Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 45 (2016) 67 – 70

www.elsevier.com/locate/procedia

3rd CIRP Conference on Surface Integrity (CIRP CSI)

Surface integrity analysis when machining Inconel 718 with conventional and cryogenic cooling

A.Iturbe, E. Hormaetxe, A. Garay, P.J. Arrazola

Faculty of Engineering, Mondragon University, Loramendi 4, Arrasate 20500, Spain

* Corresponding author. Tel.: +34-943-71-2185; fax: +34-943-71-2193. *E-mail address:* aiturbei@mondragon.edu

Abstract

Cryogenic machining together with minimum quantity lubrication (MQL), is claimed to be a promising alternative to flood cooling in industrial applications since it avoids the use of large amounts of cutting fluids and it improves the functional performance of machined components through its superior surface integrity characteristics. In this paper, the suitability of replacing conventional cutting fluids by liquid nitrogen cooling + MQL for finishing operations in industry will be discussed.
Turning operations have been carried out on Inconel 718, in finishing conditions similar to those utilized in industry for the machining of nickel-based superalloys. With both cooling/lubricating approaches, the coolant has been applied to the rake face of the tool. Tool wear and surface integrity in terms of surface roughness, microstructural damage and microhardness profile have been analysed. The results show that conventional cooling is the best option from both the machinability and the surface integrity point of view.

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)

Keywords : Cryogenic; Surface Integrity; Inconel 718

1. Introduction

Nickel based alloys are classified as difficult-to-cut materials, due to their special characteristics such as high strength at elevated temperatures, tendency to work harden, poor thermal conductivity, the presence of hard abrasive carbides in their microstructure and high chemical reactivity with the tool material and coatings [1-3].

Machining of hard-to-machine materials has historically been carried out using cutting fluids that improve the machining performance by lubricating and reducing the heat generated on the cutting zone. However, the environmental hazards associated with the use of conventional cutting fluids, have led to the development of new environmentally conscious machining techniques [4]. It is claimed that cryogenic machining, improves the process sustainability of common machining processes as it is a cleaner, safer and environmentally-friendly process [2]. It avoids the use of large amounts of cutting fluids.

As the liquid nitrogen in cryogenic machining evaporates and returns into the atmosphere leaving no residues, it does not harm the workers on the shop floor [4].

It has been widely reported that the cryogenic machining improves machining performance [5, 6] as it reduces the temperature generated in the cutting zone [7-9]. This increases the tool life by reducing diffusion, abrasion and chemical wear, when compared to dry or MQL machining [8-10]. However, other studies indicate that cryogenic cooling may increase the strength and hardness of the workpiece material [4, 10], thus reducing the tool life.

Moreover, some research claims that cryogenic machining also improves the surface quality of the machined parts in comparison with dry or MQL machining [5]: it reduces the surface roughness [6,8], it generates a thicker compressive zone beneath the surface [6] and it slightly reduces the grain size of the surface layer [6]. Nevertheless, these benefits have only been reported for very short machining times when machining nickel based alloys (Table 1).

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)
doi:10.1016/j.procir.2016.02.095

These machining times, are far from these in real industrial applications where tool lives for turning operations with nickel based alloys using conventional cooling are over 20 minutes (1200 s) [11].

Table 1: Summary of the studies carried out when machining nickel based alloys with different cooling and lubricating approaches.

		Machinability		*Surface Integrity*		
	Machin. Time	Cutting force	Tool wear	Roug-hness	Microst. damage	Micro-hardness
Dry, Cryogenic [7]	10 s		x			
Dry, MQL, Cryogenic, Cryo+MQL [6]	40 s			x	x	x
Dry, MQL, Cryogenic, Cryo+MQL [12]	80 s	x	x	x		
Dry, Coolant, Cryogenic [9]	100 s	x	x		x	
Hybrid, Plasma heating, Convent. [13]	100 s	x	x	x		
Dry, MQL, Cryogenic [8]	250 s	x	x	x		
CO2-based MQL [14]	600 s		x			
Air/Nitrogen jet, Dry, Convent. [15]	1100 s	x	x	x		
Conventional [11]	1500 s	x	x	x	x	
Oil-mist MQL [16]	2580 s		x			

Furthermore, better surface integrity characteristics were achieved when combining cryogenic machining with MQL [6, 12]. Therefore, cryogenic machining together with minimum quantity lubrication (MQL), is presented as a promising alternative to be implemented in industrial applications for the machining of nickel based alloys. Nevertheless, most of the studies address the benefits of the cryogenic machining with regards to dry or MQL machining [6-9] (Table 1); the benefits of the cryogenic machining relative to the conventional lubrication are not clear yet.

In this paper, the suitability of replacing conventional cutting fluids by liquid nitrogen cooling + MQL for finishing operations in industry will be discussed. Turning tests up to a machining time of 8-20 minutes have been carried out on Inconel 718. Tool wear and surface integrity (surface roughness, microstructural damage and microhardness profile) have been analysed for both, conventional flooding and liquid nitrogen cooling + MQL approaches.

2. Experimental procedure

2.1. Experimental Set-Up

Both, cryogenic + MQL and conventional cooling tests were carried out using the same test configuration on a horizontal turning CNC lathe Danumeric 2. For the cryogenic + MQL test configuration, the cryogenic system consisted of the phase separator, the cryogenic control and the liquid nitrogen bottle mounted on the CNC lathe (Fig. 1). Liquid nitrogen (LN_2) was delivered to the rake face of the cutting tool, with a jet cooling system in order to reduce the temperature on the tool-chip interface and facilitate chip evacuation. Minimum quantity lubrication (MQL) was also delivered to the rake face through an adjustable nozzle in order to enhance the lubrication capability of the cryogenic configuration (Fig. 1). The MQL oil used was the KLUBERTCUT CO 6-150 oil delivered by a flow rate of 65 ml/h and a pressure of 6.5 bar.

Turning tests with the conventional cooling were performed delivering coolant to the cutting zone using a nozzle.

The coolant used on these tests, has been the HOCUT 3380 at a percentage of 5-10% delivered with a pressure of 20 bar.

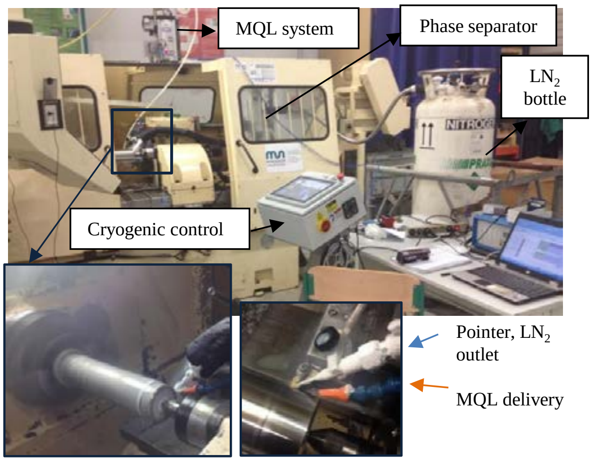

Fig. 1: Experimental Set-Up for the cryogenic+MQL turning tests

2.2. Experimental methodology

Cylindrical turning experiments were conducted in finishing conditions on rolled Inconel 718 round bars, with a diameter of 80 mm and length of 260 mm. The cutting speed, feed rate and depth of cut were Vc = 70 m/min, f = 0.2 mm/rev, DoC = 0.2 mm respectively. CVD $TiCN - Al_2O_3 - TiN$ coated carbide inserts having a tool nose radius of 1,2 mm were used on the tests. The experimental tests were carried out until reaching the target machining time of ~20 minutes, required machining time in aerospace industry, or the maximum tool life defined as Vbmax = 0.3 mm was reached. Two repetitions of each cooling/lubricating approach were carried out, using a fresh cutting tool edge, with an edge radius of 30 μm.

On finishing operations, the acceptance of the machined part strongly depends on the surface integrity produced during machining. Therefore during the experimental tests, surface integrity was addressed in terms of: (i) surface roughness, measured in-situ after each machining pass, using a Mitutoyo SJ-210 portable rugosimeter (ii) microstructural damage, measured on a Leica DM IRM optical microscope and (iii) microhardness profiles, obtained by Vickers hardness test method subjected to a load of m= 10 kgf. Additionally, tool wear was measured on a LEICA Z16 APO macroscope, as it is well known that tool wear has a direct impact on the surface integrity produced in machining.

3. Results and discussion

3.1. Tool wear

Flank wear evolution during the turning tests with cryogenic + MQL and conventional cooling approaches, is shown on Fig. 2. Results show that wear rates were greater in cryogenic machining, leading to a three times shorter tool life than in conventional machining.

These results are in accordance with flank wear results obtained by Kaynak *et al.* [8] (Fig.2) when utilizing separately dry, cryogenic and MQL cooling/lubricating approaches for the turning of Inconel 718 in similar cutting conditions (Vc=60m/min; f=0.075mm/rev; DoC=0.8mm; nose radius=0.8mm; Uncoated tool).

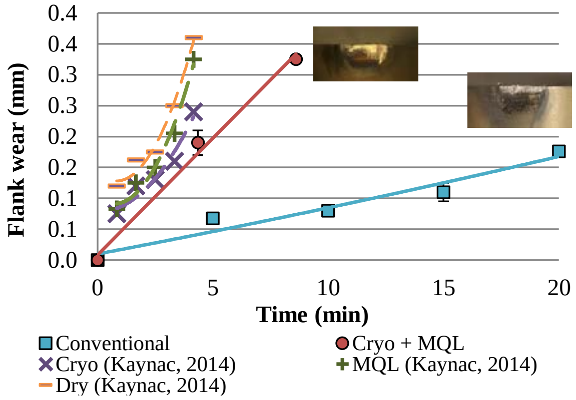

Fig. 2: Evolution of the tool flank wear when turning Inconel 718 with cryogenic [8], MQL [8], cryogenic+ MQL and conventional cooling/lubricating approaches

In conventional machining, a homogeneous tool flank wear pattern is observed even after long machining times. In cryogenic+MQL machining, wear peaks are observed from the beginning of the turning process, denoting that the cutting action is not performed homogenously.

3.2. Surface Roughness

Surface roughness increases with flank wear and depends on cooling/lubrication as shown on Fig. 3. Surface roughness produced when turning Inconel 718 seems to depend on the homogeneity of the tool flank wear. The evolution of tool wear in conventional machining is homogeneous (Fig. 2). This homogeneous wear does not seem to alter the geometry of the tool substantially, as the surface roughness can be predicted with the geometrical relation (1). Surface roughness produced with the cryogenic+MQL approach on the other hand, increases with the tool flank wear and is much greater in amplitude than the theoretical prediction (1).

$$R_t = \frac{f^2}{8R_p} \quad ; \; R_a \sim \frac{R_t}{4} \qquad (1)$$

This indicates that the non-homogeneous tool flank wear pattern obtained in cryogenic+MQL machining gives rise to the surface roughness produced with this new cooling/lubricating approach. The surface roughness generated on finish turning Inconel 718 applying the cryogenic + MQL cooling, does not meet the surface roughness requirements established by aerospace industry (Rtmax=6µm; Ramax=1.6µm).

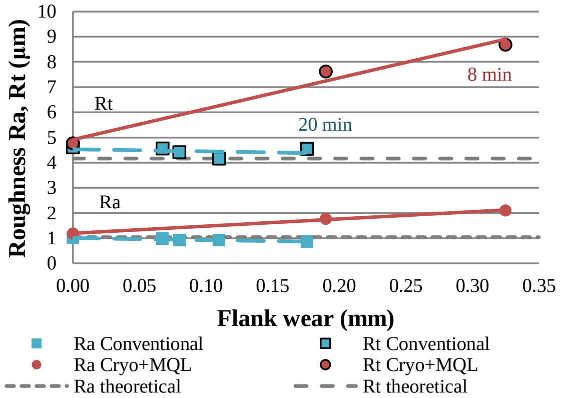

Fig. 3: Surface roughness vs. tool flank wear when turning Inconel 718 with cryogenic+ MQL and conventional cooling/lubricating approaches

3.3. Microstructural Damage

Machining induced surface microstructural damage, is one of the major concerns when addressing the surface integrity of nickel based alloys. The microstructural damage induced with both cooling/lubricating approaches, consists of a heavily deformed layer with evidence of strain bands, known as *strain hardening* (SH) defect, and a slight deformation of the grains in the cutting direction known as *surface drag* (SD).

The surface damage induced with the cryogenic + MQL cooling/lubricating technique for a given machining time is four times bigger than that induced with the conventional flooding. However, the difference on the amplitude of the affected layer can be attributed to the tool flank wear rate (Fig. 4). This indicates that the surface damage induced when turning Inconel 718 is not directly influenced by the utilised cooling/lubricating approach, but is highly dependent on the flank wear rate of the tool.

These results are in agreement with the results obtained by Arrazola *et al.* [11] for finish turning Inconel 718 with conventional flooding. They observed that surface integrity defects appeared more frequently at values of tool flank wear higher than 0.15 mm.

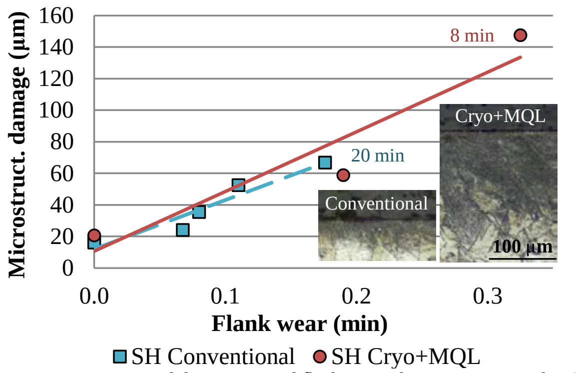

Fig. 4: Microstructural damage vs. tool flank wear when turning Inconel 718 with cryogenic+ MQL and conventional cooling/lubricating approaches

3.4. Micro-hardness profile

The micro hardness profile obtained when machining Inconel 718 utilizing conventional cooling and cryogenic + MQL cooling/lubrication is shown on Fig. 5. It is observed that higher values of micro hardness are obtained for the cryogenic + MQL cooling. The machining induced hardened layer increases with the machining time. In the case of the cryogenic + MQL machining the thickness of this hardened layer (160-200µm) is of the same order as the depth of cut (0.2 mm). Therefore, the material ahead of the cutting tool that is about to be cut, is ~50-130HV harder than the base workpiece material.

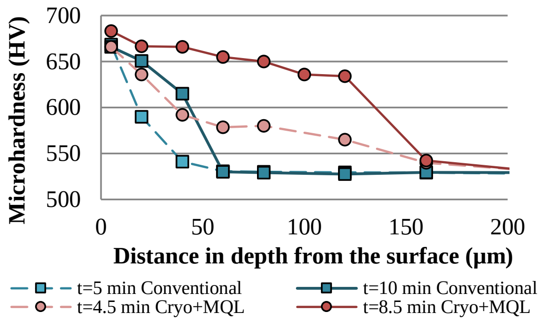

Fig. 5 : Microhardness induced when turning Inconel 718 with cryogenic+ MQL and conventional cooling/lubricating approaches

This hardened surface layer has a significant influence on the machining performance of the subsequent machining passes, making the material more difficult to cut and therefore leading to reduced tool life. This can explain the increased tool wear rates when machining utilizing the cryogenic + MQL cooling/lubricating versus conventional cooling (Fig. 2). Moreover, the machining induced hardened layer identified by microhardness measurements (Fig. 5) matches the *strain hardening* (SH) defect observed when addressing the microstructural damage.

4. Conclusions

In this study, the suitability of replacing conventional cutting fluids by liquid nitrogen together with MQL, for industrial applications when machining Inconel 718 has been analysed.

It has been widely reported that the combination between cryogenic and MQL machining improves the machining performance for short machining times in comparison with dry and MQL machining. However, this study witch analyzes continuous long machining operations with cutting conditions close to industry, shows that the benefits of the cryogenic + MQL machining are not evident. Tool lives achieved with cryogenic+MQL machining for long term turning operations, are much shorter than the ones obtained in conventional machining, and long below the tool life requirements established by the industry.

The hardened surface layer produced in cryogenic + MQL machining, is deeper than the one induced in conventional machining, leading to reduced tool life in cryogenic+MQL machining. This reduced tool life leads to a poor surface integrity in terms of surface roughness and microstructural damage in comparison with the conventional cooling.

Acknowledgements

This paper is funded from the projects CRINCOPLUS (UE2013-08), INPRORET II (IE13_365) and DESAFIO II.

References

[1] Ezugwu EO. Key improvements in the machining of difficult-to-cut aerospace superalloys. International Journal of Machine Tools and Manufacture 2005; 45(12):1353-1367.
[2] Umbrello D. The Effects of Cutting Conditions on Surface Integrity in Machining Inconel 718 Alloy. In Key Engineering Materials 2013; 554: 2093-2100.
[3] Zhu D, Zhang X, Ding H. Tool wear characteristics in machining of nickel-based superalloys. International Journal of Machine Tools and Manufacture 2013; 64: 60-77.
[4] Shokrani A, Dhokia V, Newman ST. Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids.International Journal of Machine Tools and Manufacture 2012; 57: 83-101.
[5] Kaynak Y, Lu T, Jawahir IS. Cryogenic machining-induced surface integrity: A review and comparison with Dry, MQL, and Flood-cooled machining. Machining Science and Technology 2014; 18(2): 149-198.
[6] Pusavec F, Hamdi H, Kopac J, Jawahir I S. Surface integrity in cryogenic machining of nickel based alloy—Inconel 718. Journal of Materials Processing Technology 2011; 211(4): 773-783.
[7] Courbon C, Pusavec F, Dumont F, Rech J, Kopac J. Tribological behaviour of Ti6Al4V and Inconel718 under dry and cryogenic conditions—Application to the context of machining with carbide tools.Tribology International 2013; 66: 72-82.
[8] Kaynak Y. Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining. The International Journal of Advanced Manufacturing Technology 2014; 72(5-8): 919-933.
[9] Aramcharoen A, Chuan SK. An experimental investigation on cryogenic milling of Inconel 718 and its sustainability assessment. Procedia CIRP 2014;14: 529-534.
[10] Hong SY, Zhao Z. Thermal aspects, material considerations and cooling strategies in cryogenic machining. Clean Products and Processes 1999; 1(2): 107-116.
[11]Arrazola PJ, Garay A, Fernandez E, Ostolaza K. Correlation between tool flank wear, force signals and surface integrity when turning bars of Inconel 718 in finishing conditions. International Journal of Machining and Machinability of Materials 2014; 15(1-2): 84-100.
[12] Pusavec F, Deshpande A, Yang S, M'Saoubi R, Kopac J, Dillon OW, Jawahir IS. Sustainable machining of high temperature Nickel alloy–Inconel 718: part 1–predictive performance models. Journal of Cleaner Production 2014; 81:255-269.
[13] Wang ZY, Rajurkar KP, Fan J, Lei S, Shin YC, Petrescu G. Hybrid machining of Inconel 718. International Journal of Machine Tools and Manufacture 2003; 43(13):1391-1396.
[14]Stephenson DA, Skerlos SJ, King AS, Supekar SD. Rough turning Inconel 750 with supercritical CO 2-based minimum quantity lubrication.Journal of Materials Processing Technology 2014; 214(3): 673-680.
[15] Obikawa T, Yamaguchi M, Funai K, Kamata Y, Yamada S. Air jet assisted machining of nickel-base superalloy. International Journal of Machine Tools and Manufacture 2012; 61: 20-26.
[16] Obikawa T, Kamata Y, Asano Y, Nakayama K, Otieno AW. Micro-liter lubrication machining of Inconel 718. International Journal of Machine Tools and Manufacture 2008; 48(15): 1605-1612.