CIRP Annals - Manufacturing Technology 62 (2013) 347–350

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Optimization of peripheral non-round cylindrical grinding via an adaptable constant-temperature process

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ARTICLE INFO

Keywords:
Grinding
Optimization
Thermal effects

ABSTRACT

This paper introduces two new concepts in peripheral cylindrical grinding of non-round workpieces: (1) choosing process parameters based on a thermal model for achieving a constant temperature; and (2) optimizing the grinding process for shorter cycle times while applying the concept of constant temperature. The modeling of geometry, kinematics and thermal aspects accounts for large variations in specific material-removal rate, contact length and workpiece velocity as the workpiece rotates. Optimization is validated both in simulation and with grinding experiments, including measurements of Barkhausen noise. Significantly reduced cycle times are obtained along with a better ability to avoid thermal damage.

1. Introduction

This paper is concerned with peripheral cylindrical grinding of non-round workpieces in various applications, such as punching tools, camshafts, etc. Grinding of non-round forms (e.g. square, rectangular, oblong) with a cylindrical grinder as schematically illustrated in Fig. 1, poses several unique challenges. The basic models of chip thickness, grinding energy and temperature [1,2] for cylindrical grinding do not apply due to the shifting contact point and velocities, rapidly changing depth of cut and contact length, as well as surges in material-removal rate.

In recent years, CNC cylindrical grinders have been developed for peripheral grinding of non-round workpieces, with the infeed and retraction of the wheel synchronized with the workpiece rotation to give the required form. On the shop floor, the radial infeed velocity and the workpiece angular frequency (usually set to constant values) are typically selected subjectively to achieve a certain maximum depth of cut or targeted material-removal rate. Because of the long contact length, large specific material-removal rates, Q'_w, are present only during a small region of contact, and for the remainder of the contact, Q'_w value are small or even zero, making cycle times longer than necessary. Some previous optimizations of cylindrical grinding have focused on a discrete infeed-controlled process to minimize cycle time, subject mainly to surface quality and dimensional accuracy constraints [3–5], but also incorporating additional thermal damage constraints [4], such as no-burn during the cycle [5]. In the case of peripheral cylindrical grinding of non-round workpieces such as cams, the application of the no-burn constraint requires the prediction of both grinding power and Q'_w variation around the workpiece periphery [6]. Therefore, a better understanding of geometric and kinematic relationships of the process is necessary and, once this is obtained, a thermal model applying this geometry and kinematics can be used to predict temperatures.

In this paper, two new contributions to grinding are described: (1) a thermal model for non-round peripheral grinding which considers variations in the geometric and kinematic conditions and specific grinding energy into the workpiece as the workpiece rotates, and (2) novel optimization for non-round cylindrical grinding to minimize the cycle time while satisfying constraints related to maximum surface temperature and machine limitations. The novelty of this strategy is that the constant maximum surface temperature constraint is a controlled input parameter to the optimization.

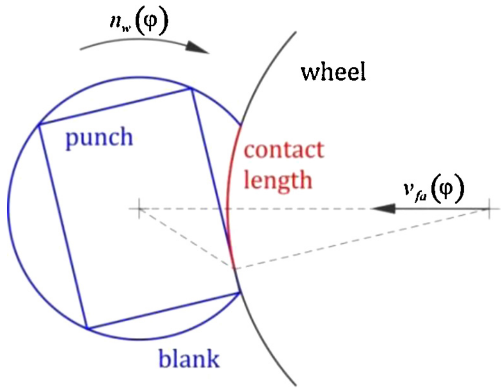

Fig. 1. Illustration of peripheral non-round cylindrical grinding.

2. Thermal model for non-round peripheral grinding

Thermal modeling is based upon moving heat-source theory [7,8]. For this purpose, the grinding zone is considered as a band source of heat which moves along the workpiece surface. A critical parameter needed for thermal modeling is the specific energy into

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0007-8506/$ – see front matter © 2013 CIRP.
http://dx.doi.org/10.1016/j.cirp.2013.03.012

the workpiece, e_w. Grinding power is typically measured for this, and the total specific energy for the process is calculated using the material-removal rate. Then, the energy partition needs to be estimated to determine e_w [8].

Values for e_w were experimentally estimated by running a set of cylindrical-grinding tests on AISI M2 steel workpieces over the rehardening temperature. From microscopic observations of the depth at which rehardening occurred, which was taken as 827 °C in case of AISI M2 a one-dimensional temperature solution [9] was then used to estimate the corresponding surface temperature. The heat transfer solution was then used to obtain the corresponding value of e_w, thereby circumventing the need to estimate the energy partition. The results for specific energy into the workpiece were then correlated with the maximum chip thickness according to the relationship:

$$e_w(h_m(\varphi)) = e_{w0} + \frac{C_w}{h_m^{\mu}(\varphi)} \tag{1}$$

where e_{w0} = 24 J/mm^3 is the invariable amount of specific energy entering the workpiece, C_w = 77.5 and μ = 4.5 are constants, with the maximum chip thickness, h_m, calculated by:

$$h_m(\varphi) = \sqrt{\frac{6}{Crv_s}\frac{Q'_w(\varphi)}{l_c(\varphi)}} \tag{2}$$

Therefore, the surface grinding temperature at every instant throughout the rotation of the workpiece becomes:

$$\theta_m(\varphi) = \frac{1.064}{\sqrt{k\rho c_p}} e_w(h_m(\varphi)) \frac{Q'_w}{\sqrt{l_c(\varphi) v_w(\varphi)}} \tag{3}$$

Our approach to thermal modeling assumes a triangular heat flux; so a constant of 1.064 is used [9]. The assumption of a rectangular heat flux would use a constant of 1.13 [8].

3. Geometry and kinematics for non-round peripheral grinding

The grinding geometry and kinematics are illustrated in Fig. 2. The derivation of grinding kinematics assumes a relative movement of the grinding wheel around a steady workpiece (neglecting deformations in the grinding zone). In an actual grinding scenario, the angular frequency of the workpiece equals $\omega(\varphi)$. The resultant relative velocity $v_{ws}(\varphi)$ between the grinding wheel and the workpiece centers, as well as the radial infeed velocity $v_{fa}(\varphi)$, and the relative workpiece velocity $v_w(\varphi)$, depend on the workpiece rotation angle φ:

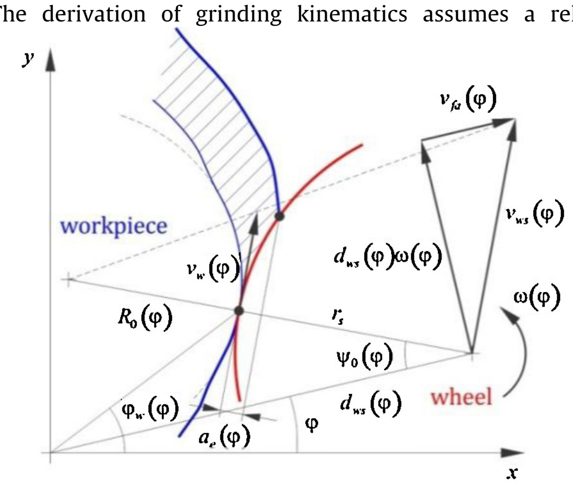

Fig. 2. Geometry and kinematics of non-round grinding.

$$v_{ws}(\varphi) = \frac{d_{ws}(\varphi)}{\cos\psi_0(\varphi)}\omega(\varphi), \quad v_{fa}(\varphi) = d_{ws}(\varphi)\tan\psi_0(\varphi)\omega(\varphi), \quad v_w(\varphi) = \frac{R_0(\varphi)}{R_0(\varphi)+r_s} v_{ws}(\varphi) \tag{4}$$

The angle φ represents the basic independent variable used for the process modeling. The geometry of the contact zone is expressed in terms of contact length, $l_c(\varphi)$, as:

$$l_c(\varphi) = \sqrt{\frac{2R_0(\varphi) r_s}{R_0(\varphi)+r_s} a_e(\varphi)} \tag{5}$$

where r_s is the radius of the grinding wheel and $a_e(\varphi)$ the instantaneous depth of cut depending on φ. Note that the reduction of r_s due to wheel wear is not considered.

The other important output from the geometrical and kinematical model is the specific material-removal rate, $Q'_w(\varphi)$, which is not only a key parameter in the thermal model, but also an indicator of grinding productivity:

$$Q'_w(\varphi) = a_e(\varphi) v_w(\varphi) \tag{6}$$

4. Constant maximum temperature in non-round grinding

Grinding thermal models are usually used to estimate maximum surface temperatures as a function of the pre-determined geometry and kinematics of the process. In this work, the thermal model is developed to keep a set $\theta_{0,m}$ constant throughout the cycle to avoid thermal damage, and then the grinding parameters are chosen to achieve this temperature. Therefore, the relationship is given as:

$$\theta_{0,m} = \frac{1.064}{\sqrt{k\rho c_p}} \sqrt{\frac{Crv_s}{6}} \sqrt{a_e(\varphi)} h_{0,m}(\varphi) e_w(h_{0,m}(\varphi)) \Rightarrow h_{0,m}(\varphi) \tag{7}$$

With this approach, the geometry of the process is known. By utilizing the fact that geometry is defined, and by selecting the maximum surface temperature, the values of the chip thickness $h_{0,m}(\varphi)$ can be obtained. Then the major output of the model is the angular frequency of the workpiece:

$$\omega(\varphi) = \frac{Crv_s}{6} \sqrt{\frac{2r_s(R_0(\varphi)+r_s)}{R_0(\varphi)} \frac{\cos\psi_0(\varphi)}{d_{ws}(\varphi)\sqrt{a_e(\varphi)}} h_{0,m}^2(\varphi)} \tag{8}$$

Eq. (7) has a solution only if $h_{0,m}(\varphi) = h_m^*$:

$$h_m^* = \left[\frac{C_w(\mu-1)}{e_{w0}}\right]^{1/\mu} \tag{9}$$

The chip thickness constraint also determines the corresponding maximum depth of cut, a_e^*:

$$a_e^* = \left[\frac{\sqrt{k\rho c_p}}{1.064} \sqrt{\frac{6}{Crv_s}} \frac{1}{\mu C_w^{1/\mu}} \left(\frac{\mu-1}{e_{w0}}\right)^{1-1/\mu} \theta_{0,m}\right]^2 \tag{10}$$

Interestingly, the upper depth of cut constraint is consistent with the underlying thermal model that assumes small contact lengths [9].

5. Kinematic constraints

While the thermal model determines the grinding kinematics for a certain constant maximum surface temperature the kinematics may be subject to machine limitations. In our case, the limitations were related to: (1) the workhead (max. angular frequency ω_m of 150 s^{-1}; max. angular acceleration α_m of 2.5 s^{-2}); (2) the wheelhead (max. infeed $v_{fa,m}$ of 150 mm/s; max. acceleration of the cross-slide $a_{fa,m}$ of 250 mm/s^2). These limitations require satisfying the following four differential equations at every workpiece position φ:

$$[\omega'(\varphi)\omega(\varphi) \le \alpha_m] \wedge [\omega(\varphi) \le \omega_m] \wedge \left[\frac{v'_{fa}(\varphi) v_{fa}(\varphi)}{d_{ws}(\varphi)\tan\psi_0(\varphi)} \le a_{fa,m}\right] \wedge [v_{fa}(\varphi) \le v_{fa,m}] \tag{11}$$