Int J Adv Manuf Technol (2015) 79:1325–1334
DOI 10.1007/s00170-015-6940-6

ORIGINAL ARTICLE

Effects of minimum quantity lubricating (MQL) conditions on machining of 7075-T6 aluminum alloy

Jules Kouam · Victor Songmene · Marek Balazinski · Patrick Hendrick

Received: 2 October 2014 / Accepted: 20 February 2015 / Published online: 3 March 2015

Abstract Clean machining is gaining ground as one of the crucial issues in future manufacturing. Many machining industries are looking for alternative solutions to wet machining because of the costs of the latter, including environmental costs, as well as its impact on occupational health and safety. Dry machining is being proposed, but in most conditions, the cutting tool wears out quicker, leading to part quality deterioration and increased machining costs. Minimum quantity lubrication (MQL) machining is also proposed to maintain a reasonable tool life and limited cost, as compared to the situation with flood or wet machining. Both the MQL and dry machining methods, however, are susceptible to the generation of aerosols containing metallic particles that can be detrimental to occupational health and safety. Minimizing particle emissions is of prime importance since these can have serious consequences on the operator's health. They have been seen to be at a minimum at two specific cutting ranges. In this study, investigations are done to examine the effect of lubrication (dry and MQL) during the turning of the 7075-T6 aluminum alloy. The performance indexes studied are the surface roughness, the chip thickness, and aerosol generation.

Keywords Aluminum · Turning · Lubrication · Aerosol · Surface finish · Chip formation

J. Kouam · V. Songmene (✉)
École de Technologie Supérieure (ÉTS), Montréal, Canada
e-mail: victor.songmene@etsmtl.ca

J. Kouam
e-mail: jules.kouam@etsmtl.ca

M. Balazinski
École Polytechnique de Montréal, Montréal, Canada
e-mail: marek.balazinski@polymtl.ca

P. Hendrick
Université Libre de Bruxelles, Brussels, Belgium
e-mail: patrick.hendrick@ulb.ac.be

1 Introduction

Today, thanks to high productivity in response to growing demand, machining processes are performed at high cutting speeds. The main consequence is increased tool temperature, which can decrease the tool life and the quality of the product and increase the tool wear [1]. The use of coolants can prevent such tool deterioration. Traditionally, cutting fluids have been used to lubricate the cutting process and cool down the cutting tool. However, using cutting fluids is costly and deteriorates the working environment air quality and the environment in general. Minimum quantity lubrication (MQL) and minimum quantity coolant (MQC) machining have been proposed to reduce the negative cost effect of cutting fluids. Semi-wet machining (MQL and MQC) increases the production of liquid aerosols as compared to dry and fully wet machining. It has been shown that when machining in wet and MQL conditions, the lubricant is projected into the air and may be harmful to health [2–4].

MQL is presented as a lubricating technology that is safe, is environmentally friendly, and improves tool life and makes production more efficient [5]. Itoigawa et al. [6] showed that MQL could provide good lubrication if the appropriate lubricant is used. However, tool damage and material pickup onto the tool surface cannot be suppressed.

In their study, Damir et al. [7] showed that the application of a coolant does not necessarily reduce tool wear since at MQL conditions, there is less tool wear, but the amount of coolant determines the level of material adhesion to the tool surface. In their work, the authors [7] found that the cutting forces were dependent on the cooling application system and that improving the quality of the workpiece surface requires MQL lubrication or cooling.

Vikram Kumar et al. [8] studied the hard turning of AISI 4340 alloy steel in dry, MQL, and wet conditions. At a given feed rate, the roughness was lower under the MQL condition

Table 1 Chemical composition of 7075 alloy

Elements	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
%	0.0526	0.1053	1.3518	0.0189	2.318	0.2243	5.3536	0.015	Balance

as compared to the wet and dry conditions. The feed rate range used in the work was too narrow (0.04 to 0.06 mm/rev), and their low values were too limited to establish a good relationship between roughness and feed rate.

Another study was conducted on hard turning in dry, MQL, and wet conditions on AISI 4340 alloy steel [9]. There, the feed rate ranged from 0.05 to 0.14 mm/rev, and the maximum cutting speed was 120 m/min. The authors observed that from 0.05 to 0.1 mm/rev, the roughness was approximately similar and constant under different lubrication conditions. From 0.1 to 0.14 mm/rev, the roughness increased with the feed rate and was low under the MQL condition, as compared to wet and dry conditions.

Ozawa et al. [10] also showed that using MQL yields good results about surface roughness. Dhar et al. 2006 [11] carried out investigations on the turning of AISI 1040 steel in dry, MQL, and wet conditions, in which they studied chip formation. In that study, the feed rate ranged from 0.1 to 0.2 mm/rev, while the cutting speed ranged from 60 to 130 m/min. The authors observed that the chip reduction coefficient decreases when the cutting speed increases at different feed rates. On the other hand, the MQL condition presented the lowest chip reduction coefficient values, versus the wet and the dry conditions.

Yoshimura et al. [12] examined the adhesion of the aluminum alloy to the tool when machining. They found that the amount of adhered material is reduced as the cutting speed increases.

Sutherland et al. [13] showed that particle emission is greater when using conventional wet machining as compared to dry machining. Their work involved turning, and they [13] also showed that particle emissions increase as the cutting speed increases. Balout et al. [14] and Songmene et al. [15] found that a ductile material generates more fine and ultrafine particles than a brittle material because of the chip formation process. They also found a correlation between chip formation and particle emission. A low segmentation chip density leads to fewer particle emissions than does a high segmentation chip density. To the authors' knowledge, no work has been carried out to examine particle emissions when turning the 7075-T6 aluminum alloy under MQL conditions.

The aim of this investigation is to study MQL conditions using different flow rates as compared to dry turning of 7075-T6 aluminum alloy. The comparisons are made in a bid to choose a good lubrication solution depending on the cutting condition, and taking into account the roughness, chip formation, and metallic particle emission.

2 Experimental procedure

Turning tests were performed on 7075-T6 aluminum alloy. A typical chemical composition of this alloy is presented in Table 1. The tested workpiece was a cylinder 150 mm in diameter and 300 mm in length. The cutting tool insert used was a carbide (DNGP-432 KC5410 KENNAMETAL) with TiB2 (80° nose angle and 11° relief angle) coating.

The experiments were conducted using a CNC machine (Mazak Quick Turn Nexus 100 II M).

The experimental parameters were as follows:

- Cutting speed of 79–661 m/min
- Feed rate of 0.0508–0.2845 mm/rev
- Cutting depth of 1 mm

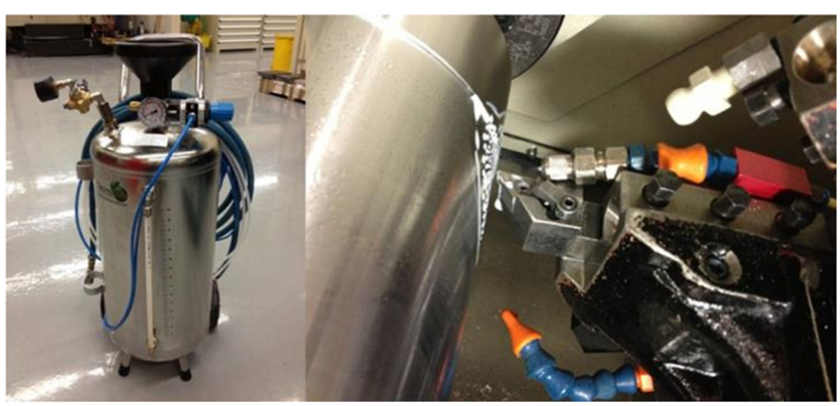

Fig. 1 Photo of pulverizing device

- Lubrication modes: dry and MQL condition using a Mecagreen 550 lubricant coolant mixed with 15 % water at 3 and 1.75 ml/min flow rate

The particle emission was monitored using an aerosol particle sizer (APS, with particle sizes ranging from 0.5 to 20 μm) which measured the particle mass concentration, the specific surface concentration, and the mass concentration against aerodynamic diameters. The Mitutoyo SJ-400 was used to measure the surface roughness.

The lubrication was performed using the Tecnolub system model SLS1.2-2 (Fig. 1). Another original cooling and lubrication method was used under for micro-lubrication or minimum quantity lubrication (MQL) [7]. The main component of this MQL system is an airblast atomizer injector (the SB202010 shown in Fig. 2, with an oil nozzle diameter of 0.25 mm, from System Tecnolub Inc.), and the injector operates with pressurized air; the pressurized air arrives at the system and passes through a filter equipped with a dryer. The air then goes through a pressure regulator and reaches the external channel of the atomizer. Oil is transported to the internal channel of the atomizer through a micro-volumetric piston pump and various regulators.

Finite element methods were used by the Université Libre de Bruxelle (ULB) team to simulate and to optimize the obtained spray phenomenon. Computational fluid dynamics (CFD) simulations with FINE/Open 2.11.1 were used to study the air injection in the ambient environment (single-phase flow simulations).

In Fig. 3, a cross section of the annular air channel of the SB-202010 nozzle shows the resulting velocity field for an air flow rate of 31 l/min. The computational domain is made up of around 1,000,000 finite elements.

Experimental characterizations of the oil-air spray were also done at ULB in order to optimize the spray shape and precision and the corresponding injector geometry, as well as its working parameters. An example of the result of such a test is shown in Fig. 4, with a particle image velocimetry (PIV) measurement. This experimental testing (also done using PDA and laser diffraction measurements) was used in conjunction with two-phase flow CFD numerical simulations (also with the FINE software) of the oil-air spray.

The oil through the central channel of the atomizer can be either pure lubricating oil or an oil/water mixture (at a ratio such as 5:95).

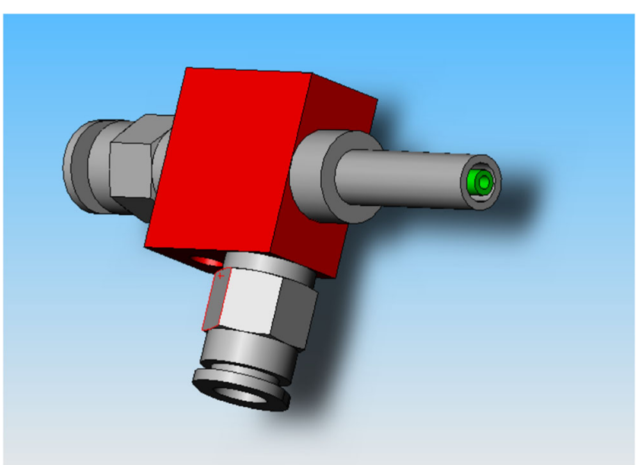

Fig. 2 Typical MQL oil-air atomizer/injector

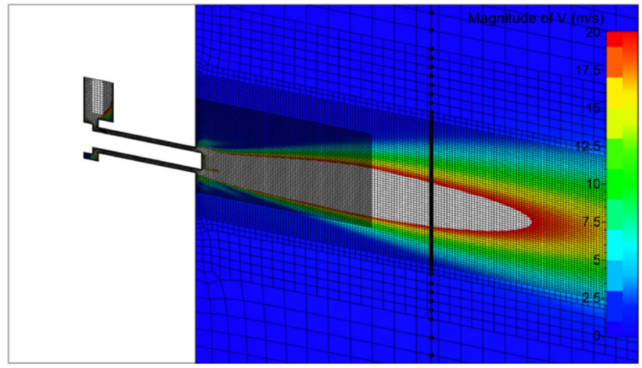

Fig. 3 Illustration of the air velocity at the exit of the injector (mg=31 l/min)

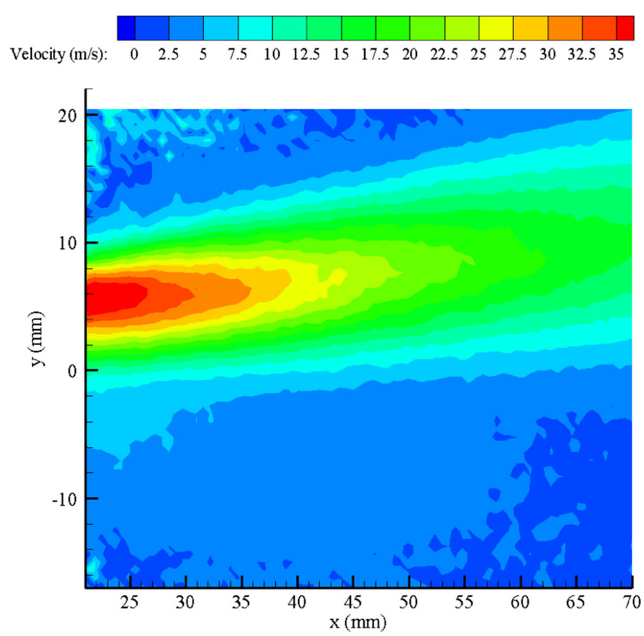

Fig. 4 PIV measurement of the oil velocity after the injector

3 Results and discussion

3.1 Surface roughness

Figure 5 presents the behavior of the surface roughness parameters (*Ra*, *Rt*, and *Rz*) in relation to the feed rates. *Ra* is the average roughness, *Rt* the height peak from the valley, and *Rz* the height mean peak from the valley. It is generally observed in Fig. 5 that the surface roughness parameters increase when the feed rate increases for both dry and MQL conditions. This observation is confirmed by the theoretical roughness R_{ath} used by Boothroyd et al.'s [16] formula in Eq. 1 as follows:

$$R_{\mathrm{ath}} = 0.0321\frac{f^2}{r_\varepsilon} \qquad (1)$$

where f is the feed rate and r_ε is the tool insert nozzle radius.

It is observed that the 1.75 ml/min MQL flow rate gives a better surface finish than the 3 ml/min MQL flow rate and the dry condition. This observation confirms the fact that a low flow rate MQL could provide a good solution in the machining process. This observation could be due to the fact that in the case of a low flow rate MQL, there may be a reduction in the built-up edge (BUE) due to the aerosol action at the tool/material interface [17]. This effect could help provide a good surface finish.

3.2 Chip formation

Figure 6 presents an optical chip morphology comparison under dry and MQL conditions at different cutting speeds and feed rates when turning 7075-T6 aluminum alloy. The general observation is the different chip forms and lengths under different lubrication conditions. Figure 6 also suggests that the chip length depends not only on the cutting speed but also on the feed rate under the same lubrication conditions. Chip breakability is one of the major issues faced in machining aluminum

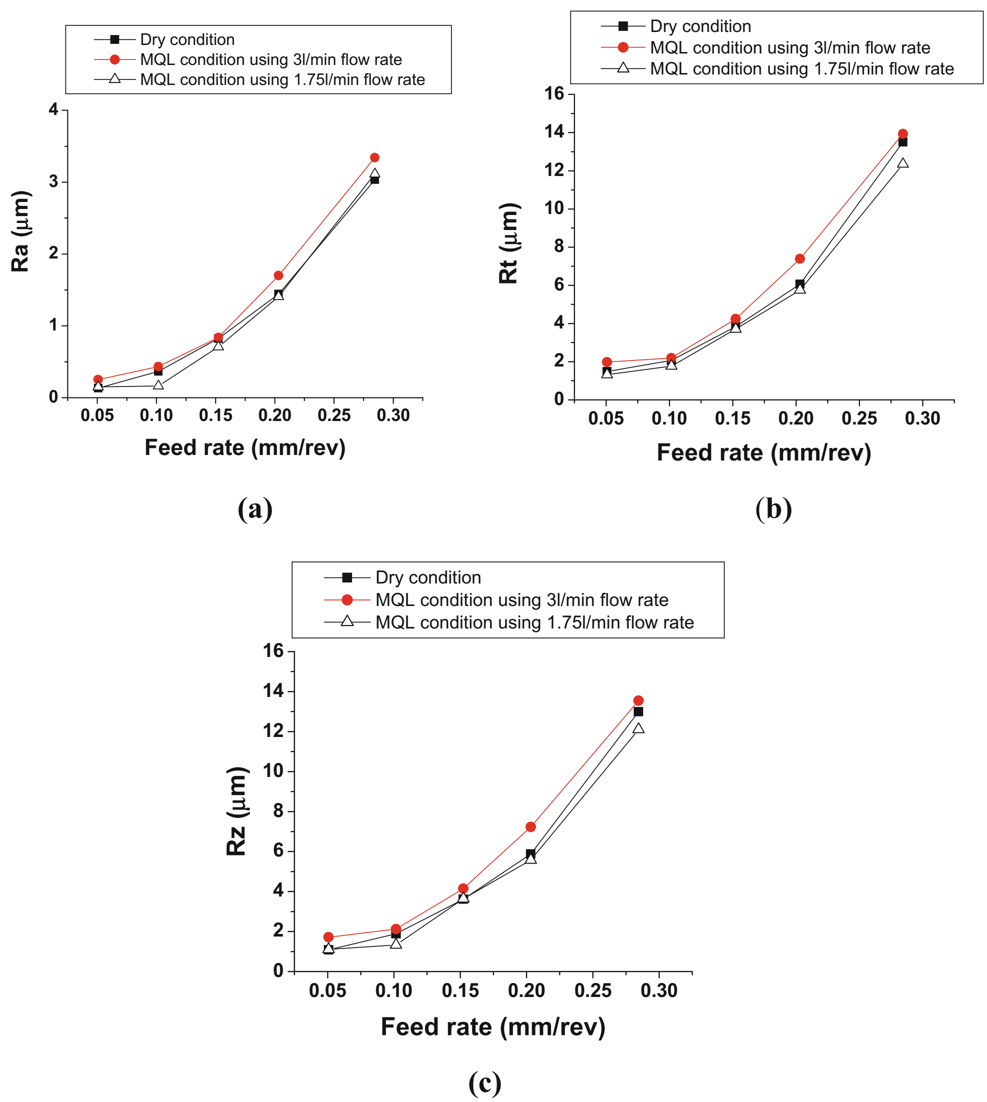

Fig. 5 Variation of the surface roughness parameters **a** *Ra*, **b** *Rt*, and **c** *Rz* at different feed rates, at 133 m/min cutting speed, and at 1-mm depth of cut

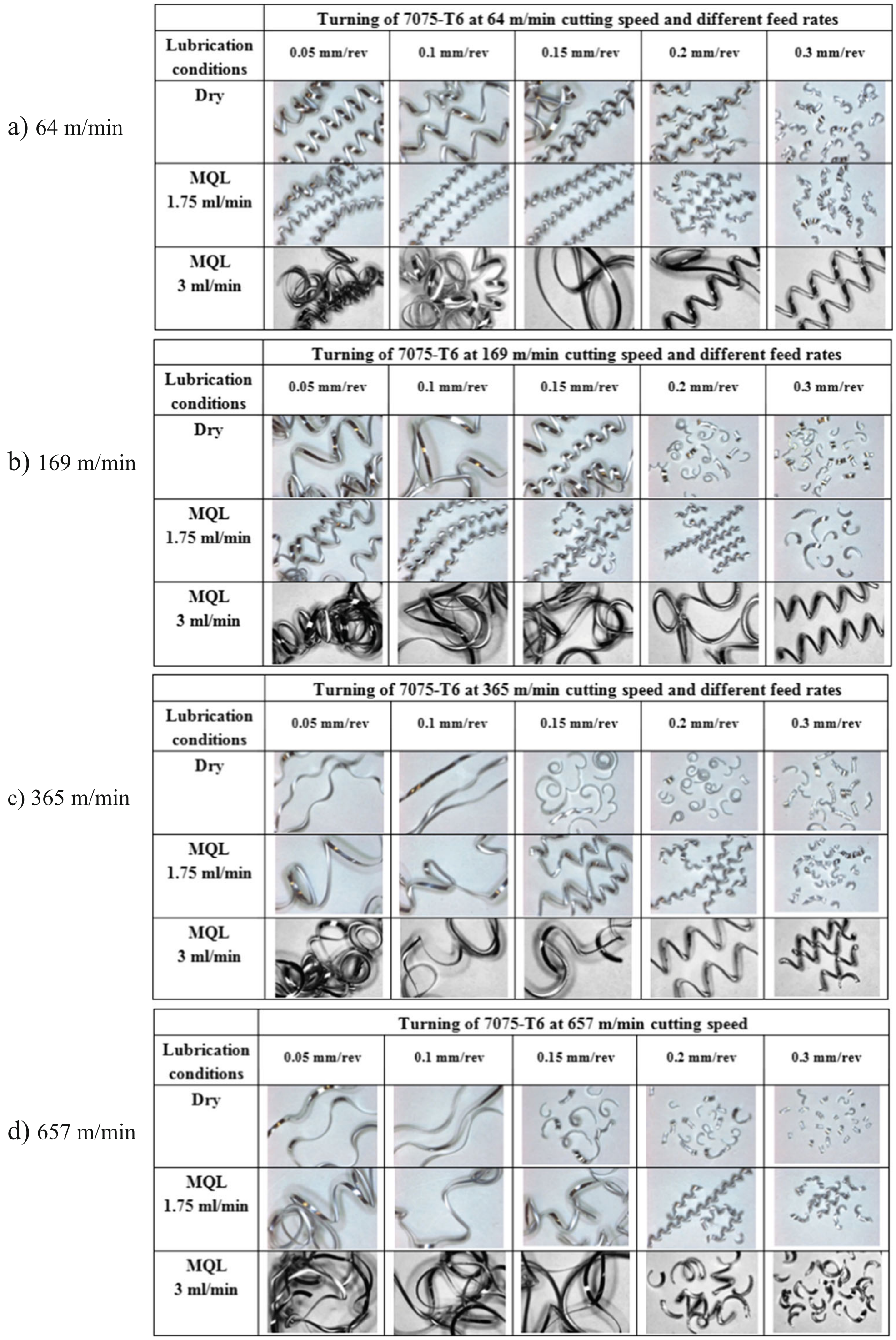

Fig. 6 Optical microscopy chip morphology image comparison at different feed rates under dry and MQL conditions: **a** 64, **b** 169, **c** 365, and **d** 657 m/min cutting speeds

alloys; in fact, long chips can cause damage to the machined surface, to the cutter, and to the machine evacuation system. Chip segmentation is one of the practical tools used to compare the chip breakability of different alloys. This observation was confirmed by Kouam et al. [18] in their study on A319 and A356. It is also observed that the chips are more segmented under dry condition as compared to under MQL condition. The 3 ml/min flow rate presents more long chips as compared to the situation with a 1.75 ml/min flow rate and dry conditions.

Figure 7 presents the representative limit zone between continuous and discontinuous 7075-T6 chips under dry condition. From Figs. 7 and 8 has been

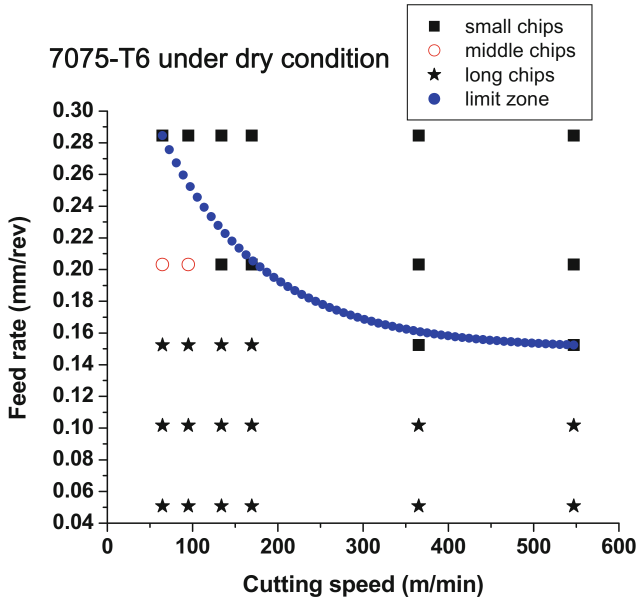

Fig. 7 Chip form transition limit of 7075-T6 aluminum alloy under dry condition

experimentally obtained by delimiting the continuous chip form zone to the discontinuous chip form zone under different lubricating conditions. Determining these limits can help in selecting cutting conditions that will yield the desired discontinuous chip.

A general observation that can be drawn from Fig. 8 is that at low cutting speeds, the chip is generally continuous under different lubrication conditions. It can also be observed that the chip length decreases as the cutting speed increases under different lubricating conditions.

Figure 8 presents four zones (zones 1, 2, 3, and 4):

– Zone 1 is for continuous chip form under all different lubrication conditions.

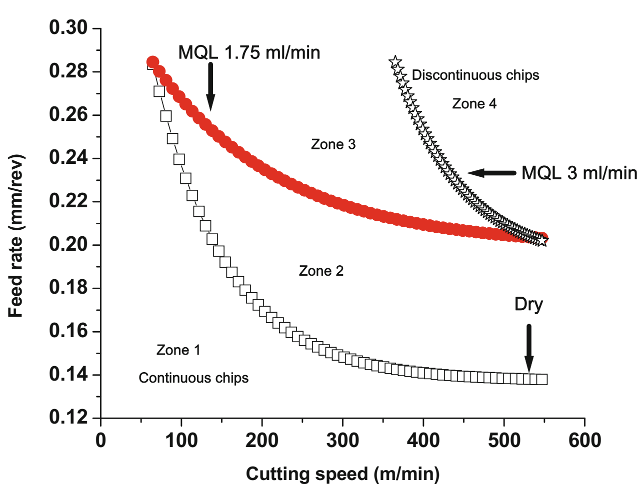

Fig. 8 Chip form transition limit zones of 7075-T6 aluminum alloy under different lubricating conditions

– Zone 2 is for continuous chip form under MQL (1.75 and 3 ml/min flow rate) lubricating conditions and discontinuous chip form under dry condition.
– Zone 3 is for continuous chip form under 3 ml/min flow rate condition and discontinuous chip form under dry and 1.75 ml/min flow rate.
– Zone 4 is for discontinuous chip form under all different lubrication conditions.

A general empirical expression (Eq. 2) was obtained from Fig. 8 for different delimiting chip form zones as a function of lubricating conditions as follows:

$$f = f_0 + A_0 e^{-\left(\frac{v}{B_0}\right)} \quad (2)$$

where f is the feed rate, v is the cutting speed, and A_0 and B_0 are constants, depending on the lubricating conditions. Equation 2 is similar to that obtained by Kouam et al. [18] and Songmene et al. [19] and could help in predicting chip forms, depending on lubricating conditions. The constants of Eq. 2 are given in Table 2.

Figure 9 presents the chip thickness at different cutting speeds and under different lubricating conditions. As expected, the effect of the feed rate on chip thickness is more significant than that of the MQL flow rate and cutting speed. The general observation is that the chip thickness decreases when the cutting speed increases.

As expected, the chip thickness increases with the feed rate (Figs. 9 and 10) and decreases at the low cutting speed.

Figures 10 and 11 present the chip reduction coefficient at different feed rates under dry and MQL conditions. The chip reduction coefficient provides an indication of the cutting energy and cutting temperature. It is generally observed that there is decreased chip reduction when the feed rate is increasing, confirming the works by Dhar et al. [11] and Khan et al [20].

It is observed that the chip reduction in the dry condition is high compared to that obtained during MQL using 3 and 1.75 ml/min flow rate, especially at low flow rates. At 1.75 ml/min lubrication flow rate, the chip reduction coefficient is high compared to that at 3 ml/min condition. MQL lubrication is expected to decrease the chip reduction coefficient when increasing the feed rate [20]. This observation

Table 2 Constant values of Eq. 2 under different lubricating conditions

Lubricating conditions	f_0 (mm/rev)	A_0	B_0
Dry	0.14	0.30	91.72
MQL (1.75 ml/min)	0.20	0.13	159.17
MQL (3 ml/min)	0.19	7.31	83.68

MQL minimum quantity lubrication

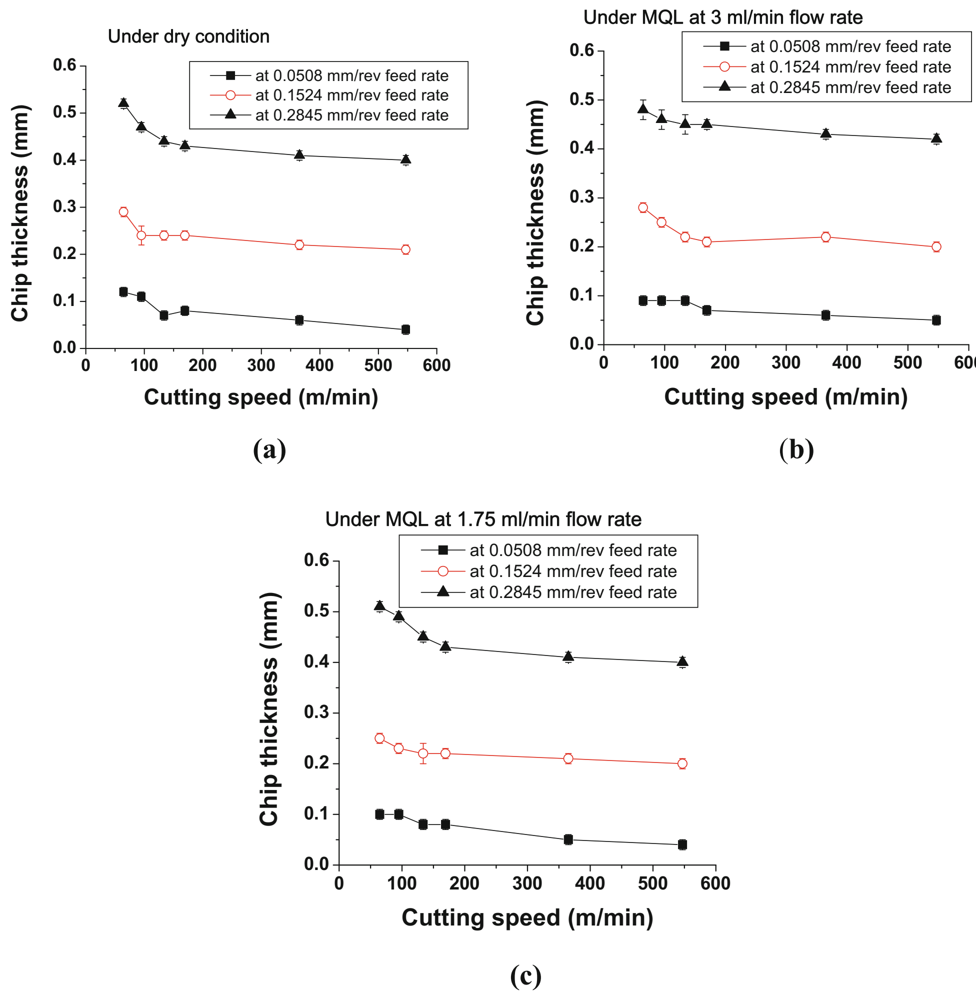

Fig. 9 Chip thickness at different cutting speeds and under different lubrication conditions: **a** dry, **b** MQL (3 ml/min), and **c** MQL (1.75 ml/min)

could indicate that under MQL lubrication conditions, a 1.75 ml/min flow rate could be more efficient in reducing energy consumption as compared to a 3 ml/min flow in the turning process. It is also observed that at high feed rates, chip reduction is similar for different lubrication conditions.

Figure 12 presents SEM images of chip segmentation under different lubricating conditions when turning 7075-T6 aluminum alloy. The × 500 magnification used was enough to show any significant segmentation of the chip. Becze and Elbestawi [21] defined the

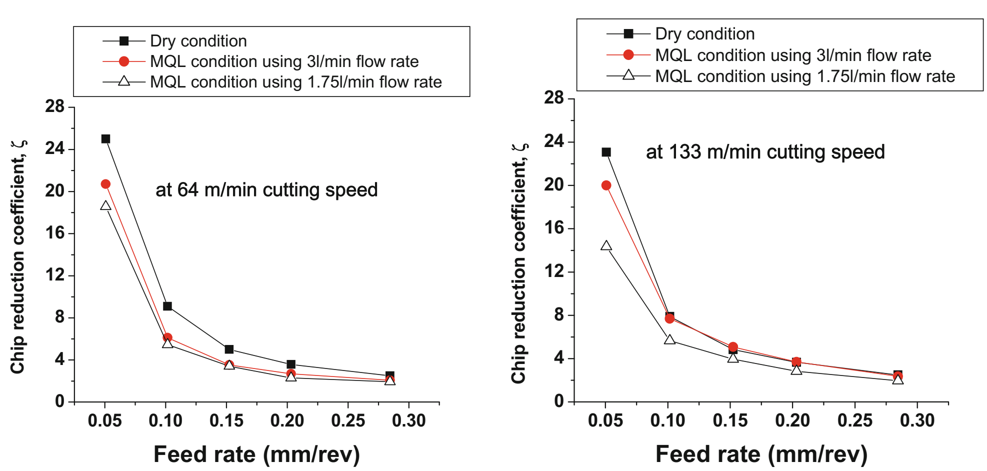

Fig. 10 Chip reduction coefficient at different feed rates under different lubrication conditions at 64 and 133 m/min cutting speeds

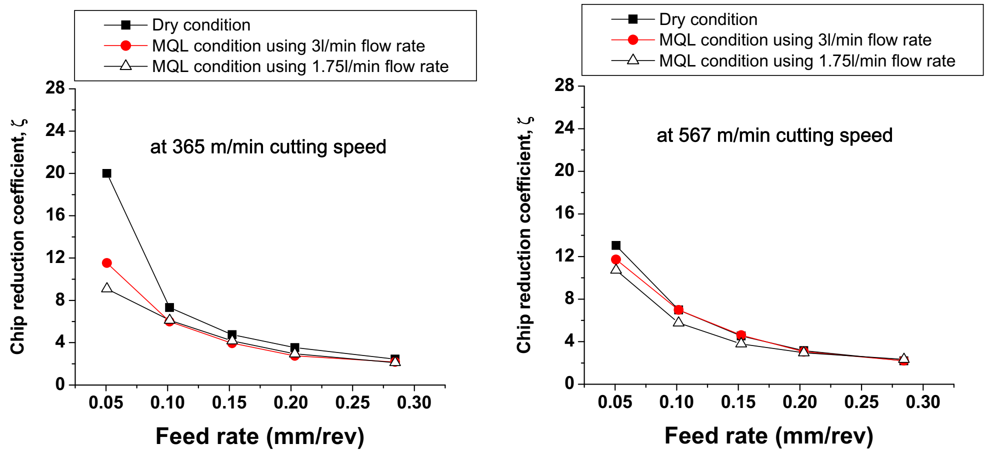

Fig. 11 Chip reduction coefficient at different feed rates under different lubrication conditions at 365 and 657 m/min cutting speeds

segmentation in their work by using the segmentation band density parameter η_s according to an empirical formulation. Based on the formulation, Khettabi et al. [22] developed a simple method for determining the chip segmentation density parameter η_s using the distance (l) corresponding to 10 segmentation bands (Eq. 3):

$$\eta_s = \frac{1}{l_b} = \frac{10}{l} \quad (3)$$

where l_b is the bandwidth.

The chip segmentation density η_s can be used to compare the effects of cutting conditions on chip formation.

Figure 13 presents the chip segmentation density parameter η_s for different lubricating conditions obtained using Eq. 3. It is seen that the chip segmentation density parameter η_s is lower during dry machining as compared to that during MQL machining, using a 1.75 and a 3 ml/min flow rate.

This observation could be due to the fact that at a low flow rate, the fine aerosol present during lubrication decreases the cutting temperature at the tool/chip interface and then facilitates chip deformation. The segmentation density could also help provide information about the brittleness of the chip and particle emission during the machining process.

3.3 Aerosol and metallic particle emissions

The machining of metallic components produces aerosols (MQL and dry) which can deteriorate the working shop floor environment. Figure 14 presents typical particle emission results, as a function of the aerodynamic diameter obtained from the aerosol particle sizer (APS), for particle diameters ranging from 0.5 to 10 µm. Most particles emitted have an aerodynamic diameter below 2.5 µm.

Figures 15 and 16 present the total concentration for the number and the mass of particle emission as a function of applied speeds at 0.15 mm/rev feed rate. It is observed that at very low speeds, the amount of particles is low; it then increases, reaches a maximum value, and then decreases. These two speed regimes have been previously observed by other authors [22–24].

The general observation is that at the same cutting speed, the total particle emission is lower under dry conditions as compared to MQL, using a 1.75 ml/min flow rate, which is also low compared to an MQL using a 3 ml/min flow. This phenomenon could be due to the fact that when the chip becomes brittle, particle

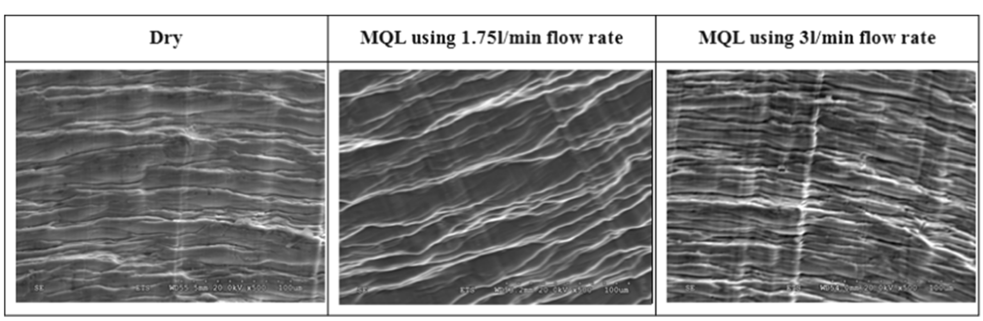

Fig. 12 SEM chip segmentation under different lubricating conditions (×500 magnification)

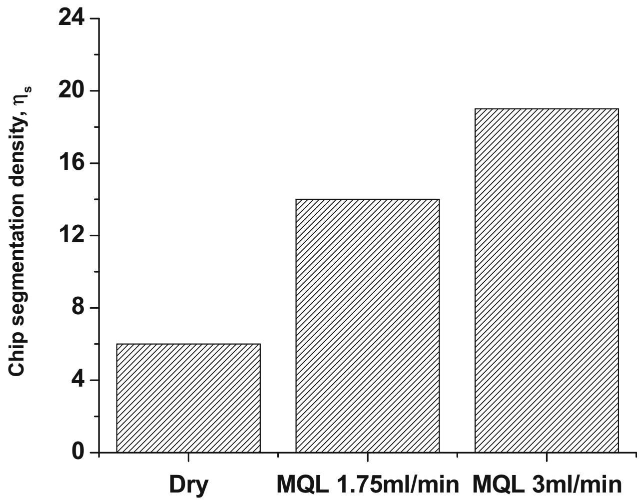

Fig. 13 Chip segmentation density η_s under different lubricating conditions at 133 m/min cutting speed and 0.15 mm/rev feed rate

emissions increase significantly [22, 25]. Moreover, the increase of the MQL flow rate increases the tendency to produce wet aerosols, which increase the total aerosol (liquid and metallic particle) measured. These effects of the tested lubricating conditions on particle emission change significantly when total mass concentration (Fig. 16) is considered.

4 Conclusions

In this work, the effect of cutting and lubricating conditions on machining process performance during turning of 7075-T6 aluminum alloy was studied. It was found that

- The particle emission depends significantly on the lubrication and cutting conditions, while the surface finish depends mainly on the feed rate used.

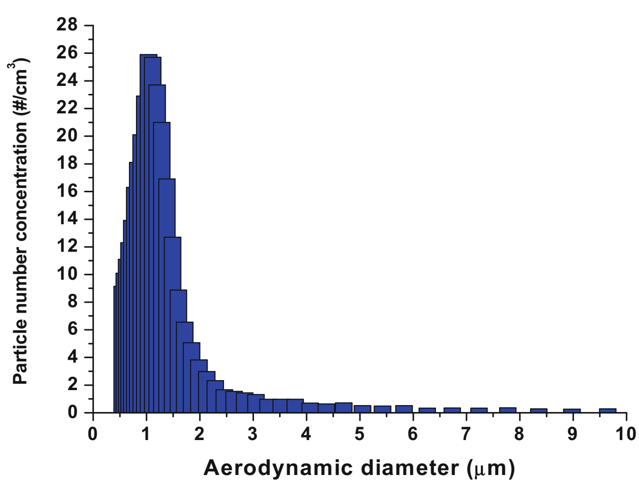

Fig. 14 Typical particle number concentration as a function of the aerodynamic diameter

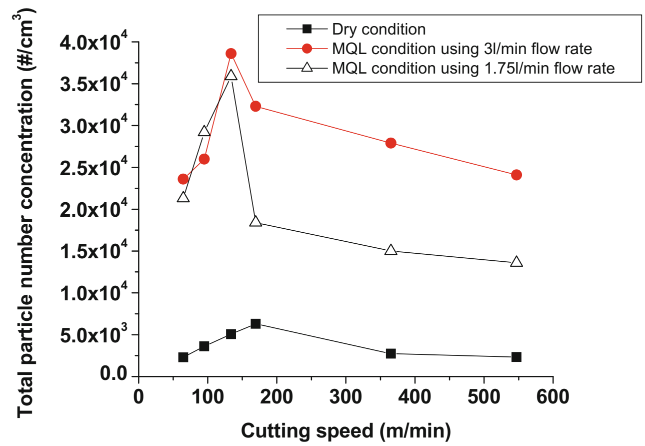

Fig. 15 Total particle number concentration under different lubrication conditions

- The chip formation and breakability were found to depend on the feed rate, on cutting speed, and on the lubricating conditions. The feed rate, the cutting speed, and the MQL flow rate can be adjusted to obtain better chip breakability for the 7075-T6 aluminum alloy known as a ductile material.
- Aerosols and metallic particle emissions were found to be affected not only by the lubrication conditions but also by cutting conditions. At very low speeds, the emission is low and then increases, reaches a maximum value, and eventually decreases. This observation could help reduce dust emissions, which can have serious consequences on the health of the operator. In general, the use of MQL produces more aerosols as compared to the dry condition which produced only metallic particles. Increasing the MQL flow rate also led to increased aerosol generation.

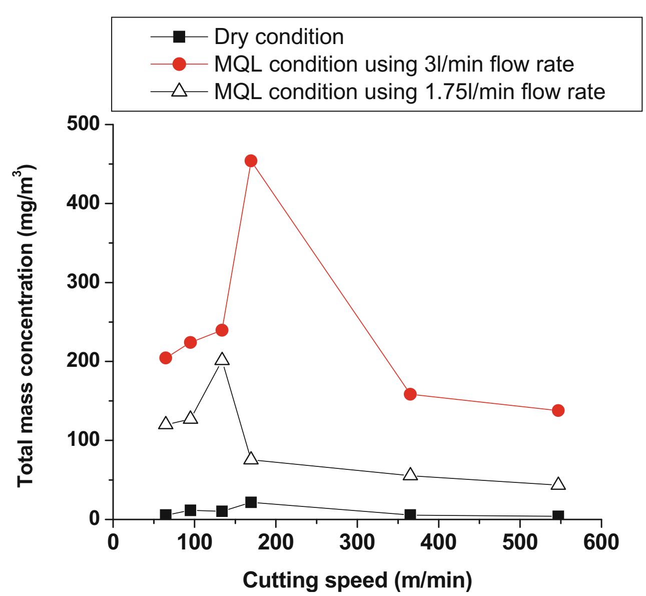

Fig. 16 Total mass concentration under different lubrication conditions

Acknowledgments A part of the research presented in this paper was financed by the Fonds de recherche du Québec - Nature et technologies by the intermediary of the Aluminium Research Centre – REGAL, Canada.

References

1. Gaitonde VN, Karnik SR, Davim JP (2008) Selection of optimal MQL and cutting conditions for enhancing machinability in turning of brass. J Mater Process Technol 204:459–464
2. Kamata Y, Obikawa T (2007) High speed MQL finish-turning of Inconel 718 with different coated tools. J Mater Process Technol 192–193:281–286
3. Kelly JF, Correrell MG (2002) Minimal lubrication machining of aluminum alloys. J Mater Process Technol 120:327–334
4. Attanasio A, Gelfi M, Giardini C, Remino C (2006) Minimal quantity lubrication in turning: effect on tool wear. Wear 260:333–338
5. Min S, Inasaki I, Fujimura S, Wakabayaski T, Suda S (2005) Investigation of adsorption behaviour of lubricants in near-dry machining. Proc Inst Mech Eng B J Eng Manuf 219(9):665–671
6. Itoigawa F, Childs THC, Nakamura T, Belluco W (2006) Effects and mechanisms in minimal quantity lubrication machining of an aluminum alloy. Wear 260:339–344
7. Damir A, Lancereau S, Attia H, Hendrick P (2010) On the performance of minimum quantity lubrication in milling Al 6061. Proceedings of 2nd International CIRP Conference on Process Machine, Vancouver, B.C., Canada, 10–11 June 2010
8. Vikram Kumar CHR, Ramamoorthy B (2007) Performance of coated tools during hard turning under minimum fluid application. J Mater Process Technol 185:210–216
9. Varadarajan AS, Philip PK, Ramamoorthy B (2002) Investigations on hard turning with minimal cutting fluid application (HTMF) and its comparison with dry and wet turning. Int J Mach Tools Manuf 42: 193–200
10. Ozawa M, Hosokawa A, Tanaka R, Furumoto T, Ueda T (2008) Minimum quantity lubrication turning using tools with oil holes, Kanazawa, Ishakawa, Japan. ASPE Proceedings, October 19 - October 24, Portland, Oregon
11. Dhar NR, Islam MW, Islam S, Mithu MAH (2006) The influence of minimum quantity lubrication (MQL) on cutting temperature, chip and dimensional accuracy in turning AISI-1040 steel. J Mater Process Technol 171:93–99
12. Yoshimura H, Moriwaki T, Ohmae N, Nakai T, Shibasaka T, Kinoshita H, Matsui M, Shimizu M (2006) Study on near dry machining of aluminum alloys. JSME Int J Ser C Mech Syst Mach Elem Manuf 49(1):83–89
13. Sutherland JW, Kulur VN, King NC (2000) Experimental investigation of air quality in wet and dry turning. CIRP Ann Manuf Technol 49(1):61–64
14. Balout B, Songmene V, Masounave J (2002) Usinabilité des Alliages de Magnésium et d'Aluminum Partie I: forces de coupe. In Proc. of the international symposium on enabling technologies for light metal and composite materials and their end-products, 41th conf. of metallurgists of CIM: 223-242
15. Songmene V, Balout B, Masounave J (2008) Clean machining: experimental investigation on dust formation part II: influence of machining strategies and drill condition. Int J Environ Conscious Des Manuf 14:17–33
16. Boothroyd G, Winston AK (2006) Fundamentals of machining and machine tools, 3rd edn. CRC Press, Taylor and Francis, New York, USA
17. Gómez-Parra A, Álvarez-Alcón M, Salguero J, Batista M, Marcos M (2013) Analysis of the evolution of the Built-Up Edge and Built-Up Layer formation mechanisms in the dry turning of aeronautical aluminum alloys. Wear 302(1–2):1209–1218
18. Kouam J, Songmene V, Zedan Y, Djebara A, Khettabi R (2013) On chip formation during drilling of cast aluminum alloys. J Mach Sci Technol 17:228–245
19. Songmene V, Khettabi R, Zaghbani I, Kouam J, Djebara A (2011) Machining and machinability of aluminum alloys, aluminum alloys, theory and applications. In: Kvackaj T (ed) ISBN: 978-953-307-244-9, InTech, India, pp 377–400
20. Khan MMA, Mithu MAH, Dhar NR (2009) Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid. J Mater Process Technol 209:5573–5583
21. Becze CE, Elbestawi MA (2002) A chip formation based analytic force model for oblique cutting. Int J Mach Tools Manuf 42:529–538
22. Khettabi R, Songmene V, Masounave J (2010) Effects of speeds, materials and tool rake angles on metallic particle emission during orthogonal cutting. J Mater Eng Perform 16(6):767–775
23. Kouam J, Songmene V, Djebara A, Khettabi R (2012) Effect of friction testing of metals on particle emission. J Mater Eng Perform 21(6):965–972
24. Kouam J, Djebara A, Songmene V (2014) Experimental investigation on the effect of pre-holes on drilling process performance of aluminum alloys: forces, surface finish and dust emission. J Adv Mater Sci Appl 3(1):13–23
25. Balout B, Songmene V, Masounave J (2007) An experimental study of dust generation during dry drilling of pre-cooled and pre-heated workpiece material. J Manuf Process 9(1):23–34