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

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Abstract

Inconel 718 is the most used nickel based super alloy. High material strength, hardness and corrosion resistance at elevated temperatures together with good creep resistance has made Inconel 718 an attractive material which is widely used in aerospace, gas turbine, marine and oil and gas industries. Due to the high material strength and work hardening tendency of Inconel 718, high temperatures and forces are produced during machining operations. Low thermal conductivity of the material prevents effective heat dissipation resulting in very high temperatures at the cutting zone. These high temperatures together with high cutting forces can lead to significantly reduced tool life and poor surface quality of machined parts. Therefore, machining Inconel is usually synonymous with poor productivity and high costs. In this paper the effect of various machining environments on machinability of solution treated and age hardened Inconel 718 in high speed milling is investigated. The investigations clearly demonstrated that high speed machining using a novel hybrid cooling system consisting of liquid nitrogen cryogenic cooling and rapeseed oil vegetable minimum quantity lubrication has major advantages in machining Inconel 718. The analysis indicated that tool life can be almost doubled using hybrid cooling when compared to conventional flood cooling whilst generating a surface roughness Ra of maximum 0.4µm.

1. Introduction

Approximately 80% of the super alloys used in aerospace industries are nickel alloys. This accounts for over 50 wt.% of materials used in an aero engine. Inconel 718 is the most widely used alloy of nickel and forms 35% of annual volume production of nickel alloys.

Inconel 718 is one of the most difficult materials to machine. It is a nickel based super alloy with high material strength, hardness, corrosion resistance and dynamic shear strength at a wide range of temperatures [1]. Inconel 718 can maintain its hardness at high temperatures and has high tensile and rupture strength with good creep resistance making it an ideal material for high temperature applications such as aerospace, gas turbine and oil and gas [2]. Inconel is used for high temperature static and rotating parts in jet engines such as blades, blisks and shafts in high pressure compressor and turbine stages [3, 4].

High material strength, hardness and low thermal conductivity and diffusivity have made machining Inconel 718 extremely difficult which is often associated with poor surface integrity, short tool life and low productivity [5]. During machining, the presence of hard carbide particles in Inconel accelerates abrasive wear. High material strength requires high power for machining which transforms into heat at the cutting zone. Due to the low thermal conductivity, the generated heat at the cutting zone cannot be dissipated effectively by the
Cutting chips and workpiece material. Therefore, the heat accumulates at the cutting zone resulting in high cutting temperatures often as high as 1300°C [6].

Cryogenic machining using liquefied gases has shown promising results in improving machinability of difficult to machine materials [7]. In this process, super cold liquid gases are used to dissipate heat from the cutting zone and alter the material properties of both workpiece and cutting tool resulting in improved tool life and surface integrity [8].

This paper investigates the effect of various cooling and lubricating methods namely, flood cooling, minimum quantity lubrication (MQL), cryogenic machining and a novel hybrid cryogenic MQL in high speed milling of solution treated and age hardened Inconel 718 nickel alloy.

2. Methodology

The machining experiments consisted of shoulder milling blocks of solution treated and age hardened Inconel 718 with the dimensions of 50mm x 50mm x 150mm. The blocks were cut from a large piece of Inconel to minimize variations in material properties. The material hardness was measured at five points for each sample and the average hardness was 42HRC. The machining environment was selected as the varying factor for the experiments whilst keeping all other machining parameters constant. Flood cooling with water based emulsion at 8% concentration was used as a baseline. MQL environment was also tested by delivering 70ml/hr atomized pure rapeseed oil in a stream of 5bar pressurized air. A new cryogenic machining setup was developed to spray LN2 into the cutting zone at 1bar pressure and 15kg/hr mass flow rate. Two external nozzles with 5mm internal diameter were used for spraying LN2. For the hybrid cryogenic MQL machining environment, the cryogenic and MQL setups were coupled together in a way that pure rapeseed oil was sprayed onto a cold tool, coating the tool with a layer of rapeseed oil.

As mentioned previously, the machining parameters were kept constant for all experiments as shown in table 1. Based on the classification by Schulz and Moriwaki [9], the cutting speed of 140m/min falls within the high speed machining region for nickel based alloys. A solid tungsten carbide cutting tool with 12mm diameter and 4 flutes were used for each experiment. The cutting tool had a rake angle of 10° and 34°/35° variable helix angle. The cutting tool was made of tungsten carbide with average 0.8µm grain size and 8% cobalt binder. The tool had a TiSiN coating as recommended by Soo et al. [10] for high speed machining of Inconel 718.

The experiments consisted of straight shoulder milling along the 150mm length of the Inconel block and repeating this procedure until end of tool life. Based on ISO 8688-2 [11], the end of tool life criterion was defined as an average flank wear VB of 300µm or a maximum flank wear of 500µm. The machining experiments were interrupted and the tool wear was measured during the process using a digital microscope. Each machining experiment was repeated twice without interruption for tool wear measurement to ensure the repeatability of the results. Furthermore, these repeated experiments eliminated the effect of heating and cooling on tool life which occur as a result of interrupting the experiments for tool wear measurement.

<table>
<thead>
<tr>
<th>Machining parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Cutting speed</td>
<td>m/min</td>
<td>140</td>
</tr>
<tr>
<td>Feed rate</td>
<td>mm/tooth</td>
<td>0.02</td>
</tr>
<tr>
<td>Axial depth of cut</td>
<td>mm</td>
<td>10</td>
</tr>
<tr>
<td>Radial depth of cut</td>
<td>mm</td>
<td>1</td>
</tr>
<tr>
<td>Tool overhang</td>
<td>mm</td>
<td>50</td>
</tr>
</tbody>
</table>

The power consumption of the machine tool was measured during each experiment for further analysis. Moreover, the power consumption of the machine tool was measured when cutting air. The difference between the power consumption in air machining and when material cutting would define the power requirements specifically for cutting Inconel 718 under different machining environments.

The surface roughness of the machined samples was measured at 10 positions and the measurements at each position was repeated 3 times. The average surface roughness of the samples was analyzed to identify the effect of machining environment on surface roughness.

3. Results

Following the machining experiments, the graph of tool flank wear as a function of machining time was generated. As shown in Fig. 1, the cutting tool used in flood cooling machining environment performed for 3min before reaching the 300µm tool wear criterion. In contrast, the cutting tool used in hybrid machining environment reached the tool life criterion after 6min of machining doubling the tool life from flood cooling. The tool life in hybrid cooling environment was 50% longer than MQL and 33% longer than cryogenic machining environment.

![Fig. 1. Flank wear vs machining time in high speed milling of Inconel 718.](image)

Analyzing the micrographs of the tools indicated that the tool wear accelerated when the TiSiN coating was removed and the tungsten carbide substrate was exposed. Irrespective of the machining environment, the coating was removed within the first 2min of machining. The use of LN2 cryogenic coolant effectively removed the heat from the cutting zone and therefore reduced the tool wear growth rate in both cryogenic machining and hybrid cooling. In contrast, the MQL machining
environment performed well in preserving the coating. However, when the coating was removed, tool wear growth rate rapidly increased as shown in Fig. 1.

This indicates the ineffective cooling performance of MQL in high speed machining. The cutting tool became red hot near the end of tool life with significant workpiece material deposits on the cutting tool. The major tool wear mechanism irrespective of machining environment was found to be crater wear adjacent to the cutting edge which resulted in chipping of the cutting edges. Therefore, the tool wear was not gradual in none of the machining environments.

It was also noticed that the workpiece deposits on the tool acted as a protective layer in MQL, cryogenic and hybrid machining environments further improving the tool life. The experiments revealed that LN2 cryogenic coolant can effectively extract heat from the cutting zone whilst MQL lubrication can reduce friction and heat generation during machining. Combining the cooling effect of cryogenic machining with lubrication effect from MQL proved to be an effective way for extending tool life in high speed milling with coated tungsten carbide tools. It is noteworthy to mention that the coating in MQL experiment lasted longer than cryogenic and hybrid machining environments. This can be attributed to the effect of high temperature gradients in cryogenic and hybrid machining resulting in flaking of the coating.

The power consumption of the machine tool was monitored during machining experiments. The results indicated that the power consumption increased with increase in tool wear as shown in Fig. 2.

There is a distinct difference between the power consumption in flood cooling and other machining environments. This is due to the power consumption of the coolant pump (approximately 1200W) in addition to the power required for running the machine tool.

Deducing the power consumption for running the machine tool and coolant pump from the power consumption data, the power used for material cutting in each machining environment can be identified as shown in Fig. 3.

Based on the results of power consumption for material cutting, initially, cryogenic machining and flood cooling required less power for material cutting. However, as the tool wear increases, the power required for material cutting in cryogenic and flood cooling surpassed that of MQL and hybrid cooling. In contrast, the power consumption for MQL and hybrid environments increases gradually when it suddenly increases for MQL after 7th machining pass. Comparing this with Fig. 1 for tool wear, at this point the tool suffered from significant tool wear with chipping of the cutting edges due to crater wear. The sudden increase in power consumption also indicated that the tool wear growth was not gradual due to abrasive flank wear as also explained above.

Comparing the power consumption in the first machining pass before significant tool wear occurred can provide an insight into the machining condition. Based on the results from Fig. 3, the lowest power consumption was measured for cryogenic machining closely followed by flood cooling. Hybrid cooling resulted in the highest power consumption in the first machining pass. On average, 50 samples of power consumption were taken for each machining pass allowing for statistical comparison of the data. As shown in Table 2, apart from the power consumption between cryogenic and flood cooling and between MQL and flood cooling, there is a statistically significant difference between the power consumption of various machining environments when the cutting tool is intact. Hence, it can be understood that at the start of the machining experiments, flood cooling and cryogenic machining are more capable of lubricating the cutting zone. Moreover, when the tool wear increases, the effect of tool wear on power consumption becomes more significant.

Analysis of surface roughness Ra, indicated that irrespective of the machining environment, the average surface roughness was between 0.3µm and 0.5µm. As shown in Fig. 4, cryogenic machining and flood cooling generated the lowest average surface roughness for bottom face and wall of the machined shoulders, respectively. Interestingly, cryogenic machining and flood cooling also generated the highest average surface roughness for wall and bottom face, respectively.
In this paper cryogenic cooling using LN2, hybrid cooling and MQL machining environments were tested against conventional flood cooling.

- The analysis indicated that hybrid cooling can increase tool life by 77% when compared to flood cooling.
- Hybrid cooling is capable of generating surface roughness of less than 0.4µm on both wall and bottom faces of a machined shoulder.
- The power consumption of the machine tool was monitored which increases with tool wear.
- This study clearly demonstrated that high speed machining of Inconel 718 with solid tungsten carbide tools is viable using hybrid cooling consisting of LN2 cryogenic cooling and vegetable oil MQL.

### References


