The comparative analysis of machinability of ABNT 304 and Villares 304 UF with hss twist drill.

Abstract. *The austenitic stainless steels represent about 70% of all kind stainless steel produced. Unfortunately 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 metallurgical control of the inclusions is presented as alternative to improve the machinability of stainless steel. The present work compares the machinability of ABNT 304 steel with the new one the Villares 304 UF, by measuring the feed force and torque, the tool wear and tool life in the drilling process. HSS TiN coated twisted drills had been used in these two different steels and the power signal from main spindle were analyzed. The Mev analysis of the tool tip shows adhering material. The EDS analysis of the adhering layer materials allows explaining the lower drilling force, the lower tool wear, the higher tool life and the good machinability of Villares 304 UF stainless steel.*

Keywords. *Drilling, austenitic stainless steel, cutting force, tool wear and tool life*

1. INTRODUCTION

Stainless steels are stainless because a protective layer spontaneously forms on their surfaces and reduces the rate of corrosion to almost negligible levels. Under normal conditions, this layer heals very rapidly if scratched, so that if stainless steels only suffered from uniform corrosion, they could survive for literally millions of years (Newman, 2002). The austenitic stainless steel is the greatest group of stainless steels in use. They represent almost 65 to 70% of the total stainless steel produced. Austenitic steels have austenite as their primary phase (face centered cubic crystal). These are alloys containing chromium and nickel and sometimes manganese and nitrogen. Austenitic steels are not hardenable by heat treatment. The surgical stainless steel is austenitic steel containing 18-20% chromium and 8-10% nickel. Many austenitic steels are low carbon content, which means less carbide precipitation in the heat-affected zone after welding and a lower susceptibility to intergranular corrosion in the room temperature. It presents high ductility, excellent drawing, forming, and spinning properties. It is essentially non-magnetic, becomes slightly magnetic when cold worked. The austenitic stainless steel has many applications in the chemical industry, oil refinery, food processing equipment, hospital surgical equipment, marine equipment, nuclear vessels, refrigeration equipment It has countless applications, mainly where good corrosion resistance are required (Modenesi, 2001). The most utilized are the 18-8 type which has 18% of chromium and 8% the of nickel (Chiaverini, 1990). The presence of nickel improves considerably the corrosion resistance and oxidation resistance at high temperature. The nickel forms a layer of oxide that protects the steel.

This steel presents an interesting phenomenon: after a work hardening the hardness increases more than any other steel at the same deformation level. The hardness increased can be explained because the stress generated in work hardening change instable austenitic in ferrite. This carbon-supersaturated ferrite is in the same conditions as a martensite and contributes to the exceptional hardening of the steel. The 18-8 cold drawn steel can reach a tensile strength as high as 250 kgf/mm2 (2450 MPa), and regular steel if applied to the same deformation, would not reach more than 140 kgf/mm2 (1370 MPa). The moderate temperature heating will restore the austenitic microstructure of the work hardening steel. It is still noticed that the effect of the strain hardening is less sharp in the austenitic stainless steel when the nickel content increases. The nickel element has the stabilizing action in the austenitic stainless steel. This phenomenon is so important that austenitic stainless steels are usually classified for the levels of resistance that is gotten by work hardening, from the annealed type up to the full hardened type (Chiaverini, 1990).

1.1. The ABNT 304 stainlees steel

The ABNT 304 steel can be considered more difficult to machine than carbon or low alloy steels. There are many factors that make ABNT 304 steel difficult to machine such as its relatively low heat conductivity. This alloy has approximately half of heat conductivity that regular carbon steel. The austenite present in stainless steel has the tendency to work hardening. (Diniz, 1999). The work hardening promotes a higher heat generation in the cutting process. The low thermal conductivity of this steel leads to high cutting temperatures and hence accelerated tool wear. There is a strong tendency to the BUE formation, which is present even at high cutting speeds due to the high fracture toughness and work hardening. The presence of the BUE deteriorates the final surface finish and the high fracture toughness results in poor chip breakability and poor surface finishing.

The machinability of this steel is improved by stable martensite and lower content of non-metallic inclusions. The austenitic stainless steel with big grain size can be machined with cutting speeds higher than the speeds used to machine the same steel with small austenitic grain size.

1.2. The V 304 UF stainlees steel

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.

In this context, in 1992, the Villares Metals S/A developed austenitic stainless steel with improved machinability without compromising the other properties. The figure 1 shows the results gotten from TESSLER , 2002

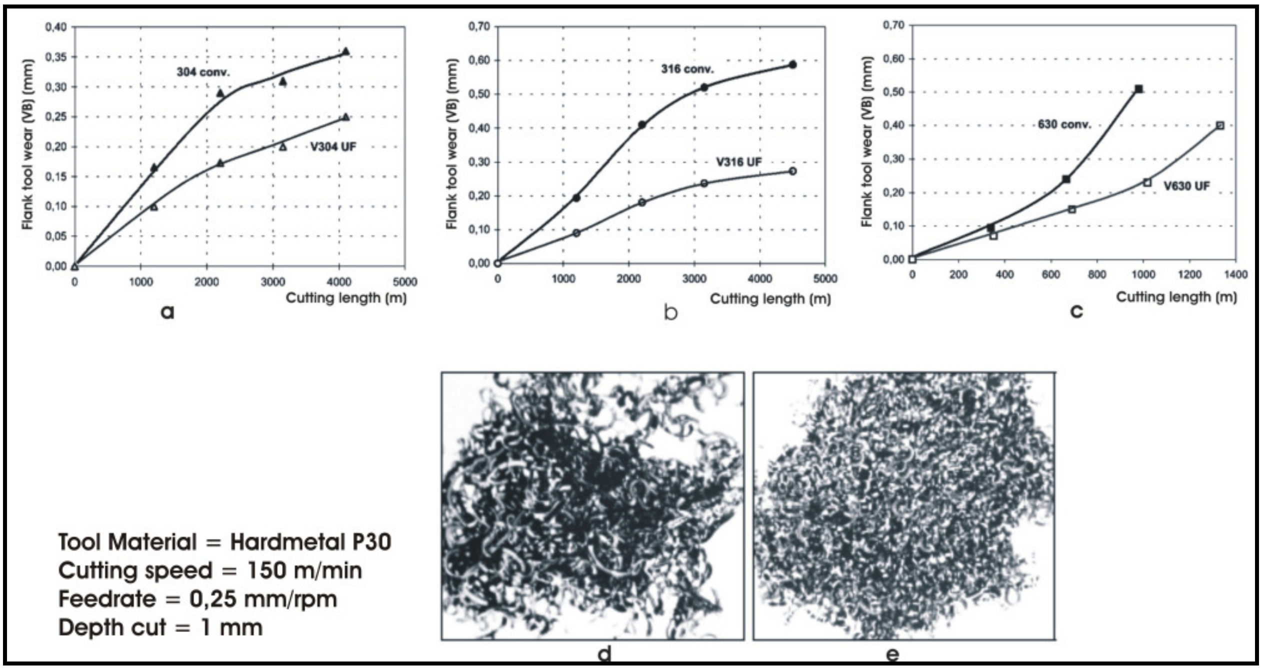

Figure 1 – Tool wear rates in turning a) V304 UF and ABNT 304 stainless steel b) V316 UF and ABNT 316 stainless steel c) V630 UF and ABNT 630 stainless steel. d) ABNT 304 chips e) V 304 UF chips.

It shows the tool wear in turning V304 UF steel and ABNT 304 steel (figure 1a). The tool wear in turning 304 UF steel is always lower. Moreover, it was observed that in turning V304 UF little vibration occurs and optimum part surface finishing are generated. The same resulted was gotten for the V316 UF steel, showed in figure 1b , and for the V630 UF steel, showed in figure 1c.

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 the 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 lubricant effect by the low melting point inclusions. The chips are then easily broken and the tool life lasts longer.

The chips collected from ABNT 304 steel and V 304UF, after turning, are shown in figure 1d and 1e. The chips collected from V304 UF steel are smaller and less oxidized. The friction between tool rake face and chips are reduced, and then temperature reduction occurs in the tool tip with consequent reduction of the tool wear.

2. EXPERIMENTAL SETUP

2.1. **Machine Tool**

The drilling tests had been carried out in a vertical machining center POLARIS V400 equipped with numerical control FANUC 0M as shown in figure 2. This machine tool is extremely rigid. It gives great stability during rough machining. The main power motor has 20 CV and maximum spindle speed of 6000 rpm. The three axles are set in motion at freely programmable speed up to 6000 mm/min. The machine tool builder is Indústrias Romi S.A.

Figure 2 – Machine tool and data acquisition system.

The dynamometer used for measurement the feedrate 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. It was possible to see the growth of the feedrate force and the moment since the acquisition was started some seconds before the drill tip touch the surface. The acquisition ended some seconds after the conclusion of the movement of retraction of the drill.

A small device was built and attached to dynamometer to guarantee repeatability in the positioning and a rigid fixture of the samples. The experimental setup was conceived intending rigidity of the measuring systems during the accomplishment of the tests. All the system was conditioned in the center of the table of the cnc machining center.

2.2. Cutting fluid

The cutting fluid used was Falcão 3000, supplied from ADLEER Lubrificantes Ltda. This is a water miscible vegetable oil for metalworking coolant with no active phenol composites, chlorine, and sulfur with additive for bacterial control (biocide without triazine). Eight nozzles equally spaced throughout a centered circumference delivered 60 l/min of cutting fluid directly to the drill tip.

2.3. Workpiece material

All the testes were carried out with two types of chromium-nickel low carbon austenitic stainless steel, from Villares Metals S/A. The first steel meets all the requirements of ABNT 304 standard. The other one is a product of modifications in the refining process. This steel, V 304 UF, exceeds the specifications of ABNT standard for the morphologic control of the inclusions. The changes in the manufacturing process promoted the addition of residual elements like calcium, copper, aluminum and molybdenum that was detected in the chemical analysis. The chemical compositions of two steels tested can be observed in the table 1. The hardness of the two sample materials were approximately of 184 HR_B.

Table 1 – Análise química dos aços utilizados nos ensaios (% em peso).

Aço	C	Si	Mn	Cr	Ni	Mo	Al	Cu	P	S	N	Ca
V304 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	-

2.4. The cutting tool

The cutting tool used for all the machining tests were the hss twist drill, 6 mm diameter, 118º tool tip angle, TiN coated and general dimensions following DIN 338 standard

2.5. The experimental procedure.

The aim if this work is studying the influence of a different refining process of the austenitic stainless steel in the cutting force, in tool wears mechanisms and in tool life. The tests had been divided in two great blocks. The first set of tests had as influence variable the workpiece material in two levels. One level was ABNT 304 steel, and the other level was V 304 UF steel. The cutting speed had been set in five different values and the federate had two values. The influence variable is shown in table 2. The response variable had been the federate force and torque.

Table 2 – Matrix of tests

	Worpiece material				Drilling parameters	
test	Level 1	sample	Level 2	sample	Cutting speed (m/min)	Feedrate (mm/rpm)
1	USIFAC 304	10	ABNT 304	10	5	0,06
2	USIFAC 304	10	ABNT 304	10	5	0,10
3	USIFAC 304	10	ABNT 304	10	10	0,06
4	USIFAC 304	10	ABNT 304	10	10	0,10
5	USIFAC 304	10	ABNT 304	10	15	0,06
6	USIFAC 304	10	ABNT 304	10	15	0,10
7	USIFAC 304	10	ABNT 304	10	20	0,06
8	USIFAC 304	10	ABNT 304	10	20	0,10
9	USIFAC 304	10	ABNT 304	10	25	0,06
10	USIFAC 304	10	ABNT 304	10	25	0,10

The drilling length in each test of measuring force and torque did not exceed 6 mm preventing the influence from main cutting edge wear. The workpiece was cylindrical and teen holes could be drilled for measuring feed force and torque. The cutting edge was continuously evaluated and aimed to reduce the influence of the main cutting edge wear the tool was replaced four times during the test

The second test block can be seen on table 3 and it was planned to analyze the influence of stainless steel refining process in the tool life and the tool wear mechanism. Thus the selected influence variable had been the type of steel in two levels and the cutting speed in five levels. The feedrate wasn't changed and set to 0,09 mm/rev. The use of five levels of cutting speed should allow identifying the constants n and C from Taylor equation. Also with this number of test it was possible to graphically compare the tool life curve of these two materials. Each tool, after tool life test was sent to the MEV to do a micron chemical analysis of the adhered layer on the rake face of the tool.

An electronic box with a programmable logical controller was built with intention to monitor the small-diameter drill tool wear. During the tool life test, for both materials, the monitoring signal was saved at each drilling before the inspection of main cutting edge. The sensitivity of system projected, mounted and installed inside of the CNC, was capable of reading the electric signal differentiating fractions of 0,394 % of the main spindle power. The spindle power was 20 CV or 14720 watts, so the minimum variation detected was 58 watts.

Table 3 – Machining parameters of drill life test

test	Steel	Cutting speed (m/min)	Spindle speed (rpm)	Feedrate (mm/rpm)	Axis feedrate (mm/min)
1	ABNT 304	12,5	663	0,09	60
2	ABNT 304	13,6	721	0,09	65
3	ABNT 304	14,8	785	0,09	71
4	ABNT 304	16,1	854	0,09	77
5	ABNT 304	17,5	928	0,09	83
6	USIFAC 304	17,5	928	0,09	83
7	USIFAC 304	20,5	1087	0,09	98
8	USIFAC 304	24,0	1273	0,09	115
9	USIFAC 304	28,2	1496	0,09	135
10	USIFAC 304	33	1751	0,09	158

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3. **THE ANALYSIS**

3.1. The feedrate force and torque and workpiece material.

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 paired data was choosing because there is a one-to-one correspondence between the values in the two samples. This is appropriate for testing the mean difference between paired observations when the paired differences follow a normal distribution The formulas for paired data are somewhat simpler than the formulas for unpaired data..

A paired t-test matches responses that are dependent or related in a pair wise manner. This matching allows accounting for variability between the pairs usually resulting in a smaller error term, thus increasing the sensitivity of the hypothesis test or confidence interval.

The graph of figure 3 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 values of feederate. In all the tests the feedrate and cutting speed has changed and a feedrate 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 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.. From these data can be said that with 95% of confidence interval for mean difference of federate force are between 112 N and 194 N. About torque can be said that the difference are between 44 N.cm and 65 N.cm.

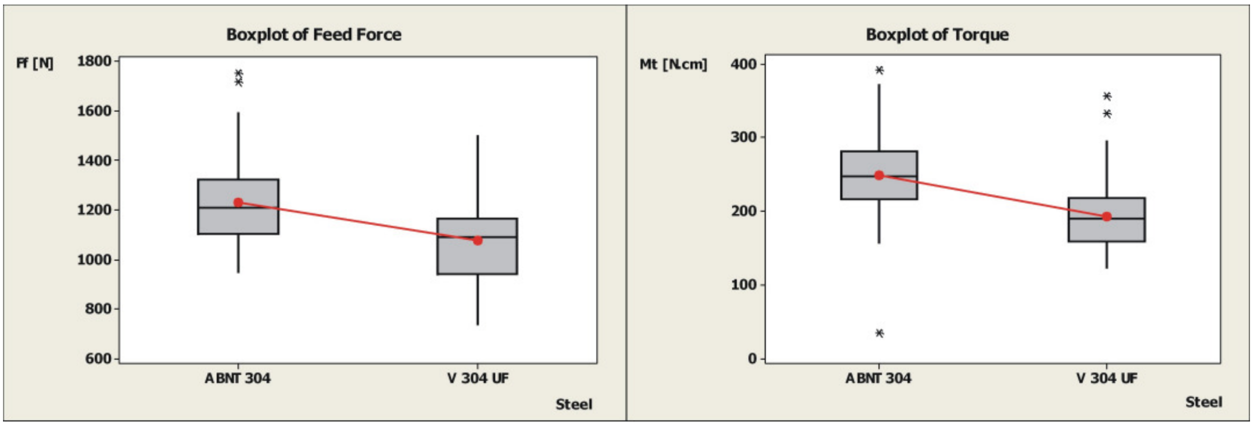

Figure 3 – Differences in feed force and torque with two austenitic stainless steels.

The graphical representation suggests and statistical analysis allows to said 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 feederate.

3.2. The drill power.

The power needed to drill the two different stainless steels could be evaluated because the torque at all tested cutting speed and feedrate were recorded in a file. The figure 4 shows how the power changes at different cutting speed and federate. Drilling V 304 UF stainless steel demands less power than drilling ABNT 304 stainless steel with the same cutting parameters. The demand for power at drill tip is practically the same when drilling ABNT 304 steel with lower feed rate of 0,06 mm/rev or when steel V 304 UF are drilled with cutting conditions that generates greater productivity, that is with 0,10 mm/rev feedrate.

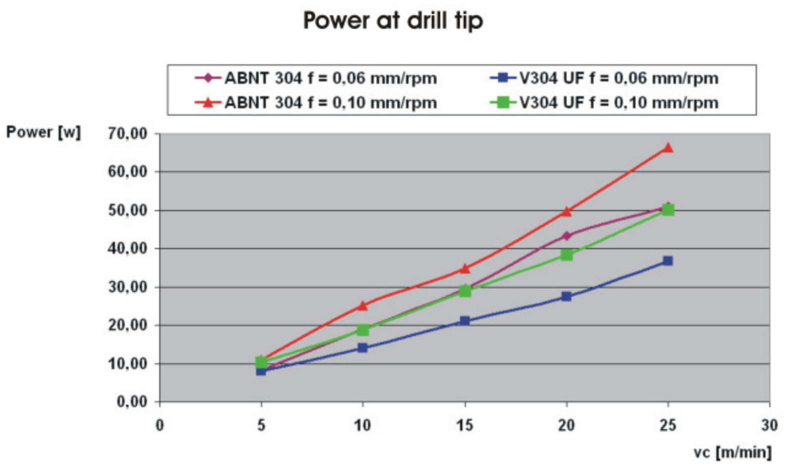

Figure 4 - Net power at drill tip

The spindle motor has 20 CV or 14720 watts and the monitoring system had the ability in detecting the relatively small change in the current. The device could sense fluctuations of 1/254 of the maximum motor current. The device sensitivity could detect only fluctuations in increments of 58 watts. The system was able to identify the beginning of drilling process but a lot of noise was present. This sensitivity wasn't good enough to detect the increasing power that occurs when the main cutting edge of a small drill becomes dull..

3.3. The drill wear and drill tool life.

The cutting edge durability of HSS drill has been improved when drilling V 304 UF steel when compared with the same tool drilling ABNT 304 steel. The tool life constant n in the Taylor equation (equation 1) for the two materials tested are not the same.

$$VT^n = C \quad (1)$$

The available data of the tool wear test located in a graph of figure 5 are the key to found the n constant in the Taylor equation. The tool life criteria was VBmax = 0,3 mm and the cutting parameters are showed on table 3. The n value for each tested material can be found using the data available on figure 6.

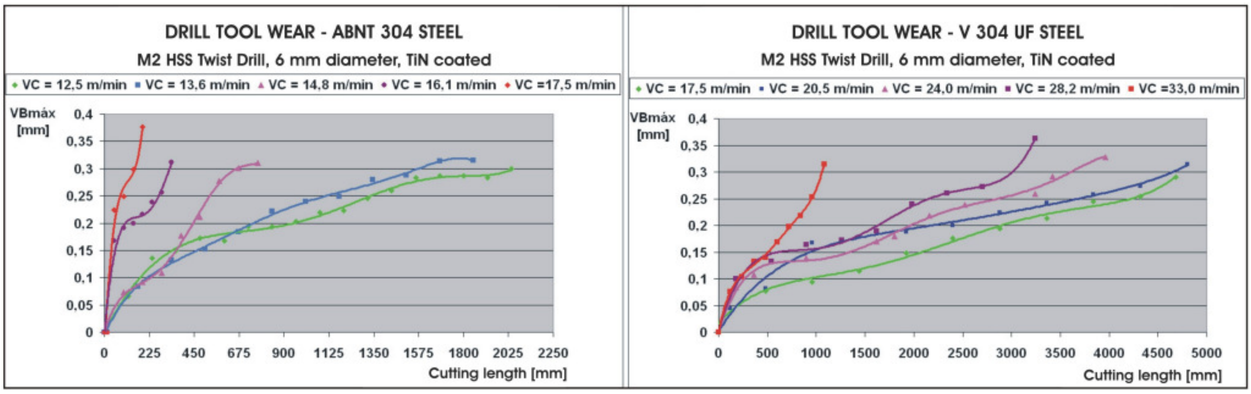

Figure 5 - Influence of workpiece material and cutting speed in hss twist drill tool wear

Each point on the graphic (figure 6) was built through the logarithmic of cutting time to reach the tool life criteria and the logarithmic of respective cutting speed. The line equation was get from the least squares technique from each material. It can be seen that the m factor from the V 304 UF steel line is almost 2,5 times bigger than the m factor from ABNT 304 steel line. Based on graphic from figure 4 the Taylor constants n and C can be found for both materials tested. The n and C constants from Taylor equation are 0,27 and 59 for V 304 UF steel and for regular ABNT 304 steel the n is 0,11 and C is 19.

The figure 6 shows that the correlation data of the straight line from ABNT 304 steel are very close showing that the experimental error during the tool life test was very small.

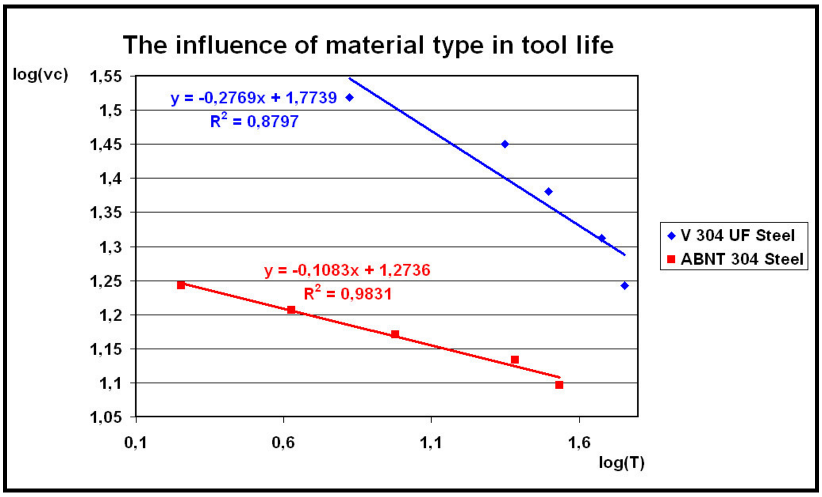

Figure 6 - Influence of workpiece material in drill tool life

The correlation data of the straight line from V 304 UF steel are lower and this can be noted by the dispersion of the five data points of tool life test throughout the straight line. This indicated that the experimental error in tool life test of V 304 UF were higher than tests in tool life test of ABNT 304.

3.4. The adherent material.

After the tool life tests the drill that had been used drilling ABNT 304 stainless steel at cutting speed of 17,5 m/min and the drill that had cut V 304 UF at same cutting speed were cleaned and analyzed at Mev.

The figure 7 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. The first thing to be noted is that the size of adhering layer are different for the two materials. This could explain way the feedrate force and torque are different for the two materials. The chemical composition of the 304 UF stainless steel layer showed calcium and sulfur contents higher 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. This could explain the lower feed force and torque needed to drill and the better tool performance at higher cutting speeds.

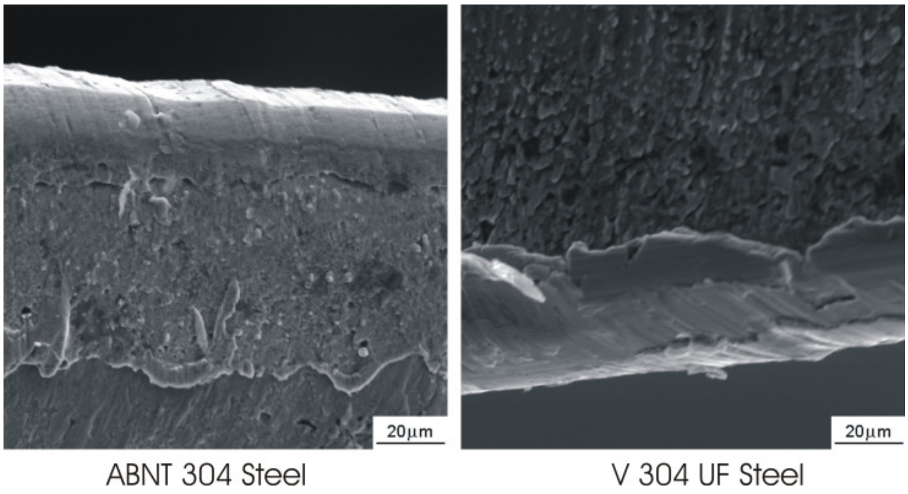

Figure 7 - Adhering layers that cover the main cutting edge.

The energy-dispersive spectrometry (EDS) system, are primarily used for qualitative identification of elemental abundances. For all the adhering layers that cover the main cutting edge observed, most of the time the EDS analysis was like figure 8. It was hard to find calcium

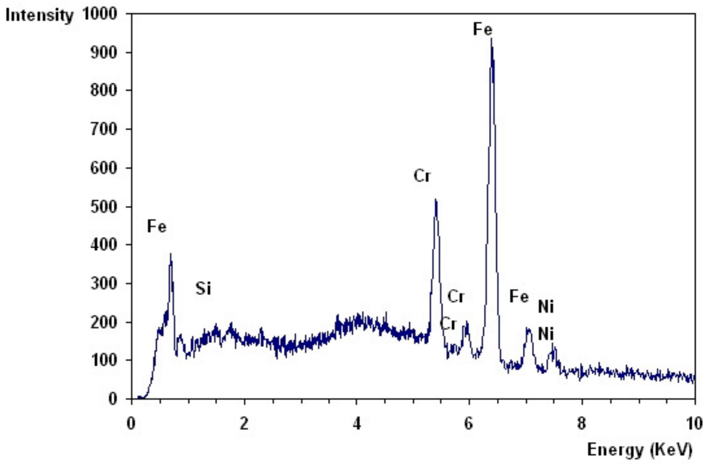

Figure 8 - EDS analysis of adhering layer that covers the main cutting edge.

Basically in an EDS analysis a solid-state detector collects and counts all of the emitted X-rays at once, and it divides the energy spectrum into different "channels" or ranges. The system collects a spectrum of X-ray energies from 0 to 10 keV and displays them on the computer screen. The peaks showed up on the spectrum correspond to energies of elements present in a sample. The EDS system can be used for quantitative analysis (one simply counts the X-rays received in the channels that correspond with a peak of interest). For many combinations of elements, however, the background noise is much higher. In that case, the EDS system need that corrections should be made for overlapping peaks and this limits sensitivity.

The wavelength-dispersive spectrometers (WDS) are in syntonization with characteristic X-ray of interest for analysis. The fine tuning is done by scattering of X-rays from a crystal positioned between a sample and the detector. The crystal will constructively diffract X-rays of specific wavelengths simply changing the angle of incidence of the X-rays. As a result, both the crystal and the detector move to accommodate the different incident angles. In addition, different crystals are used to cover the entire X-ray spectrum: The WDS analysis results in a spectral resolution and sensitivity an order of magnitude better than is possible with EDS analysis; the detection limits of WDS ordinarily varies between 300 and 30 parts per million. Also, in comparison to EDS, WDS offers more accurate quantitative analyses, particularly for light elements, and better resolution of overlapping X-rays peaks for improved element identification and quantification. These kinds of spectrometers can be sharply tuned to specific elements as the electron beam is scanned from one point to another on the surface of a specimen. The figure 9 shows the main cutting edge of drill that was analyzed by WDS. At the left are seen the main cutting edge and at right the scattered points that covers the same area show in that area the locations were higher calcium was found. The similar patterns of scattered points were found for the manganese and sulphur elements.

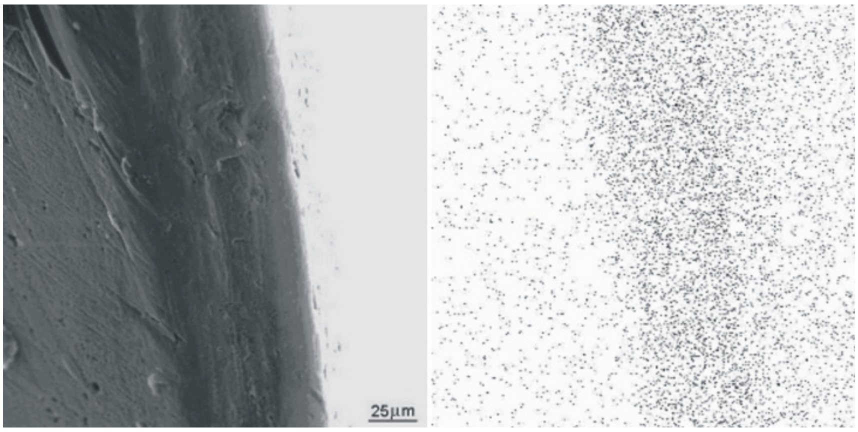

Figure 9 - WDS analysis of the drill main cutting edge.

4. **CONCLUSIONS**

The results of the machinability tests on two similar austenitic stainless steels are summarized as follows

1. The feedrate force and torque are smaller in drilling V 304 stainless steel UF than drilling ABNT 304 stainless steel.

2. The drill power is always lower drilling V 304 UF than drilling ABNT 304.

3. The drill tool life is higher in drilling V 304 UF than drilling ABNT 304

4. The elements calcium, manganese and sulphur are in inclusion composition of V 304 UF steel and covers the drill rake face giving to V 304 UF better machinability than ABNT 304

5. **ACKNOWLEDGEMENTS**

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