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An Initial Study of the Effect of Using Liquid Nitrogen Coolant on the Surface Roughness of Inconel 718 Nickel-Based Alloy in CNC Milling

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Abstract

The most used alloy of nickel, Inconel 718 is known to difficult to machine owing to its superior material and physical properties. This paper presents one of the very first studies on cryogenic CNC end milling of the Inconel 718 nickel based alloy using TiAlN coated solid carbide tools. The experimental investigations revealed that cryogenic cooling has a significant potential to improve surface roughness of machined parts as compared to dry machining without noticeable increase in power consumption of the machine tool. In addition to surface roughness, power consumption and tool wear have also been monitored in this study.

Keywords: Inconel 718 Nickel Alloy; Cryogenic Machining; CNC Milling; Difficult to machine materials

1. Introduction

High material strength, creep and corrosion resistance have made nickel based alloys attractive materials for aerospace, gas turbine and nuclear industries. It is reported [1] that approximately 80% of the super alloys used in aerospace industries are nickel based alloys. This represents over 50% of weight used in an aerospace engine, with Inconel 718 being the most used alloy of nickel forming 35% of the annual volume production of nickel alloys [1, 2].

Due to the high material strength and work hardening tendency of Inconel 718, high temperatures and forces are produced during cutting operations. Low thermal conductivity of the material prevents effective heat dissipation resulting in very high temperatures at the cutting zone [3]. These high temperatures together with high cutting forces typically lead to very short cutting tool life and poor surface quality of the machined parts. The surface quality is particularly important as it affects the service life and performance of the machined parts mostly used in aerospace engines and gas turbines. As a result, machining components made from nickel based alloys are usually associated with low cutting speeds, productivity and high machining costs [4].

Based on the first law of metal cutting proposed by Makarow, highest machinability is achieved at a particular cutting temperature known as the optimal cutting temperature (θ_{opt}) [5]. This temperature is independent of cutting parameters and machining environments and is based on the material properties of the tool and workpiece materials. On the other hand, it is known that while increases in cutting speed results in higher productivity, it reduces the tool life and exacerbates the surface finish as a result of higher cutting temperatures. This is particularly important in machining nickel based alloys where high localised temperature at the cutting zone could soften the tool material resulting in excessive tool wear. Fig. 1 illustrates the effect of cutting speed on the tool life of different types of coated carbide tools in machining Inconel 718. This could be explained by study of the material properties of the cutting tool and workpiece

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instead of temperature. For instance, while Inconel 718 can maintain almost 80% of its strength at 1200°C [6] tungsten carbide significantly loses its strength at temperatures above 600°C [7]. In addition, by considering odd behaviour of Inconel 718 which its hardness increases by increases in temperature up to 600°C [8], unlike steel alloys, machining Inconel 718 does not benefit from increases in cutting temperature. Different techniques have been adopted by industries to increase the productivity in machining. These techniques could be classifies as (i) maintain the cutting temperature below or close to θ_{opt} by using cutting fluids, controlling the cutting parameters and indirect heat dissipation; (ii) using more advanced cutting tool materials and coatings [5].

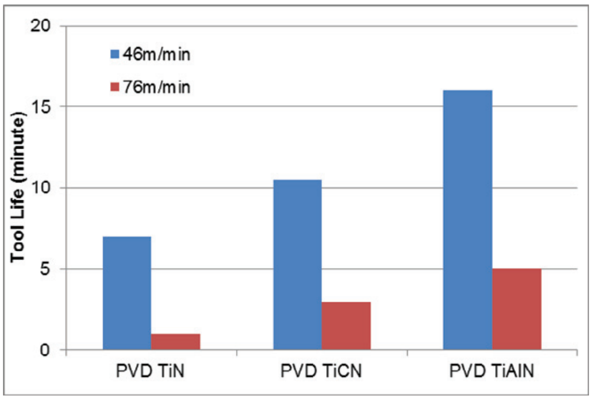

Fig. 1. Effect of cutting speed on the tool life of three different type of coated carbide tool in machining Inconel 718 [3]

Using conventional cutting fluids is known as an effective method to control the cutting temperature and improve machinability in machining some materials. However, very high cutting temperatures such as machining nickel and titanium alloys result in localised evaporation of the fluid in touch with hot surfaces. The evaporated fluid forms a gaseous cushion over the hot surface (in this case cutting tool surfaces such as rake and flank faces) preventing the cutting fluid from reaching and cooling the hot surface through conduction [5]. As a result, the effect of cutting fluids in machining nickel based alloys is limited to cooling workpiece and the body of the cutting tool and not necessarily the cutting zone. Thus, using conventional cutting fluids fail to improve the machinability and in some cases even exacerbate the machining condition. Further information about the machining characteristics of Inconel 718 nickel based alloy could be found in [3, 9]

Recently cryogenic cooling by using liquefied gases has attracted many researchers as a technique to control the cutting temperature in machining difficult-to-machine materials [10-12]. Ultimate low temperature of liquefied gases such as liquid nitrogen (-197°C) not only is capable of improving machinability but also realises higher cutting speeds thus increasing productivity. Different techniques mostly for turning operations have been designed and developed by researchers for cryogenic machining [13-15]. Hong et al. [16] suggested that the best cryogenic cooling technique for machining hard metals such as nickel and titanium alloys is to spray a small amount of a cryogen into the cutting zone along the rake and flank faces of the cutting tool. Wang and Rajurkar [14] used a cooling cap placed over the cutting tool in turning to freeze the cutting tool by liquid nitrogen and cool the cutting zone indirectly. They reported that the flank wear was 0.85mm after 62mm cutting length in dry cutting while for cryogenic machining it was 0.6mm after 110mm cutting length. They concluded that indirect cryogenic cooling technique significantly reduced the tool wear rate as compared to dry machining. Pusavec et al. [17] performed a series of experiments to study the effects of cryogenic cooling on the surface integrity in machining Inconel 718 in comparison with dry and minimum quantity lubrication (MQL) machining techniques. They reported that in turning Inconel 718, cryogenic cooling resulted in more than a 20% reduction in surface roughness as compared with dry machining. In addition, by considering residual stresses and microstructure of the machined surfaces, they concluded that cryogenic machining does not only provide a cleaner process than wet and MQL techniques but also offers enhanced finished part quality through improved surface integrity. Truesdale et al. [18] reported that in end milling Udimet 720 nickel based alloy, spraying liquid nitrogen on the workpiece surface just before the cutting operation has eliminated plucking and smearing defects on the machined surfaces. This has resulted in significant improvements in surface integrity of the machined parts and made higher cutting speeds possible whilst maintaining the surface quality higher than that obtained by conventional techniques. As a result, cryogenic cooling has resulted in up to 1100% increase in the productivity through higher cutting speeds.

The aim of this paper is to present one of the very first studies on the effects of cryogenic cooling using liquid nitrogen on the machinability of Inconel 718 in CNC milling. A series of machining experiments were conducted under different cutting environments, namely cryogenic and conventional dry and emulsion. Surface roughness of the machined parts is then studied and statistically analysed. In addition, power consumption and tool life have been monitored during each of the cutting experiments. The analysed results have then been used to investigate the effects of cryogenic cooling in CNC milling as compared to dry machining.

2. Methodology

2.1. Workpiece material and cutting tool

As mentioned previously, Inconel 718 is one of the most used nickel based alloys in industries. This together with high processing costs associated with Inconel 718 have made this alloy an appropriate candidate material for machining studies such as current research. Table 1 provides some information about the physical and material properties of Inconel 718. For this study three blocks of annealed Inconel 718 with dimensions of 100mm x 150mm x 50mm were prepared with each block being machined under different machining conditions namely, dry, wet and cryogenic.

The cutting tool for the machining trials is a physical vapour disposition (PVD) TiAlN coated solid carbide end mill. The geometries of the cutting tool is specially engineered for machining especial heat resistant alloys with 30° helix angle and a positive rake angle for more stability of the cutting edge and less cutting forces.

Table 1. Physical and mechanical properties of Inconel 718 obtained from [18]

Property	Unit	
Density	Kg/m^3	8190
Young's Modulus	GPa	200
Ultimate Tensile Strength	MPa (min)	1375
Yield Tensile Strength	MPa	1100
Thermal Conductivity	w/m°K	11.4
Specific Heat Capacity	J/Kg°C	435
Melting Point	°C	1260-1336

2.2. Cryogenic cooling system

Literature suggested [16] that the most effective approach for machining heat resistant alloys such as titanium and nickel based alloys is to penetrate a small amount of cryogen in to cutting zone. The aim of this is to reduce the temperature at the cutting zone and alter the friction while preventing excessive increases in the workpiece material hardness as a result of ultra-low temperature. As a result, a special cryogenic cooling system has been designed by the authors at the University of Bath to retrofit the requirements for cryogenic cooling on a conventional 3-axis vertical CNC milling machine. The system is designed to inject a small amount of liquid nitrogen into the cutting zone during end milling operations by considering the relative movement of the cutting tool with respect to the workpiece. Fig. 2. provides a schematic view of the cryogenic cooling system.

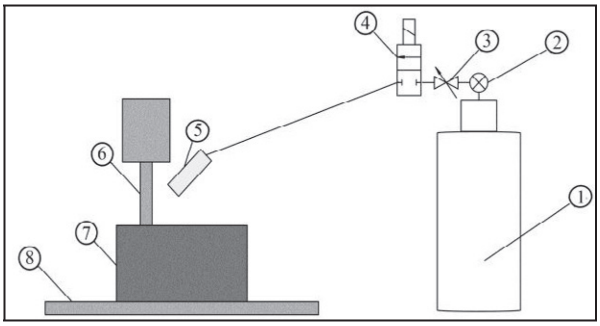

Fig. 2. Schematic setup for cryogenic machining.
(1) Cryogenic dwar; (2) pressure gauge; (3) gate valve; (4) solenoid valve; (5) specially designed nozzle; (6) cutting tool; (7) workpiece; (8) machine tool table.

2.3. Design of experiment

In order to investigate the effects of cryogenic cooling in CNC end milling of Inconel 718 a single factor full factorial design of experiment was adopted. The proposed single factor was machining environment at two levels namely cryogenic and dry while other machining parameters were kept constant during the machining trials. The details of the machining parameters are provided in table 2. The areas of investigation also known as monitoring parameters were limited to the tool wear, power consumption and surface roughness of the machined test pieces.

Based on the DoE, a series of machining experiments were conducted using a Bridgeport vertical CNC milling machine equipped with a power monitoring system attached to the main power supply line of the machine tool. The machining operations were interrupted with specific intervals and the cutting tools were examined under a tool makers' microscope in order to quantify the tool wear as a result of machining length. After the machining trials, the surface roughness of the machined test parts was measured using contact techniques. The generated data from the machining trials namely dry and cryogenic conditions have then been statistically analysed in order to give a clear view of the effects of cryogenic cooling on the power consumption, tool wear and surface roughness as compared to traditional machining environments.

Table 2. Machining parameters used for machining trials

Cutting Parameter	Unit	Value
Tool Diameter	Mm	11
Cutting Speed	m/min	50
Feed Rate	mm/tooth	0.03
Depth of Cut	mm	0.5
Immersion Rate	--	50%

3. Results and discussion

In order to compensate the effect of tool wear on the surface roughness of the machined test parts, initially the investigations was limited to the very first section of the machined path. As shown in Fig. 3, the surface roughness measurements revealed that the average arithmetic surface roughness (Ra) has been reduced from 0.21µm to 0.14µm resulting in more than 33% reduction in surface roughness. A similar trend has been observed for ISO Rz value of the surface roughness where the introduction of cryogenic cooling has reduced the ISO Rz value from 2.25µ to 1.34 resulting in 40% reduction.

Although cryogenic cooling has improved the surface roughness of the machined parts at the very first section of the machining path, significantly higher values of surface roughness was measured for the rest of the path as compared to dry machining. This indicated the inverse effect of cryogenic cooling on the tool life which has a direct effect on the surface roughness.

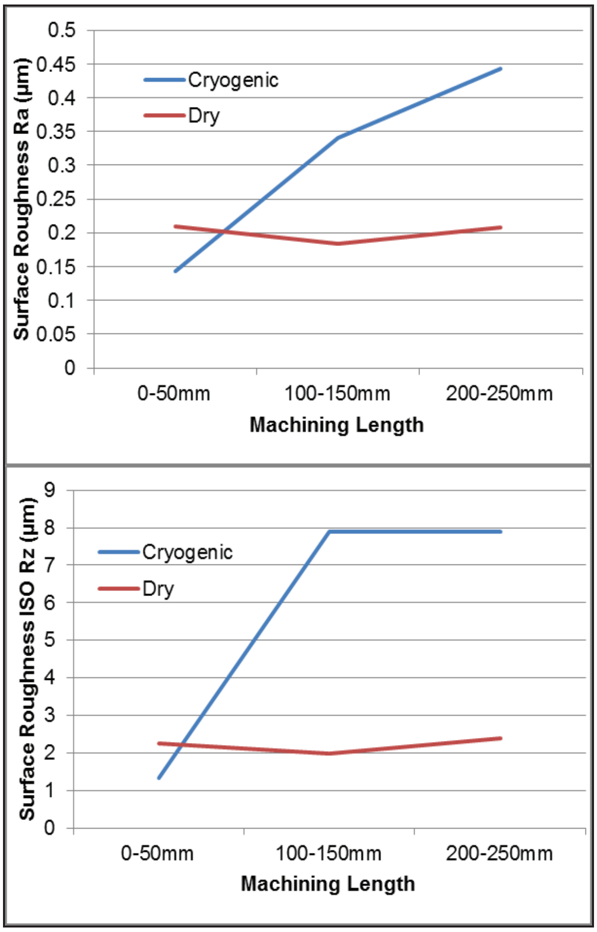

Fig. 3. Surface roughness of the machined test parts under cryogenic and dry conditions

As a result it has been found that whilst the cutting tool is intact, cryogenic cooling produces a better surface finish than dry machining. However, for longer machining lengths as the tool used for cryogenic cooling was worn faster than its counterpart in dry machining, higher surface roughness is expected after a specific machining length before tool failure. This increase in the surface roughness is illustrated in Fig. 3.

The dominant tool failure mechanism in both cryogenic and dry machining was chipping at the depth of cut. In cryogenic machining this mechanism was followed by fracture of the tool nose resulting in tool failure. In dry machining on the hand, crater wear and welding of the chips on the cutting edge were detected. This is in line with observations of Liao et al. [8] in end milling Inconel 718 using different cutting parameters where breakage and chipping was reported as the dominant tool failure. Whilst the tool failure mechanism was similar in both dry and cryogenic machining, as shown in Fig. 4, the extent of chipping was more sever in cryogenic machining which resulted in shorter tool life as compared to dry machining.

As it is shown in Fig. 5, statistical analysis of power consumption of the machine tool during machining experiments revealed that the effect of cryogenic cooling on the power consumption is significant in comparison with dry machining. Although this effect is as small as 1.9% in average whilst the effect of tool wear should be taken into account. This increase in the power consumption can be explained by the increases in the material strength and hardness of Inconel 718 as a result of cryogenic cooling.

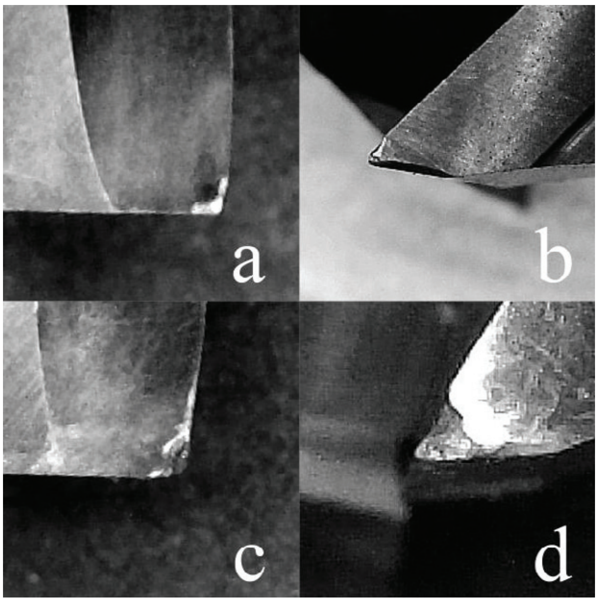

Fig. 4. Pictorial view of the cutting tools after machining 850mm3 volume of Inconel 718 material under (a) and (b) dry; (c) and (d) cryogenic machining

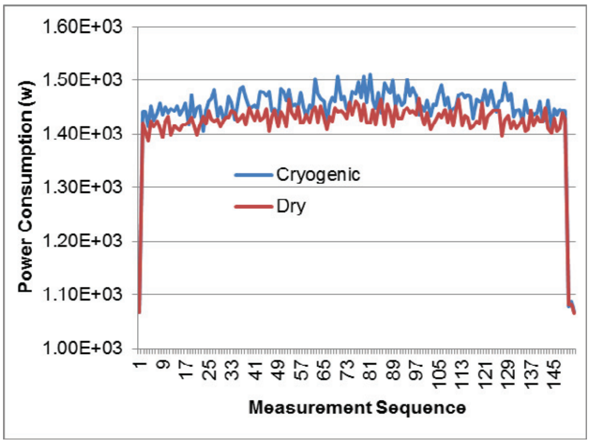

Fig. 5. Power consumption of the machine tools during machining operation under cryogenic and dry conditions

4. Conclusion

This paper presented one of the very first studies on the cryogenic CNC milling of Inconel 718 nickel based alloy. A series of experiments were conducted using PVD TiAlN coated solid carbide end mills in order to investigate the effects of cryogenic cooling on the machinability of Inconel 718 in comparison with dry machining. Statistical analysis of the results revealed that cryogenic cooling has resulted in 33% and 40% reduction in Ra and ISO Rz surface roughness of the machined parts as compared to dry machining without noticeable (1.9%) increase in power consumption of the machine tool. Despite the improvements in surface roughness of the machined parts, cryogenic cooling significantly reduced the tool life of the coated solid carbide end mills. Due to the nature of the tool failure in this experiments, chipping and fracture of the nose, quantitative analysis of the tool wear was not practical. Thus the tool life was monitored from the surface roughness of the machined parts.

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