International Journal of Automotive and Mechanical Engineering (IJAME)
ISSN: 2229-8649 (Print); ISSN: 2180-1606 (Online); Volume 11, pp. 2771-2785, January-June 2015

DOI: http://dx.doi.org/10.15282/ijame.11.2015.52.0233

EXPERIMENTAL STUDY ON MINIMUM QUANTITY LUBRICATION IN END MILLING OF AA6061-T6 USING TiAlN COATED CARBIDE TOOLS

M.S. Najiha and M.M. Rahman

Faculty of Mechanical Engineering
Unviersiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
Email: mustafizur@ump.edu.my
Phone: +6094246239; Fax: +6094246222

ABSTRACT

This paper presents an experimental investigation on the effects of output parameters during machining of aluminum alloy 6061-T6 using the minimum quantity lubrication (MQL) technique through end milling processes. In this study cutting speed, depth of cut, feed rate and MQL flow rate are selected as input parameters. Experiments are conducted using the central composite design method. Statistical models for process optimization are obtained using the response surface method. The objective of the study is to investigate and optimize the process parameters employing coated carbide cutting tools; coatings used are TiAlN. For the purpose of the study, surface roughness and material removal rate are selected as response variables. The results of the study show that the inserts coated with TiAlN perform very well, showing good machinability. According to the results of the study, MQL can easily be a suitable eco-friendly alternative to conventional flood cooling conditions. MQL proves to be more beneficial with the application of coated tools in end milling of aluminum alloys.

***Keywords*:** Aluminum alloy 6061; minimum quantity lubrication; response surface method; TiAlN; TiN; material removal rate; surface roughness.

INTRODUCTION

Dry and near-dry machining operations are the key technology of environment-friendly sustainable manufacturing[1, 2]. The minimum quantity lubrication technique has been serving as the most significant element in sustainable manufacturing since the last decade [3-5]. It aims at reducing the hazardous effects of coolants on the atmosphere and minimizing the resource consumption during a product's life cycle, which includes design, processing, production, packaging, transport, the use of the product and its disposal [6]. In operations that use traditional flood-cooling methods, coolant handling costs more than the fluid itself. For the wet machining of aluminum castings, for example, coolant-related costs are 10–20% of total machining costs—roughly twice the costs of the cutting tools. But of this, only 25% is for the lubricant itself; the rest goes towards coolant supply maintenance (42%) and operational energy costs (33%). According to [7], the total costs of cutting fluids incurred during a machining process amount to about 7% to 17% of the total machining cost. Therefore the reduction in the amount of cutting fluids used during a machining process is a direct indicator of sustainable manufacturing [8]. MQL ensures the safety of the environment and the worker and is a cost-effective technique. The objective of MQL is to use the metal-working fluid in such a quantity that the final product, chip and machine remain a dry and safe environment. This amount is usually three to four orders of magnitude less than is normally used in wet machining The typical flow rate for MQL is about 50–500ml/hr [9, 10]. MQL machining has been acknowledged as an alternative to dry and wet machining on account of its eco-friendly distinctiveness. A considerable amount of research in the mentioned field has also established its potential application in many practical machining operations [11]. Machining with MQL has been widely applied in machining processes such as drilling [12-14], milling [1, 6, 15-21], turning [13, 22, 23], and MQL grinding [24-28].

With the rising global drive towards optimization, sustainable manufacturing is also inclining to manufacturing process optimization. For optimization, not only the use of a reduced quantity of metal cutting lubricants is important but also its optimized quantity. Optimum machining parameters can play a major role in the efficient consumption of machines and materials. In workshop practices the input machining parameters and variables are determined from handbooks and suppliers' data but optimum cutting data is essential for any machining operation for an effective, inexpensive process that is correlated with sustainable development. The objective of this study is to experimentally investigate the machining characteristics of aluminum alloy in end mill processes for flooded and MQL techniques using coated carbide tools.

MATERIALS AND METHODS

Design of Experiments

The machining variables considered in this research are spindle speed, feed rate, depth of cut and the minimum quantity lubricant flow rate. The central composite design approach of response surface methodology is used for the design of experiments in order to find the effects of parameters and combinations of parameters. Five levels of machining variables are selected for the MQL employing a TiAlN-coated carbide cutting tool. Design matrices are shown in Table 1, respectively.

Table 1. Design of experiment matrix for MQL conditions.

Factors	Levels				
	1	2	3	4	5
Cutting speed (rpm)	5252	5300	5400	5500	5548
Depth of cut (mm)	0.52	1.0	2.0	3.0	3.5
Feed rate f_z (mm/min)	288	318	379	440	4769
MQL flow rate (ml/min/nozzle)	0.013	0.016	0.022	0.0275	0.030

Materials Properties

This research is performed to determine the machinability of aluminum alloy 6061-T6 under minimum quantity lubrication. The study of the aluminum alloy workpiece was conducted with different types of cutting tool. To achieve acceptable tool wear, the speed of machining was set to the optimum. Tables 2 and 3 show the chemical, mechanical and thermal properties of AA6061-T6. It is observed that the thermal conductivity is high, which reduces the chance of adhesion during machining. The dimensions of the workpiece used in this study are 100 × 100 × 30 mm.

Table 2. Physical properties of AA6061-T6.

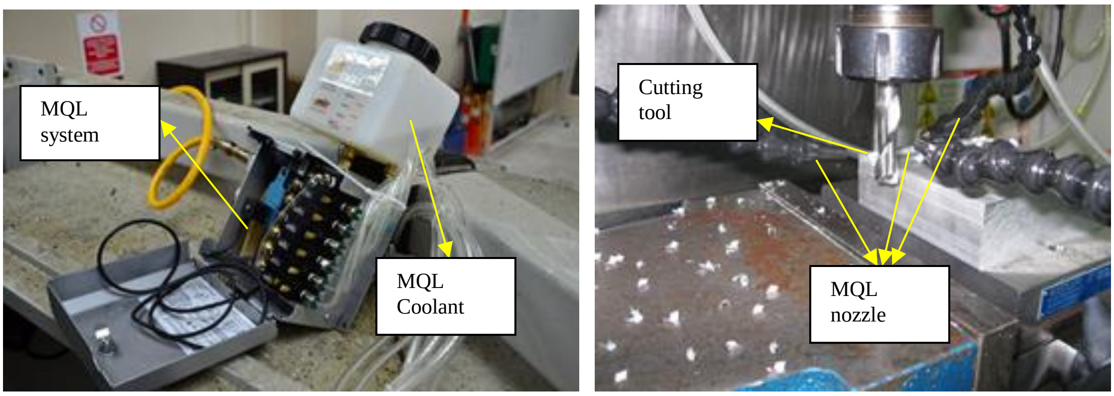
Component	Si	Mn	Mg	Ti	Zn
Weight (%)	0.4–0.8	Max 0.15	0.8–1.2	Max 0.15	Max 0.25

Table 3. Mechanical and thermal properties of AA6061-T6.

Properties	Value	Unit
Hardness, Brinell	95	-
Hardness, Knoop	120	-
Hardness, Rockwell A	40	-
Hardness, Rockwell B	60	-
Hardness, Vickers	107	-
Ultimate tensile strength	310	MPa
Tensile yield strength	276	MPa
Elongation at break	12	%
Elongation at break	17	%
Modulus of elasticity	68.9	GPa
Density	2.7	g/cc
Specific heat capacity	0.896	J/g-°C
Thermal conductivity	167	W/m-K
Melting point	652	°C

Figure 1. CNC end milling machine HAAS VF-6.

Figure 1 shows the CNC end milling machine HAAS VF-6 used to perform the machining with coated carbide inserts. The experiments conducted are based on the design of experiments mentioned in earlier sections. The minimum quantity lubricant used in this experiment is specially designed cutting oil UNIST 2210, which is a commercial non-toxic, vegetable oil-based cutting fluid. Three nozzles were fixed on the machine spindle and were set 26 degrees approximately from horizontal and 120 degrees apart so that they could cover the whole machining area. Figure 2 shows the MQL system with the coolant used and the nozzle configuration.

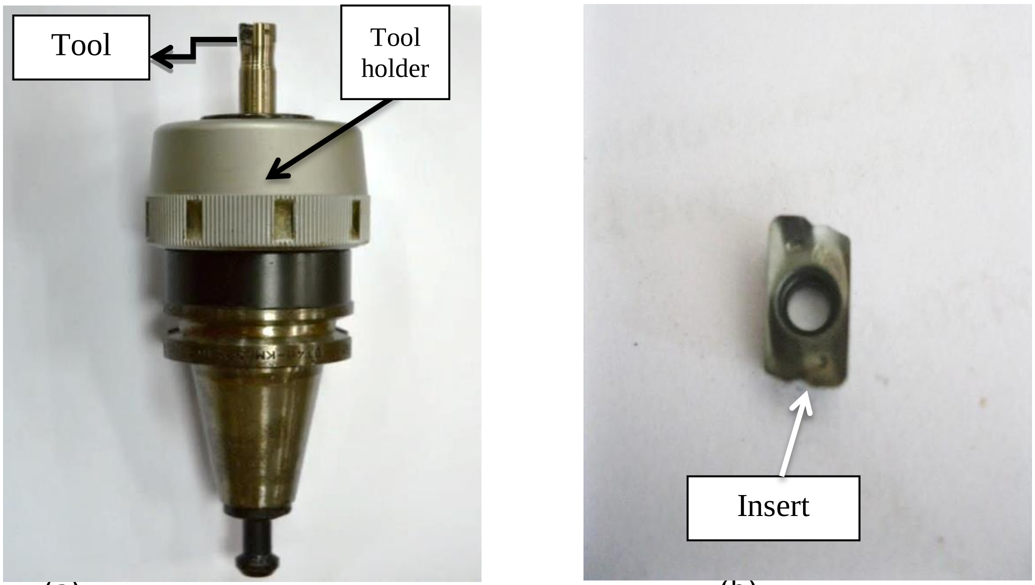


(a) (b)

Figure 2. (a) MQL system and UNIST 2210 coolant; (b) arrangement of nozzles.

Cutting Tool

The cutting tools used for this experiment are coated carbide cutting tools with PVD coatings TiAlN. According to [29], coated carbide is suitable for machining because it is possible to employ the carbide- and nitride-based tool materials at cutting speeds that are so low that mechanical wear predominates. The cutting tool, tool holder and insert are shown in Figure 3 and the composition of the carbide inserts is signified in Table 4.



(a) (b)

Figure 3. (a) Tool holder and cutting tool insert, (b) insert coated carbide tool.

Table 4. Composition of the coated carbide inserts.

Type	Composition	Hardness/coating thickness	Grade & make
PVD TiAlN-coated	Co 12.5%; mixed carbides 2.0%; WC balance	HV 1380 / 4 µm	ISO-HC P40M40, XDKT070304SR-M50, CERATIZIT

RESULTS AND DISCUSSION

The measured values of surface roughness and material removal rate under flood cooling conditions are listed in Table 5. Corresponding regression coefficients for the surface roughness and material removal rate are given in Table 6. The measured values of the surface roughness and material removal rate for the two coated inserts with minimum quantity lubrication are given in Table 7. Corresponding regression coefficients for the surface roughness and material removal rate are given in Table 8. Response surface modeling has been used to develop the mathematical models in terms of the machining parameters by using the technique of minimum quantity lubrication. Second-order statistical models have been developed based on the surface roughness and material removal rate results.

Table 5. Measured values of average surface roughness and material removal rate under flood cooling machining conditions.

Speed (RPM)	Feed rate (mm/min)	Depth of cut (mm)	Surface roughness (μm)	MRR (mm^3/min)
5400	379	0.37	0.311	1513.5
5300	318	1.00	0.851	3422.8
5300	440	1.00	0.396	4914.3
5500	318	1.00	0.555	3522.0
5500	440	1.00	0.277	4722.2
5237	379	2.00	1.361	8371.5
5400	279	2.00	0.773	6319.4
5400	379	2.00	0.830	8868.1
5400	379	2.00	0.775	8217.8
5400	379	2.00	0.908	8454.2
5400	379	2.00	0.867	8572.5
5400	379	2.00	1.015	8406.9
5400	379	2.00	0.913	8513.4
5400	479	2.00	0.764	10803.2
5563	379	2.00	1.223	8040.4
5300	318	3.00	1.202	10188.9
5300	440	3.00	1.161	14413.6
5500	318	3.00	1.234	10913.1
5500	440	3.00	1.538	13384.0
5400	379	3.63	1.363	14780.1

Regression Modeling

Table 8 shows that the model for surface roughness contains four squared terms, four linear terms and six interaction terms. The overall regression is significant with a p-value 0.000<0.05. All the four squared terms (Speed x Speed; Feed rate x Feed rate; Depth of cut x Depth of cut and MQL flow rate x MQL flow rate) show significance, i.e., the data obtained follow a curved trend. The linear term of the feed rate and the interaction between the feed rate and MQL flow rate also show significance. The quadratic model thus obtained, which shows a correlation of the surface roughness with input parameters, is given in Eq. (1). R^2 –value and lack-of-fit are 93.12% and 0.482, respectively.

$$\begin{aligned} R_a = & -234.691 + 0.092397x_1 - 0.06537x_2 + 0.182275x_3 - 11.03x_4 + 0.0000106x_1x_2 \\ & + 0.000132x_1x_3 - 0.001645x_1x_4 - 0.00048x_2x_3 - 0.01234x_2x_4 + 0.233333x_3x_4 \\ & - 8.98\times10^{-6}\,x_1^2 + 2.40\times10^{-5}\,x_2^2 - 0.18559x_3^2 + 4.044785x_4^2 \end{aligned} \quad (1)$$

Table 6. Estimated regression coefficients for surface roughness and material removal rate under flood cooling machining conditions.

Term	Surface roughness		Material removal rate	
	Coefficient	p-value	Coefficient	p-value
Regression	-	0.000	-	0.000
Linear	-	0.001	-	0.044
Square	-	0.001	-	0.105
Interaction	-	0.002	-	0.001
Constant	428.8845	0.000	-477754	0.045
Speed	-0.15276	0.000	160.5648	0.063
Feed rate	-0.05008	0.110	230.614	0.018
Depth of cut	-5.83747	0.007	2998.716	0.559
Speed x Speed	0.00001356	0.000	-0.01341	0.087
Feed rate x Feed rate	-0.00001631	0.034	-0.00023	0.990
Depth of cut x Depth of cut	-0.035	0.187	-156.308	0.052
Speed x Feed rate	0.0000107	0.067	-0.04191	0.018
Speed x Depth of cut	0.00103	0.009	-0.26562	0.776
Feed rate x Depth of cut	0.002041	0.003	8.204713	0.000

The material removal rates measured for MQL machining are listed in Table 8 along with the respective designs of experiment. Regression coefficients and analysis of variance is used to check the adequacy. The most significant terms are the quadratic term of depth of cut and the interaction of the feed rate with the depth of cut. The overall regression shows a significant p-value (0.000<0.05). The quadratic model for material removal rate is expressed as in Eq. (2). R^2 -value and lack-of-fit are 99.39% and 0.255, respectively.

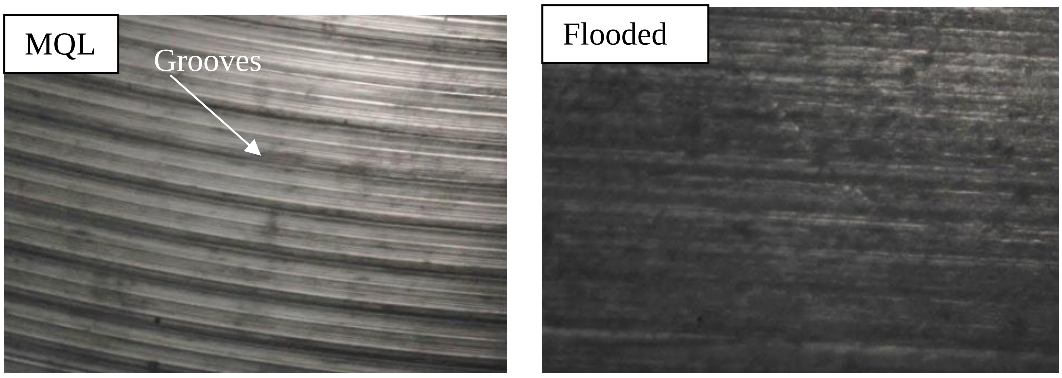
$$\begin{aligned} MRR = & 569187.1 - 221.819x_1 + 146.9746x_2 + 6218.277x_3 - 564.521x_4 \\ & - 0.02217x_1x_2 - 1.05522x_1x_3 + 1.770059x_1x_4 + 12.07621x_2x_3 \\ & - 10.1636x_2x_4 + 389.7401x_3x_4 + 0.021267x_1^2 \\ & - 0.02739x_2^2 - 273.433x_3^2 - 4723.67x_4^2 \end{aligned} \quad (2)$$

Table 7. Measured values of average surface roughness and material removal rate under minimum quantity lubrication (MQL) conditions

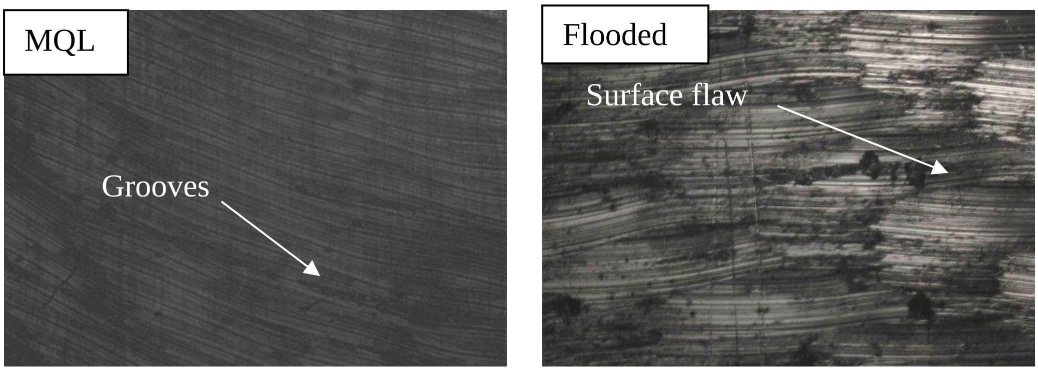
Speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	MQL flow rate (ml/min)	Surface roughness (µm)	MRR (mm^3/min)
5252	379	2.00	0.6525	0.562	9086.8
5300	318	1.00	0.48	0.845	3523.0
5300	318	1.00	0.825	0.486	3477.3
5300	318	3.00	0.48	1.034	11042.1
5300	318	3.00	0.825	0.875	10621.5
5300	440	1.00	0.48	1.017	5456.6
5300	440	1.00	0.825	0.516	5238.3
5300	440	3.00	0.48	1.175	15642.2
5300	440	3.00	0.825	0.563	15351.1
5400	288	2.00	0.6525	1.033	6680.0
5400	379	0.52	0.6525	0.212	2069.2
5400	379	2.00	0.39	1.505	8460.2
5400	379	2.00	0.6525	0.971	8773.5
5400	379	2.00	0.6525	1.091	8710.8
5400	379	2.00	0.9	0.803	8836.2
5400	379	3.48	0.6525	0.745	14601.6
5400	469	2.00	0.6525	1.132	10711.8
5500	318	1.00	0.48	0.749	3680.7
5500	318	1.00	0.825	0.623	3422.8
5500	318	3.00	0.48	0.819	9885.3
5500	318	3.00	0.825	1.098	10779.2
5500	440	1.00	0.48	1.346	5092.79
5500	440	1.00	0.825	0.606	4365.25
5500	440	3.00	0.48	1.496	14756.75
5500	440	3.00	0.825	0.906	14413.57
5548	379	2.00	0.6525	0.816	9713.51

Table 8. Estimated regression coefficients for surface roughness under minimum quantity lubrication (MQL) machining conditions.

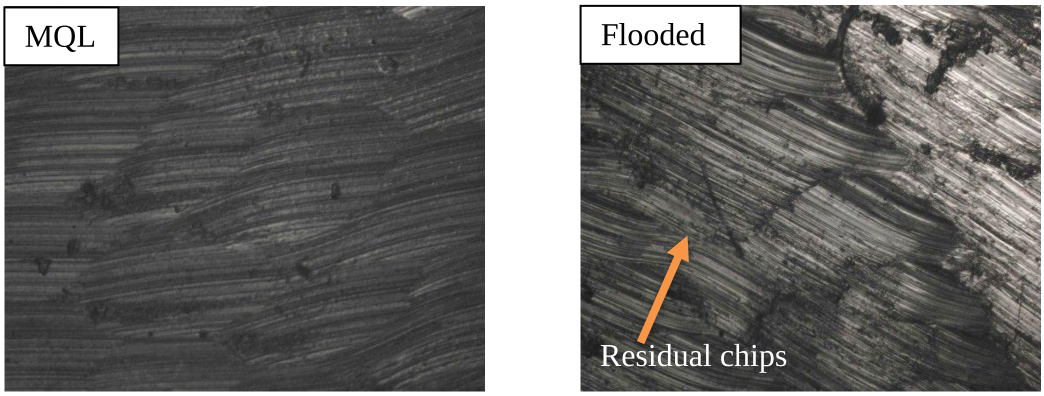
Term	Surface roughness		Material removal rate	
	Coefficient	p-value	Coefficient	p-value
Regression	-	0.000	-	0.000
Linear	-	0.072	-	0.074
Square	-	0.001	-	0.044
Interaction	-	0.018	-	0.011
Constant	-234.691	0.069	569187.1	0.178
Speed	0.092397	0.054	-221.819	0.153
Feed Rate	-0.06537	0.043	146.9746	0.072
Depth of cut	0.182275	0.916	6218.277	0.068
MQL flow rate	-11.03	0.288	-564.521	0.374
Speed x Speed	-8.98 E-06	0.045	0.021267	0.134
Feed rate x Feed rate	2.40 E-05	0.046	-0.02739	0.748
Depth of cut x Depth of cut	-0.18559	0.001	-273.433	0.007
MQL flow rate x MQL flow rate	4.044785	0.012	-4723.67	0.592
Speed x Depth of cut	1.06 E-05	0.060	-0.02217	0.079
Speed x Feed rate	0.000132	0.676	-1.05522	0.116
Speed x MQL flow rate	-0.001645	0.377	1.770059	0.375
Feed rate x Depth of cut	-0.00048	0.363	12.07621	0.001
Depth of cut x MQL flow rate	0.233333	0.218	389.7401	0.115



(a) Cutting speed



(b) Feed rate



(a) MQL (b) flooded

(c) Depth of cut

Figure 4. Image of surface roughness for maximum cutting speed, feed rate and depth of cut for MQL and flooded conditions

Figure 4(a) shows the surface condition of the machined aluminum alloy 6061T6 taken using an optical microscope. The flooded machined workpiece has a wavier pattern, composed of more valleys and a coarser surface finish compared to the minimum quantity lubrication surface finish. Comparing MQL and flooded conditions in terms of cutting speed, both are associated with each other's factor but MQL has a better result, where the points in the diagram can be seen to be the lowest in surface roughness at every speed. This means that the surface roughness value is superior in MQL compared to flooded machining. The images also show that with flooded machining the surface roughness increases when the cutting speed increases, while the surface roughness of MQL decreases when the cutting speed increases. Figure 4(b) shows the comparison of MQL and flooded conditions in terms of feed rate, where both are associated with each other's factor but MQL has a better result, where the points in the diagram can be seen to be the lowest in surface roughness compared to the flooded surface roughness. This means that the surface roughness value is superior in MQL, while the flooded condition shows the highest surface roughness value. The flooded machined workpiece has a wavier pattern, composed of more valleys and has a coarser surface finish compared to the minimum quantity lubrication surface finish. The MQL surface finish is smoother and has minimal swirl marks compared to the flooded machining. Figure 4(c) shows comparison of the surface finish of aluminum alloy 6061T6 in terms of depth of cut by using MQL machining and flooded machining, with images taken using the optical microscope. The flooded machined surface finish has a wavier pattern, composed of more valleys compared to the minimum quantity lubrication surface finish. The MQL surface finish is smoother compared to the flooded machining. As the depth of cut increases, the surface finishes of aluminum alloy become rougher. The MQL has a uniform swirled and bright buffed finish, while flooded machining produced a large-pattern matte finish.

Comparison of Predicted Response Variables

Figure 5 shows the comparison of predicted surface roughness in flood cooling, MQL (oil) and MQL (nanofluid) conditions with TiAlN-coated inserts. In Figure 5(a) variations of surface roughness are plotted with respect to cutting speed at a constant feed rate of 379 mm/min and depth of cut of 1.0 mm. Surface roughness in MQL (oil) machining gradually decreases with increasing flow rates. The surface roughness values predicted by the models for MQL machining are lower than those predicted for the flood cooling models. Only for the mid-range of cutting speed, i.e. 5350 to 5450 rpm, the surface roughness for flood cooling shows some improvements on the surface roughness furnished from an MQL flow rate of 0.48 ml/min, while for all the other flow rates, the surface roughness is always lower than the flood cooling predicted values. The variation of surface roughness for flood cooling follows an exact inverse pattern with MQL machining. As depth of cut increases to 2.0 mm (Figure 5(b)), the predicted values of the response in flood cooling are higher than those predicted from the MQL models. For a depth of cut of 3.0 mm and feed rate kept at 379 mm/min (Figure 5(c)), the surface roughness predicted from the MQL models is lower than the flood cooling values for all values of the MQL flow rate.

Variation of surface roughness with feed rate at constant depth of cut and speed shows a mixed effect (Figure 6). For a depth of cut of 1.0 mm and MQL flow rate of 0.48 ml/min the surface roughness predicted by the MQL machining models is higher than those predicted from the models for flood cooling (Figure 6(a)). As the MQL flow rate increases to 0.65 ml/min and 0.83 ml/min, the surface finish for MQL machining is superior. When the depth of cut is increased to 2.0 mm (Figure 6(b)), the predicted surface roughness increases in all cases, including flood cooling and MQL conditions. With depth of cut at 2.0 mm and MQL flow rates at 0.65 ml/min and 0.83 ml/min the predicted response is lower than the response from the flood cooling models. When the depth of cut is further increased to 3.0 mm (Figure 6(c)), the surface roughness values from flood cooling are much higher.

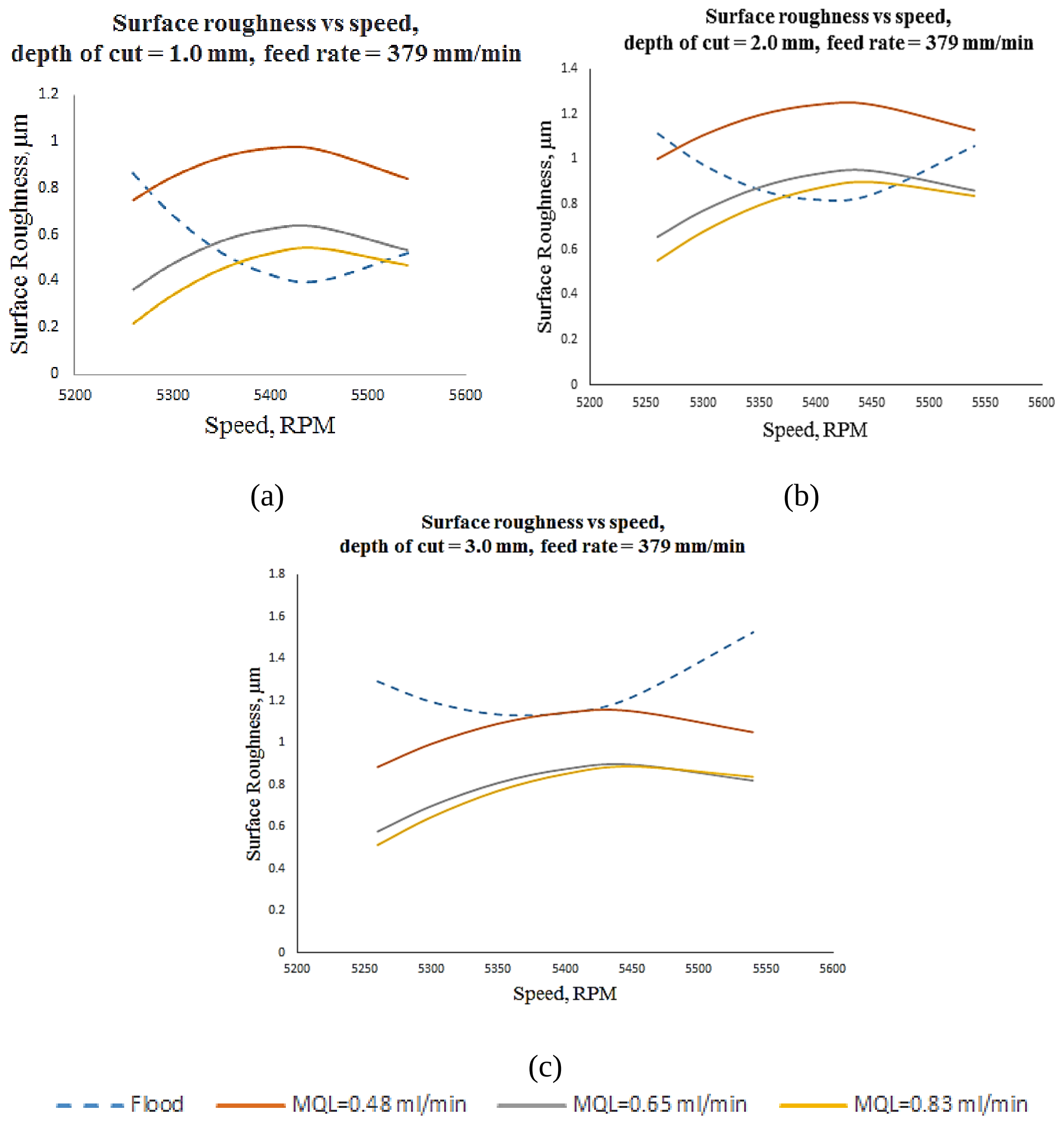


Figure 5. Comparison of model-predicted surface roughness against cutting speed at constant feed rate and depth of cut for TiAlN-coated insert

With increasing depth of cut, the variation of predicted surface roughness in flood cooling and MQL machining conditions is plotted in Figure 7. For a feed rate of 318 mm/min at constant speed, the flood cooling predicted values are higher. The surface roughness predictions show an increasing trend with increasing depth of cut. As the feed rate increases to 379 mm/min (Figure 7(b)), the surface roughness with MQL machining is higher. At a feed rate of 440 mm/min (Figure 7(c)), the surface finishes predicted are comparable in both environments, but the MQL flow rate at this feed rate yields a superior surface finish with increasing depth of cut.

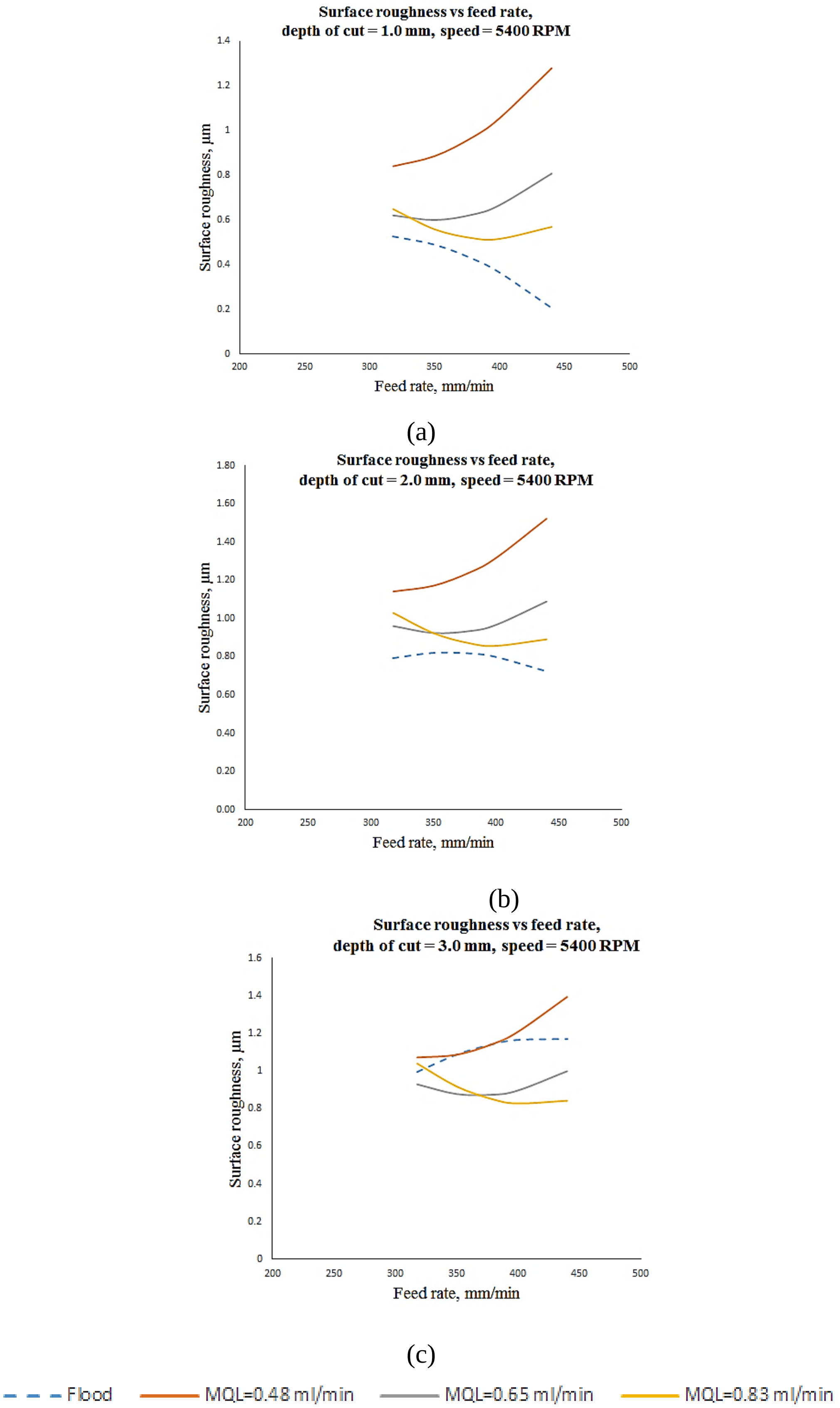


Figure 6. Comparison of model-predicted surface roughness against feed rate at constant speed and depth of cut.

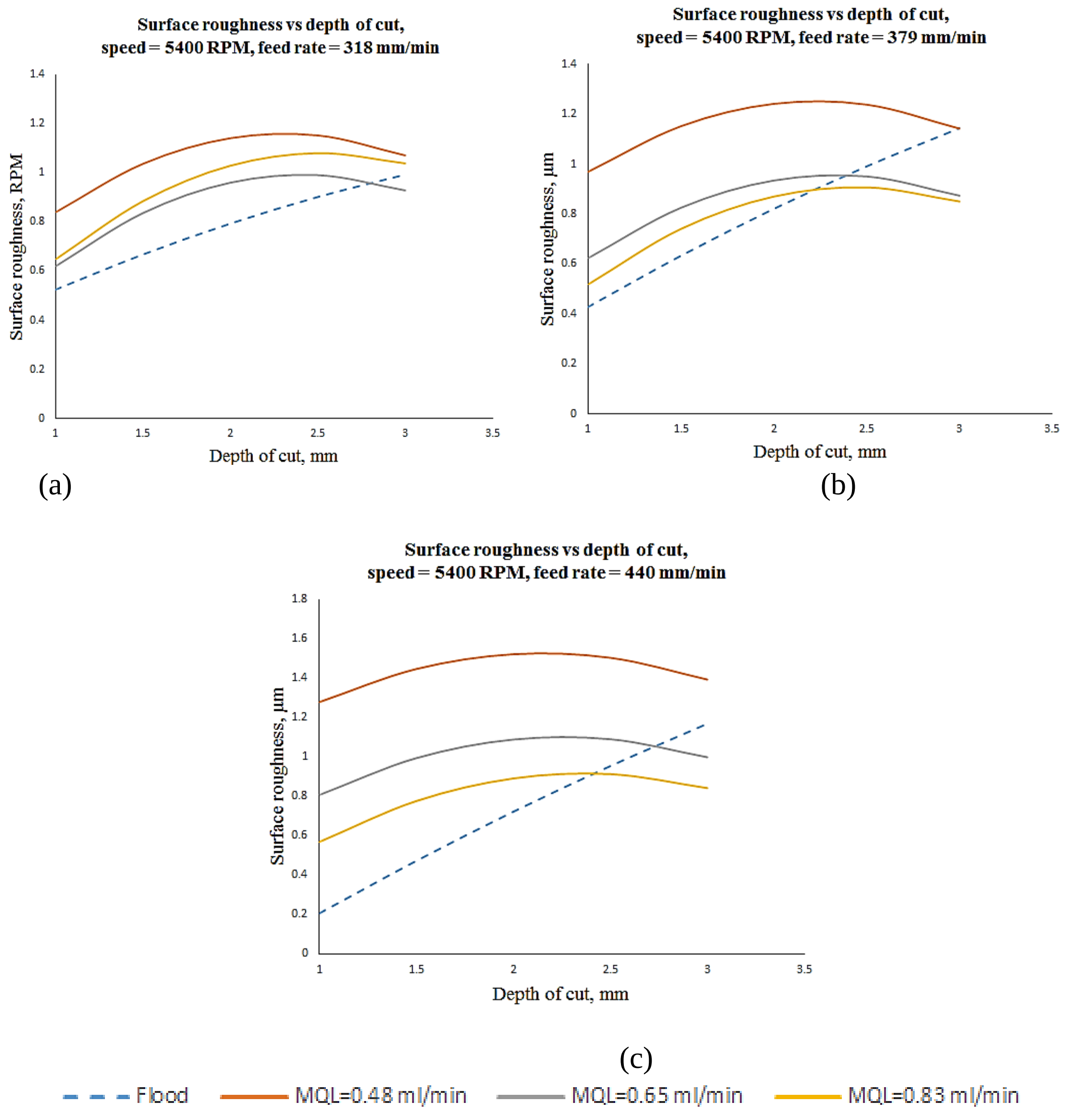


Figure 7. Comparison of model-predicted surface roughness against depth of cut at constant speed and feed rate.

CONCLUSIONS

Machining parameters such as feed rate, spindle speed, depth of cut and MQL flow rate (in the case of MQL machining) play a significant role in the machinability and productivity of a process. In this study, the effects of machining parameters on surface quality and material removal rate are investigated in flood cooling and MQL machining conditions. Second-order regression models are developed and ANOVA is applied for analyzing the experimental data. The results show that surface roughness is considerably affected by depth of cut, followed by feed rate and spindle speed. Surface roughness increases with depth of cut and spindle speed, while it decreases with increasing feed rate. The material removal rate is significantly affected by the interaction of the feed rate and depth of cut, with depth of cut being the most effective parameter on material rate. The results of machining with flood cooling are compared with those from MQL machining and it is concluded that the MQL machining results in very comparable results in terms of surface roughness and material removal rate, although at most of the design points the MQL surface roughness values are much lower than those from flood machining.

ACKNOWLEDGEMENTS

The authors would like to acknowledgements Ministry of Education Malaysia and Universiti Malaysia Pahang for providing laboratory facilities and financial support under project no. RDU110110 and Postgraduate Grant Scheme no. GRS140310.

REFERENCES

[1] Najiha MS, Rahman MM, Kamal M, Yusoff AR, Kadirgama K. Minimum quantity lubricant flow analysis in end milling processes: A computational fluid dynamics approach. Journal of Mechanical Engineering and Sciences. 2012;3:340-5.

[2] Che Ghani SAB, Cheng K, Minton T. Back chip temperature in environmentally conscious turning with conventional and internally cooled cutting tools. Journal of Mechanical Engineering and Sciences. 2013;4:356-72.

[3] Najiha MS, Rahman MM, Yusoff AR, Kadirgama K. Investigation of flow behavior in minimum quantity lubrication nozzle for end milling processes. International Journal of Automotive and Mechanical Engineering. 2012;6:768-76.

[4] Najiha MS, Rahman MM, Yusoff AR. Modeling of the end milling process for aluminum alloy AA6061t6 using HSS tool. International Journal of Automotive and Mechanical Engineering. 2013;8:1140-50.

[5] Najiha MS, Rahman MM. A Computational Fluid Dynamics Analysis of Single and Three Nozzles Minimum Quantity Lubricant Flow for Milling. International Journal of Automotive and Mechanical Engineering. 2014;10:1891-900.

[6] Rahman M, Kumar AS, Salam MU. Experimental evaluation on the effect of minimal quantities of lubricant in milling. International Journal of Machine Tools and Manufacture. 2002;42:539-47.

[7] Weinert K, Inasaki I, Sutherland JW, Wakabayashi T. Dry machining and minimum quantity lubrication. CIRP Annals - Manufacturing Technology. 2004;53:511-37.

[8] Marksberry PW, Jawahir IS. A comprehensive tool-wear/tool-life performance model in the evaluation of NDM (near dry machining) for sustainable manufacturing. . International Journal of Machine Tools and Manufacture. 2008;48:878-86.

[9] Thakur DG, Ramamoorthy B, Vijayaraghavan L. Optimization of minimum quantity lubrication parameters in high speed turning of superalloy Inconel 718 for sustainable development. World Academy of Science, Engineering and Technology. 2009;54():224-6.

[10] Dhar NR, Kamruzzaman M, Ahmed M. Effect of minimum quantity lubrication (MQL) on tool wear and surface roughness in turning AISI-4340 steel. Journal of Materials Processing Technology. 2006;172.

[11] Tan XC, Liu F, Coo HJ, Zhang H. A decision making frame work model of cutting fluid selection for green manufacturing and a case study. nternational Journal of Machine Tools and Manufacture. 2002;129:467-70.

[12] Filipovic A, Stephenson DA. Minimum quantity lubrication applications in automotive power-train machining. Machining Science and Technology. 2006;10:3-22.
[13] Davim JP, Sreejith PS, Silva J. Turning of brasses using minimum quantity of lubricant and flooded lubricant conditions. Materials and Manufacturing Processes. 2007;22:45-50.
[14] Heinemann R, Hinduja S, Barrow G, Petuelli G. Effect of MQL on the tool life of small twist drills in deep-hole drilling. International Journal of Machine Tools and Manufacture. 2006;46:1-6.
[15] Rahman M, Kumar AS, Salam MU. Evaluation of minimal quantities of lubricant in end milling. International Journal of Advanced Manufacturing Technology. 2001;18:235-41.
[16] Lacalle LNLD, Angulo C, Lamikiz A, Sanchez JA. Experimental and numerical investigation of the effect of spray cutting fluids in high speed milling. Journal of Materials Processing Technology. 2006;172:11-5.
[17] Su YL, Liu TH, Su CT, Yao SH, Kao WH, Cheng KW. Wear of CrC-coated carbide tools in dry machining. Journal of Materials Processing Technology. 2006;171:108-17.
[18] Liao YS, Lin HM. Mechanism of minimum quantity lubrication in high speed milling of hardened steel. International Journal of Machine Tools and Manufacture. 2007;47:1660-6.
[19] Kadirgama K, Rahman MM, Ismail AR, Bakar RA. Finite element analysis of HASTELLOY C-22HS in end milling. Journal of Mechanical Engineering and Sciences. 2011;1:37-46.
[20] Puvanesan M, Rahman MM, Najiha MS, Kadirgama K. Experimental investigation of minimum quantity lubrication on tool wear in aluminum alloy 6061-t6 using different cutting tools. International Journal of Automotive and Mechanical Engineering. 2014;9:1538-49.
[21] Razak NH, Rahman MM, Kadirgama K. Experimental study on surface integrity in end milling of hastelloy C-2000 superalloy. International Journal of Automotive and Mechanical Engineering. 2014;9:1578-87.
[22] Wakabayashi T, Sato H, Inasaki I. Turning using extremely small amounts of cutting fluids. JSME International Journal. 1998;41:143-8.
[23] Kamata Y, Obikawa T. High speed MQL finish-turning of Inconel 718 with different coated tools. Journalof Material Processing Technology. 2007;192:281-6.
[24] Baheti U, Guo C, Malkin S. Environmentally conscious cooling and lubrication for grinding. In: Performance PotISoIMT, editor.1998. p. 643-54.
[25] Hafenbraedl D, Malkin S. Environmentally-conscious minimum quantity lubrication (MQL) for internal cylindrical grinding. Transactions of North American Manufacturing Research Institution/Society of Manufacturing Engineers (NAMRI/SME); 2000: 149-54.
[26] Silva LR, Bianchi EC, Catai RE, Fusse RY, Franca TV. Study on the behavior of the minimum quantity lubricant - MQL technique under different lubricating and cooling conditions when grinding ABNT 4340 steel. Journal of the Brazilian Society of Mechanical Sciences and Engineering 2005;27:192-9.
[27] Rahman MM, Kadirgama K, Ab Aziz AS. Artificial neural network modeling of grinding of ductile cast iron using water based SiO2 nanocoolant. International Journal of Automotive and Mechanical Engineering. 2014;9:1649-61.

[28] Yusoff AR, Mohamed Suffian MRZ, Taib MY. Literature review of optimization technique for chatter suppression in machining. Journal of Mechanical Engineering and Sciences. 2011;1:47-61.
[29] Ghani JA, Choudhury IA, Masjuki HH. Wear mechanism of TiN coated carbide and uncoated Cermets tools at high cutting speed applications. Journal of Materials Processing Technology. 2004;153-154:1067-73.