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STUDY OF THE TURNING NICKEL BASE ALLOY PYROMET® 31V (SAE HEV8)

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Abstract. Considering the constant technological developments in the aeronautical, space, automotive, shipbuilding, nuclear and petrochemical fields, among others, the use of materials with high strength mechanical capabilities at high temperatures has been increasingly used. Among the materials that meet the mechanical strength and corrosion properties at temperatures around 815 °C one can find the nickel base alloy Pyromet® 31V (SAE HEV8). This alloy is commonly applied in the manufacturing of high power diesel engines exhaust valves where it is required high resistance to sulphide, corrosion and good resistance to creep. However, due to its high mechanical strength and low thermal conductivity its machinability is made difficult, creating major challenges in the analysis of the best combinations among machining parameters and cutting tools to be used. Its low thermal conductivity results in a concentration of heat at high temperatures in the interfaces of workpiece-tool and tool-chip, consequently accelerating the tools wearing and increasing production costs. This work aimed to study the machinability, using the carbide coated and uncoated tools, of the hot-rolled Pyromet® 31V alloy with hardness between 41.5 and 42.5 HRC. The nickel base alloy used consists essentially of the following components: 56.5% Ni, 22.5% Cr, 2,2% Ti, 0,04% C, 1,2% Al, 0.85% Nb and the rest of iron. Through the turning of this alloy we able to analyze the working mechanisms of wear on tools and evaluate the roughness provided on the cutting parameters used. The tests were performed on a CNC lathe machine using the coated carbide tool TNMG 160408-23 Class 1005 (ISO S15) and uncoated tools TNMG 160408-23 Class H13A (ISO S15). Cutting fluid was used so abundantly and cutting speeds were fixed in 75 and 90 m/min. to feed rates that ranged from 0.12, 0.15, 0.18 and 0.21 mm/rev. and cutting depth of 0.8mm. The results of the comparison between uncoated tools and coated ones presented a machined length of just 30% to the first in relation to the performance of the second. The coated tools has obtained its best result for both 75 and 90 m/min. with feed rate of 0.15 mm/rev. unlike the uncoated tool which obtained its better results to 0.12 mm/rev.

1. INTRODUCTION

Industries that manufacture components for engines with nickel alloys and special stainless steel (automotive valves), titanium alloys (aviation turbine) are characterized by presenting a high cost in the manufacture of machined parts, mainly in relation to cost time/machine. Thus, it is very important to decrease the time of machining and increase the effective use of the tools, because the relationship cost and time in these industries is higher than in conventional industries (Lopez de Lacalle et al. 1998).

Nickel base alloys constitute ~45–50% of the total material required in the manufacture of an aircraft engine due to their outstanding strength and oxidation resistance at elevated temperatures in excess of 550°C (Gossler, 1985 and Simms, 1972). Nickel base alloys are typically available in cast, wrought and forged, and in sintered (powder metallurgy) forms.

The nickel base alloys, as well as in austenitic stainless steel, harden it self when worked quickly. High pressure during machining produces an effect of hardening which may cause distortions in parts with small thicknesses, compromising the integrity and tolerance of the machined components.

The nickel base alloys can be worked through the same techniques used in alloys based on iron. However, certain requirements are imposed because of the high resistance of the nickel base alloy and its tendency to hardening when worked and loss of the cutting tool in some conditions (Breitzig, 1997).

In a machining operation tool life achieved, metal removal rate, component forces and power consumption, surface finish generated and surface integrity of the machined component as well as the shape of the chips can all be used to measure machinability. The machinability index can be significantly affected by the properties of the materials being machined, properties and geometry of the cutting tool, cutting conditions employed and other miscellaneous factors such as stability of the machine tool, cutting environment, etc. Machining productivity can be significantly improved by employing the right combination of cutting tools, cutting conditions and machining tool that will promote high speed machining without compromising the integrity and tolerance of the machined components (Ezugwu, 2003).

Some nickel base alloys are used in aggressive environments because of their ability to maintain high resistance to corrosion, mechanical and thermal fatigue, mechanical and thermal shock, creep and erosion at elevated temperatures. These properties are required for the efficient and effective performance in environments where they are employed. The aircraft blades, which operate at high temperatures and pressures, are designed and manufacture with a series of holes arranged in order to maximize internal and external cooling. These alloys containing intermetallic compound Ni_3 (Al, Ta) in a matrix of solid solution of nickel (Ni) and chromium (Cr), tungsten (W) and rhenium (Re) as elements of fortified solid solution. The tantalum (Ta) used in the intermetallic compound improves the resistance to high temperatures and oxidation. This atomic element can be replaced by titanium (Ti) to reduce the temperature and oxidation resistance. The turbine blades of nickel base alloy can operate at temperatures up to 520 °C (Miller, 1996).

Heat resistant alloys with high melting point are the major materials used in the manufacture of aero-engine components. These exotic superalloys can be grouped into four major categories: nickel base alloys, cobalt base alloys, iron base alloys (e.g. high chromium stainless steel), and titanium alloys. Figure 1 shows that two-thirds of superalloy production is consumed by the aerospace industry for the manufacture of jet engines and associated components, mainly in the hot end of aircraft engines and industrial gas turbines.

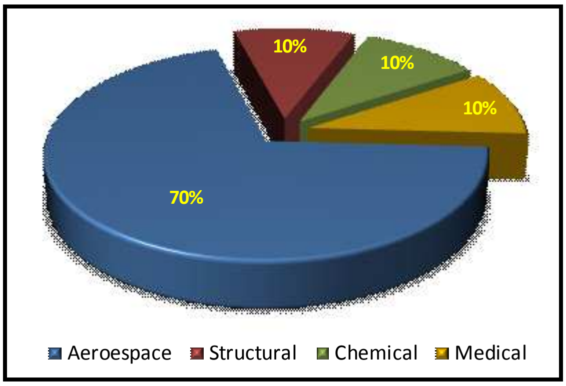

Figure 1 –Superalloy consumption (Seco Technical Guide - Modified)

The nickel base alloy Pyromet® 31V is one of materials that meet the mechanical strength and corrosion requirement at temperatures around 815 °C. This alloy is commonly used in the manufacture of exhaust valves in high power diesel engines where is required suphide resistance and good resistance to corrosion and creep.

About 50 wt.% of aero-engine alloys are nickel base alloys (Miller, 1996). They exhibit higher strength to weight ratio, relative to steel that is denser. Nickel base alloys are also used for other applications such as marine equipment, nuclear reactors, petrochemical plants, food processing equipment and pollution control apparatus (Ezugwu, 2003).

The nickel superalloy Pyromet® 31V, hot-rolled, with hardness between 41.5 and 42.5 HRC was used in the machining tests described in this work. This work aims to study the behavior of coated and uncoated cutting tools used in the conditions of machining pre-established. The performance evaluation was done by analyzing the progression rate of wear and surface quality of the conditions presented by the samples.

The low nickel or titanium base alloys machinability for aero-engine lead the cutting tools to extreme thermal and mechanical stresses in the cutting edge, often leading to tool accelerated wear and plastic deformation. The typical failure modes observed when machining nickel alloys are the apparition of notching at the tool nose and/or cutting depth region, rapid flank wear, crater wear, chipping and tool catastrophic failure. Because of the low thermal conductivity of these alloys will generate high cutting temperatures during machining, thus the cutting tools used should have adequate resistance to hot hardness. On these conditions most of the tools lose their hardness resulting in resistance in the inter-particle junctions weakening and the consequent tool wear acceleration.

The efficient machinability of aerospace alloys depends on a correct choice of tool, cutting speed to be used, the time available and the functionality of the equipment used to have an economic production.

The most tools catastrophic failures, when machining nickel base alloys, are often caused due to the notching formation, particularly at the cut line depth. This mode of failure occurs due to mechanical and chemical action between the cutting tool and work material during machining. The notching grows on a random and unpredictable mode, so all efforts are made to prevent these occurrences. The notches may increase the stress concentration in the cutting edge and even weaken the entire edge, making it prone to a catastrophic failure during the machining.

According to Ezugwu et al. (2003) and Simms (1972), the main difficulties founded in machining superalloys, in particular the nickel and titanium base alloy can be summarized as:

- High hardness and resistance to hot, causing deformation of the cutting tool during machining;
- The austenitic matrix promote a rapid work hardening during machining, is considered the principal cause of severe wear suffered by the tools;
- The presence of hard and abrasive carbides on the microstructure of these alloys leading to excessive wear and abrasion of the tool may lead to a premature failure;
- The low thermal conductivity of these alloys leads to the concentration of cutting temperatures exceeding 1000 ºC in the tool, generating high temperature gradients;
- The weldability of the workpiece material in the cutting edge, forming Built-Up-Edge, which deteriorates the machined surfaces as well, compromises the integrity of the part surface and the cutting tool.

Uncoated carbide tools (K class) are used in machining of nickel base alloys with cutting speeds ranging between 10-30 m/min. and feed rates up to 0.5 mm/rev. to obtain good productivity (Ezugwu, et al. 1999) and (Kramer, 1987). Carbide tools have low stability and thermochemistry there is significant dissolution/diffusion of the material in the tool-chip interface causing wear of the tool when used for machining speeds exceeding 30 m/min. The temperatures generated in the interface piece-tool when used at speeds above 30 m/min may exceed the 1100 ºC, promoting thus fails due to carbide in plastic deformation in the cutting edge (Kramer, 1987). The diffusion of carbide particles in the substrate of cobalt (Co) through the diffusion between the grains boundaries have been reported in the literature, when is used speed machining above 35 m/min (Liao and Hush, 1996).

The wear in the tool tip and the flank wear are predominant failure modes when nickel base alloys are machining using coated carbide tools. The erosion of the coating layer exposes the substrate of the carbide at extreme temperatures at the tip of the tool. This effect combined with a significant increase in the components of forces creates a rapid wear in the flank and tip of the tool (Jindal et. al. 1999). The superiority of the coated carbide tools in relation to the uncoated tools can be attributed to the lubrication properties of the coating, resulting in low coefficient of friction at the interface workpiece-tool during machining. Both the coated carbide tools by physical vapor deposition (PVD) or by chemical vapor deposition (CVD) are used in machining of nickel base alloys. Carbide tools with multilayer work better in terms of tool life than those with a single layer (Ezugwu and Okeke, 2000) and (Jawaid et. al. 1999).

2. EXPERIMENTAL PROCEDURE

The nickel superalloy Pyromet® 31V used in these machining tests was produced by the hot-rolled process, with final hardness between 41.5 and 42.5 HRC. Table 1 below shows the nominal composition of the alloy used in the tests. The samples used had dimensions of 185 mm in length and 52 mm in diameter. One end of the workpiece had its diameter reduced to allow the attachment to the lathe. The samples were prepared by turning with the tool sacrifice, to remove the irregularities and ensuring accurate centering of the bar resulting in an approximate diameter of 52 mm.

The tools used, as an indication of the manufacturers and literature, were the PVD coated carbides tools TNMG 160408-23 Class 1005 (ISO S15) and the uncoated carbides tools TNMG 160408-23 Class H13A (ISO S15), both using the PTGNR 2020 K16 tool holder, manufactured by Sandvik.

Table 1 – Nominal composition of the nickel base alloy (Cartech, 2009)

Composição	*Ni*	*Cr*	*Cu*	*Fe*	*Ti*	*Al*	*Nb*	*Mn*	*Si*	*S*	*Mo*	*B*	*P*	*C*
PYROMET® 31V (SAE HEV8)	57,0	22,7	-	Rem.	2,3	1,3	0,85	0,2 Max.	0,2 Max.	0,015 Max.	2,0	0,005	0,015 Max.	0,04
*Rem.: Remaining														

The cutting parameters (cutting speed, feed rate and depth of machining) were selected by recommendation of the technical literature. They were adjusted to the capacity of the machine and based on information collected from previous tests in the nickel base alloy Nimonic 80A (Faria, 2007). The cutting conditions selected for the tests were Vc= 75 and 90 m/min, f = 0.12, 0.15, 0.18 and 0.21 mm/rev. and ap = 0.8 mm and with abundant cutting fluid.

The tests were performed in a computerized numerical control lathe MACH 9-Centur 30S ROMI, with power of 7.5 HP and rotation range from 25 to 3500 rpm. The cutting fluid was used Lubrax OP-38-MS, consisting of an oil-based emulsifiable naphthenic naphtha for cutting, machining and finishing of metals.

We used a Zeiss stereoscope, model Stem SV11 for the realization of the tools images aimed at examining types and mechanisms of wear for each cutting condition used.

The machining tests were conducted so that at each step of material removal was finished, its diameter was measured and the workpiece was then taken to the bench for measuring the roughness. We considered the mean of three measurements taken at an angle of approximately 120 degrees, using a portable surface roughness Mitutoyo SJ301. The tool wear, according to Vb, was measured and recorded. It was defined as a criterion for end of tool life one of flank wear (Vb max.) equal to 0.5 mm.

The methodology used in these tests enabled to study the behavior of the tools on the progression of wear (Vb) according to the length of cut (Lc) and the evolution of surface roughness Ra of the workpiece.

3. RESULTS AND DISCUSSION

Due to the machined material characteristics such as high resistance at high temperature, the carbide presence, rapid work hardening and low thermal conductivity among others, responsible for tool high wear, it was expected reduced lengths machined. The notching was predominant in the machining of Pyromet® 31V when using the coated tools and flank wear in uncoated tools. However, in some conditions occurred the chipping of cutting edge or were presented double chips and formation of Built-Up-Edge.

The Figure 2 shows the apparition of wear found in the coated carbide tools. In general, the wear generated in the cutting tools when working with nickel base alloys are not from a single kind wear, but a several combination of them. Thus, the various factors such as high temperature, high workpiece material resistance, high plastic deformation, surface layer hardening during machining, high tension in the tool-chip interface and chip abrasive, are responsible to generate this type of wear (Richards & Aspinwall, 1989; Iuliano & Gatto, 1994 and Ezugwu et al. 1999).

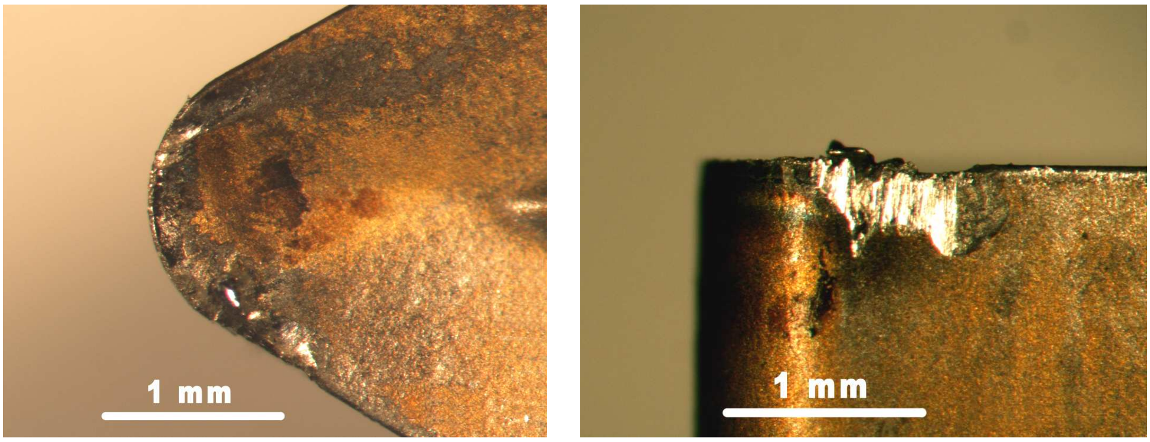

Figure 2 – Tool Wear of coated carbide aspect TNMG 160408-23 Class 1005.

Turning at 90 m/min speed machining we had cases of cutting edge chipping in the carbide tool. Figure 3 presents chipping occurred in two tools which, during the machining monitoring, it observed the Built-Up-Edge formation before this occurrence. As mentioned above, the tool's wear usually occurs due the multiple factors actions, ie, the tool material workpiece weldability associated with the abrasive carbides presence on the nickel alloy microstructure associated with the resistance increase because of the rapid work hardening were the main reasons why the tool have presented a premature failure.

It was observed in the machining with the coated tool the notch formation at the cutting depth, caused by high plastic deformation at the cutting depth, generating an increase in temperature and promoting tool workpiece material weldability. The notch wear was seen in almost all conditions in which was used the coated tool, and it was observed in some cases the double chips formation. The notch was formed already in the machining first pass, where associated with damage by abrasion, attrition and diffusion (grip and drag), would increase gradually until it reaches the limit value of 0.5 mm for the Vb or occur cutting edge chipping.

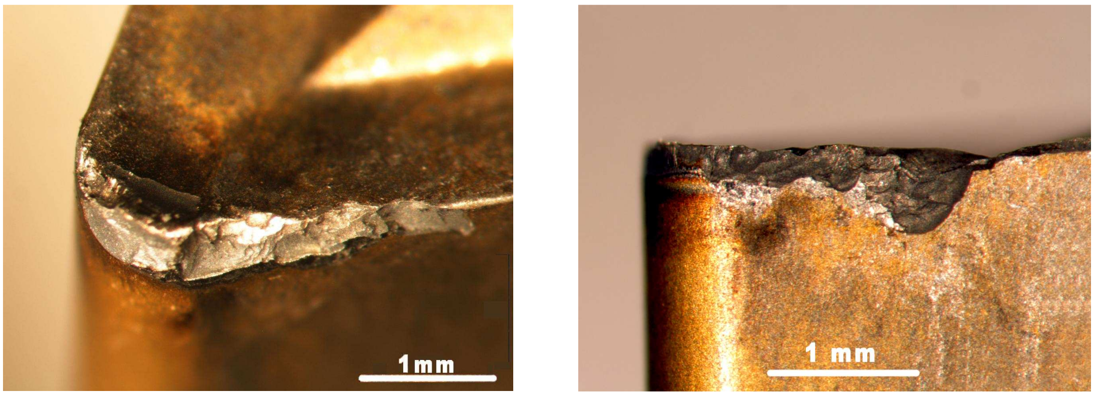

Figure 3 – Two coated carbide tools chipping due to Built-Up-Edge.

The wear aspects observed on uncoated tools TNMG 160408-23 Class H13A (ISO S15) can be seen in Figure 4. It appears that, unlike what happened with coated tools, the wear characteristic is predominantly by abrasion and diffusion, to a greater intensity at the tip of the tool than in the flank face, besides the crater wear effect in the rake face. It wasn't observed in any machining condition, using uncoated tools, the apparition of notch or Built-Up-Edge. The absence of a coating, responsible to reduce the wear, had great influence on the length of cut, as will be shown later.

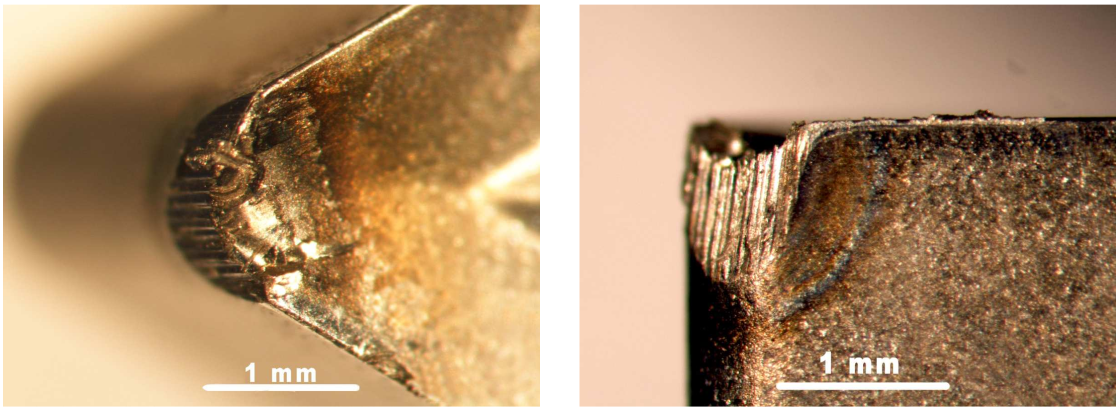

Figure 4 - The wear aspects on the uncoated carbide tools TNMG 160408-23 H13A (32X)

The chips formed are characterized by medium and long sized helical with cases of dual chips. It was observed the chip breaker had little or no practical effect, further deteriorating the tip tool, generating extremely high temperatures, which is already quite sacrificed due to the nickel alloy low conductivity. The long chips affect the cooling preventing the refrigerant efficient penetration. On the uncoated tools, the chips generated were long and helical, often damaging the workpiece surface finish (Ra). The Figure 5 shows dual chips (a) generated in turning with coated tools and (b) long chips with uncoated tools.

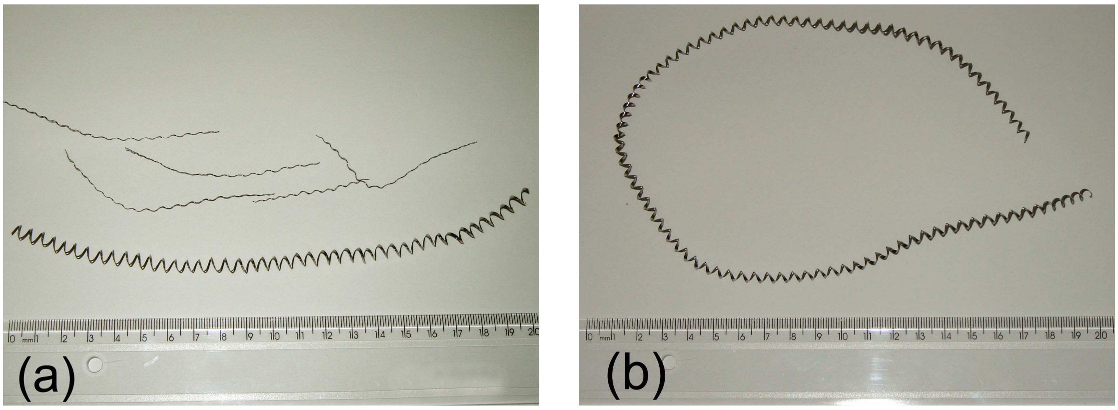

Figure 5 - The chips aspects generated with uncoated (a) and coated (b) carbide tools

The cutting length (Lc), taking as tool end of life for Vb = 0.5 mm is shown in Figure 6. In coated tools there is a trend of improvement in length machined for both speeds 75 and 90 m/min, as the feed rate is reduced, reaching a maximum value for f = 0.15 mm/rev. This trend was not observed in the machining with uncoated tools, which had a maximum length machined for feed rates of 0.12 mm/rev. The values presented in the graph shows how significant is the tool coating in machining of nickel base alloys, where we could get a maximum length of 926.8 meters for a cutting speed of 90 m/min and only 162.0 meters for the same speed but with a uncoated tool.

Unlike the results presented by machining with the coated tool, the other tool presented worse results with increasing the cutting speed of 75 to 90 m/min.

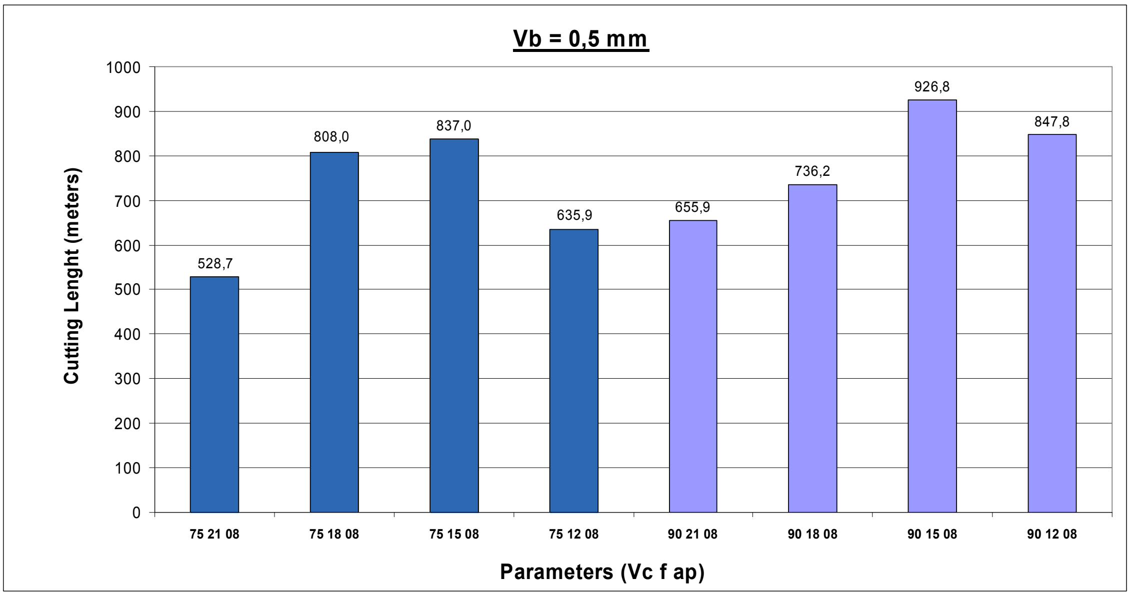

Figure 6 – Cutting Length (m) for Pyromet® 31V when turning with coated carbide tools

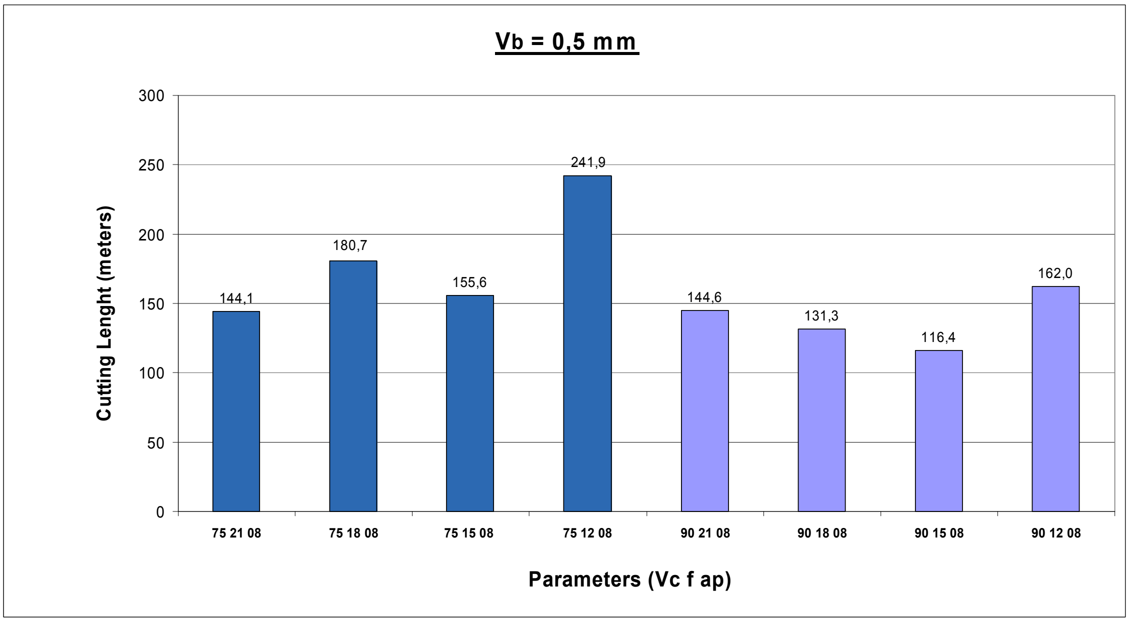

Figure 7 – Cutting Length (m) for Pyromet® 31V when turning with uncoated carbide tools

The average roughness values (Ra) measured after Vb reaches the set value of 0.5 mm is shown in Figure 8 and 9. In the coated tools analysis is shown the greater length machined for Vc = 75m/min also presented a better surface finish. The same not occur for the cutting speed of 90 m/min which returned the best roughness value with feed rates of 0.12 mm/rev. The uncoated tools presented its best results for the lowest cutting speeds. Considering the two cutting tools types, realizes the average roughness final values not present percentage values so different as which happened with the machined length.

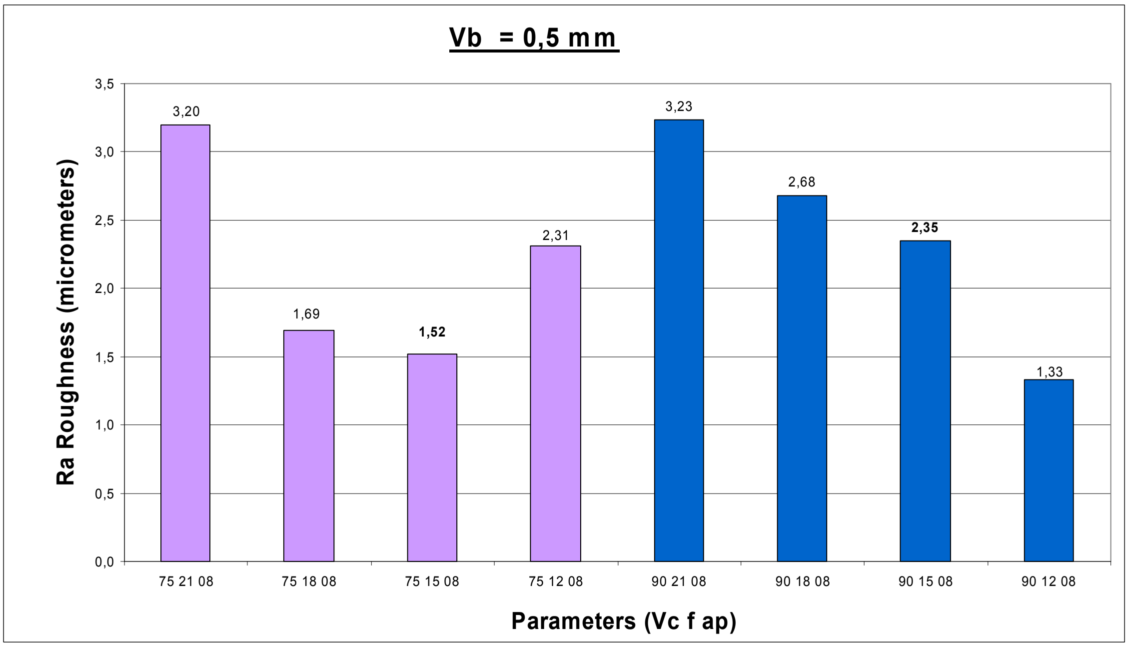

Figure 8 – Pyromet® 31V roughness (Ra) after turning with coated carbide tools

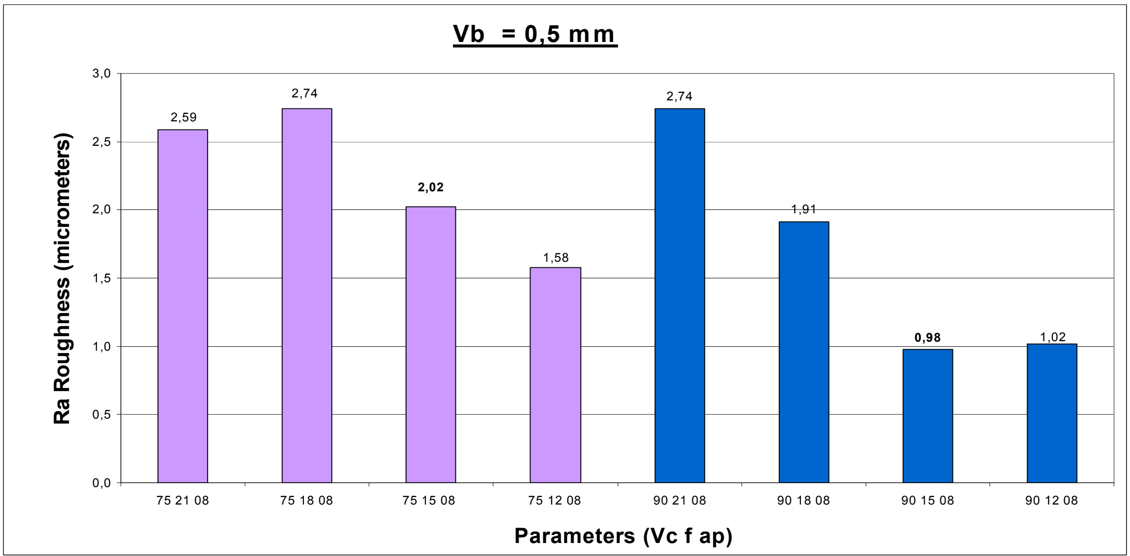

Figure 9 – Pyromet® 31V roughness (Ra) after turning with uncoated carbide tools

4. CONCLUSIONS

In front of the results presented and the discussions developed, it can conclude the following facts relating to the nickel base alloy Pyromet® 31V machining with coated and uncoated tools:

- The uncoated tools presented a machined length of only 30% obtained with the coated tools;
- The nickel alloy intrinsic characteristics does not allow large cutting lengths nor high speeds, which would aggravate further the wear mechanism;
- The predominant type of wear in the two tools was: flank (uncoated tools) and notch (coated) with mechanisms such as the abrasion, diffusion and attrition (adherence to drag). There was Built-Up-Edge formation, only the coated tools, occurring in some cases the cutting edge chipping or the double chips formation;
- Despite significant variations among the length machined in two types of tools, the average Ra roughness did not follow such difference;
- It obtained better values of Ra roughness on uncoated tools, however, its use is not feasible under the conditions tested because it presents very short life; and
- The damage degree presented by the uncoated tools, did not allow better roughness values.

5. ACKNOWLEDGMENTS

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