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Procedia Manufacturing 00 (2017) 000–000

Procedia MANUFACTURING

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27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy

Hybrid cooling and lubricating technology for CNC milling of Inconel 718 nickel alloy

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Abstract

Inconel 718 is widely used in aerospace, marine, oil and gas and gas turbine industries due to its unique material properties. These material properties such high strength, high hardness and high hot hardness have also made Inconel 718 a difficult to machine material. Machining Inconel 718 is associated with poor tool life and surface integrity resulting in high manufacturing costs and low productivity. Minimum quantity lubricant (MQL) and cryogenic machining are alternative cooling/lubricating techniques for improving machinability of difficult to machine materials. However, their application is limited in machining Inconel and most studies are concentrated on turning. In this paper, MQL, cryogenic cooling and a novel hybrid cryogenic and MQL (CryoMQL) cooling technique are used for CNC milling of age hardened Inconel 718. The analysis indicated that using the proposed hybrid CryoMQL cooling/lubricating system can almost double the tool life and improves surface roughness by 18% resulting in significant improvement in machinability of Inconel 718.

Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing.

Keywords: Cryogenic machining; Inconel 718; Hybrid cooling; minimum quantity lubricant; MQL

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1. Introduction

Inconel 718 is a heat resistant nickel alloy which is extensively used in aerospace, gas turbine, oil and gas and marine industries. Its ability to maintain its mechanical properties at elevated temperatures, high strength and hardness and excellent wear and corrosion resistance have made Inconel 718 an attractive material for harsh operational environments [1].

Owing to its austenitic microstructure, strain hardening is a major issue when machining Inconel 718 [2]. High material toughness and strain hardening properties together with high chemical affinity to most cutting tool materials have notoriously made Inconel 718 a difficult-to-machine material [3, 4]. High material toughness and hardness results in chipping of the cutting tools whilst the existence of hard carbide particles in the material rapidly wears the flank face of the cutting tools. The Inconel's tendency to weld onto the cutting tools results in crater wear during machining weakening the cutting edge and resulting in notching wear [2, 4, 5]. It is well established that a significant portion of the cutting energy is transformed into heat at the cutting zone. The poor thermal conductivity of Inconel 718 (11.4 W/m-K) results in heat accumulation at the cutting zone and particularly on the cutting tool's rake face further exacerbating crater wear [5].

Considerable attempts have been made by various researchers to improve the machinability of Inconel 718. This ranges from laser assisted machining [6-8] and ultrasonic assisted machining [9-11] to using innovative cooling/lubricating techniques such as minimum quantity lubricant (MQL) [12, 13] and cryogenic machining [14, 15].

Rahman et al. [3] studied the effect of various machining parameters on machinability of Inconel 718 in turning operations. They noted that increasing feed rate and cutting speed has a detrimental effect on tool life measured in minutes. Polvorosa et al. [16] compared the effect of high pressure (80 bar) coolant with conventional coolant (6 bar) in turning Inconel 718. The investigations revealed that employing high pressure coolant can reduce crater wear on tungsten carbide inserted tools. Moreover, it was found that using high pressure coolant reduces the flank wear growth rate when compared with conventional flood cooling. Based on the experimental results, adhesion wear and notch wear were dominant in both conditions whilst notch wear was more profound when using high pressure coolant.

Due to the environmental concerns and increasing costs of maintenance and disposal of cutting fluids, using MQL as an alternative cooling and lubricating method in machining has gained more attention. In this method, a small amount of lubricant (10-100 ml/hr) is sprayed into the cutting zone in a stream of pressurized air (4-6 bar). A study [12] on milling Inconel 718 found that when using water-miscible coolant-lubricants for MQL, the flow rate of the coolant-lubricant has a more profound effect on machinability than the water/oil ratio of the coolant-lubricant. Generally, it was reported that increasing the flow rate and oil percentage reduce the tool wear when machining Inconel 718. The authors also noted that the effect of MQL flowrate on reducing tool wear significantly reduces after 60 ml/hr flow rate. Kamata and Obikawa [13] compared MQL with dry and flood cooling in high speed turning of Inconel 718. They found that when using Ti/AlN superlattice and TiAlN coatings, MQL outperforms conventional dry and flood cooling in terms of tool life and surface roughness. The authors also investigated the effect of MQL carrier gas on tool life. They noticed that air is a better carrier gas than argon and attributed this to the lower specific heat of argon as compared to air.

Another alternative to conventional cooling-lubricating in machining operations is cryogenic cooling using liquefied gases. In this method, termed cryogenic machining, liquefied gases such as nitrogen and helium are used to cool the workpiece material, cutting tool or both workpiece and cutting tool materials [17]. It has been reported that temperatures as low as -196ºC can favourably alter material properties of both cutting tool and workpiece and improve machinability [18]. Wang and Rajurkar [19] developed a cryogenic cooling system to freeze the cutting tool during turning operations as a method for removing heat from the cutting zone. They reported that using cryogenic cooling reduced tool wear in turning Inconel 718 and tantalum. Kaynak [20] studied the effect of cryogenic cooling in turning Inconel 718 and found that cryogenic cooling reduces tool flank wear compared to dry and MQL. However, the effectiveness of cryogenic cooling did not extend to notch wear and almost identical wear was observed for all machining environments. Shokrani et al. [14] conducted a feasibility study on cryogenic milling of Inconel 718 and concluded that cryogenic cooling has the potential to reduce surface roughness as compared with conventional dry and flood cooling. Furthermore, the authors noted that all tools suffered catastrophic tool failure and no significant difference in tool life was observed between various machining environments. Pusavec et al. [15] investigated the effect of cryogenic cooling and CryoMQL in turning Inconel 718 and reported that both cryogenic and CryoMQL environments reduce surface roughness and improve surface integrity in comparison with dry and MQL machining environments. They highlighted that CryoMQL outperformed cryogenic cooling in terms of surface roughness where an almost 40% reduction in Ra was achieved.

Following the literature review, it was found that there is a significant research gap in CNC milling of Inconel 718 using cryogenic and hybrid CryoMQL machining environments. Furthermore, there is limited knowledge on the effectiveness of these methods on tool life and power consumption. This paper intends to close this gap by comparing tool life, surface roughness and power consumption in end milling Inconel 718 using coated solid carbide tools under MQL, cryogenic and hybrid CryoMQL machining environments.

2. Methodology

The machining experiments were conducted on a Bridgeport VMC 610XP[2] vertical machining center. A block of annealed and age hardened Inconel 718 was used for each machining experiments. The blocks were supplied in one batch to minimize variation and had dimensions of 50x50x150mm.

The cutting parameters for machining experiments were kept constant throughout the experiments and only the machining environment was changed. The experiments consisted of shoulder milling using the parameters provided in table 1 and climb milling as the machining strategy. Three machining environments of MQL, cryogenic and CryoMQL were investigated. Each experiment was repeated three times to minimize environmental errors.

Table 1. Cutting parameters for machining experiments

Cutting parameter	Value	Unit
Cutting speed	60	m/min
Feed rate	0.05	mm/tooth
Axial depth od cut	20	mm
Radial depth of cut	1	mm

A 12mm diameter, 4-flute solid tungsten carbide end mill with TiSiN coating and 12 degree cutting angle and 250µm corner geometry was used for each machining experiment. The cutting tool was constructed from YL10.2 carbide with 0.8µm average grain size and 10% cobalt binder. Each tool was inspected prior to experimentation using a tool makers' microscope and the tool overhang was kept constant at 50mm for all experiments.

For MQL experiments, rapeseed oil was used at 60ml/hr flowrate in a stream of 6bar pressurized air. Two nozzles with 120º angle were used targeting the cutting zone as shown in fig 1a.

A single external nozzle was used for cryogenic machining experiments. The nozzle has a 5mm diameter to deliver liquid nitrogen at 1.2 bar pressure and 20 kg/hr flowrate. The position of the nozzle with regards the cutting tool is shown in fig 1b. A 180 liter cryogenic Dewar was used for storing liquid nitrogen which was connected to the nozzle through a series of vacuum jacketed pipes. The flow rate of the liquid nitrogen was controlled using a globe valve and the delivery was controlled via a solenoid normally closed 2/2 valve.

The MQL and cryogenic nozzles were used together for the hybrid CryoMQL experiments. In this method, the rapeseed oil was sprayed on a cold tool. Therefore, the tool was coated with a layer of frozen oil prior to engagement with the workpiece material. The setup for the hybrid CryoMQL environment is shown in fig 1c and the actual machining setup is illustrated in fig 2.

A Hioki power analyzer was wired to the machine tool and the power consumption of the machine was monitored and recorded during the experiments. The power analyzer sampled the voltage and current of the machine at a rate of 1 sample/second and calculated the power consumption. The machining experiments were carried out and tool life recorded until complete tool failure at a flank wear of 600µm. The cutting tools were then cleaned and analyzed using a toolmakers' microscope. Furthermore, the surface roughness of the workpieces was measured using a Taylor Hobson S100 contact profilometer using 5 cut offs of 0.8mm sampling lengths.

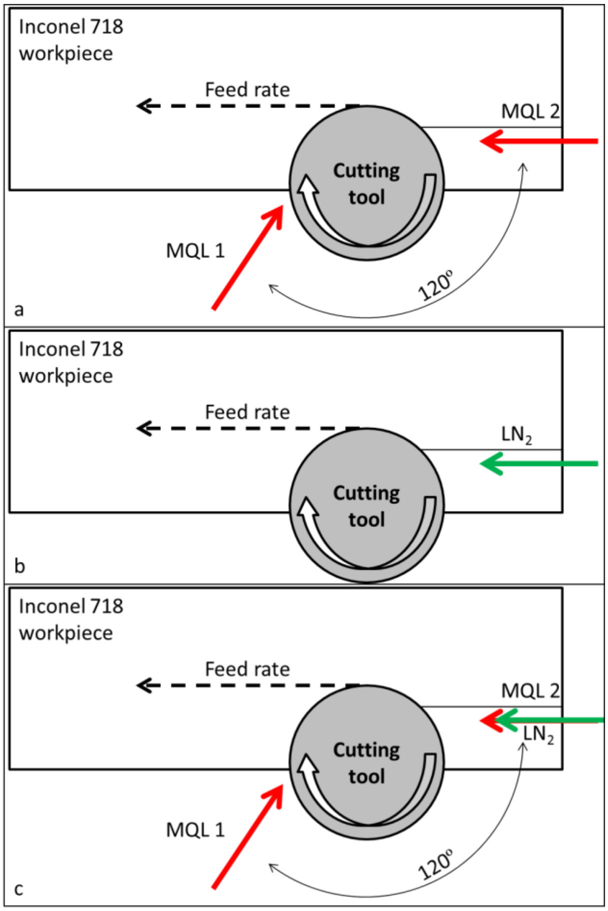

Fig. 1. Arrangement of the nozzles for a) MQL b) cryogenic and c) CryoMQL experiment

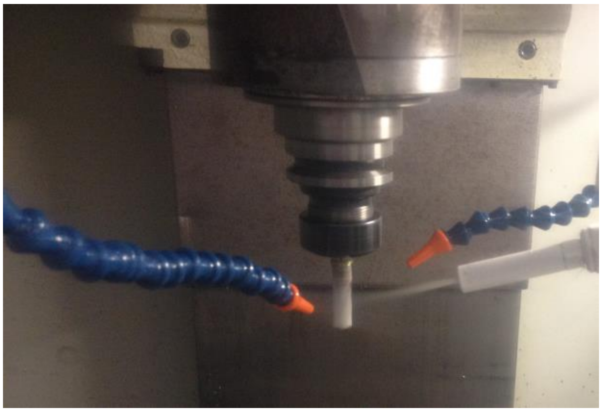

Fig. 2. Pictorial view of the hybrid CryoMQL setup

3. Results and Analysis

In total 9 machining experiments were conducted and tool life, tool wear, surface roughness and power consumption were monitored for each experiment. Tool life is one of the important parameters defining machinability [21]. One of the main issues in machining Inconel with solid carbide tools at cutting speeds exceeding 30m/min is thermal softening. This is mainly due to the thermal softening of the carbide binder used in solid carbide tools. The hardness of a typical solid carbide tool drops by 50% at 800ºC [22]. Furthermore, the existence of hard and abrasive carbide particles results in abrasion wear [4]. As shown in fig 3, the cutting tool used under MQL environment completed 10 machining passes of 150mm equivalent to 283secs of tool life. In comparison, the tool under cryogenic machining environment only completed 7 machining passes or 198s of machining time before failure. The longest tool life was achieved in hybrid CryoMQL machining environment in which the cutting tool lasted for 523s before failure. From these results, it can be observed that high cutting temperature is not the only cause of tool failure in machining Inconel 718. In fact, the tool wear is initiated by abrasion followed by adhesion of the workpiece material onto the tool rake face as explained also by Zhu et al. [23]. The adhesion of workpiece material onto the rake face of the cutting tool forms built up edge (BUE) which alters the cutting geometry [4]. The experiments showed that liquid nitrogen fails to reach the cutting zone when an external nozzle is used. This is evidenced by adhesion of workpiece material and chips onto the cutting tool and particularly onto the rake face which resulted in formation of built up edge at the cutting edge as shown in fig 4. In contrast, using MQL reduces the friction coefficient by lubricating the mating surfaces and therefor the abrasion wear on the tool is delayed resulting in a longer tool life when compared to cryogenic machining. Zhang et al. [24] explained that in MQL environment, the oil droplets form a film of lubricant on the tool-chip and tool-workpiece interfaces which reduces the friction and therefore, cutting forces. Fig 4 illustrates microscopic images of the cutting tools at the end of tool life used for each machining environments. The flank face, rake face and rake face at the depth of cut are shown in this figure. All of the cutting tools, irrespective of the machining environment, suffered from abrasion and adhesion wear. From these images, it can be observed that the tool wear was initiated with chipping adjacent to the cutting edge exposing the tools' substrate. It was then followed by rapid abrasion wear resulting in excessive heat generation. The accumulated heat at the cutting zone facilitated chemical reaction and welding of the workpiece material onto the flank face of the cutting tool. This is in line with findings of other researchers [4, 20, 22] that a combination of abrasion, adhesion and diffusion wear mechanisms results in tool failure in machining Inconel. As shown in the second row in fig 4, crater wear was observed on all cutting tools to a varying extent and it was more dominant for cryogenic machining environment. Kaynak [20] also reported that BUE was observed in dry and cryogenic turning on Inconel 718. The microscope images in the third row in fig 4 illustrate the flank wear at the depth of cut. It is clear from the images that flank wear at the depth of cut was worst under the cryogenic machining environment, followed by MQL. The introduction of cryogenic cooling together with MQL has reduced the flank wear at the depth of cut. Zhuang et al. [25] attributed the occurrence of wear at the depth of cut to the formation of a strain hardened layer beneath the workpiece surface.

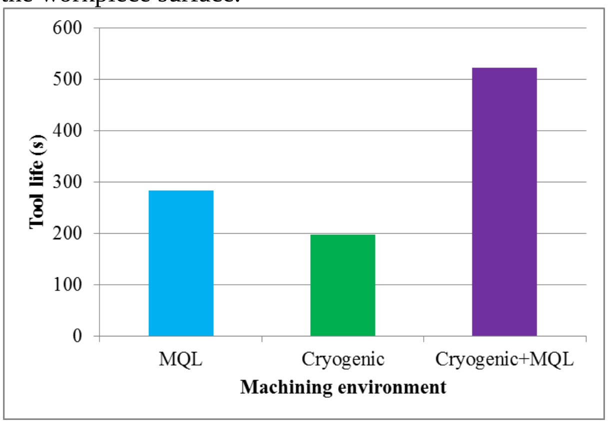

Fig. 3. Tool life graph for each machining environment

It is noteworthy to mention that the main tool failure for all cutting tools was flank wear adjacent to the tool nose as shown in fig 4. However, the flank wear was larger at the depth of cut for cryogenic machining environment than at the tool nose. This can be explained by the fact that in cryogenic machining, excess liquid nitrogen reduced the temperature at the workpiece surface resulting in increased material hardness which can be responsible for increased tool wear at the depth of cut. The analysis of the tools indicated that using hybrid CryoMQL delays chipping and abrasion wear and therefore longer tool life can be achieved however, it does not change the tool failure mechanism.

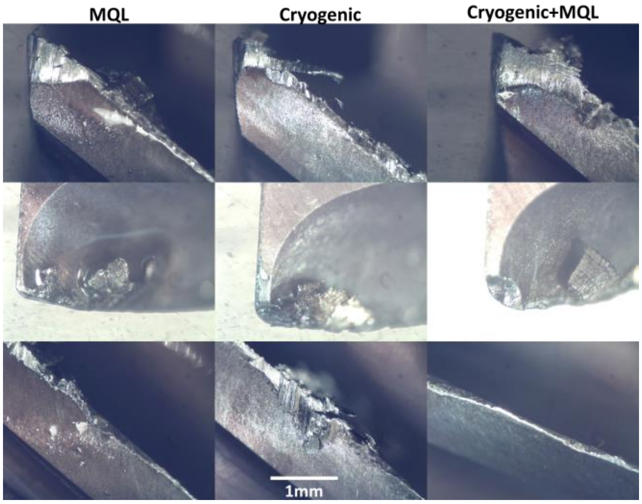

Fig. 4. Micrographs of the cutting tools used for machining experiments

The power consumption of the machine tool was monitored during machining experiments as detailed in the methodology. The average power consumption for material cutting for each machining pass is shown in fig 5a. The power consumption of the machine tool when the tool is not engaged with the material was also measured and its average was calculated to be 1362 Watts as indicated by the dashed line in fig 5a.

Deducing the average machine tool's power consumption when it is not cutting material from the average power consumption during experiment indicates the amount of power used for material cutting in each machining experiment as demonstrated in fig 5b.

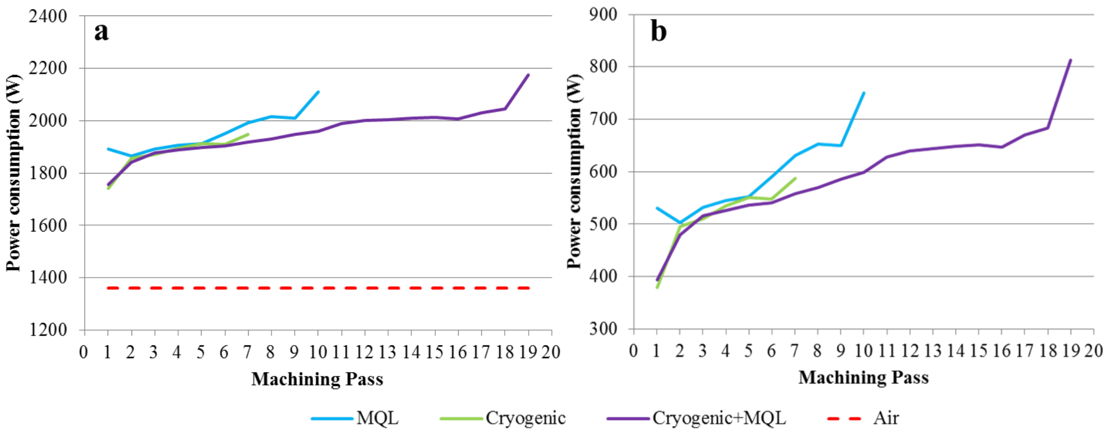

Fig. 5. a) The average power consumption a) of the machine tool and b) for cutting material at each machining pass using various machining environments

As shown in fig 5, irrespective of the machining environment, the power consumption increased as the tool wear progresses from the machining first pass until tool failure. A sharp increase in power consumption was recorded just before tool failure. For instance, in hybrid CryoMQL machining, the power consumption was increase significantly from the 18th pass (683W) to 19th pass (813W) where the cutting tool failed before reaching the end of the 150mm machining pass. The effect of tool wear on power consumption is studied by various researchers [26, 27].

It is noteworthy to mention that the power consumption was smaller for cryogenic machining in the first pass than that of MQL and hybrid CryoMQL machining environments. Although the difference in power consumption was very small between cryogenic and hybrid CryoMQL cooling environments (15W), they were significantly smaller than MQL. This can be attributed to the increased hardness of the cutting tool at the start of the machining process where the cutting tool is cryogenically cooled prior to engagement with the workpiece material. After the first pass, the power consumption is almost identical for all machining environments until 750mm is machined (5th pass). The tool wear was accelerated after this point in the cryogenic machining experiment and reached the tool life criterion after machining 1050mm.

The surface roughness of the machining samples was measured at 7 points and the average surface roughness was calculated for the bottom and wall surface of each sample. As shown in fig 6, the analysis demonstrated that using the average surface roughness of the bottom surface reduced by 18% using CryoMQL compared to MQL environment. Cryogenic machining environment produced the lowest surface roughness (1.1µm) on the wall of the machined shoulder where the periphery of the tool is used. The CryoMQL only reduced the surface roughness by 5% on the wall as compared to MQL environment. The result demonstrated that the surface roughness on the wall is significantly higher than that of the bottom surface indicating that further investigation on tool design is necessary to improve surface roughness. Pusavec et al. [15] investigated the effect of various cooling methods in turning Inconel 718 and concluded that cryogenic cooling and CryoMQL can improve surface integrity. There is an inherent difference between single point continuous turning operation and intermittent multi point milling. The inconsistencies in the results can be due to the fact that in turning, the cutting tool is accessible and the MQL/cryogenic nozzle can be targeted towards the rake/flank face of the tool. In contrary, in milling, the cutting tool is rotating and the contact length between the tool and workpiece can be larger than the area covered by the MQL/cryogenic nozzle. This is evident from the differences in the surface roughness results for the wall and the bottom of the machined shoulders.

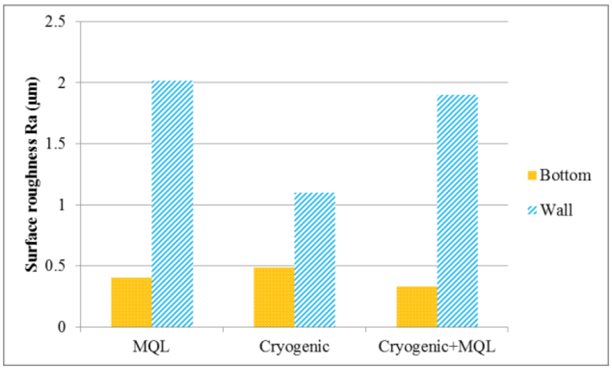

Fig. 6. Average surface roughness results for each machining environment

4. Conclusions

Inconel 718 is an important material increasingly used across various industries such as aerospace, oil and gas, marine and gas turbine industries. The use of Inconel 718 is limited in industries due to its poor machinability often associated with high manufacturing costs, low productivity, poor surface quality and short tool life. In this research, a novel cooling-lubricating system consisting of cryogenic cooling with liquid nitrogen and MQL with vegetable oil was used. It was found that using cryogenic cooling on its own is not beneficial in improving the machinability of

Inconel 718 as it results in increased material hardness and therefore rapid tool wear. Analysis of the tool wear demonstrated that using CryoMQL machining environment does not change the tool wear mechanism. Nevertheless, it reduces the tool wear growth rate resulting in longer tool life. The results clearly indicated that using the proposed method almost doubled the tool life and improved surface roughness.

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