Evaluation of the machinability of stainless steel ABNT 304 and stainless steel Villares 304 UF with hss TiN coated twisted drills.

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Abstract. *Thanks to its mechanical properties and good corrosion resistance embraced, 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 the chips and concentrate on the cutting edge, and high malleability that indicates softness and tenacity makes chip evacuation difficult due to chip elongation. Yet the work hardening, a phenomenon that occurs near the cutting edge gives poor machinability to the stainless steel. The stainless steel with metallurgical control of the inclusions and calcium addition is presented as alternative, without loss of corrosion resistance. The present work compares the machinability of ABNT 304 steel with the similar steel, Villares 304 UF, with calcium addition using the drilling process. HSS TiN coated twisted drills had been used in the two different steels with different cutting speeds to evaluate the effect of the calcium addition in the machinability. The feed force and tool life measured allow explaining the upper machinability of the stainless steel Villares 304 UF.*

Keywords*. Drilling, machinability, austenitic stainless steel, TiN coating*

1. Introduction

The drilling process is very important in many production industries, since many holes must be drilled for component assembly in mechanical structures, e.g. to install mechanical fasteners like bolts and rivets. Amongst the traditional machining processes, drilling is one of the most important metal cutting operations, comprising almost 33% of all metal cutting operations (Chen, 2000). 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. However, drills have been used widely in 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. 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 life and high penetration rate (Schaw, 1986). TiN-coated high-speed steel tools are nowadays used frequently in metal cutting operations and increasingly replace uncoated drills, taps, milling cutters, etc. Similar to other cutting tools, after a certain limit, drill wear can cause catastrophic failure that can result in considerable damage to the workpiece and even to the machine. A drill begins to wear as soon as it is placed into operation. As it wears, cutting forces in the process increase; the temperature of the drill rises and this accelerates the physical and chemical processes associated with drill wear; and therefore the drill wears faster. Different types of drill wear, such as outer corner wear, flank wear, crater wear, chisel edge wear, and margin wear can be observed on the drill because the geometry of the drill and the cutting conditions vary along the cutting lips from the margin to the chisel edge (Ertunc, 2001). Drill wear is a progressive process which takes place at the outer margin of the flutes of the drill due to the intimate contact and elevated temperatures at the tool workpiece contact. However, under constant cutting conditions drill failure is a stochastic process. The reasons for varying drill life are the inhomogeneities in the workpiece and drill materials, the irregularities in the cutting fluid motion and the unavoidable asymmetry introduced during the grinding of the cutting edges (Jantunen, 2002).

1.1 The Steel

The group of alloys that today make up the family of stainless steels had their beginnings in 1913 in Sheffield, England. Harry Brearley was testing a number of alloys for possible gun barrel steels and observed that samples cut from one of these trial heats did not rust. Upon investigation it was shown to contain 13% chromium and this discovery lead to the development of stainless for use in cutlery. Development work was also being carried out in France and culminated in the production of the first austenitic stainless steel.

Silva and Mei (1988) define stainless steels as an iron-based alloy containing a minimum of about 12 % chromium. The chromium forms a protective self-healing oxide film, which is the reason why this group of steels has its characteristic 'stainlessness' or corrosion resistance. The ability of the oxide layer to heal itself means that the steel is corrosion-resistant, no matter how much of the surface is removed. The classification of stainless steels is based upon the nature of their metallurgical structure. Depending on the exact chemical composition of the steel, the microstructure may be made up of the stable phases of austenite or ferrite, a 'duplex' mix of these two, the phase martensite created when some steels are rapidly quenched from a high temperature, or a structure hardened by precipitated micro-constituents. An austenitic stainless steel contains at least 16% chromium and 6% nickel (the basic grade ABNT 304 is referred to as 18/8) and range through to the high alloys grades. Although all stainless steels depend on the presence of chromium, other alloying elements are often added to enhance their properties. Additional elements can be added such as molybdenum, columbium or niobium, copper, and aluminum to modify or improve their properties, making them suitable for many critical applications involving high temperature as well as corrosion resistance. This group of steels is also suitable for cryogenic applications because the effect of the nickel content in making the steel austenitic avoids the problems of brittleness at low temperatures.

The austenitic stainless steels represent the largest group of stainless steels in use, making up 65–70% of the total for the past several years. The austenitic stainless steels are, from the corrosion resistance point of view, superior to other types; their specific characteristics are demonstrated in low yield strength and relatively high tensile strength at room temperature and very high elongation. The austenitic alloys used most often are those of the AISI 300 series. Martensite may form in austenitic steels during plastic deformation from mechanical working or due to thermal effects. Two types of martensite can form: ε - martensite, which forms on close-packed (1 1 1) planes in the austenite and has a hexagonal close-packed crystal structure; and body-centered cubic α'- martensite, which forms as plates with (2 2 5) habit planes in groups bounded by faulted sheets of austenite on (1 1 1) planes. The formation of martensite from austenite can occur by:

1. $\gamma \rightarrow \varepsilon$ - martensite transformation;
2. $\gamma \rightarrow \alpha'$ - martensite directly;
3. $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ - martensite.

All austenitic stainless steels are paramagnetic in the annealed, fully austenitic condition. The h.c.p. ε - martensite is paramagnetic in contrast to the b.c.c. α'- martensite, which is strongly ferromagnetic (hard magnetic) and the only magnetic phase in the low-carbon austenitic stainless steels (O'Sullivan, 2002).

1.2 The Machinability

Austenitic stainless steels are generally regarded to be more difficult to machine than carbon or low alloy steels. This is due to several factors, such as the tendency of these steels to work-harden 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 utilization 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 growth the interaction even further. The higher the temperature, the stronger the interactive forces, resulting from, e.g. adhesion and or inter-diffusion 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).

It is widely accepted that work hardening of stainless steels is due to a martensite formation. The austenitic lattice has a higher tendency to deform due to the greater number of sliding planes, while the increase in strength and hardness during the deformation result also as a transformation of metastable austenite. Because of the low conductivity of austenitic steels, the chips are formed on the basis of catastrophic failure in narrow shear surfaces. In such a way, unfavorable, segmental chips are formed. In machining, these characteristics cause: the formation of built-up edges (BUEs), breakage of ceramic inserts, and sudden falls in hardness of tools made from high-speed steels. Low values of tool life, increased cutting forces and the appearance of unfavorable tough chips are the main characteristics which rank these steels among the group of materials that are difficult to machine.

Dolinsek (2003) shows that metal cutting, viewed as a plastic deformation process, is quite unique. It is unconstrained, localized, asymmetric deformation that operates at very large strains and exceptionally high strain rates. Theoretical investigations are endeavoring to develop expressions for the magnitude and the direction of the flow stress of a material within a given process. While the microscopical theories of materials explain the phenomena in shear surfaces by dislocation mechanisms, the macroscopical theories are directed towards establishing the equations by which the magnitude of the shear angle can be computed by the inclusion of the influences of the deformational work hardening. In metal cutting, extensive plastic deformation occurs in the workpiece material ahead of the shear (Figure 1). Therefore, the dislocation motion and interactions produce cell structures and multiple slip line structures on the workpiece (from the easy glide region at stage I to the hardening region at stage III). The formation of cellular dislocation structures, known to be related to the work-hardening process, is additionally induced due to compressive deformation ahead of the shear, thus the shear follows the compression. A sharp tool tip acts as concentrated source of the dislocation movements and in such a way develops a catastrophic shear front in a narrow region. The catastrophic shear, which releases the applied load, is related to the interference of the dislocation movements caused by the work hardening or the increases in compressive strains ahead of the tool tip.

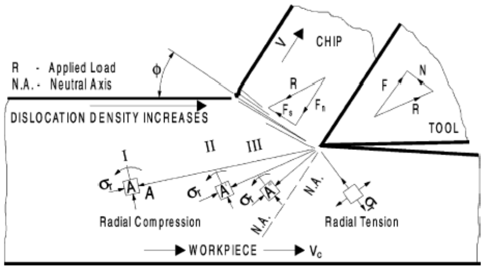

Figure 1. The orthogonal cutting model and compression ahead of the shear process

Some materials with poor thermal properties, and whose ability to deform plastically varies with temperature, demonstrate the difficulties in cutting by a particular chip shape. The thermal energy is due to poor thermal conductivity concentrated in narrow bands, with the catastrophic shear failure occurring along a thin shear surface. In cutting these materials such as austenitic stainless steels, catastrophic shear chips can be observed. Generally the machining stainless steels is regarded as a demanding task with short tool lives, poor chip control, and a high level of heat and cutting forces which threaten the cutting edges with rapid breakdown. With a high work-hardening rate and low thermal conductivity, they are generally more difficult to deal with than other alloy steels. The austenite in itself has a high work-hardening rate; additionally it also depends on the transformation of the austenite into martensite when the material is exposed to high deformation rates. In many cases, machining problems with austenitic steels are associated with BUE formation, bad surface, burr formation and unfavorable chip shape.

Dolinsek (2003) concluded that it is not possible to avoid a high degree of the work-hardening appearance in the drilling of austenitic stainless steels. A higher level of cutting resistance could be observed at the chisel edge of the drill. A study of the chip formation in austenitic stainless steels shows that a less continuous process and higher variations in cutting forces characterize the cutting with the lower rake angles. A sharp cutting edge means softer cutting action with lower forces involved and less burr formation on the workpiece. BUE formation, which is manly related to a temperature and a cutting speed, and after repeated removal, leads to the chipping of the tool. The formation of the BUE is one of the most interesting subjects in studying metal cutting principles. Since the cutting mechanisms significantly differ when the BUE occurs, special attention should be paid when we machine materials sensitive to the BUE. From Fig. 2, where the stress distribution at the BUE boundaries is presented, it can be seen that the attached material acts as the cutting edge. The changeable geometrical shape changes the magnitude and direction of cutting force and affects to the momentum of the cutting force. The main influences of the BUE are in unusual friction stress and in increase of the tool rake angle. The tool tip no longer acts as a concentrated source of dislocation movements; the production of cellular structures is intensive, and the high degree of the work-hardening process ahead of the tool tip cause additional difficulties in the machining of austenitic stainless steels.

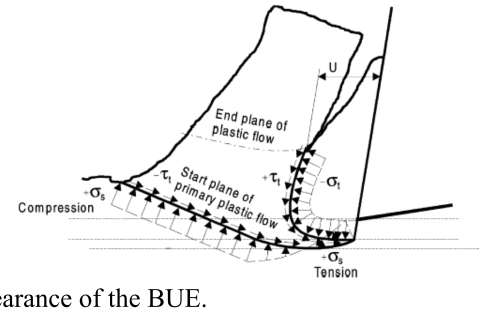

Figure 2. The shear process in the appearance of the BUE.

Nordin (2000) related that several investigations have presented ways to improve the machinability of steel by adding oxide-forming elements, such as S and Ca. The improvement is associated with the plastic behavior of the sulfides during machining. Low-friction compounds accumulate on the tool surface, giving lower cutting forces and thereby lower heat generation. The protective layer can also act as a diffusion barrier, impeding dissolution wear of the tool.

Fang and Zhang (1996) have showed that when machining Ca-S free-cutting stainless steel with carbide cutting tools at cutting speed from 80 to 120 m/min, the cutting force is reduced by about 25% and tool life is about three times that when machining ordinary stainless steel. That indicating there is a direct relation between tool life and the existence of an adherent layer. Although the percentage of the inclusions in steel is small, the number of inclusions is large. Therefore during of the machining process a large number of inclusions units may pass through the cutting edge with more chances to be extruded out. There are two kinds of inclusions that can be extruded and coated on the tool surface: the inclusions on the cutting line and those above near the cutting line (Figure 3). Under the effect of a high cutting temperature and high pressure stress, the inclusions in the steel in the cutting zone become soft and are in a plastic state, thus the inclusion unit, taking one inclusion unit for example, begins to deform and a microcrack is generated approximately along the shear direction. As the inclusion unit gradually approaches the cutting edge, it undergoes plastic deformation in a further step, and then the inclusion units are divided into two parts. One part of the chip will flow along the rake face, a fraction of which is extruded and coated on the tool rake face when the chips slides along the rake face; the part that is under the cutting line will pass below the cutting edge and form the machined surface. Due the severe tool-chip friction and pressure, the inclusions will deform and soften in a further step and both part of the inclusion unit will be extruded and coated on the rake and flank face near the tool nose separately. For the inclusions in the region near and above the cutting line, the microcrack that is generated during the deformation process may extend to the tool rake face, and the and a fraction of the inclusion can be extruded and coated the tool rake face. The resultant adhering layer is relatively harder and can be coated on the tool face in a solid state, which is not easily taken away by chip flow. At the same time, the temperature between the chip and the layer is high enough that the inclusion in the chip near the chip-layer interface are still in a viscous and soft state, and can be continuously extruded and coated on the rake face or to be exact, on the older layer previously formed. When the amount of the newly formed layer and of the layer taken away by chip flow tends to equality, the adhering layer is in relatively stable state.

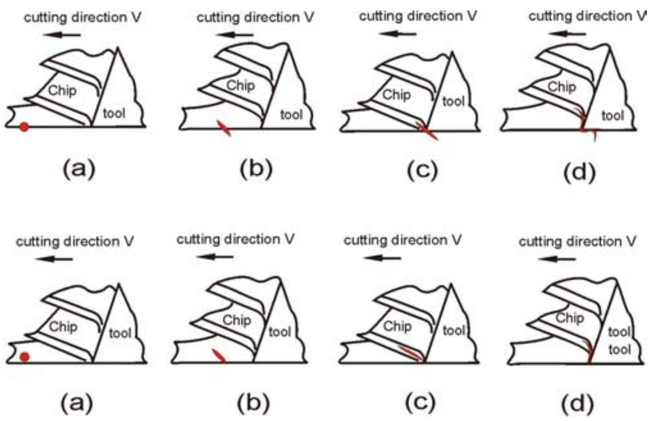

Figure 3.Estruing and coating process of inclusions on the tool rake face.

Qi and Mills (1996) showed that the formation process of the adhering layer could be summarized in four stages. First there is extrusion of low viscosity non-metallic inclusions onto tool surfaces. After that there is the adhesion of the non-metallic inclusions making a coating onto the tool surface. Then the growth of the layer occurs and the hardening process starts. Finally when the wear rate of the adhered layer is equal to the rate of the layer build up it becomes stable in thickness and shape. The adhering layer improves the tool life by inhibiting abrasive wear and adhesive wear. The adherent layer changes the normal dynamic diffusion model between the tool and the chip into a quasi-static diffusion model between the tool and adherent layer.

2. Experimental set-up

The cutting parameters of the experimental set-up used in this study are showed on table 1. Drilling life tests were conducted on the HERMLE C-600 a computer numerical controlled (CNC) three-axis machining center. A special CNC program was run to track feed force and torque signals as a function of drill wear.

Table 1. Cutting parameters programmed in CNC to test the machinability of the workpiece materials.

Cutting speed [m/min]	Spindle speed [rpm]	Feed rate [mm/min]
10	318	29
22	700	63
27,5	875	79
33	1050	95

The feed force (Fz) and torque (T) were measured by a four-component dynamometer Kistler model 9272. The dynamometer was coupled with charge amplifier Kystler 5019b that converted the signals from piezoelectric dynamometer into output voltages proportional to the force and torque. These signals were simultaneously sampled at 10 kHz using NI-PCI 6025E, the 12-bit data acquisition card used to collect the data. On a personal computer running Labview software, the data were displayed on the screen and then saved on the hard disk of the computer.

The drill was a DIN 338 HSS TiN coated 10 mm diameter and a 118° point angle. The feed rate was kept constant at 0,09 mm/rpm and different spindle speeds were used to obtain cutting speed of 10, 22, 27,5 and 33 m/min (Table 1). All drilling tests were performed using Vasco 1000, a water-miscible cutting fluid based on natural ester from Blaser Swisslube AG. The workpiece materials were V 304 produced by VILLARES METALS S.A., an austenitic stainless steel that fits all requirements of ABNT 304. The other materials were V 304 UF another austenitic stainless steel also produced by VILLARES METALS S.A with few differences in chemical composition. The chemical compositions of the steels are showed on table 2.

Table 2. Chemical composition of the two steels workpieces and the ABNT 304 mass %.

Steel	C	Si	Mn	Cr	Ni	Mo	Al	Cu	P	S	N	Ca
V 304	0,027	0,29	1,80	18,30	8,75	0,46	0,007	0,42	0,034	0,003	0,049	0,0011
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 figure 4 shows the workpiece used after the measuring the feed force and torque. It was fixed on dynamometer by two M10 screws.

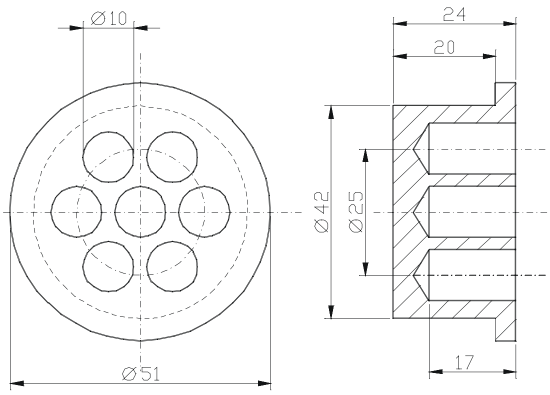

Figure 4.Workpiece after the drilling tests on dynamometer.

The experimental procedure had two stages. In the first step, holes were made on both steel workpieces to see if there was a difference in feed force and torque when these two austenitic steels are drilled at 10 m/min cutting speed.

The second stage was to test these two stainless steels at three different cutting speeds. Using a new drill at each different cutting speed, the first hole was made on a workpiece material fixed on a dynamometer (Figure 4). To promote the drill wear, a 31,75 mm x 150 m x 200 mm blank from each material was available. Nine holes were drilled to a depth of 25 mm to promote the tool wear on a blank that was fixed on the machine bed. The drill was then observed on toolmaker microscopic to measure the wear and this procedure were repeated until the drill life criteria were reached or a hundred holes were made. After sixty holes, if the tool life wasn't ended, a new one workpiece was replaced on the dynamometer.

3. Results and discussion

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

3.1- Feed force.

Four workpieces of each stainless steel were drilled on the dynamometer during the earlier stages of this study. Holes were made on both steel workpieces at 318 rpm and fed rate 29 mm/min for testing the CNC program and the charge amplifier parameters. From the 43- feed force saved on pc 25 were from ABNT 304 and 18 were from 304 UF. A statistical test provides a mechanism to see if the feed forces are the same. The results are showed on tale 3. Since the standard deviation of the feed force are unknown for these two steels, the 2-Sample t was chosen to perform a hypothesis test and compute a confidence interval of the difference between the two feed force. Using the Minitab Statistical Software can be seen that the mean of feed force is the same for both materials using a confidence interval of 95%. The graphical visualization of the data (figure 5) shows that the ABNT 304 steel has more dispersion in feed force than the 304 UF.

Table 3. Feed force statistical analysis of the two steels workpieces

	N	Mean	StDev	SE Mean
Fz (ABNT 304)	25	1170,7	94,7	19
Fz (304UF)	18	1183,2	50	12

Difference = μ Fz (ABNT 304C) - μ Fz (304-UF)
Estimate for difference: -12,5
95% CI for difference: (-57,6; 32,6)
T-Test of difference = 0 (vs. not =): T-Value = -0,56 P-Value = 0,578 DF = 38

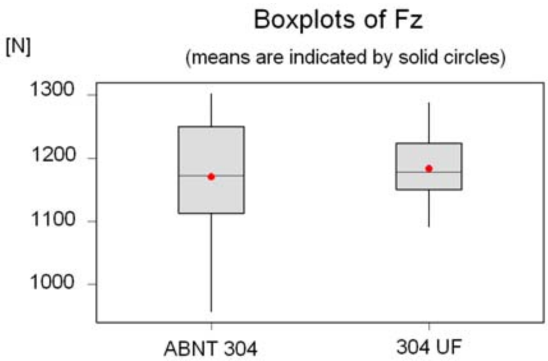

Figure 5.Graphical representation of the feed force statistical test

During the tool life test of the stainless steel ABNT 304 two cutting speed were used, 22 m/min and 27,5 m/min. The feed force were measured at the beginning of the test and after 10 holes of 25 mm deep what means 250 mm of cutting length between two feed force measuring. As can be expected and seen on figure 6 the cutting force increased with cutting length showing that the tool was progressively wearing.

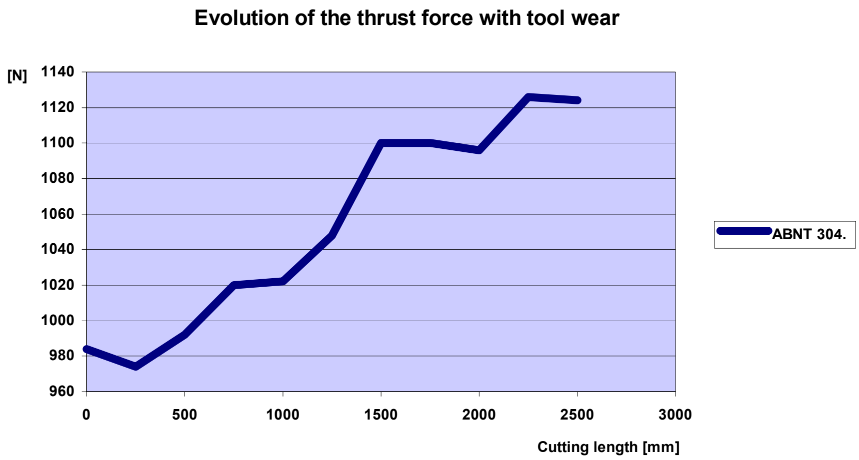

Figure 6. The relation between feed force and cutting length.

Since the 304 UF stainless steel could have better machinability than ABNT 304 the tests began at 27,5 m/min cutting speed. As the tool wear did not reach the tool life criteria after hundred holes drilled, the cutting speed was increased to 33 m/min using a new drill. The procedure to register the cutting force at each ten holes was used and the results shown on figure 7. When comparing the two graphics there are two remarkable differences. First there is no increase in feed force showing no tool wear at these cutting speeds. And second the feed force is lower, almost 30% lower than the feed force needed to drill the ABNT 304 steel.

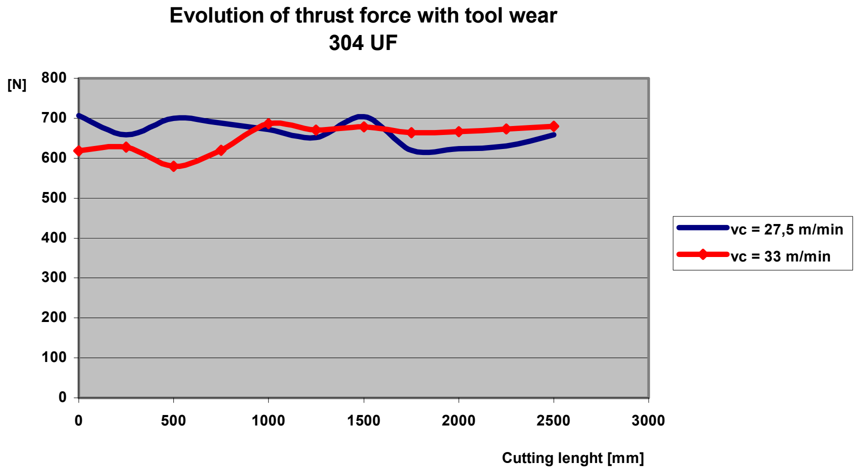

Figure 7. 304 UF stainless steel feed force for at two different cutting speeds.

3.2-Wear and tool life when drilling ABNT 304

The cutting edge of the drill showed adhesions of the workpiece material since the beginning of tool life tests. After drilling 250 mm length at cutting speed of 22 m/min the BUE has been formed as showed on figure 8a. The adhesion of material on the chisel edge was remarkable after cutting 2000 mm (figure 8b) and on the main cutting edge (figure 8c) Finally; the wear land reached 0,18 mm after drilling 2500 mm length (figure 8d). At a cutting speed of 27,5 m/min the chisel edge showed some adhesion after 250 mm cutting length and BUE has been formed at rake face. The drill broke after 400 mm cutting length. At a cutting speed of 33 m min the drill broken after 50 mm cutting length

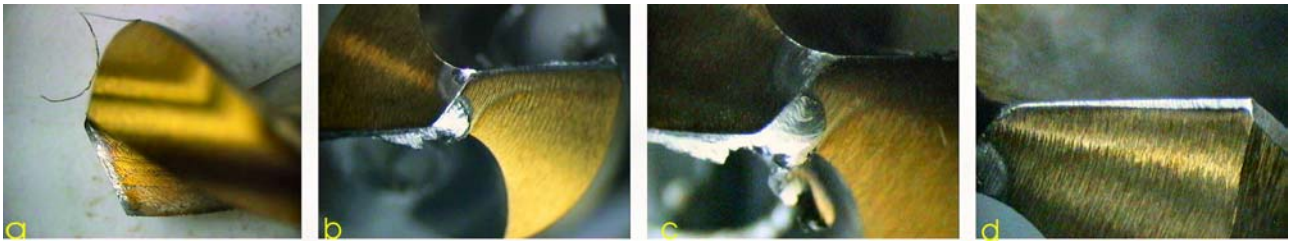

Figure 8.Wear of the drill at different cutting length. .

3.3-Wear and tool life when drilling 304 UF

All the photos taken from the cutting edge of the drill showed some adhesions of the workpiece material since the beginning of tool life tests. From the 250 mm cutting length at cutting speed of 27,5 m/min until the 2500 mm cutting length the adhesion of the material workpiece was present. At this cutting speed no the wear land was noted after drilling 2500 mm length. At the cutting speed of 33 m/min the adhesion was present and the wear length was insignificant during the cutting test. After a hundred holes at a cutting speed of 33 m/min there wasn't a significant wear land on the main cutting edge.

3.4-The metallurgical aspects.

Both steels were examined at microscopy to see the non-metallic inclusions, morphological aspects and proportions. The ABNT 304 stainless steel showed fewer inclusions; finally dispersed A1 type and the 304 UF showed inclusions more elongate A3 type (Figure 9). The adherent layer formed when drilling 304 UF steel where analyzed on EDX. The figure 10 shows on the left, the main cutting edge and the 304 UF layer that covers the rake surface. On the right, the clearance surface and the main cutting edge is covered by the 304 UF layer on top. The chemical composition of the 304 UF stainless steel layer showed higher calcium and sulfur contents than that was present on a 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 needed to drill and the better tool performance at higher cutting speeds.

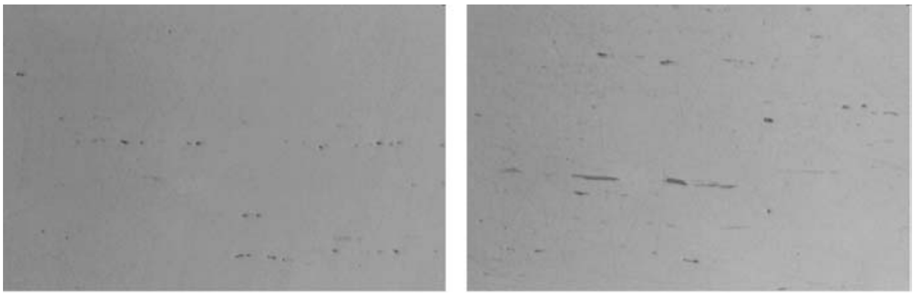

Figure 9.Inclusions of both steels. On the left the ABNT 304 shows A1 finally dispersed inclusion

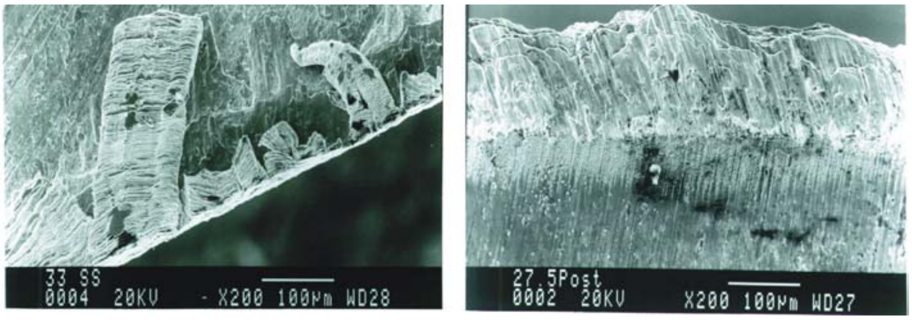

Figure 10. Adhesive layer on main cutting edge.

4. Conclusions.

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 at 10 m/min is almost the same for both stainless steel. 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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