DEVELOPMENT OF NEW COOLING METHODS FOR GRINDING

by

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B.E. (Mech. Eng., 1st Hons.)

A thesis submitted in fulfilment of

the requirements for the degree of

Doctor of Philosophy

at The University of Sydney

School of Aerospace, Mechanical and Mechatronic Engineering

The University of Sydney

2005

Acknowledgements

I would like to express my sincerest appreciation to Prof. Liangchi Zhang for his kind guidance, encouragement and every support during this project's progression. Great thanks are due to Dr. Irena Zarudi for help and invaluable words of advice.

Thanks are due to the technical officers, Mr. T. Shearing, Mr. B. Oliver, Mr. H. Nibbe, Mr. B. Scaysbrook, Mr. S. Karkada and Mr. R. O'Shannessy in the laboratory and the workshop for help in constructing the experiments.

Help from members of staff, Mr. A. Sikorski and Dr. I. Kaplin at the Electron Microscope Unit (EMU), The University of Sydney is greatly acknowledged.

Thanks are due to Mr. Y.L. Pai and Mr. J. Huang at Kinik Grinding Wheel Corp. for making the wheel segments.

Thanks are also due to Dr. D. Cheong, Dr. K. Mylvaganam, Dr. T. Vodenitcharova, Dr. K. Xiao, Dr. J.A. Arsecularatne and all of my colleagues at the school of AMME for enriching my stay at The University of Sydney.

The continuous financial support from the Australia Research Council (ARC) and the Australian Postgraduate Awards (APA) scholarship is highly appreciated.

Finally, I would like to delicate 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.

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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

A	area, (m^2)
B	grinding wheel width, (m)
b_{ch}	inner coolant chamber width, (m)
b_r	inner rim width of a segmented wheel, (m)
C_c	pumping power coefficient in Eq.(7.22), (m^2)
C_f	coolant chamber design coefficient defined in Eq.(6.7), (m^{-4})
C_{fw}*	geometrical influence number in Eq.(8.10)
C_m	coefficient of mist generation's correlation, Eq.(6.14)
Co	grinding wheel concentration number
C_p	coefficient of pumping power's correlation, Eq.(8.12)
C_s	pumping power coefficient in Eq.(7.29), (m^2)
C_ψ	dimensionless separation coefficient in Eq.(7.36)
C_θ	specific heat in Eq.(4.1), ($Jkg^{-1}K^{-1}$)
D	grinding wheel diameter, (m)
D_m	diameter of an inspirable drop in Eq.(A7.3), (m)
$\overline{D}_m$	Rosin-Rammler mean of drop diameters in Eq.(A7.3), (m)
d_I	diagonal length of an indent, shown in Fig. 2.23, (m)
d_l	diameter of a coolant ligament, (m)
d_{sub}	depth below the ground surface, (m)
d_w	grinding depth of cut, (m)
d_X	lattice spacing, (m)
erf	Gaussian error function, Eq.(4.1)
F	force, (N)

$F(D_m)$	fraction of drops with diameter less than D_m , Eq.(A7.3)
f	film thickness on the wheel surface in Eq.(7.32), (m)
f_c	centrifugal force exerting on a unit volume of coolant, (Nm^{-3})
g	gravitational constant, (ms^{-2})
H	pumping head, (m)
h	equivalent liquid layer thickness in Eq.(7.8), (m)
h_θ	heat transfer coefficient, ($Wm^{-2}K^{-1}$)
K	correction coefficient in Eq.(7.34), (m)
k_θ	thermal conductivity, ($Wm^{-1}K^{-1}$)
k_c	coolant concentration
l	break-up length of a ligament in Eq.(6.17), (m)
l_{cv}	control volume arc length defined in Figs. 7.1 and 7.2, (m)
l_w	wheel-work contact length, (m)
M	moment, (Nm)
$\dot{m}$	mass flow rate, (kgs^{-1})
$\dot{m}_a$	mass flow rate of chemical additives contaminated in mist, (kgs^{-1})
N	total number of segments fitted in a wheel
N_l	number of ligaments, in Eq.(6.1)
$\vec{n}$	normal unit vector
n_{ch}	number of perforated holes in contact with the coolant chamber
n_{cv}	number of perforated holes within the pumping control volume
OES	occupational exposure standard, Eq.(A7.1), (kgm^{-3})
Oh	Ohnesorge number, ($Oh = \mu(\rho\sigma d_l)^{-0.5}$)
P	pumping power, (W)
P^*	power number, ($P\rho^{-1}R^{-5}\omega^{-3}$)

P_g	grinding power, (W)
P_{min}	minimum pumping power required, (W)
p	pressure, (Pa)
p_I	indenting load in Eq.(2.2), (kg)
p_{sur}	mean surround resistance pressure in Eq.(6.8), (Pa)
p_{tran}	mean transverse pressure on a ligament in Eq.(6.8), (Pa)
Q	total flow rate of coolant, (m^3s^{-1})
Q^*	flow rate number, ($Q/R^3\,\omega$)
Q_c	spin-off flow rate in Eq.(7.33), (m^3s^{-1})
Q_{sp}	film liquid flow rate in Eq.(7.30), (m^3s^{-1})
Q_j	jet flow rate in Eq.(7.30), (m^3s^{-1})
Q_l	flow rate of coolant contributed to ligament mode, (m^3s^{-1})
Q_m	mist flow rate, (m^3s^{-1})
Q_{max}	maximum coolant flow rate required, (m^3s^{-1})
Q_{min}	minimum coolant flow rate required, (m^3s^{-1})
$Q_{m,\,max}$	allowable mist flow rate, (m^3s^{-1})
Q^*_m	mist flow rate ratio in Eq.(6.13)
Q_N	flow rate of liquid nitrogen, (m^3s^{-1})
Q_{sp}	splashing flow rate in Eq.(7.30), (m^3s^{-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_{crit}	critical Reynolds number in Eq.(6.21)

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

v_{sp}	splash flow velocity, shown in Fig. 7.6, (ms^{-1})
v_w	grinding table speed, (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, (m)
Y_m	dimensionless grinding variable, defined in Eq.(6.14)
Y_p	dimensionless grinding variable, defined in Eq.(8.13)
α	correlation constant in Eq.(7.35) ($mrad^{-1}s$)
α_θ	thermal diffusivity in Eq.(4.1), (m^2s^{-1})
β	correlation constant in Eq.(7.35), (m)
γ	control volume angle, (rad)
Δp	pressure drop through a perforated hole, (Pa)
Δp^*	pressure influence number
$\Delta\overline{p}_0$	mean static pressure drop through the perforated holes, (Pa)
Δp_N	internal gauge pressure of the liquid nitrogen reservoir, (Pa)
Δt_e	exposure time, Eq.(A6.2) (s)
δ	spin-off liquid thickness in Eq.(7.34), (m)
δ_o	disturbance amplitude, Eq.(6.17), (m)
ε_ϕ	distortion strain in Eq.(2.5)
ζ	angle where coolant jet impinges the wheel in Eq.(7.38), (rad)
η	orientation of maximum principle stresses in Eq.(A3.4), (rad)
Θ	temperature, (K)
Θ_a	austenite transition temperature, (K)

Θ_s	surface temperature, (K)
Θ_∞	surrounding temperature, (K)
θ_X	diffraction angle, (rad)
θ_ψ	position of diffraction peak in direction ψ_X, (rad)
λ	mean separated distance between the wheel grits in Eq.(7.8), (m)
λ_X	wave length of X-rays, (m)
μ	dynamic viscosity, (Nsm^{-2})
ν	Poisson's ratio
ρ	coolant density, (kgm^{-3})
ρ_N	density of liquid nitrogen, (kgm^{-3})
σ	surface tension of coolant, (Nm^{-1})
σ_x, σ_y, σ_{xy}	component residual stress in xx, yy and xy direction, (Pa)
τ_{max}, τ_{min}	maximum/minimum shearing stress, (Pa)
ϕ	alignment angle of the coolant chamber defined in Fig. 6.3, (rad)
ϕ^*	transverse flow influence number, Eq.(6.13)
φ	distortion angle of a ligament defined in Fig. 6.4, (rad)
ψ	separation angle in Eq.(7.37), (rad)
ψ_X	inclination angle between the normal to the diffraction lattice plane and sample plane, (rad)
ω	rotational grinding wheel speed, ($rads^{-1}$)
Ω	relative velocity of the wheel to the workpiece, ($rads^{-1}$)

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)
ξ	distribution parameter in Eq.(A7.3)

Subscripts

1, 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 δ_o
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
ψ	diffraction peak
∞	surrounding
θ	thermal

Contents