O_3SiO_2$) and a few elements of the steel base and the cutting tool; cross sectional photomicrographs indicated that the thickness of the adhering layer was 2 to 40 µm; the distribution of the elements in the cross section of the adhering layer shows that there is an element distribution gradient across the tool layer interface; the temperature range for the adhering layer formation was between 650 and 1000 °C. The melting point of of gehlenite, which covers a range of composition in the ternary $CaOAl_2O_3SiO_2$ system, is 1300 – 1500 °C. A hypothesis for the formation of the adhering layer has been proposed and described in four stages: extrusion of viscous non-metallic inclusions onto the tool surfaces; adhesion of the coating onto the tool; hardening and growth in thickness of the coating; formation of the stable adhered layer (Mills B., 1997)

In this context, in 1992, the Villares Metals S/A developed V 304 UF austenitic stainless steel with improved machinability without compromising the other properties. The improved machinability is gotten through the rigid control of the chemical composition and the new deoxidation process in the steel manufacture. This new procedure makes possible the attainment of inclusions with specific characteristics. The hard and abrasive inclusions are reduced and the distribution and morphology of the inclusions are controlled. The inclusions of the structure consist mainly of sulfides and sulfides are surrounding a core of another kind of inclusions. The sulfides has low melting point. The high temperature developed at tool tip promotes the lubricate effect by the low melting point inclusions. The chips are then easily broken and the tool life lasts longer.

2. EXPERIMENTAL SET-UP

This work was planned to identify the machinability differences between ABNT 304 steel with the new one V 304 UF, measuring the feed force and torque in the drilling process. The tool was a 6 millimeter HSS TiN coated DIN 338 twisted drills. The feed rate was set at 0,06 mm/rev and at 0,10 mm/rev and the cutting speed was set to 5, 10, 15, 20 and 25 m/min. The cutting fluid used was Falcão 3000, supplied from ADLEER Lubrificantes Ltda. The water miscible oil for metalworking coolant was delivered at 60 l/min directly to the drill tip.

The drilling tests had been carried out in a vertical machining center POLARIS V400 equipped with numerical control FANUC 0M. The main power motor has 20 CV and maximum spindle speed is 6000 rpm. The three axles are set in motion at freely programmable speed up to 6000 mm/min.

The dynamometer used for measurement the feed rate force and moment was Kistler model 9272A connected to the load amplifier model 5019A. The data acquisition card PCI-MIO-16E-4 from National Instruments was used to receive the signals at sample rate of 5 kHz. Labview software allowed controlling all the acquisition process and all the data collected was stored in a personal computer. The acquisition time of 30 seconds was enough to capture the signals since the beginning of the hole until the end.

The figure 1 shows one workpiece used after the measuring the feed force and torque. Its cylindrical form facilitates the centralization on dynamometer. The option to make ten holes in the workpiece intended to reduce the experimental error. It was fixed by a special device that placed it on the dynamometer center using two M10 screws.

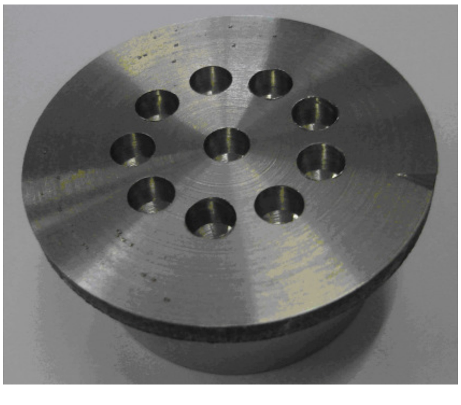

Figure 1. Workpiece after the measuring the feed force and torque.

The workpiece materials were austenitic stainless steel that fits all requirements of ABNT 304 and V304 UF, another austenitic stainless steel with improved machinability produced by VILLARES METALS S.A. The chemical compositions of theses steels are showed on table 1.

Table 1. Chemical composition of the two steels workpieces mass %.

Steel	C	Si	Mn	Cr	Ni	Mo	Al	Cu	P	S	N	Ca
V 304 UF	0,058	0,38	1,90	18,30	8,57	0,42	< 0,005	0,46	0,031	0,026	0,037	0,0036
ABNT 304	< 0,08	< 1,00	< 2,00	18,00-20,00	8,00-10,50				<0,045	<0,030	<0,10	

The sample workpiece was ten for each material tested. The number of influences variable of this study and the levels of them (feed rate with two levels, spindle speed with five levels and material type with two levels) plus the number of sample workpiece generated two hundred data files.

The randomization in the experimental procedure was partial, the sequence in table 2 were randomized in two group; 1 to 10 and in 11 to 20. The sample workpiece material to be drilled was randomized and the workpiece was replaced only after all the ten holes were drilled. The cutting parameters were randomized to assure that for example, the central hole of ten replicas workpiece were drilled with ten different cutting parameters. The experimental procedure was designed to guarantee that all ten holes of workpiece were drilled with ten different cutting parameters and the replicas were randomly chosen.

Table 2. Influence variable and levels of Experimental Design

Sequence	Steel type	Cutting speed (m/min)	Feed rate (mm/rpm)
1	ABNT 304	5	0,06
2	ABNT 304	5	0,10
3	ABNT 304	10	0,06
4	ABNT 304	10	0,10
5	ABNT 304	15	0,06
6	ABNT 304	15	0,10
7	ABNT 304	20	0,06
8	ABNT 304	20	0,10
9	ABNT 304	25	0,06
10	ABNT 304	25	0,10
11	V 304 UF	5	0,06
12	V 304 UF	5	0,10
13	V 304 UF	10	0,06
14	V 304 UF	10	0,10
15	V 304 UF	15	0,06
16	V 304 UF	15	0,10
17	V 304 UF	20	0,06
18	V 304 UF	20	0,10
19	V 304 UF	25	0,06
20	V 304 UF	25	0,10

The hole depth in the workpiece did not exceed 6 mm to prevent the influence of tool wear. During the measurement of the feed rate force and torque the main cutting edge of the cut tool was continuously evaluated to minimize the influence of the tool wear. The tool was replaced 4 times during the tests.

3. RESULTS AND DISCUSSION.

The results obtained from the drilling tests are presented and discussed in this section.

3.1. - The two austenitic stainless steel.

A hundred data files had feed force and torque gotten in drilling of steel ABNT 304 and another hundred had feed force and torque gotten in drilling V 304 UF. In each one of these two sets of data files there was ten different cutting data and for one single cutting data there were ten replicates. The graph of figure 2 summarizes a simple statistics analysis of two materials with regard to feed force and torque. The high dispersion value can be explained by the presence of other influence factors presents in the data set such as the two different levels of feed rate. In all the tests the feed rate and cutting speed has changed and a feed rate value has strong influence in torque and feed force. The two-sample t-test was used to determine if bolts sets of data means are equal. A common application of this two-sample t-test t is to see if a new process or treatment is superior to a current process or treatment. The paired data was choosing because there is a one-to-one correspondence between the values in the two samples. The formulas for paired data are somewhat simpler than the formulas for unpaired data.

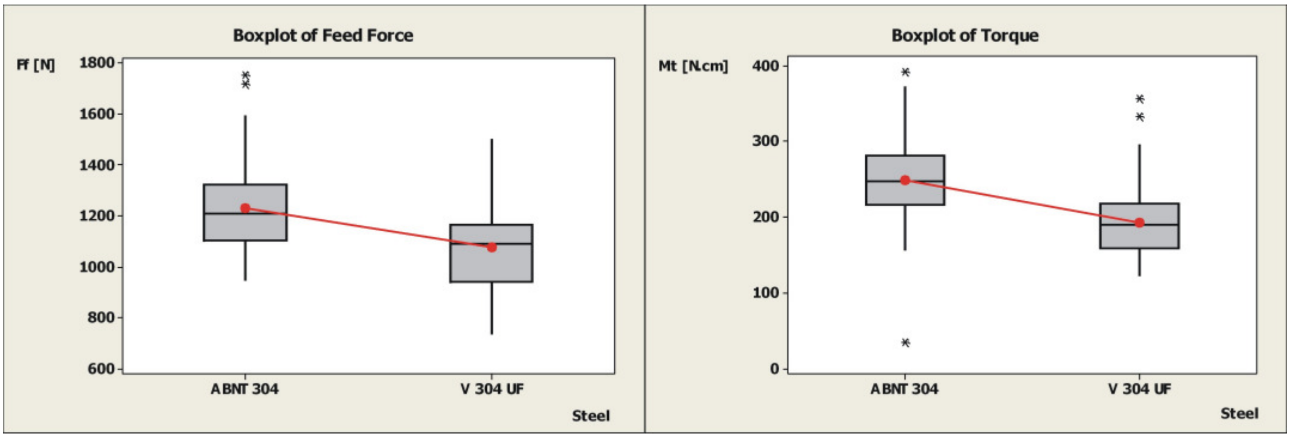

Figure 2 – Differences in feed force and torque with two austenitic stainless steels.

The mean of feed force of ABNT 304 steel is 1231 N with standard deviation of 167 N and the mean of feed force of V 304 UF steel is of 1077 N with standard deviation 190 N The mean torque needed to drill ABNT 304 steel is 247 N.cm with standard deviation of 53 N.cm and the mean torque to drill V 304 UF steel is 193 N.cm with standard deviation of 44 N.cm.. The graphical representation suggests and statistical analysis allows saying that feed force and torque are bigger in drilling steel ABNT 304 than drilling V 304 UF. The standard deviations of the data set seem bigger because the data has the influence of the feed rate.

3.2. – The two feed rate.

The same reasoning could be applied to feed rate. A hundred data files had feed force and torque gotten in drilling with 0,06mm/rpm and another hundred had feed force and torque gotten in drilling with 0,10mm/rpm. In each one of these two sets of data files there was ten different cutting data and for one single cutting data there were ten replicates. In all the tests the steel and cutting speed has changed and the analysis done before shows that torque and feed force are different when different type of steel is drilled. The two-sample t-test with paired data shows that there are difference in the mean feed force data (table 3) and mean torque data (table 4) of the two tested feed rate.

Table 3. - Two-sample T for feed force

feed rate	N	Mean	StDev	SE Mean
0,06	100	1061	172	17
0,10	100	1248	169	17
Difference = mu (0,06) - mu (0,10)				
Estimate for difference: -187,125				
95% CI for difference: (-234,706; -139,544)				
T-Test of difference = 0 (vs not =): T-Value = -7,76 P-Value = 0,000 DF = 197				

Table 4. - Two-sample T for torque

feed rate	N	Mean	StDev	SE Mean
0,06	100	192,	49,0	4,9
0,10	100	248,5	47,6	4,8
Difference = mu (0,06) - mu (0,10)				
Estimate for difference: -56,5206				
95% CI for difference: (-69,9915; -43,0498)				
T-Test of difference = 0 (vs not =): T-Value = -8,27 P-Value = 0,000 DF = 197				

The graph of figure 3 summarizes a simple statistics analysis of the two feed rate value with regard to feed force and torque. The high dispersion value can be explained by the presence of other influence factors presents such as the two different austenitic stainless steels in data set.

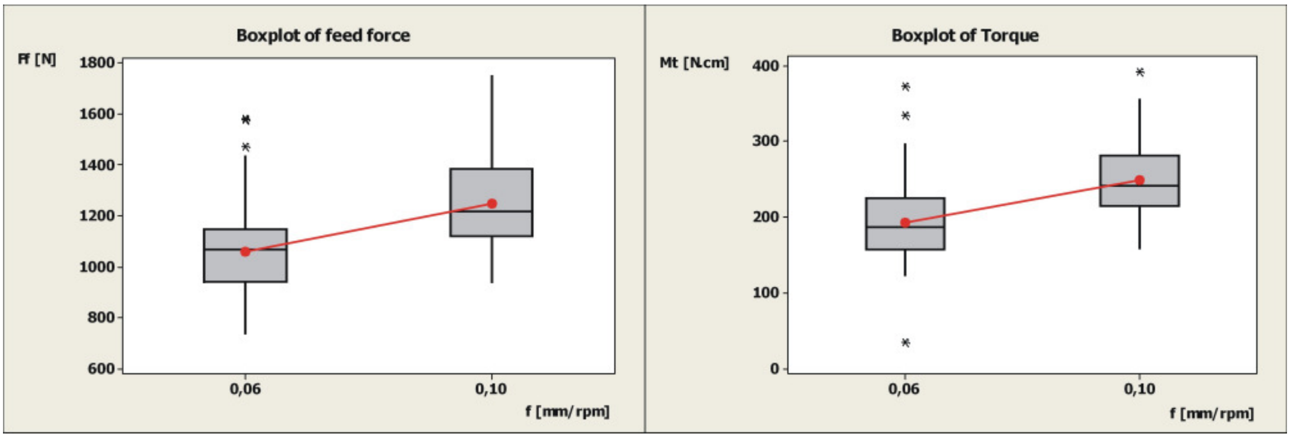

Figure 3 – Differences in feed force and torque with two drill feed rates.

The lowest feed rate generated lowest feed force and lowest torque. As the feed rate increased almost 66% (from 0,06 mm/rpm to 0,10 mm/rpm) the mean feed force increased only 20% and mean torque increased 29%.

All data files could be classified by material type and feed rate and then four data sets with fifty files will be formed. Each set will be composed of feed force and torque generated at five different cutting speed and with teen replicas. The statistical analysis of these sets is showed graphically in figure 4. It shows the influence of feed rate value and the influence of steel type in feed rate force and torque

The analysis of all data on table 5 helps to understand the influence of feed rate and the influence of steel type in feed force and torque. Drilling the V 304 UF with the lowest feed rate generates the lowest feed force and lowest torque. It's more easily drilling V 304 UF than drilling ABNT 304 at same feed rate.

Table 5 – Feed rate force and torque classified for material type and feed rate

Material Type	Feed rate [mm/rev]	Feed rate force [N]	Torque [N.cm]
ABNT 304	0,06	1156	220
ABNT 304	0,10	1306	276
V 304 UF	0,06	965	164
V 304 UF	0,10	1190	221

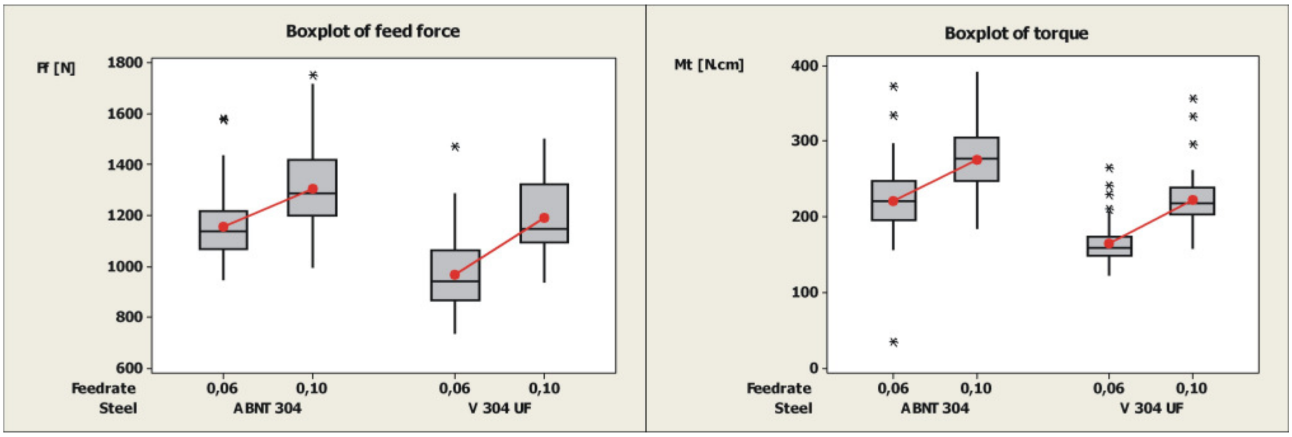

Figure 4 – Differences in feed force and torque with two feed rate drills and two austenitic stainless steels.

The growth rate of feed rate was the same for the two materials. It was 66,67% because the levels of feed rate were 0,06 mm/rpm and 0,10 mm/rpm.

The growth rate of the feed force with the feed rate growth was different for the two materials. The feed force needed to drill ABNT 304 steel changed from 1156 N to 1306 N when feed rate changed from 0,06 to 0,10 mm/rpm. The feed force growth rate was 13%. Meanwhile feed force needed to drill V 304 UF steel changed from 965 N to 1190 N. The feed force growth rate was 23% for V 304 UF.Also the growth rate of the torque with the feed rate growth was different for the two materials. The torque needed to drill ABNT 304 steel changed from 220 N.cm to 276 N.cm when feed rate changed from 0,06 to 0,10 mm/rpm. The torque growth rate was 25%. Meanwhile the torque needed to drill V 304 UF steel changed from 164 N.cm to 221 N.cm. The torque growth rate was 34% for V 304 UF. Another interesting comparison can be made with regard to percentile difference of feed force and torque of the two materials. For the 0,06 mm/rev feed rate the variation of the feed force between the two materials is of the 19,83% being bigger the feed force of ABNT 304 steel, but when the feed rate is set to 0,10 mm/rev the percentile variation drops to 9,64%. The same happens to torque. These variations suggest that the two materials have a different Ks value each other and the behavior of Ks with variation of chip thickness are different for the two materials.

3.4. – The five cutting speed.

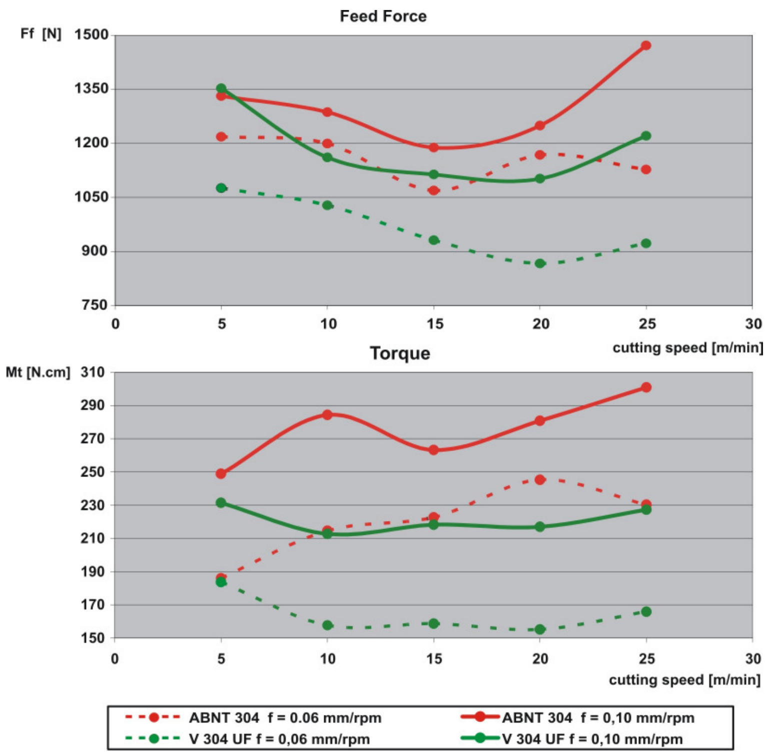

Figure 5 – Differences in feed force and torque at five cutting speeds.

The mean value of feed force and torque get from tests carried out with ABNT 304 steel are indicated in red color in figure 5 and the test carried out with V 304 UF steel are indicated in green. The differentiation of feed rate drill is given by line style. The continuous line was used for the biggest feed rate and the doted line for the small one.

It can be seen that the feed force and torque measured in the drilling V 304 UF steel is almost always lower than the feed force and torque measured in the drilling ABNT 304 steel at the same cutting conditions. Each line of the graph connects five different cutting speed points, each point with ten sample data.

The feed force graph shows only the mean results and not the standard deviation of all collected data. The ANOVA tests done for feed force measured in the same steel at the same feed rate shows that the there are statistical significant differences in feed forces measured at different cutting speeds. This is not true only for the data get from drilling tests of ABNT 304 steel at 0,06 mm/min feed rate. The measurements of the torque shows that as the cutting speed increase, the torque tends to be higher in drilling of ABNT 304 Steel. This is not happening with V 304 UF. The ANOVA test shows that there is no influence of cutting speed in the measured torque when V 304 UF was drilled at five different cutting speeds. There is a direct relation between torque and cutting force, so is correct to suppose that the cutting speed has influence in the cutting force in ABNT 304 steel drilling, but this influences is minimized in V 304 UF steel drilling.

3.5. - The SEM analysis

The adherent layer formed when drilling ABNT 304 steel and V 304 steel where analyzed on SEM. The figure 6 shows on the left the ABNT 304 steel layer that covers the rake surface. On the right, shows the V 304 UF steel layer that covers the rake face. The length of ABNT 304 adherent layer is bigger than the V 304 UF adherent layer. Trent showed that the cutting force is proportional to contact length and the contact length is affected by some alloying elements. It could help to explain the differences in feed force and torque measured in the two types of steel. The chemical composition of the 304 UF stainless steel layer showed higher calcium and sulfur contents than that was present on the base metal. It suggests that the adhesive layer on TiN coated HSS drill could be formed by the same way this layer is formed on carbide cutting tools as Fang (1996) and Qi (1996) suggests.

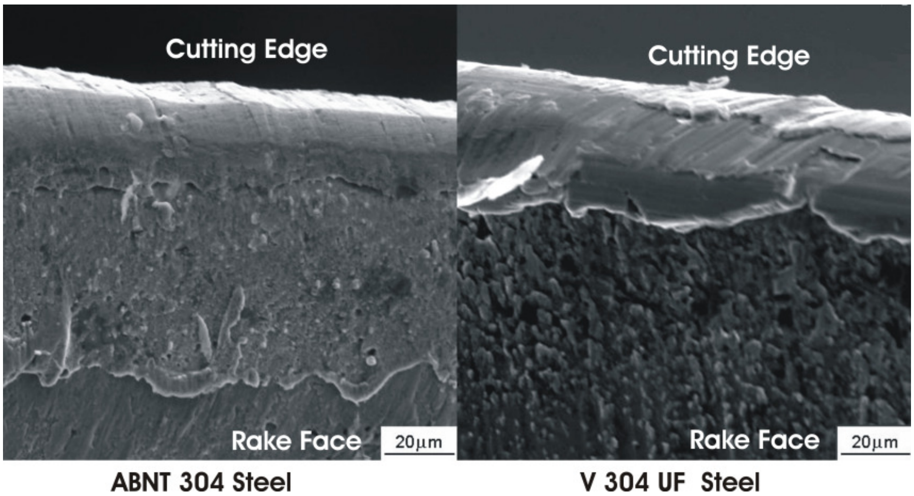

Figure 6 Adherent layer that covers the drill main cutting edge.

4. CONCLUSION

The machinability of 304 UF Villares austenitic stainless steel is much better than that the corresponding ABNT 304 stainless steel using as a cutting tool a TiN coated HSS drill.

The feed force and torque are smaller in drilling V 304 UF at all cutting speeds tested. As the cutting speed increase the differences on feed force becomes remarkable.

Using as workpiece material Villares 304 UF stainless steel, the cutting speed, the tool life and the productivity of drilling can be higher than using the ABNTt 304 stainless steel.

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