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ORIGINAL ARTICLE

Comparative evaluation of soybean oil–based MQL flow rates and emulsion flood cooling strategy in high-speed face milling of Inconel 718

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Abstract

The increasing environmental and health concerns of conventional emulsion flood coolants have motivated the use of vegetable oil in the form of minimum quantity lubrication (MQL) in machining. This paper presents comparative evaluation of high oleic soybean oil (HOSO)–based MQL flow rates at 10, 30, 50, 70, and 90 ml/h with a mineral oil–based emulsion flood coolant as a benchmark in face milling of Inconel 718 using AlTiN/TiN-coated carbide inserts. Cutting forces, tool wear, and surface roughness were measured and analyzed. The results show that MQL oil flow rate at 70 ml/h gave the longest tool life comparable to that of mineral oil–based emulsion flood cooling, while 10 ml/h flow rate gave the shortest tool life. Also, 70 ml/h flow rate gave the lowest resultant cutting force among all MQL oil flow rates and conventional emulsion cooling at tool life. Increasing HOSO-based MQL flow rate improves surface roughness and reduces tool wear by providing enough thin lubrication film but also leads to an increase in chip affinity and formation of large built-up edges (BUEs) as the MQL flow rate reaches 90 ml/h. At lower HOSO-based MQL flow rate, tool wear mechanism is predominantly abrasion due to large surface friction, while at higher HOSO-based MQL flow rate, tool wear mechanism is adhesion leading to excessive BUEs. HOSO-based MQL flow rate of 70 ml/h and air pressure of 4.14 bar are recommended when face milling Inconel 718 and are demonstrated to be a potential replacement of mineral oil–based conventional emulsion flood cooling strategy for machining of difficult-to-cut metals.

Keywords Inconel 718 · Emulsion flood cooling · High-speed face milling · Soybean vegetable oil · MQL flow rate · Coated carbide inserts

Highlights

- HOSO-based MQL is a potential replacement to EC strategy in face milling Inconel 718.
- Tool life and surface roughness improve with increase in HOSO-based MQL flow rate.
- MQL oil flow rate at 70 ml/h gives optimum performance in high-speed face milling.
- MQL flow rates of 10 and 90 ml/h lead to rapid tool wear and thus not recommended.
- Increasing HOSO-based MQL flow rate leads to formation of excessive BUE at 90 ml/h.

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1 Introduction

Difficult-to-cut metals like Inconel 718 are predominantly used in aerospace, gas turbine, nuclear, and automotive industries for producing components used in the hot compartment of jet and rocket engines, such as turbine blades, compressor discs, and cryogenic applications due to their excellent strength-to-weight ratio, high rupture strength, and toughness and resistance to corrosion at elevated and sub-zero temperatures [1]. These metals exhibit serious problems to the cutting edges of cutting tools during machining, leading to high cutting force components, tool chatter, vibration, rapid tool wear, short tool life, and hence poor surface roughness of the machined surface due to the physical, chemical, and thermal properties of metals. Machinability expresses the ease and economy with which a given material can be cut under average conditions. Maximum cutting forces exerted on the tools, power consumption, tool wear and tool life, and surface finish of machined parts can be used to determine the machinability of the workpiece and performance of the tool. Ning et al. [2] compared predicted cutting forces when turning ultra-fined grained titanium using extended chip formation analytical modeling and compared them with values obtained from orthogonal experiments. The sensitivity analysis shows that the prediction error increases as the cutting condition values change. Okafor and Sultan [3] developed a mechanistic cutting force model to predict cutting forces in high-speed end-milling of Inconel 718 using wavy-edge, bull-nose, helical end mill. The model incorporated the effects of emulsion cooling strategy into the mechanistic cutting force model through experimental determination of six specific cutting force and edge force coefficients. The model was validated experimentally. The predicted values agreed fairly well with the experimentally measured values in both magnitude and shape. At high cutting speeds, when machining Inconel 718, tremendous heat is formed at the cutting zone which when not removed or inhibited can lead to heat softening of tool materials and welding of metals to tool surface causing built-up edges (BUEs) or material diffusion [4, 5]. Coated carbide inserts are used for intermittent and constant engagement machining operations. The thermo-physical properties of such tools are inferior to difficult-to-cut metals likes Inconel 718, and hence there is the need to maintain the chemical, thermal, and mechanical properties of the insert materials. Lubricating and cooling of the cutting zone are the most effective ways to maintain the thermal and mechanical properties of these inexpensive tool inserts during machining of difficult-to-cut metals, decreasing the tool wear rate and increasing tool life of the tool inserts. Conventional emulsion and high-pressure emulsion cooling strategies are widely used for cooling and lubricating cutting zones with the use of a high-pressure pump to produce a lubricating layer when machining difficult-to-cut materials. Mineral base oil (synthetic and semi-synthetic) is widely used in industries to form the emulsion coolants used in emulsion flood cooling strategy. Ezugwu and Bonney [6] investigated the application of high-pressure coolants supplied at 1200–3000 l/h in turning Inconel 718 with coated carbide tools and compared with conventional flood cooling at 300 l/h. It was reported that the tool life when turning Inconel 718 at 300 l/h emulsion flow rate was shorter than that of turning at 1200–3000 l/h emulsion flow rate in high-speed turning of Inconel 718. Mia and Ranjah [7] investigated the influence of duplex jet high-pressure coolants on the machinability of titanium alloy and compared to dry turning. Two orifices were used to supply coolants at 360 l/h each to the cutting zone. In double jet cooling strategy, reduction in cutting forces, surface roughness, and tool wear were accredited to enhanced heat dissipation compared to dry machining. Adhesion and rubbing were the most dominant tool failure mechanisms when dry machining. The use of high-pressure conventional coolants in emulsion flood cooling strategy is very effective in cooling and lubricating the cutting zone when machining, especially in difficult-to-cut metals like Inconel 718. These fluids are non-biodegradable, non-renewable, unfriendly to the environment, and hazardous to the health of machine operators.

For decades, researchers have been investigating more environmentally friendly methods to cool and lubricate cutting zones. Cetin et al. [8] evaluated the performance of vegetable-based cutting fluids with extreme pressure additives made from sunflower and canola; cutting fluids were made from semi-synthetic and mineral oil to form 8% volume concentration of emulsion in turning. It was observed that the extreme pressure additive has a significant influence on turning performance in terms of surface roughness and cutting forces. Some of these extreme pressure additives are non-biodegradable, take time to activate during machining operation, and can be detrimental to low-speed operations. Kumar et al. [9] investigated the performance of green cutting fluid using a flood cooling strategy. The idea was to replace mineral oil with vegetable oil in forming emulsion cutting fluid. One of the problems observed was the suspension stability of the synthesized vegetable oil in emulsion cutting fluid. Another idea is to reduce the amount of lubricant oil (mineral or vegetable) used during machining and supply just enough amount of the fluid needed in the cutting zone through internal holes of the tool or via an external nozzle.

Minimum quantity lubrication (MQL) refers to a technique that minimizes the use of coolants by mixing a small amount of lubricant and compressed air to form aerosol, which is sprayed in mist form to the cutting zone with the help of a pressurized nozzle; the oil in the mist acts as a lubricant and the compressed air acts as a coolant and flushes the chips away from the cutting surface in the mist form instead of flooding the workpiece and cutting tool [10]. Kang et al. [11] investigated the effect of MQL in end-milling of AISI steel using coated carbide and compared with wet cooling and dry machining. The oil was supplied at a flow rate of 6 ml/h in MQL and was observed to outperform wet and dry machining using 0.1 mm maximum flank wear as a tool failure criterion. This flank wear criterion is too low to be considered for comparison. Zhang et al. [12] investigated the influence of MQL using Bescut 173 oil at 8 ml/h with cryogenic compressed air to form mist during end-milling of Inconel 718 and compared with dry machining using 0.6 mm maximum flank wear as a tool failure criterion. It was observed that tool wear in dry machining was more severe after the coating wore out. Liao et al. [13] observed the lubricating and cooling effects of MQL using synthetic ester at 10 ml/h oil flow rate compared to dry machining of hardened steel. Park et al. [14] observed that during machining of difficult-to-cut metals like titanium alloy, vegetable oil in the form of MQL and cryogenic liquid nitrogen (LN_2) can improve machining performance compared to dry and wet machining but cryogenic LN_2 can lead to thermal shock of the tool and harden the workpiece resulting in excessive tool wear, micro-fracture, and increase in cutting forces. Hadad and Sadeghi [15] investigated the influence of MQL turning when fluid is supplied to flank, rake, and flank/rake. It was observed that the most effective method is supplying fluid to both flank and rake, which is also not significantly better than supplying just to the flank surface and the least effective is coolant supplied to the rake surface. Sharma et al. [16] investigated the effects of dry and MQL turning of AISI D2 steel using commercially made Acculube LB6000. Surface roughness, micro-hardness, and temperature were the machining parameters investigated. It was concluded that biodegradable MQL turning of AISI D2 steel using tungsten carbide insert is better than dry turning and can be a sustainable turning machining process. Kaynak [17] investigated the machining performance of Inconel 718 under dry, cryogenic, and MQL at 60 ml/h oil flow rate; it was observed that the cutting force can be effectively reduced when machining with MQL using UNIST coolube 2210EP lubricant at oil flow rate of 60 ml/h under cutting speed of 60 m/min turning. The type and amount of mist formed are dependent on the volume of oil mixed with air under a certain pressure. Heavy mist form can be dangerous to the working environment without an effective extractor and ventilation in place. The concentration of oil in the mist to effectively lubricate and cool the cutting zone is also dependent on the type of machining, the material being machined and cutting conditions. Shaikh et al. [18] investigated the micro-hardness of AISI 1018 steel using Acculube LB2000 biodegradable oil as MQL at 12 ml/h oil flow rate and observed that subsurface hardness was significantly less compared to dry machining and stated that lubricant concentration in MQL varies between 0.2 and 500 ml/h and air pressure at roughly 5 bar. Li and Lin [19] investigated the influence of MQL in micro-grinding of SK3 steels on surface roughness and tool life using Bluebe LB1 oil flow rates of 1.88 and 0.63 ml/h. It was observed that MQL flow rate of 1.88 ml/h resulted in a better surface finish and longer tool life than 0.63 ml/h and dry grinding. Tawakoli et al. [20] investigated the influence of oil mist parameters on MQL grinding process using an LB8000 oil flow rate of 20, 50, and 100 ml/h on tangential force and surface roughness of hardened steel. It was observed that the increase in oil mist reduces the tangential grinding force and surface roughness of hardened steel. Sadeghi et al. [21] investigated the effect of MQL grinding using synthetic and vegetable oil under oil flow rates of 20 to 140 ml/h and compared with wet grinding using 5% concentration of Blaser BC35 soluble oil of titanium alloy. It was observed that the use of synthetic oil in MQL performs better in terms of surface roughness and tangential grinding force than vegetable oil at 15 and 40 m/min cutting speed. Conventional wet grinding resulted in the lowest surface roughness. It was also observed that at an oil flow rate above 100 ml/h, the tangential and normal grinding forces increase drastically with cutting speed of 15 m/min when compared to 40 m/min. This is likely due to the internal friction of the lubricant layers and low shear grinding velocity. Pervaiz et al. [22] investigated internally (through hole) using rapeseed oil at varying flow rates in MQL turning of titanium alloy and compared with dry and flood turning. Rapeseed oil flow rate of 60 to 100 ml/h was investigated and it was observed that 60–70 ml/h oil flow rate provided the most reliable turning performance in terms of surface roughness, tool wear, and resultant cutting force compared to dry and flood turning at 0.1, 0.2, and 0.3 mm/rev. All tools are not capable of supplying lubricant and coolant via tool holes and the integrity of some tool is reduced due to tool holes and is difficult to design. A review on the effects of minimum quantity lubrication in machining—processes using conventional and nanofluid-based cutting fluids—shows that little work has been done on the effective oil flow rate to improve the face milling performance of difficult-to-cut materials like Inconel 718 using biodegradable vegetable oil and most works done are on grinding and turning [23].

The mechanism and machining parameters for grinding, turning, and milling are different and affect the machinability of materials especially difficult-to-cut metals like Inconel 718 differently. Conventional emulsion flood cooling strategy is still predominantly used in machining industries for machining difficult-to-cut materials like Inconel 718 and other materials like steel and aluminum. MQL is still been investigated as a potential replacement for this environmentally unfriendly practice in industries. From the above literature, most of the work has concentrated on comparing MQL with dry machining using commercially available oil, using arbitrary or fixed MQL oil flow rate and in turning or grinding of materials like AISI steel or aluminum.

There is a need to study other environmentally friendly and available vegetable oil with different viscosity and fatty acid compositions and compare with effective emulsion flood cooling strategy when face milling of difficult-to-cut materials like Inconel 718. The present work focuses on the comparative evaluation of modified high oleic soybean oil flow rate (10, 30, 50, 70, and 90 ml/h) in face milling of Inconel 718 using inexpensive shell mill–coated carbide inserts and compared to 7% concentration of a semi-synthetic emulsion coolant supplied at 1200 l/h used commercially in machining industries for machining difficult-to-cut metals like Inconel 718 using optimal machining parameters for face milling Inconel 718 and potentially replace it.

2 Experimental plan and procedures

An AlTiN/TiN-coated carbide insert with two cutting edges from Kennametal was used to conduct face milling experiments on a Cincinnati Milacron Sabre 750 VMC equipped with an Acramatic 2100 CNC controller. The linear positional accuracy of the Cincinnati Milacron Sabre 750 VMC was maintained during each experiment by allowing the axis to cool before starting the next set of experiments [24]. The geometry and dimensions of the shell mill and insert were obtained from NOVO, Kennametal software shown in Fig. 1 and Table 1. Machining experimental parameters are summarized in Table 2 and the workpiece schematic showing the machining setup is shown in Fig. 2. Down-milling experiments were performed under MQL for oil flow rates at 10, 30, 50, 70, and 90 ml/h using HOSO-based MQL and emulsion flood cooling strategies at constant face milling parameters: cutting speed of 40 m/min, chip load of 0.1 mm/tooth, axial depth of cut 2 mm, and radial depth of cut 6.25 mm using 1 insert (KCSM40) in a 37.5-mm-diameter 4-insert shell mill tool holder. Cutting parameters and milling method were selected from a range of literature, tool manufacturer's recommendation, and previous experimental work done under emulsion flood cooling strategy to obtain the optimal parameters and milling method for face milling Inconel 718 using AlTiN/TiN-coated carbide insert. Face milling performances investigated were surface roughness, cutting forces, tool wear, and tool life. Minimum quantity lubrication using modified high oleic soybean from ADA (Archer Daniels Midland) at different oil flow rates and

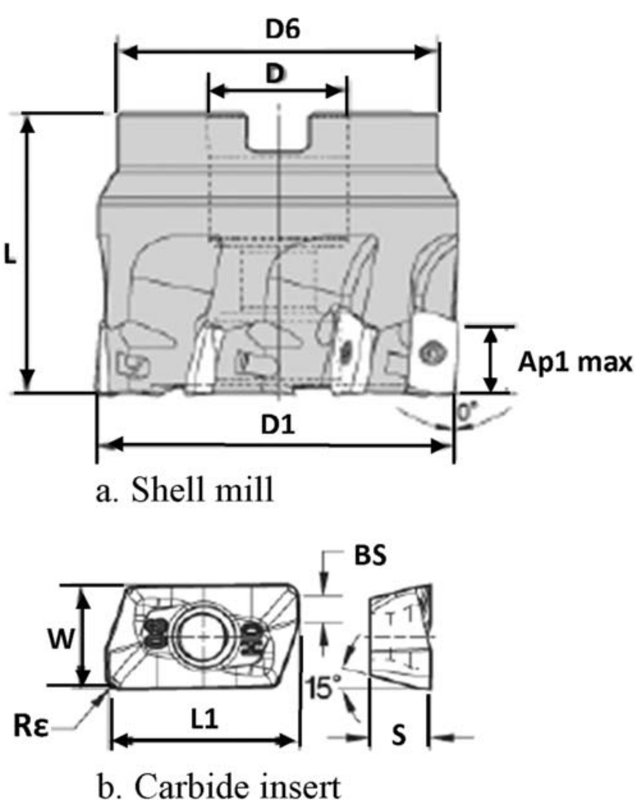


Fig. 1 Tool insert and holder information

60-Psi (4.14 bar) shop air pressure to atomize the oil molecules to form aerosol and transport it to the cutting zone using the Acculube precision applicator set at constant 60 cycles/min (1 Hz) frequency generator and amount of oil flow per cycle controlled by the secondary controller. The vegetable oil selected was based on a previous work, which shows the fatty acid composition, oxidation stability, long shelf life, and high viscosity over a range of temperatures for modified HOSO vegetable oil compared to other oils investigated [25].

2.1 Coolant and workpiece preparations

Modified HOSO from Archer Daniels Midland was used for MQL flow rate experiments due to its biodegradability, availability, oxidation stability, and high viscosity. HOSO was selected from a range of oil tested for shear stress-shear rate, viscosity, and thermal conductivity over a range of temperatures. The oil at a different flow rate is supplied through an externally pressurized nozzle after being atomized with compressed shop air at 60 Psi (4.14 bar) in an Acculube precision pump applicator at a frequency of 60 cycles/min (1 Hz). The amount of oil flow rate was controlled by the secondary lubricant control. Fatty acid composition and physical property of the modified HOSO are shown in Table 3. The high oleic fatty acid, flash point, and iodine value are the primary reasons for the suitability of HOSO use as MQL fluid compared to other tested fluids. The emulsion flood coolant was prepared by mixing VP-TECH-005B semi-synthetic oil from VAL cool with distilled water to form 7% concentration of emulsion cooling fluid supplied at a pressure of 10 bar and 1200 l/h flow rate. The thermo-physical property of coolants used was characterized using a US digital pH meter tester (range 0–14 pH, resolution 0.1 pH, and accuracy ± 0.1 pH at 20 °C) to determine the pH level of the flood emulsion coolant and the viscosity of the emulsion flood coolant, and HOSO MQL was determined using a Brookfield DV-III rheometer (CP40 cone/plate setup and 0.5-ml sample size), and thermal conductivity was determined using a Thermtest TLS-100 thermal conductivity meter at room temperature as summarized in Table 4.

Inconel 718 workpiece dimension of 150 × 75 × 37.5 mm used in the experiments was purchased from Altemp alloys with the chemical composition shown in Table 5. The Inconel 718 AMS 5596 plate saw cut to the dimensions was further processed using G and M codes to carefully drill and countersunk and tapped to obtain two parallel holes for clamping the workpiece onto a 4-component Kistler dynamometer.

2.2 Measurement setup

Measurements were obtained and analyzed for the face milling performance (cutting force components, surface roughness, tool wear, and tool life). HOSO-based MQL flow rate

Table 1 Tool dimensions in millimeter

Shell mill					Carbide insert				
D1	D	D6	L	Ap1 max	LI	W	S	BS	$R\varepsilon$
37.5	18.75	35.5025	39.375	9.7825	11.85	6.625	3.7	1.675	0.775

experiments were set up using an Acculube precision pump to supply a precise amount of lubricant needed at a constant set pump cycle and air pressure to atomize the oil into an aerosol. The machining parameters shown in the experimental plan were set constant using the same CNC program and milling method as shown in Fig. 3. The cutting force components were acquired using a Kistler dynamometer connected to a Tektronics TDS 420A digitizing oscilloscope data acquisition system via a low-filter Kistler 5010 B dual amplifier for both HOSO-based MQL flow rates and emulsion flood cooling strategy experiments as shown in Fig. 4. Inconel 718 was clamped firmly onto the Kistler dynamometer using a torque wrench to evenly distribute bolt load on the workpiece. The signals acquired (F_X—perpendicular to feed, F_Y—feed, and F_Z—Axial) were further processed to obtain the maximum cutting force components and used to calculate the resultant cutting force component F_R using Eq. 1. Tool wear data was collected after every machining pass (2.69 min) using a Hirox digital microscope (KH-8700). The average surface roughness R_a data were obtained both in the longitudinal and traverse directions of the machined surface with a portable Brown and Sharpe pocket surface tester using the following parameters: traverse length of 5 mm, evaluation length of 4 mm, traverse speed of 5.08 mm/s, and cut-off length of 0.8 mm, giving a total number of 5 record measurements. Surface roughness measurements were made at 3 different locations (25 mm) apart in the feed (longitudinal) and perpendicular to the feed (traverse) directions, and the average results were reported. Tool life was based on the total machining time achieved when the flank wear curve exceeds the set tool wear failure criteria of 0.35-mm maximum normal flank wear.

3 Results and discussions

3.1 Cutting force analysis

3.1.1 Sample cutting force signal

Figure 5 shows a sample plot of acquired force signal in F_X—perpendicular to feed, F_Y—feed, and F_Z—axial directions versus acquisition time using the oscilloscope attached to a dynamometer. The signals obtained where collected for HOSO-based MQL at flow rates of 10 ml/h at the 1st and 5th passes. As seen, the perpendicular to the feed signal is higher than the feed and axial signal in both the 1st and 5th passes. This is typical of the down-milling method when machining Inconel 718. The signal magnitude is higher in the 5th pass compared to the 1st pass. This is due to wear as the machining pass increases and frictional force increases due to a larger contact surface and hence vibration. The signals in all directions are processed to determine the maximum cutting force for all machining pass achieved and stopped just after the inserts exceed the tool life criteria. Each maximum cutting force component is then plotted against the cutting pass for analysis as shown in the section below.

3.1.2 Maximum cutting force component versus the number of machining pass

Maximum cutting force components (F_X, F_Y, and F_Z) were obtained from the processed force signal data acquired using the Tektronics TDS 420A digitizing oscilloscope. The components were later used to obtain the resultant cutting force component F_R using Eq. 1. Figure 6 shows the plot of cutting force components

Table 2 Experimental plan for MQL and emulsion flood cooling strategies

Exp. no.	Cutting speed V_c (m/min)	Milling method	Oil flow rate (ml/h)	Spindle speed, n (rpm)	Feed rate, F (mm/min)	Feed per tooth, f_t (mm/z)	Depth of cut	
							Axial, a_a (mm)	Radial, a_r (mm)
1	40	Down-milling	10	339.7	33.97	0.1	2	6.25
2			30					
3			50					
4			70					
5			90					
6			Emulsion flood					

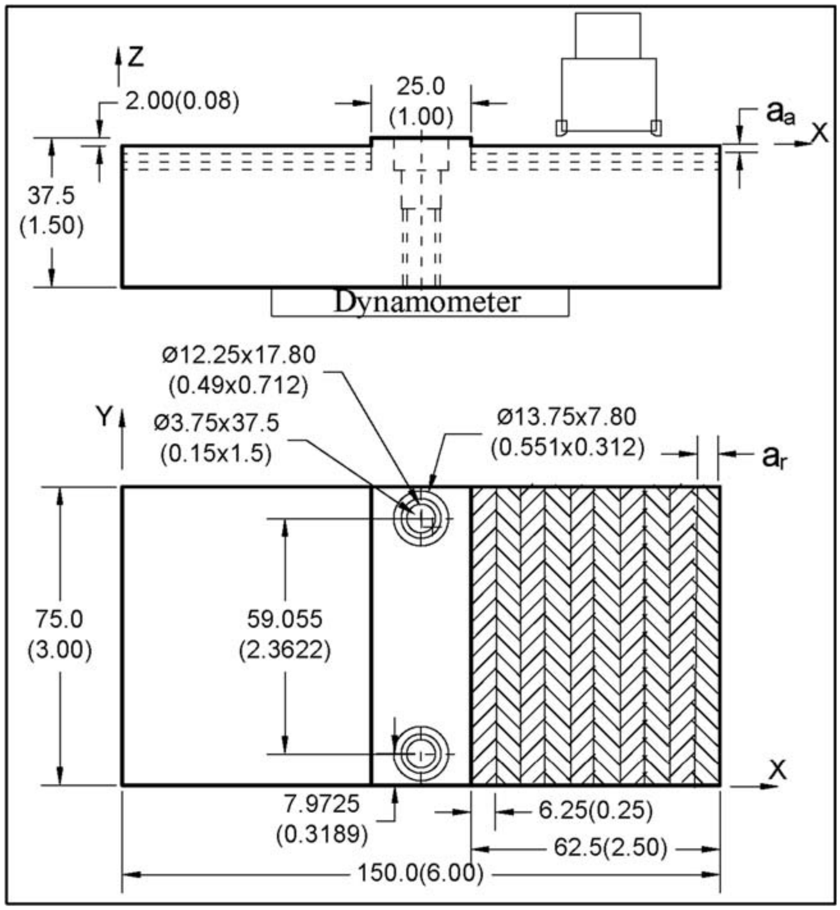


Fig. 2 Workpiece dimensions and experimental setup. All dimensions are in millimeter (in.)

(F_X, F_Y, and F_Z) for HOSO-based MQL oil flow rates and emulsion flood cooling strategy. In all the experiments, it is shown that perpendicular to feed force component F_X is the largest in all captured cutting force components followed by the feed force F_Y and least is the axial force F_Z. This phenomenon is typical of the down-milling method and it is due to the clockwise rotation of the tool and direction of the table feed, which is in the same direction as the tool drives into the workpiece, and hence highest resistance to chip formation occurs in the X-coordinate (perpendicular to the feed direction). The axial direction experiences the least resistance in down-milling chip formation and it is due to the constant axial depth along the length of cut during face milling. The feed and axial force components remained constant at about 100 N and below 100 N respectively during machining for all experiments until termination of experiments. HOSO-based MQL flow rate of 10 ml/h is shown in Fig. 6a; cutting force F_X increases gradually from 200 to 245 N at the 4th pass before a rapid increase of force and vibration is observed. In Fig. 6b–e, an increase in flow rate reduced the initial cutting force at the 1st pass below 200 N and increased gradually beyond the 4th pass. This is likely due to the amount of aerosol and size of atomized oil droplets formed reaching the cutting zone for oil flow rate above 10 ml/h. In Fig. 6e, the cutting force increased rapidly after the 5th pass. BUEs after the 5th pass led to large flank wear due to its removal during the intermittent impact of the insert during face milling and hence large cutting force compared to flow rates

Table 3 Fatty acid composition and physical properties of HOSO

Veg. oil	Fatty acid percentage composition (%)					Physical properties			
	Saturated		Mono-unsaturated	Poly-unsaturated		Color	Flash point (°C)	Iodine value	Water solubility
	Palmitic (C16:0)	Stearic (C18:0)	Oleic (C18:1)	Linoleic (C18:2)	α-Linolenic (C18:3)				
HOSO	5.9	4.32	74.5	7.5	2.13	Light yellow	325	86.4	Insoluble

Table 4 Thermo-physical properties of emulsion coolant and modified HOSO at 25 °C

Lubricating/cooling fluid	Viscosity (mPa s)	Thermal conductivity (W/mK)	pH value
Emulsion coolant	1.08	0.698	9.2
Modified HOSO	47.71	0.192	–

at 30 to 70 ml/h. Increasing HOSO-based MQL oil flow rate increases its number of machining pass achieved but also led to excessive BUEs as observed at 90 ml/h. The type of mist distribution and droplet sizes formed are likely the reasons for these differences in performance under different oil flow rates during HOSO-based MQL face milling [20, 26]. Figure 6f shows the emulsion flood cooling strategy under the down-milling method; the cutting force component F_X increases gradually up to the 14th pass. This is possible due to the fluidity of emulsion and the amount of power exerted on the fluid during emulsion flood cooling strategy machining, providing the needed lubrication layer in the cutting zone. The thermal conductivity of the emulsion coolant is also an added advantage of emulsion flood cooling strategy when machining Inconel 718. Heat formed in the cutting zone is easily removed during chip formation and hence reducing chip affinity to the tool surface and preventing any form of excessive BUEs which will normally increase cutting force component F_X drastically once the BUEs are removed by the intermittent engagement of milling operations.

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{1}$$

3.1.3 Resultant cutting force analysis of modified HOSO at varying oil flow rates and emulsion flood

Figure 7 shows a comparison of resultant cutting force components under HOSO-based MQL and mineral oil–based emulsion flood cooling strategies from the 1st machining pass to the final machining pass, where tool life is reached or exceeded. It was observed that all HOSO-based MQL flow rates and emulsion flood have a gradual increase in the resultant cutting force until close to and just before the final pass where a drastic increase in resultant force is observed similar to the maximum cutting force component F_X. Figure 8 shows a comparison of the resultant cutting force for the 1st to the 5th machining passes. It was observed that resultant cutting forces at 10 ml/h HOSO-based MQL flow rate are significantly higher from pass 1 to the 5th pass than those of flow rates at 30, 50, 70, and 90 ml/h, while MQL oil flow rate at 70 ml/h gave the lowest resultant cutting force among all HOSO-based MQL flow rates and emulsion flood cooling strategy. This is due to insufficient thin lubrication film around the cutting edges during face milling of Inconel 718 at 10 ml/h, leading to high cutting friction and abrasive wear in the cutting zone. At tool life criterion of 0.35-mm normal flank wear VB, the resultant cutting forces generated at 30 to 90 ml/h are equal and comparable in magnitude with those generated under mineral oil–based conventional emulsion flood cooling strategy. This shows that HOSO-based MQL can provide a comparable lubricating surface provided by the environmentally unfriendly emulsion flood cooling supplied at high volume and pressure. Insufficient lubrication is the primary cause of high resultant cutting force components during machining, and the heat generated and accumulated around the cutting edge is the primary cause of tool wear and tool failure in face milling of Inconel 718 using coated inserts. Enough lubrication film can be provided by applying HOSO-based MQL at flow rates of 30, 50, and 70 ml/h without the negative effect of large BUEs or large droplet sizes leading to excessive insert wear. Large BUEs can easily be sheared/pulled when the insert impacts the workpiece, leading to rapid insert surface wear. The major limiting factor is the low thermal conductivity of HOSO-based MQL in effectively replacing mineral oil–based emulsion flood cooling fluid in face milling of Inconel 718 using coated carbide inserts.

3.2 Tool wear and tool life analysis

3.2.1 Tool wear

Figure 9 shows the plot of tool flank wear versus machining time for HOSO-based MQL flow rates and emulsion flood cooling. Three regions of tool wear are shown, namely rapid initial tool wear, uniform tool wear rate, and accelerated tool wear rate for HOSO-based MQL flow rates and emulsion flood cooling. The rapid initial tool wear region is the region where the sharp cutting-edge wears rapidly at the beginning of

Table 5 Chemical composition of Inconel 718

Element	Ni	Cr	Fe	Nb	Mo	Ti	Al	Co	Cu	Mn	Si	C
Wt%	53.67	18.70	17.72	4.83	2.85	.92	.58	.24	.12	.10	.08	.03

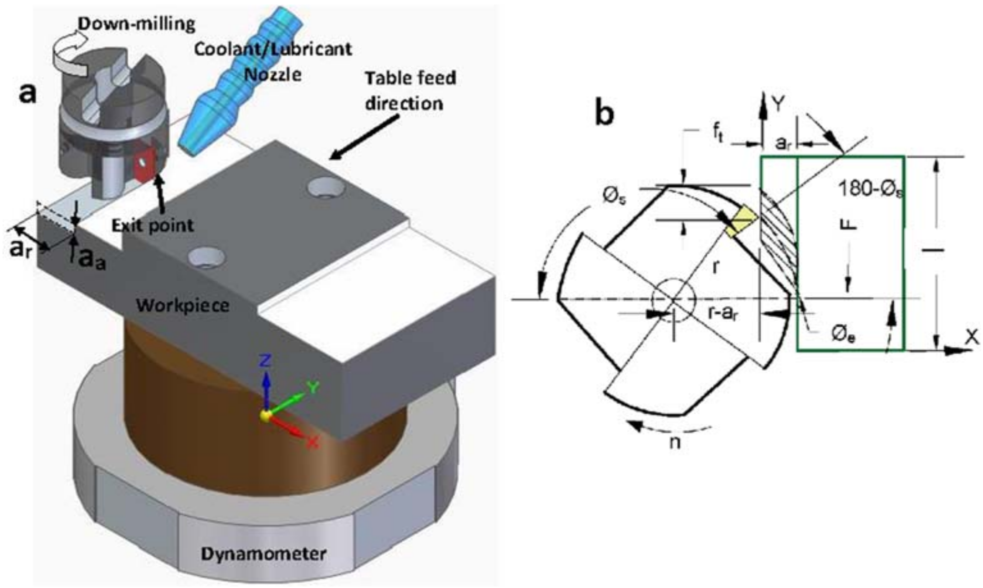


Fig. 3 Setup drawing of down-milling (**a** 3D view, **b** 2D schematic (Øs—entry angle and Øe—exit angle))

its use. At this stage, the carbide coatings are worn out around the edges of the inserts, which takes a few minutes of cutting. All the cooling strategies investigated are observed to have a comparable rapid initial wear rate. A uniform or gradual tool wear region, which tends to follow a linear trend, is dependent mainly on the cooling strategy and MQL flow rate applied. The shortest uniform wear duration occurred under the HOSO-based MQL flow rate of 10 ml/h. The shortest duration is likely due to insufficient cooling and lubrication at the cutting zone during machining of Inconel 718, which is closest to dry machining. The shortest regular tool wear duration observed is likely due to the largest abrasive wear caused by high friction at the cutting zone, which leads to notch wear and increases tool wear rate and lower tool life. HOSO-based MQL at 90 ml/h flow rate is observed to have a longer regular tool wear region than HOSO-based MQL of 10 ml/h flow rate but shorter than MQL at flow rates of 30, 50, and 70 ml/h. This phenomenon is likely due to mist distribution and large size of atomized HOSO droplet formed during atomization [27, 28]. Non-uniform mist distribution and large size of

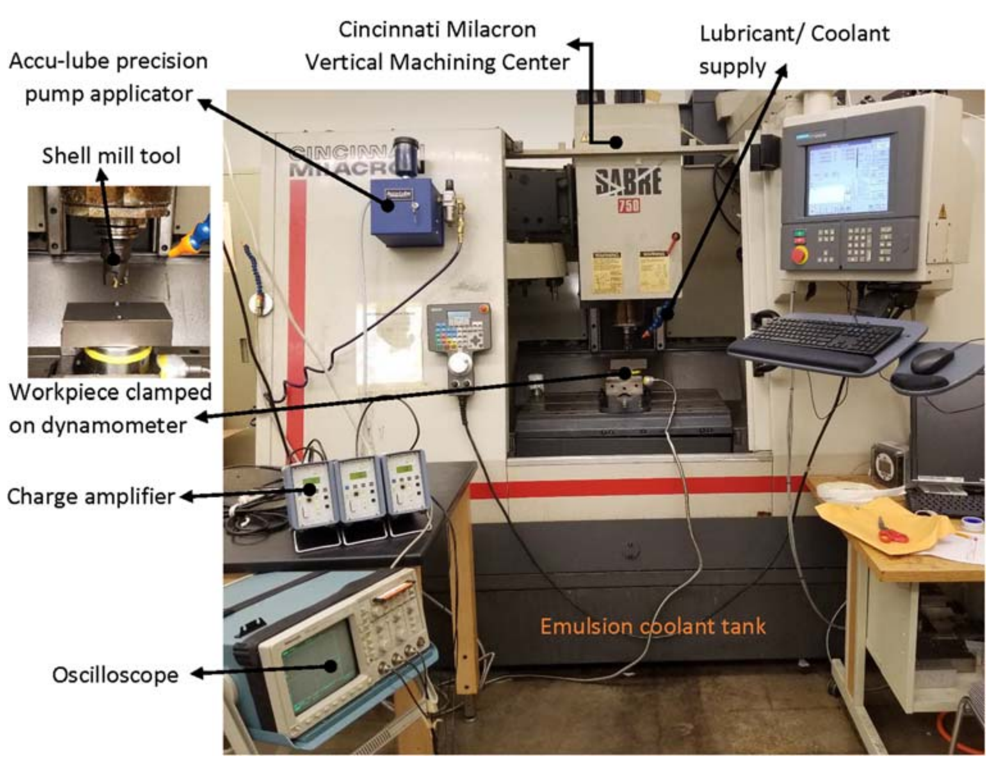


Fig. 4 Photograph of the experimental setup with emulsion flood cooling, modified HOSO-based MQL, and cutting force data acquisition system

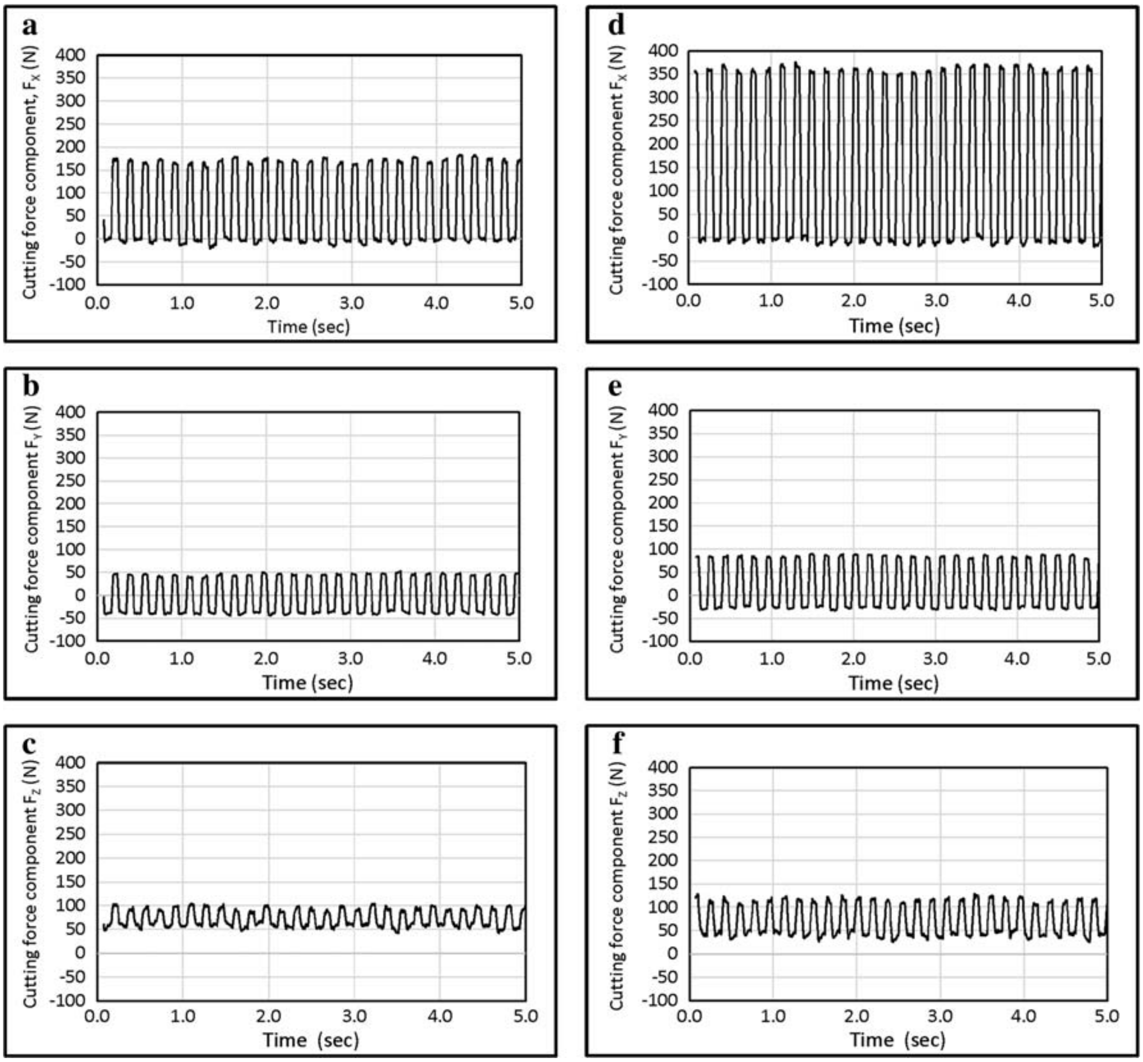


Fig. 5 Cutting force signal versus acquisition time for HOSO-based MQL at 10 ml/h flow rate at the 1st pass (**a** F_X—perpendicular to feed force, **b** F_Y—feed force, **c** F_Z—axial force) and 5th pass (**d** F_X—perpendicular to feed force, **e** F_Y—feed force, **f** F_Z—axial force)

droplet formed are not easily penetrated the cutting zone and cause excessive lubrication film not easily sheared and act as heat storage within the cutting zone. In addition, the internal friction between layers of the thick film increases the heat generated leading to the formation of excessive BUEs, high tool wear rate, and short tool life. HOSO-based MQL at 30, 50, and 70 ml/h provided enough thin lubrication film that reduces friction without acting as heat storage in the cutting zone and produces a longer uniform tool wear region compared to 10 and 90 ml/h flow rates. A combination of lower abrasive wear and initial protection of small BUEs can explain this longer protection of inserts during face milling of Inconel 718. Figure 10 shows tool wear of inserts at the 5th machining pass for HOSO-based MQL flow rates and mineral oil–based emulsion flood cooling. As observed, increasing the HOSO-based MQL flow rate reduces tool wear and protects tool surface by providing enough thin lubrication film but also leads to chip affinity and formation of large BUEs as the MQL flow rate reaches 90 ml/h. The right amount of oil flow rate and air pressure will help in the formation of effective uniform mist distribution and the size of oil droplets that provide enough thin film lubrication without increasing the internal friction or act as heat storage due to thick film lubrication leading to high internal friction and heat generation. Mineral oil–based emulsion flood cooling has a uniform tool wear duration like that of the HOSO-based MQL flow rate at 70 m/h. The accelerated tool wear region is the final region where tool failure occurs. The region duration increases with an increase in the MQL flow rate from 10 to 70 ml/h. Mineral oil–based emulsion flood cooling is observed to have longer accelerated tool wear duration compared to MQL flow rates except at 70 ml/h, which is similar. This is probably due to the high volume, high fluidity, and high pump pressure application forcing a lubricating layer into the cutting zone. In

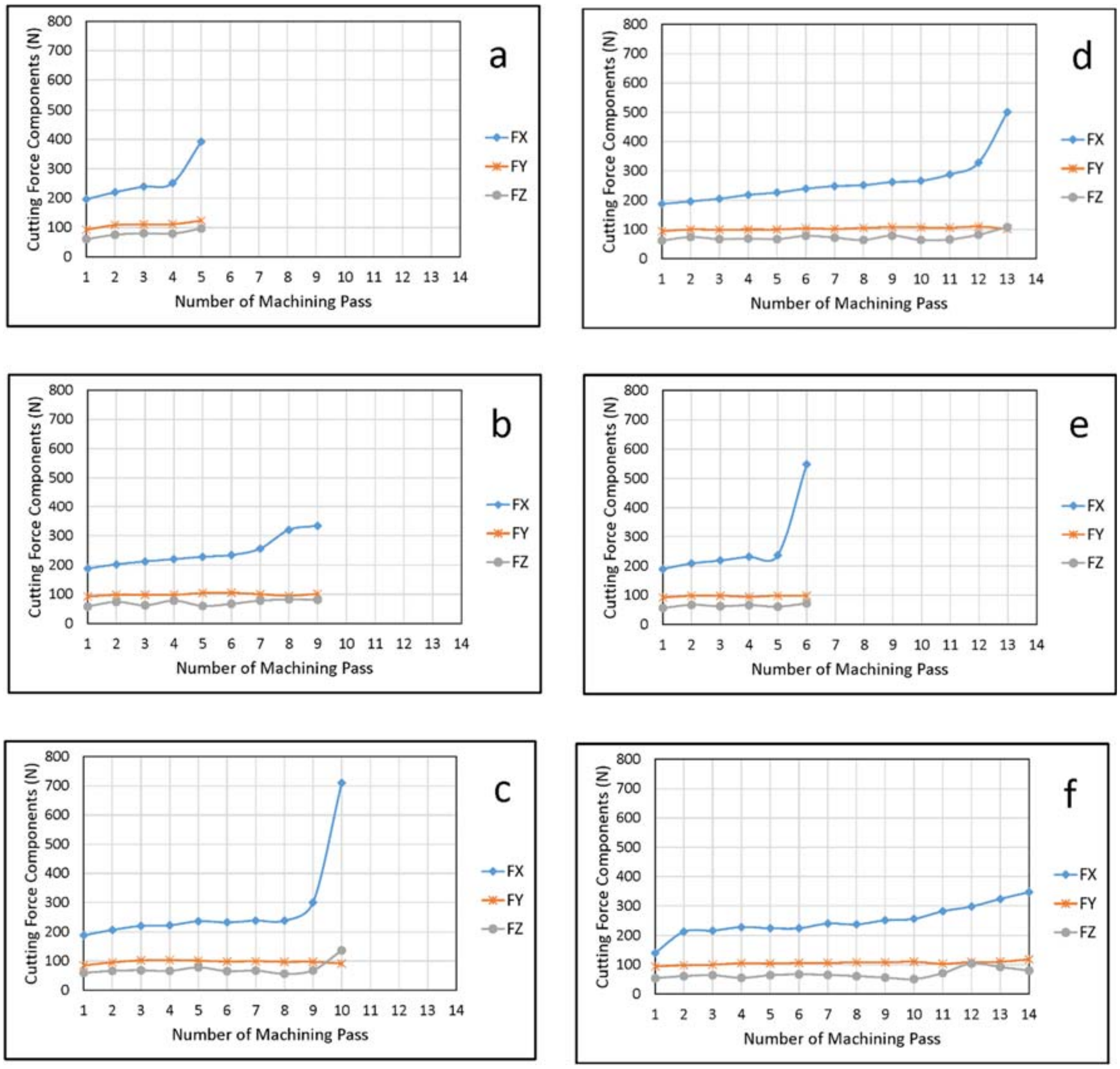
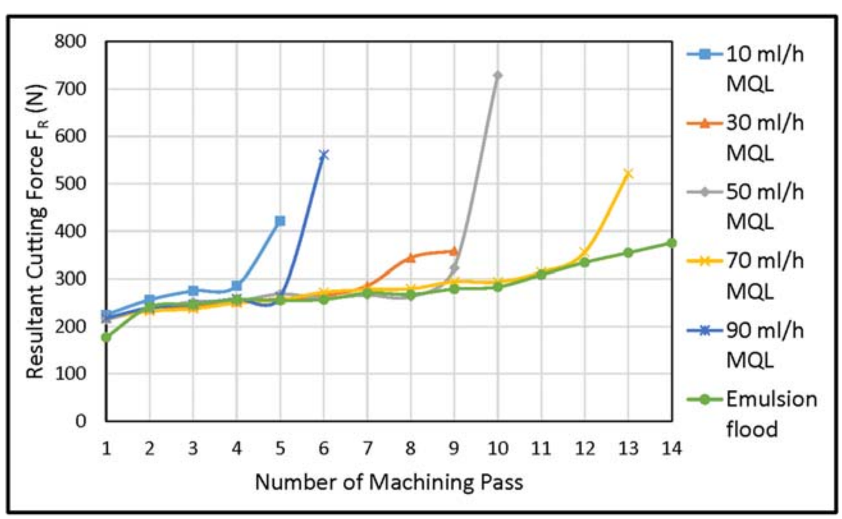


Fig. 6 Cutting force components vs. machining pass under cooling-lubrication strategies (**a** 10 ml/h MQL, **b** 30 ml/h MQL, **c** 50 ml/h MQL, **d** 70 ml/h MQL, **e** 90 ml/h MQL, and **f** emulsion flood cooling)

Fig. 7 Resultant cutting force versus machining pass from the 1st to final pass



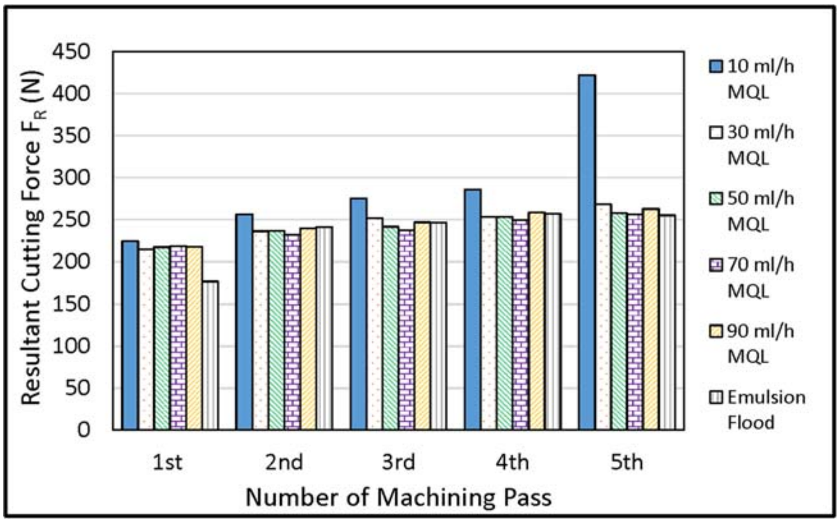


Fig. 8 Resultant cutting force versus machining pass from the 1st to 5th

addition, the high pH value and higher thermal conductivity of mineral oil–based emulsion flood cooling compared to HOSO-based MQL contribute to reducing cutting temperature and the formation of excessive BUEs. Unlike increasing the oil flow rate in MQL, the fluidity of emulsion flood cooling allows heat generated to travel and hence dissipation of the generated heat. Therefore, emulsion flood cooling fluid does not act as heat storage but heat removal. At lower HOSO-based MQL flow rates, tool wear mechanism is predominantly abrasion due to large surface friction, while at higher HOSO-based MQL flow rate, tool wear mechanism is adhesion due to excessive BUE formation. BUE formation was not observed in mineral oil–based emulsion flood cooling due to the higher thermal conductivity of emulsion flood cooling compared to HOSO-based MQL. The high temperature in the cutting zone leads to softening of the insert material leading to either large flank wear or BUEs that are easily pulled when the cutter impacts the workpiece. Similar BUEs are also reported by Ozbek and Saruhan [29] when turning of AISI D2 steel using an oil flow rate of 150 ml/h. The effect of the formation of large BUEs is worsened in milling due to the intermittent operation and impact of the tool with the workpiece.

3.2.2 Tool life

Figure 11 shows the tool life of emulsion flood cooling and HOSO-based MQL oil flow rates determined using maximum normal flank wear criterion, VB, of 0.35 mm for face milling of Inconel 718. Tool life was calculated based on the length of time the tool wear curve crosses or reaches 0.35-mm maximum normal flank wear (VB). HOSO-based MQL flow rate of 10 ml/h gave the shortest tool life of 12.36 min and tool failure occurred before any other cooling strategy investigated. The longest tool life of 32.31 min was observed for the HOSO-based MQL oil flow rate at 70 ml/h. This is due to the effective thin lubrication film and penetration into the cutting zone both in the uniform and accelerated tool wear regions. Mineral oil–based emulsion flood cooling strategy gave the

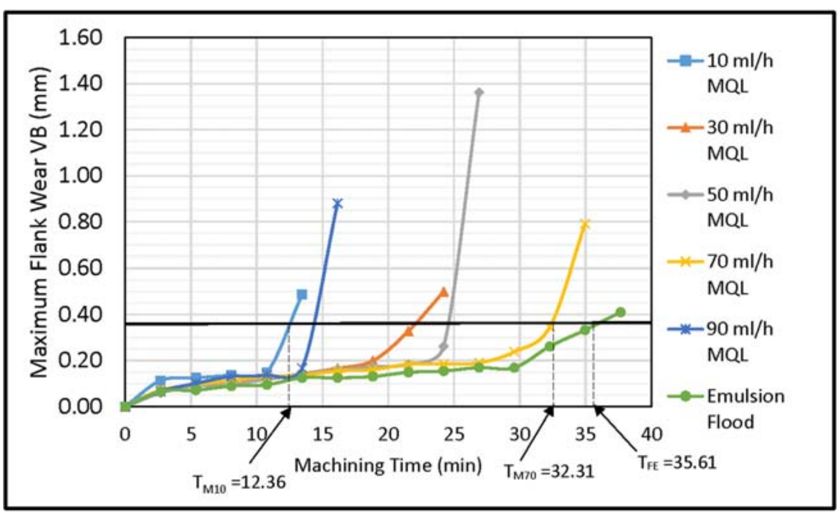


Fig. 9 Maximum flank wear vs. machining time under cooling-lubrication strategies (T_{M10}, tool life at 10 ml/h MQL; T_{FE}, tool life at emulsion flood)

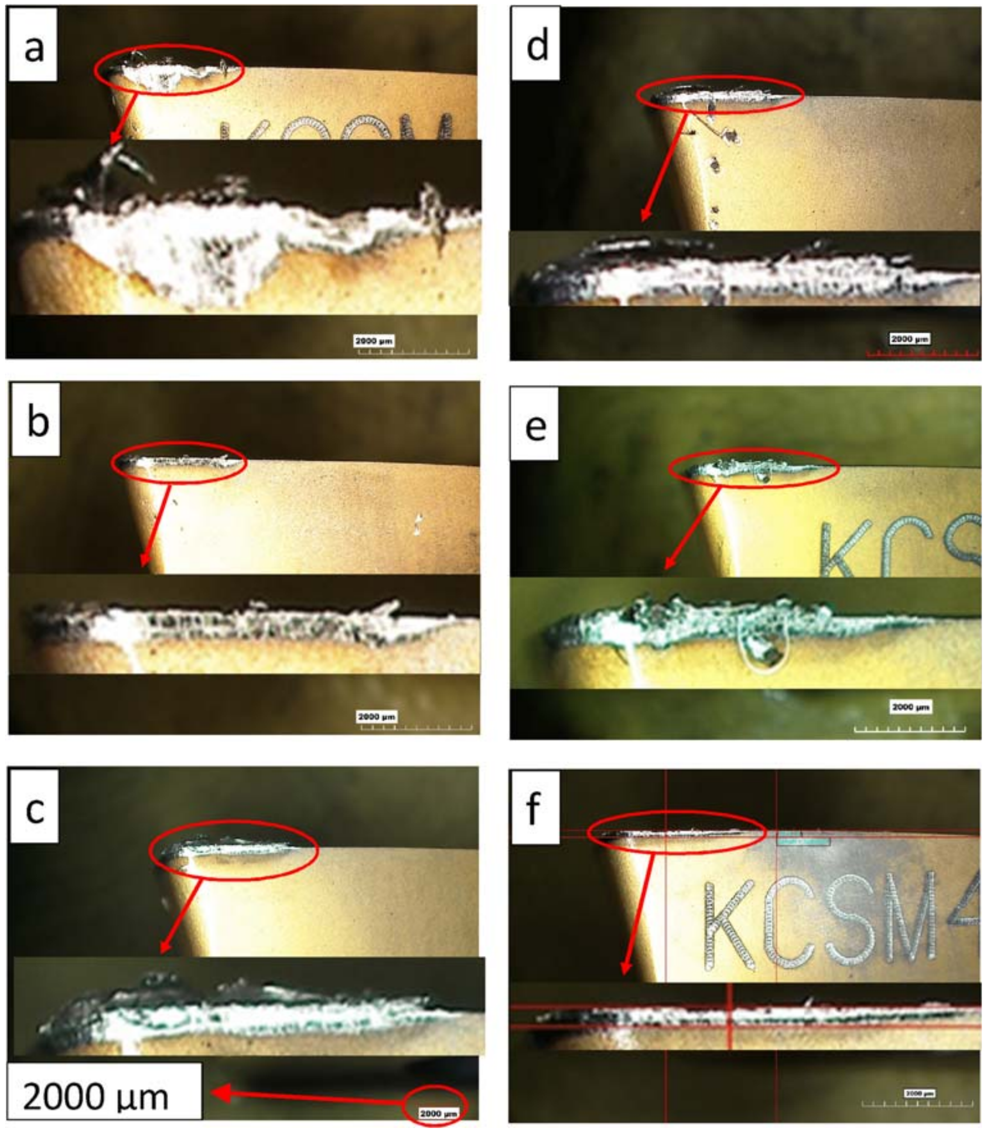


Fig. 10 Tool wear at the 5th pass (**a** 10 ml/h MQL, **b** 30 ml/h MQL, **c** 50 ml/h MQL, **d** 70 ml/h MQL, **e** 90 ml/h MQL, and **f** emulsion flood)

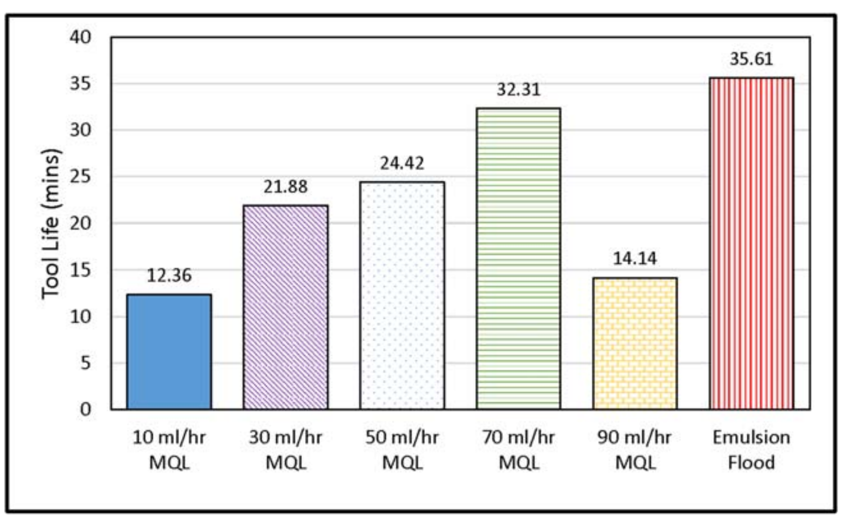


Fig. 11 Tool life at maximum normal flank wear VB 0.35 mm

longest tool life of 35.61 min compared to all HOSO-based MQL flow rates investigated.

3.3 Surface roughness analysis

The average surface roughness plots of the face-milled Inconel 718 workpiece using coated carbide inserts under HOSO-based MQL oil flow rates and mineral oil–based emulsion flood cooling strategy are shown in Fig. 12. The average surface roughness is shown in the longitudinal and traverse to the feed directions. As can be observed from the surface roughness plot, surface roughness perpendicular to the feed direction is higher than that in the feed direction. This is due to the feed lines and pulling action of the chips away from the metal surface during chip formation. Surface roughness improves with an increase in the HOSO-based MQL oil flow rate. This is due to the large surface of the lubricating film between the tool and workpiece interfaces. HOSO-based MQL oil flow rate of 10 ml/h gave the highest surface roughness of 0.45 and 1.21 μm in the longitudinal and traverse directions respectively. Surface roughness for MQL flow rates at 30, 50, 70, and 90 ml/h is not significantly different from each other in the traverse and longitudinal directions and is all below 0.8 μm, but flow rates at 70 and 90 ml/h gave the best surface roughness of 0.67 μm in the traverse direction, and 0.35 and 0.33 μm in the longitudinal direction respectively. Emulsion gave the best overall surface roughness of 0.32 and 0.5 μm in the longitudinal and traverse directions, respectively, and this is likely due to the lubricating layer provided by the high pump pressure of the emulsion coolant and its higher thermal conductivity compared to vegetable oil in conducting the heat away from the cutting zone and reducing the welding of workpiece to the insert.

Thus, we propose a hypothesis that higher viscosity and thermal conductivity of vegetable oil can be improved by the addition of nanoparticles to the base vegetable oil to obtain nanofluid, which will translate to lower cutting forces, lower cutting temperature, lower tool wear, and longer tool life. This nanofluid will surpass the performance of mineral oil–based conventional emulsion flood cooling strategy and serves as its replacement and probably reduces the amount of oil flow rate needed in the MQL machining strategy.

4 Conclusions and future work

The results show that MQL-modified high oleic soybean oil is a promising environmentally friendly, sustainable, biodegradable alternative and a potential replacement for mineral oil–based emulsion flood cooling strategy fluid for face milling of difficult-to-cut materials like Inconel 718. From the results, the following conclusions can be made: MQL soybean oil flow rate at 70 ml/h gave the lowest resultant cutting force due to a combination of effective thin lubrication and lower storage of heat in the cutting zone and is recommended for face milling of Inconel 718 with coated carbide insert under down-milling. Surface roughness improves with an increase in MQL soybean oil flow rate. Flow rates at 70 and 90 ml/h gave the best surface roughness of 0.67 μm in the traverse direction, and 0.35 and 0.33 μm in the longitudinal direction respectively due to low cutting force and vibration, and also the large surface of the lubricating layer and reduces tool and workpiece contacts.

Increasing MQL soybean oil flow rate reduces tool wear and protects tool surface by providing enough thin lubrication film but also leads to chip affinity and formation of large BUEs as the oil flow rates reach 90 ml/h. At lower MQL soybean oil flow rates, tool wear mechanism is predominantly abrasion, while at higher MQL soybean oil flow rates, tool wear mechanism is adhesion due to large BUE formation. The increase in oil flow rate leads to larger oil aerosol droplets which act as heat storage.

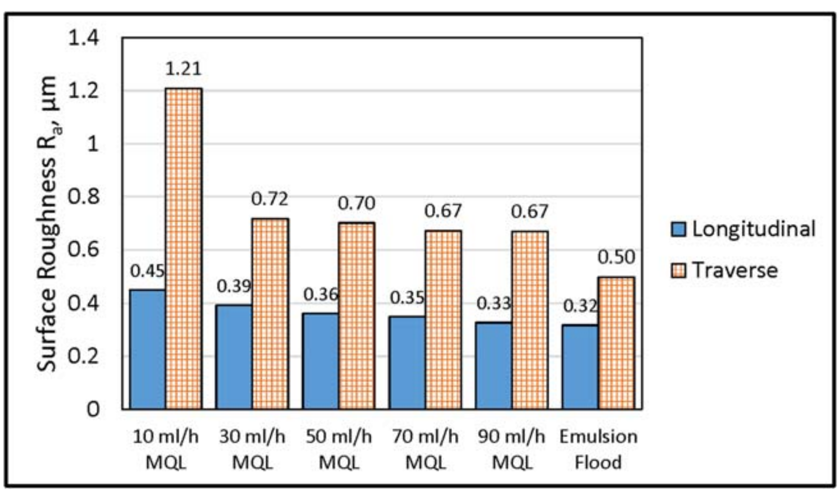


Fig. 12 Surface roughness under different MQL flow rates and emulsion flood cooling

HOSO-based MQL flow rate at 70 ml/h gave the longest tool life of 32.31 min, comparable with that of mineral oil–based emulsion flood cooling with a tool life of 35.61 min, while HOSO-based MQL flow rate of 10 ml/h gave the shortest tool life of 12.36 min and tool failure occurred before any other cooling strategy investigated. The thermal heat dissipation ability of emulsion flood cooling and fluidity gives it an edge above HOSO-based MQL oil flow rate at 70 ml/h.

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References

1. Ezugwu EO, Bonney J, Yamane Y (2003) An overview of the machinability of aeroengine alloys. J Mater Process Technol
2. Ning J, Nguyen V, Liang SY (2019) Analytical modeling of machining forces of ultra-fine-grained titanium. Int J Adv Manuf Technol 101:627–636. https://doi.org/10.1007/s00170-018-2889-6
3. Okafor AC, Sultan AA (2016) Development of a mechanistic cutting force model for wavy-edge bull-nose helical end-milling of inconel 718 under emulsion cooling strategy. Appl Math Model 40:2637–2660. https://doi.org/10.1016/j.apm.2015.09.040
4. Ning J, Liang SY (2019) A comparative study of analytical thermal models to predict the orthogonal cutting temperature of AISI 1045 steel. Int J Adv Manuf Technol 102:3109–3119. https://doi.org/10.1007/s00170-019-03415-9
5. Kara F, Aslantaş K, Çiçek A (2016) Prediction of cutting temperature in orthogonal machining of AISI 316L using artificial neural network. Appl Soft Comput J 38:64–74. https://doi.org/10.1016/j.asoc.2015.09.034
6. Ezugwu EO, Bonney J (2004) Effect of high-pressure coolant supply when machining nickel-base, Inconel 718, alloy with coated carbide tools. J Mater Process Technol 153–154:1045–1050. https://doi.org/10.1016/j.jmatprotec.2004.04.329
7. Mia M, Ranjan N (2018) Effects of duplex jets high-pressure coolant on machining temperature and machinability of Ti-6Al-4V superalloy. J Mater Process Technol 252:688–696. https://doi.org/10.1016/j.jmatprotec.2017.10.040
8. Cetin MH, Ozcelik B, Kuram E, Demirbas E (2011) Evaluation of vegetable based cutting fluids with extreme pressure and cutting parameters in turning of AISI 304L by Taguchi method. J Clean Prod 19:2049–2056. https://doi.org/10.1016/j.jclepro.2011.07.013
9. Kumar K, Suvin PS, Vasu S, Ravi M (2019) Hard machining performance of indigenously developed green cutting fluid using flood cooling and minimum quantity cutting fl uid. J Clean Prod 206:108–123. https://doi.org/10.1016/j.jclepro.2018.09.178
10. Okafor AC, Jasra PM (2018) Effects of cooling strategies and tool coatings on cutting forces and tooth frequency in high-speed down-milling of Inconel 718 using helical bull-nose solid carbide end mills. Int J Adv Manuf Technol 97:2301–2318. https://doi.org/10.1007/s00170-018-2096-5
11. Kang MC, Kim KH, Shin SH et al (2008) Effect of the minimum quantity lubrication in high-speed end-milling of AISI D2 cold-worked die steel (62 HRC) by coated carbide tools. Surf Coat Technol 202:5621–5624. https://doi.org/10.1016/j.surfcoat.2008.06.129
12. Zhang S, Li JF, Wang YW (2012) Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions. J Clean Prod 32:81–87. https://doi.org/10.1016/j.jclepro.2012.03.014
13. Liao YS, Lin HM (2007) Mechanism of minimum quantity lubrication in high-speed milling of hardened steel. Int J Mach Tools Manuf 47:1660–1666. https://doi.org/10.1016/j.ijmachtools.2007.01.007
14. Park KH, Suhaimi MA, Yang GD et al (2017) Milling of titanium alloy with cryogenic cooling and minimum quantity lubrication (MQL). Int J Precis Eng Manuf 18:5–14. https://doi.org/10.1007/s12541-017-0001-z
15. Hadad M, Sadeghi B (2013) Minimum quantity lubrication-MQL turning of AISI 4140 steel alloy. J Clean Prod 54:332–343. https://doi.org/10.1016/j.jclepro.2013.05.011
16. Sharma J, Sidhu BS (2014) Investigation of effects of dry and near dry machining on AISI D2 steel using vegetable oil. J Clean Prod 66:619–623. https://doi.org/10.1016/j.jclepro.2013.11.042
17. Kaynak Y (2014) Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining. Int J Adv Manuf Technol 72:919–933. https://doi.org/10.1007/s00170-014-5683-0
18. Shaikh VA, Scharf TW, Boubekri N (2017) Microlubrication machining of 1018 steel: the effect of a biodegradable lubricant on the microstructural integrity. Lubr Sci 29:357–376. https://doi.org/10.1002/ls.1373
19. Li KM, Lin CP (2012) Study on minimum quantity lubrication in micro-grinding. Int J Adv Manuf Technol 62:99–105. https://doi.org/10.1007/s00170-011-3789-1
20. Tawakoli T, Hadad MJ, Sadeghi MH (2010) Influence of oil mist parameters on minimum quantity lubrication - MQL grinding process. Int J Mach Tools Manuf 50:521–531. https://doi.org/10.1016/j.ijmachtools.2010.03.005
21. Sadeghi MH, Haddad MJ, Tawakoli T, Emami M (2009) Minimal quantity lubrication-MQL in grinding of Ti-6Al-4V titanium alloy. Int J Adv Manuf Technol. https://doi.org/10.1007/s00170-008-1857-y
22. Pervaiz S, Rashid A, Deiab I, Nicolescu CM (2016) An experimental investigation on effect of minimum quantity cooling lubrication (MQCL) in machining titanium alloy (Ti6Al4V). Int J Adv Manuf Technol 87:1371–1386. https://doi.org/10.1007/s00170-016-8969-6
23. Sharma AK, Tiwari AK, Dixit AR (2016) Effects of minimum quantity lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: a comprehensive review. J Clean Prod 127:1–18
24. Okafor AC, Ertekin YM (2000) Vertical machining center accuracy characterization using laser interferometer. Part 1. Linear positional errors. J Mater Process Technol 105:407–420. https://doi.org/10.1016/S0924-0136(00)00662-2
25. Okafor AC, Nwoguh TO (2020) A study of viscosity and thermal conductivity of vegetable oils as base cutting fluids for minimum quantity lubrication machining of difficult-to-cut metals. Int J Adv Manuf Technol 106:1121–1131. https://doi.org/10.1007/s00170-019-04611-3
26. Rahim EA, Dorairaju H (2018) Evaluation of mist flow characteristic and performance in minimum quantity lubrication (MQL) machining. Measurement 123:213–225. https://doi.org/10.1016/j.measurement.2018.03.015

27. Maruda RW, Krolczyk GM, Feldshtein E et al (2016) A study on droplets sizes , their distribution and heat exchange for minimum quantity cooling lubrication (MQCL). Int J Mach Tools Manuf 100: 81–92. https://doi.org/10.1016/j.ijmachtools.2015.10.008
28. Park K, Olortegui-yume J, Yoon M, Kwon P (2010) A study on droplets and their distribution for minimum quantity lubrication (MQL). Int J Mach Tools Manuf 50:824–833. https://doi.org/10.1016/j.ijmachtools.2010.05.001
29. Özbek O, Saruhan H (2020) The effect of vibration and cutting zonetemperature on surface roughness and tool wear ineco-friendly MQL turning of AISI D2. J Mater Res Technol. https://doi.org/10.1016/j.jmrt.2020.01.010