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

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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.

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).

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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.

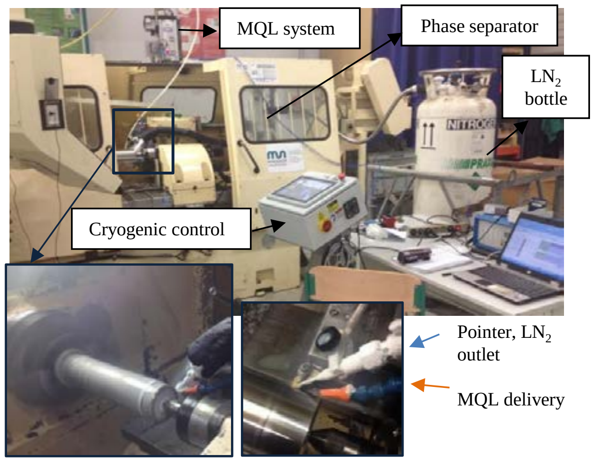

Fig. 1: Experimental Set-Up for the cryogenic+MQL turning tests

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.