Queensland University of Technology
Brisbane Australia

This may be the author's version of a work that was submitted/accepted for publication in the following source:

Senevirathne, S W Mudiyanselage Amal Ishantha & Punchihewa, H. K.G. (2017)
Comparison of tool life and surface roughness with MQL, flood cooling, and dry cutting conditions with P20 and D2 steel.
IOP Conference Series: Materials Science and Engineering, *244*, Article number: 012006.

This file was downloaded from: https://eprints.qut.edu.au/208205/

© 2017 The Author(s)

This work is covered by copyright. Unless the document is being made available under a Creative Commons Licence, you must assume that re-use is limited to personal use and that permission from the copyright owner must be obtained for all other uses. If the document is available under a Creative Commons License (or other specified license) then refer to the Licence for details of permitted re-use. It is a condition of access that users recognise and abide by the legal requirements associated with these rights. If you believe that this work infringes copyright please provide details by email to qut.copyright@qut.edu.au

License: Creative Commons: Attribution 4.0

Notice: *Please note that this document may not be the Version of Record (i.e. published version) of the work. Author manuscript versions (as Submitted for peer review or as Accepted for publication after peer review) can be identified by an absence of publisher branding and/or typeset appearance. If there is any doubt, please refer to the published source.*

https://doi.org/10.1088/1757-899x/244/1/012006

IOP Conference Series: Materials Science and Engineering

Comparison of tool life and surface roughness with MQL, flood cooling, and dry cutting conditions with P20 and D2 steel

To cite this article: S W M A I Senevirathne and H K G Punchihewa 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **244** 012006

Comparison of tool life and surface roughness with MQL, flood cooling, and dry cutting conditions with P20 and D2 steel

S W M A I Senevirathne[1] and H K G Punchihewa[2]

1, 2 Department of Mechanical Engineering,
University of Moratuwa
Moratuwa, Sri Lanka
amal@mech.mrt.ac.lk , hkgpunchihewa@gmail.com

Abstract. Minimum quantity lubrication (MQL) is a cutting fluid (CF) application method that has given promising results in improving machining performances. It has shown that, the performance of cutting systems, depends on the work and tool materials used. AISI P20, and D2 are popular in tool making industry. However, the applicability of MQL in machining these two steels has not been studied previously. This experimental study is focused on evaluating performances of MQL compared to dry cutting, and conventional flood cooling method. Trials were carried out with P20, and D2 steels, using coated carbides as tool material, emulsion cutting oil as the CF. Tool nose wear, and arithmetic average surface roughness (Ra) were taken as response variables. Results were statistically analysed for differences in response variables. Although many past literature has suggested that MQL causes improvements in tool wear, and surface finish, this study has found contradicting results. MQL has caused nearly 200% increase in tool nose wear, and nearly 11-13% increase in surface roughness compared flood cooling method with both P20 and D2. Therefore, this study concludes that MQL affects adversely in machining P20, and D2 steels.

1. Introduction

Cutting Fluid (CF) or Metal Working Fluid (MWF) are highly important in metal cutting, as these fluids provide three main functions in machining: Primary function- heat transfer from the cutting area; Two secondary functions- providing lubrication in cutting area, and removing the debris from the cutting area. Most common type of fluid used in metal cutting is emulsion CF [1]. However, the expenditure for cutting fluid in the European automotive industry is to be nearly 20% of the total manufacturing cost [2]. According to the same source, the cost of tools was only 7.5% of the total manufacturing cost, making the cutting fluid cost to be comparatively high than other costs associated with manufacturing. Typically, metal cutting operations are generating a great amount of heat, therefore it is obvious that most of the energy consumed by the operation is converted into heat [3]. If not controlled properly, this heat will affect the cutting system adversely, leading in to poor performances in cutting systems, and manufacturing defects as well [3]. Thus, effective heat dissipation from the working area is essential to bring down manufacturing defects, and improve performances in the cutting systems such as reducing tool wear, reducing surface roughness of machined parts, etc. There are many CF application methods developed in industry such as flood cooling and high pressure cooling [1]. Development on material has demanded more performance from these CFs and CF application methods, but found to be insufficient for machining modern material. There are newer methods developed, for example, cryogenic machining and minimum quantity lubrication (MQL), in the recent history [1]. However, under numerous circumstances, these newer methods have also shown limitations [4], [5]. Previous studies have shown that, both cryogenic machining and MQL machining have shown promising results [6][7]. However, cryogenic machining has several disadvantages over MQL machining such as higher cost and potential safety hazards.

In MQL a minute amount of CF is mixed with high-pressure air and the resulting aerosol is directed to the cutting area through a nozzle that flutters aerosol to the cutting area at high speed [8], [9] [10]. The flow rate of CF is typically 50 – 400 ml/hour [4], [11]–[15]. While air in the aerosol provides the cooling function and chip removal, the liquid provides lubrication and by droplet evaporation, it also provides cooling [16]. Primarily, the CF will absorb heat from the cutting area due to evaporation, and in addition, to a minor extent, by vaporisation also [17]. MQL method does have several advantages over the other CF application methods. Since the amount of CF being used is low, the chip, work-piece, and the tool holder will have low amount of fluid residue after the machining operation making cleaning function easier and cheaper [17]. Also the cutting operation can be easily observed as the CF is not obstructing the view as in flood cooling method. However, previous research shows that the cooling capacity of MQL is depending on the work-tool material combination. The effect of MQL on machining AISI P20 and D2 tool steels has not been previously done. However, these two tool steels are popular in the tool making industry, and hence warrants an investigation.

2. Methodology

A custom designed MQL aerosol application system which comprises of refrigeration system and CF aerosol distribution system, was used for the experiments. After reviewing previous literature, an initial set of parameters were selected for the experiment, and further refined after a pilot run. The response variable was the wear of the tool tip, and the arithmetic average surface roughness (Ra) of the machined work-piece. The results of the pilot study were also used to further refine the experiment parameters. A two level factorial experiment was designed [18]. Work-piece material was taken as the level one with two types of material, i.e. AISI P20 and AISI D2. Three cooling conditions, i.e. dry cutting, conventional flood cooling, and MQL, were taken as the second level.

During the trials, parameters were controlled as given in Table 1. In order to enable comparison of results with past research, and ensure simplicity of the machining operation and ease of operation, straight turning operation was selected for the study. Feed rate and depth of cut were selected based on the tool manufacturers' recommendation and by reviewing literature. Spindle speed was also chosen following the tool manufacturers' recommendation based on the surface cutting speed. Length of the cut was determined by the results of the pilot run. MQL aerosol flow rate, pneumatic pressure, nozzle target location and nozzle direction was selected through a literature review.

Table 1. Controlled parameters for the experiments.

Parameter	Value	Parameter	Value
Turning Operation	Straight	Flow Rate (MQL)	160 ml/ hour
Feed Rate	0.5 mm / rev	Pneumatic Pressure	7 bar
Depth of Cut	0.5 mm	Flow Rate (Flood)	9 l/min
Length of the Cut	500 mm	Nozzle Target Area	Rake Face
Surface Cutting Speed	150 m/min	Nozzle Angle (H)	$\approx 60^{o}$
Spindle Speed	1220 rpm	Nozzle Distance	150 mm

2.1. Experimental setup

A 3.0 kW horizontal manual lathe machine was used for the straight turning operation. A total of 18 work-pieces with 9 pieces from AISI P20 and 9 pieces from AISI D2 tool steels were used for the trials. The cylindrical work-pieces were of 45 mm diameter with 100 mm length. The cutting length of 500 mm was obtained by 10 passes of 50 mm. Chemical Vapour Deposition (CVD) coated carbide turning tool from a popular commercial brand was used to machine both types of work-piece material.

The coating on the tool was TiCN-Al_2O_3-Ti with a hardness of 90.3 HRA. The prepared CF had a ratio of 1:9 emulsion oil to water by volume, followed by the CF manufacturers' recommendation. The orientation of the aerosol was in a vertical plane perpendicular to the axis of rotation of the work piece with an upward inclination to the horizontal by 60º and the aerosol was directed to the rake face of the tool as shown in Figure 1. The MQL aerosol nozzle was calibrated to spray 160 ml of CF per hour with a pneumatic pressure of 7 bar. The orifice diameter of the nozzle was 1.2 mm. calibration of the nozzle was performed by measuring the time taken to spray a measured quantity of CF. After each 500 mm long simple turning operation, both the workpiece and the cutting tool were coded to enable identification. Afterwards the workpiece was wrapped in an airtight plastic container and immediately taken to measure the roughness of its machined surface. This process was repeated for all 18 workpieces to minimise the effect of corrosion and contamination of the machined surface.

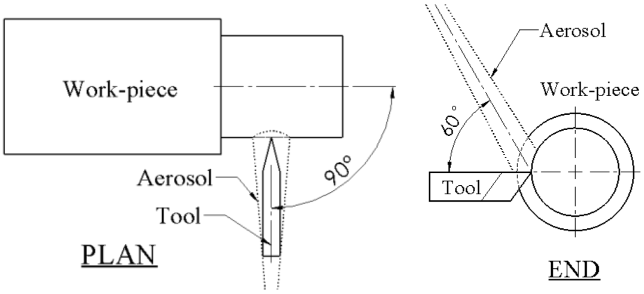

Figure 1. Target direction and orientation of the aerosol.

2.2. Response variables

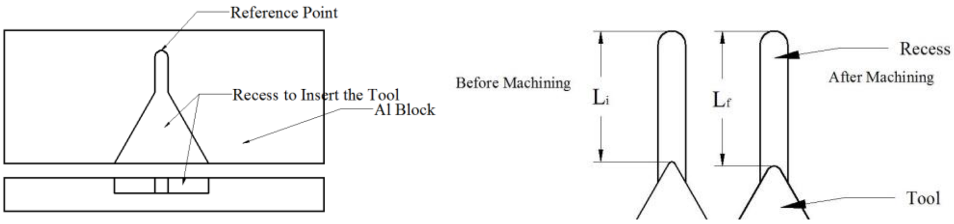

Figure 2. Tool nose wear was measured by the difference in the measured distance from the tool tip to a reference point in a measuring jig.

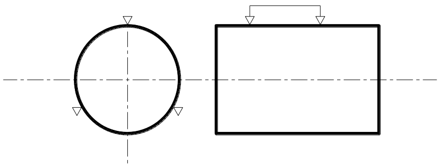

Figure 3. Surface roughness measurement locations and direction.

A CNC-CMM, was used for measuring tool tip radius, and distance between tip and reference point in the specially made measuring jig as shown in the Figure 1. The CMM has a resolution of 0.0001 mm. Since tool nose radius readings were given unexpected results, it was decided to use direct nose wear as the indicative measure for tool wear. A measuring jig was prepared by measuring several samples of unused tools and creating a recess in a steel block as shown in Figure 2, using a CNC machining centre. Used tool was inserted in this block and distance between the worn nose and reference point in the jig was measured as illustrated in Figure 2. Tool nose wear was found by taking the difference in tool nose and reference point distance with used tool and unused tool. A digital surface roughness tester was used to obtain the surface roughness of the machined surface. It directly read the arithmetic average surface roughness (Ra) along the measured distance to an accuracy of 0.01 µm and a cut-off length of 2.5 mm. The surface roughness was measured parallel to the principal axis, across the lay at three different locations on the periphery of machined cylindrical surface, which were 120º apart, as shown in Figure 3. All measurements were repeated thrice.

3. Analysis

3.1. Statistical significance of differences in groups of tool nose wear and Ra

One-way ANOVA was done for each P20 and D2 groups separately for each response variable, tool nose wear and Ra. Tool nose wear readings and Ra readings of three groups of cooling condition as shown in Table 2 with an equal sample size and repeated for each work material. Samples from dry cutting, flood cooling, and MQL were taken for each work material as the groups. A null hypothesis "Mean tool nose wear / Ra of all groups are equal" with an alternative hypothesis "At least one mean tool nose wear / Ra is different" was used for the test.

Table 2. Groups for ANOVA of tool nose wear and Ra.

	Tool nose wear			Ra		
Group	Dry	Flood	MQL	Dry	Flood	MQL
P20	✓	✓	✓	✓	✓	✓
D2	✓	✓	✓	✓	✓	✓

3.2. Statistical significance of differences in between mean Tool wear groups and in between mean Ra groups

Single-tailed Student's t-test was used to compare means of tool nose wear Ra of work-pieces in each cooling condition using 95% confidence level for each of the work material separately. Mean Ra of each group was tested against the rest to evaluate the difference in means Ra is significant or not, and high or low if the difference is found to be significant. Pairs of mean Ra of groups were taken as shown in Table 3. This was repeated for both work material for mean tool nose wear and mean Ra.

3.3. Effect of work material on Ra

Single-tailed Student's t-test was used to evaluate the significance of mean tool nose wear and mean Ra of each cooling condition in each material against the corresponding group of the other material. The pairs for the Student's t-test is shown in Table 3.

Table 3. Pairs of mean tool nose wear and mean Ra for Student's t-test.

Same material groups

Group / Group	Dry	Flood	MQL
Dry		×	×
Flood			×
MQL			

Between P20 and D2 groups

		P20		
		Dry	Flood	MQL
D2	Dry	×		
	Flood		×	
	MQL			×

4. Results

4.1. Tool nose wear and Ra in AISI P20 and D2

Mean Tool nose wear calculated with the three different cooling methods, and Ra measured for AISI P20 and D2 is shown in Table 4. With each work material, the mean tool nose wear measured with MQL machined tools was observed to higher than that of dry cutting and flood cooling methods. Further, the mean tool nose wear in tools machined with each work material seen to be similar. Mean of arithmetic average surface roughness measured in each steel is shown in Table 4. P20 work-pieces had its highest mean Ra with MQL while D2 had the highest with dry cutting. Lowest mean Ra with either work material was seen with flood cooling. Patterns of Ra through dry cutting, flood cooling, and MQL were dissimilar for the two materials

Table 4. Tool nose wear and Ra results for AISI P20 material.

	Mean Tool Nose Wear (mm)		Mean Ra (μm)	
Cooling Condition	P20	D2	P20	D2
Dry	0.0643	0.0557	1.514	1.623
Flood	0.0283	0.0299	1.406	1.373
MQL	0.0867	0.0907	1.594	1.518

4.2. Analysis of Variance (ANOVA)

One-way ANOVA with a confidence level of 95% resulted following conclusions. P20 tool nose wear groups concluded with an F-value of 33.37, and P-value of 0.001 (<0.05). Hence it is concluded that at least one mean tool nose wear of the tested three groups of cooling condition is significantly different from the others. D2 tool nose wear groups concluded with an F-value of 42.12, and P-value of 0.000 (<0.05). Hence it is concluded that at least one mean tool nose wear of the tested three groups of cooling condition is significantly different from the others. P20 Ra groups concluded with an F-value of 308.32, and P-value of 0.000 (<0.05). Hence it is concluded that at least one mean Ra of the tested three groups of cooling condition is significantly different from the others. D2 Ra groups concluded with an F-value of 251.87, and P-value of 0.003 (<0.05). Hence it is concluded that at least one mean Ra of the tested three groups of cooling condition is significantly different from the others.

4.3. Students' t-test on tool nose wear and Ra groups of AISI P20

Students' t-test on tool nose wear in each cooling condition resulted that, tool nose wear with dry cutting, and flood cooling is significantly lower than that of MQL. Compared to flood cooling, dry cutting has given significantly higher tool nose wear. t-test on Ra of P20 groups showed that, Ra with dry cutting, and flood cooling was significantly lower than that of MQL. Flood cooling has given significantly lower Ra than dry cutting. Results are presented in Table 5.

Table 5. Students' t-test results of tool nose wear, and Ra with P20.

	Tool nose wear		Ra	
	Flood	MQL	Flood	MQL
Dry	Significantly high	Significantly low	Significantly high	Significantly low
Flood		Significantly low		Significantly low

4.4. Students' t-test on tool nose wear groups of AISI D2

Students' t-test on tool nose wear in each cooling condition resulted that, tool nose wear with dry cutting, and flood cooling is significantly lower than that of MQL. Compared to flood cooling, dry cutting has given significantly higher tool nose wear. t-test on Ra of P20 groups showed that, Ra with dry cutting was significantly higher than that of MQL. However, flood cooling has given significantly lower Ra than both dry cutting, as well as lower than MQL. Therefore, Ra with MQL was lower than dry cutting, but higher than flood cooling. Results are presented in Table 6.

Table 6. Students' t-test results of tool nose wear, and Ra with D2.

	Tool nose wear		Ra	
	Flood	MQL	Flood	MQL
Dry	Significantly high	Significantly low	Significantly high	Significantly high
Flood		Significantly low		Significantly low

4.5. Effect of work-piece material on tool nose wear

Students' t-test on groups of tool nose wear of each material with each cooling condition shown in Table 7, proved that, there is no significant difference in mean tool nose wear between the two materials in each cooling condition. In dry cutting condition, the Ra of D2 was seen significantly higher than that of P20. However, in flood cooling, and in MQL, the Ra of D2 was seen to significantly lower that of P20.

Table 7. Comparison of tool nose wear, and Ra in each material.

	Tool nose wear			Ra		
	Dry (P20)	Flood (P20)	MQL (P20)	Dry (P20)	Flood (P20)	MQL (P20)
Dry (D2)	Not sig.			Sig'tly high		
Flood (D2)		Not sig.			Sig'tly low	
MQL (D2)			Not sig.			Sig'tly low

Variation of the mean tool nose wear, and mean Ra with respect to the three cooling methods, and two work material is shown in Figure 4. The differences in mean tool nose wear between the two materials was found to be not significant. D2 showed a larger reduction in Ra with flood cooling compared to dry cutting. D2 had a 15% surface roughness reduction in flood cooling compared to dry cutting, while P20 had only 7% reduction. However, the increase in Ra with MQL compared to flood cooling was, 13% in P20, and 11% in D2. P20 had 206% increase in tool nose wear in MQL compared to flood cooling, while D2 had 203% increment. Tool nose wear was reduced by 56% in P20 with flood cooling compared to dry cutting, while D2 showed a reduction of 46%.

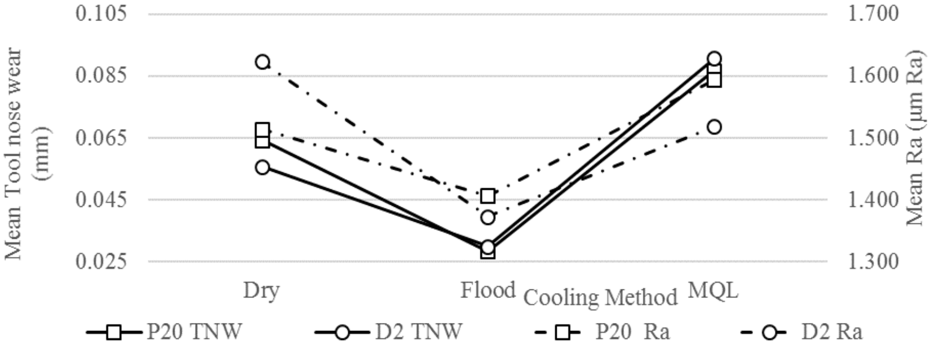

Figure 4. Mean tool nose wear (TNW), and mean Ra variation with cooling method, and work material.

5. Discussion

Although there is literature that suggests, MQL improves tool life and surface roughness in machining, this study found results that contradicts with them. However, it has seen by other researchers that MQL aerosol application has reduced tool life compared to flood cooling in some work-tool material combinations in certain machining conditions [19], [20]. It has been argued by many researchers that the performances of a cooling method, or machining performances in general, does depend on the work and tool materials. Evidence from this study supports that argument, as there is no similar patterns of tool nose wear or Ra with respect to the cooling methods.

Initially it was planned to take tool nose radius as the indicative measurement for tool wear. Radius of the tool nose after the tool was used for turning 500 mm of work-piece, was measured using the CMM. Upon usage, a reduction in the tool nose radius was expected but there were odd results which gave higher tool nose radius than the initial. Further investigation on this matter reveals that the curve approximation done for the tool tip in CMM leads to errors. Picking points on the worn edge with the CMM was vague and hence it was leading in to erroneous results.

The experiment was conducted with only two commonly used work-piece material and one type of tool. This has reduced the generalizability of the findings of the study. Therefore, the experiment needs to be extended to cover more work-piece material types, cutting tool materials, cutting fluid types and environmental conditions.

6. Conclusion

MQL aerosol cooling causes higher tool nose wear in machining AISI P20 and D2 material using coated carbide tools, compared to machining with conventional flood cooling method or dry cutting method.

The surface roughness of the work-pieces of both materials machined with MQL was higher than that obtained with flood cooling method. Particularly in P20 work-pieces, the surface roughness with MQL was even significantly higher to that of dry cutting as well.

Therefore, in terms of improving tool life, or surface finish of the machine parts, MQL does not provide a favourable performance with neither P20 nor D2 steels.

Tool nose wear in coated carbide tools, in machining AISI P20 and D2, in dry cutting, flood cooling condition, or MQL, is not significantly different. However, surface roughness varied significantly with the material. In dry cutting, surface roughness in D2 was significantly lower than P20, while the opposite occurred in flood cooling and MQL.

7. References

[1] E Brinksmeier, M Garbrecht, C Heinzel, T. Koch, and J Eckebrecht, "Current Approaches in Design and Supply of Metalworking Fluids," *Tribol. Lubr. Technol.*, pp. 36–49, 2009

[2] T Brockhoff and A Walter, "Fluid Minimization in Cutting and Grinding," *Abrasives*, pp. 38–42, 1998

[3] S Kalpakjian and S R Schmid, *Manufacturing Engineering and Technology*. Prentice Hall, 2010

[4] N Boubekri, "An Investigation in Drilling 1020 Steel Using Minimum Quantity Lubrication," *Int. J. Appl. Sci. Technol. Vol.*, vol. 1, no. 5, pp. 60–67, 2011

[5] S W M A I Senevirathne and M A R V Fernando, "Effect of Cryogenic Cooling on Machining Performance on Hard to Cut Metals - A Literature Review," in *National Engineering Conference 2012, 18TH ERU Symposium*, 2012, pp. 38–46

[6] H A A Kishawy, M Dumitrescu, E -G Ng, and M A A Elbestawi, "Effect of coolant strategy on tool performance, chip morphology and surface quality during high-speed machining of A356 aluminum alloy," *Int. J. Mach. Tools Manuf.*, vol. 45, no. 2, pp. 219–227, Feb. 2005

[7] Y Sun, B Huang, D A Puleo, and I S Jawahir, "Enhanced machinability of Ti-5553 alloy from cryogenic machining: Comparison with MQL and flood-cooled machining and modeling," *Procedia CIRP*, vol. 31, pp. 477–482, 2015

[8] M Z A Yazid, C H Che Haron, J A Ghani, G A Ibrahim, and A Y M Said, "Surface integrity of Inconel 718 when finish turning with PVD coated carbide tool under MQL," *Procedia Eng.*, vol. 19, pp. 396–401, Jan. 2011

[9] K Weinert, I Inasaki, J W W Sutherland, and T Wakabayashi, "Dry Machining and Minimum Quantity Lubrication," *CIRP Ann. - Manuf. Technol.*, vol. 1, no. 1, pp. 511–537, Jan. 2004

[10] M M A Khan, M A H Mithu, and N R Dhar, "Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid," *J. Mater. Process. Technol.*, vol. 209, no. 15–16, pp. 5573–5583, Aug. 2009

[11] P W Marksberry and I S Jawahir, "A comprehensive tool-wear/tool-life performance model in the evaluation of NDM (near dry machining) for sustainable manufacturing," *Int. J. Mach. Tools Manuf.*, vol. 48, no. 7–8, pp. 878–886, 2008

[12] R Autret and S Y Liang, "Minimum Quantity Lubrication in Finish Hard Turning," in *HNICEM*, 2003, pp. 1–9

[13] S S Bhambale, C V Patil, and S R Nirmal, "Experimental Investigation on Wet Lubrication System in Turning Operation of Mild Steel by Minimizing the Flow Rate of Cutting Lubricants," *Int. J. Eng. Innov. Technol.*, vol. 1, no. 4, pp. 201–205, 2012

[14] N R Dhar, M T Ahmed, and S Islam, “An experimental investigation on effect of minimum quantity lubrication in machining AISI 1040 steel,” *Int. J. Mach. Tools Manuf.*, vol. 47, no. 5, pp. 748–753, Apr. 2007
[15] A Attanasio, M Gelfi, C Giardini, and C Remino, “Minimal quantity lubrication in turning: Effect on tool wear,” *Wear*, vol. 260, no. 3, pp. 333–338, Feb. 2006
[16] V Upadhyay, P K Jain, and N K Mehta, “Minimum Quantity Lubrication Assisted Turning - An Overview,” in *Daaam International Scientific Book 2012*, K. BRANKO, Ed. Vienna: DAAAM International Vienna, 2012, pp. 463–478
[17] T Walker, *The MQL Handbook*. Unist Inc., 2013
[18] D C Montgomery, *Design and Analysis of Experiments Eighth Edition*, Eighth., vol. 2. John Wiley & Sons, Inc., 2013
[19] A D Jayal and A K Balaji, “Effects of cutting fluid application on tool wear in machining : Interactions with tool-coatings and tool surface features,” vol. 267, pp. 1723–1730, 2009
[20] Y Kamata and T Obikawa, “High speed MQL finish-turning of Inconel 718 with different coated tools,” *J. Mater. Process. Technol.*, vol. 192–193, pp. 281–286, Oct. 2007

Acknowledgements

The authors wish to thank the Senate Research Committee (SRC) of University of Moratuwa, Sri Lanka, for funding the research, and National Science Foundation (NSF) of Sri Lanka, for funding dissemination of research findings. Authors express their sincere gratitude for Mr. I.M.J Priyankara, and Mrs. N.H.S. Dias for their technical assistance.