The International Journal of Advanced Manufacturing Technology (2020) 110:2015–2022
https://doi.org/10.1007/s00170-020-05979-3

ORIGINAL ARTICLE

Effects of lubricants and flow rates on the surface roughness and chip thickness when MQL turning of aero-engine aluminum alloys 6061-T6 and 7076-T6

Seyed Ali Niknam [1,2] • Alireza Jalali [3,4]

Received: 14 March 2020 / Accepted: 18 August 2020 / Published online: 1 September 2020

Abstract
It is agreed upon that labor's health conditions, as well as environmental pollutions, are broadly influenced by cutting fluids used in machining operations. In order to secure cleaner work parts and environment as well as reduced machining expenses, less fuel consumption is highly recommended. However, the quality of machined parts in the absence of fluid is considered a delicate subject. Under such conditions, the quality of machining process, as well as productivity, could be evaluated by different parameters and criteria including edge and surface quality, chip thickness, cutting force, and tool wear and life, which all seem to be highly influenced by many factors, including lubrication mode (dry and wet) and chip evacuation process. In order to take the benefits while avoiding the disadvantages of lubricated machining, novel lubrication method the so-called minimum quantity lubrication (MQL), which is micro lubrication near dry machining, is proposed. Review of literature denotes that under MQL condition, a low volume of information is available on the effects of mineral and bio-lubricants and various levels of flow rate on machining attributes, in principle average surface roughness (R_a) and chip thickness (h_c) when machining aluminum alloys (AAs). To remedy the lack of knowledge determined, the effects of cutting conditions, in principle cutting speed, feed rate, lubricant, and various levels of flow rate on R_a and h_c in MQL turning of AA 6061-T6 and AA 7076-T6, are presented. Therefore, three different experimental models, including multiplicative, 2-factor interactions (2FI), and linear models, were used in this study to assess the effects of cutting parameters on the machining outputs. According to experimental observations and despite the design models used, both R_a and h_c are statistically significant responses and could be controlled by variation of the cutting parameters used. A strong relationship can be formulated between both responses and experimental parameters used. Although negligible, however, biodegradable cutting fluid with higher viscosity denoted better capability to improve the surface finish. The use of a higher flow rate also led to improved surface finish (up to 50%). It was observed that despite the material used, both flow rate and cutting fluid have insignificant effects on h_c.

Keywords Turning · Aluminum alloy · Average surface roughness · Chip thickness · MQL

1 Introduction

MQL is the abbreviation of minimum quantity lubrication or simply micro lubrication near dry machining, which aims to reduce hazardous environmental and health conditions during machining operations. However, there is not yet an exact and standardized definition of MQL. The use of an average of not more than 50 ml/h of lubricant is the definition of minimum quantity lubrication [1]. Referring to high machining expenses associated with the use of cutting fluids and their detrimental influences on the operator health and environmental pollutions, alternative methods were always demanded [2]. To remedy the difficulties abovementioned, MQL was proposed, and

✉ Seyed Ali Niknam
saniknam@iust.ac.ir; seyed-ali.niknam@polymtl.ca

Alireza Jalali
alireza.jalali@volvo.com

1 Sustainable Manufacturing Systems Research Laboratory, School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

2 Department of Mechanical Engineering, Polytechnique Montreal, Montreal, Canada

3 Department of Mechanical Engineering, École de Technologie supérieure, Montreal, Canada

4 Dedicated Quality Team, Nova Bus, Volvo Canada, St-Eustache (QC), Canada

it became an exciting and popular method in machining industries. As a result of MQL machining, the thermal shock of the cutting tool is reduced. This may lead to improved tool life and performance [3]. This implies that the operated tool and nozzles model and location, as well as the mounting strategy, must be selected precisely. In general, the nozzles must be located within 2.5–5 mm away from the cutting zone [4]. The high-pressure jet of lubricant into the chip-tool interface may decrease the cutting temperature. Consequently, it may lead to a prolonged tool life [5]. However, the main drawbacks of MQL are the inability of complete heat transfer and chip evacuations, which are considered the main reasons for corrosion in the work parts, which also tends to affect the machinability of the tested materials. Comprehensive investigations on the effects of MQL on machinability attributes are then strongly required.

The effects of lubrication modes, in principle MQL on various aspects of machining and machinability attributes of AAs, were reported in numerous work [6–12]. For instance, as noted in [6], proper lubrication is highly related to the type of lubricant used. However, despite using lubricants with excellent quality, the tool damage cannot be avoided. Damir et al. [7] denoted that the amount of coolant determines the level of material adhesion to the tool surface, and the MQL may not certainly reduce the tool wear. Furthermore, a direct relationship could be formulated between the cooling application system and the recorded cutting forces.

Vikram Kumar et al. [8] studied the hard turning of AISI 4340 alloy steel in dry, MQL, and wet conditions. Although the better surface quality resulted under MQL than wet and dry conditions, however, referring to the narrow range of feed rate used (0.04–0.06 mm/rev), no relationship can be established between roughness and feed rate. Another study was conducted on the hard turning of AISI 4340 alloy steel under dry, MQL, and wet conditions [9]. Within the feed rate range of 0.05–0.14 mm/rev and cutting speed 120 m/min, the roughness was approximately similar and constant under different lubrication conditions when the feed rate was within the range of 0.05–0.1 mm/rev. According to Ozawa et al. [10], MQL yields to good surface roughness results. The chip formation under dry, MQL, and wet turning of AISI 1040 was studied by Dhar et al. [11]. The feed rate and cutting speed ranges were 0.1–0.2 mm/rev and 60–130 m/min, respectively. As noted in [11], despite the feed rate used, the chip reduction coefficient decreases when the cutting speed increases and the lowest chip reduction coefficient values were obtained under MQL condition. Yoshimura et al. [12] studied the tool wear modes under MQL machining of aluminum alloy. It was observed that the amount of adhered material is reduced when the cutting speed increases.

Among machinability attributes, special attention is paid to surface quality after machining operation. As noted earlier, among the surface quality attributes, the average surface roughness (R_a) is considered the main parameter, which represents the random and repetitive deviations of a surface profile from the nominal surface [13]. The surface roughness is generally determined by Eq. (1) as follows:

$$R_a = {f^2}\big/_{32r} \tag{1}$$

where f is the feed rate, and r denotes the nose radius.

It is agreed that adequate surface roughness can be achieved with reduced friction, wear, and noise, as well as improved corrosion resistance [14]. The effects of the abovementioned cutting parameters on the surface roughness were studied in numerous experimental studies [11, 15–21]. However, the impact of multiple machining parameters such as tool geometry, machine tool rigidity, lubrication modes, lubrication flow rate, and vibration is not yet incorporated into Eq. (1) [22]. Furthermore, to obtain adequate surface quality as well as multiple response optimization, optimum process parameters were proposed using sophisticated optimization tools [23].

To the authors' knowledge, limited studies were found on the factors governing surface quality, in principle, average surface roughness (R_a), and chip thickness (h_c) in turning of AA 7075-T6 and AA 6061-T6 when various types of lubricants and different levels of flow rate are used. The adequate selection of cutting parameters to guarantee acceptable surface quality may reduce the needs of protracted deburring and edge finishing processes, which are associated with additional non-desirable expenses and harmful effects on environments and operator's health, aligned with green machining [6]. In general, within most of the reported research works on MQL, vegetable oil is the prime choice of lubricant. A low amount of works has considered the effects of various flow rates on machining outputs. In order to remedy the lack of knowledge abovementioned, a parametric design of an experiment based on multilevel factorial was used to determine the influence of cutting parameters, lubricants, and flow rates on the R_a and h_c when turning two aero-engine aluminum alloy 6061-T6 and 7075-T6 under micro lubricated condition (MQL). The statistical tools, including ANOVA, were also used as a supportive tool for statistical analysis.

2 Experimental procedure

The turning tests were conducted on the cylindrical aluminum alloy 6061-T6 and 7076-T6 (Ø150 × 450 mm) using different levels of cutting parameters (Table 1). It was intended to use similar levels of experimental parameters used in the world-class industrial sectors. Therefore, to cover the wide range of cutting capabilities, the experimental conditions, as presented in Table 1, were selected according to industrial recommendations under MQL. To that end, a multilevel full factorial

Table 1 Experimental process parameters and tools

Cutting parameters	Experimental levels
(A) Feed rate (mm/rev)	0.0508, 0.1016, 0.1524, 0.2032, 0.254
(B) Cutting speed	79,116,163,206,442,660
(C) Flow rate (ml/min)	0.686, 1.715, 3.087
(D) Lubricant	Mecagreen 550 and Microkut 400
(E) Material	AA 6061-T6; AA 7075-T6

Depth of cut: 1 mm; cutting tool: coated carbide insert KC5410

design of experiments, including 180 tests (5 × 6 × 3 × 2), was used for each material (Table 1). In total, 720 tests were conducted, including one replication for each test. The experimental tests were completed on the CNC machine (Mazak Quick Turn Nexus 100 II M). The average value of responses was considered for results analysis. The new carbide cutting insert (DNGP-432 KC5410 Kennametal) was used in each test. Figure 1 depicts the experimental setup, equipped with an MQL system. The surface roughness of generated surfaces was evaluated using the Mitutoyo SJ 400 profilometer (Fig. 1c). The surface roughness was recorded at four different positions (90° apart), and the measurements were repeated twice at each point. Five surface roughness parameters, including R_a, R_q, R_t, R_v, and R_p, were recorded. However, the results of R_a were only used for additional analysis. A detailed overview of the effects of cutting parameters on other surface quality attributes is within the scope of further study. The

Table 2 Adjustment of Microlub system

Micropump	34.3 mm^3
Pulse generator	20, 50, and 90 stroke/min
Air spray pressure	1.4 bar
Micropump air control pressure	6 bar

Hitachi scanning electron microscope (SEM) S-3600N, as shown in Fig. 1d, was used to capture the high-resolution images of the chips. The samples were ultrasonically cleaned in ethanol bath before being transferred to the SEM machine. The burr formation morphology was also monitored using a high-resolution optical microscope.

The operated micro lubrication system, as depicted in Fig. 1, consisted of a volumetric micropump that injects a low volume of lubricant through a capillary tube to an outlet nozzle (Fig. 1b). Simultaneously, a low-pressure pulverization air was injected into the cutting zone using a second capillary tube. The lubricant source is installed at the top of this machine, and the flow rate could be adjusted by setting the micropumps which are pulsed either by a pneumatic sequencer that allows set up from 1 to 180 strokes per minute [24]. The adjustments of the micro lubrication system are shown in Table 2. The specifications of two lubricants proposed by System Tecnolub Inc. are shown in Table 5 (Annex).

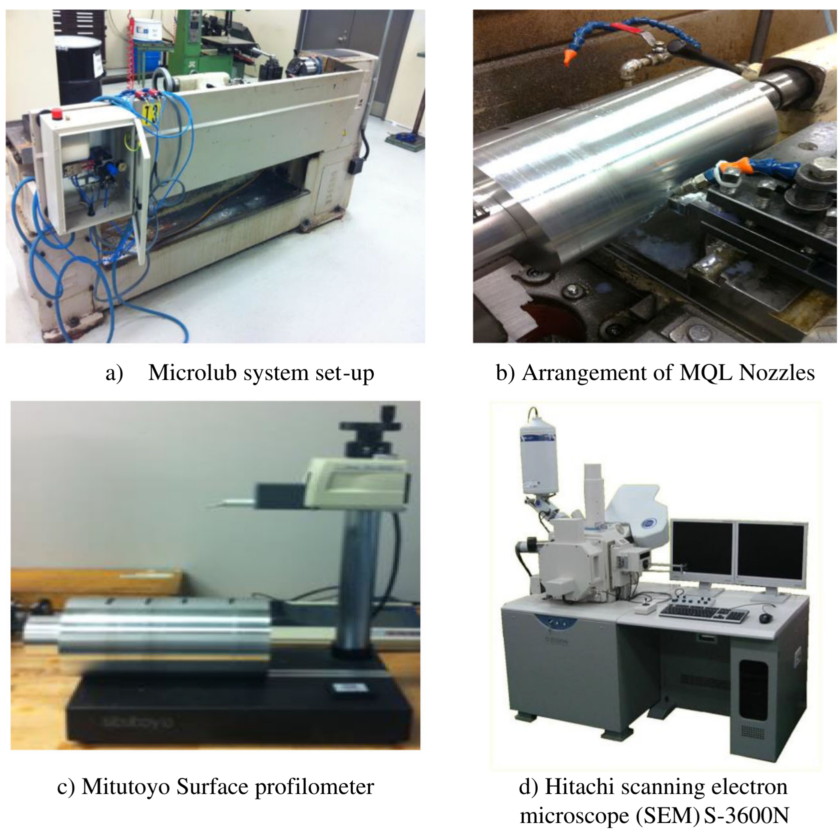

Fig. 1 Experimental setup. **a** Microlub system setup. **b** Arrangement of MQL nozzles. **c** Mitutoyo Surface profilometer. **d** Hitachi scanning electron microscope (SEM) S-3600N

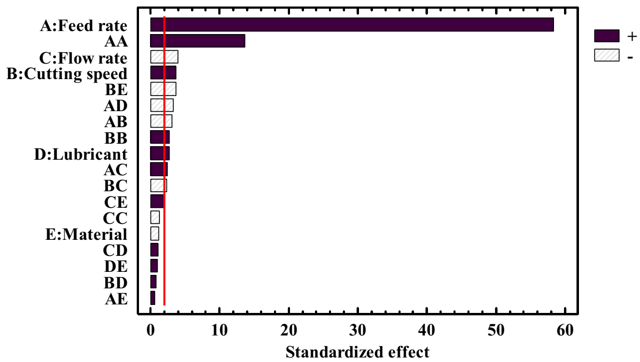

Fig. 2 Pareto chart of average surface roughness R_a ($R^2 = 0.915$; $R^2_{adj} = 0.911$)

3 Results

3.1 Method of analysis

It is believed that adequate selection of cutting fluid and flow rate leads to significant improvement in the lubrication performance and adequate machining expenses are expected. As noted earlier, it is believed that R_a is one of the critical surface quality attributes which is affected by different cutting parameters including work material, tool geometry, cutting conditions, and lubrication strategy [25]. To determine the effects of cutting parameters, including feed rate, cutting speed, flow rate, and lubricant on both R_a and h_c, different statistical methods such as Pareto analysis, main effect plot, and analysis of variance (ANOVA) were used. In addition, the results were presented in various design models, mainly known as linear, 2-factor interactions, and multiplicative models. A complete overview of the statistical parameters used is shown in [26].

3.2 General analysis

In the first step, to evaluate the effects of material properties on the machining outputs, all obtained results were analyzed using statistical tools. According to Fig. 2, it can be stated that although different materials with completely different mechanical properties were used [27], it can be however observed that variation of surface roughness values mainly depends on the feed rate and cutting speed, nor material properties. This can be related to the mechanism of machining operation, the chip formation morphology, and the effects of lubrication conditions. However, different results are expected in the case of milling operations where surface roughness may be widely affected due to progressive chip formation [26].

3.3 Individual material analysis

In the second step, the individual analysis was conducted concerning each material. According to statistical analysis, the correlation of determination R^2 and R^2_{adj} of R_a and h_c (Table 3) denote that except linear model of R_a, it can be exhibited that despite the design model used, design models of machining responses are statistically significant ($R^2 > 0.8$ and P value < 0.05) concerning the variation of process parameters used. The negligible difference between R^2 and R^2_{adj} in linear and quadratic models in both responses denotes the non-significant influence of interaction effects between cutting process parameters. Therefore, the linear design model was used in the following analysis as the primary statistical significant model. The difference between R^2 and R^2_{adj} in linear and quadratic models of R_a and h_c is about 10%. Moreover, the P value of 0 in linear and 2-factor interaction models of both R_a and h_c indicates a negligible contribution of interactive effects on the presented results. Therefore, as well

Table 3 ANOVA table of average surface roughness and chip thickness

Material	Response	Design model	R^2	R^2_{adj}	P value	Remark
AA 6061-T6	Average surface roughness R_a	Linear	0.792	0.787	0	Mid-significant
		2-factor interactions	0.818	0.807	0	Significant
		Quadratic	0.875	0.865	0	Significant
	Chip thickness h_c	Linear	0.945	0.943	0.0016	Significant
		2-factor interactions	0.969	0.967	0.0032	Significant
		Quadratic	0.977	0.976	0.13	Significant
AA 7075-T6	Average surface roughness R_a	Linear	0.937	0.935	0	Significant
		2-factor interactions	0.945	0.942	0	Significant
		Quadratic	0.988	0.987	0	Significant
	Chip thickness h_c	Linear	0.973	0.972	0	Significant
		2-factor interactions	0.978	0.977	0	Significant
		Quadratic	0.985	0.984	0	Significant

Table 4 Statistical results of regression models between chip thickness and surface roughness

Materials	Regression models	R^2	R^2_{adj}	Correlation coefficient r	P value
AA 6061-T6	Linear	0.753	0.752	0.868	0
	Exponential	0.736	0.734	0.858	0
	Multiplicative	0.757	0.755	0.87	0
AA 7075-T6	Linear	0.924	0.923	0.961	0
	Exponential	0.894	0.891	0.944	0
	Multiplicative	0.907	0.906	0.952	0

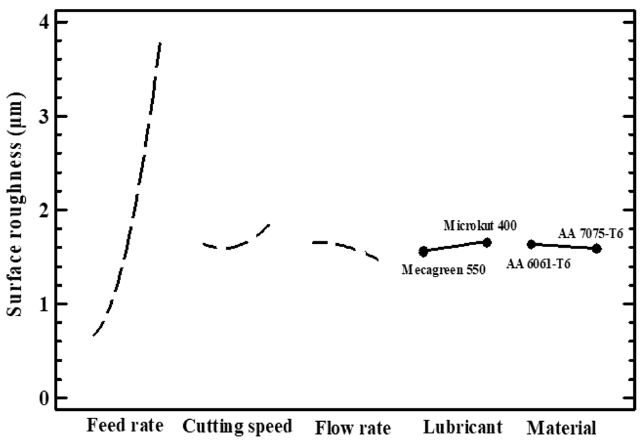

Fig. 3 Main effect plot of average surface roughness R_a

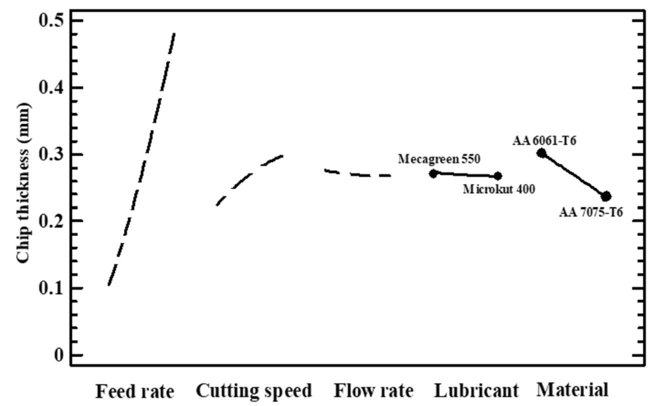

Fig. 5 Main effect plot of chip thickness h_c

as the first part of this experimental study, the linear design model is used for further analysis.

Figure 6 a and b show that feed rate (A) has the most significant effect on R_a while cutting speed (B) and lubricant (D) have negligible effects on it. According to Fig. 7b, an increased feed rate leads to a more deteriorated surface quality. This could be attributed to the direct influence of feed rate on h_c and directional cutting forces, which cause severe deviations on the surface texture and profile [25, 28]. When the cutting parameters listed in Table 1 are used, the model as fitted has the capability to control the variability of R_a up to 82.08%. Figure 7 a and b denote that feed rate (A) and cutting speed (B) have the most significant effects on the h_c. Increased cutting speed leads to decreased h_c, and inversely, increased feed rate led to thicker chips. The correlation of determination R^2 indicates that under similar experimental conditions as presented in Table 1, the h_c can be controlled up to 93.58% when

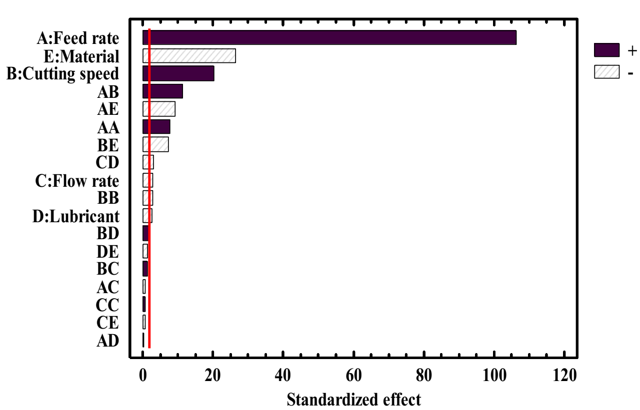

Fig. 4 Pareto chart of chip thickness ($R^2 = 0.974$; $R^2_{adj} = 0.973$)

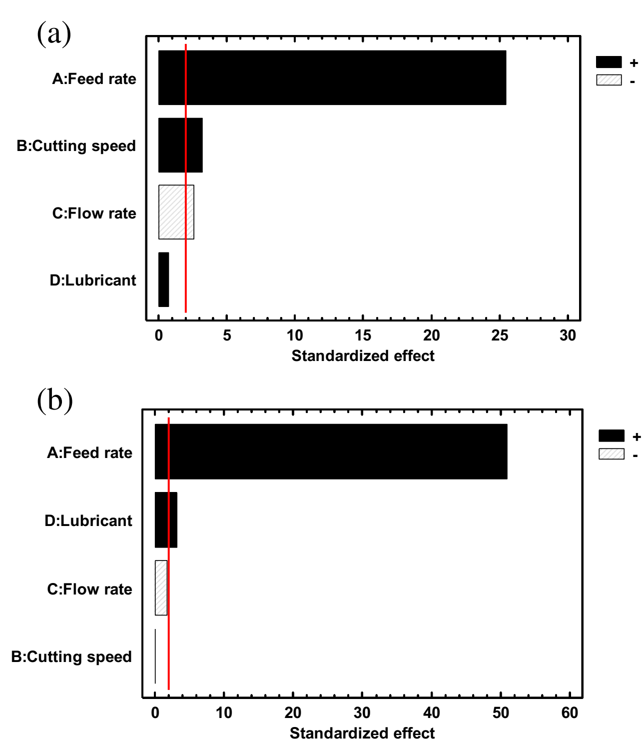

Fig. 6 Pareto chart of R_a in linear design model. **a** AA 6061-T6. **b** AA 7075-T6

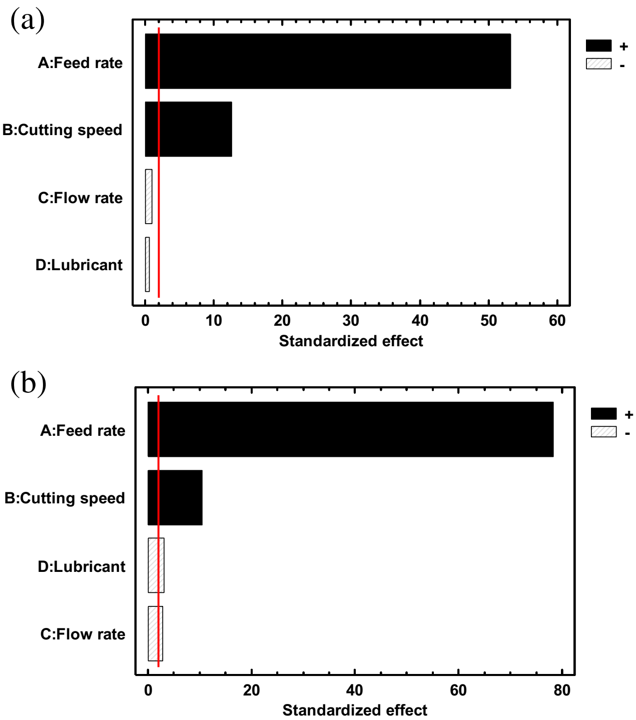

Fig. 7 Pareto chart of h_c in linear design model. **a** AA 6061-T6. **b** AA 7075-T6

using the linear design model. It can be observed that lubricant has an insignificant effect on R_a and h_c. This can be related to the intense impacts of flow rate on the generated temperature in the cutting zone as well as friction, which both tend to be reduced at higher levels of flow rate.

The regression models between R_a and h_c in linear, exponential, and multiplicative models are shown in Table 4. A statistically significant relationship exists between R_a and h_c at the 95.0% confidence level. A negligible difference can be observed between the correlation coefficients of both linear and multiplicative

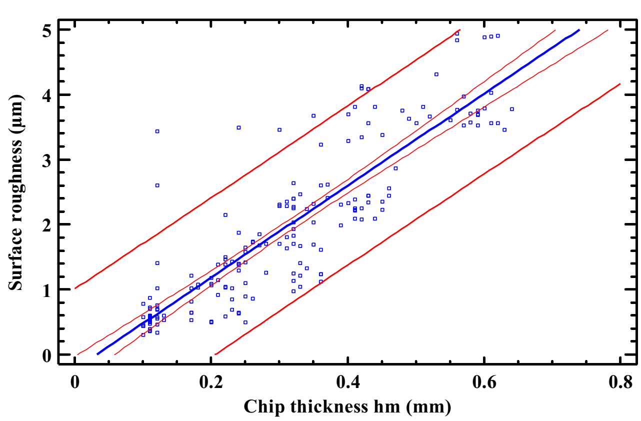

Fig. 8 Linear regression model of average surface roughness and chip thickness in AA 6601-T6

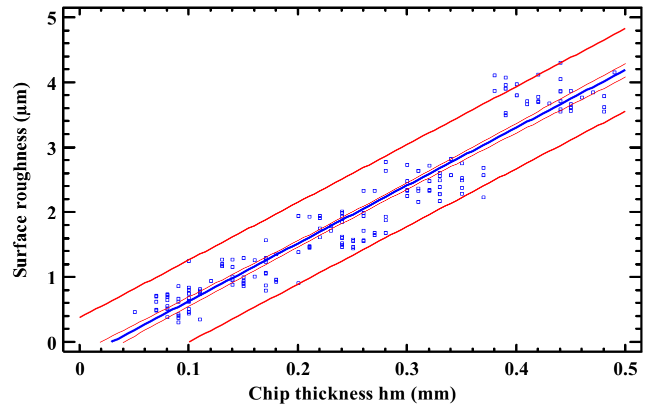

Fig. 9 Linear regression model of average surface roughness and chip thickness in AA 7075-T6

models. According to Table 4, it can be exhibited that despite regression models presented, the R_a and h_c are strongly correlated with each other. According to Eq. (2), knowing that the chip thickness is directly formulated as a function of feed rate, therefore, increased feed rate and chip thickness lead to a higher chip thickness ratio, which itself may tend to increase the shear angle and decrease the friction angle, as shown in Eqs. [3–5], respectively [29]. Friction forces, to a large extent, affected by friction angle [30]. Therefore, as shown in Eq. (6), lower friction force has resulted when the feed rate increases. This tends to generate an excellent surface finish.

$$r_c = \frac{h}{h_c} \quad (2)$$

$$\varphi_c = \tan^{-1}\frac{r_c \cos\alpha_r}{1 - r_c \sin\alpha_r} \quad (3)$$

$$\varphi_c = \frac{\pi}{4}(\beta_\alpha - \alpha_r) \quad (4)$$

$$\mu_\alpha = \tan\beta_\alpha \quad (5)$$

$$\mu_\alpha = \frac{F_u}{F_v} \quad (6)$$

Referring to Table 4, higher values of R^2 were found for regression models of R_a and h_c in AA7075-T6 than those observed for AA6061-T6. In other words, R_a and h_c in AA7075-T6 are more controllable under the variation of cutting parameters as compared with AA6061-T6. Furthermore, the differences between the resulted values of R^2 and $R^2{}_{adj}$ of design models in both materials can be attributed to the difference between governing factors on the R_a and $h_{c,}$ which were discussed in Figs. 2, 3, 4, 5, 6, and 7. Therefore, despite the design model used, better regression was found between R_a and h_c in AA7075-T6 than AA6061-T6 (Figs. 8 and 9).

4 Conclusion

Following experimental studies and statistical analysis presented, the following conclusion can be drawn with respect to operating conditions used:

- Despite three different experimental models, including multiplicative, 2-factor interactions (2FI) as well as linear models used, both R_a and h_c are statistically significant responses and could be controlled by variation of cutting parameters used. A strong relationship can be formulated between both responses and experimental parameters used.
- It can be observed that feed rate has a significant effect on R_a and h_c while cutting speed has just the considerable impact on h_c. The effects of feed rate can be attributed to powerful influences on the friction and chip thickness, which may lead to increased levels of temperature in the cutting zone and fluctuated force, which all lead to diminished surface quality.
- According to experimental observations, although negligible, however biodegradable cutting fluids with higher viscosity denoted better capability to improve the surface finish. The use of a higher flow rate also led to improved surface finish (up to 50%). It was observed that both the flow rate and cutting fluid have insignificant effects on h_c.
- Significant correlations were found between R_a and h_c in linear, multiplicative, and exponential models under different levels of flow rate.

Acknowledgments The authors would like to appreciate the fanatical supports by "Fond de la Recherche du Quebec sur la Nature et les Technologie" (FQRNT).

ANNEX

Table 5 Specifications of Mecagreen 550 and Microkut 400 [9–11]

Lubricant specification	MECAGREEN 550	MICROKUT 400
Aspect	Limpid	Clear (light)
Color	White	Blond
Odor	Low	Odorless
Viscosity	21 mm^2/s	37 mm^2/s
Solubility	Water 10–15%	–
Biodegradability	Not information	After 21 days
Application	Machining very hard chipping	Sawing, machining
	Aluminum, aluminum alloy, stainless steel	Metal forming
		(blanking, drawing, and stamping)
Maximum storage	1 year	2 years

References

1. Weinert K, Inasaki I, Sutherland J, Wakabayashi T (2004) Dry machining and minimum quantity lubrication. CIRP Ann-Manuf Technol 53(2):511–537
2. Niknam SA, Songmene V (2013) Factors governing burr formation during high-speed slot milling of wrought aluminium alloys. Proc Instit Mech Eng Part B: Journal of Engineering Manufacture 227(8):1165–1179
3. Jun MB, Joshi SS, DeVor RE, Kapoor SG (2008) An experimental evaluation of an atomization-based cutting fluid application system for micromachining. J Manuf Sci Eng 130(3):031118
4. Jalali A (2013) Performance of minimum quantity cooling (MQC) when turning aluminium alloy 6061-T6: surface roughness, tool temperature and aerosol emission: École de technologie supérieure
5. Dhar NR, Islam S, Kamruzzaman M (2007) Effect of minimum quantity lubrication (MQL) on tool wear, surface roughness and dimensional deviation in turning AISI-4340 steel. Gazi Univ J Sci 20(2):23–32
6. Itoigawa F, Childs T, Nakamura T, Belluco W (2006) Effects and mechanisms in minimal quantity lubrication machining of an aluminum alloy. Wear. 260(3):339–344
7. Damir A, Lancereau S, Attia H, Hendrick P, editors. (2010) On the performance of minimum quantity lubrication in milling Al 6061. Proceedings of 2 nd International CIRP Conference on Process Machine, Vancouver
8. Kumar CRV, Ramamoorthy B (2007) Performance of coated tools during hard turning under minimum fluid application. J Mater Process Technol 185(1):210–216
9. Varadarajan A, Philip P, 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(2):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
11. Dhar N, Islam M, Islam S, Mithu M (2006) The influence of minimum quantity of lubrication (MQL) on cutting temperature, chip and dimensional accuracy in turning AISI-1040 steel. J Mater Process Technol 171(1):93–99
12. Yoshimura H, Moriwaki T, Ohmae N, Nakai T, Shibasaka T, Kinoshita H et al (2006) Study on near dry machining of aluminum alloys. JSME Int J Ser C Mech Syst Mach Elem Manuf 49(1):83–89
13. Islam MN, Boswell B, editors (2011). An investigation of surface finish in dry turning. Proc World Congress Eng
14. Niknam SA, Khettabi R, Songmene V (2014) Machinability and machining of titanium alloys: a review. Machining of Titanium Alloys: Springer, Berlin Heidelberg, pp 1–30
15. Özel T, Hsu TK, Zeren E (2005) Effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and forces in finish turning of hardened AISI H13 steel. Int J Adv Manuf Technol 25(3):262–269
16. Davim J, Sreejith P, Gomes R, Peixoto C (2006) Experimental studies on drilling of aluminium (AA1050) under dry, minimum quantity of lubricant, and flood-lubricated conditions. Proc Inst Mech Eng B J Eng Manuf 220(10):1605–1611
17. Braga DU, Diniz AE, Miranda GW, Coppini NL (2002) Using a minimum quantity of lubricant (MQL) and a diamond coated tool in the drilling of aluminum–silicon alloys. J Mater Process Technol 122(1):127–138
18. Wakabayashi T, Suda S, Inasaki I, Terasaka K, Musha Y, Toda Y (2007) Tribological action and cutting performance of MQL media in machining of aluminum. CIRP Ann-Manuf Technol 56(1):97–100
19. Silva LR, Corrêa EC, Brandão JR, de Ávila RF. (2013) Environmentally friendly manufacturing: behavior analysis of minimum quantity of lubricant-MQL in grinding process. J Clean Prod
20. Kouam J, Songmene V, Balazinski M, Hendrick P (2015) Effects of minimum quantity lubricating (MQL) conditions on machining of 7075-T6 aluminum alloy. Int J Adv Manuf Technol 79(5–8):1325–1334
21. 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
22. Upadhyay V, Jain P, Mehta N (2012) In-process prediction of surface roughness in turning of Ti-6Al-4V alloy using cutting parameters and vibration signals. Measurement.
23. Niknam SA, Songmene V (2013) Simultaneous optimization of burrs size and surface finish when milling 6061-T6 aluminium alloy. Int J Precis Eng Manuf 14(8):1311–1320
24. Technical booklet – (2010) Microlubrication machine specifications, Z.I, Kaiserbaracke. In: Tecnolub, editor. 4, B-4780 Recht , Belgium
25. Niknam SA, Kouam J, Songmene V (2016) Experimental investigation on part quality and metallic particle emission when milling 6061-T6 aluminium alloy. Int J Mach Mach Mater 18(1–2):120–137
26. Niknam SA. Burrs understanding, modeling and optimization during slot milling of aluminium alloys Ph.D. Thesis, École de Technologie Superieure, Universite du Quebec, 2013
27. Tiabi A (2010) Formation des bavures dùsinage et finition de pieces M. Sc Thesis, École de technologie superieure, Canada
28. Niknam SA, Songmene V (2014) Analytical modelling of slot milling exit burr size. Int J Adv Manuf Technol 73(1–4):421–432
29. Altintas Y (2000) Manufacturing automation: Cambridge Univ. Pr
30. Niknam SA (2016) Modeling and experimental characterization of the friction effects on orthogonal milling exit burrs. Int J Adv Manuf Technol:1–11