Jet heat transfer in the vicinity of a rotating grinding wheel

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The manuscript was received on 24 October 2005 and was accepted after revision for publication on 28 February 2006.

DOI: 10.1243/09544062JMES215

Abstract: Impinging jets are known as a method of achieving high convective heat transfer coefficients. One potential application of impinging jet heat transfer is the air jet cooling of a grinding process. A grinding process generates heat that must be dissipated to avoid thermal damage. To date, this has been achieved using flood cooling with a traditional coolant such as an oil and water mixture; however, using a jet of air in its place has obvious environmental and economic benefits. For a range of grinding test configurations, results are presented of the convective heat transfer from the workpiece, along the notional plane of cut, and of the air flow velocity in a two-dimensional plane perpendicular to the workpiece. It has been shown that a boundary layer that develops around the rotating grinding wheel has the effect of displacing a peak in the distribution of the local heat transfer coefficient from the notional arc of cut. To effectively cool the grinding zone, therefore, it is necessary to penetrate this boundary layer and this can only be achieved when the jet velocity is substantially greater than the tangential velocity of the wheel.

Keywords: grinding, impinging jet, heat transfer, cooling

1 INTRODUCTION

Convective heat transfer due to an impinging air jet yields high local and area-averaged heat transfer coefficients. As a result, it has potential for the cooling of a grinding process. Grinding is a widely employed machining process used to achieve good geometrical form, dimensional accuracy, surface finish, and surface integrity. However, grinding generates heat that must be dissipated, as high temperatures may damage the workpiece. High temperatures adversely affect process times because the depth of cut and feed rates cannot be increased without compromising surface quality. Thermal damage can manifest itself in many ways. Most notably, it results in the softening of the ground surface which can cause rehardening and embrittlement. In addition, thermal expansion can compromise the geometrical accuracy and may leave residual tensile stresses in the workpiece. Excessive temperatures may also have the adverse effect of inducing accelerated wear of the grinding wheel. The current research focuses on the use of an air jet as an alternative to traditional methods, such as flood cooling with a mixture of oil and water, to cool a grinding process. It is expected that an air jet can achieve the necessary workpiece cooling while reducing the machining cost and the environmental impact of grinding processes.

The geometric parameters of a grinding process are depicted in Fig. 1. The grinding wheel is shown to rotate in a clockwise direction with a tangential velocity V_g. The workpiece is fed with a velocity V_w in the direction of the wheel. This configuration is termed down grinding. Up grinding is the case where the wheel rotates in the opposite direction to the movement of the workpiece. The depth of cut, a, shown exaggerated in the diagram, is typically $\sim$5 μm during conventional grinding. The workpiece exerts a tangential force, F_t, on the grinding wheel. In this configuration, the jet flows in the direction of the

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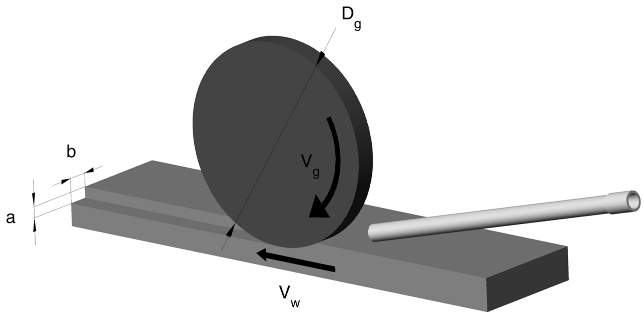

Fig. 1 Grinding process setup

workpiece with velocity V_j. The power generated during the grinding process is dissipated as heat in the grinding zone, where this heat flux is defined as

$$q''_{\text{total}} = \frac{F_t V_g}{b\sqrt{aD_g}} \tag{1}$$

With conventional flood cooling, this heat is dissipated in four ways: (a) conduction to the grinding wheel grains, (b) conduction into the workpiece, (c) convection to the cutting fluid, and (d) with the removal of the cutting chip. An energy balance, presented in equation (2), defines the modes of heat dissipation. Typically, the heat transferred to the chip is small when compared with the overall heat generated and is neglected in studies by Lavine and Jen [**1**], for example

$$q_{\text{total}} = q_{\text{workpiece}} + q_{\text{wheel}} + q_{\text{fluid}} + q_{\text{chip}} \tag{2}$$

During grinding, heat is generated by the grains of the wheel cutting the workpiece as they pass at high speeds in the grinding zone. According to Rowe *et al.* [**2**], individual grains are responsible for localized and intense heat generation, resulting in short duration spike temperatures at the workpiece surface. However, the total effect of a large number of grains cutting the relatively slow moving workpiece surface can be considered to be a continuous band source of heat passing over the workpiece. The temperature due to this band source is a background temperature that occurs for a substantial period of time. Spike temperatures are not of consequence for thermal damage, because thermal damage such as re-austenitization requires time to occur.

An investigation by Ebbrell *et al.* [**3**] recognized the effect of ambient air entrainment by the spinning grinding wheel. It was determined that the hydrodynamic boundary layer that forms around the spinning grinding wheel produces a back flow when the grinding wheel boundary layer comes into close proximity with the workpiece. This back flow can inhibit the cutting fluid from reaching the grinding zone. Ebbrell *et al.* [**3**] also presented various nozzle configurations to overcome the effect of the boundary layer.

Rowe *et al.* [**2**] conducted a numerical and experimental investigation of energy partitioning in a grinding process for two different grinding wheel materials, where the partition ratio is defined as the ratio of the heat transferred to the workpiece to the total heat generated

$$R_{\text{partition}} = \frac{q_{\text{workpiece}}}{q_{\text{total}}} \tag{3}$$

A grain contact model was used to predict the partition ratio by assuming that the heat transported by the cutting fluid and the chip was negligible. The model also required a value of the effective thermal conductivity of the grain. This value was arrived at when both the model and the experimental temperatures correlated.

A theoretical model for heat transfer during grinding was developed by Lavine and Jen [**1**]. This model assumed that the heat flux to the fluid from the workpiece was uniform and that the fluid moved at the same velocity as the tangential velocity of the wheel. Therefore, the fluid was modelled as a solid, with a uniform heat flux at its surface. It was also shown that the convective heat transfer to the fluid from the grinding wheel was small, typically 0.4 per cent of the heat transfer to the grinding wheel. A later model by Jen and Lavine [**4**] addressed some of the assumptions made by the original model, particularly by modifying the assumption of uniform heat flux to the grinding wheel grains, fluid, and workpiece. In an investigation by Jen and Lavine [**5**], a model was developed which predicted the effect on workpiece temperature of the occurrence of film boiling. In addition, in an investigation by Lavine [**6**], an exact solution for the surface temperature in a grinding process was developed. In the previous models, it had been assumed that the heat was generated at the wear flats. This is known to be untrue, as much of the heat is generated at shear planes because of plastic deformation.

In all of the earlier works, the cutting fluid was a liquid, typically an oil and water mixture. The function of the cutting fluid is primarily to reduce the amount of heat generated by lubricating the process rather than transporting heat away by convection. The present research is concerned with the cooling of a grinding process with an impinging air jet, a procedure that has received little attention until now. Instead of targeting the heat generation in the grinding zone, this method reduces the high temperatures by substantially increasing the convective cooling.

High-speed air jet cooling of a grinding process has been investigated by Babic *et al.* [**7**]. This investigation showed that a high-speed jet can slightly reduce the heat generated in the grinding zone by reducing the tangential force. However, the main mechanism for the reduction in temperature in the grinding zone was considered to be enhanced-convective heat transfer to the impinging air jet. In a subsequent investigation by Babic *et al.* [**8**], a small quantity of water was injected into the air flow before the nozzle, which generated a high-speed jet mist. The use of this jet mist in a grinding process was shown to further reduce the tangential force and to increase the convective cooling. To date, convective heat transfer coefficients have not been quantified in the available literature. In the present study, experiments have been performed that measure the convective heat transfer coefficient to the impinging jet flow used by Babic *et al.* [**7**].

The current research is concerned with the fundamental heat transfer mechanisms that occur in an impinging jet flow and with the application of air jet cooling to a grinding process. Convective heat transfer distributions along the workpiece are reported together with the associated flow fields. The convective heat transfer mechanisms that occur in an air-cooled grinding process are investigated with a view for determining an optimal jet configuration.

2 EXPERIMENTAL SETUP

A schematic of the experimental rig is presented in Fig. 2. This setup is designed to approximate a grinding process. The workpiece is represented by a composite plate, measuring 425 mm × 550 mm, that consists of three main layers mounted on a carriage. The top surface is a 5 mm thick copper plate. A silicon rubber heater mat, ∼1.1 mm thick, is fixed to the underside of the copper plate with a thin layer of adhesive. It has a power rating of 15 kW/m^2 and a voltage rating of 230 V. The voltage is varied using a variable transformer that controls the heat supplied to the copper plate. A thick layer of insulation prevents the heat loss from the heating element rather than through the copper. The plate assembly is such that it approximates a uniform wall temperature boundary condition, operating typically at a surface temperature of 60 °C.

An RdF Micro-Foil® heat flux sensor is flush mounted on the heated surface to measure the surface heat flux. The heated plate is mounted on a carriage that travels on a track, thus allowing the sensor to be placed in any location along the notional cutting plane. This sensor contains a differential thermopile that measures the temperatures above and below the known thermal barrier. The heat flux through the sensor is, therefore, defined by equation (4).

$$q'' = k_s \frac{\Delta T}{\delta} \tag{4}$$

where k_s is the thermal conductivity of the barrier (kapton) and ΔT is the temperature difference across the thickness (δ) of the barrier. A single pole thermocouple is also embedded in this sensor to measure the temperature locally.

The flow velocity field has been measured and mapped using digital particle image velocimetry (DPIV), as illustrated in Fig. 3. The DPIV system consists of a 15 mJ Nd:YAG double pulse laser and a double shutter PCO Sensicam. The resolution of the camera is 1280 × 1024 pixels and the minimum time between frames is 200 ns. Glycerine particles (∼5 μm diameter) were used to seed the main flow and the entrained air of the jet.

A grinding wheel is suspended ∼0.5 mm above the surface and is driven with an AC Motor. Its rotational

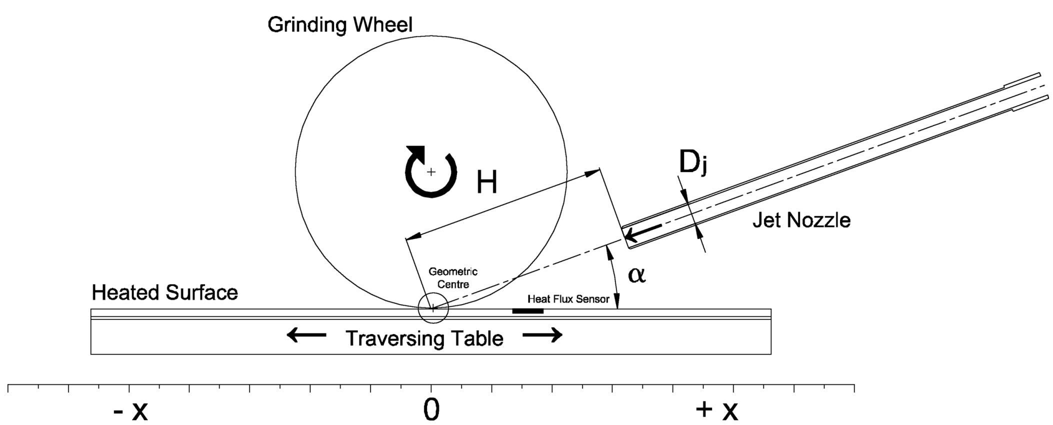

Fig. 2 Experimental setup

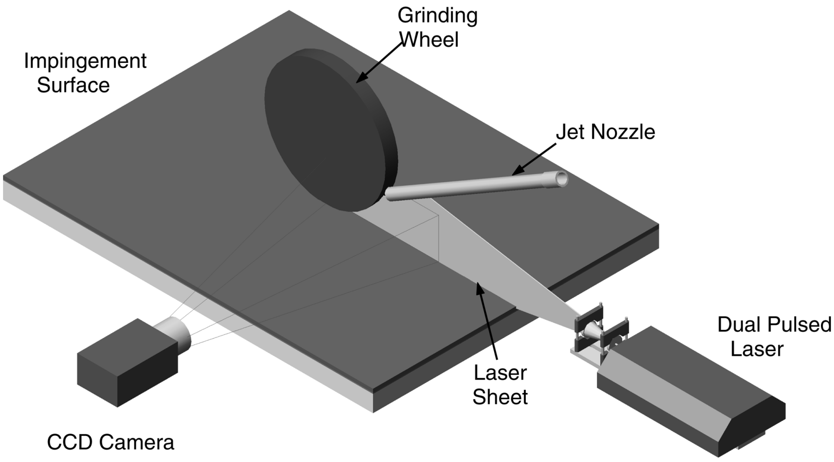

Fig. 3 Particle image velocimetry setup

speed is controlled using a frequency inverter. Contact is not made between the grinding wheel and the surface; this is to ensure that the sensors are not damaged by the rotating wheel. The grinding wheel is an aluminium oxide wheel of diameter 180 mm and thickness 19 mm.

Two nozzle types are used in this investigation. The first consists of a brass pipe of 13.5 mm internal diameter. The pipe is 20 diameters long and a 45° chamfer is machined at the nozzle lip to create a sharp edge to minimize entrainment. The second has a diameter of 2.6 mm. This nozzle is used to create a high-speed jet that can approach sonic velocities and has been used for impingement jet cooling of an actual grinding process, as described by Babic *et al.* [**8**]. The nozzle is clamped on a carriage in an arrangement that allows its height above the impingement surface and its angle of impingement to be varied. The height of the nozzle can be varied from 0.5 to 10 nozzle diameters above the impingement surface and the jet can be set at oblique angles ranging from 15°, in 15° increments, up to the normal angle of impingement (90°).

Air is supplied to the jet nozzle by a compressor. An Alicat Scientific Inc. Precision Gas Flow Meter is installed on the compressed air line to monitor both the air volume flowrate and the temperature. It is important that the jet exit temperature is maintained within 0.5 °C of the ambient air temperature. To this end, a heat exchanger is installed on the air line. The heat exchanger consists of a controlled temperature water bath in which a series of copper coils are placed. The air flows through the copper coils to increase the jet exit temperature to the required setting.

A number of differences exist between this test setup and the typical setup for a grinding process, as illustrated in Fig. 1. First, the surface being ground is represented as a flat surface in the heat transfer testing. This approximation is not considered to be significant for conventional grinding as the depth of cut is in the region of 0.005 mm; however, for creep feed grinding, the depth of the cut varies up to 20 mm. Second, it was necessary to mount the grinding wheel slightly above (0.5 mm) the heated surface to protect the heat transfer sensor that is flush mounted on the heated surface. This contrasts with the situation in an actual grinding process where the wheel is in contact with the surface. The setup used is similar to that used by Ebbrell *et al.* [**3**] who investigated the effect of such a gap on the pressure distribution along the grinding plane and on the back flow resulting from the grinding wheel boundary layer. The gap was found to exert a significant influence on the flow characteristics, as the peak pressure varied from 250 to 50 Pa for a gap of 0.005–1.5 mm, respectively. It is important to realize that the smallest gap of 0.005 mm investigated by Ebbrell *et al.* [**3**] approximates the grinding process quite accurately as the contact area between the grinding wheel grits and the workpiece in the grinding zone is typically only a few per cent of the total grinding zone area. The consequence of the relatively large gap used in this study is a reduction in the magnitude of the back flow by allowing some flow under the grinding wheel surface.

The heat transfer experiments were conducted for a uniform wall temperature boundary condition, which differs appreciably from the point heating that would occur in the grinding zone. This thermal boundary condition was chosen as a reference condition to facilitate comparison with the published data and to ensure that there is a temperature difference between the air and all the points on the test surface. The main significance of the different thermal boundary conditions is the heating of the fluid, as it moves along the isothermal test surface. The difference between the bulk or jet air temperature

(T_j) and the local surface temperature (T_{surf}) is used to calculate the convective heat transfer coefficient. Thus, the heat transfer coefficient will tend to be underestimated in this study, as the calculation is based on a larger temperature difference than actually exists locally. However, the location of peaks and troughs in the heat transfer distributions will not change significantly. Finally, the heated surface that represents the workpiece is stationary during experimental testing. In a grinding process, the workpiece would typically traverse under the grinding wheel with a velocity of ~ 0.2 m/s. This velocity is small relative to both the air jet and the grinding wheel tangential velocities, and therefore, neglecting it will not have a significant influence on the results.

Results are presented in the form of the local convective heat transfer coefficient as follows

$$h(x) = \frac{\ddot{q}(x)}{(T_{\text{surf}}(x) - T_j)} \tag{5}$$

A complete calibration and uncertainty analysis for this experimental setup are presented by O'Donovan [**9**]. The uncertainty of the convective heat transfer coefficient is calculated to be ± 6 per cent, and the jet exit velocity can be set to an accuracy of 5 per cent.

3 RESULTS

3.1 Rotating grinding wheel

A rotating grinding wheel entrains air from the surroundings and induces a flow pattern that influences the heat dissipation in grinding. In an experimental investigation by Rowe *et al.* [**2**], back flow was reported for the air entrained by the grinding wheel. The air entrained by the wheel flows in the same direction as the wheel until it comes into close proximity with the surface or workpiece. As the air reaches the minimum gap between the wheel and the plate, some of the flow stagnates and then flows backwards away from the grinding zone. In the present study, this is confirmed by the PIV data presented in Fig. 4(a), where the wheel is rotating with a tangential velocity of 20 m/s. The back flow magnitude is small and occurs far from the minimum gap, in this case, beyond the stagnation point at $x \approx 85$ mm. This is understandable as the relatively large gap between the wheel and the surface (0.5 mm) allows much of the entrained air to pass under the wheel.

Figure 4(b) presents heat transfer distributions because of the flow induced by the entrainment of ambient air by the rotating grinding wheel. The convective heat transfer coefficient is plotted along the centre-line of the notional grinding plane. In this case, where there is no jet, the convective heat transfer coefficient is based on the temperature difference between the surface and the ambient air as follows

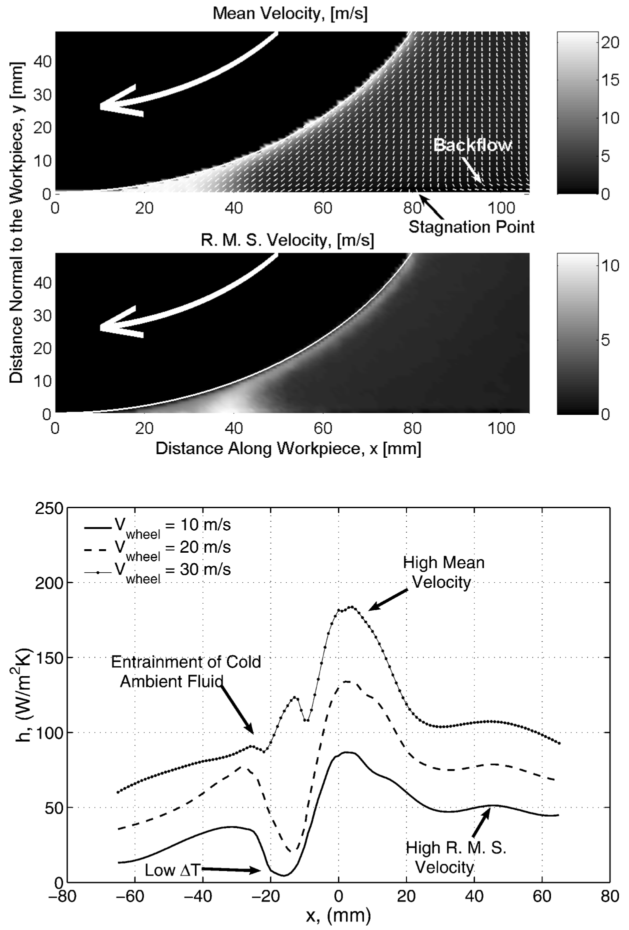

Fig. 4 Fluid flow and heat transfer due to rotating grinding wheel

$$h(x) = \frac{\ddot{q}(x)}{(T_{\text{surf}}(x) - T_{\text{amb}})} \tag{6}$$

From the right, a subtle peak occurs at a position of $x \approx 42$ mm. This is due to a region of high turbulence intensity occurring in the wedge between the grinding wheel and the surface, as evident in Fig. 4(a). The main peak in heat transfer is because of the peak velocity at the minimum gap ($x = 0$). Measurements of the velocity flow field have not been acquired beyond this point ($x < 0$) because of blocking of the laser sheet by the grinding wheel. As the air moves beyond this point, however, it is thought that the heat transfer rate decreases because of the low temperature difference between the surface and the local fluid, leading to a minimum heat transfer. This could also be due to a local flow characteristic. As the gap between the wheel and the surface increases, again further fluid is entrained, increasing the heat transfer rate once more. Eventually, the heat transfer coefficient falls off as the local fluid velocity decreases with the distance from the grinding wheel.

3.2 Low-speed air jet

In Figs 5 and 6, the fluid flow and the corresponding heat transfer distributions are presented for a jet impinging on the notional grinding zone at angles of 30° and 15°, respectively. The distance of the jet exit from what would be the grinding zone (notional arc of cut) in a grinding process is the same for both configurations and is defined as the minimum gap possible for positioning the jet at an angle of 30°. These heat transfer distributions differ somewhat from those in Fig. 4(b) because the largest peak is now due to the stagnation point of the jet flow and occurs at $x = 30$ and 35 mm for $\alpha = 30°$ and 15°, respectively. From Figs 5(a) and 6(a), it is apparent that the jet flow is blocked by the spinning grinding wheel in both configurations; however, this is more severe for the larger angle. At 30°, the peak in the heat transfer distribution that is attributed to the jet stagnation point is displaced by ~10 mm, from the expected location of 20 mm from the geometric centre for an unobstructed jet flow to 30 mm from the notional arc of cut in the grinding configuration. In the case where the jet impinges at an angle of 15°, this displacement is less significant with the maximum heat transfer occurring at 35 mm from the notional arc of cut, rather than the 30 mm expected for an unobstructed jet. This peak also has a greater magnitude for the impingement angle of 15°. This enhancement has also been attributed to the air jet flowing, unobstructed by the grinding wheel, to the grinding zone at this angle.

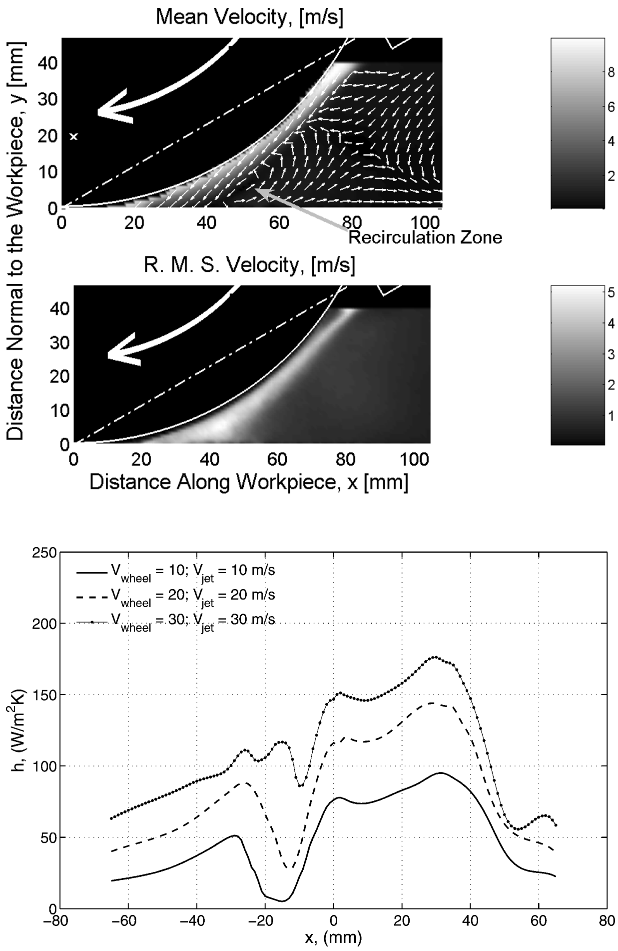

Fig. 5 Fluid flow and heat transfer due to jet cooling with rotating grinding wheel: $\alpha = 30°$ and $H = 101$ mm

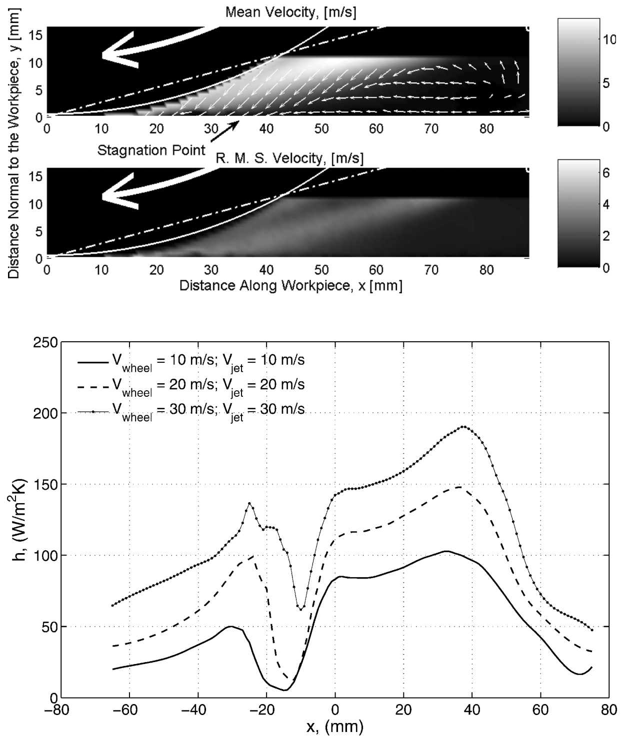

Fig. 6 Fluid flow and heat transfer due to jet cooling of a grinding process: $\alpha = 15°$ and $H = 101$ mm

The r.m.s. velocity flow field has not changed significantly with the addition of the impinging air jet; the magnitude of the turbulence intensity remains high in the wedge made between the grinding wheel and the surface. The streamlines in the velocity flow field also indicate that some of the air flow recirculates, and is entrained by the wheel, after it has been in contact with the heated surface. The recirculation zone is indicated by an arrow in Fig. 5(a) and occurs at ~45 mm from the grinding zone. In general, recirculations in the flow have a negative effect on the heat transfer coefficient; however, the magnitude of the velocity of the recirculating air is small and therefore it does not significantly influence the distribution of the heat transfer coefficient. Overall, the magnitude and distribution of the heat transfer coefficients are relatively unaffected by this low-speed impinging jet.

Figure 7 presents the results for a grinding wheel turning in the opposite direction to the impinging jet flow. It can be seen from Fig. 7(b) that this configuration does not have a favourable influence on the convective heat transfer coefficient in the grinding zone. Although the heat transfer distributions exhibit similar peaks to the previous distributions, they occur at different locations and have altered magnitudes. In particular, the convective heat transfer coefficient is a minimum at the notional grinding zone ($x = 0$). This local minimum has been attributed to the local flow stagnating at the location of the minimum gap and is associated with a large recirculation pattern in the fluid flow. Figure 7(a) shows that much of the air leaving the notional grinding zone is recirculated and re-enters the grinding zone. This has a negative effect on the heat transfer coefficient because the air entering this critical zone has an elevated temperature.

The maximum intensity of turbulence (≈9.2 per cent) is higher in this grinding configuration, but at a large distance from the surface. The peak turbulence intensity is measured along the stagnation zone that occurs between the two distinct flow regions corresponding to the wheel-induced flow and jet flow, respectively. The turbulence intensity close to the surface (≈6.6 per cent), where the influence on heat transfer is greatest, remains comparable with the case where both the jet and wheel velocities are in the same direction.

Although the heat transfer coefficient is high at other locations, this is an unfavourable configuration for cooling of a grinding process because of the local minimum in convective heat transfer coefficient in the critical region of the arc of cut.

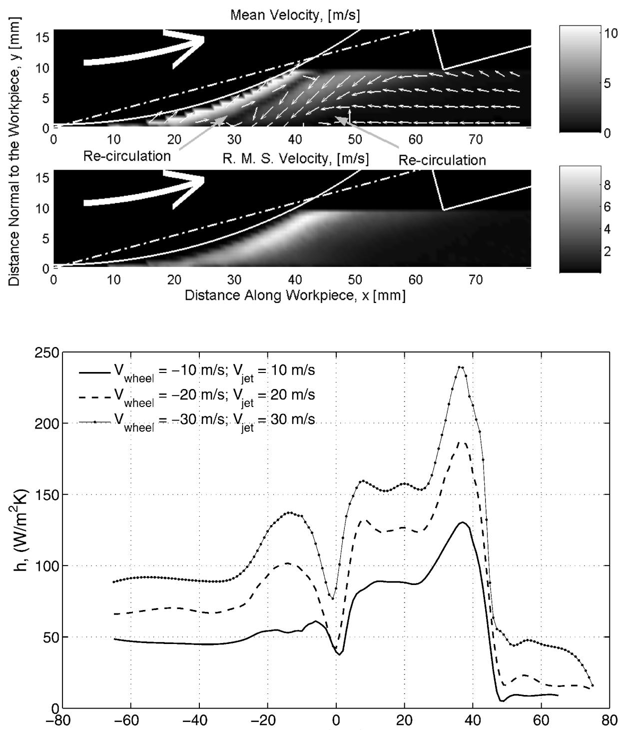

Fig. 7 Fluid flow and heat transfer due to jet cooling of a grinding process: $\alpha = 15^\circ$ and $H = 65$ mm

3.3 High-speed air jet

Heat transfer data were also acquired for a high-speed jet of diameter 2.6 mm directed towards the instrumented test plate. However, PIV data were not obtained because of a difficulty in seeding the high-speed jet flow. This jet has been used for cooling of an actual grinding process, as described by Babic *et al.* [**8**], and has proven to be a surprisingly effective cooling arrangement. Two different jet positions were tested in this part of the heat transfer investigation and these are illustrated in Fig. 8. The first jet position tested is the same as used for the previous 15° test, namely, where the wheel rotates about a point directly above the geometric centre of the jet. The second position was chosen to counteract the effect of the wheel in blocking the jet flow; thus the jet was positioned at a minimum height above the plate but still at an angle of 15°.

The distributions of heat transfer coefficient shown in Fig. 9 no longer exhibit the same number of local maxima and minima, as the high-speed of the jet has managed to penetrate the boundary layer flow around the grinding wheel. The predominant peak still occurs at the stagnation point of the jet ($x \approx 25$ mm) and the heat transfer distribution also exhibits a more subtle change in slope at the grinding zone ($x = 0$ mm). However, the most significant change to be noted is that the heat transfer is greatly enhanced over the entire grinding zone in comparison with the low-speed jets.

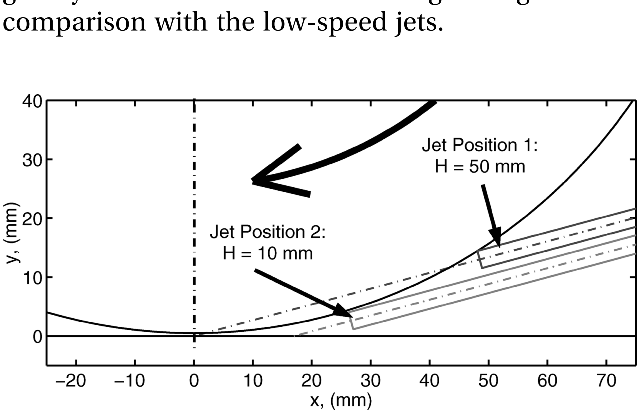

Fig. 8 Schematic of high-speed impinging jet setup

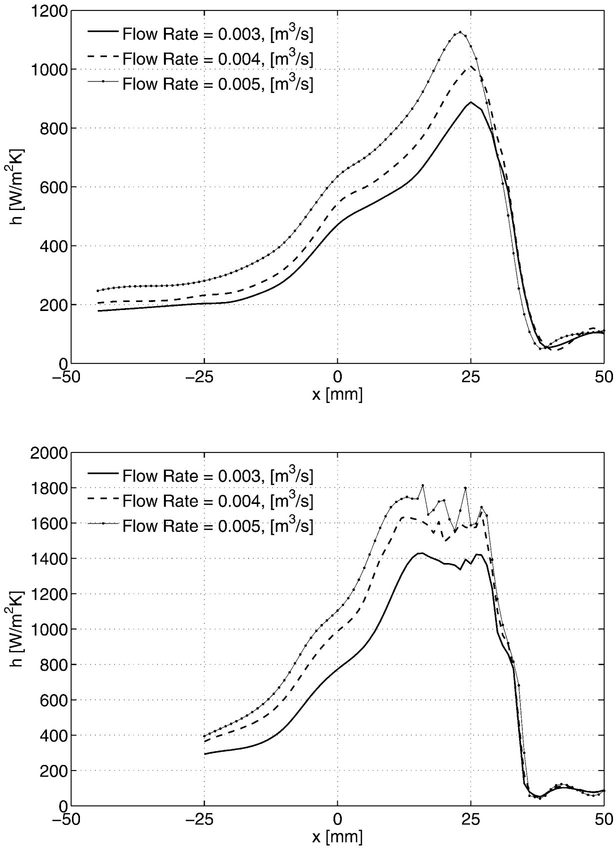

Fig. 9 Wheel and high-speed impinging jet heat transfer distributions

The first jet position considered is thought to be less favourable because the jet is effectively impinging on the wheel and not on the grinding surface. In a grinding process, cooling of the grinding wheel itself may well be an effective method of reducing the temperature in the grinding zone. In this investigation, however, direct convective cooling of the workpiece itself is under consideration. For this reason, the obliquely impinging jet was positioned so that the convective heat transfer from the workpiece would be maximized and thus the height of the jet was minimized. In this case, the jet impingement position is not directed at the minimum gap but slightly to the right of it. Heat transfer coefficients for this jet setup have proven to be even more favourable, although the peak heat transfer coefficient still does not occur close to the grinding zone. Despite this, the second jet setup shown in Fig. 8 has managed to almost double the heat transfer coefficient in the grinding zone for the same flowrate of air.

High-speed air jets have been applied to an actual grinding process by Babic *et al.* [**8**]. The maximum workpiece temperatures were measured for various cooling methods and are shown in Table 1. In this case, the depth of cut was 10 μm and the tangential velocity of the wheel was 28 m/s.

Table 1 Grinding temperatures [**8**]

Cooling method	$T_{\mathrm{Workpiece}}$ (°C)
No cooling	320
Water emulsion (5% HOCULT B60CB coolant oil) 1 × 2.6 mm diameter nozzle; speed = 2.9 m/s	218
Dry air jet 2 × 2.6 mm diameter nozzles; speed ≈ Mach 1	268
Air and water mist 2 × 2.6 mm diameter nozzles; 1 g/s water; speed ≈ Mach 1	214

It has been shown that the air jets reduce the workpiece temperature, but not quite so much as a conventional cutting fluid. However, when a small volume of water is added to the air stream, the mist cooling becomes more effective than with a conventional coolant.

4 CONCLUSIONS

PIV data have been used to illustrate some of the flow characteristics that occur when an air jet impinges on a flat plate with a rotating grinding wheel mounted above the surface, representative of the workpiece in a grinding process. From these data, the influence of the flow on heat transfer has been inferred. The two main differences between the experimental setup and an actual grinding process are the thermal boundary condition and the non-contact between the surface and the wheel. The significance of these approximations has been discussed and it can be concluded that the convective heat transfer coefficient is probably underestimated as a result of these differences. However, it is likely that the peaks in the distributions occur in the same locations.

1. The rotating grinding wheel entrains a boundary layer that impinges on the grinding surface. The heat transfer to this induced flow has a convection coefficient comparable with that of an impinging air jet of similar velocity. In general, the boundary layer developed around the rotating grinding wheel has a negative effect on the cooling of a grinding process, as it prevents the jet flow from reaching the grinding zone. It also has the effect of moving the stagnation point, where the peak in heat transfer coefficient occurs, away from the grinding zone.
2. Depending on the grinding configuration, recirculations in the flow have been revealed. These have a negative effect on the heat transfer coefficient as the local surface to fluid temperature difference would be reduced.
3. Peaks in the heat transfer distributions have been successfully linked to regions of high fluid velocity

and turbulence intensity. For the conditions investigated, the r.m.s. velocity or the turbulence intensity is a maximum in the wedge made between the grinding wheel and the grinding surface. It has also been established that an angle of impingement of 15° is preferable to 30° as the maximum peak in the heat transfer distributions occurs at this angle.

4. When a counterflow cooling configuration is tested, the heat transfer coefficient is usually a minimum at the arc of cut. This coefficient tends to zero for low velocities, suggesting the occurrence of an instantaneous stagnation point in the flow. This indicates that a countercurrent configuration is not appropriate for the cooling of a grinding process.
5. It has been shown that a high-speed jet effectively penetrates the boundary layer flow around the grinding wheel, providing good cooling of the grinding zone.
6. Positioning of the high-speed jet has also been shown to be critical in enhancing the convective heat transfer. In general, the high-speed jet provides more effective cooling than the low-speed jet; however, if the distance of the jet from the grinding zone is decreased, the heat transfer coefficient can be further increased by a factor of 2.

The cooling of a grinding process has many characteristics that are unique to the specific application.

Although this investigation has been predominantly directed towards cooling of the grinding zone itself, it is worth noting that the area surrounding the grinding zone will be at a somewhat elevated temperature and more of the heat transfer coefficient distribution will be utilized in the overall cooling of a grinding process. It would also be of benefit if the impinging air jet was colder than the ambient air or workpiece. In this case, the precooling of the entire workpiece would also serve to reduce the temperature in the grinding zone. Future work should include an investigation of the effect on heat transfer of a difference in temperature between the ambient air and the jet air.

ACKNOWLEDGEMENT

This work was supported in part by Enterprise Ireland under grant SC/2001/0071 and also by Science Foundation Ireland grant 04/BR/EO108.

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APPENDIX

Notation

a	depth of cut (m)
b	grinding wheel thickness (m)
D	diameter (m)
F	force (N)
h	convective heat transfer coefficient (W/m^{2}K)
H	height of nozzle above impingement surface (m)
k	thermal conductivity (W/mK)
q	rate of heat transfer (W)
q''	heat flux (W/m^2)
R	partition ratio
T	temperature (K)
V	velocity (m/s)
x	horizontal coordinate
α	angle of impingement (°)
δ	sensor thickness (m)

Subscripts

amb	ambient
g	grinding wheel
j	jet
s	sensor
surf	surface
t	tangential
w	workpiece