COMPARISON OF MACHINING INCONEL 718 WITH CONVENTIONAL AND SUSTAINABLE COOLANT

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The use of super-alloys, most of them Ni- or Ti-based, has significantly increased during the last decade. Industries such as the aerospace, energy or transport, use these kinds of materials due to their excellent properties that combine hardness, high temperature strength and thermal shock and corrosion resistance. These desirable material properties make these alloys extremely difficult to machine, since high values of temperature and shear forces are easily achieved and a quick cutting tool wear turns out to be an important process constraint. Thus, with the objective to overcome this phenomenon, several methods can be used; the most common one is to add large amounts of water-based or oil-based cutting fluids directly into the cutting zone. However, nowadays other less conventional fluids are also being studied with the aim of achieving a more ecological and efficient process in the machining of these difficult-to-cut materials. Examples of this are vortex cold air or cryogenic cooling, among others. In this study a comparison between different cooling methods in turning of Inconel 718 is presented, which is the most commonly used nickel based alloy in the industry. Tool life and workpiece surface finish has been analyzed in each case, searching the pros and cons of each cooling technique. The results reveal the possibility of replacing traditional pollutant cooling fluids by other more ecologically friendly alternatives.

KEYWORDS
cryogenic, machining, inconel, turning

1. INTRODUCTION

The evolution of modern industry tends to use advanced materials which, thanks to superior technological properties, enable new designs or better performance in products. Sectors such as aerospace, automotive, medical and power generation, among others, have promoted the use of thermo-resistant alloys, able to fulfil the industrial requirements due to its high resistance to corrosion and high elastic limits. Amongst these types of alloys are nickel based ones, which represent around 80 % of super alloys used in the aircraft industry [Krain 2007].

The most notable nickel based alloy is Inconel 718, which is characterized by high strength, good oxidation, fatigue and creep resistance at high temperature [Dudzinski 2004]. These properties are of great interest in domains such as the ones cited before, but result in an added difficulty in machining. Its high strength, hardening tendency and low thermal conductivity involve cutting processes with high forces and temperatures values. The machining of these materials, accordingly, is associated with low machinability and productivity [Leshock 2001], where tool wear, finishing accuracy and/or high production costs greatly limit the efficiency.

Several alternatives arise as solutions to this problem: the use of new tool materials and cutting geometries, more resistant tool coatings and/or new lubrication strategies, among others. The aim is to reduce tool wear and in turn increase the cutting conditions, looking for increased productivity. For reasons of cost saving and ease of implantation, the most common solution is the use of refrigerant fluids in order to evacuate heat from the cutting zone. The use of coolants and lubricants is a common technique in conventional machining. Traditionally pure oils and water based emulsions have been used in cutting processes, despite the environmental deficit and health risk involved.

Given the high temperatures that occur when machining nickel based alloys, which can exceed 1200 °C in the rake face, high demands of refrigeration are required, and there is also a necessity of solutions not detrimental from an ecological point of view. Taking into account these industrial demands, the use of advanced sustainable cooling methods that can replace traditional methods is evaluated in this work.

Firstly a process based on a cryogenic cooling fluid, liquid nitrogen (LN) has been studied. This emerging technology allows dipping the cutting area with a fluid available in the atmosphere, which reaches –196 °C, in a way that is safe and not harmful to the environment. Secondly, a low cost technology as cold air (vortex tube) has been studied. This compact device transforms a stream of compressed air into two opposing flows, one hot and the other cold. The cold one, which is used as coolant, reaches temperatures up to –30 °C, without the use of external energy. This technology has no detrimental effect on environment as only air is used.

The use of LN as coolant has been quite a popular technology in the last decade. Numerous experiments in different configurations have been done in cutting processes, such as pre-cooling the work material, as a material surface treatment or like a direct coolant jet in the cutting zone. This last method is the most common and successful, as shown by studies such as those by Hong and Broomer [Hong 2000] where a 67 % improvement in tool life is achieved in machining of AISI 304 austenitic stainless steel at high speed with LN, compared with conventional emulsion or experiments by Dhar et al. [Dhar 2006] with LN jets cooling in C60 steel, in which a reduction in uncoated carbide inserts wear is obtained in comparison to dry and flood machining. Bicek et al. [Bicek 2012] reported that in turning of hardened AISI 52100 steel a drastic improvement in tool life (up to 370 %) occurs when conventional coolant is replaced by LN. There are some other studies, such as the one by Ahmed et al. [Ahmed 2007], where tool holder is modificated/developed to incorporate the LN cooling system.

Hong et al. [Hong 2001a] used different methods for applying LN coolant like singular and combined rake & flank LN jet and pre-cooling the workpiece in difficult to machine Ti6Al4V. They have measured lower temperatures compared with dry and emulsion machining and best results with LN rake and flank simultaneous cooling. Berminghan et al. [Berminghan 2011, 2012] conclude that even if the optimal machining parameters are used the tool life can be improved further with cryogenic coolant when machining Ti6Al4V.

Related to thermo resistant nickel based alloys, like the one used in present work, there are also several studies: Pusavec et al. [Pusavec 2010] reported that cryogenic coolant and High Pressure Jet result in a drastic decrease in overall production cost (up to 30 %) due to the higher productivity with 3 times increased cutting speed. Wang et al. [Wang 2000] proposed a LN coolant through a sealed cap located on the top of the cutting insert to reduce cutting temperature in machining ceramic, titanium alloys, Inconel alloys and Tantalum, observing an improvement in tool life and surface quality. Wang et al. [Wang 2003] suggested an approach that combines cryogenically enhanced machining and plasma assisted cut; in machining of Inconel 718 surface roughness was reduced 250 %, the cutting force was decreased by approximately 30-50 % and the tool life was extended up to 170 % over conventional methods.

Nitrogen has been applied as a coolant also in milling of different materials such as AISI H13, Udimet 720 or AISI 304 [Ravi 2011, Truesdale 2009, Nalbant 2011]. Shokrami et al. [Shokrani 2012] have studied Inconel 718 milling with LN coolant, concluding that cryogenic cooling has a significant potential to improve surface roughness of machined parts as compared to dry without noticeable increase in power consumption.

Regarding the study of machining assisted by air coolant or vortex tube device, there are few published works. Some authors [Ko 1999, Boswell 2009, Liu 1997, 2007] confirm the ability of the cold air to reduce tool wear and temperatures reached in turning of materials as aluminium alloys or hardened steel. Kim et al. [Kim 2001] and Rahman et al. [Rahman 2003] confirm the effect of chilled air also in milling of similar materials.

Considering low machinability materials, two remarkable studies were found in the literature: Yamazaki et al. [Yamazaki 2003] investigated the use of air coolant devices in turning of an aeronautic alloy (Ti6Al4V), concluding that tool wear was similar using MQL (Minimum Quantity of Lubrication) and cold air. Su et al. [Su 2007] have analyzed the effect of cooling air in finish turning of Inconel 718 compared with other methods such as dry cutting, MQL or MQL with cold air. This last option and simple cooling air resulted in a drastic reduction in tool wear and surface roughness.

The aim of this paper is to present a comparative study between four cooling options in turning of Inconel 718. Liquid nitrogen and vortex tube jetting have been selected as clean cooling alternatives that have been compared to dry machining and flood emulsion as traditional cooling/lubricating strategies this paper describes the experimental series made to determine the efficiency of each tested cooling method in terms of cutting tool wear and surface finish quality of machined material. The work shows an optimized built-in tool cryogenic system with an exactly focused jet and optimized consumption, developed by IK4-Tekniker.

2. EXPERIMENTAL METHODS

2.1 WORK PIECE MATERIAL

The material used in the experiments is Inconel 718 nickel based alloy, in solution annealed state (AMS 5662). Material properties are listed in Tab. 1 and 2. The samples for machining tests are 128 mm diameter per 168 mm length cylinders.

Ni	Cr	Fe	Nb	Mo	Ti	Others
52	19	18	5	3	1	Balance

Table 1. Chemical composition of Inconel 718 (AMS 5662) (weight %)

Density	8,22 g/cm^3
Hardness	255–277 BHN
Melting range	649 °C
Tensile Strength	1000 MPa
Yield Strength	862 MPa

Table 2. Physical properties of Inconel 718 (AMS 5662)

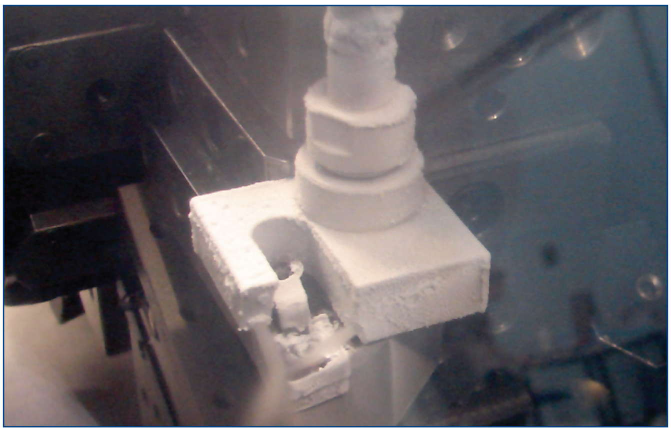

Figure 1. Cryogenic cooling system

2.2 CRYOGENIC COOLING SYSTEM

The cryogenic system consists on a circulation that starts in a liquid nitrogen stock and flows through a hose, up to a tool holder adapter with two fluid outlets. These two jets are directed to the rake face and the flank face of the cutting insert, which is the most efficient configuration according to the literature [Pusavec 2010] to reduce temperature in cutting area. The storage ranger pressure is about 6 bar, which provides a fluid flow of 1,4 l/min. The built adapter that directs fluid to the cutting tool was specially designed to avoid excessive pressure… drops and keep the fluid in liquid phase. The cryogenic cooling system designed by Tekniker is shown in Fig. 1.

2.3 COLD AIR COOLING SYSTEM

The cold air system is based on a commercial stainless steel Vortex Tube supplied by Exair. This low cost device using an ordinary compressed air supply creates two streams of air, one hot and one cold, with no moving parts. Compressed air is ejected tangentially through a generator into the vortex spin chamber. At up to 1.000.000 rpm, this air stream revolves toward the hot end where some escapes through the control valve. The remaining air is forced back trough the centre as cold air. The inner stream gives off kinetic energy in the form of heat to the outer stream. The cold air stream is directed to the insert as Fig. 2. shows.

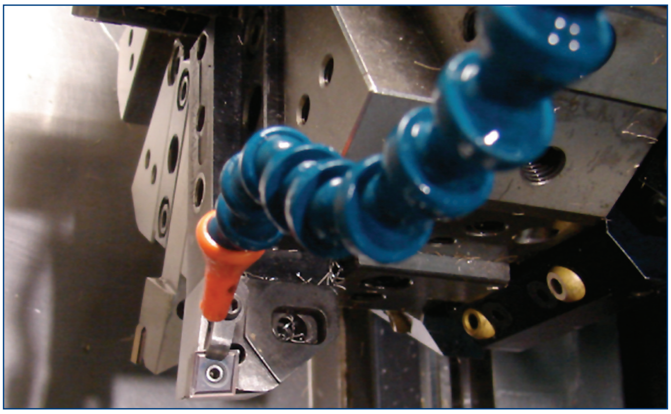

Figure 2. Cold air cooling system Set-up

2.4 FLOOD EMULSION COOLING SYSTEM

Flood coolant system is based on two outputs that bathe the cutting area with a big amount of fluid, using the standard cooling system of the lathe. The base oil used in the emulsion is Sitala AF-800.

2.5 PROCEDURE

The experiments consisted of external turning cuts on a test bar of Inconel 718.

The lathe used in the experiments is a TL–15M CMZ model (5000 rpm, 14 kW). The cutting tool for the machining tests is a PVD coated carbide tool with CNMG geometry, from Mitsubishi supplier. The 85° rhombic inserts have a nose radius of 0,8 mm. The reference is CNMG120408-MS with VP10RT quality.

The main objective is to compare four different methods of cooling: dry, flood emulsion, cryogenic (with LN) and cold air. Tool life tests have been performed for each of the configurations under the same cutting conditions, which are summarized in Tab. 3. Tool wear and surface roughness have been monitored during the study. The wear of the cutting tool has been measured with a contact optical microscope KEYENCE VH-5901. The criterion for completion of the test (criteria for turning tool life finish) is either breakage of the insert or flank wear (VB) exceeding 0.3 mm, as dictated by ISO 3685:1993. Finish surface roughness measurement is done with a Mitutoyo SJ–201P roughness tester. Tool wear and surface roughness have been evaluated every machined length of 150 mm.

Vc (cutting speed)	50 m/min
Ap (depth of cut)	0,3 mm
f (feed rate)	0,25 mm/rev

Table 3. Cutting conditions used in the study

3. RESULTS AND DISCUSSION

3.1 TOOL WEAR

The results of tool life tests are shown in Tab. 4. It can be seen clearly that dry machining is the case with the worst results (lower tool life), because no coolant is used and the heat generated produces a more aggressive wear on the tool. The cold air improves slightly process performance compared with dry machining but it doesn't reach the efficiency values of the base oil emulsion that increases in about 30 % the total volume of material removed with regard to the dry process. Cryogenic machining improves all previous settings with higher machining length and times. The total amount of removed material with this method is 92,29 cm^3, 34 % more than the emulsion that is the second best configuration, and 75 % better than dry machining.

Cooling method	Total machining time (min)	Total removed volume of material (cm^3)
LN_2	30,60	92,29
Emulsion	22,79	68,54
Dry	17,50	52,63
Cold air	19,68	59,22

Table 4. Tool life tests results

In Fig. 3 the evolution of tool flank wear with the removed material volume in each turning test is gathered. Each point in the graph marks tool wear value measured after each 150 mm length of cut.

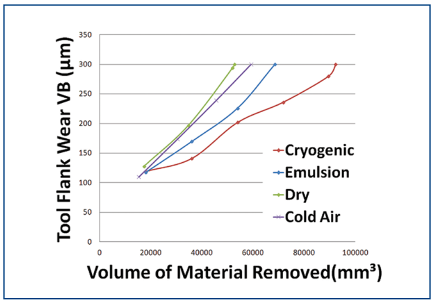

Figure 3. Evolution of tool life in dry turning, turning with oil based emulsion, cold air turning and cryogenic turning of Inconel 718.

Tool wear is progressive in all 4 tests done, as can be observed in Fig. 3, and there is no catastrophic break or wear peaks. The evolution of wear, however, is different in each case: wear increase is similar in dry and cold air assisted cutting and more pronounced than in the other two cases. The curve in the oil emulsion configuration is longer, which shows the capacity of this kind of refrigeration to absorb heat and protect the tool edge. Cryogenic machining shows the lowest rate of tool wear increase compared to the other cooling systems, so the superior cooling capacity of this technique is evidenced.

One point to note is that the case of nitrogen maintains the same trend when the tool wear is quite pronounced, at around 200 μm. Other methods tend to a more vertical curve, which indicates a faster wear when the tool has already a substantial waste. The cold provided by the nitrogen seems to help the tool to address the cut despite having been heavily damaged.

In Fig. 4 and 5 some pictures are gathered of tool wear in the four machining processes for two different machining times (i.e. two different volumes of removed material).

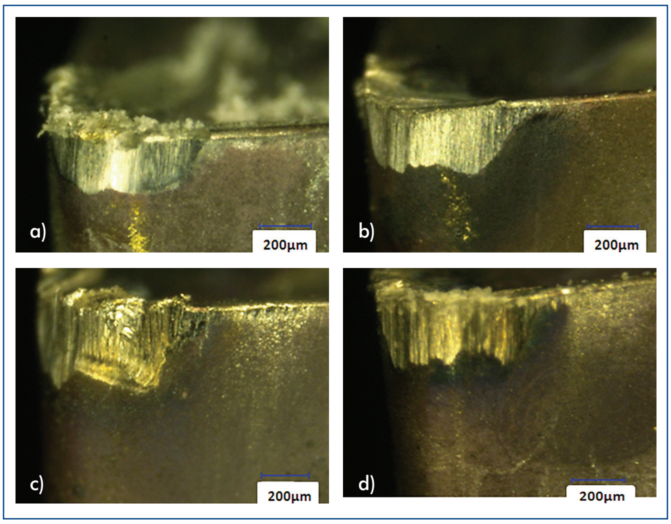

Figure 4. Tool flank wear after cryogenic machining (4a), emulsion coolant (4b), dry turning (4c) and turning with cooled air (4d), for a machining time around 17 min.

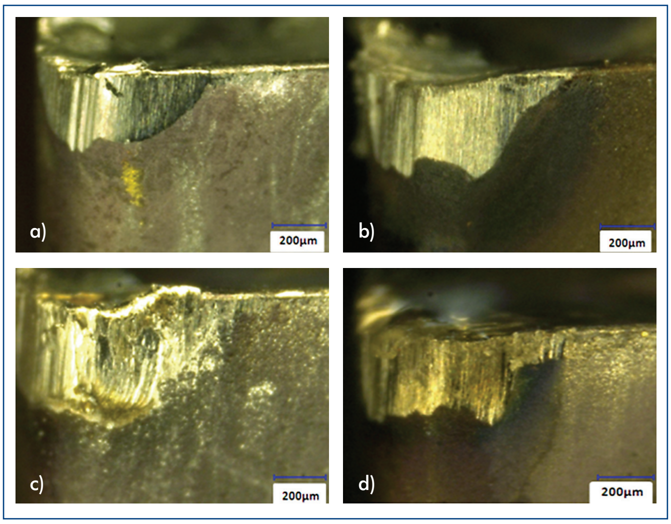

Figure 5. Tool flank wear after cryogenic machining (5a), emulsion coolant (5b), dry turning (5c) and turning with cooled air (5d), for a machining time around 20 min.

Predominant wear during all machining tests is flank wear. The presence of carbide particles in the microstructure of the material is the cause of this wear by abrasion. Also other types of wear are observed, crater and notch wear, especially when the tool reaches values close to end of life. The micro welding generation and adhesion occurs frequently in the tools during machining of nickel based alloys, causing this type of wear [Zurecki 2003].

In most efficient machining processes (cryogenic and flood emulsion), a lower wear value is clearly observed, comparing the photographs with the other two machining methods. The wear has a much more uniform aspect in cryogenic machining and flood emulsion than in the rest of the cases, but in the case of flood emulsion the formation of a quite large crater wear is observed. This effect can result from gas cushions formed when the refrigerant is vaporised because of the high temperatures. This phenomenon prevents the flood coolant's easy arrival to the cutting zone and the heat subtraction efficiency to the cooling process. The liquid nitrogen, which has a much higher cooling capacity, could overcome this phenomenon, or even be capable of cooling in an effective way the cutting zone although forming gas. Dry machining shows a much less homogeneous wear and deformation in cutting edge, due to micro welding and adhesion that occurs when not as much as necessary heat is dissipated. This leads to an obvious steep crater wear. Cold air has a wear with many notches, resulting from strain hardening of the surface because of the plastic deformation.

Prolonged tool life with LN observed in this work agrees with studies made by Want et al. [Berminghan 2012] where wear increases in much slower rate when applying cryogenic cooling in machining of Inconel 718. They state that the improvement in tool life is achieved due to the maintenance of the hardness and strength of the tool material and reduction of chemical afinity with the workpiece. This can be observed also in this paper, where crater wear is reduced, and less notches and lower plastic deformation is generated in cryogenic machining, which are phenomenas related to chemical reactions and loss of material properties.

The results obtained for cryogenic machining show increased tool life compared to the other methods, in agreement to studies in other materials by authors such as Zurecki [Zurecki 2003], Kumar et al. [Kumar 2007] or Dhar et al. [Dhar 2006] among others. Reduction of flank wear is attributed in those works to retention of hardness and sharpness of the cutting edge in intensive cooling, protection from oxidation, corrosion, adhesion and absence of BUE formation. This is reflected in the tests conducted, especially in the absence of crater wear and flank wear more defined when LN is applied.

It was also seen in some studies [Hong 2001b] that improvements when using a cryogenic coolant are greater when higher cutting speeds are used. In present work low cutting conditions are used as for a conventional machining. Perhaps, further improvements could be obtained by trying to increase the cutting conditions, with higher cutting speeds due to higher cooling capacity.

3.2 *SURFACE ROUGHNESS*

Surface roughness of machined samples was measured after each 150 mm length of cut, as in the tool wear analysis. Surface roughness has been measured at points at both ends of the machined workpiece. In Fig. 6 is gathered the evolution of mean surface roughness (Ra) with the removed material volume for each turning test.

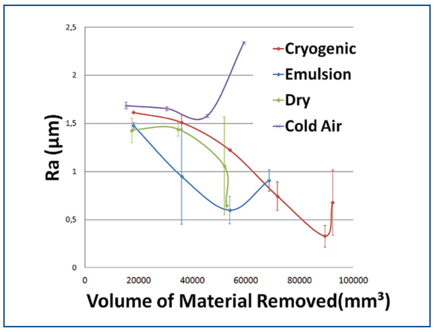

Figure 6. Evolution of finish surface roughness in dry turning, turning with oil based emulsion, cold air turning and cryogenic turning (LN2) of Inconel 718.

The graph shows a better result for the emulsion assisted machining. Given that it is the only fluid that provides lubrication capability this seems quite logical. Furthermore nitrogen system is a prototype with improvement possibilities and the fluid reaches to the workpiece, besides the cutting zone. This leads to freezing of the block, and thus tightening of the material that makes the cut difficult and entails a poorer surface finish, although a lower amount tool wear should bring better results in this aspect. Cold air shows the worst finishing values, it seems to have a negative effect on the finish quality. With no lubricant capacity and a jet cooling the workpiece as cryogenic machining test, but without counteracting the high temperatures of the cutting area, this results in a poor quality finish.

Cryogenic, cold air and emulsion assisted machining processes tend to result in lower surface roughness of the machined sample as the tool wear increases. This trend change when the tool life is close to its end. This is probably due to the deterioration of the tool at the end of its life cycle. This fact is not seen in the dry process, what could be explained by different wear phenomena (BUE, micro welding, flank wear etc.) related to very high cutting temperatures.

As is already known, surface roughness depends on the accuracy of tool nose and wear should be a relevant point in surface quality during turning process. But in this study another point seems more relevant, the singularity of some of the coolant fluids employed. That's why instead of less tool wear, lubricant capacity or workpiece properties changes determine the surface roughness of machined sample.

4. CONCLUSIONS

In the machining test with cold air, the results show an improvement over the dry machining, but underperformed compared with traditional methods based on oil. These data are corroborated in the literature by Su et al. [Su 2007] where tool wear tendency and also a poor surface finish quality is confirmed compared to using MQL which introduces oil in refrigeration.

With this work it is demonstrated the added value of ecological coolants to replace contaminant cooling methods used today. Cryogenic machining results in less tool wear than emulsion based, cold air and dry machining, having a tool life increase of 34,6%, 55,9% and 75,4% respectively. Therefore this is a more efficient and not harmful to the environment process. The cold air assisted machining, although being an economic solution, is not able to match the performance of conventional methods and therefore is not a valid alternative. Thus, the main conclusion of this work is that cryogenic fluids are a potentially valid way to improve the cutting process of advanced materials in an ecologically responsible way.

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