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Cycle optimization in cam-lobe grinding for high productivity

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ABSTRACT

Cycle optimization in cam-lobe grinding is presented for improving productivity. It includes novel modeling of the instantaneous geometry, kinematics and temperature for any workpiece form. A technical assessment of three process-control strategies – (1) constant specific material removal rate, (2) constant power, and (3) constant temperature – is made. The constant-temperature process provides the shortest cycle time without thermal damage. A detailed analysis of this process considers the role of machine limitations, including maximum speed, acceleration, and jerk, as well as the cam-lobe geometrical effects. The optimization results are validated by grinding tests in an actual production line.

1. Introduction

Assembled camshafts, shown in Fig. 1(a), are a relatively new engine-part design in commercial vehicles. They weigh less than solid camshafts, therefore reducing fuel consumption and emissions [1], and are less expensive to manufacture. Cam lobes can accommodate different materials and enable easier implementation of new form geometries, such as concave flanks. High-performance grinding processes using cubic boron nitride (CBN) wheels running at high speeds and removing large amounts of material in a single set-up can replace the multi-set-up operations of soft machining, hardening and grinding.

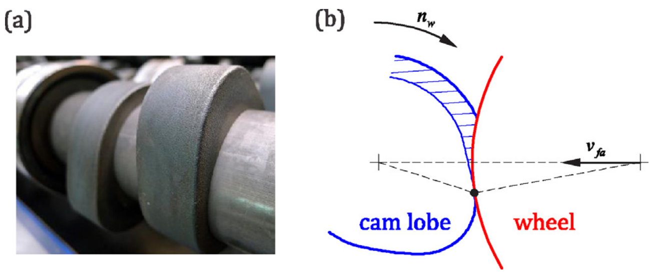

Fig. 1. Assembled camshaft (a); illustration of cam-lobe grinding (b).

In the automotive industry, CNC cam grinders have largely replaced rocker-type machines. On most CNC cam grinders, the wheel moves horizontally with the infeed velocity v_{fa}, which is synchronized with the workpiece rotational speed n_w to achieve the required cam-lobe form (tool path), as illustrated in Fig. 1(b). In both rocker- and CNC-grinding machines, if the workpiece rotates at a constant speed, drastic changes in the instantaneous grinding conditions (material removal rate, contact length, depth of cut, grinding temperatures, etc.) occur during a single workpiece revolution [2]. For example, on the cam-lobe flank, the instantaneous material-removal rate increases drastically, and this surge can cause localized thermal damage (grinding burn). In addition, the related increase in the normal force can cause deflections, resulting in workpiece form errors. These issues necessitate employing various cycle-optimization methods as early as the process-planning phase. Optimization tools usually come supplied with the machine and are typically used to achieve a constant specific material removal rate Q'_w [3] or sometimes a constant grinding power P [4]. Achieving these in practice would require huge variations in process kinematics, exceeding the machine limitations – mainly in acceleration and jerk – resulting in only partial utilization. Both process-control strategies improve productivity compared to conventional grinding with constant rotational speed. However, they do not consider grinding temperatures. A more direct strategy would be to employ a constant-temperature process, ensuring that the grinding process stays just below the burn threshold, while targeting the shortest possible cycle times. Therefore, a technical assessment is made to compare the constant-temperature process to the other two commonly used process-control strategies in production.

2. Geometric, kinematical and thermal modeling

Modeling of geometric, kinematical and thermal quantities is based on the generalized non-round cylindrical grinding model [5], where the rectangular form was described with three parameters only (corner radius and lengths for long and short sides). In this work, the cam-lobe form is defined as a continuous function. In practice, this geometry is given using a lift table via the follower center path around the cam-lobe circumference. The discrete data points used consist of two-variable couples, (φ_i, b_i), where φ_i is the

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follower center angle and b_i is the distance between the cam lobe and the follower center defined for every degree (i = 1, 2, . . ., 360). In this way, 360 input parameters are used in modeling the geometry. The outputs are not related to the follower and are expressed either in terms of the workpiece rotation angle φ_{ws} or workpiece contact angle φ_w.

The geometry of the contact zone is expressed in terms of instantaneous contact length $l_{c,i}$ as:

$$l_{c,i} = \sqrt{\frac{2R_{0,i}r_s}{R_{0,i}+r_s}a_e}, \tag{1}$$

where r_s is the radius of the grinding wheel and a_e the depth of cut, which is constant for every feed increment. In practice, a_e is calculated by dividing the total stock removal δ by the number of feed increments n, which is simply the number of workpiece revolutions to reach the final cam-lobe form. The radius of cam-lobe curvature $R_{0,i}$ is used for a circular approximation of the workpiece geometry in each i-th contact point.

The major parameter of grinding kinematics is the instantaneous relative workpiece velocity $v_{w,i}$ defined as:

$$v_{w,i} = \frac{R_{0,i}d_{ws,i}}{(R_{0,i}+r_s)\cos\psi_{0,i}}\omega_i, \tag{2}$$

where $d_{ws,i}$ is the distance between the grinding wheel and the workpiece rotation centers, $\psi_{0,i}$ is the angle of contact, and ω_i is the workpiece angular speed. The resulting instantaneous specific material removal rate $Q'_{w,i}$ can now be calculated as:

$$Q'_{w,i} = a_e v_{w,i}. \tag{3}$$

The cam-lobe-grinding geometry and kinematics, with corresponding parameters, are illustrated in Fig. 2.

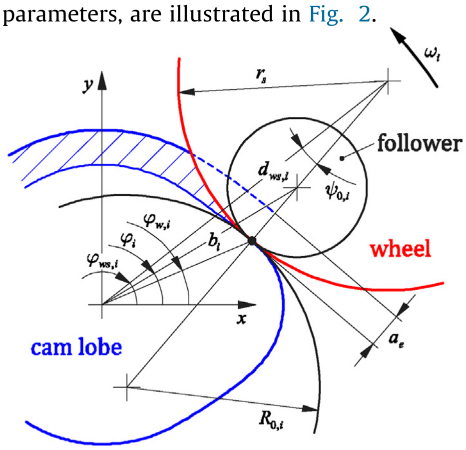

Fig. 2. Geometry and kinematics of cam-lobe grinding.

Thermal modeling, based upon the moving-heat-source theory [6,7] with a triangular heat flux is adapted to cam-lobe grinding, with the maximum surface temperature $\theta_{m,i}$:

$$\theta_{m,i} = \frac{1.064}{\sqrt{k\rho c_p}}e_w(aggr_i)\frac{Q'_{w,i}}{\sqrt{l_{c,i}v_{w,i}}}, \tag{4}$$

where k is the thermal conductivity, ρ is the density, and c_p is the specific heat of the workpiece material. The instantaneous specific energy into the workpiece e_w depends on the aggressiveness number $aggr_i$ [8]:

$$aggr_i = \frac{C_{aggr}}{v_s}\frac{Q'_{w,i}}{l_{c,i}}. \tag{5}$$

Values of $aggr_i$ are small, hence a constant of $C_{aggr} = 10^6$ is used in production to give more practical values, which are typically between 10 and 120. This non-dimensional parameter is proportional to the maximum chip thickness h_m, but circumvents the problem of estimating cutting-point density and chip-shape factor [9], which are difficult to quantify, particularly for CBN wheels. In addition, it uses only the parameters which can be altered on a machine (e.g. wheel speed v_s) and is hence more appropriate for industrial implementation. Therefore, the characteristic e_w curve is given in terms of $aggr_i$:

$$e_w(aggr_i) = e_{w0} + \frac{C_w}{aggr_i^{\mu}}. \tag{6}$$

The values in the characteristic curve – invariable amount of specific energy into the workpiece e_{w0} = 7 J/mm^3, constant C_w = 1280 J/mm^3, and exponent μ = 1.6 – were obtained experimentally by a procedure that avoids estimating the energy partition [10].

3. Constant-temperature process optimization

The novel cam-lobe grinding technology promoted here uses an adaptable process to maintain a fixed workpiece surface temperature θ^*. The calculation of θ^* combines the models (Eq. (3)–(5)) described in Section 2:

$$\theta^* = 1.064\sqrt{\frac{v_s\delta}{C_{aggr}k\rho c_p}}e_w(aggr^*)\sqrt{\frac{aggr^*}{n}}, \tag{7}$$

where $aggr^* = aggr^*(\theta^*, n)$ is aggressiveness number needed to maintain the set θ^*. Based on the definition of aggressiveness number (Eq. (5)), the workpiece angular speed ω_i to achieve θ^* can be calculated as:

$$\omega_i = \frac{v_s\cos\psi_{0,i}}{C_{aggr}d_{ws,i}}\sqrt{\frac{2r_s(R_{0,i}+r_s)}{R_{0,i}\delta}}aggr^*\sqrt{n}, \tag{8}$$

with a corresponding workpiece rotational speed of $n_{w,i} = 30\omega_i/\pi$

However, this speed is ideal and does not take into account machine limitations. In reality, the achievement of $n_{w,i}$ is subject to several machine limitations related to: (1) the headstock (max. angular speed ω_{max}, max. angular acceleration α_{max}, and max. angular jerk j_{max}); (2) the wheelhead (max. infeed $v_{fa,max}$; max. acceleration $a_{fa,max}$, and max. jerk $j_{fa,max}$). Jerk limits the rate of change in acceleration and smooths a speed profile.

Minimizing the grinding time per cam lobe t_g of the constant-temperature process requires employing the optimal number of feed increments, which depends on the set temperature θ^* and the given limitations (see example in Table 1). The t_g-index is calculated by dividing the grinding time per cam lobe by the reference grinding time; in this case the time obtained by the constant-Q'_w process using n = 20 feed increments.

Fig. 3 shows that lower grinding times per cam lobe can be obtained with higher values of θ^* – up to 50% for the temperatures considered. It also reveals that the optimal number of feed increments decreases with increasing set temperature.

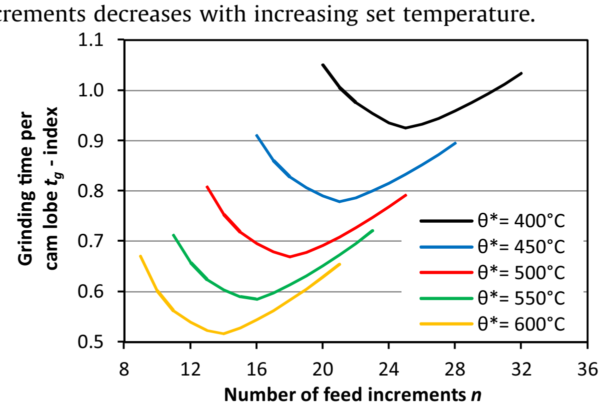

Fig. 3. Effect of set temperature on optimization results.

4. Analysis of process-control strategies

Cycle optimization in cam-lobe grinding involves choosing either a Q'_w, P or θ_m process-control strategy and then calculating