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Investigation for convective heat transfer on grinding work-piece surface subjected to an impinging jet

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HIGHLIGHTS

- ► Illustrate flow and heat transfer features in vicinity of a grinding wheel.
- ► Assess heat transfer enhancement of the mist/air jet impingement.
- ► Swirl flow over rotating disk affects the wall jet flow structure of oblique impinging jet.
- ► Heat transfer is enhanced near grinding zone if jet direction is reasonable.
- ► Mist/air ratio and rotational speed are important factors affecting heat transfer in vicinity of grinding wheel.

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ABSTRACT

Investigation was carried out to illustrate some of the flow and heat transfer characteristics that occur when a single-air jet or mist/air jet impinges on a flat plate with a rotating disk mounted above the surface, representative of the work-piece in a grinding process. The first objective aimed to assess the detailed flow and heat transfer features in the vicinity of a rotating grinding wheel with single-air jet impingement directed at grinding zone by numerical investigation. The second objective aimed to assess the quantitative evaluation for heat transfer enhancement on a grinding work-piece surface subjected to the mist/air jet impingement by experimental investigation. The results show that the coupled action of swirl air entrainment and jet impingement is benefit somewhat for overall convective heat transfer in relative to stationary disk case whether the disk rotates in clockwise or contrary clockwise. When the jet impinging direction is consistent with the rotational direction of rotating disk, convective heat transfer enhancement is achieved near grinding region, especially at higher rotating speed. Furthermore, the increasing of water droplet in mist/air jet impingement showed significant enhancement of the cooling effect.

1. Introduction

Grinding is a widely employed machining process used to achieve good geometrical form, dimensional accuracy, surface finish, and surface integrity. The grinding process requires higher energy expenditure per unit volume of material removed. Virtually all of this energy is dissipated as the heat at the grinding zone where the wheel interacts with the work-piece. The heat generated at the grinding zone is then transferred to work-piece (Q_w), grinding swarf (Q_{sw}), coolant (Q_{co})and grinding wheel (Q_{gw}), as seen in Fig. 1. It is often considered that in most cases a larger part of the heat will end up in the work-piece. As a consequence, a high temperature may be experienced by the grinding surface, which can cause various types of thermal damage, such as burning, metallurgical phase transformations, softening of hardened surfaces, unfavorable residual tensile stresses, cracks and oxidation [1,2]. The traditional method for the cooling of the grinding zone is the use of liquid coolants, usually an oil-in-water emulsion, or neat oil. Liquid coolants provide bulk cooling of the work-piece and removal of swarf, but unless special pumps are used, their low speed and kinetic energy will not allow them to penetrate the fast moving boundary layer forming around a fast-rotating grinding wheel, so they never reach the grinding zone. In addition, liquid coolants, based on water, have relatively low boiling points and with the onset of film boiling their heat transfer capabilities diminish dramatically [3]. Furthermore, strong arguments against their continued use are the expensive cost and pollution both in the exploitation and disposal phases.

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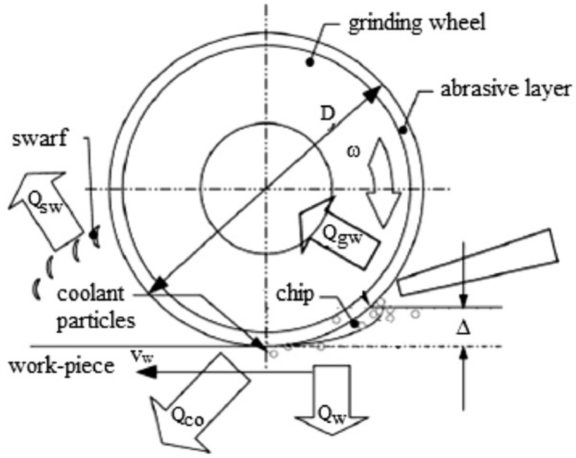

(a) Q_w to work-piece, (b) Q_{sf} to swarf, (c) Q_{co} to coolant, (d) Q_{gw} to grinding wheel

Fig. 1. Schematics of grinding energy transfer.

Substantially, environmental and resource problems have urged the search for alternative cooling agents without or with less chemical additives becoming an active study in recently. Paul et al. [4] reported an application of liquid nitrogen which was found to be more advantages in grinding harder materials with higher infeeds. Shaji et al. [5] investigated the grinding of a high-speed steel using graphite as lubricant. They found that the normal grinding force could be lower. However, these methods have not been widely applied in industry because of the associated high cost of refrigerants and oxygen starvation in the working environment. Choi et al. [6] studied the cooling effects of compressed cold air in cylindrical grinding of harden steels with a CBN wheel. It was reported that the effectiveness of the cold air in reducing thermal defects was nearly comparable with the conventional coolant when the depth of cut was small. However, surface tensile stresses tended to appear and surface roughness would rise when the depth of cut increased. It was concluded that the lack of lubrication in using dry cold air was probably the cause of the problems.

Mist/air jet impingent directed at grinding zone is regarded as one of the promising cooling solutions to satisfy the following conditions – to be effective, cheap and environment-friendly. Mist/air jet is easily formed by injecting a small amount of liquid into the high-speed air flow. Nguyen and Zhang [7] made an assessment of the applicability of cold air and oil mist in the grinding surface. The investigation showed that cold air can be used to suppress surface burning under certain material removal rates and has an advantage of reduced grinding forces. With the addition of very small amount of vegetable oil, a larger depth of cut could be performed without burning while keeping a good grinding quality. There was no significant difference in subsurface hardness of the components ground with coolant or with cold air and oil mist (CAOM), although the latter showed a stronger dependence of surface residual stresses on the depth of cut due to the limited cooling capacity of CAOM. Babic et al. [8] described some experiments on the grinding process with a mist/air jet cooling by injecting a small amount of water into air flow. Evaporation of the miniaturized droplets of water impinging upon a superheated surface through the phase change process considerably added to the overall heat removal, and this made the discussed type of cooling much more efficient as compared with that caused by air flow under otherwise identical conditions.

Numerous investigations on the heat transfer enhancement of two-phase impinging jet have been conducted and are available in literature. The mechanism of using mist-jet to enhance cooling effectiveness is discussed by Li et al. [9]. Chang and Su [10] described the detailed heat transfer distributions of an atomized air-water mist-jet impinging orthogonally onto a confined target plate with various water-to-air massflow ratios. Results showed that the high momentum mist-jet interacting with the water-film and wall-jet flows created a variety of heat transfer contours on the impinging surface. Li et al. [11,12] reported results of a mist/steam slot jet impinging on a heated flat surface. They concluded that stagnation point heat transfer could be enhanced over 200% by the addition of 1.5% mist. The mist enhancement was found to decline to near zero by five slot widths downstream. Wang et al. [13] experimentally investigated the mist/steam heat transfer of three rows of circular jet impingement in a confined channel. The results indicated that the cooling enhancement region of the three-row jet impingement jets was more extensive than those employing one row of circular jets or a slot jet. The highest enhanced region spanned about five jet diameters and became negligible downstream. The maximum local enhancement was up to 800% by injecting 3.5% of mist at low heat flux condition and 150% at high heat flux condition.

However, the inherent nature of the jet impingement heat transfer on grinding work-piece is perhaps distinctive to the cases of free jet impingement. Owing to the spinning grinding wheel, the interaction between the swirl flow entrainment induced by the spinning disk and jet impingement provides the conjugate effect in the vicinity of a rotating grinding wheel, making the convective heat transfer on grinding work-piece surface more complexity. Some investigations have been done for the heat transfer enhancement over rotating disk by jet impingement. Saniei and Yan [14] presented local heat transfer measurements for a rotating disk cooled with an impinging air jet. Several important factors such as rotational Reynolds number, jet Reynolds number, jet-to-disk spacing, and the location of the jet center relative to the disk center were examined. Minagawa and Obi [15] studied turbulent fluid flow structure of an impinging jet on a rotating disk. They concluded that rotation has a significant effect on skew of mean flow and centrifugal force. Fattah [16] investigated the fluid flow characteristics numerically by using $k-\varepsilon$ RNG model and compared his results with those of Minagawa and Obi [5]. Temperature filed and convective heat transfer coefficient on a rotating disk with a jet impinging on was evaluated experimentally by Astarita and Cardone [17]. They considered the interaction of turbulent jet and boundary layer on disk due to rotation. O'Donovan et al [18] made an experiment on jet heat transfer in the vicinity of a rotating grinding wheel. In their experiment, a grinding wheel was suspended about 0.5 mm above the surface and was driven with an AC Motor. Contact was not made between the grinding wheel and the surface to ensure that the sensors were not damaged by the rotating wheel. It had been shown that a boundary layer that develops around the rotating grinding wheel had 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 was necessary to penetrate this boundary layer and this could only be achieved when the jet velocity was substantially greater than the tangential velocity of the wheel. Ebbrell et al. [19] 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 from 0.005 mm to 1.5 mm, respectively. It was important to realize that the smallest gap of 0.005 mm investigated by Ebbrell et al. [19] approximated the grinding process quite accurately as the contact area between the grinding wheel and the work-piece in the grinding zone was typically only a few percent of the total grinding zone area. The