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CIRP-1816; No. of Pages 4
ARTICLE IN PRESS
CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx
Contents lists available at ScienceDirect
CIRP Annals - Manufacturing Technology
journal homepage: http://ees.elsevier.com/cirp/default.asp

Thermal modeling and optimization of interrupted grinding

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ARTICLE INFO

Keywords:
Grinding
Temperature
Modeling

ABSTRACT

Finishing parts such as blade tips of assembled engine rotors is an interrupted grinding process. Thermal issues such as burn often become more prominent for interrupted grinding because of the low thermal capacity during the entry and the exit of each interruption. This paper presents models to calculate the transient and steady state temperatures for interrupted grinding. The developed models are then used to investigate the influence of grinding process parameters and cooling on the transient temperature rise. The model results can be used to develop new grinding cycles with variable work speed to increase material removal rate while maintaining temperature below burn limit.

1. Introduction

Finishing of parts such as blade tips of assembled compressor or turbine rotors is an interrupted grinding process. Thermal damage, which is often the main factor affecting workpiece quality and limiting the grinding production rates, becomes especially important for interrupted grinding because of the unfavourable thermal conditions caused by the low thermal capacity and variable cooling during the exit of each interruption.

Extensive research work has been published to investigate the grinding thermal problems for both straight and cylindrical surface grinding [1–4]. Malkin and Guo presented detailed review of grinding thermal research [4]. Thermal analyses of grinding processes are usually based upon the application of the moving heat source theory [4]. A critical parameter needed for calculating the workpiece temperature response is the energy partition to the workpiece, which is the fraction of the total grinding energy transported to the workpiece as heat at the grinding zone. The energy partition depends on the type of grinding, the grinding wheel and workpiece materials, coolant type, and the operating conditions. Extensive research has also been done on cooling effectiveness and energy partition in grinding [4–9]. Energy partition for regular grinding with conventional abrasive wheels is typically in the range of 60–70%, and 3–5% for creep–feed grinding [4]. Grinding with super abrasive wheels has found to have lower energy partition of 20–25% due to the higher thermal conductivity of both CBN and diamond abrasives.

Thermal models in the literature that produce a quasi–steady state temperature distribution are insufficient for interrupted grinding. The objective of this paper is to develop transient thermal models to understand the underlying factors which affect the grinding temperature rises in interrupted grinding and develop process optimization strategies to increase removal rate.

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https://doi.org/10.1016/j.cirp.2018.04.083
0007-8506/© 2018 Published by Elsevier Ltd on behalf of CIRP.

2. Thermal model for interrupted grinding

For external cylindrical grinding as shown in Fig. 1a, the temperature will reach a quasi–steady state after the grinding wheel has travelled a distance greater than ~5 times of the wheel-workpiece contact length which is typically a few millimetres. The maximum quasi–steady state temperature at the grinding zone θ_m can be readily calculated using the following equation [4]:

$$\theta_m = \frac{1.128 q_w \alpha^{1/2} a^{1/4} d_e{}^{1/4}}{k v_w{}^{1/2}} = \frac{1.128 q_w (l_c/2)}{k P_e{}^{0.5}} \tag{1}$$

where d_e [m] is the equivalent diameter, a [m] is the wheel depth of cut, v_w [m/s] is the work speed, k [W/m K] and α [m^2/s] are the thermal conductivity and thermal diffusivity of the workpiece respectively, P_e is the Peclet number defined as $Pe \equiv v_w l_c / 4\alpha$ and q_w [W/m^2] is the heat flux to the workpiece which can be calculated using the grinding power per unit width of grinding P', the wheel-workpiece contact length l_c and the energy partition to the workpiece ε as follows:

$$q_w = \varepsilon \frac{P'}{l_c} \tag{2}$$

The above thermal model has been experimentally verified successfully applied to optimize and control grinding processes to increase productivity while avoiding thermal damage to the workpiece [10–13].

For interrupted grinding as illustrated in Fig. 1b, however, the thermal quasi–steady state as described above may not be reached. The short workpiece such as a blade tip starts exiting the grinding zone before a quasi–steady state temperature can be reached. For example, the width of a blade tip for high compressor stages or turbine of modern jet engines might be only ~1–2 mm which is close to the wheel-workpiece contact length at small depths of cut ~0.025 mm. Hence, a transient thermal situation may prevail during each of the interrupt grinding where the workpiece is

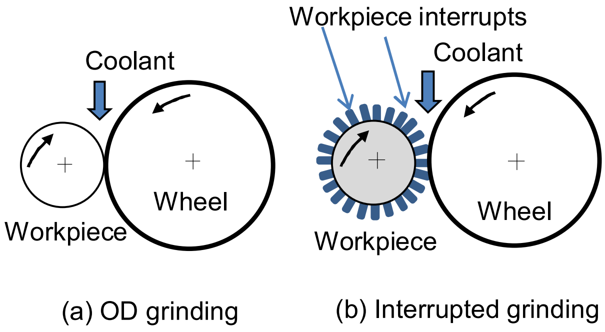

Fig. 1. Illustration of interrupted grinding.

heated up during grinding and then cooled down after it exits the grinding zone.

For analysing the thermal situation of interrupted grinding, a transient thermal model is needed to account for all the factors that contribute to the transient behaviour of the thermal problem.

First, the heat flux to the workpiece is a variable for interrupted grinding (Fig. 2). The variation of the heat flux q_w will depend on the grinding condition. If a smaller wheel grinds a relatively thicker blade (Case I in Fig. 3) at a smaller depth of cut, the heat flux goes up gradually when the blade tip enters the grinding zone. It reaches a constant value during grinding the middle portion of the blade tip. The heat flux starts to decrease when the blade tip starts exiting from the grinding zone. For Case II, the full depth of cut will not be reached because of the larger grinding wheel, larger depth of cut and the relatively thinner blade tip. The grinding wheel starts exiting the grinding zone before the full depth of cut is reached.

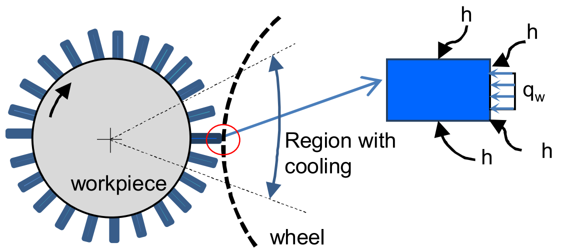

Fig. 2. Thermal model of interrupted grinding.

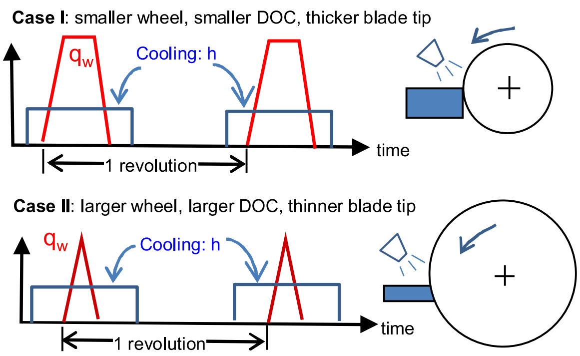

Fig. 3. Heating and cooling during interrupted grinding.

Secondly, the cooling can occur at both the top and the side surfaces of the blade as illustrated in Fig. 2. Cooling starts before the blade enters the grinding zone and it can also continue for a short time after it exists from the grinding zone. The region of cooling as illustrated in Fig. 2 depends on the cooling condition and the nozzle setup condition [14,15]. The cooling variation within each workpiece revolution is also illustrated in Fig. 3.

Finally, the workpiece geometry is another contributor to the transient behaviour. For continuous cylindrical grinding, the heat into the workpiece can conduct into the workpiece in all directions as illustrated in Fig. 4b. For interrupted grinding, however, the workpiece is not available for heat conduction during both entry and exit as shown in Fig. 4a and c. This entry and exit situation occupies most, if

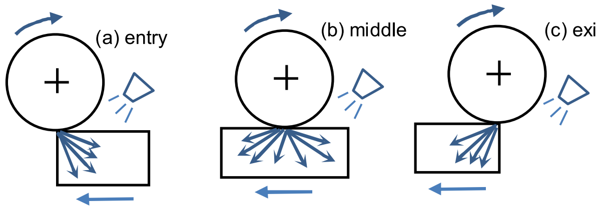

Fig. 4. Illustration of heat conduction during entry and exit.

not all, of the grinding cycle for some of the interrupted grinding cases. It should be noted that the effect of the workpiece geometry on the grinding heat transfer will become even more pronounced for workpiece materials with higher thermal conductivity.

For the thermal problem described above, obtaining a closed form solution for the transient temperature distribution was not successful. In this paper, a finite difference method under MATLAB is used to calculate the transient temperature distribution. First, a full model containing all the blades was established. It was verified that there is no temperature difference among blades during and after grinding. However, the full model is very computational intensive in order to keep track the temperature distribution history of all the blades. A simplified model with one blade is used in this paper. Fig. 5 shows the model setup and the boundary conditions. There are 3 regions R1, R2, R3 during each workpiece revolution. Region R1 is the grinding region during which grinding heat flux calculated using Eq. (2) is applied at the top. Within Region R2, cooling is applied at portion of the top surface outside the grinding zone and the side surfaces. The bottom of the blade is set at a constant temperature of 20° because it is far from the top surface. There is no heating and only air cooling when the blade is in Region R3.

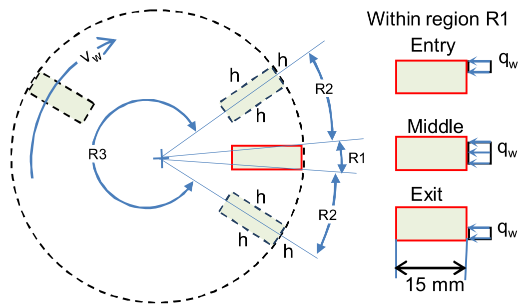

Fig. 5. Thermal model.

For calculating the heat flux at the grinding zone with Eq. (2), the grinding power per unit width P' is calculated using the following grinding power model [16]:

$$P' = u_{ch}(av_w) + \mu p_a A(ad_e)^{0.5} v_s + F'_{pl} v_s \quad (3)$$

where p_a is the average contact pressure at the wheel-workpiece contact, which is proportional to the curvature difference as discussed in Ref. [16]. The model coefficients for the nickel alloy IN100 were obtained as: specific chip formation energy u_{ch} = 17.6 J/mm^3, coefficient of friction μ = 0.27, plowing force per unit width F_{pl} = 0.42 N/mm, wheel wear flat area A = 0.01, and the constant for contact pressure p_0 = 3.02 × 10^6 MPa mm [16]. The energy partition to the workpiece can vary with grinding conditions. In this paper, ε = 25% is used for grinding Ni alloy with plated CBN wheels [17].

3. Results and discussions

In this section, model results for grinding a part resembling a rotor with a number of blades are presented to discuss the influence of grinding process parameters on the temperature rises. The blade is made of a nickel super alloy (IN100) with the following properties: thermal conductivity k = 11.4 W/(m K), specific heat c_p = 435 J/(kg K), density ρ = 8000 kg/m^3, and yield strength σ_s = 1100 MPa. Wheel diameter d_s = 200 mm, diameter at the blade tip d_w=500 mm, wheel speed v_s = 60 m/s will be used for the examples below unless they are specified.

Please cite this article in press as: Guo C, Chen Y. Thermal modeling and optimization of interrupted grinding. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.04.083