Analysis of Workpiece Temperature and Grinding Burn in Creep Feed Grinding*

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This paper aims to clarify workpiece temperature and the mechanism of grinding burn in creep feed grinding. The workpiece is modelled thermally by a three dimensional finite element method. The cooling effect of coolant is measured and the fraction of mechanical energy conducted as heat into the workpiece is estimated by Jaeger's moving heat theory extended to include the cooling effect. The analytical results are shown to agree well with the experimentally obtained temperature distribution. From the experimental evidence that the onset of grinding burn is closely related to the boiling of the coolant used, the mechanism of the grinding burn can be considered as follows; when the grinding zone temperature reaches a point at which bubbles begin to form, the bubbles grow up rapidly in the wheel-workpiece interface and block heat transfer to the coolant. This is verified by the above-mentioned thermal model.

Key words : Creep Feed Grinding, Workpiece Temperature, Workpiece Burn, Finite Element Method, Heat Conduction, Boiling, Burn Out

1. Introduction

It has been reported that although creep feed grinding has some advantages over conventional grinding, the principal limitation to the process is found to be thermal, e.g. workpiece burn, as would be anticipated from the grinding conditions. The authors⁽¹⁾ and Shahto⁽²⁾ have found that if grinding energy per unit contact area per unit time (which is named grinding energy flux) exceeds a critical value, then grinding burn occurs. It was also found that the transition from normal grinding conditions to burning was accompanied with a sudden rise in the grinding zone temperature from about 130°C to in excess of 1000°C. Thus Shahto proposes from this that the burn phenomenon in creep feed grinding is qualitatively analogous to the burn-out phenomenon in boiling. However the relation between the grinding energy flux and the grinding zone temperature at burn or just before burning has not yet been clarified. Hence the mechanism of grinding burn is not clearly understood.

Creep feed grinding is usually done in one pass at full depth of cut, so that the effect of grinding heat on the surface integrity and the thermal deformation of workpiece is important. If the temperature at burn is clarified, it may be possible to anticipate analytically the grinding energy flux just before burning for arbitrary

workpiece shape and to select grinding conditions to avoid burning. Moreover it may be expected to realize an adaptive control system which can suppress the occurrence of burn.

The present paper aims to clarify the relationship between the grinding energy flux and the workpiece temperature by using a three dimensional finite element method and to elucidate the mechanism of grinding burn.

2. Analysis of Workpiece Temperature Distribution by the Finite Element Method

2.1 Finite element representation of heat conduction problem

Taking into account the boundary conditions that the temperature is known on the boundary S_1 and/or heat transfer occurs on the boundary S_2 , the functional χ of the differential equation which governs heat conduction phenomenon is given by

$$\begin{aligned} \chi = & \int_V \frac{1}{2} \left[K_x \left(\frac{\partial T}{\partial x} \right)^2 + K_y \left(\frac{\partial T}{\partial y} \right)^2 \right. \\ & \left. + K_z \left(\frac{\partial T}{\partial z} \right)^2 - 2 \left(Q - \rho C \frac{\partial T}{\partial t} \right) T \right] dV \\ & + \int_{S_2} \left[qT + \frac{1}{2} h (T - T_\infty)^2 \right] dS \quad \dots\dots\dots (1) \end{aligned}$$

where T =temperature, T_∞ =fluid temperature, K_x, K_y, K_z =thermal conductivities in x, y and z directions respectively, Q =internal heat source, q =heat flux, ρ =density, C =specific heat, t =time and h =convection coefficient of fluid.

Temperature T to be found is given by the following equation in the form of finite element representation.

$$\frac{\partial \chi}{\partial \{T\}} = \sum_{e=1}^E \left([C^{(e)}] \frac{\partial \{T\}}{\partial t} + [K^{(e)}] \{T\} + \{f^{(e)}\} \right)$$

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$$=0 \dots\dots\dots(2)$$

Element capacitance matrix $[C]$ is

$$[C] = \int_V \rho C [N]^T [N] dV \dots\dots\dots(3)$$

Element stiffness matrix $[K]$ is

$$[K] = \int_V [B]^T [D] [B] dV + \int_{S_s} h [N]^T [N] dS \dots\dots\dots(4)$$

Element load vector $\{f\}$ is

$$\{f\} = - \int_V Q [N]^T dV + \int_{S_1} q [N]^T dS - \int_{S_2} h T_\infty [N]^T dS \dots\dots\dots(5)$$

where $[N]$ =shape function, $[B]$ =gradient matrix and $[D]$ =material property matrix.

In the present analysis, three dimensional rectangular prism elements each of which has eight nodal points $T_1 \sim T_8$ are used and the temperature within these elements is approximated by

$$T = \sum_{i=1}^8 N_i T_i \dots\dots\dots(6)$$

2.2 Finite element model

The workpiece is modelled as shown in Fig.1. The model has 960 elements and 1476 nodal points and the arc contact between wheel and workpiece is approximated as in Fig.1. In creep feed grinding, because of

Fig.1 Finite element model

large wheel depth of cut the workpiece changes its shape as it is fed under the grinding wheel. To include this effect in the theoretical model, finite elements in front of heat source are eliminated with the movement of heat source. Generally the temperature distribution varies with time and the movement of heat source, so that a transient heat flow analysis is required. However comparison between the transient and the steady state temperature in the present model indicates that because of very slow movement of heat source the transient temperature amounts to 95% of the steady state one in about 2.5 sec. Therefore when the workpiece speed is less than 1 mm/s it is assumed that the steady state temperature distribution is established.

2.3 Boundary conditions

Figure 2 shows thermal boundary conditions to be determined. According to

- (1) Heat flux conducted into the workpiece
- (2) Heat transfer from the workpiece to coolant outside the grinding zone
- (3) Heat conduction into the workpiece holder
- (4) Heat transfer from the holder to coolant

Fig.2 Thermal boundary conditions to be determined

many studies presented so far, nearly all the energy required in the grinding process is transformed into thermal energy and the fraction of the energy conducted as heat into the workpiece increases significantly with the decrease of workpiece speed as in creep feed grinding. In the finite element model of Fig.1, if the grinding energy flux of 100% is flowing as heat into the workpiece through the wheel-workpiece interface and the outside of grinding zone is subjected to convection cooling with coolant (the convection coefficient is 1.22×10^4 W/m²K, which is the measured average value as will be shown later), then the theoretical analysis shows that the maximum grinding zone temperature exceeds 1000°C. Obviously such a high temperature is never encountered in normal grinding conditions. As has been emphasized⁽³⁾, therefore, the coolant should play an important role in dissipating the energy consumed in the wheel-workpiece contact area.

2.3.1 Cooling effect of coolant

Sauer⁽⁴⁾ analyzed the cooling effect of coolant on the workpiece temperature and found that a large reduction of grinding zone temperature was possible as the workpiece speed was decreased. According to his theoretical analysis, when a band heat source of linearly varying strength is moving with the speed of V_w on the surface of a semi-infinite body which is subjected to convection cooling, the surface temperature T_{surf} is given by the equation.

$$\begin{aligned} \frac{\pi K V_w T_{surf}}{2 \kappa q} = & \frac{1}{2L} \int_0^\infty \left[\sqrt{\frac{\pi}{2U}} (X+L+U) \left\{ \operatorname{erfc} \left(\frac{X-L+U}{\sqrt{2U}} \right) - \operatorname{erfc} \left(\frac{X+L+U}{\sqrt{2U}} \right) \right\} \right. \\ & + \left. \left\{ \exp \left(-\frac{(X+L+U)^2}{2U} \right) - \exp \left(-\frac{(X-L+U)^2}{2U} \right) \right\} \right] dU \\ & - \frac{\pi H}{4L} \int_0^\infty \operatorname{erfc} \left(\frac{HU}{\sqrt{2U}} \right) \left[(X+L+U) \left\{ \operatorname{erfc} \left(\frac{X-L+U}{\sqrt{2U}} \right) - \operatorname{erfc} \left(\frac{X+L+U}{\sqrt{2U}} \right) \right\} \right. \\ & + \left. \left. \sqrt{\frac{2U}{\pi}} \left\{ \exp \left(-\frac{(X+L+U)^2}{2U} \right) - \exp \left(-\frac{(X-L+U)^2}{2U} \right) \right\} \right] dU \dots\dots\dots(7) \end{aligned}$$

$$X = \frac{V_w}{2\kappa} \tau, L = \frac{V_w}{2\kappa} l, U = \frac{V_w^2}{2\kappa} \tau, H = \frac{2\kappa h}{KV_w} \quad (8)$$

where $2l$ =length of heat source, q =mean strength of heat source, K =thermal conductivity, κ =thermal diffusivity, τ =time, $\text{erf}(x)$ =error function and $\text{erfc}(x)$ =co-error function.

H , which represents the cooling effect, is called the dimensionless heat transfer coefficient and it can be increased by increasing the convection coefficient h or reducing the speed of heat source which here is the workpiece speed V_w . By using Eq.(7) the effect of H on the temperature reduction can be calculated and the result which is expressed in terms of the ratio $(T_{\text{surf}})_{H=H} / (T_{\text{surf}})_{H=0}$ is shown in Fig.3.

Fig.3 Cooling effect of grinding fluid on the reduction of workpiece surface temperature (Temperature reduction means the ratio of temperature with cooling to that without cooling)

Saito et al.⁽⁶⁾ used an electrically heated mock workpiece to study heat transfer in grinding process and found that the convection coefficient of coolant h ranged from 1×10^4 to 1×10^5 W/m²K. Substituting these values into Eq.(8), the dimensionless heat transfer coefficient H becomes about 0.05 in the case of conventional grinding with the workpiece speed of around 10 m/min and it can be seen from Fig.3 that only about 10% reduction of temperature is expected. On the other hand, in creep feed grinding where workpiece speed is reduced by a factor of 1000, H increases up to 50 and the temperature rise can be expected to be only about 5% of that without cooling ($H=0$), that is about 95% reduction.

Convection coefficient of coolant depends on many factors and it is very

difficult to estimate theoretically.

Therefore the convection coefficient around the workpiece was obtained experimentally by measuring the temperature change of a small copper cylinder which was heated and then put in the coolant flow as shown in Fig.4. The results for five locations denoted by ① to ⑤ are also presented in Fig.4.

As mentioned before, the coolant must dissipate the energy generated in the wheel-workpiece contact area. The effect of it may be predicted if the convection coefficient in the contact area is known. It is found experimentally that the coolant penetrates into the entire wheel-workpiece contact area, so that the cooling effect can be expected. However it is impossible to evaluate its effect quantitatively because the convection coefficient of coolant in the grinding zone can not be measured.

2.3.2 Strength and distribution of heat source

Although it is a rule of thumb, strength of heat source, that is the fraction of mechanical energy conducted as heat into the workpiece is estimated as follows; if the convection coefficient of the coolant in the wheel-workpiece contact area is assumed to be the same value as in workpiece surface outside the grinding zone, then the dimensionless heat transfer coefficient H in Eq.(8) becomes about 13 to 27 in the present experiment. In this case it can be seen from Fig.3 that the temperature rise with cooling is about 10% of that without cooling. The steady state temperature is proportional to heat input. Therefore the fraction of mechanical energy flowing as heat into the workpiece is assumed to be 10%.

The distribution of heat source strength may be considered to coincide with that of grinding force, and so the heat source is regarded as having a linearly varying strength in conventional grinding. In creep feed grinding, however, it is considered that the coolant in the wheel-workpiece contact area affects the distribution of heat source strength. Figure 5 shows the temperature distribution along the arc contact length in up- and down-cut creep feed grinding. This figure clearly indicates the difference of temperature distribution between up- and down-cut. This will be due to the difference in coolant delivery. That is, in up-cut grinding the coolant is supplied to the bottom of arc where the grinding force is small but to the top of arc where the grinding force is large in down-cut grinding. From the result the heat source is assumed to have a linearly varying strength in up-cut and a constant strength in down-cut.

Heat source length, namely the real contact length between wheel and workpiece is assumed to be equal to the theoretical arc contact length, because the real contact length is longer than the theoretical value by less than 10% in the present experiment.

Fig.4 Measuring method of convective cooling coefficient of grinding fluid and the measured value

Fig.5 Difference of grinding zone temperature between up- and down-cut grinding

3. Analytical and Experimental Results

Three dimensional steady state temperature distribution of a workpiece being creep feed ground is analyzed by the finite element method with the boundary conditions (see Fig.2) as follows.

Boundary conditions;

(1) Because the real contact length is assumed to be the same as the theoretical value, the grinding energy per unit contact area per unit time, that is the grinding energy flux ϕ , is given by the equation.

$$\phi = \frac{F_t V_s}{b \sqrt{a} D} \quad (9)$$

where F_t =tangential grinding force, V_s =grinding wheel speed, b =width of cut, a =depth of cut and D =wheel diameter.

The energy conducted as heat into the workpiece, that is the heat flux is assumed to be 10% of ϕ as mentioned in Sec. 2.3.2.

(2) Heat transfer from the workpiece to coolant outside the grinding zone is proportional to the measured convection coefficient h shown in Fig.4.

(3),(4) Heat conduction into the workpiece holder and heat transfer from the holder to coolant are neglected. These heat losses are replaced by the convection cooling and the convection coefficient is assumed to be the same as in Fig.4. Fortunately this parameter was found to have very little influence on the temperature in the workpiece, because the temperature of the workpiece surface outside the grinding zone was found to be very close to the coolant temperature. From this reason, variations of the assumed convection coefficient by factors of 0.1 and 10 had negligible influence on the analytical results.

Experiments were performed using a creep feed grinding machine shown in Fig.6. The wheel spindle is supported by hydrostatic bearings and driven by a 15 kW hydraulic motor with variable speed. The table is guided hydrostatically and driven

Fig.6 Creep feed grinding machine used in the experiment

Fig.7 Comparison between theoretical and experimental temperature distributions of work

by a stepping motor via a ball screw. Coolant of 25 l/min is supplied through five nozzles as shown in Fig.6. The grinding force is measured by a piezo-electric dynamometer. Temperatures are measured by CA thermocouples inserted into the workpiece.

Figure 7 (a) and (b) show experimentally obtained temperatures together with theoretical isotherms. It is clear from the figures that theoretical values coincide well with experimental thermocouple measurements. It is notable that the temperatures in the wheel-workpiece contact area are relatively low. Even in Fig.7(b) where the grinding energy flux ϕ is close to the burning limit, the temperatures are far below that for which a grinding burn might be anticipated.

In this chapter, the workpiece

temperature is investigated analytically and experimentally, and it is found that the temperature is relatively low. Nevertheless it is claimed that the grinding burn often becomes troublesome and in many cases it suddenly occurs. In the next chapter, the mechanism of the grinding burn will be studied experimentally and analytically.

4. Mechanism of Grinding Burn

As was reported elsewhere⁽¹⁾, grinding burn takes place when the grinding energy flux ϕ exceeds about $8 \text{ J/mm}^2\text{s}$ in creep feed grinding. But the maximum grinding zone temperature is far below that for which the burn might be anticipated. Figure 8 shows

WA80G8V, SUJ2, Soluble Type Coolant
Down Cut, $V_s=18 \text{ m/s}$, $V_w=0.6 \text{ mm/s}$, $a=1 \text{ mm}$

Fig. 8 Occurrence of workpiece burn during grinding zone temperature measurement

an example where a grinding burn occurred during the grinding zone temperature measurement. It can be seen that the grinding burn occurred suddenly though the maximum grinding zone temperature just before burning was about 100°C , and the temperature rose rapidly, being accompanied with a sudden change of the grinding force.

In order to clarify the temperature at burn, the relation between the maximum grinding zone temperature and the grinding energy flux was studied experimentally. Figure 9 shows the results for water- and oil-based coolant. The maximum grinding zone temperature increases almost in proportion to the grinding energy flux ϕ and finally a grinding burn occurs when ϕ exceeds about $9 \text{ J/mm}^2\text{s}$ in water-based coolant and $6 \text{ J/mm}^2\text{s}$ in oil-based coolant. Paying attention to the temperature, the maximum grinding zone temperature just before burning is about 100°C in water and about 300°C in oil, and these temperatures nearly coincide with boiling temperatures of coolants respectively. Therefore it seems that the mechanism of a grinding burn is closely related to the boiling of coolant. Taking account of the experimental evidence, two ideas will come up on the mechanism of grinding burn.

Fig. 9 Relation between grinding energy flux and maximum grinding zone temperature

One idea is the vanishing of cooling effect of coolant due to the vaporization by heating while the coolant passes through the wheel-workpiece contact zone. Supposing that the coolant contained within the wheel pore is heated and then vaporized, the volume of coolant within the pore is calculated from the wheel specification and it is possible to estimate the heat flux required to heat and vaporize the coolant while it passes through the grinding zone. Calculated example of the required heat flux is presented in Fig. 10. The required heat flux will become smaller as wheel speed is lower and/or arc contact length is longer. Even in longer arc contact length than in the present experiment, for example wheel depth of cut a is 10 mm , heat flux of at least $30 \text{ J/mm}^2\text{s}$ is required in case of water-based coolant. Therefore this idea

Fig. 10 Energy flux necessary for fluid vaporization during a grain-workpiece engagement

on the mechanism of grinding burn can not be accepted.

As mentioned before, Shafto proposes that the burn phenomenon in creep feed grinding is qualitatively analogous to the burn-out phenomenon in boiling. Consequently another idea on the mechanism of grinding burn comes up; the obstruction of heat transfer to the coolant by bubbles. It is known that one reason for burn-out, for example, in pool boiling is the obstruction of heat transfer to fluid due to bubbles sticking on the heating surface. Applying this to the grinding process, at least one bubble should form, grow up rapidly and then fill the wheel pore while the coolant passes through the wheel-workpiece contact zone. Many researchers have tried to calculate the growth of bubble and given the bubble radius r at time t by

$$r = \sqrt{\pi \kappa_L t} \left(\frac{\rho_L}{\rho_V} \right) \frac{C_{PL}(T_W - T_s)}{L_V} \dots (10)$$

where κ_L =thermal diffusivity of fluid, ρ_L, ρ_V =densities of liquid and gas respectively, C_{PL} =specific heat of liquid, T_W =heating surface temperature, T_s =saturation temperature and L_V =vaporization heat. Figure 11 shows the calculated results of Eq.(10) for water and the hatched area indicates the volume of a wheel pore obtained from the wheel specification. As can be seen, a

Fig.11 Growing up process of a bubble

bubble grows up in very short time and fills a pore in about 0.005 to 0.2 ms. On the other hand, time needed for a pore to pass through the arc contact is about 0.96 to 1.9 ms ($V_s=18$ m/s, $D=300$ mm, $a=1\sim4$ mm). Therefore there is enough time for a bubble to form and fill a pore while the pore passes through the arc contact. Generally bubbles begin to form when the temperature becomes around $100+10^\circ\text{C}$ in case of water. Hence the required heat flux may be smaller than that in the first idea, because it is unnecessary to vaporize the coolant.

By using the thermal model described in Chapter 2, the grinding energy flux which gives the maximum grinding zone temperature of 110°C can be obtained analytically and the results are compared with the experimental values in Fig.12(a) and (b). Figure 12 (a) shows the effect of wheel depth of cut, namely arc contact length and (b) shows the effect of width of cut. In both cases the grinding energy flux tends to decrease as the wheel depth of cut or width of cut becomes larger. This may be attributed to the reduction of cooling effect.

Figure 12 indicates that the analytical values almost coincide with the experimental

(a)

(b)

Fig.12 Comparison between analytical and experimental values of grinding energy flux just before workpiece burning

Fig.13 Schematic representation of mechanism of workpiece burn

ones and the grinding burn may be due to the obstruction of heat transfer to the coolant by bubbles. Hence the mechanism of a grinding burn is considered as shown in Fig.13. Nearly all the grinding energy required in the grinding process is transformed into thermal energy and the workpiece temperature goes up. The coolant flowing into the grinding zone dissipates the energy and the temperature of the coolant itself rises while passing through the grinding zone. If the generation of heat increases, then the temperature of the coolant rises and bubbles begin to form. The bubbles grow up rapidly

to fill wheel pores and there induce an obstruction of heat transfer to the coolant. Thus a burn-out, that is workpiece burn occurs.

In creep feed profile grinding, the thermal condition in the wheel-workpiece contact area may be the same as in creep feed surface grinding, and so taking account of the boundary conditions outside the contact area it is possible to anticipate the burning limit in terms of grinding energy flux. Figure 14 shows the comparison of the grinding energy flux just before burning between the finite element analysis and the experiment.

Fig.14 Grinding energy flux just before workpiece burning in creep feed profile grinding

As mentioned above, if the boundary conditions are given the grinding burn limit can be determined in terms of the grinding energy flux, that is the grinding energy per unit contact area per unit time, both in creep feed surface and profile grinding. Therefore it will be possible to select an optimal grinding condition in view of grinding burn or to realize the adaptive control of grinding burn by the in-process measurement of grinding energy flux.

5. Conclusions

- (1) Although depending on the method of coolant delivery, the cooling effect of the coolant is very high and the real heat input to the workpiece is very small.

The fraction of the mechanical energy conducted as heat into the workpiece can be roughly estimated from Jaeger's moving heat theory extended to include the cooling effect, and in the present study it is estimated to be about 10%.

- (2) Workpiece temperature distribution can be obtained quantitatively by a three dimensional finite element method taking account of the boundary conditions of heat input and convection coefficient on the workpiece surface.

- (3) Grinding burn takes place when the maximum grinding zone temperature reaches the boiling point of the coolant at which bubbles begin to form. Occurrence of a grinding burn is attributed to the obstruction of heat transfer to the coolant by bubbles.

- (4) Because of (1) and (3), the workpiece temperature is lower than the boiling point of the coolant in normal grinding conditions. That is, the temperature is lower than 100°C in the case of water-based coolant.

- (5) Because of (3), it is possible to anticipate the burn limit quantitatively in terms of grinding energy flux.

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