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Thermal analysis in MQL end milling operations

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Abstract

The impact of various additives such as Al_2O_3, polycrystalline diamond (PCD) and graphite as well as water in MQL oil has been investigated on convective heat transfer and machinability in end milling Ti6Al4V for the first time. The analysis indicated that suspending PCD in oil improves heat transfer by 43% from 557 W/m°K in conventional MQL to 970 W/m°K resulting in 1.6 times increased tool life in high speed machining of Ti6Al4V alloy. This can potentially allow for high speed end milling of Ti6Al4V titanium alloy resulting in increased productivity.

Keywords: End milling; Titanium; Thermal effects

1. Introduction

MQL has emerged as a viable alternative to conventional flood cooling in material cutting processes [1]. A small amount of lubricant is sprayed through compressed air and into the cutting zone. Majority of the lubricant is evaporated and burnt at the cutting zone, leaving minimal residues. It also eliminates the need for maintenance and disposal commonly associated with water-based cutting fluids. Vegetable oils have been used to further enhance the sustainability of MQL by replacing synthetic and petroleum based oils. However, MQL is known to have limited cooling capability and can fail to deliver suitable performance at high cutting speeds.

Nano and micro fluids have been generated by suspending micro and nano particles in MQL oils as a method to improve their lubrication and thermal performance in machining. Vasu et al. [2] reported using Al_2O_3 nano particles in oil has reduced tool wear and cutting forces in turning Inconel 600. Using diamond suspension, Nam et al. [3] reported that 72% improved tool life can be achieved in micro drilling 6061 aluminum alloy. There is minimal research on milling operations with nano/micro fluids. Specifically, there is no data available on cooling performance of these cooling-lubricating fluids (CL) in complex machining scenarios such as in end milling.

Titanium alloy, Ti6Al4V, is extensively used in aerospace industries due to its high specific strength. It has a combination of thermal and mechanical properties which results in short tool life and poor productivity notoriously making it a difficult-to machine material. Due to its high strength and hardness and low thermal conductivity, low cutting speeds are used [4]. Cutting temperature is directly related to cutting speed. MQL reportedly fails to deliver sufficient cooling in high speed machining. Specifically, in end milling operations, the cutting tool is rotating at high speed which inhibits effective heat transfer between the CL and the cutting zone.

In this paper, the underlying theory for convective heat transfer for a rotating cutting tool is provided. The impact of Al_2O_3, polycrystalline diamond (PCD) and graphite additives as well as water on thermal and machining performance of rapeseed oil MQL has been investigated in high speed end milling of Ti6Al4V alloy using a coated solid carbide tool. Convective heat transfer coefficient for various MQL CLs has been calculated and tool life, power consumption and bending moment are investigated in machining Ti6Al4V at 200 m/min.

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Nomenclature

A	Heat transfer area
C	Cooling rate
C_p	Specific heat
D	Tool diameter
d	Nozzle diameter
h	Convective heat transfer coefficient
k	Thermal conductivity
L	Characteristic length
m	Mass
ν	Fluid kinematic viscosity
Nu=hl/k	Nusselt Number
$Pr=C_p\mu/k$	Prandtl number
Re	Reynolds number
Re_j	Jet Reynolds number
Re_ω	Rotating Reynolds number
T	Temperature
t	Time
Uj	Fluid velocity
V_c	Tool peripheral speed
W	Distance between tool and nozzle
a, b, c, n	

2. Heat transfer

The heat transfer in MQL is through convection between the mist and the cutting zone. However, most studies are limited to characterizing conduction of the CLs or static convective heat transfer and the dynamic behavior is neglected. Studies on convective heat transfer of the cutting fluids are mostly limited to characterization of the mist instead of the thermodynamic system. Convective heat transfer is a complex problem directly related to the flow characteristic of the surrounding media in which the geometry, position and orientation of the object to be cooled/heated is of utmost importance. Due to the non-slip condition of the fluid layer adjacent to the surface of the object, heat transfer is through conduction. Heat transfer from this layer to subsequent layers are through convection. The heat transfer convected from a surface is estimated in terms of Nusselt number which is a ratio of convection to conduction heat transfer [5] and is a function of Re,rs and the shape of the object.

The heat transfer from a cutting tool can be simplified to a rotating cylinder. For a rotating cylinder in a uniform air stream perpendicular to its axis of rotation, the fluid rotates at the tangential velocity of the cylinder's outer surface due to non-slip condition. This movement is transferred to adjacent layers due to the fluid's viscosity as shown in Fig. 1a.

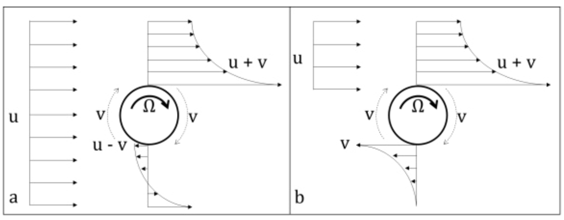

Fig. 1. Impact of rotation on flow velocity across a cylinder in (a) symmetrical flow, (b) asymmetrical flow

This leads to the formation of Magnus effect as the flow on one side is accelerated and decelerated on the opposite side resulting in deformation of the flow [6]. The heat transfer is therefore dependent on the condition of the flow. The ratio (λ) between the rotational Reynolds number (Re_ω) and jet Reynolds number (Re_j) around the cylinder can be used to characterize the flow around a rotating cylinder [7]:

$$\lambda = \frac{Re_\omega}{Re_j} \ (2), \qquad Re_j = \frac{U_j D}{\nu} \ (3), \qquad Re_\omega = \frac{V_c\, D}{\nu} \ (4)$$

The Nusselt number and therefore, heat transfer are correlated with the Reynolds number [6, 7]. Smyth and Zurita [8] noted that the Nusselt number is correlated with the jet Reynolds number as in $Nu = \alpha Re_j^{\beta}$. Jeng et al. [9] identified that in an impinging jet on a rotating cylinder, Nu is correlated with Re_j as in:

$$Nu = aRe_j^n \frac{D}{w}^b \frac{d}{w}^c \qquad (5)$$

In MQL, the nozzle is usually targeted towards the cutting zone on the periphery of the cutting tool and therefore, forced flow only takes place on one side of the rotating cylinder as depicted in Fig. 1b. In addition, the complex geometry of an end mill is ignored.

In end milling, the cutting tool rotates and moves around the workpiece. The flow characteristics around the cutting tool and hence heat transfer is dependent on the geometry of the tool and its rotational speed as well as the geometry of the workpiece.

3. Convective heat transfer around a rotating end mill

The convective heat transfer when using different MQL CLs have been investigated. Rapeseed oil was used as a base lubricant fluid and various suspensions were generated as follows: (i) 50% Al_2O_3 suspension (OA50%), (ii) 4% Al_2O_3 suspension (OA4%), (iii) 50% PCD suspension (OD), (iv) 1% graphite suspension (OG) and (v) oil-water (OW). The Al_2O_3 and PCD slurries had maximum 5 µm particle size. MQL with only rapeseed oil was used as a reference. A single nozzle with 2 mm diameter outlet was used for MQL tests incorporating 0.5 MPa compressed air and 100 ml/h lubricant. The nozzle was positioned at 25 mm distance directed towards the cutting zone, tangent to the cutting tool periphery with 45° inclination angle equivalent to the cutting tools' helix angle.

In order to capture the complexities of cooling in MQL, position of the nozzle and tool geometry, a setup was developed to assess the convective heat transfer of a heated rotating 12 mm diameter end mill cutting tool. A FLIR 6000 scientific series infrared camera together with two pyrometers were used to monitor the temperature of the cutting tool. They were calibrated individually at varying temperatures using a thermocouple system. The cutting tool was heated to 350 °C and subsequently cooled using different CLs explained above. The tests were conducted at V_c= 60, 120, 150, 180 and 200 m/min speed and repeated. The temperature of the heated tool subject to various cooling methods and time were recorded based on [10]. The convective heat transfer can be modelled based on the Newton's law of cooling (Eq. 6) and lumped capacitance method (Eq. 7) [11]:

$$\frac{dT}{dt} = -C\,(T_{\infty} - T_0) \quad (6), \qquad \frac{dT}{dt} + \frac{hA}{mC_p}T_0 = \frac{hA}{mC_p}T_{\infty} \quad (7)$$

The Biot number was less than 0.07 for all experiments confirming the validity of the analysis. The average convective heat transfer coefficient has been calculated as shown in Fig. 2. Cooling with only air resulted in 541 W/m°K which is provided as a reference. An average coefficient of 557 W/m°K was achieved in MQL. The highest convective heat transfer coefficient was 1090 W/m°K for OA50% followed by OD at 971 W/m°K. Larger concentration of micro particles results in larger deviation in heat transfer at various rotational speeds.

4. Machining experiments

4.1. Machining methodology

The machining experiments consisted of straight-line end milling alongside a block of Ti6Al4V α-β titanium alloy with 50×50×150 mm dimensions and 348±10 HV hardness using a vertical CNC milling centre retrofitted with an MQL system. A 12 mm diameter solid carbide end mill with 5 flutes and TiSiN coating was used for machining experiments. A high cutting speed of V_c=200 m/min with f_z=0.03 mm/tooth feed rate, a_p=3 mm axial depth of cut and a_e=4 mm radial depth of cut were used. Identical MQL nozzle setup used for heat transfer analysis was employed for machining. The only variable parameter for experiments were the CL medium for MQL explained in 4. A new cutting tool was used for each experiment and tool life was monitored. Tool life criterion of VB=300 μm was selected. The bending moment of the tool assembly was measured using a Spike system. A Hioki 6920 power analyzer wired into the machine was used for measuring machine tool's power consumption at 1 Hz.

4.2. Machining results

As shown in Fig. 3, OD resulted in the longest tool life of nearly 600 s followed by OW. The shortest tool life was associated with MQL. OG surpassed OA4% and MQL in terms of tool life however, it was less than OA50%.

The investigations showed the progression of tool bending moment during machining as the tool wear increases. As shown in Fig. 4, the lowest initial bending moment was associated with OW followed by OD which may be translated into forces acting on the tool given 100 mm length of the tool assembly. The cutting power consumption was calculated by deducing none-material cutting power consumption from the total machine tool power consumption. This gives a clear indication of the forces and friction during machining.

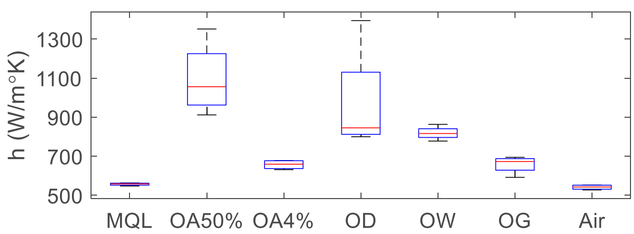

Fig. 2. Convective heat transfer coefficient for various MQL CLs

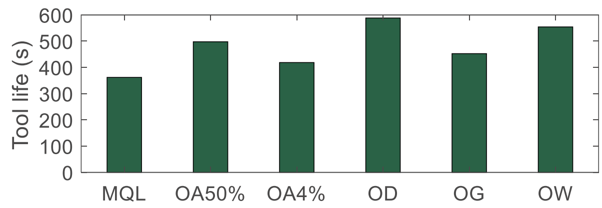

Fig. 3. Tool life for various CL medium

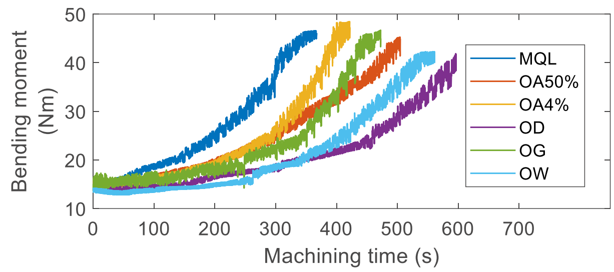

Fig. 4. Bending moment for tool assembly during machining experiments

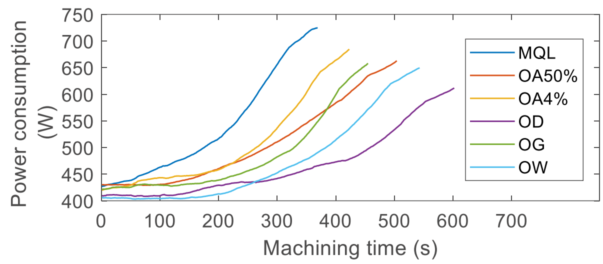

Fig. 5. Power consumption graphs for various experiments

Similar to the results from bending moment, OW resulted in the lowest power consumption followed by OD as illustrated in Fig. 5. OA50% resulted in the highest initial power consumption which was quickly surpassed by that of MQL as the tool wear progressed. Similar pattern can be observed between power consumption and bending moment as the tool wear progresses.

As shown in Fig. 6, the tool wear was concentrated at the depth of cut in all experiments but OW which produced the most uniform tool wear. Built-up-edge and crater wear was dominant specifically in MQL, OA50%, OA4% and OG. In these experiments, deep crater wear resulted in chipping of the cutting edge exacerbating flank wear. This is evidently shown in Fig. 6 for OA4%. Tool wear was initiated by chipping and removal of the coating exposing the substrate. This was then followed by thermomechanical wear and adhesion of workpiece material on WC-Co substrate.

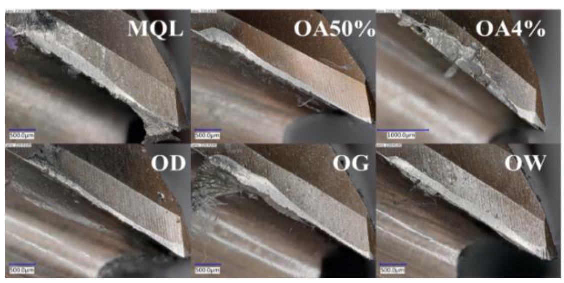

Fig. 6. Microscopic images of tool wear

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

5. Discussion

The impact of adding various micro particles in MQL oil on cooling capability and machinability have been studied in end milling Ti6Al4V. Six CL media namely, rapeseed oil, 5 μm Al_2O_3-rapeseed oil suspension at 50% and 4%, 5 μm PCD-rapeseed oil, graphite-rapeseed oil and rapeseed oil-water were investigated. It is known that the addition of certain micro particles improves heat transfer and therefore cooling capabilities of fluids. Sharma et al. [12] reported that the addition of Al_2O_3 increases thermal conductivity and reduces specific heat of MQL oil. However, thermal conductivity is only one of the factors affecting convective heat transfer specifically in end milling operations. The addition of 4% Al_2O_3, resulted in 18% increase in convective heat transfer compared with MQL. This translated into 15% increased tool life. The results clearly show that the increased cooling capability in OA50% improved tool life by 20% compared with OA4%. The bending moment for OA50% and OA4% were almost similar up to 25 Nm. After this point, the superior cooling capability of OA50% reduced progression of tool wear and hence heat generation. Power consumption and therefore heat generation increases as the tool wear grows. Higher heat generation and therefore cutting temperature facilitates tool wear forming a viscous cycle leading to tool failure. Similar to OA experiments, in OG, the rate of increase in bending moment was accelerated after 25 Nm bending moment. This acceleration, took place at 15 Nm in OW and at about 20 Nm in OD. The initial tool wear is mechanical in high speed machining of Ti6Al4V which rapidly transforms into thermo-mechanical when the coating is removed. At this point, the cooling capability of the CL facilitates extending tool life by reducing the impact of temperature on tool wear.

Although the increase in convective heat transfer was over 60% from OA4% to OA50%, the improvement in tool life was only 20%. This can be explained by the abrasive behavior of Al_2O_3 suspension. As the Al_2O_3 particles rub against the cutting tool, they also abrade the flank face of the tool. This resulted in removal of tool coating and exposing WC-Co substrate in OA50%. Moreover, the abrasive behavior of Al_2O_3 prevented accumulation of workpiece material on the surface of the tool resulting in a smooth flank face. OD resulted in the longest tool life and only second to OA50% in terms of heat transfer. PCD particles tend to be spherical in nature which resulted in improved lubrication as well as heat transfer. The lubrication effect is evident from the bending moment and power consumption results. Graphite modestly improved heat transfer to that of OA4%. Graphite is recognized as a solid lubricant. However, it oxidizes and burns at high temperatures in atmosphere. This prevented effective lubrication at high cutting temperatures expected in high speed machining of Ti6Al4V. Cooling with water can suffer from Leiden-frost effect. This can be minimized by using high pressures or generating fine droplets as in MQL. OW benefitted from both lubrication of oil and cooling effect of water. However, its cooling capability was not as high as OD and OA50%. The tool wear was a combination of flank and crater wear for all machining experiments to different extents.

6. Conclusions

The impact of suspending different additives into the MQL oil is investigated in high speed end milling of Ti6Al4V titanium alloy. Firstly, the convective heat transfer for different additives namely, Al_2O_3, PCD, graphite and water in MQL is assessed for the first time. The analysis showed that Al_2O_3, PCD and graphite suspended in oil increases convective heat transfer coefficient. Machining experiments revealed that in high speed machining, improved cooling capability can extend tool life specifically, when thermally induced tool wear is more pronounced. This was also evident in power consumption and tool assembly bending moment. PCD suspended in oil performed best resulting in 1.6 times increased tool life compared with conventional MQL. Realization of high speed end milling of titanium alloy can potentially increase the productivity and throughput of aerospace manufacturing. Future investigations will concentrate on optimizing the suspension percentages as well as other MQL parameters.

Acknowledgements

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