The tool wear and tool life of hss TiN coated helical drill in machining tests of ABNT 304 And Villares 304 UF stainless steel.

Abstract. *The ABNT 304 steel has excellent corrosion resistance the in the environment, high resistance to attack of corrosive agents and keeps good tenacity in low temperatures. 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 new stainless steel is Villares 304 UF, with metallurgical control of the inclusions is presented as alternative to ABNT 304. The present work compares machinability trough drilling tests of ABNT 304 steel with the new one, measuring the flank tool of the drill. HSS TiN coated twisted drills had been used in these two different steels with nine different cutting speeds to plot the tool life. Yet, the main power signal from spindle was analyzed during the tool life. The lower tool wear and higher tool life measured in drilling Villares 304 UF allows to explain the upper machinability of this steel.*

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

1. Introduction

The stainless steels are iron-base alloys containing chromium. Silva., 1988, define stainless steels as an iron-based alloy containing a minimum of about 12 % chromium. These alloy steels usually contain less than 30% chromium and more than 50% iron. They attain their stainless characteristics because there is a formation of an invisible and adherent chromium-rich oxide film on the material surface. This oxide film establishes itself on the surface and heals alone in the oxygen presence. Some other alloying elements like nickel, molybdenum, copper, titanium, aluminum, silicon, niobium, and nitrogen are added to enhance specific characteristics. The carbon is usually present in amounts ranging from less than 0.03% to over 1.0% in certain martensitic grades. The corrosion resistance and mechanical properties are commonly the principal factors in selecting a grade of stainless steel for a given application. The stainless steels are divided into martensitic stainless steels, ferritic stainless steels, austenitic stainless steels, duplex (ferritic-austenitic) stainless steels and precipitation-hardening stainless steels.

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 have a austenitic, face centered cubic (fcc) crystal structure. The austenite is formed through the generous use of austenitizing elements such as nickel, manganese, and nitrogen. Austenitic stainless steels are effectively nonmagnetic in the annealed condition and can be hardened only by cold working. 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). Some ferromagnetism may be noticed due to cold working or welding.

1.1. The ABNT 304 austenitic stainless steel

The ABNT stainless steel grade 304 has excellent corrosion resistance in a wide range of media. It resists ordinary rusting in most architectural applications. It is also resistant to most food processing environments, can be readily cleaned, and resists organic chemicals, dye stuffs and a wide variety of inorganic chemicals. The ABNT stainless steels grade 304L is a low carbon 304 often used to avoid possible sensitisation corrosion in welded components and grade 304H has a higher carbon content than 304L, which increases the strength. This grade is not designed for applications where sensitisation corrosion could be expected. The ABNT 304 has good oxidation resistance in intermittent service to 870ºC and in continuous service to 925ºC. Continuous use of 304 in the 425-860oC range is not recommended if subsequent exposure to room temperature aqueous environments is anticipated, but it often performs well in temperatures fluctuating above and below this range. Grade 304L is more resistant to carbide precipitation and can be used in the above temperature range. Where high temperature strength is important, higher carbon values are required.

The ABNT 304 has excellent forming characteristics. It can be deep drawn without intermediate heat softening - a characteristic that has made this grade dominant in the manufacture of drawn stainless parts, such as sinks and saucepans. It is readily brake or roll formed into a variety of other parts for application in the industrial, architectural and transportation fields. It has outstanding weldability and all standard welding techniques can be used (although oxyacetylene is not normally used). Post-weld annealing is often not required to restore 304's corrosion resistance, although appropriate post-weld clean-up is recommended. The ABNT 304L does not require post-weld annealing and finds extensive use in heavy gauge fabrication.

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 BUE 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. The higher the temperature, the stronger the interactive forces, resulting from, e.g. adhesion andror 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,U, 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'Saoubi**a**, 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 live , 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 (CaOAl2O3SiO2) 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 CaOAl2O3SiO2 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, 1997)

1.3. The drilling process.

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).

The wear and failure of high-speed steel (HSS) drills are of significant technological and economic importance in industrial machining operations. A worn-out drill tip affects the quality of the drilled hole, whereas, each tool change is associated with decreased productivity and increased production costs. One of the approaches adopted by the industry to reduce wear and enhance tool life and productivity is the use of physical vapor deposition (PVD) techniques to apply a titanium nitride (TiN) coating onto cutting tool substrates. The beneficial characteristics of the TiN coating include: high hardness and wear resistance; low coefficient of friction; high-temperature strength and chemical stability; and the ability to improve the contact conditions at the cutting edge. This gives the TiN coating its excellent resistance to abrasion, adhesion, galling, welding, cratering, and the formation of a built-up edge especially at low cutting speed. (Nickel, 2000)

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).

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 flank tool wear. The tool was a 6 millimeter HSS TiN coated DIN 338 twisted drills. The federate was set at 0,09 mm/rev and the cutting speed ranged from 12,5 to 33 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 figure 1 shows one workpiece used to make a drill life test. The availability of material was restricted so the hole depth was set to 12 mm. It was possible to use bolts sides of the plate. For the drill tool wear of ABNT 304 steel a block of 30 x 200 x 400 mm was available and seven M2 high speed steel twist drills, and for V 304 UF the same amount of material was available.

Figure 1 - Workpiece sketch for drilling tool life test.

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	

3. Results and discussion

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

3.1 The drill tool wear test in ABNT 304 Steel

Two of the seven drills had been used in previous tool life tests. This previous tests aimed to set the maximum cutting speed and the minimum cutting speed and the expected number of drilled holes at both speeds. The number of drilled holes before tool life criteria was reached was important because it helped to set the hole sequence to be carried through between the periodic inspection of the main cutting edge. The previous knowledge of the two cutting speeds limits helped to set the intermediate cutting speeds. All the intermediate cutting speed had been set at same step in a logarithmic scale.

The sequence of drilled holes carried through between the inspections of the main cutting edge was function of the cutting speed. It was desired to construct each curve of tool wear with 10 points since the beginning of the test until the established tool life criteria.

Two microhardness indentations were made at 0,3 mm from main cutting edge and the distance between them was 1,0 mm. During the tool life test the edge was photographed and the VB wear value was quickly evaluated. Later all the photos taken were evaluated and the measurements reviewed. This procedure reduced the time needed to keep the machine stopped during the measurements of the tool wear.

The table 2 shows all the cutting parameters used in the tool life test, the number of drilled holes carried through between the inspections of the main cutting edge and the expected number of drilled holes to be gotten until the tool life criteria was reached.

Table 2 – Planned drill life test. Workpiece material ABNT 304 Steel

Cutting speed [m/min]	Spindle speed [rpm]	Federate [mm/min]	Holes expected to drill	Holes between photos
12,5	663	60	160	16
13,6	721	65	140	14
14,8	785	71	60	6
16,1	854	77	30	3
17,5	928	83	20	2
Tool life criteria = 0,3 mm VBmax				

The figure 2 shows the five curves of the tool wear in drilling ABNT 304 steel with cutting speeds showed in table 2. Each curve was built trough the measured main edge tool flank wear and the respective product of number holes drilled by hole depth. The lowest cutting speed tested generated the longest cutting length and the highest cutting speed in the drilling test drilled less holes. As the cutting speed increases the number of drilled holes decreases, and an acceleration of the drill tool wear happens. The results show that the high speed steel is extremely sensible to the increase of the cutting speed in drilling austenitic stainless steel.

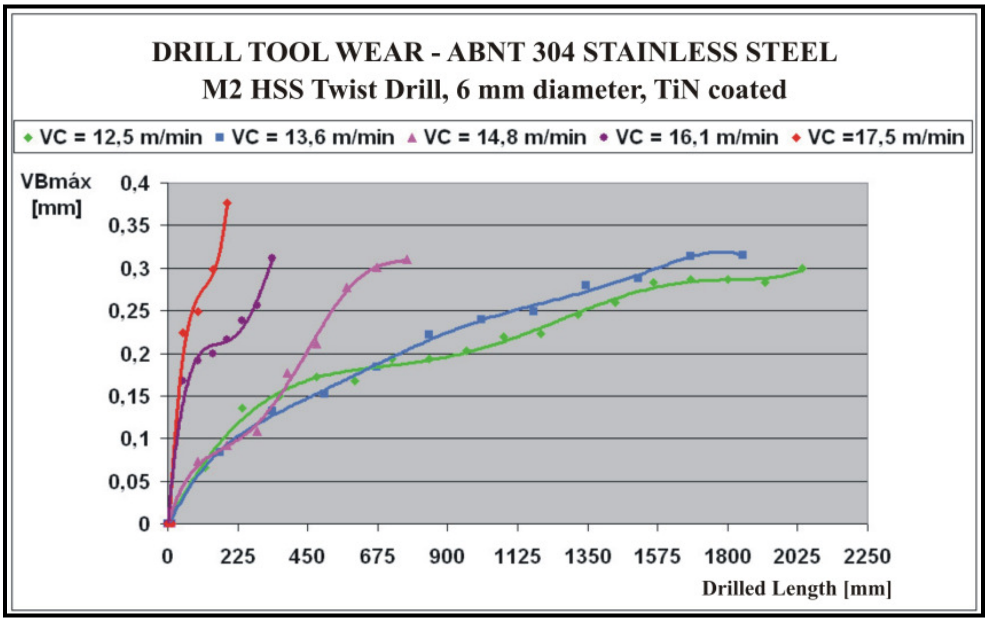

Figure 2 - Flank tool wear in drilling ABNT 304 austenitic stainless steel.

The austenitic stainless steel is characterized for presenting austenitic structure in the ambient temperature, the chips are long and has high rate of strain hardening and great plastic zone. It presents low thermal conductivity, high coefficient of attrition and high coefficient of **linear** thermal expansion. All these properties become unfavorable the machining

3.2 The drill tool wear test of V 304 UF Steel

The same amount of material workpiece and drills were available for the accomplishment of the tool wear test in V 304 UF steel. Two of the seven drills had been used in previous tool wear tests to define the two cutting speed limits. The amount of drilled holes to be carried through between the periodic inspection of the main cutting edge were gotten from this previous test. This were necessary because there was the premise of better machinability of steel V 304 UF and the restriction of the amount of available workpiece material. The cutting speed limits of 33 m/min and 17,5 m/min hab been defined from the previous test. The intermediate cutting speed had also been determined using a logarithmic scale.

The table 3 shows the cutting parameters from all the tool wear tests, the amount of drilled holes carried out between the inspections of the main cutting edge and the expected amount of drilled holes to be gotten in until the tool wear life criteria was reached.

Table 3 – Planned drill life test. Workpiece material V 304 UF sttel

Cutting speed [m/min]	Spindle speed [rpm]	Federate [mm/min]	Holes expected to drill	Holes between photos
17,5 m/min	928	83	400	40
20,5 m/min	1087	98	280	28
24,0 m/min	1273	115	190	19
28,2 m/min	1496	135	130	13
33,0 m/min	1751	158	90	9
Tool life criteria = 0,3 mm VBmax				

The figure 3 shows the five curves of the tool wear in drilling V 304 UF steel with cutting speeds showed in table 3. Each curve was built trough the measured main edge tool flank wear and the respective product of number holes drilled by hole depth. The same trend of behavior can be seen, the lower cutting speeds are associated to a tool life of the main cutting edge.

The direct quantitative comparison of the two graphs is complex, therefore although the same tool life criteria have been adopted, the cutting speeds tested had not been the same. The cutting speed of 17,5 m/min is the only one that is common in the two tests of materials. This cutting speed was the highest in the tool wear test of ABNT 304 steel and the length drilled in this material was 150 mm only. The tool wear test of V 304 UF steel had this cutting speed as minimum tested and, with the same tool life criteria, were possible drilling the length of 4750 mm. The ratio between the two drilled lengths at the same cutting speed, do not seems as an adequate index to compare the differences in the tool life of the two materials workpiece. It does not make sense suggesting that drilling V 304 UF steel, the tool life are 31 times higher than drilling ABNT 304 steel.

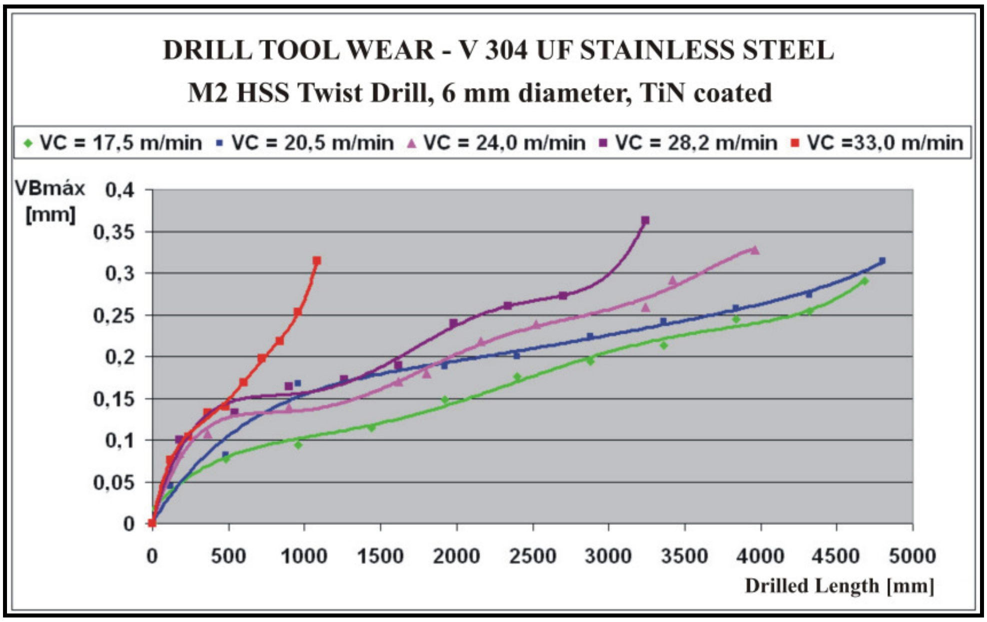

Figure 3 - Flank tool wear in drilling V 304 UF austenitic stainless steel .

3.3 The tool life constant *n* in the Taylor equation.

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.

$$VT^{n}=C \qquad (1)$$

The *n* value for each tested material can be found in a figure 4. The available data of the tool wear test located in a graph of figure 2 and 3 are the key to found the n constant in the Taylor equation. Each point on the graphic was built through the logarithmic of cutting time to reach the tool life criteria and the logarithmic of respective cutting speed. The line 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 4 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.

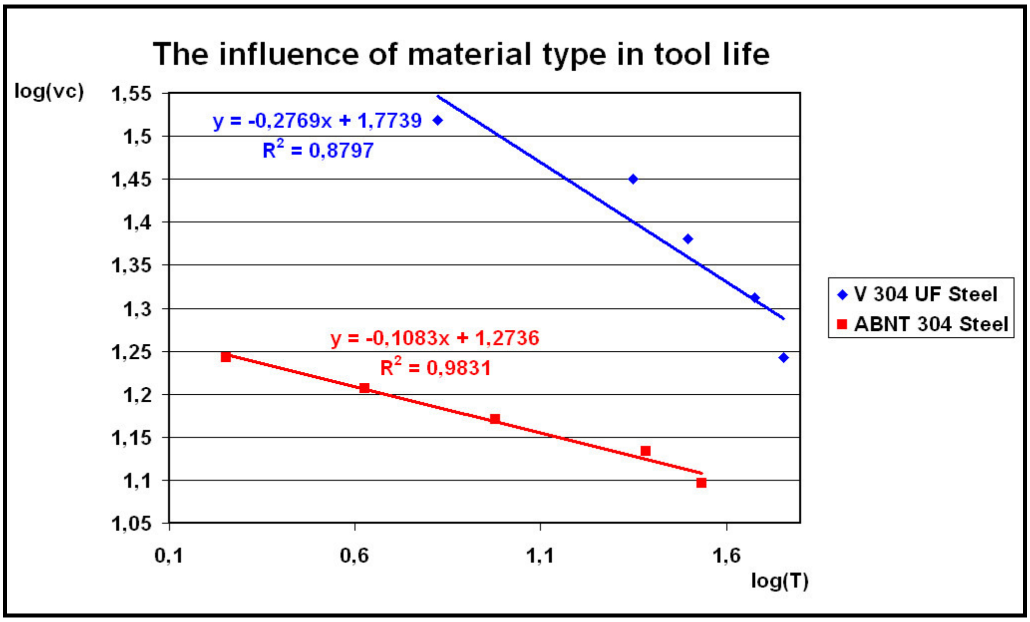

Figure 4 - HSS drill tool life.

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.

3.3. The main power signal from spindle.

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 0,393 % of the main spindle power. The spindle power was 20 CV or 14720 watts, so the minimum variation detected was 58 watts. The system was able to identify the beginning of drilling process as show in figure 5 but a lot of noise was present.

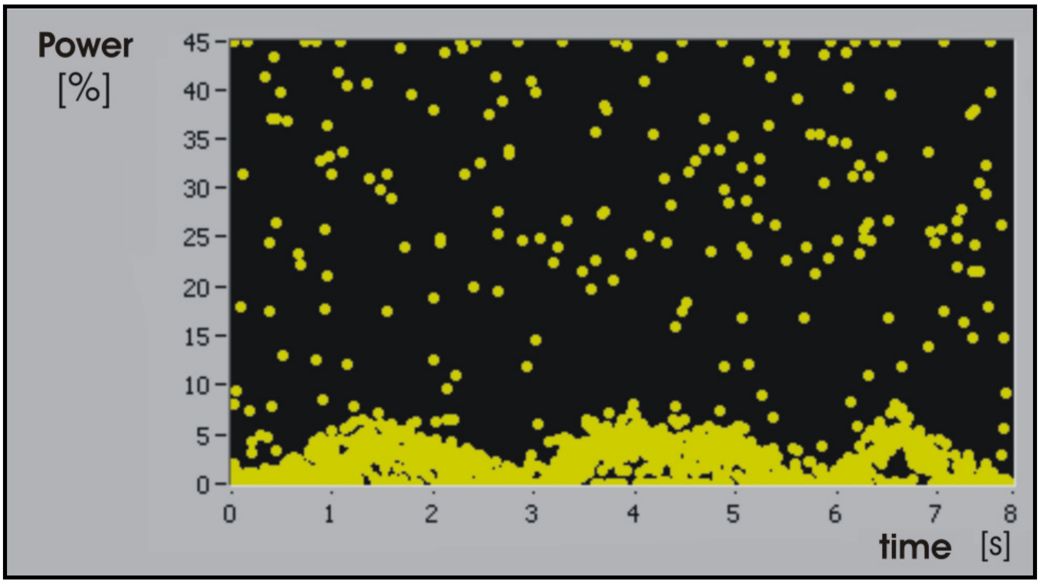

Figure 5. The monitoring system signal

The currently available monitoring method of tool wear based on current signals can only sensible if used for small machines with small spindle motor drilling smalls holes. This is due to the difficulty in detecting the relatively small change in the current caused by the drilling process compared to the current needed to rotate the spindle attached at big motors. The main challenge in monitoring small drillings is the resolution and the noise interference. The monitoring system wasn't able to detect a differential current signal generating power between 0.1 and 14720W. All the saved data wasn't able to identify the progressive tool wear by detecting small changes in current.

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 tool life n constant from Taylor equation is 2,5 times bigger for hss drill coated and workpiece material V 304 UF stainless steel than workpice material ABNT 304 stainless steel

The tool life and the productivity in drilling can be higher with Villares 304 UF stainless steel workpiece material than using the ABNT 304 stainless steel.

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