THEORY AND THERMAL ANALYSIS OF HIGH EFFICIENCY DEEP GRINDING PROCESS

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Abstract: *Particular emphasis of the paper is given to the application of achieved research findings in high efficiency deep grinding process (HEDG) and thermal modelling. A new thermal model based on the inclined heat source developed for the HEDG process is reviewed. The effect of grinding contact length on temperature is also discussed and advanced calculation of contact length is applied in the thermal model.*
Key words: *High efficiency deep grinding, thermal model, contact length, temperature.*

1. INTRODUCTION

The study aim is to establish the thermal and physical conditions for high efficiency deep grinding (HEDG) and to develop a strategy to achieve damage free grinding at the highest possible stock removal rates. This part of the study is focused on the thermal modelling of grinding process because thermal analysis of the process have to be known at first to right understanding of issues involving with investigation of the grinding regime HEDG. Development and validation of thermal models for HEDG and development of methods of temperature measurement in grinding are the first main issues to be solved in the exploration of principles in HEDG process.

2. HIGH EFFICIENCY DEEP GRINDING

Grinding is commonly employed as a finishing process and is used to achieve high surface integrity and quality according to prescribed requirements. Grinding, however, also has potential to compete as a primary removal process replacing other process technologies e.g. hard turning and milling and this is one reason why grinding technology is attracting increased research and industrial interest.

HEDG is classified as deep grinding at high workspeed and very high removal rates [1,2]. The process is further characterized by deep cut, low workpiece surface temperature and high efficiency, having values of specific grinding energy $\mathbf{e_c}$ usually below 10 J.mm^{-3}. HEDG is achieved through application of high workspeed, deep cut and correct process conditions. HEDG is highly sensitive to process variations therefore the definition of process conditions is very important. HEDG does not conform to the findings of conventional grinding, which predict that increasing individual parameters, such as wheel speed, depth of cut, or specific removal rate, brings about an increase in temperature that can damage the workpiece. These parameters are set at a very high level in HEDG, and yet the grinding temperatures are lower than in conventional grinding.

Despite its fundamental advantages, HEDG has not yet achieved wide application. This may be explained by the general lack of understanding regarding the design, monitoring, and control aspect of this relatively new technology.

3. THERMAL ANALYSIS

In grinding a significant portion of the heat generated at the workpiece / wheel interface is transferred to the workpiece. If the heat to the workpiece exceeds a threshold value the workpiece will experience thermal damage. Thermal damage may be evidenced by temper colours, residual tensile stresses, micro-cracking or phase transformations. Thermal analysis of the process enables the conditions associated with thermal damage to be predicted.

3.1. ENERGY PARTITIONING

In grinding the heat generated at the workpiece / wheel interface is distributed between the workpiece, wheel, chips and fluid [1]. The grinding temperatures are dependent on the heat flux generated in the contact zone. In order to calculate the grinding temperatures, it is necessary to specify the heat flux distribution in the grinding zone. The total heat flux $\mathbf{q_t}$ is the sum of the four flux components:

$$\mathbf{q_t = q_w + q_s + q_{ch} + q_f} \tag{1}$$

where
$$\mathbf{q_t = \frac{P}{b \cdot l_c} = e_c \cdot \frac{Q'_w}{l_c}} \tag{2}$$

and where $\mathbf{P}$ is grinding power, $\mathbf{b}$ is width of cut, $\mathbf{l_c}$ is theoretical contact length, $\mathbf{e_c}$ is specific grinding energy and $\mathbf{Q'_w}$ is specific volumetric material removal.

The heat flux to the workpiece $\mathbf{q_w}$, wheel $\mathbf{q_s}$, fluid $\mathbf{q_f}$ and chips $\mathbf{q_{ch}}$ may be expressed in terms of convention / conduction factors defined in relation to maximum contact temperature, mean contact temperature, fluid boiling temperature and material melting temperature as follows:

$$\mathbf{q_w = h_w \cdot T_{max}}, \quad \mathbf{q_s = h_s \cdot T_{max}}, \quad \mathbf{q_f = h_f \cdot T_{max}}, \quad \mathbf{q_{ch} = h_{ch} \cdot T_{mp}} \tag{3, 4, 5, 6}$$

where $\mathbf{h_w}$, $\mathbf{h_s}$, $\mathbf{h_f}$ and $\mathbf{h_{ch}}$ are convention factors of workpiece, wheel, fluid and chips.

The maximum workpiece temperature in the contact plane based on the theory of the sliding heat source for one-dimensional conduction [12] is defined as:

$$\mathbf{T_{max} = C \cdot \frac{q_w}{\beta_w} \cdot \sqrt{\frac{l_c}{v_w}}}\ . \tag{7}$$

where $\mathbf{C}$ is temperature constant for workpiece conduction and $\mathbf{v_w}$ is workspeed.

The convection factor for the workpiece may be expressed as:

$$\mathbf{h_w = \frac{\beta_w}{c} \cdot \sqrt{\frac{v_w}{l_c}}} \tag{8}$$

where $\mathbf{c}$ is specific heat capacity. The thermal diffusivity $\mathbf{\beta_w}$ and theoretical contact length $\mathbf{l_c}$ are given by

$$\mathbf{\beta_w = \sqrt{k_w \cdot \rho_w \cdot c_w}} \quad \text{and} \quad \mathbf{l_c = l_g = \sqrt{a_e \cdot d_e}} \tag{9, 10}$$

where $\mathbf{k_w}$ is thermal conductivity and $\mathbf{\rho_w}$ mass density of workpiece, $\mathbf{l_g}$ is geometric contact length $\mathbf{a_e}$ is real depth of cut and $\mathbf{d_e}$ is effective wheel diameter.

The sliding heat source model gives a value for **C** approximately equal to unity but precise values depend on the value of Peclet number **Pe**:

$$\mathbf{Pe} = \frac{\mathbf{v_w \cdot l_c}}{\mathbf{4 \cdot \alpha_w}} \tag{11}$$

since $$\mathbf{l} = \frac{\mathbf{l_c}}{\mathbf{2}} \quad \text{and} \quad \alpha_w = \frac{k_w}{\rho_w \cdot c_w} \tag{12, 13}$$

where $\boldsymbol{\alpha_w}$ is thermal diffusivity of workpiece. The convention factor for the abrasive grains can be evaluated from the value of $\mathbf{h_w}$, equation (8).

$$\mathbf{h_s = h_w \cdot \left[\frac{1}{R_{ws}} - 1\right]} \tag{14}$$

where $\mathbf{R_{ws}}$ is the workpiece-wheel partition ratio and may be written as:

$$\mathbf{R_{ws}} = \frac{\mathbf{q_w}}{\mathbf{q_w + q_s}} = \frac{\mathbf{h_w}}{\mathbf{h_w + h_s}} = \left[\mathbf{1} + \frac{\mathbf{0.97 \cdot k_g}}{\beta_w \cdot \sqrt{\mathbf{r_0 \cdot v_s}}}\right]^{-1} . \tag{15}$$

Parameter $\mathbf{r_0}$ represents an effective radius of contact of the abrasive grains and 15 μm is a sensible value for a reasonably sharp wheel. For a given abrasive type, the ratio $\mathbf{R_{ws}}$ does not change significantly. The flux to the chips is assumed to be close to the limiting chip energy $\mathbf{e_{ch}}$ required to raise the temperature of the chip material to melting. For ferrous materials, this value is approx. 6 J.mm^{-3}. The flux to the chips can be expressed as:

$$\mathbf{q_{ch} = e_{ch} \cdot \frac{Q'_w}{l_c}} \tag{16}$$

where $$\mathbf{e_{ch}} = \rho_w \cdot \mathbf{c_w \cdot T_{mp}} . \tag{17}$$

The fluid convention factor $\mathbf{h_f}$ is the most difficult to estimate with any confidence. One method is to use the “fluid wheel” assumption [3]. By using the triangular sliding heat source, the fluid convention factor is:

$$\mathbf{h_f = 0.94} \cdot \beta_f \cdot \sqrt{\frac{\mathbf{v_s}}{\mathbf{l_c}}} . \tag{18}$$

Two values of $\mathbf{T_{max}}$ for the maximum theoretical temperatures reached in the contact zone in wet and dry grinding may be calculated from equations (3-6) using the convention factors from equations (8, 14) and (18):

$$\mathbf{T_{max\,wet}} = \frac{\mathbf{q_t - q_{ch}}}{\frac{\mathbf{h_w}}{\mathbf{R_{ws}}} + \mathbf{h_f}} \quad \text{and} \quad \mathbf{T_{max\,dry}} = \frac{\mathbf{q_t - q_{ch}}}{\frac{\mathbf{h_w}}{\mathbf{R_{ws}}}} . \tag{19, 20}$$

3.2. GRINDING CONTACT LENGTH

In predicting the temperature of the workpiece, it is very important to know the effective length of the heat source over which the energy conducts into the workpiece. It has been found that the real contact length in grinding is often much greater then the geometric contact length $\mathbf{l_g}$. A theoretical solution for real contact length proposed by Rowe and Qi [10] was

$$\mathbf{l_c^2 = l_f^2 + l_g^2} \tag{21}$$

where $\mathbf{l_f}$ is contact length between surfaces acted on by a normal force and $\mathbf{l_g}$ is geometric contact length defined by equation (10). The length $\mathbf{l_f}$ is evaluated from

$$\mathbf{l_f = \sqrt{8 \cdot F'_n \cdot (K_s + K_w) \cdot d_s}} \tag{22}$$

where $\mathbf{F'_n}$ is specific normal force, $\mathbf{d_s}$ is wheel diameter and $\mathbf{K_s}$ and $\mathbf{K_w}$ are

$$\mathbf{K_s} = \frac{\mathbf{1-\upsilon_s}^2}{\pi \cdot \mathbf{E_s}} \quad \text{and} \quad \mathbf{K_w} = \frac{\mathbf{1-\upsilon_w}^2}{\pi \cdot \mathbf{E_w}}. \qquad (23, 24)$$

Variables $\mathbf{K_s}$ and $\mathbf{K_w}$ are determined by physical properties of materials in the contact. υ_s and υ_w are Poisson's ratios, $\mathbf{E_s}$ and $\mathbf{E_w}$ are moduli of elasticity. The real contact length can be expressed in two ways - a surface roughness approach and a contact area approach. The first yields more faithful results in comparison with the experimental results [11]. Based on the roughness approach, the magnitude of the grinding contact length is represented as

$$\mathbf{l_c} = \sqrt{\mathbf{l_{fr}}^2 + \mathbf{l_g}^2} = \sqrt{(\mathbf{R_r} \cdot \mathbf{l_f})^2 + \mathbf{l_g}^2} \qquad (25)$$

where $\mathbf{l_{fr}}$ is contact length for rough surfaces with a normal force and $\mathbf{R_r}$ is roughness factor. The magnitudes of roughness factor are acquired as experimental values from the tests. $\mathbf{R_r}$ is sensitive to the grinding conditions for some material combinations. For general analysis of the grinding conditions, it is suggested that the value $\mathbf{R_r}$ is equal 13.

Combining equations 10, 22 and 25 yields the relationship:

$$\mathbf{l_c} = \sqrt{\mathbf{8} \cdot \mathbf{R_r}^2 \cdot \mathbf{F'_n} \cdot (\mathbf{K_s} + \mathbf{K_w}) \cdot \mathbf{d_s} + \mathbf{a} \cdot \mathbf{d_s}} \qquad (26)$$

Equation (33) determines the contact length between the wheel body and the workpiece taking account not only elastic deflection and geometric effect but also roughness of both surfaces in the contact.

3.3. HEDG APPROACH

The values obtained from equations (19) and (20) represent the maximum theoretical temperatures reached in the contact zone between a workpiece and a wheel when grinding with the use of a coolant ($\mathbf{T_{maxwet}}$) or without ($\mathbf{T_{maxdry}}$). However, the thermal model described is appropriate only for shallow grinding because the theory of the thermal analysis is based on the plane sliding heat source by Jaeger and Carslaw [4]. This solution consists in a sliding of heat source parallel to the plane of motion [5-7].

It is shown for deep grinding processes, and in particular for HEDG, that the sliding heat source model is unsuitable and the temperature results obtained from it are overestimated [8]. The model is re-analysed for HEDG, based on a moving circular arc of contact [9], Fig. 1. The contact surface is assumed to lie around a circular arc.

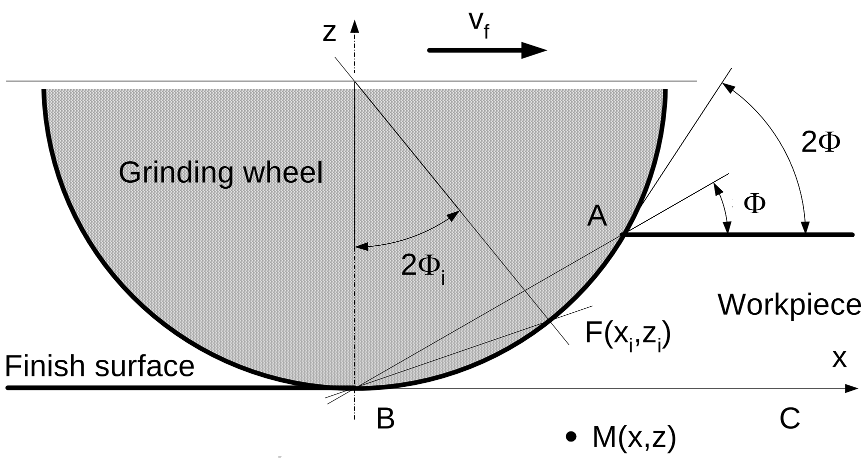

Fig. 1 *Curved heat source for HEDG*

The heat source is the sum of an infinite number of moving line sources disposed around the contact arc. The contact length $\mathbf{l_c}$ is arc AFB. The arc length BF is $\mathbf{l_i}=\mathbf{d_e}.\mathbf{\Phi_i}$. The temperature rise at a point M(x,z) due to a line source $\mathbf{dl_i}$ moving at speed $\mathbf{v_f}$ at the angle $2\mathbf{\Phi_i}$ to the surface is given by

$$\mathbf{T} = \frac{1}{\pi \cdot k} \int_0^{l_c} q \cdot e^{-\frac{v_f}{2\cdot\alpha}\cdot(x - l_i \cdot \cos\phi_i)} \cdot K_0 \cdot \left[\frac{v_f \cdot r_i}{2 \cdot \alpha}\right] dl_i \qquad (27)$$

where $$r_i = \sqrt{(x - l_i \cdot \cos\phi_i)^2 + (z - l_i \cdot \sin\phi_i)^2} \quad \text{and} \quad q = \overline{q} \cdot (n+1) \cdot \left(\frac{l_i}{l_c}\right)^n \qquad (28, 29)$$

with $\mathbf{n}$=**1** for a triangular heat flux. Equation (27) yields field temperatures of the contact surface AFB and the finish plane surface BC.

There is a limiting value of specific energy in grinding [9] which is the value needed to raise the chips to melting temperature. For steel this value is approx. 6 J.mm^{-3}. For achievement of high material removal rates characteristic for HEDG, it is possible to take advantage of the size effect to increase grinding efficiency [10]. As equivalent thickness $\mathbf{h_{eq}}$ is increased, specific energy $\mathbf{e_c}$ is reduced as shown by the expression:

$$\mathbf{P} = F_t \cdot v_s = k' \cdot b \cdot h_{eq}{}^n \cdot v_s \qquad (30)$$

where **k’** and **n** are empirical factors, $\mathbf{v_s}$ is wheelspeed. Equation (30) leads to relationships

$$a_e = e^{\frac{1}{n}\log\left[\frac{P}{k' \cdot b \cdot v_w{}^n \cdot v_s{}^{1-n}}\right]} \quad \text{and} \quad e_c = \frac{k'}{h_{eq}{}^{1-n}}. \qquad (31, 32)$$

The charts shown in Fig. 2 were generated using equations (31) and (32) and the coefficient **n** was assumed to be 0.85 and **k’** was evaluated accordingly.

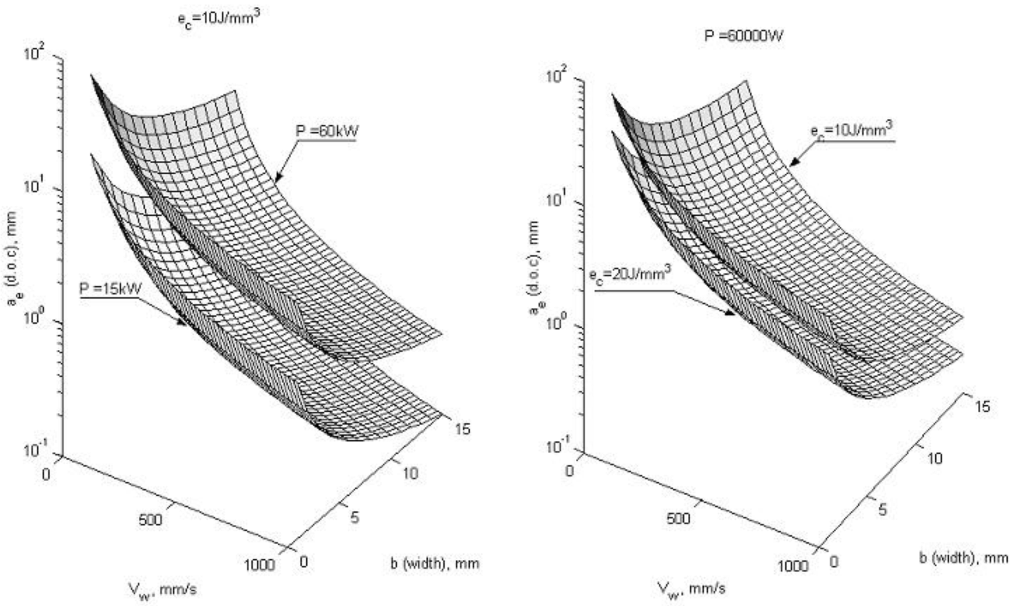

Fig. 2 *Three-dimensional surface diagrams showing limiting material removal rates in HEDG according to power (2a) and specific energy (2b) constraints*

The relationships (31) and (32) enable a surface to be constructed showing the boundary of possible workspeed, depth of cut and grinding width combinations for the available power. It is evident from chart 2a that for a high workspeed and deep cut there is a maximum grinding width allowance for the available power i.e. larger grinding width requires a higher power. Chart 2b shows that lower efficiency reduces the allowable depth of cut for a given workspeed and width of the workpiece.

4. CONCLUSION

Energy and temperature analysis is able to reveal remarkable differences between grinding processes. In conventional grinding, most of the heat usually goes into the workpiece, however, this situation changes in HEDG mode. Under right process conditions, it is possible to reduce specific energy and reduce remarkably high material removal rates with low temperatures. Some of these deductions have been already confirmed by the experimental measurements. Description of the measurement results is beyond the range of this paper. The research work continues.

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