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ORIGINAL ARTICLE

Minimum quantity lubrication advantages when applied to insert flank face in milling

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Abstract This study compares tool life and surface roughness in milling of X100CrMoV5 mold steel for different lubrication conditions: dry machining, minimum quantity lubrication (MQL) through inner channels oriented to insert rake face, and MQL through inner channels oriented to insert flank face. It was proven that the tool life using MQL to flank face is increased by about 28.5% compared to dry cutting and about 11% compared with MQL to rake face. The improvement was proved to be a consequence of better lubrication on tool/chip and tool/workpiece interfaces. In fact, applying MQL to flank face generated longer and thinner chips compared to MQL applied to rake face and dry machining due to a lower friction effect. Additionally, SEM analysis revealed that MQL to insert flank face reduced the amount of adhesion materials compared to MQL on rake face and dry machining. Thus, this work shows that MQL applied through inner channels to insert flank face in milling can provide significant improvements in the cutting tool wear rate and/or productivity of cutting tool.

Keywords Minimum quantity lubrication · Surface roughness · Rake face · Flank face · Chip

1 Introduction

Minimum quantity lubrication (MQL) consists in spraying oil mist with pressurized air, in order to lubricate the cutting zone [1]. Studies by several authors have been focused on the parameters that may affect MQL effectiveness. In fact, oil choice is very important; Duchosal et al. [2] compared three different oils on a static setup and high viscous oil led to the most efficient MQL oil in terms of oil consumption, particle size, and velocity. Nanofluid addition can improve further the effectiveness of MQL. Zhang et al. [3] investigated MQL grinding of Ni-based alloy with different concentrations of nanofluids with molybdenum disulfide (MoS_2), carbon nanotubes (CNTs), and their mixtures (MoS_2-CNTs). Results showed that given the same mass fraction, MoS_2-CNTs achieved lower grinding force ratio G and surface roughness than MoS_2 and CNTs. Eight percent of MoS_2-CNTs was the optimum concentration for nanofluid MQL in the experiment towards friction coefficient and *Ra*. Sharma et al. [4] investigated a new nanofluid prepared by mixing Al_2O_3 nanoparticles in conventional cutting fluid at different concentrations. Machining performance is examined in turning workpiece of AISI 1040 steel using MQL technique. Results reveal that Al_2O_3 nanofluid reduced cutting force up to 59.1, 29.2, and 28.6% compared to dry, conventional mist, and wet machining, respectively.

One of the most important parameters that may affect MQL effectiveness is the choice of mixing device. Kurgin et al. [5] compared the performance of single and dual-channel MQL for reaming spool bores in automotive aluminum transmission valve body. Results showed that dual-channel MQL system performed better than the single channel MQL system in terms of surface roughness, diameter precision, surface temperature rise, and spindle power.

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After selection of the oil and mixing device, we need to take care of the setting parameters on the generator, settings of air flow rate, oil flow rate, and air pressure. In fact, Kamata and Obikawa [6] studied the impact of air pressure and oil flow rate of MQL for two different grades on tool life in turning Inconel 718. Results showed that increasing oil flow rate led to increase tool life with the first coating (TiCN/AL_2O_3/TiN) but did not improve surface finish. In contrast, with the second coating (TiN/AlN superlattice), an increase in the quantity of lubricant in MQL cutting did not extend the tool life but improved surface finish slightly. However, increasing air pressure from 0.4 to 0.6 MPa led to decrease tool life for both studied grades. Park et al. [7] studied the distribution of oil droplets to determine the MQL optimal pressure. Results showed that higher nozzle pressure provided the more droplets but the smaller droplets were obtained. It has been determined that smaller the droplets diameter is, higher content of active compounds in the tribofilms formed on the machined surface leading lo larger intensity of the lubricating film formation. Iskander et al. [8] investigated milling of carbon fiber-reinforced plastics with MQL. Results showed that optimum MQL spray can be achieved with the combination of a high air flow rate and low oil flow rate. This combination promotes the breaking mechanism of the droplets, providing good atomization, and large number of small droplets at high axial velocity.

Other authors tried to increase the performance of MQL by using cooled air. This method is called minimum quantity cooling lubrication (MQCL) or cooled air with MQL (CAMQL). Zhang et al. [1] found that MQCL cutting with biodegradable vegetable oil can effectively improve the machinability of Inconel 718, such as extension of tool life and reduction of cutting forces comparing to dry machining. Saberi et al. [9] studied the effect of cold air jet by using vortex tube in MQL technique on surface grinding performance. For this purpose, CK45 soft steel was ground under three coolant-lubricant environments including dry, fluid, and CAMQL. Results show that heat transfer coefficient of CA and CAMQL are very close to each other implying less importance of lubricant in cooling (just about 5%). Also, at high thermal power (200 W), air pressure is a more important factor than temperature in cooling process.

Other studies focused their researches on MQCL with emulsion mist with phosphate ester-based EP/AW additives [10–12]. Maruda et al. [11] found that wear of the inserts using MQCL EP/AW method is reduced by about 40% compared to dry cutting and about 25% compared with MQCL in finish turning of AISI 1045 carbon steel.

To summarize, there are lots of parameters to take into consideration in an MQL study: right selection of the oil, the best additives, the recommended device, and the setting of the device. Moreover, it is necessary to pay close attention to the manner of supplying the MQL to the cutting zone.

Recent studies focused on spraying MQL through the tool by inner channels [13]. This process provides small distance from the outlet channels to the cutting edge with better locations and orientations compared to usual external nozzles that are less reliable [14]. With tools having inner channels, each tool has its own internal channels and the machining area is not cluttered by external nozzles. But which face (rake face or flank face) do we have to lubricate? And is the lubricant able to penetrate to the interfaces tool/chip or tool/workpiece? Several suggestions have been advanced in this regard:

- Fluid may fully penetrate the interface tool/chip thanks to capillarity network between chip and tool, gap created by vibrations, voids with built-up edge formation, and chemical action (diffusion, evaporation, chemical reaction…) [15, 16].
- Fluid may partially penetrate to the interface due to the contact imperfections (roughness); neither gaseous nor liquid lubricants can reach 100% real contact region [17].
- No fluid penetrates nor remains in this interface due to the “perfect” chip and tool contact zone due to very high contact pressure (up to 3 GPa between the chip and the tool). Fluids cannot penetrate to the interface; it only contributes to reduce contact length [18].

Several authors propose the idea that the cutting fluid can penetrate to the interface but cannot remain there [17, 19, 20], especially in continuous machining like turning (high engagement time). In this particular process, the continuous chips prevent the oil mist spraying on the cutting edges. Hence, it is important to establish the oil mist supplying method in which oil mist reaches to the cutting edges successfully. In intermittent cutting like milling (low engagement time), oil droplets penetrate easily into the cutting edges leading to lower friction and lower contact length [21, 22]. MQL process efficiency is ensured when applied to flank face. The lubricant simply penetrates the tool/workpiece interface which leads to a better surface roughness.

Some studies have focused on MQL applied to flank face conveniences compared to rake face lubrication. In a turning process, equivalent tool life was observed with dry cutting as spraying MQL to rake face regardless of the feed rate. But better tool life was obtained when MQL was sprayed on the flank face when turning 100Cr6 steel [23] and better surface finishing was obtained when turning 4140 steel [21].

Applying MQL to the flank face is rather simple with external nozzles. But as explained above, better quality and tool life are achieved with inner MQL channel. The adaptation of turning tools with inner channels oriented to the flank face is quite simple because of the single insert and the fixed tool. Copper plate was added for spraying the flank face for turning machining [6] with different rates (30% on the rake face and 70% on flank face) or for grooving [24]. However, adapting a milling tool for lubrication on the body is more complex than turning. The milling tool is rotating and has several inserts. The MQL flow is subjected to face a big shear in the channels.

There are lots of studies about MQL machining in turning and milling. Commonly, the MQL is applied to insert rake face. Few articles investigate the influence of MQL when applied to rake face compared to flank face lubrication in turning (continuous machining). This study tends to evaluate the effect of MQL when applied to flank face in milling (intermittent machining).

To sum up, there are lots of studies investigating MQL in turning and milling. Commonly, the MQL is applied to insert rake face. Few articles investigated the influence of MQL when applied to rake face compared to flank face lubrication in turning (continuous machining). These articles showed that better results were obtained in terms of tool life and surface finishing when applying MQL to flank face in turning compared with rake face. But there is a lack of knowledge concerning the impact of MQL when applied to flank face compared to rake face lubrication in milling (intermittent machining). Therefore, the aim of this article is to study the influence of the MQL to rake face (RF) and flank face (FF) separately on surface integrity. A milling prototype was tested to compare the results of machining with MQL applied on both RF and FF separately and dry machining on X100CrMoV5 steel alloy. The effects of lubrication configurations were analyzed in terms of tool life, surface roughness, chips shape, and thickness.

2 Experimental materials and measurements

The workpiece material used for the experiments was X100CrMoV5 steel alloy used in molding application. The chemical composition is presented in Table 1. Blocks derive from the same casting. All the cutting tests were performed on a computer numerical control (CNC) machine tool Hermle C40. The oil mist was generated by an external mixing device (Lubrilean Digital Super device developed by SKF). The 32-mm-diameter milling tool was a prototype from Sandvik Coromant with three carbide inserts with inner canalizations oriented on rake face (standard tool). Some changes were made on the same tool and the insert in order to lubricate flank face (special design) (Fig. 1). Rake face and flank face can be lubricated separately. Mechanical procedure was used to spray MQL either on rake face or on flank face separately. Machining tests were carried out with one RCKT 12 04 M0-PH 4240 insert type. The PX5130 totally biodegradable tested oil from total was synthetic polyolester base oil with sulfur and phosphorous additives. This high viscous oil ($80\ \mathrm{mm\ s^{-2}}$) has a density of $930\ \mathrm{kg\ m^{-3}}$ and a flash point higher than 300 °C. This specific oil has the capacity to maintain small particles in a micro lubrication process through inner channels [2]. This oil led to a better surface roughness as shown in previous studies with the same cutter and same material [25]. Finishing cutting conditions were considered as in mold steel machining used in industrial configurations (Table 2).

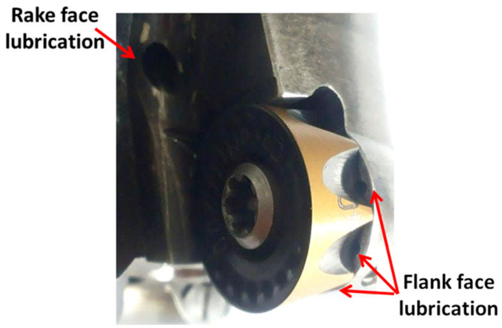


Fig. 1 Tool coolant channels to lubricate rake face and flank face

The experimental procedure consisted in controlling tool flank wear and machined surface roughness after every machined layer (1.22 min of contact material) until reaching a flank wear of 0.3 mm. It is the common tool life time limit recommended by tool manufacturers. Flank wear was measured under a magnification device and surface roughness was controlled with a Mahr perthometer.

Table 1 Chemical composition of the X100CrMoV5

Composition given by Thyssen	C	Si	Mn	P	S	Cr	Mo	V
Containing (in wt%)	1	0.3	0.70	≤0.025	≤0.025	5.3	1.1	0.20

3 Results and discussion

3.1 Tool life results

Tool life was evaluated for dry machining, machining with MQL applied to rake face (MQL RF) and machining with MQL applied to flank face (MQL FF). Every test was repeated three times to have a mean value of tool life.

During the machining tests, two different maximal wear zones were observed on the flank face: wiper zone and $a_{p\ \max}$ zone, as shown on Fig. 2a.

Table 2 Cutting conditions

Cutting velocity v_c (m/min)	Feed rate f_z (mm/rev)	Cutting depth a_p (mm)	Radial engagement a_e (% of tool diameter)
135	0.38	2	70

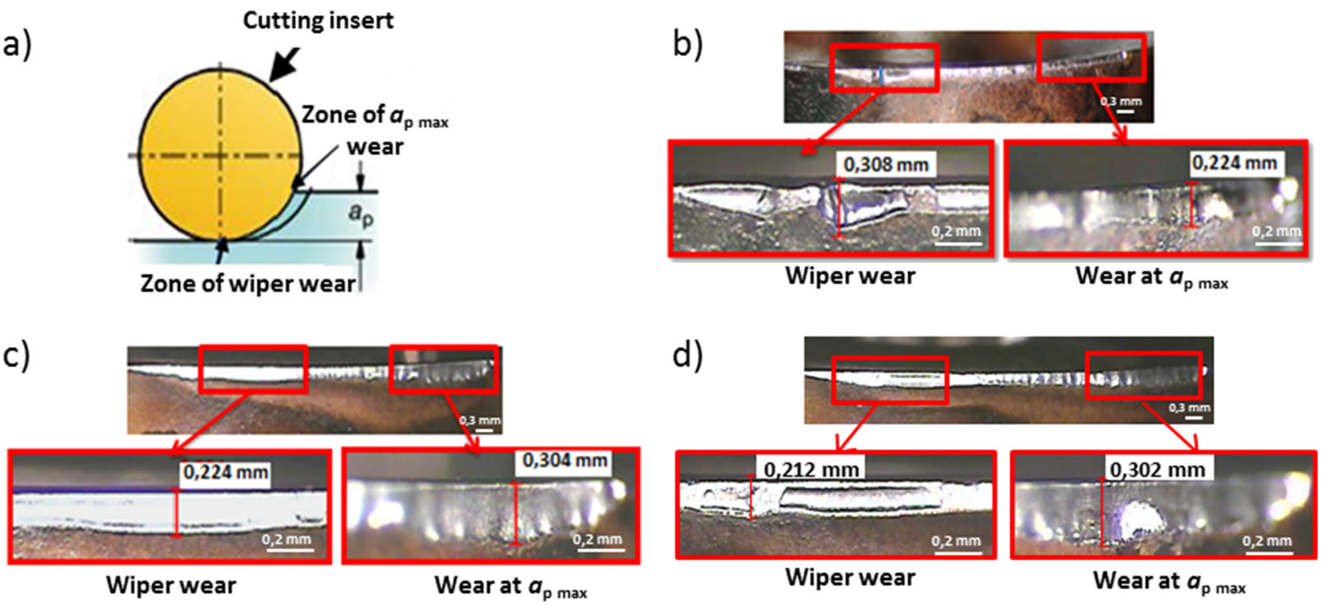


Fig. 2 **a** Zones of wear on a round cutting insert; flank wear at the end of tool life under optical microscope after **b** dry machining, **c** machining with MQL applied to rake face, and **d** machining with MQL applied to flank face

In MQL RF and MQL FF machining, the maximal flank wear (V_b) was reached in the $a_{p\ max}$ zone (Fig. 2c, d), whereas in dry machining, the maximal flank wear was reached in the wiper zone (Fig. 2b).

Figure 3 shows both wear zones evolution during tool life tests for each lubrication process. In dry machining, both zones of wear showed a linear evolution of wear with higher coefficient (0.0115 mm/min) for wiper zone (Fig. 3a). For MQL machining (RF and FF), wear on wiper zone was linear also with a lower progression. The coefficient of wear evolution line was divided by two: 0.0063 and 0.0055 mm/min for RF and FF, respectively. However, the wear evolution at $a_{p\ max}$ zone was not linear; it became as a second order polynomial shape for both RF and FF lubrication (Fig. 3b, c).

Tool life test for each lubrication process was repeated three times and tool life duration was 14.93, 14.93, and 13.7 min for dry machining; 19.9, 18.7, and 16.2 min with MQL RF, and 19.9, 21.15, and 19.9 min with MQL FF. Calculation of average lifetime reveals a significant enhancement in tool lifetime when using MQL FF comparing to dry machining of 28.5 and 10% comparing to MQL RF.

3.2 SEM analysis

Inserts were controlled at the end of tool life under a scanning electron microscope (SEM) (Fig. 4a–c). Microanalysis of the flank face of the insert revealed the presence of high amount of adhesive materials mainly Fe and Cr for the case of dry

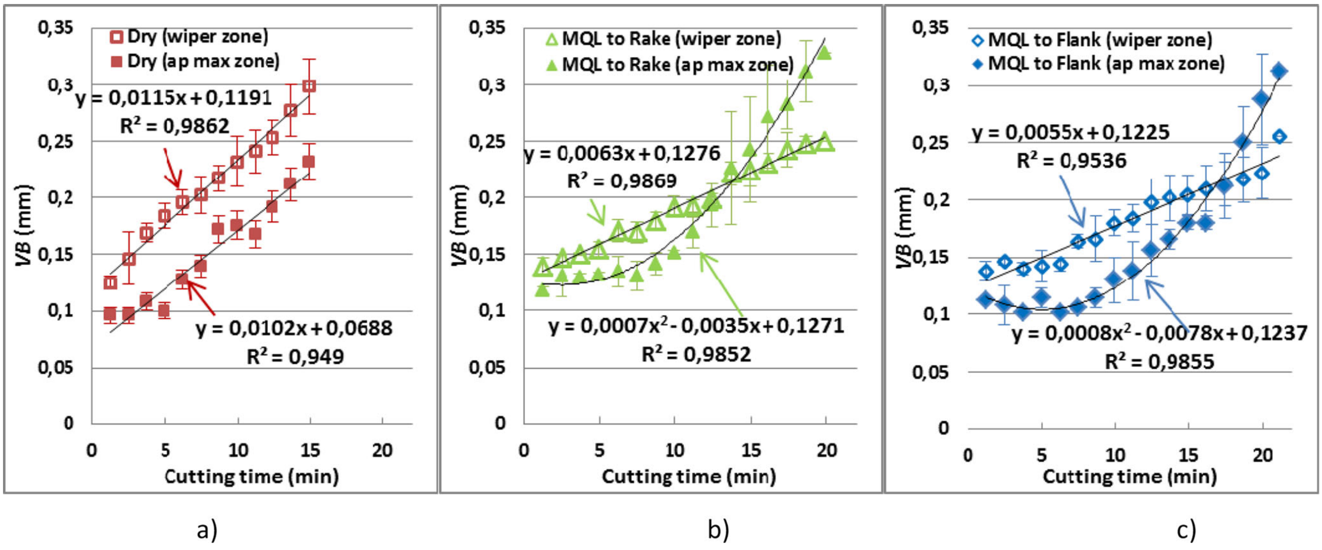


Fig. 3 Flank wear measurements after **a** dry machining, **b** machining with MQL to rake face, and **c** machining with MQL to flank face

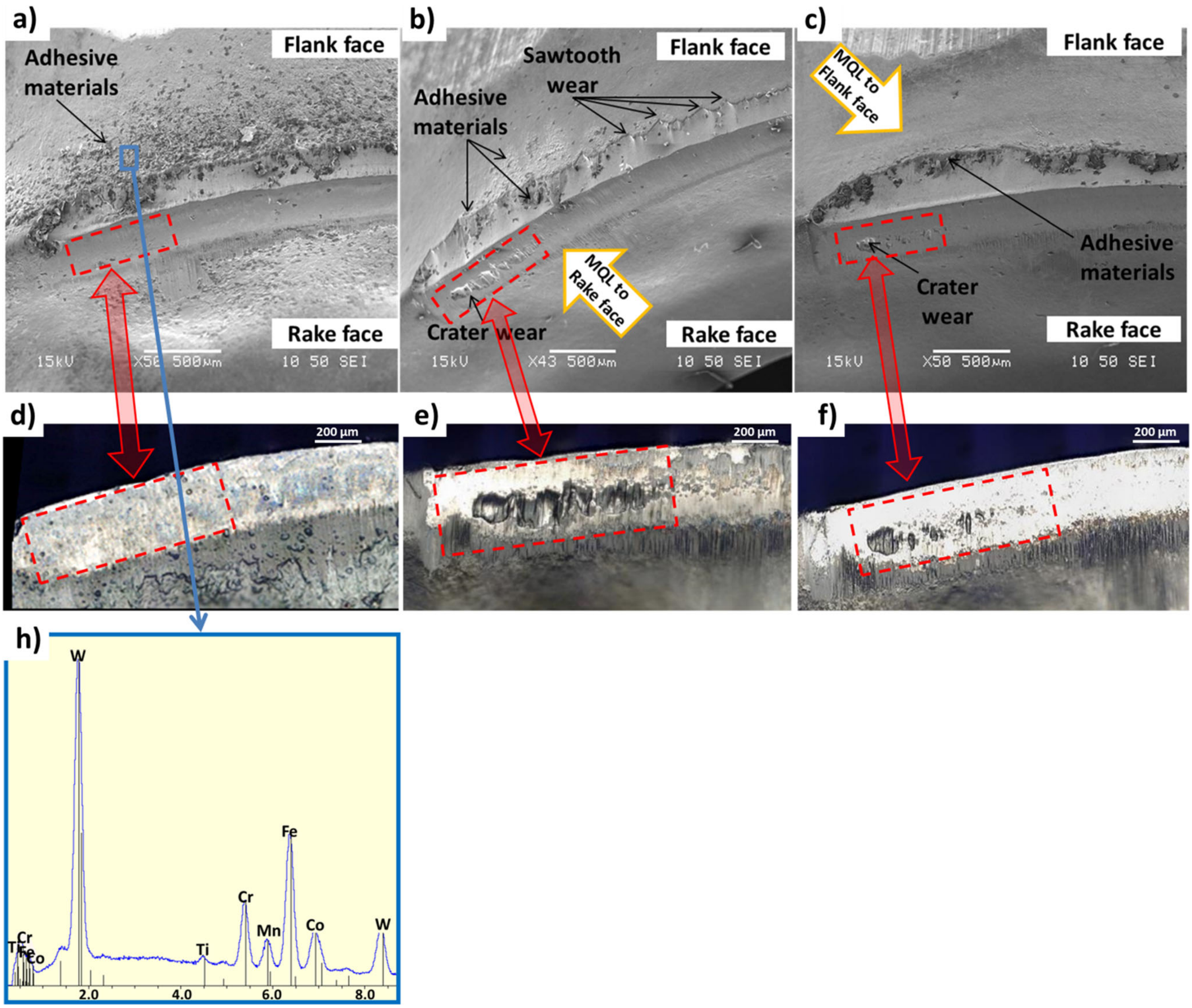


Fig. 4 Insert wear analysis at $a_{p\ max}$ zone after **a** dry machining (under SEM), **b** machining with MQL RF (under SEM), **c** machining with MQL FF (under SEM), **d** dry machining (under Keyence), **e** machining with MQL RF (under Keyence), **f** machining with MQL FF (under Keyence), and **h** microanalysis of adhesive materials

machining (Fig. 4h). Even after machining with MQL, adhesive materials were observed on the flank face but in lesser quantity with the use of MQL RF and MQL FF respectively (Fig. 4b, c). In the case of MQL RF, the flank wear had a sawtooth form. This is mainly due to the adhesive materials which removed the coating suddenly and prematurely leading to a flaking wear (Fig. 4b). However with MQL FF, the flank wear was homogenous revealing an abrasive wear (Fig. 4c). Furthermore, SEM observations revealed that insert has crater wear with MQL lubrication in $a_{p\ max}$ zone (Fig.4b, c). On the other side, with dry machining, there was no crater wear on the zone of $a_{p\ max}$ (Fig. 4a). The crater wear in dry condition can be seen only after prolongation of the lifetime test and it appeared when the flank wear on $a_{p\ max}$ zone reached 0.28 mm, which demonstrated a deep dependency of crater wear apparition and flank wear value.

Crater depth *KT*, crater width *KB*, and crater center distance from cutting edge *KM* were measured under a digital multiscan microscope VHX-5000 Keyence with magnifications of 5000× for tests with MQL at the end of tool life (Fig. 4e, f). Results are presented on Fig. 5. Crater wear showed deep similarities between MQL FF and MQL RF. Nevertheless, *KB* and *KM* were slightly lower for MQL FF comparing to MQL RF.

3.3 Results of roughness measurement

Figure 6 shows the evolution of the surface roughness for different machining conditions. As expected, the

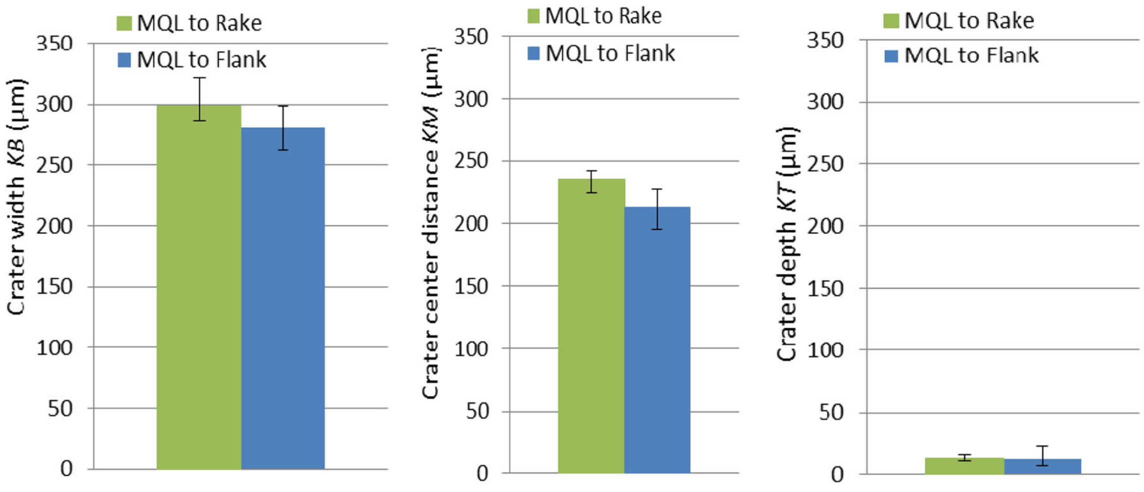


Fig. 5 Crater wear characterization

application of MQL leads to a lower roughness of machined surface. The lowest roughness *Ra* was found with MQL applied on FF. The roughness almost doubled with MQL RF and multiplied by 13 for dry machining after 15 min of time contact material. This is mainly explained by the zone of maximal wear: maximal wear in dry machining was located on the wiper zone (Fig. 2b), a non-homogeneous wear directly affecting surface roughness. The flank wear with MQL was homogeneous on the wiper zone and the maximal wear was located in the zone of $a_{p\ max}$ (Fig. 2c, d).

3.4 Discussion with chip characterization

Figure 7 shows the chips obtained under dry machining, MQL RF, and MQL FF. The shape and color of the chips were different for each environment.

The gold color of chips generated after dry machining indicated that they were colder when compared to those generated with MQL. The blue color of chips after MQL RF machining and the blue purple color of chips after MQL FF machining indicated an extreme heat exchanged into the chips (Fig. 7) [26]. Most of the heat is exchanged into the chip in

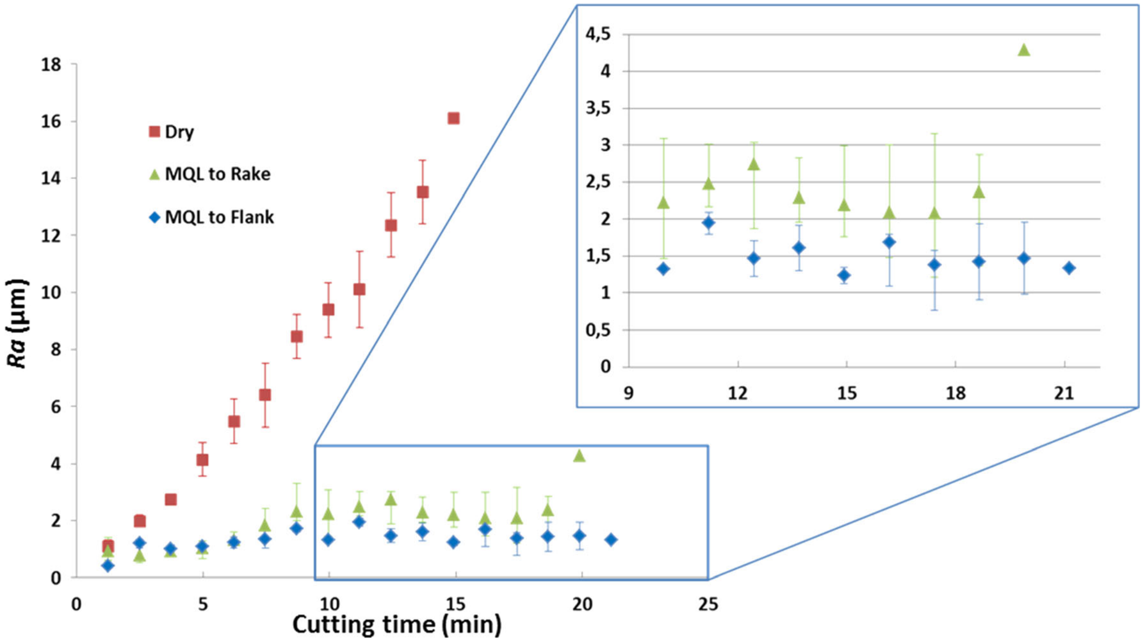


Fig. 6 Roughness of machined surface towards different machining environments

Fig. 7 Shape of the chips after different machining environments

MQL (FF and RF) and not into the tool. In fact, previous studies carried with the same tool, same oil, same cutting conditions, and same workpiece material showed that measured temperature on the cutting tool was 45% higher in dry machining compared to MQL machining [25]. To conclude, thanks to the MQL (RF or FF), the high heat generated during machining was being directed into the chip and not being kept in the insert. The temperature of the chips did not affect only chips' color but also their shape (Fig. 7).

The length and the thickness in the perpendicular plane to shear plane of the chip were measured by Keyence with magnifications of 100× and 1000×, respectively. After dry machining, chips indicated an intensive friction due to a smaller chip size (Fig. 7) compared to MQL FF and RF machining.

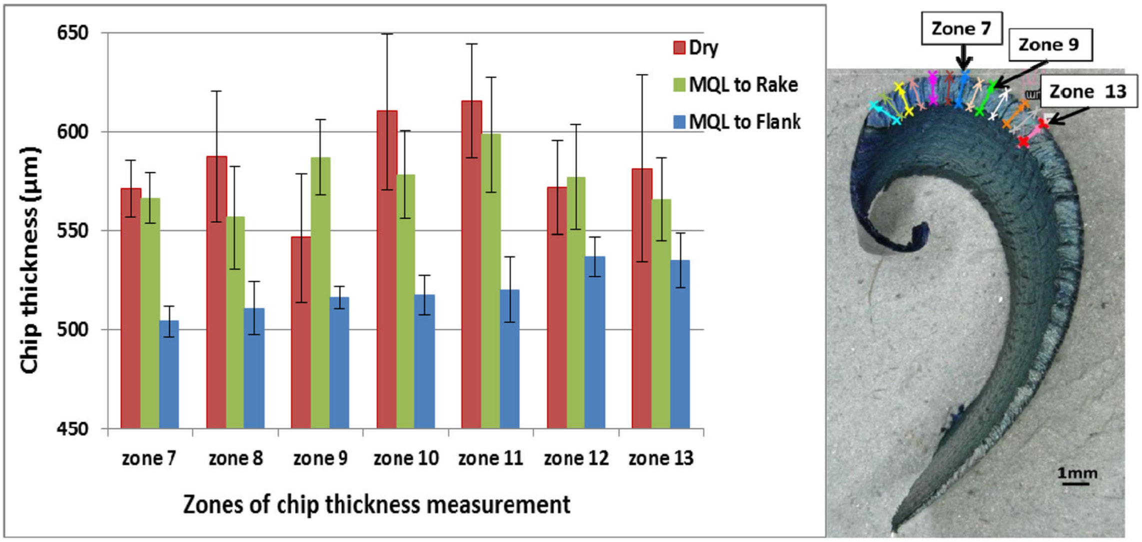
Chip thickness was measured in different zones spaced at 200 μm to find the zone of maximal thickness (Fig. 8a, b). Due to cutting conditions with 70% engagement, maximal chip thickness was located in zones 10 and 11 (at 1900 and 2100 μm). Except for the chips with MQL FF, the maximal chip thickness was located in zone 13 (at 2500 μm). Maximal chip thicknesses were compared between machining in different environments. Chips with MQL FF were 11.7 and 17.8% thinner than MQL RF chips and dry chips respectively (zone 10) (Fig. 8) highlighting the lowest friction [27].

After chemical attack of chips, further investigations were carried under Keyence with magnification of 5000×. Inclination of deformed grains Θ was measured at different depths (Fig. 9) and led to the calculation of grain equivalent deformation ε through Eq. 1 [28].

$$\varepsilon = \frac{\tan(\Theta)}{\sqrt{3}} \tag{1}$$

This analysis shows higher equivalent deformation of chip under dry machining compared with MQL RF and MQL FF. At a depth of 120 μm, grain deformation is similar between MQL RF and MQL FF. Closer to the intensively deformed zone, smaller deformation with MQL FF compared to MQL RF is observed. These results confirm that at tool/chip interface, MQL FF led to the lowest friction behavior leading to a reduced adhesion.

Furthermore, chips with MQL FF were 16.7 and 44% longer than MQL RF and dry chips, respectively (Table 3). Standard deviation was calculated from the average of five chips. In order to investigate the difference between chips



a) b)

Fig. 8 **a** Chip thickness after different machining environments. **b** controlled zones on chips

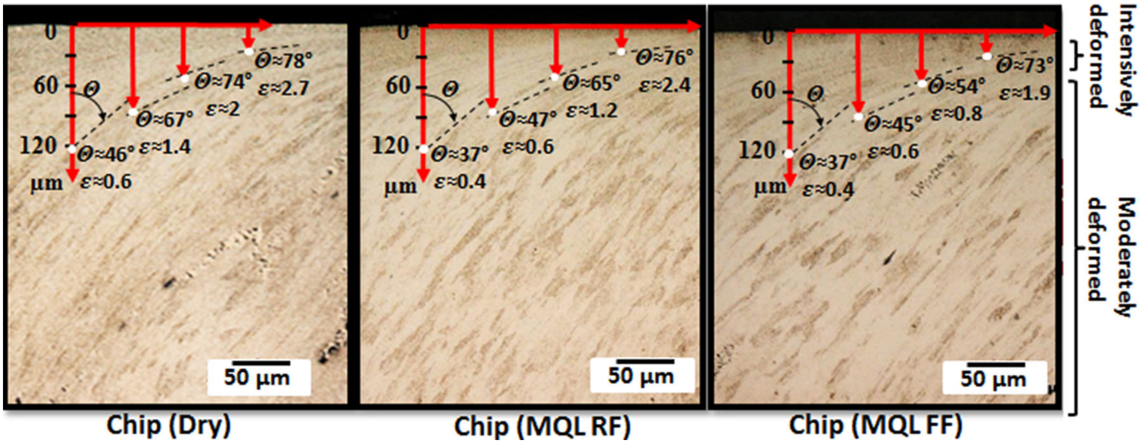


Fig. 9 Grain deformation in secondary shear zone of chips from different machining environments

while sliding on rake face, chip sliding velocity was calculated as follows:

$$V_{sc} = \frac{L_c}{t} \tag{2}$$

where L_c is the chip length and t is the cutting time per rotation.

Results are presented on Table 3. Sliding velocity of chip with MQL RF is 47.8% higher than dry, reaching 77% increase in sliding performance with MQL FF.

All of these findings could explain the better tool life while using MQL FF. MQL FF was more efficient in removing most of the heat generated at the cutting zone during machining. Under MQL FF, chips were sliding fast compared to MQL RF and dry machining. Time of heat exchange between insert and chip was short. That was observed on chips' color, very hot blue purple chips with MQL FF followed by blue MQL RF chips and gold color dry chips. Limitation of heat transmitted to the insert can provide significant improvements in the cutting tool wear rate.

Furthermore, MQL FF reduced the amount of adhesive materials on insert flank face resulting in a homogenous flank wear which could explain lower surface roughness when compared to MQL RF and dry machining.

Table 3 Chip length after machining in different environments

Machining environment	Chip length L_c (mm) (±38 µm machine error)	Standard deviation (mm)	Chip sliding velocity V_{sc} (m/s)
Dry	9.315	0.19	41
MQL RF	13.853	0.19	61
MQL FF	16.640	0.048	73

4 Conclusions

Common milling tool designs are based on rake face lubrication thanks to channels and nozzles targeting the rake face. The aim is to lubricate and to cool especially secondary heat source due to friction on the tool/chip interface. However, the results in this study showed that applying the MQL lubricant to the flank face led to even better results than applying the MQL to the rake face. In fact, applying MQL to the flank face aiming the tertiary shear zone led especially to the following:

- Increase tool life by 10% compared to MQL applied to rake face thanks to a better lubrication of flank face which led to generate a more homogeneous and progressive flank wear development
- Reduce surface roughness by 40% compared to MQL applied to rake face thanks to less adhesive materials on insert flank face and more homogenous wear
- Longer and thinner chip forming compared to MQL applied to rake face due to a lower friction effect which contributed to increase tool life
- Increase chip sliding velocity on insert rake face leading to a small time of heat exchange with the insert. Most of the generated heat is stocked in the chip and not transmitted to the insert which reduced tool wear rate

This study led to a better understanding of MQL and its effects during milling operations and highlighted the advantage from applying the MQL to the flank face. This study offers new perspectives in terms of tool design.

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