HIGH-SPEED WATER JET AS A COOLANT/LUBRICANT IN GRINDING

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ABSTRACT

Grinding is an important metal removal process which is widely used in the production of components requiring fine tolerances and smooth finishes. Compared with other machining processes, grinding requires extremely high energy per unit volume of removed material. Virtually all of this energy is converted to heat which is concentrated within the grinding zone. This leads to elevated temperatures which can cause thermal damage to the workpiece and accelerated wheel wear. To avoid these undesirable effects, grinding fluids are typically used. Grinding fluids serve three functions: they lubricate, thereby reducing the amount of heat generated, they remove heat from the wheel and workpiece surfaces via convection, and they help prevent grinding debris from sticking to the surfaces of the workpiece and grinding wheel. The effectiveness of the grinding fluid depends on the location of placement, flow velocity, quantity of flow and direction of application. In this paper the authors present a newly developed technique for applying ultra-high speed coolant/lubricant as a mean of improving grinding process performance. The developed technique represents an extension of the work on improving machining processes performance by applying high-pressure waterjet as a coolant/lubricant performed at the Abrasive Waterjet Laboratory of the University of Kentucky, for which patent No. 5,288,186 [1] was granted.

INTRODUCTION

The conventional method of grinding fluid application is in the form of a flood through a remote nozzle. Most often, this method of fluid application is not very effective, especially under severe grinding conditions, as the energy of the fluid is not sufficient to overcome the centrifugal force of the wheel or penetrate the boundary layer of air surrounding the wheel. As a result only 5% to 30% of the grinding fluid is effectively used in conventional flood application in grinding operations [2]. Another serious problem associated with grinding operations is the need to perform frequent wheel dressing to remove the debris adhering to the pores of the wheel and resharpen the wheel. It should be noted that about 90% of the wheel material is lost during dressing and only about 10% of the wheel is consumed during grinding, making the process highly uneconomical and inefficient. This dressing process also requires grinding interruptions, machine down time and additional setup time.

Different methods have been adapted in the past to improve the effectiveness of the grinding fluid application. Wagner et al. [3] developed an apparatus for grinding fluid application at lower speeds and higher volume flow rate through a plurality of nozzles. However, the lower speeds were not sufficient to overcome the centrifugal force of the wheel and hence led to improper cooling/lubrication of the grinding zone. Pigott [4] developed another apparatus for application of grinding fluids at a pressure of 1.7 MPa so that the jet discharges from the nozzle at a speed sufficient to overcome the peripheral speed of the grinding wheel. A nozzle that supplies coolant in a direction opposite to the direction of wheel rotation was developed by Klassen et al. [5] to remove the air film and loose particles from the wheel surface. Apparatuses such as air deflection flood nozzles [6], radial or spiral grooved grinding wheels [7], etc. were used to penetrate the air cushion around the wheel, but they were not very successful in overcoming the wheel centrifugal force or providing effective cleaning and cooling/lubrication. Pressurized water jets up to 2 MPa were used by Borkowski et al. [8] and Lincoln et al. [9] for cleaning and cooling the grinding wheel. However, even though the input pressure in most of the above cases was sufficient to deliver the grinding fluid at a speed higher than the peripheral speed of the grinding wheel and capable of penetrating through the air envelope surrounding the wheel, the quantity of the fluid delivered at such low pressures was not enough to provide effective cooling/lubrication or cleaning of the wheel. At high temperatures, the effectiveness of the convective cooling of the grinding fluid applied at lower pressures is reduced considerably because of the rapid evaporation of the fluid film under severe grinding conditions. Faster convective cooling associated with ultra-high speed jets is very effective in preventing the fluid film evaporation and alleviating the above problems.

In this paper, a technique for applying an ultra-high speed (up to 360 m/sec) coolant/lubricant jet in a grinding operation is described. The primary objectives of using an ultra-high speed waterjet in conjunction with grinding operations are to effectively penetrate the air envelope surrounding the wheel and overcome the centrifugal force thereby providing proper cleaning, cooling/lubrication, resharpening of the wheel and reducing the wheel loading effect. The effectiveness of the developed technique is evaluated in terms of grinding force, surface finish, acoustic emission (AE) signal, metal removal rate, and generated heat in the grinding zone. Different materials such as Al6064, SS304, and U720 were used as workpieces for the investigations and the experimental studies were conducted for a surface grinding operation.

COOLING THE GRINDING ZONE WITH ULTRA-HIGH SPEED WATER JET

In grinding, the size, shape, and distribution of cutting edges as well as the condition of the pores on the surface of the wheel play a dominant role. Similar to other cutting tools, the abrasive grains of the wheel are dulled by usage and lose their effectiveness. Loading of grinding wheels is a frequently occurring phenomenon when grinding ductile (aluminum) or high adhesion (stainless steel, titanium) materials. Loaded chips alter the grain edge geometry resulting in increased cutting forces which may lead to a break down of the grinding wheel structure. In principle, an ideal grinding wheel would automatically be resharpend when the abrasive grains become ineffective. They would either fracture or entirely break away from the wheel face thus exposing new cutting edges. But in practice, both the geometric and functional characteristics of the grinding wheel must be restored periodically by dressing.

Although grinding can be performed dry, the use of a fluid prevents temperature rise and improves the surface finish and the efficiency of the operation. Grinding fluids are typically water-based emulsions (for general grinding) and oils (for tread grinding). Grinding fluids may be applied as a stream (flood) or as a mist, which is a mixture of fluid and air. Because of high surface speeds, it is believed that there is an air stream or air blanket around the periphery of the rotating wheel that prevents the fluid from reaching the grinding zone. For these cases, special nozzles have been designed with the fluid applied under high pressure in the proper direction.

In order to penetrate the air barrier formed around the rotating grinding wheel and also to suppress its centrifugal force, the grinding fluid must travel with a speed at least equal to that of the surface speed of the grinding wheel. The surface speed of conventional grinding wheels (aluminum oxide and silicon carbide) could reach magnitudes of over 30 m/sec. In the last several years extensive research and development work on improving the performances of the metal removal processes by applying ultra high-speed waterjets as coolant/lubricant has been performed in the Abrasive Waterjet Laboratory of the University of Kentucky. This work resulted in an awarded patent and a number of publications presented in technical journals and national and international conferences.

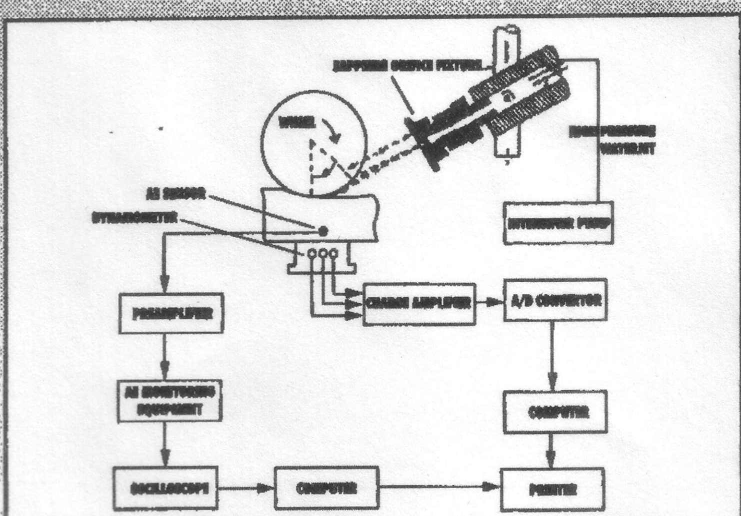

Fig. 1. Experimental Setup For Surface Grinding With High Speed Grinding Fluid

A schematic of the developed high-speed waterjet assisted grinding operation is shown in Fig. 1. The fluid jet (in our case pure water was used as the grinding fluid) is brought tangentially to the grinding wheel about 50 mm from the entrance into the grinding zone. The water jet is oriented in the same direction as the direction of the wheel rotation. The grinding fluid (water) that can be pressurized up to 380 MPa using a high pressure intensifier pump is brought through a flexible hose towards the grinding wheel. A sapphire orifice placed at the end of the flexible hose converts the pressure energy of the fluid into kinetic energy. Suitable fixturing is provided for the orifice assembly to facilitate easy manipulation of the angle at which the ultra-high speed water jet is delivered and the stand-off distance of the orifice from the grinding wheel. The orifice assembly can accommodate orifices of diameters ranging from 0.2 mm to 0.52 mm. The stand-off distance and the angular position of the water jet will depend on the wheel diameter and its width. The optimal water jet speed will depend on the workpiece material and its required surface quality.

RESULTS AND DISCUSSION

The experiments were conducted to investigate the effect of ultra-high speed grinding fluid on the surface grinding performance. In order to study the effect of the velocity of water jet on grinding performance, the experiments were performed by

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varying the speed of the grinding fluid (0 to 365 m/sec) while keeping the conventional parameters, namely traverse speed and depth of cut, constant. Grinding force components, acoustic emission signals, and workpiece surface profiles were monitored at four different instances during grinding, namely 2.5, 5. 7.5 and 10 minutes, in order to study the effect of high speed grinding fluid with progressive wheel wear. A newly dressed wheel was used for experiments conducted at each water jet speed setting and grinding condition. The surface roughness of the workpiece was quantified in terms of Ra. The results in this paper are a part of our previous paper entitled "Effect of High Speed Grinding Fluid on Surface Grinding Performance", SME Paper No. MR95-213 [10]. The process parameters for these experiments are given in Table 1.

TABLE 1. PROCESS PARAMETERS

Workpiece material	SS304
Wheel material - Al Oxide (WA543-731-556106)	
Wheel speed	30 m/sec
Wheel width	10 mm
Wheel diameter	300 mm
Cross feed	0.81 mm/pass
Orifice diamete	0.46 mm
Type of cooling - flood and high-speed water jet	
Traverse speed	120 mm/sec
Depth of grinding	0.062 mm
Grinding time	2.5 to 10 min.
Water jet speed	173 - 365 m/sec

The tangential and normal force components for the different grinding times and water jet speeds are plotted in Fig. 2. For both flood cooling and high-speed water jet cooling, the magnitude of the grinding force components increase with increasing grinding time. As grinding progresses, the wheel surface is initially subjected to grain fracture and bond fracture, followed by gradual attritious wear. The effect of wheel loading also increases. These trends affect the cutting capability of the grinding wheel leading to increased grinding forces. The magnitude of the grinding force compo-

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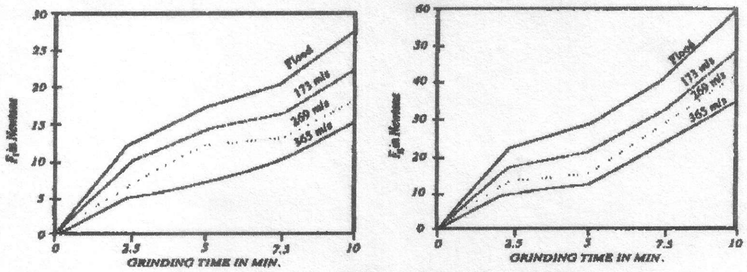

Traverse Speed = 120 mm/s, Depth = 0.062 mm

Fig. 2. Grinding Force Components VS. Grinding Time

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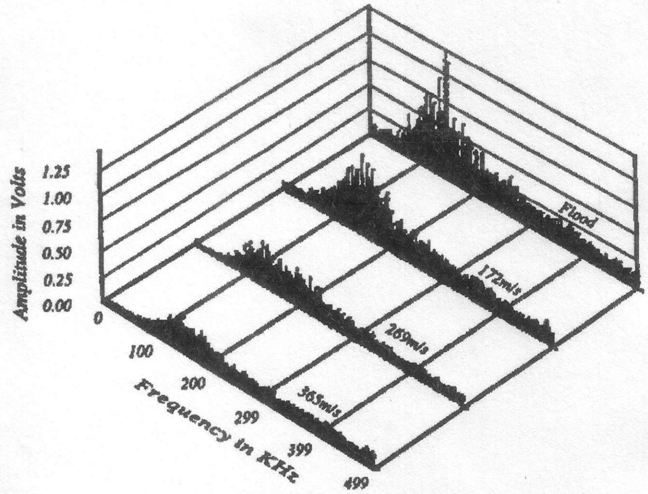
nents are reduced by almost 50% with the application of high speed water jets. The improved cooling/lubrication effect at the grinding zone, effective cleaning action and reduced wheel loading effect of the high speed water jet are responsible for the improvement in process performance. The water jet at high speeds also provides a gentle dressing/resharpening effect on the wheel by removing a tiny layer of abrasive grains and exposing new grains on the surface of the grinding wheel. The high flow rate of the water jet improves the convective cooling effect and provides complete evaporation of the fluid film at the grinding zone. The effectiveness of the high speed grinding fluid increases as the jet velocity increases. As a result, the grinding forces, abrasive wheel wear and work-burn are reduced leading to overall improvement in grinding process.



Traverse Speed = 120 mm/s, Depth = 0.062 mm, Time = 10 min.

Fig. 3. Frequency Domain AE Signals

A plot of frequency domain acoustic emission (AE) signals acquired for flood cooling and high speed water jet cooling after 10 minutes of grinding time is shown in Fig. 3. It can be noted that the peak frequency for all grinding conditions is around 150 KHz. The effect of bond fracture and grain fracture on these signals can be eliminated as they are acquired after

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10 minutes of grinding time. The peak amplitude is highest for flood cooling conditions indicating the presence of high attrition wear of the wheel. With application of high speed water jet, the peak response at 150 KHz drops down initially to about 40% and then to 25% due to reduction in wheel loading and attritious wear. The decrease in the area enclosed by the FFT curve indicates that the energy of the AE signal reduces with the application of water jet. At higher water jet speeds the amplitude of the frequency domain AE signal drops through all the frequency range which could be due to the resharpening of the wheel by the jet. The above peak frequency of the AE signal (150 KHz) can be considered as a good indicator of the average number of active grains in contact with the workpiece per unit time. The average number of active grains (N) per unit area is given by

$$N = (\text{Peak Frequency})/(\text{Peripheral Speed of the Wheel} \times \text{Cross Feed})$$

The value of "N" as per the above equation was calculated to be approximately 6/mm². This was found to be in good agreement with the actual number of grains per mm² as per wheel specifications. The high amplitude for the peak frequency of 150 KHz in flood cooling indicates the presence of excessive rubbing action of the grains caused by the blunt cutting edges. However, the resharpening effect of the ultra-high speed water jet produces randomly oriented and randomly distributed cutting edges which causes relatively flat response on the FFT curve. Thus the trend exhibited by the frequency domain AE signal supports the previous observations made about the role played by high speed grinding fluid in improving the process performance.

Surface roughness indicated by Ra is plotted against grinding time for flood cooling and high speed

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harder bond material be used for rial. By applying the high speed

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water jet cooling in Fig. 4. With progressive grinding time, the surface finish for both the cooling conditions deteriorates which could be attributed to increased wheel wear and wheel loading. It can be noted that for all conditions of grinding time, the surface finish improves with increase in water jet speed. Ra reduces by more than 50%. A combination of factors during high speed water jet grinding such as the improved cooling/lubrication effect of the grinding zone, reduced abrasive wheel wear and its loading, improved dressing/resharpening effect, absence of wheel/workpiece particles at the grinding zone caused by improved washing action, etc. are responsible for the improvement in surface quality.

The heat flux into the workpiece during the grinding operations estimated using the experimentally determined temperature histories through an inverse heat transfer method [11] is plotted in Fig. 5. Grinding fluid in the form of high pressure water jet reduces the heat input by up to 75% of that of flood cooling.

In the classical grinding operation the hardness of the bond material is determined by the strength of the workpiece material. In order to provide the so-called self-sharpening effect, namely removal of the worn-out or fractured abrasive grains by dislodging them from the bond material, it is recommended that harder bond material be selected for grinding softer workpiece material, and softer bond material be selected for grinding harder workpiece material ... grinding fluid for dressing and cooling/lubrication, a hard bond materi-

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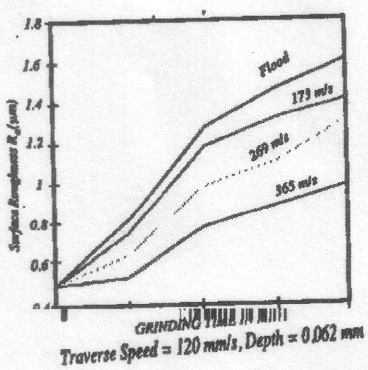


Fig. 4. R_a VS. Grinding Time

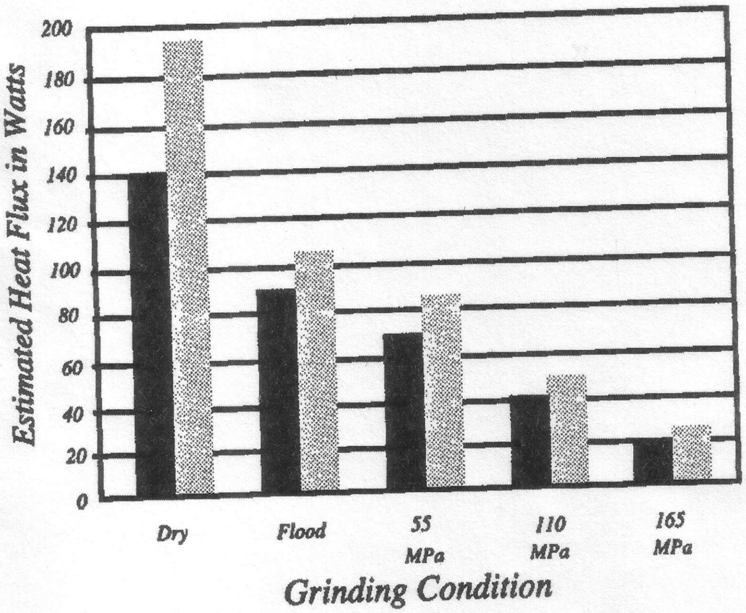
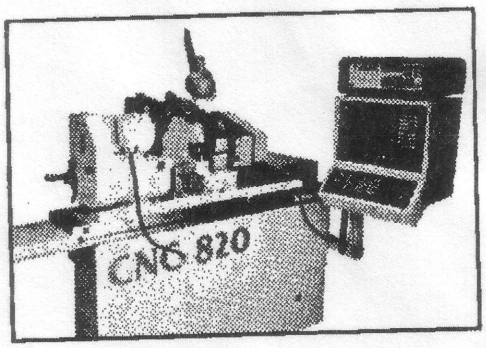


Fig. 5. Average Heat Flux At The Grinding Zone For Different Grinding Conditions



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taper is measured on diameter, the taper error would be .000218 in/in and in a hole 2 inches long .000436 in.

The MICROANGLING/ FORCE-SENSING subplate under the wheelhead and a PC-CONTROL with open architecture, provides a system for holding close tolerances on fast cycles without sparkout and without using expensive in-process gaging and post-process taper™trend gaging.

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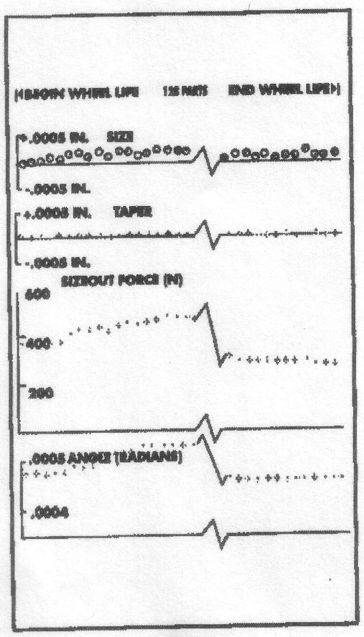

Fig 2

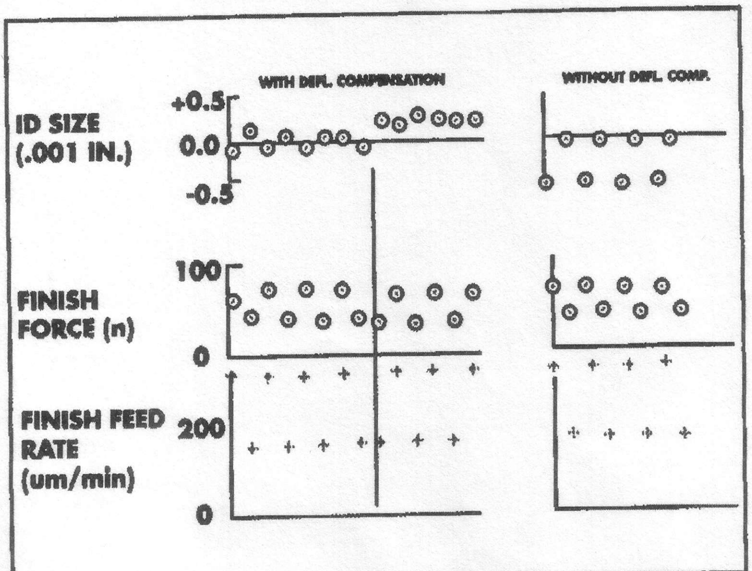

Fig 3 - bore Grinds showing ID size plot with and without deflection - compensated sizing for alternating finish feedrates of 300 and 150 um/min/ System stiffness= 4200 n/mm (24027 lb/in)

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al could be used for grinding any type of workpiece material. Namely, the self-sharpening effect for the case of applying high speed grinding fluid is no longer a matter of concern since the grinding wheel is continuously resharpened by the fluid jet. Evidently, the rate of abrasive grain removal from the wheel surface and its topography will depend on the speed of the grinding fluid. The optimization of the grinding fluid speed should be done for the selected type of grinding wheel, its dimensions and given workpiece material.

CONCLUSIONS

A new way of providing grinding fluid to the grinding zone was developed. This approach is based on injecting high pressure water jet tangentially at the abrasive wheel about 50 mm from the entrance into the grinding zone. In order to penetrate the air layer formed around the rotating grinding wheel and also to suppress its centrifugal force, the grinding fluid must travel with a speed at least equal to that of the surface speed of the grinding wheel. Through extensive experimentation it was found that the pressurized water jet breaks the air layer, overcomes the high centrifugal force and finally penetrates effectively into the grinding zone. Due to the improved cooling/lubrication, cleaning, and washing actions of the high speed water jet coolant/lubricant, the overall grinding process performance is significantly improved.

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