DEVELOPMENT OF NEW COOLING

METHODS FOR GRINDING

by

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Finally, I would like to dedicate this thesis to my parents for their continuous encouragement.
Declaration

I declare that this thesis contains no material which has been previously presented for the award of any other degree or diploma in any university or institution; and to the best of my knowledge, the material is original except where due reference is made in the text of the thesis.

NGUYEN, Thai Hien-Hoa
Abstract

This research aimed to develop new cooling methods to replace, or at least minimise, the use of currently used grinding coolants which are known to be harmful to the environment. The methods used involved the application of a cold air and vegetable oil mist mixture (CAOM), and the use of liquid nitrogen as cooling media. Allied research focused on the development of a segmented grinding wheel equipped with a coolant chamber.

The feasibility of a grinding system using CAOM was assessed on the surface grinding of plain carbon steel 1045. It was found that at low material removal rates, ground surfaces were obtained with a quality comparable to that from grinding with a conventional coolant in association with a reduction of grinding forces. There was no significant difference in the subsurface hardness of the components using CAOM, although the latter method showed a stronger dependence of surface residual stresses on the depth of cut due to the limit in cooling capacity of CAOM.

The effects of using liquid nitrogen as a cooling medium on the microstructure of quenchable steel were explored. It was found that a martensite layer was induced on the ground surface. The microstructure featured a dispersion of very fine carbides within the martensite lattice, resulting in a remarkable increase in hardness and high compressive residual stresses within the layer. The topography of the ground surfaces indicated that the material was predominantly removed by brittle fracture. Furthermore surface oxidisation was suppressed.

In the interest of coolant minimisation, a segmented wheel equipped with a pressurized coolant chamber was developed. A higher quality ground surface was obtained in
conjunction with a coolant saving of up to 70%. In addition, the adhesion of ground chips on the wheel surface largely disappeared. Furthermore, surface tensile residual stresses caused by thermal deformation were minimised.

The mechanism of coolant disintegration to form mists using this type of wheel system was studied. The Weber theory for Newtonian jet instability was applied to quantitatively determine the contribution of coolant flow rate to mist and ligament modes. A semi-analytical model was then developed to predict the mist flow rate by taking into account both grinding parameters and coolant properties. The model prediction was in agreement with experimental measurements.

Based on the principles of fluid motion and the mechanisms of spin-off and splash, analytical models for both conventional and segmented wheels were established to provide a physical understanding of the mechanisms of coolant penetration into the grinding zone. Coolant minimisation was evident using the segmented wheel where the coolant pumping power into the grinding zone increased with wheel speed, but for the conventional wheel it decreased. A quantitative analysis was developed that accounted for the coolant properties and system design characteristics governing the penetration mechanism revealed by the theory established above. In conjunction with the mist formation analysis, the developed model offers a practical guideline for the optimal use of grinding coolants in achieving a balance between the demands of productivity and care for the environment.
## Nomenclature

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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>$A$</td>
<td>area</td>
<td>(m$^2$)</td>
</tr>
<tr>
<td>$B$</td>
<td>grinding wheel width</td>
<td>(m)</td>
</tr>
<tr>
<td>$b_{cb}$</td>
<td>inner coolant chamber width</td>
<td>(m)</td>
</tr>
<tr>
<td>$b_r$</td>
<td>inner rim width of a segmented wheel</td>
<td>(m)</td>
</tr>
<tr>
<td>$C_c$</td>
<td>pumping power coefficient in Eq.(7.22)</td>
<td>(m$^2$)</td>
</tr>
<tr>
<td>$C_f$</td>
<td>coolant chamber design coefficient defined in Eq.(6.7)</td>
<td>(m$^{-4}$)</td>
</tr>
<tr>
<td>$C_{fv}^*$</td>
<td>geometrical influence number in Eq.(8.10)</td>
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</tr>
<tr>
<td>$C_m$</td>
<td>coefficient of mist generation’s correlation, Eq.(6.14)</td>
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<tr>
<td>$C_o$</td>
<td>grinding wheel concentration number</td>
<td></td>
</tr>
<tr>
<td>$C_p$</td>
<td>coefficient of pumping power’s correlation, Eq.(8.12)</td>
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</tr>
<tr>
<td>$C_s$</td>
<td>pumping power coefficient in Eq.(7.29)</td>
<td>(m$^2$)</td>
</tr>
<tr>
<td>$C_{\psi}$</td>
<td>dimensionless separation coefficient in Eq.(7.36)</td>
<td></td>
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<tr>
<td>$C_\theta$</td>
<td>specific heat in Eq.(4.1)</td>
<td>(Jkg$^{-1}$K$^{-1}$)</td>
</tr>
<tr>
<td>$D$</td>
<td>grinding wheel diameter</td>
<td>(m)</td>
</tr>
<tr>
<td>$D_m$</td>
<td>diameter of an inspirable drop in Eq.(A7.3)</td>
<td>(m)</td>
</tr>
<tr>
<td>$\overline{D}_m$</td>
<td>Rosin-Rammler mean of drop diameters in Eq.(A7.3)</td>
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<tr>
<td>$d_l$</td>
<td>diagonal length of an indent, shown in Fig. 2.23</td>
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</tr>
<tr>
<td>$d_l$</td>
<td>diameter of a coolant ligament</td>
<td>(m)</td>
</tr>
<tr>
<td>$d_{sub}$</td>
<td>depth below the ground surface</td>
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</tr>
<tr>
<td>$d_w$</td>
<td>grinding depth of cut</td>
<td>(m)</td>
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<tr>
<td>$d_X$</td>
<td>lattice spacing</td>
<td>(m)</td>
</tr>
<tr>
<td>$erf$</td>
<td>Gaussian error function, Eq.(4.1)</td>
<td></td>
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<tr>
<td>$F$</td>
<td>force</td>
<td>(N)</td>
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\( F(D_m) \) \quad \text{fraction of drops with diameter less than } D_m, \text{ Eq.(A7.3)}

\( f \) \quad \text{film thickness on the wheel surface in Eq.(7.32), (m)}

\( f_c \) \quad \text{centrifugal force exerting on a unit volume of coolant, (Nm}^3\text{)}

\( g \) \quad \text{gravitational constant, (ms}^2\text{)}

\( H \) \quad \text{pumping head, (m)}

\( h \) \quad \text{equivalent liquid layer thickness in Eq.(7.8), (m)}

\( h_\theta \) \quad \text{heat transfer coefficient, (Wm}^2\text{K}^{-1}\text{)}

\( K \) \quad \text{correction coefficient in Eq.(7.34), (m)}

\( k_\theta \) \quad \text{thermal conductivity, (Wm}^{-1}\text{K}^{-1}\text{)}

\( k_c \) \quad \text{coolant concentration}

\( l \) \quad \text{break-up length of a ligament in Eq.(6.17), (m)}

\( l_{cv} \) \quad \text{control volume arc length defined in Figs. 7.1 and 7.2, (m)}

\( l_w \) \quad \text{wheel-work contact length, (m)}

\( M \) \quad \text{moment, (Nm)}

\( \dot{m} \) \quad \text{mass flow rate, (kgs}^{-1}\text{)}

\( \dot{m}_c \) \quad \text{mass flow rate of chemical additives contaminated in mist, (kgs}^{-1}\text{)}

\( N \) \quad \text{total number of segments fitted in a wheel}

\( N_l \) \quad \text{number of ligaments, in Eq.(6.1)}

\( \vec{n} \) \quad \text{normal unit vector}

\( n_{ch} \) \quad \text{number of perforated holes in contact with the coolant chamber}

\( n_{cv} \) \quad \text{number of perforated holes within the pumping control volume}

\( OES \) \quad \text{occupational exposure standard, Eq.(A7.1), (kgm}^{-3}\text{)}

\( Oh \) \quad \text{Ohnesorge number, } (Oh = \mu(\rho\sigma l_1)^{-0.5})

\( P \) \quad \text{pumping power, (W)}

\( P^* \) \quad \text{power number, } (P\rho^{-1}R^{-5}\omega^{-1})
$P_g$  
grinding power, (W)

$P_{\text{min}}$  
minimum pumping power required, (W)

$p$  
pressure, (Pa)

$p_l$  
indenting load in Eq.(2.2), (kg)

$p_{\text{sur}}$  
mean surround resistance pressure in Eq.(6.8), (Pa)

$p_{\text{tran}}$  
mean transverse pressure on a ligament in Eq.(6.8), (Pa)

$Q$  
total flow rate of coolant, (m$^3$s$^{-1}$)

$Q^*$  
flow rate number, ($Q/R^3\omega$)

$Q_c$  
spin-off flow rate in Eq.(7.33), (m$^3$s$^{-1}$)

$Q_{vp}$  
film liquid flow rate in Eq.(7.30), (m$^3$s$^{-1}$)

$Q_j$  
jet flow rate in Eq.(7.30), (m$^3$s$^{-1}$)

$Q_i$  
flow rate of coolant contributed to ligament mode, (m$^3$s$^{-1}$)

$Q_m$  
mist flow rate, (m$^3$s$^{-1}$)

$Q_{\text{max}}$  
maximum coolant flow rate required, (m$^3$s$^{-1}$)

$Q_{\text{min}}$  
minimum coolant flow rate required, (m$^3$s$^{-1}$)

$Q_{m, \text{max}}$  
allowable mist flow rate, (m$^3$s$^{-1}$)

$Q^*_m$  
mist flow rate ratio in Eq.(6.13)

$Q_N$  
flow rate of liquid nitrogen, (m$^3$s$^{-1}$)

$Q_{vp}$  
splashing flow rate in Eq.(7.30), (m$^3$s$^{-1}$)

$Q_v$  
ventilation rate in Eq.(A7.2) (m$^3$/s)

$r$  
integrated radius in Eqs.(7.12) and (7.23), (m)

$R$  
radius, (m)

$Ra$  
average surface roughness, (m)

$Re$  
Reynolds number defined in Eq.(6.13), ($Re^* = \rho \omega R^2 \mu^{-1}$)

$Re_{\text{crit}}$  
critical Reynolds number in Eq.(6.21)
<table>
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<td>$Re_{j\omega}$</td>
<td>Reynolds number defined in Eq.(7.39), $Re_{j\omega} = \frac{\rho v_{j\omega} \mu}{l}$</td>
</tr>
<tr>
<td>$Re_l$</td>
<td>Reynolds number defined in Eq.(6.20), $Re_l = \frac{\rho v_l d_l \mu}{l}$</td>
</tr>
<tr>
<td>$R_g$</td>
<td>mean grit radius in Eq.(7.8), ($m$)</td>
</tr>
<tr>
<td>$S$</td>
<td>cross sectional area of the splashing stream in Eq.(7.32), ($m^2$)</td>
</tr>
<tr>
<td>$Sc$</td>
<td>grinding wheel screen number in Eq.(7.9)</td>
</tr>
<tr>
<td>$T$</td>
<td>pumping torque, (Nm)</td>
</tr>
<tr>
<td>$t$</td>
<td>thickness of coolant layer entering into the grinding zone, Eq.(7.42), ($m$)</td>
</tr>
<tr>
<td>$u$</td>
<td>specific grinding energy, ($J/m^3$)</td>
</tr>
<tr>
<td>$u_{chip}$</td>
<td>specific grinding energy for generating chips, ($J/m^3$)</td>
</tr>
<tr>
<td>$u_{plow}$</td>
<td>specific grinding energy contributed to plowing, ($J/m^3$)</td>
</tr>
<tr>
<td>$u_{rub}$</td>
<td>specific grinding energy contributed to rubbing, ($J/m^3$)</td>
</tr>
<tr>
<td>$V$</td>
<td>volume of the liquid occupying within the grinding zone, ($m^3$)</td>
</tr>
<tr>
<td>$V_e$</td>
<td>sampling volume in Eq.(A7.2), ($m^3$)</td>
</tr>
<tr>
<td>$V_w$</td>
<td>enclosed working volume in Eq.(A7.2), ($m^3$)</td>
</tr>
<tr>
<td>$\dot{V}_w$</td>
<td>material removal rate, ($m^3/s$)</td>
</tr>
<tr>
<td>$v$</td>
<td>mean velocity, ($ms^{-1}$)</td>
</tr>
<tr>
<td>$v_e$</td>
<td>mean velocity of coolant at the outlet of the control volume shown in Figs. 7.3 and 7.5, ($ms^{-1}$)</td>
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<tr>
<td>$v_f$</td>
<td>liquid film velocity, shown in Fig. 7.6, ($ms^{-1}$)</td>
</tr>
<tr>
<td>$v_i$</td>
<td>mean velocity of coolant at the inlet of the control volume shown in Fig. 7.3, ($ms^{-1}$)</td>
</tr>
<tr>
<td>$v_j$</td>
<td>jet velocity, shown in Fig. 7.6, ($ms^{-1}$)</td>
</tr>
<tr>
<td>$v_{j\omega}$</td>
<td>combined jet-wheel velocity in Eq.(7.33), ($ms^{-1}$)</td>
</tr>
<tr>
<td>$v_{lk}$</td>
<td>velocity of an individual flow discharged through a perforated hole of the segmented wheel, shown in Figs. 6.4 and 7.5, ($ms^{-1}$)</td>
</tr>
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</table>
\( v_{\text{s}} \) splash flow velocity, shown in Fig. 7.6, \((\text{ms}^{-1})\)

\( v_w \) grinding table speed, \((\text{ms}^{-1})\)

\( We \) Weber number defined in Eq.(6.13) \((We = \rho \omega^2 R^3 \sigma^{-1})\)

\( We_l \) Weber number defined in Eq.(6.18) \((We_l = \rho d l v_l^2 \sigma^{-1})\)

\( X \) magnification of an optical microscope in Eq.(2.3)

\( x, y, z \) \(x, y\) and \(z\) coordinate, \((\text{m})\)

\( Y_m \) dimensionless grinding variable, defined in Eq.(6.14)

\( Y_p \) dimensionless grinding variable, defined in Eq.(8.13)

\( \alpha \) correlation constant in Eq.(7.35) \((\text{mrad}^{-1}\text{s})\)

\( \alpha_\theta \) thermal diffusivity in Eq.(4.1), \((m^2s^{-1})\)

\( \beta \) correlation constant in Eq.(7.35), \((\text{m})\)

\( \gamma \) control volume angle, \((\text{rad})\)

\( \Delta p \) pressure drop through a perforated hole, \((\text{Pa})\)

\( \Delta p^* \) pressure influence number

\( \Delta p_0 \) mean static pressure drop through the perforated holes, \((\text{Pa})\)

\( \Delta p_N \) internal gauge pressure of the liquid nitrogen reservoir, \((\text{Pa})\)

\( \Delta t_e \) exposure time, Eq.(A6.2) \((\text{s})\)

\( \delta \) spin-off liquid thickness in Eq.(7.34), \((\text{m})\)

\( \delta_o \) disturbance amplitude, Eq.(6.17), \((\text{m})\)

\( \varepsilon_\phi \) distortion strain in Eq.(2.5)

\( \zeta \) angle where coolant jet impinges the wheel in Eq.(7.38), \((\text{rad})\)

\( \eta \) orientation of maximum principle stresses in Eq.(A3.4), \((\text{rad})\)

\( \Theta \) temperature, \((\text{K})\)

\( \Theta_a \) austenite transition temperature, \((\text{K})\)
\( \Theta_s \)  
\text{surface temperature, (K)}

\( \Theta_\infty \)  
\text{surrounding temperature, (K)}

\( \theta_\lambda \)  
\text{diffraction angle, (rad)}

\( \theta_\psi \)  
\text{position of diffraction peak in direction } \psi_\lambda, \text{ (rad)}

\( \lambda \)  
\text{mean separated distance between the wheel grits in Eq.(7.8), (m)}

\( \lambda_N \)  
\text{wave length of X-rays, (m)}

\( \mu \)  
\text{dynamic viscosity, (Nsm}^{-2} \text{)}

\( \nu \)  
\text{Poisson’s ratio}

\( \rho \)  
\text{coolant density, (km}^{-3} \text{)}

\( \rho_N \)  
\text{density of liquid nitrogen, (kgm}^{-3} \text{)}

\( \sigma \)  
\text{surface tension of coolant, (Nm}^{-1} \text{)}

\( \sigma_x, \sigma_y, \sigma_{xy} \)  
\text{component residual stress in xx, yy and xy direction, (Pa)}

\( \tau_{\text{max}}, \tau_{\text{min}} \)  
\text{maximum/minimum shearing stress, (Pa)}

\( \phi \)  
\text{alignment angle of the coolant chamber defined in Fig. 6.3, (rad )}

\( \phi^* \)  
\text{transverse flow influence number, Eq.(6.13)}

\( \varphi \)  
\text{distortion angle of a ligament defined in Fig. 6.4, (rad)}

\( \psi \)  
\text{separation angle in Eq.(7.37), (rad)}

\( \psi_N \)  
\text{inclination angle between the normal to the diffraction lattice plane and sample plane, (rad)}

\( \omega \)  
\text{rotational grinding wheel speed, (rads}^{-1} \text{)}

\( \Omega \)  
\text{relative velocity of the wheel to the workpiece, (rads}^{-1} \text{)}
Superscripts

. rate
* dimensionless number
_ mean value

\(a, b, c\) and \(d\) correlation power factors, Eq.(6.15)

\(m, n, q\) and \(r\) correlation power factors, Eq.(8.13)

\(\xi\) distribution parameter in Eq.(A7.3)

Subscripts

\(l, 2\) corresponding to plane 1 and 2
\(a\) austenite transition or chemical additives or actual
\(c\) spin-off or centrifugal
\(ch\) coolant chamber
\(chip\) chip
\(crit\) critical
\(cv\) control volume
\(e\) exit
\(f\) liquid film
\(fw\) combined fluid-wheel
\(g\) wheel grit or grinding
\(h\) perforated hole of the segmented wheel
\(I\) indenter
\(i\) inlet
\(ik\) individual inlet
\(j\) jet
\(j\omega\) combined jet-wheel
\( k \) individual

\( l \) ligament

\( lk \) individual ligament

\( m \) mist or measured

\( max \) maximum

\( min \) minimum

\( N \) nitrogen

\( o \) static or amplitude in \( \delta \)

\( op \) optimised

\( p \) pumping power

\( plow \) plowing

\( r \) inner rim of a segmented wheel

\( rub \) rubbing

\( s \) surface or workpiece

\( sp \) splashing

\( sub \) subsurface

\( sur \) surrounding resistance

\( tran \) transverse effect

\( w \) workpiece or wheel-work contact

\( X \) X-ray

\( x, y, z \) x, y, z direction

\( \psi \) diffraction peak

\( \infty \) surrounding

\( \theta \) thermal
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