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Through-tool minimum quantity lubrication and effect on machinability

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ABSTRACT

This paper simulated through-tool minimum quantity lubrication (MQL) to characterize micromist droplet size and distribution. The effect of nozzle surface roughness and air pressure was experimentally performed to study the lubricant droplet and its effectiveness in micromilling of Inconel alloy. The external MQL simulated internal flow in commercially available drill with internal cooling channels. Droplets were collected on a glass plate from which the average airborne diameters and standard deviation were calculated. The droplet diameter and distribution were most sensitive when using nozzle with rough internal surface. MQL at different conditions was used in micromilling of Inconel 718 blocks that were additively printed by selective laser melting technique. Micromist generated from a rough nozzle at 550 kPa effectively improved tool life and produced micromilled slots with surface finish S_a of 1.5 µm.

1. Introduction

Flood cooling or wet machining has been traditionally used to improve machinability in metal cutting. However, applying a large amount of cutting fluid would raise the manufacturing cost while having a negative impact on the environment. With ever increasing of environmental control and manufacturing cost competitiveness, the use of minimum quantity lubrication (MQL) –or near dry lubrication– has been gaining momentum not only because of the above mention effects but also because of tool life improvement when properly applying MQL. Although many researchers have shown the effectiveness of externally applied MQL on tool life enhancement in machining, very limited study was published for results of MQL applied through built-in channels inside a cutting tool. The objectives of this paper are to:

i) Simulate through-tool MQL and experimentally characterize the resulting liquid droplets.
ii) Apply the results to study machinability of 3D-printed Inconel 718 (IN718).

2. Literature review

2.1. Minimum quantity lubrication

A MQL system uses compressed air to aerosolize a typically oil based lubricant. The resulted pressurized air-oil mixture is then flow at high speed toward cutting tool and being-machined workpiece. The amount of lubricant used in MQL was reported to be in the range of 5–100 mL/h which was significantly lower than 20 L/min in typical flood lubrication. As MQL is applied in form of micron-size droplets, a system can be adjusted so that the droplets are completely used up and evaporated due to heat generated in machining; any excess amount could be wiped /rinsed off after machining [1].

Both flood coolant and MQL remove the heat generated due to the friction at the tool-chip interface and from the shear plane during cutting. The desired effect is to lower the tool and workpiece temperature, prolong tool life, and enhance the part quality after being machined. Lubricants formulated from vegetable oils and with surfactant additives are commonly used for MQL due to better lubricity of vegetable oils and minimum environmental impact [1].

2.2. Characterization and effect of MQL

Tai et al. [2] compared tribological and physical properties of commonly used MQL fluids and their performance during drilling and reaming operations with through-tool MQL. The study showed that straight oil-based lubricants used for MQL were better in terms of lubrication and wettability, but lack of the heat removal properties inherent to water-based fluids. Contact angles of vegetable oil-based lubricants on common cutting tool material such as tungsten carbide were in the range 7.6–26.5°; whereas for water-based lubricants, the corresponding contact angles increased to approximately 36°. Li et al. [3] reported contact angles of Coolube 2210 EP was about 5-10° on 316 L stainless steel, pure titanium, and polished tungsten carbide.

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Various studies have been done to characterize the MQL droplets for better understanding of their effects on machining. Dasch and Kurgin [1] compared the mist concentration and droplet characteristics of the mist generated using internal single and internal dual MQL systems. The MQL droplets generated by the internal single MQL system were the smallest with the Mass Median Aerodynamic Diameter (MMAD) of 1.7 µm. On the other hand, an external MQL produced the largest droplets with MMAD of 6.9 µm. Droplets generated using the internal dual channel MQL system had a MMAD of 3.4 µm. Duchosal et al. [4] tested different models with various inner channels to determine a relationship between characteristics of generated droplets and different configurations for internal channels of the tool. They concluded that particle velocities were independent of oil type when model of a 6-mm internal diameter was used, and any reduction of the cross sectional area of the internal channels would decrease the flowrate of the mist. Li et al. [3] and Lerma et al. [15] reported that the airborne droplets of Coollube 2210 EP oil depended on the air speed at nozzle and distance from a nozzle. Droplet sizes of 4–6 µm were obtained when air speed of MQL system exceeded 100 m/s.

2.3. Machining Inconel 718 in MQL

The superalloy IN718 has been widely used in aerospace, oil and gas, and nuclear industries for its excellent mechanical properties at high temperature and corrosive environment. Kamata and Obikawa [5] investigated tool wear and surface finish when turning Inconel. Tool coated with TiCN/Al_2O_3/TiN, TiN/AlN, and TiAlN were used in either MQL or flood coolant. Cutting speed range was 1–1.5 m/s, depth of cut was 0.1 mm, and tool feed was 0.1 mm/rev. The study showed that an increment of MQL pressure from 0.4 MPa to 0.6 MPa would decrease the tool life of TiN/AlN coated tools from 24 to 17 min. Such reduction of tool life was attributed to an increase in oxidation of the tool coating. However, the trend was reversed when grooving carbon steel in MQL: tool life improvement was observed with increasing MQL air pressure. There was no difference observed in the surface finish of machined IN718, the study concluded. Obikawa et al. [6] reported an increase in tool life from 24 min to 37 min for turning Inconel using MQL when concentrated spraying of mist was applied at a flowrate of 0.2 mL/h using a cover type nozzle. Zhang et al. [7] compared tool lives and cutting forces for milling IN718 under dry machining conditions and with the application of MQL. Down milling was done at speed of 56 m/min, 875 rev/min rotational speed, and 0.5 mm axial depth of cut. They reported that MQL enhanced tool life 1.57 times longer than when dry machining was done. Ucun et al. [8] investigated the effects of AlTiN, TiAlN/AlCrN and AlCrN tool coatings on the tool wear during micromilling of Inconel using MQL. The authors used ϕ768 µm tools with two flutes at cutting speed of 48 m/min. They observed that at tool feed of 5 µm/flute feed, there was only 3.75% in the reduction of tool diameter, i.e. tool wear, when MQL was used as compared to a reduction of 5.64% during dry machining. Thamizhmanii and Hasan [9] observed the effect of MQL flowrates on surface roughness of machined IN718 and corresponding tool wear. Milling was done at 10, 20, 30 m/min cutting speeds at constant 0.15 mm/tooth feed rate. They reported an improvement in surface roughness from 0.6 µm to 0.4 µm when the flow rate of MQL was increased from 25 mL/h to 37.5 mL/h. Kayanak [10] compared machining of Inconel using cryogenic cooling, MQL and dry machining. The study concluded that the maximum temperature was above 800 °C during dry machining, and reduced to nearly 600 °C when MQL was used.

Although significant information was published for machining extruded or rolled IN718, there is yet a study on machining of additively built Inconel. Similarly, most published literatures were seen for externally applied MQL and limited research was published on through-tool MQL. This research study fills the gap by simulating through-tool MQL and applies the results on micromilling of selective laser melted (SLM'ed) Inconel 718.

3. Experiments

Experiments were performed in two stages. The first stage characterized the resulting droplets due to different air pressures and surface roughness of a MQL nozzle. In the second stage, MQL at different operating conditions were applied when micromilling SLM'ed IN718 with uncoated WC microtools. Tool wear and surface finish were used to assess the effectiveness of MQL. The effect of different tool coatings was investigated in a parallel study, and would not be covered in this paper.

3.1. Experimental setup

Since an internal MQL system is complex, simulated through-tool MQL was performed based on an existing drill for internal coolant (Sanvik Coromat: Corodrill R840-0510-70-A1A 1220). It was assumed that:

- Micromist, formed by atomizing of lubricating oil and compressed air at a coaxial junction, flows through a hollow spiral channel to an edge of a cutting tool.
- The internal coolant channel in this twist drill is ø3 mm, 25.4 mm long, with 45° helix angle.
- The exit droplet velocity along the channel axis dominates other component, i.e., its radial velocity component due to drill rotation is negligible.
- The micromist, flowing through a narrow channel nozzle, affects by the turbulent flow in the nozzle.
- Micromist flow in a helical path with rough wall surface is equivalent to flowing through a rough straight channel and then through a smooth helical channel.

To simulate the spiral channel inside a drill, two 3D printed tool adapters were printed with ABS plastic and rigidly attached to the original nozzle of the MQL Unist system (Fig. 1). The inner channel surface of one adaptor was left in the as-printed condition, while the other was polished with acetone. A cotton bud was dipped in acetone, quickly inserted into and removed from the inside diameter of the adaptor. The exit end of this adaptor was connected to a polyvinyl tubing wound around a helical adapter. The length of the adapter was 25.4 mm with 25.4 mm pitch distance. This adapter simulated the helical profile of the inner passageway of a twist drill that supplies

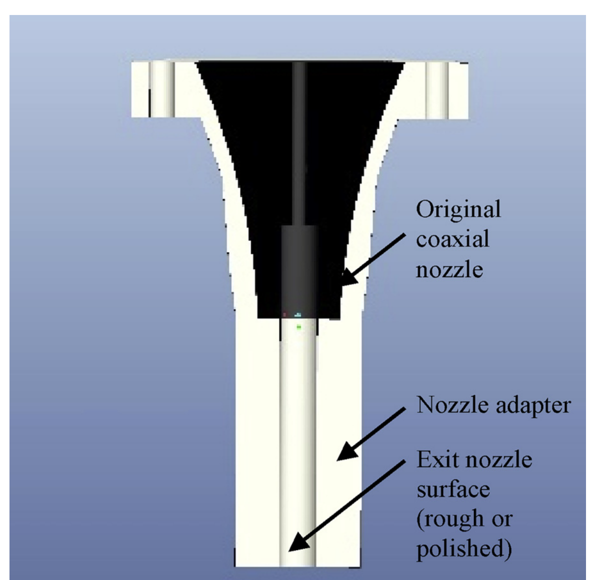

Fig. 1. Design of nozzle adaptor.