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The effects of the flow rate and speed of lubricoolant jets on heat transfer in the contact zone when grinding a nitrided steel

B. Lavisse[a], A. Lefebvre[a,*], A.A. Torrance[b], O. Sinot[a], E. Henrion[a], S. Lemarié[c], A. Tidu[a]

[a] *Laboratoire d'Étude des Microstructures et de Mécaniques des Matériaux (LEM3), UMR CNRS 7239, Université de Lorraine, F-57078, Metz Cedex 03, France*
[b] *Trinity College, Dublin, Ireland*
[c] *Naval Group - Centre de Nantes-Indret, Nantes, France*

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ABSTRACT

In this paper, the influence of lubrication parameters, such as flowrate and jet velocity, on the cutting fluid efficiency are studied. A foil/workpiece thermocouple and an inverse matching method are used to observe changes in the heat partition ratio, the heat flux absorbed into the fluid, the convection heat transfer coefficient (CHCT) and the maximum temperature in the contact area. Low jet velocity and flowrate tend to decrease the cutting fluid efficiency however excessive flowrate or jet speed in grinding are useless and do not lead to an extra decrease in the temperature of the grinding zone.

The "burn out" phenomenon is also studied and the temperature at which it occurs is compared to the auto-ignition point of the cutting fluid. When burn occurs, the fluid no longer lubricates or cools the contact area. It allows an increase in the temperature in the grinding zone which may damage the microstructure of the workpiece, and produce distortions and cracks.

1. Introduction

Grinding is widely used in industry to obtain precision and a good surface finish. However most of the energy generated in the grinding zone is converted into heat which is mainly dissipated into the surface of the workpiece [1]. If the temperature gets too high, workpiece integrity is compromised [2] but the defects may be hard to detect [3]. Excessive temperature, especially in the finishing stage, may compromise dimensional accuracy, the material's microstructure, and the residual stresses which will reduce the useful life of the ground component. To limit temperature, it is usual to employ high volume and/or high pressure coolant delivery systems. This also helps to reduce friction [1] in the grinding zone and keeps the machine structure cool. However, high flow rates require powerful pumps and large settling and cooling reservoirs which may seriously increase the costs of production [4]. Furthermore, these techniques generate a high level of aerosol pollution which must be safely evacuated to preserve the health of the machine operator [5]. Therefore, coolant flow should be limited, but not so much as to affect the workpiece quality or to cause grinding burns, so it is crucial to maximize the fluid's cooling efficiency. The efficient supply of fluid in grinding is closely related to the thermal conditions in the grinding zone and the coolant type, and this has always been a well-researched topic [1,6].

Webster et al. [7] explain in their study that cooling performance is little affected by nozzle angle as long as the flow is directed toward the grinding zone. They also explain that the cooling performance tends to be reduced if the distance between the nozzle and the grinding zone is increased.

In their work Marinescu et al. [8] explain that the fluid flowrate in the outlet nozzle is much greater than the flow through the grinding arc of cut. Indeed, much of the fluid is rejected away from the wheel before it can reach the interface between the wheel and the workpiece. This part of fluid is sometimes called the "rejected flow-rate" and contributes little to cooling the grinding zone. The aim should be to raise the fraction of the fluid flowrate passing through the grinding zone.

In the literature the term "useful flowrate" is often used. It represents the effective flowrate which passes between the wheel and the workpiece. Physically it is difficult to determine because it depends on many parameters such as such as the nozzle outlet flowrate, the jet velocity, the nozzle position, the wheel specifications (and more precisely wheel porosity). This useful flowrate may be increased but not indefinitely since it is limited by the size of the pores in the wheel and by its overall porosity. Morgan et al., Morris, Marinescu et al. [8–10] define a maximum useful flowrate, denoted Q_{fu}. This maximum useful flowrate varies linearly with the wheel speed. However Morgan et al. [10] show that it is limited by the jet velocity at the outlet nozzle. At

* Corresponding author.
E-mail address: andre.lefebvre@univ-lorraine.fr (A. Lefebvre).

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Symbols and abbreviation

a_p	nominal depth of cut(μm)
a_{ed}	depth of dressing cut (μm)
b	width of cut (m)
F_t	tangential force (N)
F'_t	specific tangential force (N/mm)
F'_{tmean}	averaged specific tangential force over the study (N/mm)
h_c	convection heat transfer coefficient (CHCT) ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
h_{pores}	mean pore depth (m)
l_c	ceometric contact length (m)
l_{cmean}	averaged geometric contact length over the study (m)
l_{hf}	length of positive heat flux (m)
n	wheel letter grade
P_t	grinding power (W)
Q_w	heat part conducted into the workpiece (W)
Q_{fu}	maximum useful flowrate ($l{\cdot}min^{-1}$)
q_{ch}	heat flux density into the chip ($W{\cdot}m^{-2}$)
q_f	heat flux density into the cutting fluid ($W{\cdot}m^{-2}$)
q_s	heat flux density into the wheel ($W{\cdot}m^{-2}$)
q_t	total heat generated in the grinding zone ($W{\cdot}m^{-2}$)
q_t^{dry}	total heat generated in the grinding zone in dry grinding conditions ($W{\cdot}m^{-2}$)
q_t^{wet}	total heat generated in the grinding zone in wet grinding conditions ($W{\cdot}m^{-2}$)
q_w	heat flux density into the workpiece ($W{\cdot}m^{-2}$)
q_w^{dry}	heat flux into the workpiece in dry grinding conditions ($W{\cdot}m^{-2}$)
q_w^{wet}	heat flux into the workpiece in wet grinding conditions ($W{\cdot}m^{-2}$)
R_w	heat partition ratio to the workpiece
R_{ws}	workpiece-grain partition ratio
R_f	part of heat evacuated into the fluid over the total cutting power
T	temperature rise relative to the ambient temperature (°C)
T_c	temperature in the contact area (°C)
T_j	n spaced temperature measurements (°C)
T_{maxi}	maximum background temperature in the grinding zone (°C)
T_{norm}	normalized temperature (°C)
U_d	overlap dressing ratio
V_s	wheel speed ($m{\cdot}s^{-1}$)
V_{sd}	dressing wheel speed ($m{\cdot}s^{-1}$)
V_w	workpiece speed ($m{\cdot}s^{-1}$)
V_j	jet velocity ($m{\cdot}s^{-1}$)
s	wheel structure number
$\sqrt{(\lambda\rho C)_w}$	workpiece material thermal effusivity ($W/s^{1/2}/K/m^2$)
β	constant
α_w	workpiece material thermal diffusivity (m^2/s)
λ_w	workpiece material thermal conductivity ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
ξ	local coordinate in x-direction (m)

wheel speeds greater than this, Q_{fu} levels off. Other things being equal, they show that an increase of the nozzle flowrate has no influence on the useful flowrate and explain that most of time the maximum useful flowrate at best corresponds to 25%–50% of the nozzle flowrate.

Heinzel et al., [11] investigate how the jet velocity from the nozzle influences the maximum temperature in the grinding zone. The aim of their study is to define an efficient Metal Working Fluid (MWF) in order to limit the amount of rejected fluid. To do this, the authors simulate machining by heating the area under the wheel electrically at constant power. A thermocouple is placed in the middle of this zone. Changes in the cooling conditions provoke changes in the temperature measured by thermocouple. The authors suggest that a decrease of this measured temperature reveals an improvement in the fluid efficiency. Heinzel et al., [11] show that with constant nozzle position and constant jet speed, that below a certain threshold, a rise in the outlet nozzle flowrate leads to a decrease in the maximum temperature in the grinding zone. They deduce that the level of this threshold determines an optimum for the outlet nozzle flowrate which minimizes fluid rejection and avoids grinding damage. This optimized flowrate resembles the maximum useful flowrate of Morgan et al. [10]. Heinzel et al., [11] also study the influence of the ratio jet speed/wheel speed on the maximum temperature in the grinding zone. They show a minimum temperature for a jet speed between 70 and 90% of the wheel speed. Smaller or greater jet speeds seem to decrease the fluid efficiency. In the same way Morgan et al. [10] advise 80% to 100% of the wheel speed. However Heinzel et al.'s study is only a grinding simulation. That is why real grinding may give different results. Moreover, the authors do not study the influence of the fluid on the partition ratio.

Guo et al. [12] found that in regular grinding under water based lubricant, the coolant has no effect in the grinding zone. In their case, coolant application does not reduce the heat partition ratio but simply cools the bulk of the workpiece. For these authors, coolant is effective simply in creep feed grinding and reduces the heat partition ratio to less than 5%. However some more recent work shows that even in finish grinding, coolant application causes a significant temperature decrease in the grinding zone. For example, Hadad et al. [13] with an Al_2O_3 wheel in dry finishing conditions (a_p = 30 μm V_w = 2 m/min, V_s = 30 m/s) obtain a heat partition ratio of 0.82. Then with the same grinding conditions and a neat oil coolant, the heat partition ratio drops to 0.36. Differences in the heat partition ratio are also seen when grinding burn occurs [14]. Therefore it is clear that the coolant is able to evacuate a significant fraction of the heat flux from the grinding zone. In another study

The effect of the flowrate of the coolant has also been investigated in conventional machining. Mia et al. [15] in their work determine, using a Grey based Taguchi method, that a flowrate of 150 ml/h ensures the minimum cutting forces and surface roughness for the end milling of hardened steel. In another study Mia et al. [16] show that MQL in hard turning predominantly influences surface roughness compared to feed rate.

Therefore the scope of this work is to better understand the effects of flowrate of coolant and jet speed on the grinding so as to optimize this parameters to ensure workpiece integrity.

In this article we focus on finding conditions which could optimize fluid injection into the interface between the wheel and the workpiece, a nitrided steel. We study (independently) the influence of jet speed and flowrate at the nozzle outlet on the maximum temperature and the heat partition ratio in the grinding zone. The main aim is to determine the cooling conditions (flowrate and jet speed) which avoid the risk of thermal damage when grinding nitrided 32CrMoV12-9 steel.

2. Test setup and grinding parameters

To carry out this research, a temperature measurement was needed. These measurements are made with a single pole foil/workpiece thermocouple, which has a short enough time constant to follow the temperature at the wheel/workpiece interface [17,18].

The thermocouple used is created by clamping a head to a body, each of 32CrMoV12-9 nitrided steel. Between them is a stack of sheets mica/constantan/mica. The mica sheet thickness is 6 μm and the constantan 25 μm. To ensure that the temperature is correctly measured, the Constantan/32CrMoV12-9 thermocouple was calibrated from 0 °C to 1000 °C against S thermocouple. The calibration was made in a controlled oven with a thermal equalization block. Over this range of