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

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

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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, workpiece, 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.

| 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)        | ~60°        |
| 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-Al₂O₃-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 60° 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.

| Group | Tool nose wear | Ra |
|-------|---------------|----|
|       | 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.

| Same material groups |
|----------------------|
| Group / Group | Tool nose wear | Ra |
| Dry | Flood | MQL | Dry | Flood | MQL |
| Dry | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Flood | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MQL | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Between P20 and D2 groups |
| Group / Group | Tool nose wear | Ra |
|       | P20 | Dry | Flood | MQL |
| D2   | ✓ | ✓ | ✓ | ✓ |

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.

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.

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.

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

| Cooling Condition | Mean Tool Nose Wear (mm) | Mean Ra (μm) |
|-------------------|--------------------------|--------------|
|                   | 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        |

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

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

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

| Tool nose wear | Flood | MQL | Ra  | Flood | MQL |
|----------------|-------|-----|-----|-------|-----|
| Dry            | Significantly high | Significantly low |                |                |
| Flood          |                |                | Significantly high | 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 | Tool nose wear |
|---------------|---------------|
| Dry (P20)     | Flood (P20)   | MQL (P20)     |
| Not sig.      | Not sig.      | Not sig.      |

| Ra            | Ra            |
|---------------|---------------|
| Dry (P20)     | Flood (P20)   | MQL (P20)     |
| Sig’tly high  | Sig’tly low   | 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 been 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 erroneous. 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.

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**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.