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Research Paper

Environmentally friendly machining with a revolving heat pipe grinding wheel

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HIGHLIGHTS

- Revolving heat pipe is applied in grinding wheel to replace the coolants.
- Natural convection dominates the heat transfer mechanism in the evaporator.
- Film condensation is found in the condenser of RHPGW.
- RHPGW shows better heat transfer performance in dry grinding of Inconel 718.

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ABSTRACT

Defects caused by high grinding temperatures on both workpieces and grinding wheels become more significant with the development of difficult-to-machine materials and creep-feed grinding procedures. The coolants normally used to dissipate heat can cause harm to the environment as well as increase machining costs. A novel idea that incorporates a revolving heat pipe into the grinding wheel has been proposed to enhance heat transfer in the contact zone. In this study, a simulation is performed to investigate the heat transfer mechanism in the evaporator and condenser section of a revolving heat pipe grinding wheel (RHPGW) at a wheel velocity of 45 m/s. The results indicate that natural convection heat transfer and film condensation occur under this condition. The heat transfer and startup performance of the RHPGW are investigated in further experiments with different working fluids, fluid loadings and rotational speeds. Finally, experiments on creep-feed grinding of Inconel 718 are performed using a RHPGW and a grinding wheel without a revolving heat pipe, without application of any coolant. The results show that grinding temperatures can be maintained below 100 °C with a RHPGW and both the workpiece and grinding wheel show better quality than those when grinding is performed without a revolving heat pipe.

1. Introduction

Grinding is often used as the final machining method in the production of components owing to its ability to achieve high surface quality with fine tolerance and roughness. With the increasing use of difficult-to-machine materials such as titanium alloys and superalloys, high-efficiency grinding processes such as creep-feed grinding [1], high-speed grinding [2] and high-efficiency deep grinding [3] have been developed to meet the machining requirements of these materials. However, the high specific energy requirements in high-efficiency grinding can result in a greater heat generation and consequently a higher grinding temperature in the contact zone, which in turn will affect the quality of the ground surface and cause wear of the grinding wheel [4]. Therefore, the major goal in improving the grinding process is to dissipate the heat generated in the contact zone between the workpiece and the grinding wheel.

Many research efforts have been devoted to heat flux distributions during grinding [5,6]. The partitioning of the thermal energy among the workpiece, the chips, the coolant and the grinding wheel has been estimated. For difficult-to-machine materials like Inconel 718, the dissipation of the heat by the workpiece is poor owing to the low thermal conductivities of such materials. In addition, the amount of the heat that can be carried away by chips is limited because of the limiting chip energy [7]. Therefore, approaches using coolant to dissipate heat have been developed, improved and optimized in the last few decades. Some of these

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have concentrated on the geometry [8] and the numbers [9] of the nozzles in the system, while others have focused on the velocity [10] and the pressure of the coolant. These methods have produced considerable cooling effects during the grinding process. However, the fluids that are used to cool and lubricate the machinery can cause harm to both the environment and the machine operators, which is not in compliance with the principles of green manufacturing and sustainable development. Therefore, many attempts have been made to reduce the coolant consumption in the machining process. One attractive line of research concerns environmentally friendly minimum-quantity lubrication grinding [11]. Vegetable oils have been used as the base oils in this process to reduce environmental pollution [12]. A minimum amount of lubricant is initially mixed with the compressed air and then evaporated and sprayed into the grinding zone, which has a number of advantages compared with pouring the coolant into the zone.

Another approach to cooling involves reducing the thermal resistance of the grinding wheel matrix, thereby facilitating transfer of heat through the grinding wheel itself. Heat pipes have become indispensable components of many thermal engineering systems since the very birth of the idea of passive heat removal in the early 1940s [13]. The passive heat removal device uses no power source to transfer heat between its source and the sink. Among the different varieties of heat pipes, revolving heat pipes are highly effective two-phase heat transfer devices that employ centrifugal forces to return condensate from the condenser section to the evaporator section [14]. In contrast to a rotating heat pipe, a revolving heat pipe is one in which the axis of rotation is vertical or parallel to (but offset) its own axis. Such pipes can be used for thermal management in rotating systems or machinery, including high-speed drills, electric motors and compressors [15]. A novel cooling method that incorporates a revolving heat pipe in the annular disk of a grinding wheel has been proposed by He et al., in which the pipe aids the dissipation of the heat through the wheel matrix [16]. The goal of this method is to move toward dry grinding by changing the heat distribution ratios between the workpiece, the chips and the grinding wheel. In He's study, dry grinding of AISI 1045 steel and wet grinding of titanium alloy Ti-6Al-4V were carried out. Results using the RHPGW showed significant improvement in cooling compared to a traditional grinding wheel. However, the heat transfer mechanism in the heat pipe was not investigated and the corresponding parameters for the heat pipe such as the type of working fluid, the fluid loading and the rotational speed were not optimized. Therefore, dry grinding of difficult-to-machine materials hasn't been realized in his study.

In this paper, the mechanism of heat transfer in a revolving heat pipe grinding wheel (RHPGW) is analyzed. The influence of the factors including the type of working fluid, the fluid loading and the rotational speed are investigated in a RHPGW evaluation system. Comparative experiments involving dry grinding with both RHPGW and grinding wheel without a revolving heat pipe are performed in the context of creep-feed grinding of Inconel 718. The results are compared in terms of grinding temperature, microstructure of the workpiece and surface conditions on the grinding wheels.

2. Revolving heat pipe grinding wheel

2.1. Concept of RHPGW

Fig. 1 shows the configuration of the RHPGW, in which the cylindrical grinding surface with grains is the evaporator section and the cooled rotating sides form the condenser section. During the grinding process, the heat generated in the contact zone is conducted to the liquid layer through the grains and the solid wall of the matrix. The heat is then transferred to the working fluid, resulting in a phase change from liquid to vapor. The vapor flows to the condenser section due to the pressure gradient in the vapor phase, where it condenses, releasing latent heat through cooling by external impinging cold air jets. The condensate flows back to the evaporator under the actions of centrifugal force and the interaction between the countercurrent liquid and vapor flow, completing the thermodynamic cycle.

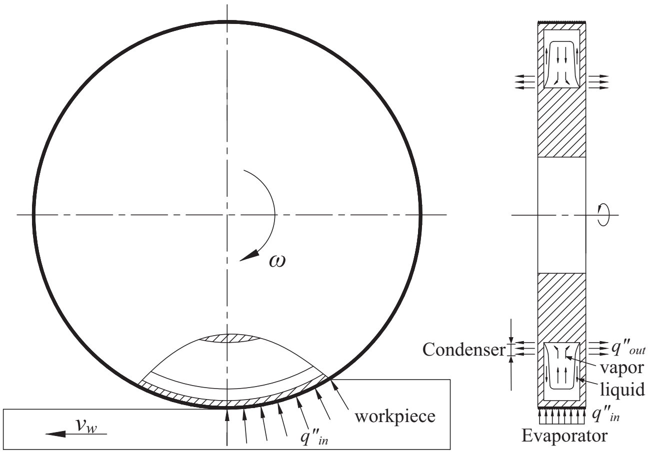

Fig. 1. Schematic of grinding wheel with an annular revolving heat pipe.

2.2. Simulation of heat transfer mechanism in RHPGW

As shown in Fig. 2, a CFD model for the cross section of the RHPGW is constructed to help analyze the heat transfer mechanism in the heat pipe. A constant heat flux of 63,200 W/m^2 is set as the boundary condition outside the evaporator, while a constant temperature is defined as the condition for the outer wall of the condenser. An acceleration of 10,125 m/s^2 is applied along the negative y direction to represent the wheel velocity of 45 m/s. An initial liquid layer of thickness of 3 mm is used as the fluid loading with space above the liquid initialized as vapor, as shown in Fig. 2(b). The 2D grid with 66,216 elements is displayed in Fig. 2(c). The simulations are performed on ANSYS/FLUENT by using Volume of Fluid (VOF) method. User defined functions (UDF) are applied to simulate the phase change process as reported by Fadhl et al. [17] and De Schepper et al. [18] for the governing equations in the FLUENT package. Mass sources of both liquid and vapor are determined by:

For liquid:

$$\begin{cases} S_{\mathrm{ML}} = -0.1\rho_{\mathrm{L}}\alpha_{\mathrm{L}}\frac{T_{\mathrm{mix}}-T_{\mathrm{sat}}}{T_{sat}}, & (T_{\mathrm{mix}} > T_{\mathrm{sat}}, evaporation) \\ S_{\mathrm{ML}} = 0.1\rho_{\mathrm{L}}\alpha_{\mathrm{L}}\frac{T_{\mathrm{sat}}-T_{\mathrm{mix}}}{T_{\mathrm{sat}}}, & (T_{\mathrm{mix}} < T_{\mathrm{sat}}, condensation) \end{cases} \tag{1}$$

For vapor:

$$\begin{cases} S_{\mathrm{MV}} = 0.1\rho_{\mathrm{V}}\alpha_{\mathrm{V}}\frac{T_{\mathrm{mix}}-T_{\mathrm{sat}}}{T_{\mathrm{sat}}}, & (T_{\mathrm{mix}} > T_{\mathrm{sat}}, evaporation) \\ S_{\mathrm{MV}} = -0.1\rho_{\mathrm{V}}\alpha_{\mathrm{V}}\frac{T_{\mathrm{sat}}-T_{\mathrm{mix}}}{T_{\mathrm{sat}}}, & (T_{\mathrm{mix}} < T_{\mathrm{sat}}, condensation) \end{cases} \tag{2}$$

Energy sources in the energy equation used in the present study are determined by multiplying the calculated mass sources in Eqs. (1) and (2) by the latent heat of evaporation (LH) for the working fluid, which can be expressed as follows:

$$\begin{cases} S_{\mathrm{EE}} = -0.1\rho_{\mathrm{L}}\alpha_{\mathrm{L}}\frac{T_{\mathrm{mix}}-T_{\mathrm{sat}}}{T_{\mathrm{sat}}}LH, & (T_{\mathrm{mix}} > T_{\mathrm{sat}}, evaporation) \\ S_{\mathrm{EC}} = 0.1\rho_{\mathrm{V}}\alpha_{\mathrm{V}}\frac{T_{\mathrm{sat}}-T_{\mathrm{mix}}}{T_{\mathrm{sat}}}LH, & (T_{\mathrm{mix}} < T_{\mathrm{sat}}, condensation) \end{cases} \tag{3}$$

where ρ is the density, α is the volume fraction and the subscripts L and V represents liquid and vapor phase respectively. T_{mix} means