TRIBOLOGICAL ASPECTS OF NICKEL BASE ALLOY INCONEL713C EXTERNAL TURNING OPERATION USING CARBIDE CUTTING TOOLS AND DIFFERENT COOLING CONDITIONS

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Abstract. *The automotive components industry has increased its own quality standard level with the use of super alloys for high temperarture applications, such as combustion related components. The inconel 713 has proved to be one of the most difficult material to be machined due to its very high hardness and strain resistance. Special tool material like CBN or reinforced ceramics showed to be very obscure for machining this material. Water base cutting fluid were compared with neat oil for cooling the tool and the tribological conditions showed that carbide is still a very cost-effective solution for machining this kind of material. The lubrication conditons were manipulated in order to set a suitable cutting condition. Theoretical models were suggested to explain the tool life improvement with the use of neat oil. The worpiece roughness were evaluated to ilustrate the cutting tool wear progression and the flank wear was measured to outline the need of special cutting conditons to machine this kind of materials..*

Keywords*: Machining, Superalloy, turning*

1. INTRODUCTION

The tribological aspects related with the machinability of nickel-base alloys are very important and must be considered when the machining is about to happen with regular lubrication/coolant conditions. One of the most important features of this type of material is its poor heat transfer coefficient. This aspect is strictly related with the chemical compounds, like niobium, aluminum and titanium which represent a respectable percentage within the nickel base alloy Inconel 713C.

A low heat transfer coefficient indicates that the heat generated by the machining process will be concentrated at the cutting zone. This zone can be divided in three areas: the primary shear zone within the work piece material, the chip – tool rake surface interface and the work piece – tool clearance surface interface. The fig 1 presents the cutting zone and its sub areas.

When the heat is concentrated at the cutting zone, the major part of this energy is not dissipated (diffused) and the tool temperature increases. The discussion about how high the concentrated temperature is has been the subject of many researchers but the tribological aspects of this increase have not been completely explained yet.

The tribological aspects of any material removal process must be considered when the phenomenon happens not only at microscale but at large scale contact. This case involves the metal cutting conditions at lathes, machining centers or any other machining process where the removal rate represents the usual manufacturing conditions.

According to the contact area described at fig.1, it is possible to affirm that only the secondary and the tertiary areas are supposed to be affected by the external conditions of lubrication. The shear area heat generation depends strictly on the cutting conditions (cutting speed and feed rate), cutting tool geometry and, of course, on the material resistance to shear effects. This analysis is not the purpose of this paper which is supposed to deal with the analysis of the cutting conditions of the Inconel 713C when it is machined under two types of coolant/lubrication and two classes of tool material. The use of neat (integral) oil or water base coolant are the coolant/lubrication aspects manipulated through this paper in order to present which conditions are more severe or cost effective to the machining process. Two types of coated tungsten carbide interchangeable insert tools were used.

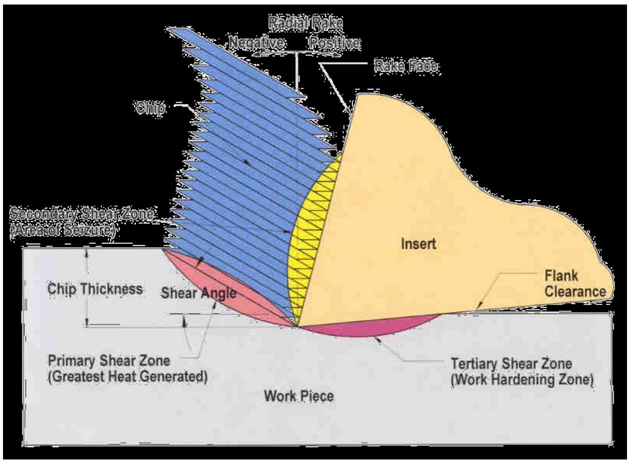

Figure.1 Cutting zone and the three areas of heat generation.

2. REVIEW OF LITERATURE

2.1. Metallurgical aspects of the Inconel 713C alloy

The Inconel 713C is a nickel-base alloy whose chemical composition is presented at table 1. Despite its high content of carbide formers, the microstructure of the alloy is a combined solution of the following phases:

- γ - phase (primary gamma): It is the CFC austenitic matrix phase formed by the Nickel-Chromiun-Molibdineum phase. Its first duty is to keep the mechanical and corrosion resistance at medium temperatures.

- γ' - phase (secondary gamma): It is an intermetallic phase formed by the precipitation of aluminiun or titanium. It is responsible for increase the hardness of the alloy. In some special cases, the titanium is added to reduce the hardening effect of the aluminiun precipitation.

Carbides: Different sorts of carbides are formed. First of all, the MC and after that its decompositions like M6C and M23C6. All carbides distribution is placed at grain boundary and it is responsible for the mechanical resistance of the alloy, especially for tensile effects. It is a very hard component reflecting directly at the abrasion potential of the alloy, specially at high temperatures.

- TCP – phases (topologically closed package phase): It is a hexagonal phase formed by the matrix transformation during its solidification which has chemical and geometrical affinity with the CFC structure. This phase increases the number of slip planes within the matrix which represents a respectable increase at ductility of the alloy.

Table 1. Nominal Chemical Composition (weight %) of Inconel 713C

Nickel-base	Ni	Cr	Mo	Cb	Al	Ti	C	B	Zr	Other
Alloy 713C	74	12,5	4,2	2	6,1	0,8	0,12	0,012	0,1	-----

The inconel 713C, like many other nickel-base alloy, is produced at a high vacuum furnace plant. This results in a controlled dentric aspect for the γ- phase with a natural hardness round 42 HR_C. All the carbides have a higher hardness and some of them, like titanium and aluminum carbides are also used like tool cover due to their low thermal conductivity, hot hardness and low friction coefficient.

The low machinability of this alloy is related with many aspects like abrasion, hardness and work hardening potential. This last is a common sense within the nickel-base alloys. Down milling strategies compared with up milling obtained a respectable increase in tool life Rodrigues (2006). The reason was the work hardening condition of the up milling during the penetration of the cutting edge and the tensile effect during the exit of the cutting edge from the inside of he material. During the sudden penetration, the nickel base alloys do not offer as huge resistance as during a progressive one. The elongation percentage is about 50% and during the strain it increases its ductility, getting strengthened as soon as it is subjected to tensile.

The figures 2 (a-e) shows the microstructure of the Inconel 713C alloy at different magnification. A dendritic structure can be easily identified and the carbides randomly distributed at the grain boundary indicate the convergence of the classical literature and the micrograph of the material used in this article (ASM, 1984).

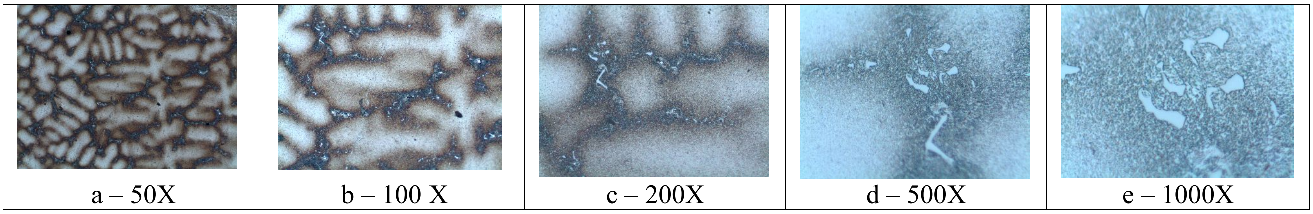

Figure 2 – Inconel 713C micrographs at different magnification. (a) dentric structure;(b,c,d) grain boundary with carbides; (e) cardides randomly disposed on the grain boundary. The clear areas at e are MC and its decomposition in $M_{23}C_6$ and M_6C.

2.2. Tribological aspects of the turning process

It is correct to state that the turning process has a particular condition of cutting when the tool does not leave the workpiece since its first contact until the end of the cutting length. This condition is called continuous cutting and the fig. 3 shows the process details.

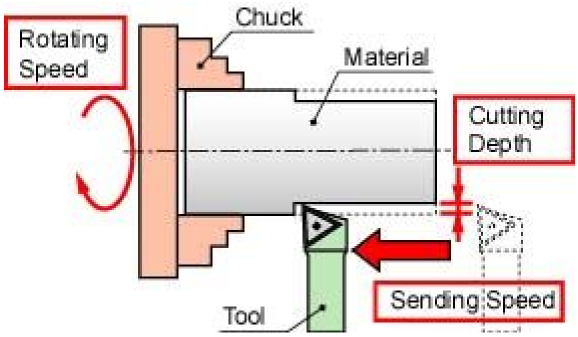

Figure 3. Detailed representation of the turning process and its components.

One important aspect of the continuous cutting is that the coolant/lubrication condition is not effective through the entire cutting length. The reason for that is the chip formation which interrupts the coolant action despite its geometry and the position from where it is being applied. The fig. 4 presents the constrained coolant condition despite the chip generation and tool – work piece interaction.

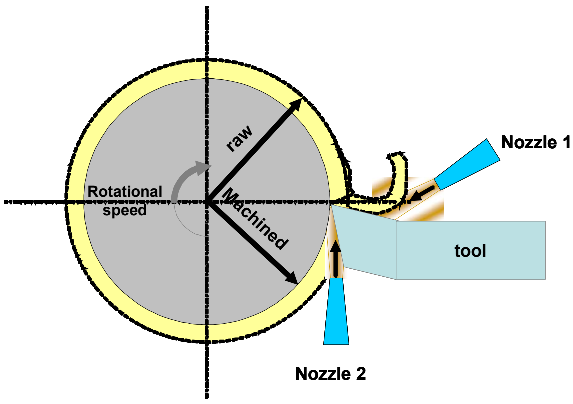

Figure 4. Cross section of the external turning operation. Fluid nozzle 1 is blocked up by the chip. Fluid nozzle 2 is blocked up by the tool flank surface and also by the turning rotational speed.

Even tough the machining process without coolant/lubrication is about to be chosen as the first choice for every machining process planning, due mainly to economical and environmental affairs, the nickel base alloys are almost impossible to be machined without the presence of cutting fluid.

Investigating the particular reasons for the statement above, it is true to affirm that every surface has a roughness profile that produces a real contact area smaller than the apparent one between two surfaces (Adamson & Gast, 1997). This decrease is a statistical deviation function of peaks and valleys contact between the two surfaces involved: the tool and the work piece surfaces. High pressure is the result of this unavoidable decrease of area.

Considering two tribological pairs involved throughout the cutting operation like "chip-tool rake face pair" and "work piece – tool clearance face pair", it is supposed to exist two types of lubrication condition operating at the same time: a boundary condition for the first pair and a mixed condition for the second. The figure 3 illustrates these two tribological pairs.

The Stribeck curve presented at fig. 5 shows the five possible lubrication conditions as a function of the absolute viscosity (η), the rotational speed (N), the load per unit area (P), the gap between surfaces (h) and the composite standard deviation of surface heights of the two surfaces (σ).

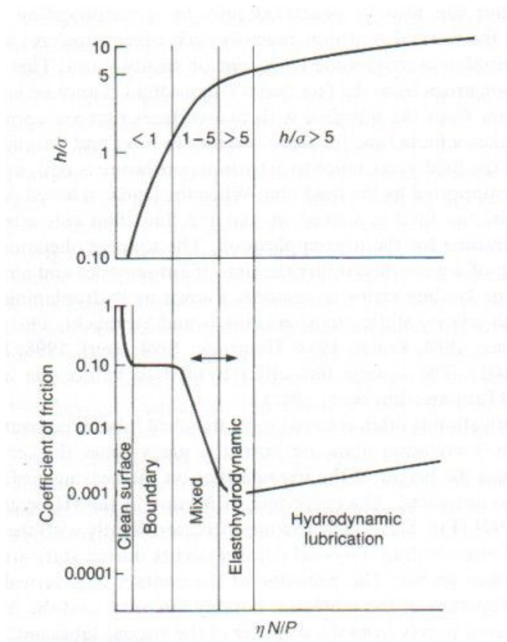

Figure 5 – Stribeck curve showing different lubrication regimes observed in fluid lubrication.

The "chip-tool rake face pair" is under high loads and low speeds. So the parameter η N/P is small and this lubrication tends to a clean surface contact where almost no lubrication affects the friction coefficient. Bushan, 2002 affirms that the contact between clean surfaces readily adsorb traces of foreign substances, such organic compounds like oil, water or reactive gases. This condition is not completely satisfactory to assume a layer of foreign material (e.g.: oil film) at the interface but lubricants are applied in order to reduce the friction and the wear. Adamson & Gast (1997) considers the solubility of the chemical compounds of the pair under temperature and relative flow as the reason for an interfacial layer between the tool face and the work piece material, but it is true to affirm, after Adamson & Gast (1997) that no external influence is affecting this film because it is relatively constrained as can be seen at fig. 4 and this layer is not influenced by the coolant/lubricant application. This film will be an oxide and this can change the value of the friction coefficient (μ). Even if it is almost a clean surface contact, the use of lubrication reduces the wear so it ca not be considered as clean surface contact. Though, the "chip-tool rake face pair" is under a boundary lubrication condition. Bushan, 2002 characterize the boundary lubrication as the condition which the two surfaces are so close together that the interaction between monomolecular or multimolecular films or lubricants and the solid asperities dominates the contact.

The failure in the boundary lubrication occurs by adhesive and chemical wear. The melting point and the shear strength of the film are important due to the high temperature and the shear orientation of the chip flow contact. Bushan 2002 affirms that the bulk flow properties of the lubricant (viscosity) play a little role in the friction and wear behavior. Figure 6 illustrate the boundary lubrication condition.

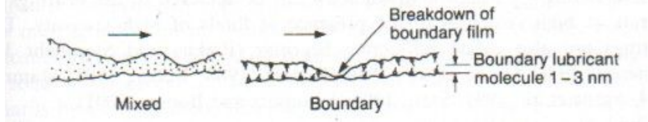

Figure 6 – Boundary and mixed lubrication condition

Theoretically, the "work piece-tool clearance face pair" is unloaded and the gap between these two surfaces is only a geometrical result of the cutting tool – work piece interaction. However, despite the chip breaker profile and the negative flank angle of the tool, a radial force exists and its projection on the tool clearance face is a load that ca not be neglected by the wear perspective. Thus, the "work piece-tool clearance face pair" is under a mixed lubrication condition (fig.6). The mixed condition represents a transition area between hydrodynamic/elastohidrodynamic and boundary lubrication regimes. At this pair, there may be more frequent solid contacts, but at least a portion of the surface interaction is supported by a hydrodynamic film. Bushan 2002 considers that the solid contacts, between unprotected surfaces could lead to cycle of adhesion, metal transfer, wear particles formation (debris) and eventual seizure.

Adamson & Gast (1997) affirm that the temperature generated at the interface (in both pairs) should not have much effect on μ. This value (μ) depends on the relative velocity of the two surfaces, the shear and yield behavior and finally the work hardening potential. It is contrary to friction Coulomb´s lawn which state that μ is not dependant of the sliding speed.

2.3. Neat oil / water base fluid aspects for the machining operation

Considering the constrained condition showed at figure 4, and the controversy about the friction coefficient decrease by the use of fluid films at boundary lubrication condition, some aspects of the fluid technology must be explained in order to justify its use.

A boundary lubrication condition at sliding contact concludes that the fluid will be immediately removed as soon as the slider moves along the fixed object (called slave). Considering the chip as the slider and the tool rake surface (for the first tribological pair) as the slave and, the machined work piece surface as the slider and the tool clearance surface as the slave (for the second tribological pair), only a randomic distribution will occur for the oil application over these surfaces. The chip breaking could be an explanation for the fluid film penetration between the chip and the tool rake surface. Although this intermittence is very fast, the fluid being pumped from the nozzle 1 could assure this forced lubrication. The nozzle 2 has a different condition of constraining but the rotational speed and the continuous cutting profile do not offer a gap for the fluid to getting into the interface between the tool clearance face and the work piece easily. So this lubricant penetration is also randomic.

The two important aspects related with the cutting fluid characteristic are the lubricity and coolant potential. Since Taylor (about 1901), the use of water base coolant fluids is considered the best heat removal for cutting operation. This condition is firstly because of the high percentage of water at the fluid and secondly the oil content reduces friction forces generated during the cutting dynamic.

On the other hand, the use of neat oil intends to achieve a higher reduction at the friction coefficient and consequently reduction of the cutting forces. This reduction is believed to decrease the wear even at higher temperatures.

For both types of fluids, the atomic chain size is important to be considered because of the very small spaces where the fluid will be put in. This space is about the volume of the asperities profile of both surfaces under the sliding condition. At this condition, is certain to affirm that the chain size will be broken and the molecule size is the only responsible for the lubrication at these constrained areas.

2.4. Thin film solid lubrication

From the viewpoint of tribological processes, there are two general reasons for the use of appropriate surface protection: to increase the wear resistance of a material surface; to influence the frictional conditions in the contact zone. (Kopac et al., 2001)

There are two major ways in which a coating may influence tool wear. On the one hand, the known wear mechanisms can be influenced directly by increasing wear resistance. These wear mechanisms may first be classified into the three surface effects of adhesion, abrasion and tribo-oxidation. Diffusion is a mechanism which begins at the tool face, but which also influences the properties of the bulk material and can therefore also be regarded as a volume effect. Finally, fatigue is a typical volume effect that leads to losses of tool material due to fractures which follow the formation of cracks. On the other hand, tool coatings can help to vary contact conditions by altering friction, heat generation or heat flow. These are indirect means of influencing wear by decreasing wear attack. (Klock & krieg, 1999).

Adhesion or adhesive wear, also known as attrition wear, occurs mainly at low temperature. This mechanism often leads to the formation of a build up edge (BUE). It is a dynamic process, with successive layers from the chip being welded and becoming part of the cutting edge. The BUE can be sheared off but it will start to form again. When it reaches an unstable size, it breaks away in small pieces or fracture. When higher cutting temperatures are reached, the conditions for this phenomenon are largely removed. Abrasive wear is mainly caused by the hard particles of the workpiece material. Diffusion wear is more affected by chemical factors during the cutting process. The chemical properties of the tool material and affinity of the tool material to the workpiece material will determine the development of the diffusion wear mechanism. The metallurgical relationship between the materials will determine the amount of wear. Fatigue wear is often a thermo-mechanical combination. Temperature fluctuations and the loading and unloading of cutting forces can lead to cracking and breaking of cutting edges. Intermittent action leads to repetitive heating and cooling as well as shock from cutting edge engagement. Pure mechanical fatigue can also occur when the cutting forces are too high for the mechanical strength of the cutting edge. [7]

Nowaday, coatings obtained by chemical vapor deposition (CVD) are widely used in the cemented carbide industry. Although the coatings, which consist primarily of TiC, TiCN, TiN, alumina, and their combinations provide a considerable increase in tool life of the coated cemented carbides, the conventional high temperature CVD process carried out at temperatures of more than 1000º C leads to decarbonization of cemented carbides, resulting in a significant decrease in toughness and transverse rupture strength (TRS) that limits the application of the coated inserts. Usually, the coated inserts are not utilized in applications where sharp cutting edges are essential or high durability of carbide tools ender unfavorable cutting conditions are necessary. (Konyashin, 1995)

Physical vapor deposition (PVD) processes are carried out at lower temperatures, which allows elimination of the substantial decarbonization of carbide substrates and maintenance of their toughness and strength. In spite of this, the tool life of coated carbide inserts obtained when using conventional PVD processes is far less than that of CVD coated carbide tools, which is associated with relatively poor adhesion and the higher level of internal stress of the PVD coatings. On these grounds the PVD coated carbide tools have only limited applications and the PVD processes are not so wide-spread in the cemented carbide industry as the CVD processes are. (Mari & Gonseth, 1993)

3. EXPERIMENTAL PROCEDURE

3.1. Materials

To carry out the experiments it was used a Traub TND 360 CNC lathe with a 14kW spindle power. The workpieces were cylindrical rod of 25,4 mm (diameter) X 130mm (length) of Inconel 713C produced at vaccum furnace. No heat treatment was applied. The average hardness of this alloy, measured at a standard hardness test was $50HR_C$. The workpieces were fixed using a hydraulic chuck with a tailored made jaw set for a 25 mm grip on to the external cylindrical surface. A center hole was produced at the opposite extreme of the gripped area in order to the use of a hydraulic tailstock. The figure 7 presents the experiment assemblage. It was used two different types of cutting fluid: a synthetic water base fluid (Castrol Syntilo 9954) and an Integral cutting fluid (neat oil – Castrol Ilocut 5725). The water base fluid has been applied with 8% of oil on clean water balance. Both fluids were pumped on to cutting operation by an external nozzle with 4,98 l/min outflow. Two different grades of a WC trigonal insert were applied. The ISO 1832 designation for the insert is WNMG 080408. The first grade is called Sandvik GC 1005 and the second is Sandvik GC 1105. The external layers of the tool covers are TiC and TiAlN respectively. The toolholder is a MWLNR 2525-08W.

An optical microscope with 40X magnification lens and a digital camera for taking pictures of the tool wear were used to measure and evaluate the wear progression and a manual refractometer to measure the fluid concentration of the water base fluid.

Figure 7 – Experiment assemblage for the external cylindrical cutting operation.

3.2. Experimental methodology

The main purpose of this work was investigate the tool life during external cylindrical turning operation of Inconel 713C under two types of coolant/lubrication fluids, two types of tool material coating and 13 different cutting speeds. For the neat oil, they were tested 13 different cutting speeds as mentioned, after that, using the water based oil, just the ones that presented better results and the extremes were repeated.

Aiming this goal the CNC was programmed to apply a 0,4mm depth external cylindrical cutting operation straightly on a 97mm length. The tool wear was measured after every pass. The feed rate was fixed at 0,16 mm/min. The end of tool life criteria adopted was flank wear equal or higher than 1,0 mm.

The table 2. presents the experimental planning for the description cited above. This experimental planning was performed four times. The reason for this number is the combination of two coolant condition versus two types of tool materials. So, the table 2 shows the experiments for each of the 2^2 combination.

Table 2 - Experimental planning for the 2^2 combination

Exp. nº	Cutting Speed	Feed rate	Cutting length	Cutting depth	Fluid outflow
1	30				
2	35				
3	40				
4	45				
5	50				
6	55				
7	60	0,16	100	0,4	4,98
8	65				
9	70				
10	75				
11	80				
12	85				
13	90				
	(m/min)	(mm/min^{-1})	(mm)	(mm)	(l/min)

4. RESULTS

The fig.8 presents the results for the GC 1005 grade with the two coolant/lubrication condition.

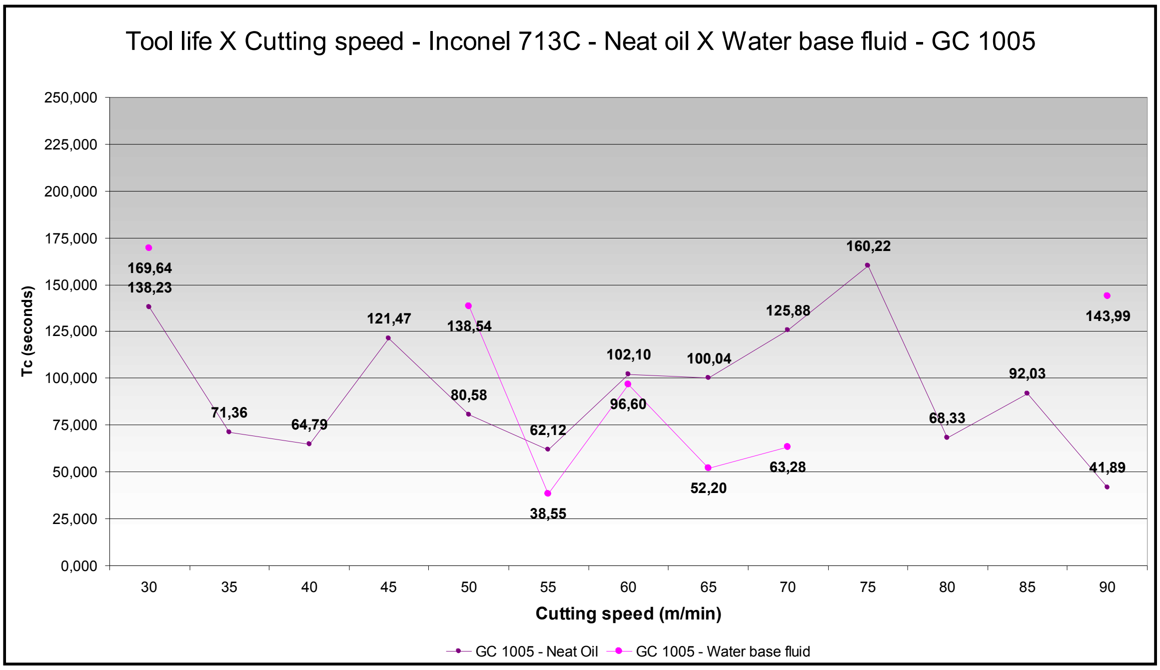

Figure 8 – Tool life versus cutting speed for the GC 1005 under the two coolant/lubrication conditions.

The fig.9 presents the results for the GC 1105 grade with the two coolant/lubrication condition.

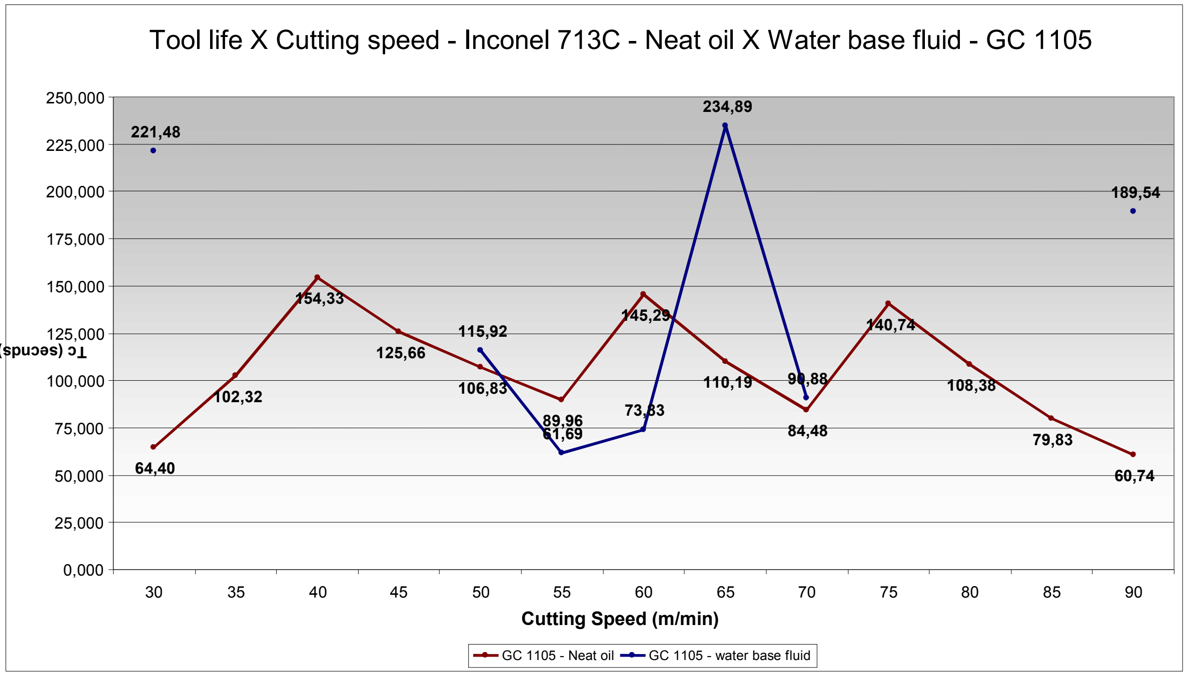

Figure 9 – Tool life versus cutting speed for the GC 1105 under the two coolant/lubrication conditions.

The figure 10 presents samples of tool wear images. The wear mechanisms through the tests look similar so, it was chosen some samples to illustrate the discussion.

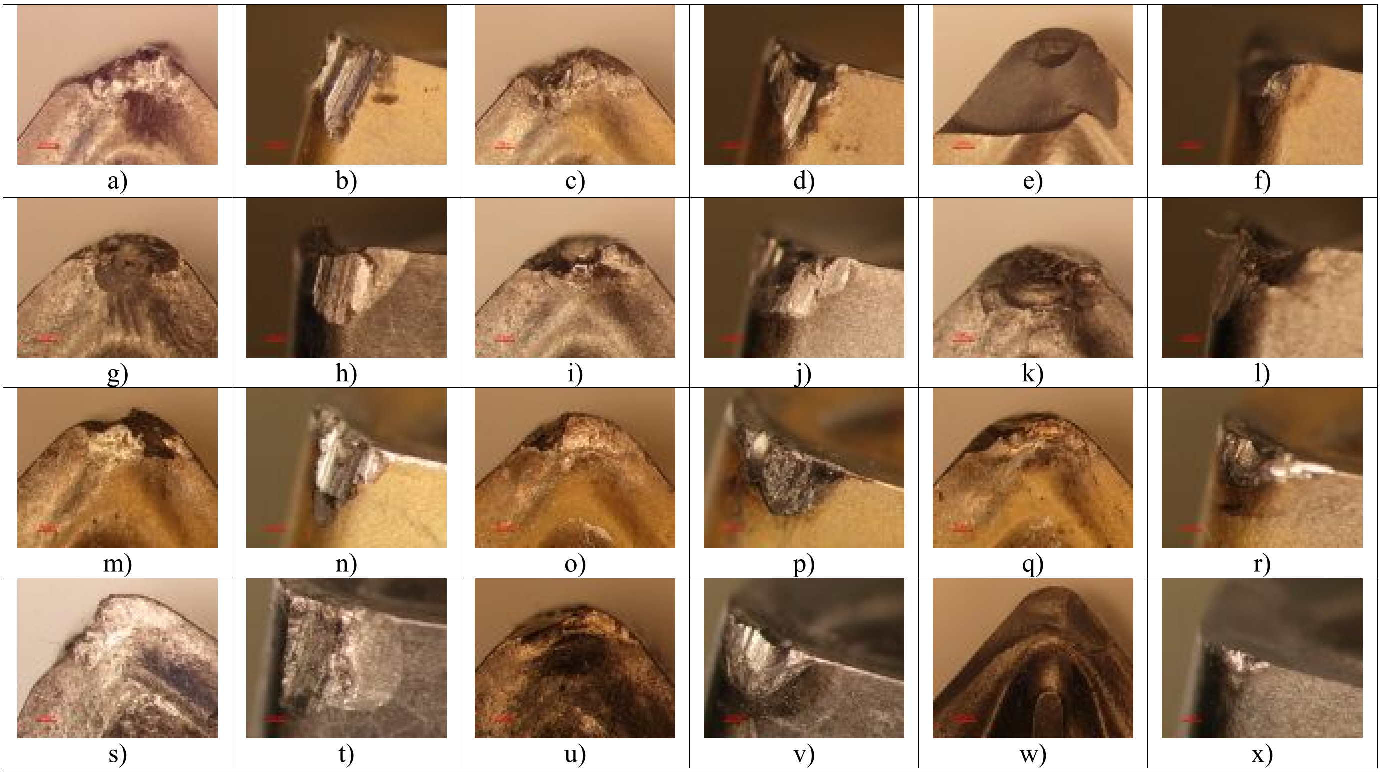

Figure 10. Images of the tool wear. a) to f) grade 1005, water based fluid, rake face and clearance face vc = 30 m/min, 65 m/min e 90 m/min respectively; g) to l) grade 1005, neat oil, rake face and clearance face vc = 30 m/min, 65 m/min e 90 m/min respectively; m) to r) grade 1105, water based fluid, rake face and clearance face vc = 30 m/min, 65 m/min e 90 m/min respectively; s) to x) grade 1105, neat oil, rake face and clearence face vc = 30 m/min, 65 m/min e 90 m/min respectively

5.DISCUSSION

Observing the figure 8 for the grade GC 1005, the behavior of the machining performance for both the cutting fluids was similar, and it did not presented a very better condition. The two highest cutting tool life were the obtained using the cutting speed 30 m/min (169 s) and 75 m/min (160 s) the good performance when a low cutting speed was used, probably was due to the built up edge, and the higher value can be explained by a combination of wear mechanisms, a local point of optimum.

In figure 9 the water based fluid helped the GC 1105 grade to achieve the two best results in terms of tool life, namely 221 and 235 seconds for 30 m/min and 65 m/min of cutting speed respectively.

Comparing figures 8 and 9 it is possible to notice that the GC 1105 was better then the GC 1005 grade, on the other words, the TiAlN presented a better performance than the TiN as a coating material, especially when the water based fluid was used. Both the curves presented an irregular behavior, probably because the wear mechanisms are associated with temperature (that in its turn is associated with cutting speed), so at low temperatures the abrasion is the governing mechanism and as the cutting speed increases the thermal activated mechanisms start to happen [9].

Figure 10 presents optical images of the cutting after each test. The images are very similar, showing that although the mechanisms being different the final result is very similar.

6. CONCLUSIONS

Based on the results obtained, for the cutting conditions used, is possible to conclude that:

The TiAlN was better as a coating material to turn the Inconel 713 than the TiN;

The cutting speeds near 70 m/min presented the better cost/benefit relation;

Neat oil and water base fluid presented similar behavior as cutting fluid, so this work recommend the use of the second one, since it is more environmental friendly than the former;

They were present several wear mechanisms during the tests, each one being the factor that determined the end of the cutting too life, depending on the cutting temperature;

The best cutting tool life achieved was around 4 minutes, much less than the tool producers advise, even when the recommended cutting conditions were used, what means that more effort need to be done in this research line.

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9. RESPONSIBILITY NOTICE

The authors are the only responsibles for the printed material included in this paper.