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ORIGINAL ARTICLE

Temperatures in fine grinding with minimum quantity lubrication (MQL)

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Abstract Minimum quantity lubrication (MQL) is a promising new fluid delivery technique in grinding. However, the thermal behaviour of the process under such cooling conditions remains unclear. This work reports on the results of a recent investigation of MQL in fine-cut plane surface grinding. The experimental study considered three conditions: conventional low pressure fluid delivery, dry grinding and MQL delivery. Common steels EN8, M2 and EN31 were ground with a general purpose alumina wheel. Conventional fluid used was a general purpose 5% by volume emulsion; MQL fluid was a general purpose machining oil. Grinding temperatures were measured using the single-pole thermocouple method. Grinding temperatures obtained from experiment are compared with those predicted from theory. Results obtained demonstrate that MQL can deliver a comparable thermal performance to conventional flood delivery under the conditions investigated. Grinding kinematics are discussed to explain the outcomes and to improve understanding of MQL grinding performance.

Keywords Minimum quantity lubrication · MQL · Near dry machining · Grinding · Surface temperature · Thermal model

1 Introduction

Grinding is one of the most important processes for high-precision machining. It is a much faster process than polishing and lapping and can shape parts from the solid even down to optical quality. To achieve target quality and productivity, a grinding fluid is almost always employed as it plays a vital role through lubrication and cooling. Lubrication is particularly important to reduce friction and wear of the abrasive grains which result in unwanted changes in machining forces and surface roughness. The lubrication effect of the fluid strongly depends on whether the fluid penetrates the contact zone and generates an effective lubrication layer.

Conventional fluid delivery Alternative strategies for fluid application developed for high-removal rate processes are 'high volume–low velocity' and 'lower volume–high velocity'. In each case, maximum useful flowrate is achieved through the grinding contact region. The technique reduces costs associated with fluid delivery while improving material removal rates achievable through more effective delivery [1]. However, the highest precision grinding processes are performed at lower removal rates using finer-grained wheels for low surface roughness, low dimensional errors and longer wheel life. For these requirements, smaller useful flow rates are preferred, helping to reduce wheel separating forces and maintain high precision. This technique also reduces energy consumption and equipment costs.

Alternative fluid delivery processes The next logical step might appear to be a move towards dry machining. Dry machining satisfies the requirement of environmentally friendly manufacturing [2, 3]. In reality, however, the process is considerably less effective when improvements in machining efficiency, surface finish quality and productivity are required. Tawakoli [4] investigated the effects of ultrasonic vibrations on dry grinding of soft steel and achieved a 70% reduction in grinding forces and improved surface roughness parameters. However, the system required special vibratory arrangements (=*further power input*) and purposely designed wheel characteristics.

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For dry machining, common colloidal-form solid lubricants, such as graphite and molybdenum disulphide [5], owe their superior lubrication properties to a layered morphology and crystal structure. These have been reported to show benefits compared with un-lubricated dry grinding and with conventional wet grinding. However, difficulties have been experienced in the grinding of ductile materials due to wheel loading. Graphite nano-platelets, delivered in a dispersion medium of non-toxic solvent, were investigated [6] and reported to offer comparable performance to conventional fluid delivery. Their diameter and delivery method were found to have a strong effect on process performance, and the study identified challenges in understanding the lubrication mechanism. Cryogenic cooling using liquid nitrogen is another possibility [7, 8]. It offers significant promise and addresses many of the environmental issues. However, the large temperature differences involved influence the dimensions of the workpiece in a poorly controlled manner, affecting the accuracy and repeatability that can be achieved. Also, lubrication is adversely affected by an inert atmosphere, and the occurrence of tensile stresses and poor surface quality were identified as key problems attributed to a lack of lubrication through the contact zone. Further promising work by Torrance [9] reported on a novel method of cooling the grinding process using a water and air mist jet delivered at speeds approaching Mach 1. Improved cooling, high convection coefficients and improved grinding performance were reportedly achieved from the method. However, the volumes of fluid required were very much higher than those expected from a near-dry system. Other methods investigated in the search for better cooling solutions include, for example, intermittent grinding by slotted wheels [10] and on-line ultrasonic cleaning of the wheel surface [11]. Such methods do offer benefit, but they also attract a disadvantage and are consequently less suitable as practical industrial solutions.

Minimum quantity lubrication Minimum quantity lubrication (MQL) refers to the delivery of small volumes of fluid via an aerosol to the cutting region. It has the potential to radically change high-precision grinding practice by drastically reducing coolant consumption, energy costs and waste disposal requirements. In conventional MQL, fluid is delivered immediately prior to the contact zone as a liquid/air mix with typical flow rates less than 0.05 l/h—significantly lower than reduced quantity flood delivery methods typically 360 l/h. MQL fluids include environment-friendly vegetable oils and synthetic esters [12]. These play a vital lubrication role even with very small quantities. Lubrication in MQL occurs under boundary lubrication or 'thin-film' conditions, where the rheological properties of the fluid are not very important and where the degree of separation between the sliding surfaces depends not only the chemical and physical properties of the lubricant but also on the nature of the surfaces and their relative movement [13]. Understanding this phenomenon in MQL grinding will be the key to unlocking its potential and application regimes. Though it has been argued [14] that MQL may be appropriate in a wide range of grinding regimes the work reported in this paper is focussed toward precision grinding with depths of cut (DOC) in the range 5 μm<DOC<25 μm.

2 Experimental study

The aim of the experimental work was to establish the performance of MQL in fine grinding. It was achieved by studying the effects of MQL in comparison to conventional flood delivery and dry grinding conditions. The parameters: grind power P, tangential force F_t, normal force F_n, grinding temperature θ, surface roughness R_a and real depth of cut a_e were measured and used as performance indicators.

2.1 Equipment

Experiments were performed on a Dominator 624 Easy, full CNC grinding machine (Fig. 1), using a general purpose aluminium oxide wheel, type WA 100 JV.

For the conventional grinding tests, a common emulsion of 5% of Castrol Hysol XF was used. The coolant delivery system used was the Arboga Darenth with delivery conditions of 1 bar and approximately 27 m/s fluid velocity.

Grinding tests under MQL were carried out using Castrol Carecut ES1 oil. The MQL system was the Lubrimat L50—lubricating through the spraying method. The MQL system utilised a purpose designed nozzle. It worked at a supplied air pressure of 0.40 MPa and delivered approximately 33 ml/h of oil. A Kistler, Type 9257A, three-component dynamometer was employed to measure tangential and normal forces. The nozzle, dynamometer and thermocouples were calibrated prior to use.

2.2 Temperature measurement

Grinding temperatures were measured using the thermocouple technique. Thermocouples may be placed either in the workpiece or within the surface of the grinding wheel. They may be used in either single- or double-pole configuration. The single-pole thermocouple has been shown to be the simplest and most reliable arrangement and was selected for this research. An Omega CO2-T thermocouple was adapted to a single-pole arrangement (Fig. 2).

With this configuration, a J-type thermocouple forms a junction when the grinding wheel passes over the exposed single pole. The pole is smeared onto the workpiece, thereby forming a junction with the ground surface (Fig. 3).

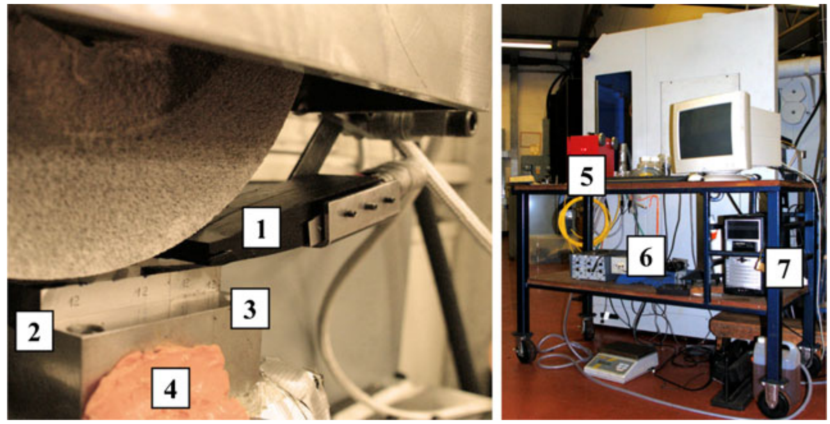

Fig. 1 CNC Jones & Shipman Dominator 624: *1* nozzle, *2* workpiece, *3* dynamometer, *4* thermocouples plugs seal, *5* MQL system, *6* amplifiers, *7* DAQ system

2.3 Procedure

Experimental design was based on the Taguchi method resulting in a high definition L_8 (2^7) orthogonal array (Tables 1 and 2). The three fluid conditions: WET, DRY and MQL were investigated for a range of three materials, in the down-cut mode. Prior to each test, the wheel was dressed. Each test was repeated three times. The mean value of the three tests is presented.

The real depth of cut (DOC) was obtained in a separate process. Surface height readings were taken at 12 defined points along the workpiece surface and the mean value of these measurements used to calculate the real DOC.

3 Measured temperatures

3.1 Temperatures for hardened steel, EN31

These are shown in Fig. 4a, b. In trial A, the achieved specific material removal rates Q'_w are very similar for both MQL and WET; however, temperatures produced by WET are approximately 20% lower than under MQL. The better performance of WET is due to higher cutting efficiency and the effect of improved cleaning action of the larger volume of fluid. It is worth noticing that the temperatures with WET are in the region of the film boiling temperature. This would have the effect of reducing the convection ability of the fluid and hence give rise to higher local temperatures.

In trial B, WET achieved the highest value of Q'_w, whereas the performance of both MQL and DRY were similar. The lowest temperature also occurred with WET. Such a good performance with WET was due principally to the wheel that was designed for very hard material, high speeds and coarse dressing in conventional flood cooling conditions.

The higher temperature observed for DRY is caused by the absence of lubrication. In MQL, wetting of the workpiece–grain interface with fluid aids chip removal reduces loading and hence results in more efficient grinding. This was evidenced through the lower force ratio and better surface finish.

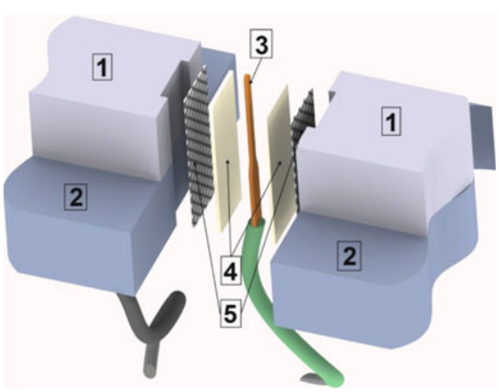

Fig. 2 Schematic of single pole thermocouple configuration with visible groove for the thermocouple, where: *1* workpiece, *2* workpiece base, *3* thermocouple, *4* mica, *5* varnish layer

3.2 Temperatures for hardened steel, M2

In this set of trials, the same grinding conditions as those used in the previous results were applied. However, the workpiece material was a softer (~52HRC) M2 tool steel. Results are presented in Fig. 5a, b.

In trial A, the performance of DRY in terms of temperature, is seen to improve when compared with EN31 steel. There is a small reduction in WET temperatures. However the temperature in MQL was similar to that in WET with a very similar Q'_w. The likely reason for MQL and DRY to provide better results in terms of temperature is that M2 steel is an easier to machine material than EN31 (the HRC hardness value is approximately 10 lower than that of EN31), with more favourable thermal properties.

Different grinding conditions are presented in trial B, where it is seen that M2 steel is an easier to machine material than EN31 and in general produces lower temperatures for MQL and DRY. However, a large decrease in

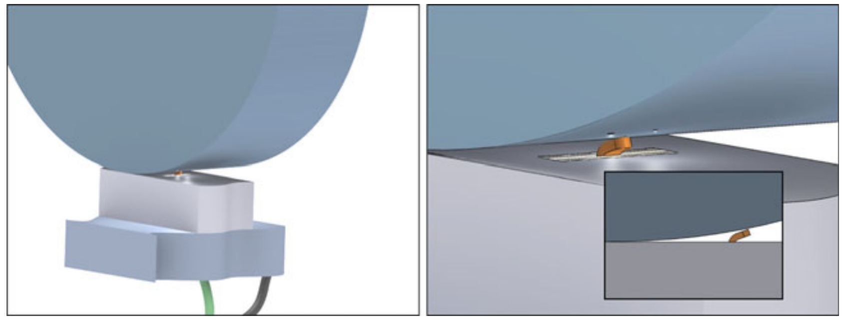

Fig. 3 A passing wheel bends the thermocouple and creates the junction with the workpiece material

temperature under DRY compared to the case for EN31 is observed.

Referring to the above set of trial conditions alone, it is seen that grinding under MQL delivery can result in very similar performance in terms of specific material removal rate and temperature and with further development of the MQL technique even better results may be achieved.

3.3 Temperatures for mild steel, EN8

The much improved cutting efficiency in MQL is noticeable in the case presented in Fig. 6a. This is due largely to the combined effects of lubrication (the lowest friction coefficient was recorded under MQL) and the softer material. Moreover, the temperature is kept at a very low level and actually is lower than in the case of WET.

In the case of DRY, where the process was highly inefficient, the grinding temperature was relatively high for the low Q'_w achieved. The reason for low cutting efficiency was the fine dressing parameters and soft material. There was additionally a problem with lack of wheel cleaning and wetting in DRY.

Under the WET condition, the wheel (fine abrasive and low porosity) tended to struggle with the performance, as it was not suited to this application. In this situation, it is speculated that material would flow plastically upwards and sideways but would not be removed productively (i.e. sliding and ploughing components dominate).

In the trial B, the lowest temperature occurred under MQL and the highest under WET. The relatively low temperature in MQL implies more efficient material removal conditions (the lowest forces ratio was recorded in MQL).

The WET temperature, which was 25% greater than that in DRY, implies film boiling but effective flushing aids the achievement of a higher Q'_w than in DRY.

The value of Q'_w was similar for both DRY and MQL, but the lower temperature in MQL can be attributed to the improved lubrication situation. The good results achieved by MQL indicate a more efficient grinding situation. This demonstrates strong promise for MQL in this region.

4 Theoretical temperatures

In this section, we compare the values of temperature predicted from theory with the temperatures obtained from experiment.

4.1 Thermal analysis

Thermal modelling has greatly clarified the importance of the various physical processes involved in grinding supporting radical developments such as high-efficiency deep grinding [15]. The major advances in the progress towards a reliable thermal model have been fully reported in a wide number of texts and are summarised by Rowe [16]. Equations of the

Table 1 Parameters sets

	Parameter	Level	
		1	2
A	Wheel speed, v_s	25 m/s	45 m/s
B	DOC, a_e	5 µm	15 µm
A×C	Interaction	–	–
C	Workpiece speed, v_w	6.5 m/min	15 m/min
B×C	Interaction	–	–
D	Dressing, Dre	Coarse	Fine
E	Materials, Mat	EN8	EN31/M2

Table 2 Taguchi array

Trial no.	v_s A	a_e B	– A×C	v_w C	– B×C	Dre D	Mat E
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	2	1	2
4	1	2	2	2	1	2	1
5	2	1	2	1	1	2	2
6	2	1	2	2	2	1	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

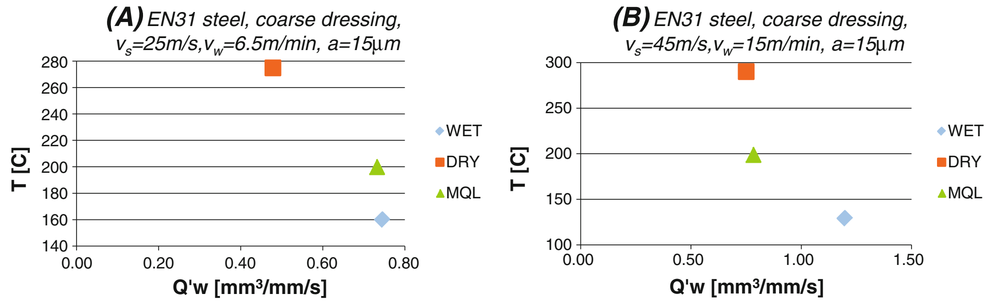

Fig. 4 Temperature as a function of specific removal rate Q'_w for hard material EN31

model have been developed from fundamental laws of heat conduction, from contact mechanics and from fluid dynamics. The thermal model can be employed without calibration. However, the accuracy of the model is considerably improved by testing, taking account of the particular wheels and grinding conditions, and model validation via temperature measurements undertaken in the research laboratory.

The model of Rowe and Morgan [17] is used for temperature prediction in this study as it accommodates workpiece variants, accounts for system deflections and is amenable to this approach. The model also provides for the cases of wet and dry grinding, though it has not been validated under MQL conditions. It is anticipated that fluid convection values are lower for MQL than WET grinding and for highly accurate predictions, partitioning to the fluid may have to be defined. In studies reported by Rowe et al., [18] partitioning to the fluid in conventional operations under WET grinding is typically of the order of 5% to 10%. As a consequence, the DRY model is used for MQL, and slightly higher temperatures for damage are predicted. This errs on the side of safety.

In order to predict temperatures and compare them against experimentally obtained values, the following relationships were used:The grinding power P was monitored and the total process heat flux obtained from:

$$q_t = \frac{P}{b_w\, l_c} \tag{1}$$

where:

b_w is workpiece width
l_c is real contact length.

Real contact length was determined from the orthogonal relationship proposed by Rowe and Qi [19] that includes parameters for elastic deformation, wheel sharpness and contact roughness, that is:

$$l_c = \sqrt{l_g^2 + l_f^2} \tag{2}$$

where l_g is geometric contact length and l_f is the deflection contact length given by:

$$l_f = \sqrt{\frac{8R_r^2 F'_n d_e}{\pi E^*}} \tag{3}$$

where R_r is roughness factor equal to 1 for a smooth cylinder but ranges from 5 to 15 for a grinding wheel [19]. $F_n{}'$ is the specific normal grinding force per unit width, d_e is the equivalent wheel diameter, and E^* is the combined elastic properties of the grinding wheel and workpiece.

$$\frac{1}{E^*} = \frac{1-\upsilon_1^2}{E_1} + \frac{1-\upsilon_2^2}{E_2} \tag{4}$$

where suffix 1 and 2 refer to the wheel and workpiece, respectively, E is the modulus and υ is Poisson's ratio. Values used for this study, obtained from the work of Morgan [20], were: υ_1=0.22; υ_2=0.29; E_1=50 kN/mm^2; E_2=213 kN/mm^2; and R_r=10.

Heat flux to the chips, expressed as:

$$q_{ch} = \frac{e_{ch}\, v_w\, a_e}{l_c} \tag{5}$$

was calculated using the material melting temperature Θ_{mp}. The symbol v_w refers to the workpiece speed and a_e the real depth of cut.

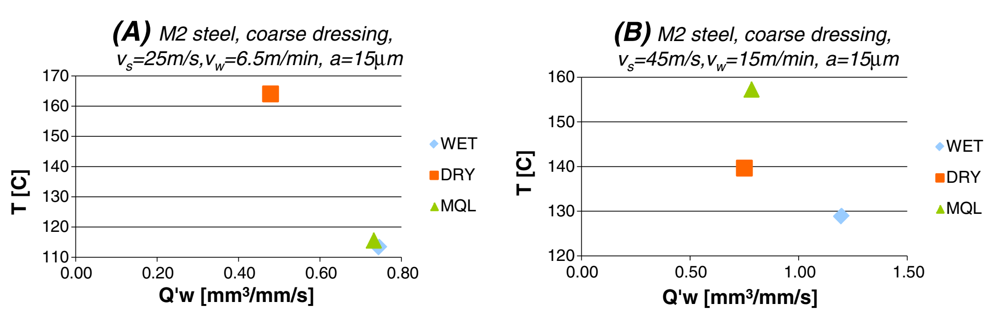

Fig. 5 Temperature as a function of specific removal rate Q'_w for hard material M2

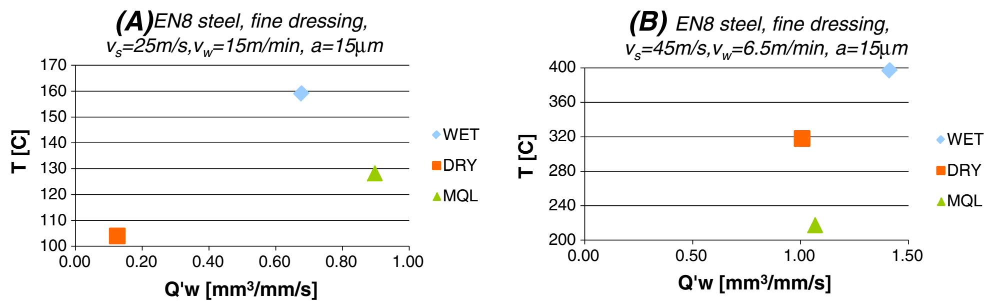

Fig. 6 Temperature as a function of specific removal rate Q'_w for soft material EN8

The workpiece convection factor is calculated as:

$$h_w = \frac{\beta w}{C}\sqrt{\frac{v_w}{l_c}} \tag{6}$$

where:

β_w is the geometric mean thermal property given by:

$$\beta_w = \sqrt{k_w \rho_w c_w}. \tag{7}$$

and k_w is the workpiece thermal conductivity, $\rho_w c_w$ is the product of density and specific heat. The thermal constant C in Eq. 6 is determined from the Peclet number and in conventional processes is approximately unity.

The partition ratio R_{ws} for heat flow to the workpiece and abrasive is

$$R_{ws} = \left[1 + \frac{0.97k_g}{\beta w\sqrt{r_0 v_s}}\right]^{-1} \tag{8}$$

where:

k_g is grain thermal conductivity
r_0 is effective radius of contact of grains.

In each test, a freshly dressed grinding wheel was used resulting in a similar sharpness, and hence, a constant value of r_0=15 µm was used for this analysis.

The maximum temperature for grinding is calculated from:

$$\theta_{max} = \frac{q_t - q_{ch}}{\frac{h_w}{R_{ws}} + h_f} \tag{9}$$

Values of fluid convection factor h_f for water-based fluid vary broadly from 0 to 290,000 W/m^{2}K depending on the effectiveness of fluid delivery and the type of fluid. In dry and burnout conditions, the fluid convection is effectively zero. The value used for this study was h_f=72,000 W/m^{2}K [21].

4.2 Predicted temperatures for hardened steel, EN31

Results for EN31 steel are presented in Fig. 7a, b.

In Fig. 7a, a small difference is observed between the experimental and predicted temperature results for WET grinding. However DRY and MQL cases exhibit a different tendency to WET in that the measured temperature was higher than predicted. It is hard to explain the reason for such a situation, but it may occur due to the value of material properties employed. For the material EN31, there exists in the literature a wide range of values of material properties and the mid-range was used for this study. Applying the higher end values reduces the discrepancy.

The predicted temperatures for both MQL and WET were similar in magnitude. If the model were refined to include fluid convection effects, lower MQL temperatures would be predicted.

For the conditions of Fig. 7b and the case of WET, a reasonable correlation with theory is observed, however, not as good as in Fig. 7a. Again in the cases of DRY and MQL, predicted temperatures are lower than measured. For both conditions A and B, the difference between theory and experiment for MQL is similar though conditions have changed. Moreover in both cases similar measured temper-

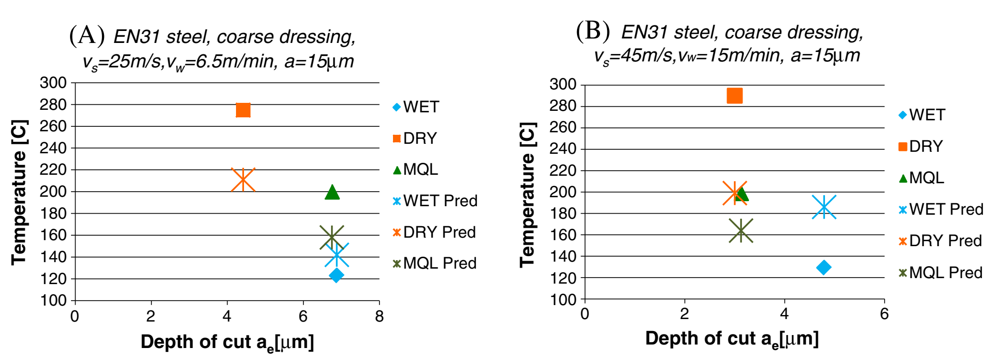

Fig. 7 Experimental and predicted temperature as a function of DOC for EN31 steel

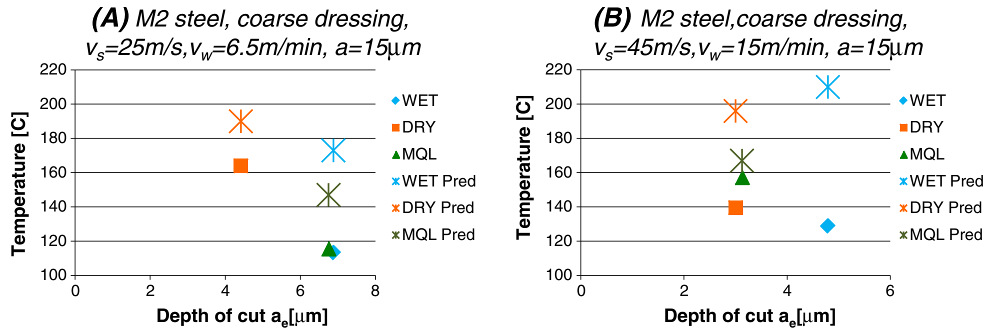

Fig. 8 Experimental and predicted temperature as a function of DOC for M2 steel

ature was registered and is indicative of a repeatable performance under the range of conditions studied.

4.3 Predicted temperatures for hardened steel, M2

The grinding conditions for the M2 trials were identical to those for EN31 steel, and the results are presented in Fig. 8a, b.

In case A, achieved DOC was of the order 4 μm< DOC<7 μm. Predicted temperature values are higher than measured values, though reasonable correlation is observed with MQL and DRY temperature results. The temperature predicted for MQL assumes the DRY situation, and this has the effect of increasing theoretical temperatures. Results for the case of WET do not match as well and may be due to over prediction of fluid convection. It can also be reasoned that a lower value of h_f would help bring these results closer; however, the justification is not suited to all results and additional validation work is necessary on this matter.

The further set of results for M2 steel in case B, see an increase in both wheel and workpiece velocities and in DOC. A relatively large difference occurs between predicted and experimental values in the cases of WET and this time in DRY. There is however good correlation for MQL values. Of further interest are the temperature values predicted for both MQL and DRY. The lower temperatures for MQL align with results one would expect from the process mechanics.

In both cases A and B, predicted temperature under MQL is lower than in WET conditions. Such an observation is important and should be considered in further development of the temperature model employed.

4.4 Predicted temperatures for mild steel, EN8

The final set of results, for mild steel, EN8 are presented in Fig. 9a, b.

In trial A, reasonable correlation is observed between predicted and experimental temperatures for the case of MQL with a difference of approximately 5%. The measured temperature is marginally higher than predicted which suggests that the DRY assumption may be inappropriate for MQL. It is also interesting to note that the lowest temperature generated in this trial was for MQL despite the DOC achieved being the highest in this case.

In the final set of results (case B), a very close match can be seen for the case of WET with a difference of less than 6%. This result suggests that at the higher temperatures, often associated with the deeper cuts, the thermocouple measurements are more consistent.

The results for MQL are similar to DRY differing by approximately 20%. The lowest temperatures are again identified for the case of MQL. However, it is reasoned that there should be little difference between the temperatures under WET and MQL at the same achieved DOC, and it could in fact be the case that the lowest temperature occurs under MQL. It is to be emphasised that the DRY model was

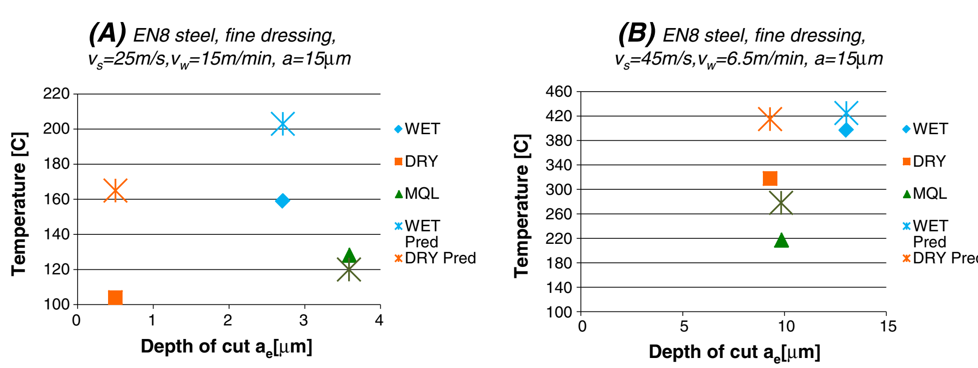

Fig. 9 Experimental and predicted temperature as a function of DOC for EN8 steel

used for prediction of temperatures in MQL and further work on the thermal analysis of MQL is required.

As a final remark, it can be seen that in case of EN8 material, the predicted temperature trends follow those of measured temperature.

5 Discussion

The thermal analysis has worked reasonably well for the case of MQL. This may suggest that earlier assumptions for evaporation being responsible for a small but significant cooling performance may not be entirely correct, as the evaporation of oil will occur only when the grinding temperature exceeds the film boiling temperature. However, no such high temperatures were obtained under MQL. Therefore, a quantitative assessment of the effects of convection remains unclear.

The analytical model does not provide for direct cooling effects resulting from the high speed air jet, though it has been proved that such an effect exists. This aspect should also be taken into account in future studies.

The temperature model has been shown to produce results that correlate well for the cases of WET and DRY. Results for MQL also correlate well, and taking into account current model limitations (grinding below the oil boiling temperature and using surrounding temperature air and oil), it is assumed that the model can be used for maximum grinding temperature prediction. Nevertheless, additional work is required with other grinding cases, to accommodate use of different wheels and material variants to confirm the model validity with MQL. Further work is also needed to assess the sensitivity of the model predictions to changes in the value of convection factor assumed.

6 Conclusions

The thermal performance of MQL is similar to that of WET grinding under the conditions studied. This would suggest an applicable regime for application of the MQL method. The thermal model employed in this study correlates well with measured temperatures.

Although the model produced good results for the MQL regime, further research and model refinement are needed to clarify uncertainties, such as the presence of a high speed jet cooling effect and convection. Nevertheless, current results tend to indicate that the MQL phenomenon comes directly from decreased force ratio.

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