Influence of deficient cutting oil supply on machining performance during minimum quantity lubrication (MQL) assisted micro-milling

WCMNM 2021

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Abstract

Minimum Quantity Lubrication (MQL) strategy in metal cutting inherently fulfills the ever-growing demand of sustainable manufacturing through the usage of minimum volume of cutting fluid without sacrificing overall machining performance. Application of MQL in micro-milling reduces flank wear, increases overall tool life, improves dimensional accuracy of the milled features, discourages chip adherence and built-up edge formation, lowers the minimum uncut chip thickness for shearing, assists in chip evacuation, helps improving surface quality. A wide variety of oil flow rate, from as low as 1.88 mL/h to as high as 150 mL/h, was also reported in literature during MQL assisted green or sustainable micro-milling. Oil supply at higher flow rate deviates the process from sustainable one, while a lower flow rate can disadvantageously affect overall machining performance. This article first discusses the abundant, adequate, and deficient MQL oil supply conditions that arise with the variation in spindle speed. Influences of abundant and deficient oil supply on top-burr formation and surface roughness are further analyzed through slot milling on copper samples using TiAlN coated tungsten carbide micro-end mills of 0.5 mm diameter. Results are also compared with dry micro-milling to assess the influences of oil deficiency. Adequate supply of MQL oil can reduce top-burr width by 28 – 33% and surface roughness by 16 – 18% as compared to dry cutting.

Keywords: Micro-milling, MQL, Minimum quantity lubrication, Burr formation, Surface roughness.

1. Introduction

Mechanical micro-milling is a tool-based micro-fabrication process where material is selectively removed from the workpiece in the form of solid chips using a miniaturized cutting tool. The tool is rotated at a very high speed (usually higher than 10,000 rpm), while the workpiece is fed against the rotating tool at a predefined feed rate. Similar to every cutter-based machining process, there always exist solid-to-solid physical contact under high pressure and relative velocity among the chip-tool-workpiece in micro milling. Such tribo-contact scenario can be manipulated through the application of appropriate cutting fluid during machining. A number of cutting fluid delivery techniques during micro-milling were studies by different proponents. Such techniques include compressed air, chilled air, minimum quantity lubrication (MQL), flood cooling, cryogenic pre-cooling, solid lubricant, and hybrid lubrication (liquid carbon dioxide plus MQL).

Minimum Quantity Lubrication (MQL) strategy in metal cutting inherently fulfils the evergrowing demand of sustainable manufacturing through the usage of minimum volume of cutting fluid without sacrificing overall machining performance. In MQL technique, the cutting fluid is mixed with dehumidified compressed air, and the mixture is sprayed into the machining zone in the form of a jet consisting of fine oil droplets. Nozzles are employed to convert the pressure energy of the air into the kinetic energy, and hence, flowing oil droplets are obtained. Potential benefits of MQL when applied in micromilling include (i) conspicuous reduction in flank wear leading to overall increase in tool life, (ii) palpable improvement in dimensional accuracy of the milled features, (iii) less tendency of chip adherence and built-up edge formation, (iv) reduction in minimum uncut chip thickness value required for ploughing to shearing transition, (v) lesser increase in post-milling nano-hardness of the machined surface, (vi) reduction in burr size, (vii) improvement in surface finish, (viii) assistance in chip evacuation, etc. [1].

During micro-milling, a wide range of MQL oil flow rates were also reported in literature. During slot milling on SKD 61 steel using 0.6 mm diameter micro-mills, Li and Chou (2010) [2] varied lubricant flow rate from 1.88 – 7.5 mL/h. High viscous (34 cSt) vegetable oil at 350 mL/h flow rate was used by Vazquez et al. (2015) [3] for MQL assisted micromilling of Ti-6Al-4V. Mineral oil at a flow rate of 240 mL/h was delivered by Hassanpour et al. (2016) [4] during MQL assisted micromilling of Ti-6Al-4V using 0.5 mm diameter TiAlN coated tungsten carbide tools. To evaluate the role of MQL lubrication on the elastic-plastic deformation to shearing transition during micromilling of Ti-6Al-4V, Rezaei et al. (2018) [5] employed a flow rate of 15 mL/h under 6 bar air pressure. Kumar et al. (2020) [6] also varied flow rate in three levels (6, 50, and 100 mL/h) MQL assisted micromilling of Ti-6Al-4V samples using 0.5 mm diameter TiAlN coated WC tools. Working with the same set-up, the authors in an earlier work [7] assessed that 6 mL/h oil flow rate is abundant for 15,000 rpm, adequate for 25,000 rpm, and deficient for higher speeds.

Objective of the current work is to study the emergence of abundant, adequate, and deficient conditions of MQL oil supply with the variation in spindle speed; and the corresponding effect on the top-burr formation and surface roughness during sustainable micro-milling of full-immersion straight slots on copper samples using TiAlN coated tungsten carbide micro-end mills of 0.5 mm diameter.

2. Experimental details

Full immersion slots of 0.5 mm width and 5 mm long are micro-milled on commercially pure copper samples. Prior to micro-milling, samples are made flat by facing using a larger end mill of diameter 5.0 mm. Both facing and micro-milling experiments are carried out on KERN Evo CNC machining centre (KERN Microtechnik GmbH, Germany). Two-flute TiAlN coated tungsten carbide (WC/6Co) micro-milling tools (AXIS-Microtools, India) of 500 μm diameter flat-end are used for cutting micro-slots. End mills have edge radius of about 1.3 μm, helix angle of 30°, orthogonal rake angle of 13.5°, and clearance angle of 19°.

Table 1: Experimental details

Parameter	Value
Workpiece	Copper (20 × 20 × 10 mm^3)
Tool material	TiAlN coated WC/6Co
Tool feature	0.5 mm diameter, 30° helix
Spindle speed	15,000 - 45,000 rpm
Feed per flute	4 μm/flute
Axial depth of cut	40 μm
Lubrication	Dry, MQL using UNILUBE 2032
MQL system	2-nozzles, 6 mL/h oil flow rate

During MQL based sustainable micro-milling, environment friendly (biodegradable) UNILUBE 2032 cutting oil is sprayed to the cutting zone using two nozzles placed behind the tool along the tool-feed direction maintaining 45° angle with tool-feed vector at 10 mm nozzle-tool distance. The oil flow rate is kept unchanged to 6 mL/h across all the trials. During dry cutting, however, no lubricant is supplied separately. Spindle speed is varied from 15,000 – 45,000 rpm in four intervals, while the feed per flute and axial depth of cut are kept unchanged to 4 μm/flute and 40 μm. For an end-mill having 1.3 μm edge radius, ploughing-to-shearing transition for copper material is likely to occur at 0.65 μm uncut chip thickness (assuming h_{min} = 50% of r_e) [8]. Since h_{min} value is significantly lower than selected feed per flute, chip formation by each cutting edge in every tool rotation is expected to occur.

As-micromilled slots are observed under a scanning electron microscope (SEM) (EVO 18, ZEISS) to observe the top-burr. Surface area of the burr for 0.5 mm length is measured from this top view using AxioVisison software to find out the average burr width. Burrs of the up and down milling sides are reported separately. After burr measurement, the samples are ultrasonically cleaned to remove re-deposited chips from the micro-milled slots. Thereafter the slots are scanned using a non-contact type surface profilometer (CCI MP, Taylor Hobson, UK), and the scanned files are analysed using TalySurf software (Taylor Hobson).

3. Results and discussion

In full immersion micro-milling of straight slots, each cutting edge remains in physical contact with the workpiece for only half of the tool rotation. In rest 180° rotation of the tool, the same cutting edge remains disengaged from workpiece. This engagement and disengagement repeat in every revolution of the cutter, and the corresponding tool-workpiece contact duration is also independent of the number of cutting edges present within the cutter body. This disengagement period (T_{dis}) for each cutting edge for one tool rotation can be expressed in terms of spindle speed (N rpm).

In micro-milling, the cutting zone temperature usually does not exceed 100°C owing to relatively low chip load and low contact duration. Thus cutting oil predominantly acts as lubricant rather than coolant. Thus it is essential to immerse (or lubricate) entire chip-tool-workpiece contact region for harnessing perceptible improvement in machining performance owing to the application of MQL. However, MQL oil droplets do not usually possess sufficient kinetic energy to penetrate deep into the contact region. So MQL oil droplets can be directly deposited on the trailing end of the cutting edges during the 180° disengaged period by properly placing the delivery nozzle(s) behind the tool along the tool-feed direction.

$$T_{dis} = \frac{60}{2N} \qquad (1)$$

In micro end milling, a higher rotational speed (>10,000 rpm) is usually imparted on the tool in order to obtain necessary cutting velocity for efficient shearing of the material. As the rotation speed increases, the corresponding disengagement period reduces following the Eq. 1 (T_{dis} is inversely proportional to N). Since the intention is to directly deposit the MQL oil droplets on the active portion of the cutting edges during the disengagement period, lesser time is available at higher rotational speed for depositing the oil droplets. Accordingly, the micro-milling process runs in a lubricant deficient condition whenever spindle speed exceeds certain limit for given oil flow rate and air-oil MQL jet characteristics.

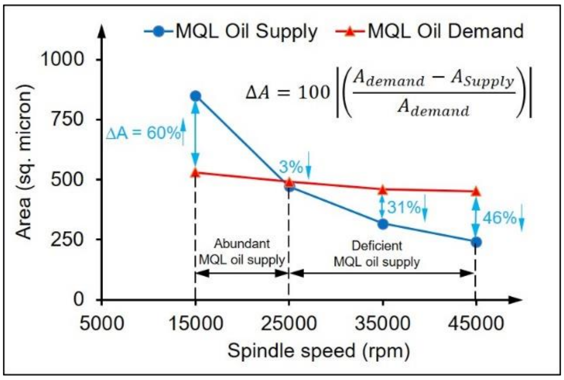

Fig. 1: Variation of MQL oil demand and supply scenario with spindle speed for constant feed of 4 μm/flute and axial dept of 40 μm; here 60% more oil is supplied at 15,000 rpm whereas 46% less oil is supplied at 45,000 rpm

In an earlier work [7], the authors determined the net intended lubricated area for each cutting edge where oil should be applied for each rotation of the end mill, and thereafter assessed the lubrication condition by tallying the number of oil droplets deposited on the active area within the disengagement period. It was observed that 6 mL/h oil flow rate is abundant for 15,000 rpm, adequate for 25,000 rpm, and deficient for higher speeds (Fig. 1). The degree of deficiency also increases proportionally with the increase in speed beyond 25,000 rpm. Since the MQL jet diameter is significantly larger than the typical feed (1 – 6 μm/flute) and axial depth of cut (10 – 200 μm) in micro-milling, these two parameters do not primarily induce lubricant deficiency. It is only the spindle speed that determines such deficient condition. To understand the influence of deficient oil supply, process output can be compared between dry and MQL cutting – both carried out under same parametric condition.

Burr is the part of workpiece material that is plastically deformed but failed to completely detach from the workpiece even after the completion of the machining. Burrs remains physically attached with the open edges of the machined feature and thus hampers dimensional accuracy and functional requirements of the finished components. In micro-milling, smooth shearing and chip formation begins only when the uncut chip thickness (h_i) is higher than a minimum uncut chip thickness (h_{min}). For $h_i \leq h_{min}$, the entire stripe of workpiece material undergoes elastic-plastic deformation that leads to lateral bending of deformed material in the form of burr. For $h_i > h_{min}$, a strip of material having thickness h_{min} undergoes plastic deformation to generate burr, while rest of the material having thickness $(h_i - h_{min})$ experiences shearing to produce micro-chips. Although Gillespie (1976) [9] categorized burrs into four types (Poisson, roll-over, tear, and cut-off burr), micro-milling burrs are usually identified based on the location of formation. As shown in Fig. 2a, top-burr that forms on the top-open-edges of both up and down milling sides are mostly Poisson burr that forms owing to the lateral deformation of the workpiece material of thickness h_{min}.

Influence of lubrication on top-burr formation can be discussed through the capability of cutting oil in altering h_{min} value. Rezaei et al. (2018) [5] showed that the h_{min} value reduced from 25–49% of r_e in dry cutting to 15–34% of r_e in MQL cutting. A lower h_{min} value reduces the volume of plastically deformed material, and thus, burr area reduces proportionally. Application of MQL cutting oil also reduces dynamic co-efficient of friction (μ) between the chip-tool interface, which, in turn help reducing the apparent friction angle (η). Malekian et al. (2012) [10] established that the h_{min} value reduces when coefficient of friction was reduced (or lubricant is applied). Accordingly, lower top-burr width is expected for MQL assisted sustainable micro-milling as compared to dry cutting. In other words, the difference in top-burr width (ΔW_B) between dry and MQL cutting is positive, and the same can be observed in Fig. 2 for all the spindle speeds. ΔW_B for up-milling side and down-milling side are reported separately.

$$\Delta W_B^{(Up)} = 100 \times \left\{ \frac{W_{B,Dry}^{(Up)} - W_{B,MQL}^{(Up)}}{W_{B,Dry}^{(Up)}} \right\} \qquad (2)$$

$$\Delta W_B^{(Down)} = 100 \times \left\{ \frac{W_{B,Dry}^{(Down)} - W_{B,MQL}^{(Down)}}{W_{B,Dry}^{(Down)}} \right\} \qquad (3)$$

A higher ΔW_B value indicates that the MQL is more efficient in reducing top-burr width as compared to dry cutting. Similarly, lower ΔW_B value indicates that the MQL is not much capable in reducing top-burr width. As shown in Fig. 2, ΔW_B is significantly higher at lower spindle speed (15,000 rpm). At this spindle speed, 6 mL/h MQL oil flow rate is about 60% abundant, and thus a significant difference in top-burr width is noticed. At 25,000 rpm speed, only marginal change in ΔW_B is observed as compared to 15,000 rpm. This is owing to the fact that MQL oil flow rate is adequate at this 25,000 rpm. Accordingly, abundant supply of MQL oil has no palpable influence in reducing top-burr formation. Considering the lubricant cost and sustainability issues, it is preferred to supply only adequate flow rate of oil rather than abundant one especially when up-milling burr formation is only under consideration. As spindle speed increases beyond this limit, the micro-milling process proceeds into a lubricant deficient region and accordingly the ΔW_B reduces steeply. In other words, deficient oil supply transforms the MQL cutting towards the dry cutting. At highest speed of 45,000 rpm, only 13% ΔW_B is observed. This indicates that the deficient supply of cutting oil can significantly reduce the extent of capability of MQL in lowering top-burr formation.

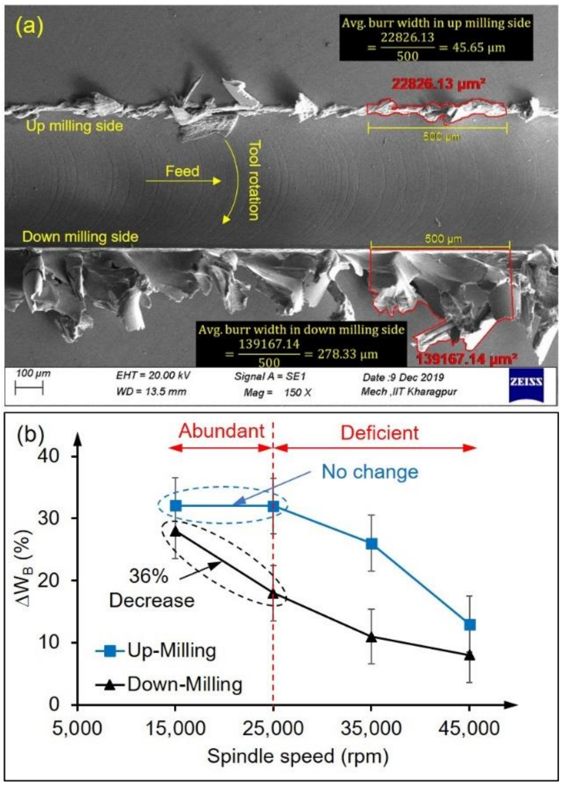

Fig. 2: (a) SEM image of a typical top-burr with its measured average width [11], and (b) variation in ΔW_B with spindle speed for up- and down-milling sides

Although a similar trend of ΔW_B variation can be observed for down-milling side (Fig. 2b), the difference values are somewhat smaller than the corresponding values for up-milling side. As mentioned earlier, both up-milling and down-milling occur one after another for each cutting edge engagement in every tool rotation. In this investigation, the workpiece feed and tool rotation directions are set in such a way that the up-milling quarter-cycle occurs initially, and the same is followed by a down-milling quarter-cycle. As MQL droplets are directly deposited on the active portions of the cutting edges during the 180° disengagement period, the initial up-milling quarter-cycle receives the well-lubricated cutting edge and thus produces better results (i.e. higher ΔW_B). A significant proportions of such MQL oil droplets flows away with chips during the up-milling quarter-cycle, and accordingly, the down-milling runs in a lubricant deficient condition. The capability of MQL strategy in lowering down-milling top-burr width also reduces owing to the lack of lubricant in the down milling side. In this regard, somewhat abundant oil supply is beneficial.

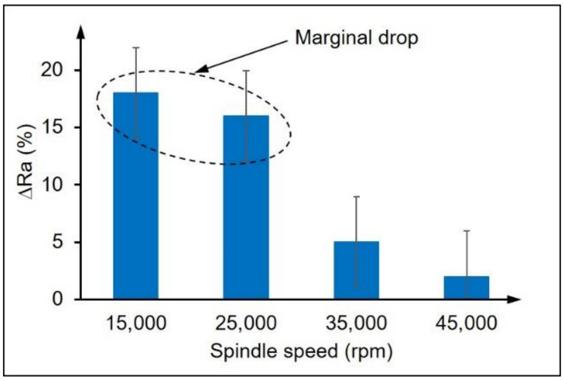

Fig. 3: Difference in surface roughness between dry and MQL assisted cutting for varying spindle speeds

Influences of optimum MQL oil flow rate on surface finish are also assessed through 2-D average surface roughness (R_a). An imaginary plane (parallel to feed direction) is first taken at the middle of the slot on the 3-D scanned file, and the R_a value is measured from the 2-D profile. It is worth mentioning that the micro-end milling process is capable of generating very smooth surfaces having R_a in the order of 8 – 25 nano-meter. To study the effects of abundant, adequate, and deficient MQL oil supply on surface roughness, the R_a values for sustainable MQL cutting are compared with that obtained in dry cutting. The difference in R_a value (ΔR_a) between dry and MQL micro-milling is calculated using Eq. 4. Similar to the burr analysis, a higher ΔR_a value indicates that the value for MQL cutting is significantly smaller than that obtained in dry cutting under similar set of process parameters. On the contrary, a lower ΔR_a value indicates that MQL is not effective enough in improving surface finish as compared to the dry cutting.

$$\Delta R_a = 100 \times \left\{ \frac{R_a^{(Dry)} - R_a^{(MQL)}}{R_a^{(Dry)}} \right\} \qquad (4)$$

As shown in Fig. 3, ΔR_a is considerably high at lower spindle speeds. At lower speeds, the oil supply lies in abundant to adequate domain, and thus MQL is more effective in conspicuously improving surface finish as compared to dry cutting. Only marginal change in ΔR_a value between 15,000 and 25,000 rpm is recorded, which indicates that the abundant supply of MQL oil is not desired. An adequate oil flow rate is enough for achieving desired lubrication effect when surface roughness is the response variable. As speed exceeds beyond 25,000 rpm, lubricant deficiency occurs, and accordingly the ΔR_a value reduces to a lower one. Thus deficient oil supply reduces the effectiveness of MQL in lowering roughness.

4. Conclusions

- Average top-burr width in both up-milling and down-milling sides is lesser for MQL assisted cutting as compared to dry cutting. At 15,000 rpm spindle speed, top-burr width is 28 – 33% lower with MQL assisted sustainable micro-milling.
- Adequate (or abundant) supply of MQL oil helps reducing top-burr width considerably. With increase in spindle speed, the MQL oil supply becomes deficient, and hence effects of MQL application cannot be perceived significantly at higher speeds. At higher speeds, top-burr width for MQL cutting gradually becomes similar to that obtained in dry cutting.
- Abundant oil supply marginally (<1%) reduces up-milling top-burr width, and thus supplying MQL oil more than adequate one is not desired. However, abundant oil supply can significantly (36%) reduce top-burr width in down-milling side. Therefore, somewhat abundant oil supply is beneficial when the intention is top-burr reduction.
- The surface roughness (R_a) in dry cutting is 18 – 16% higher as compared to that of the MQL assisted sustainable micro-milling. Abundant oil supply does not have significant effect in reducing R_a value, and thus an adequate oil flow rate (6 mL/h for 25,000 rpm) is recommended. Deficient oil supply does not provide palpable benefit in improving surface finish as compared to dry cutting.

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