Force Modeling and Machining Characteristics of the Intermittent Grinding Wheels

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In the surface grinding operations, the grinding fluid cannot be supplied sufficiently in the cutting zone. Temperature generated in the cutting zone increases rapidly and causes thermal damage such as burning on the surface of a workpiece. To reduce thermal damage, the intermittent grinding wheels, which have an excellent cooling effect, have been applied. This paper describes machining characteristics by using intermittent grinding wheels. The grinding force of the intermittent wheels has been simulated by the SIMULAB, which is a program for simulating dynamic systems. Using the intermittent grinding wheels, the characteristics of grinding force, temperature, surface roughness, and geometric error have been evaluated experimently.

Key Words : Intermittent Grinding Wheel, Surface Grinding, Thermal Damage, SIMULAB

1. Introduction

In recent years, the demand for a mirror-like surface has increased for many conventional components. However, because of localized heating between cutting tools and material, thermal problems on the surfaces of components can arise in various metal removal processes, such as the turning or milling processes. Temperatures of a sufficient magnitude, which cause an adverse change in a workpiece metallurgical structure, loss in dimensional accuracy, and accelerated wear or dulling the tool edge, can occur. The most effective method for machining the mirror-like surface is the grinding operation, but the complex nature of the process precludes the precise analysis of the temperature, the surface roughness, and the grinding force.

There have been many papers published on the subject of analysis of the grinding temperature. The most important research, which laid the foundation for almost all later works, was the paper on the moving heat source model by Jaeger (1942). Rowe and Pettit (1988) adopted aspects of various works in that the coolant effects and the maximum convection effects were used to modify the grinding energy applied at the grain-workpiece interaction. They compared with results obtained by using and not using these effects. The effect of a deformable wheel was also included. Kwak et al. (2000) tried to analyze factors affecting the thermal damage, such as burning, on the grinding operation and performed the qualitative evaluation of those factors. Through the in-process monitoring technique of the grinding power and acoustic emission signals they detected the burning by the neural network.

Matsui and Syoji (1986) presented experimental results of the grinding temperature in the creep feed grinding. In this work, segments of 6, 12 and 24 pieces were consisted of a portion cut off from the conventional grinding wheel. They were inserted in the circumference of a cylindrical alumi-

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num holder. The segmental wheel had the reduction effect of both the grinding force and the temperature. However, the construction strategy of a segmental wheel was very complex and it is impossible to use it for general purposes in a workshop.

The works presented previously are not completely satisfactory in evaluating the grinding force, the temperature, the surface roughness, and the geometric error. The focus of this paper is to represent a simulation model for predicting the grinding force and to prove experimentally the superiority of various aspects in the intermittent wheels.

2. Intermittent Grinding Wheel

An application scheme of the intermittent wheel, which directly supplies fluid and air at the cutting zone, is an effective cooling method for the grinding temperature and facilitates the chip removal process from the grinding wheel.

Figure 1 presents a schematic drawing of an intermittent wheel, which has some grooves on the circumference of a grinding wheel. These grooves were cut by a diamond wheel in the tool grinder and inclined to the angle of γ from the radial direction in order to prevent serious wear or the chipping phenomenon of the intermittent wheel during the machining process. In intermittent grinding, the intermittent ratio η has an influence on the grinding performance. The intermittent ratio was defined as follow:

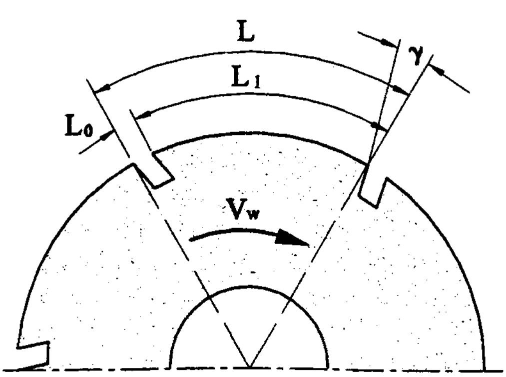


Fig. 1 Schematic drawing of an intermittent grinding wheel

$$\eta=\frac{L_1}{L_1+L_0} \tag{1}$$

where L_0 is a length of a groove and L_1 is an effective cutting length of the grinding wheel. The Eq. (1) means the intermittent ratio is a ratio between circumference length and contact length in intermittent wheels. Based on a geometry of intermittent grinding wheels, the intermittent ratio varies and the grinding performance differentiates also. Table 1 lists the specifications of the intermittent wheels used in this study.

3. Development of Simulation Model for Estimating the Grinding Force

3.1 Simulation model

The equation, which governs the grinding process, is (Vinolas et al., 1997):

$$\delta_w(t)+\delta_s(t)=u(t)-y_k(t)-y_m(t) \tag{2}$$

where the wear of the workpiece $\delta_w(t)$ plus that of the grinding wheel $\delta_s(t)$ must be equal to the depth of the cuts $u(t)$ minus the deformation of the area of contact $y_k(t)$ and minus the machine deformation $y_m(t)$. Taking into consideration with instantaneous magnitudes of the workpiece wear and the wheel wear, the following regenerative effects of the workpiece τ_w and that of the wheel τ_s are related.

$$\Delta\delta_w(t)=\delta_w(t)-\delta_w(t-\tau_w) \tag{3}$$
$$\Delta\delta_s(t)=\delta_s(t)-\delta_s(t-\tau_s) \tag{4}$$

Assuming a linear relation between the grinding force F_c and the instantaneous wear of the wheel $\Delta\delta_s$ and that of the workpiece $\Delta\delta_w$, the following equations are obtained:

$$F_c=K_s\cdot\Delta\delta_s \tag{5}$$
$$F_c=K_w\cdot\Delta\delta_w \tag{6}$$

Table 1 Specifications of the intermittent wheels

Items / Wheels	No. of grooves	L_0(mm)	L_1(mm)	η
IW-06	6	6	101.0	0.94
IW-12	12	6	47.5	0.89
IW-24	24	6	20.8	0.78

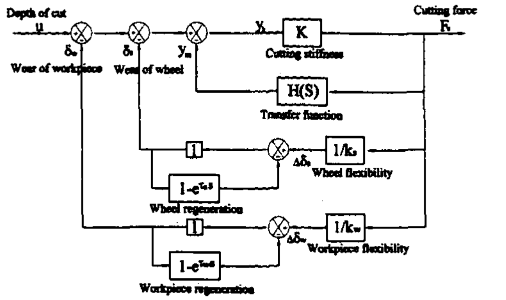


Fig. 2 Representation of a block diagram for estimating the grinding force

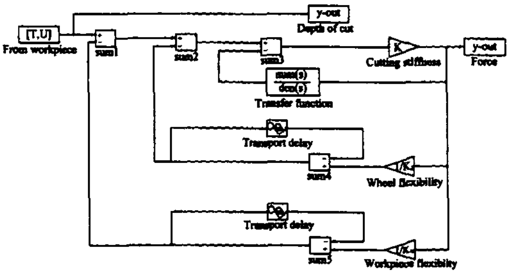


Fig. 3 SIMULAB model of the intermittent grinding process

where K_s is a stiffness of the grinding wheel and K_w is a stiffness of the workpiece. A transfer function $H(s)$, which relates the dynamic deformation of the machine due to the grinding force, is defined as the machine deflection over the grinding force.

$$H(s)=\frac{\omega_n^2}{s^2+2s\zeta\omega_n+\omega_n^2}+\frac{1}{K_i} \qquad (7)$$

In the Eq. (7), K_i is a consideration coefficient for machining the workpiece with an intermittent wheel. To get the transfer function, a simplified experimental modal analysis (EMA) can be carried out. Based on the deformation of the area of contact at the wheel and the workpiece, the following equation is obtained:

$$F_c=K\cdot y_k \qquad (8)$$

where K is the contact stiffness between the grinding wheel and the workpiece. According to the Eqs. (2) to (8), a block diagram as shown in Fig. 2 can be created.

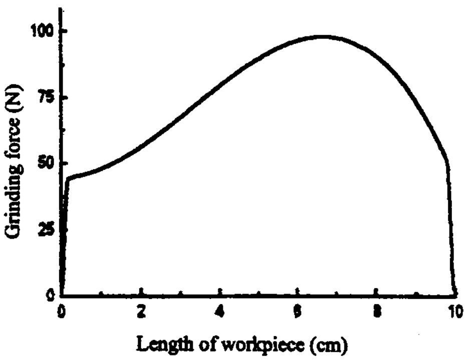
From this block diagram, a SIMULAB model, which was presented in Fig. 3, has been derived. The data for simulating the previous model were included in a M-file, which was used as an input file in the SIMULAB program. These data were obtained from a real test or from the general references of the grinding operation. Through the EMA of the grinding machine, the damping ratio and the natural frequency were acquired as $\zeta=0.05$ and $\omega_n=500$ Hz respectively.

Because the wheel revolution speed was 1800 rpm, the time delay constant, τ_s, of the wheel was determined as 0.033sec. Based on the machining-cycle time of the wheel passing the workpiece, the time delay constant, τ_w, of the workpiece was applied to the value of 5sec. The consideration coefficient of the intermittent wheel was 0.85, which was equal to the average intermittent ratio of the grinding wheel. The stiffness of the wheel and the workpiece were referred in the previous work (Hashimoto et al., 1985). The stiffness of the wheel and the workpiece were determined as 0.7N/mm and 10N/mm respectively. The contact stiffness obtained was 0.8N/mm from the same reference.

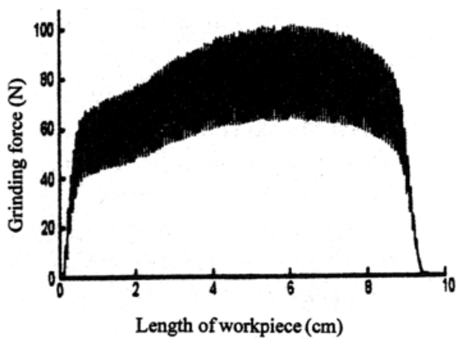
3.2 Simulation results

A simulation was conducted in order to estimate the grinding forces of the intermittent wheels with the previous SIMULAB model. Figure 4 shows the results of the simulation and an experimentation using the same conditions. It shows that the result of the simulation is similar to that of the experimentation with respect to the force curves. The oscillation of the power signal obtained by the experimentation is due to the discontinuity of the intermittent grinding wheel.

Figure 5 shows the result of the simulation and the experimentation of the grinding force. This result clearly shows that the grinding force increases linearly to the depth of cuts and to the workpiece velocity. Non-consideration factors, which have a more complex relationship in the machining, cause this simulation model, for estimating the grinding force, to make a difference between the simulation and the experimentation. However, because the difference between the simulation and the experimentation is very small this model can use for the estimation of the grinding



(a) Simulation result



(b) Experimental result

Fig. 4 Grinding forces of the simulation and experimentation

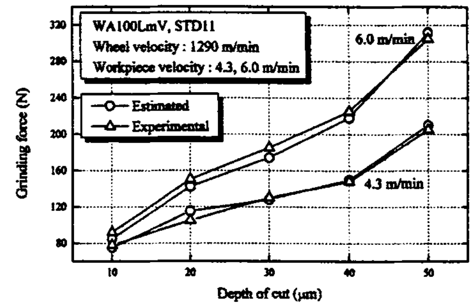


Fig. 5 Result comparison of the simulation and experimentation for grinding force

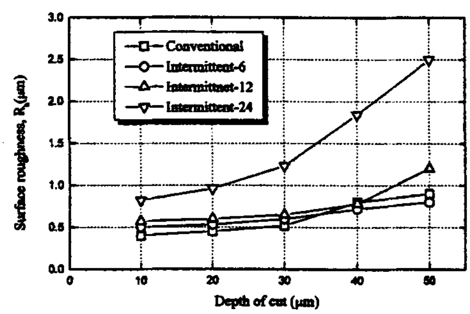


Fig. 6 Surface roughness of the conventional and intermittent wheels

force.

4. Characteristics by the Experimentation

4.1 Experimental conditions

A series of grinding tests were conducted on a surface grinder with a WA100LmV wheel of 228mm diameter. This is commonly used in workshops. For a comparison of the characteristics between the conventional and intermittent wheels, the intermittent wheel is made from the same wheel type as the conventional wheel. Specimens STD11, which are preferred to the die and mold materials, were tested. The velocity of the wheel was 1290m/min and the velocity of the workpiece was 4.3m/min. The depth of cuts varied in the range of 10~50 μm. For the cooling effect of the workpiece, a soluble coolant with 10% dilution was supplied. The instruments for testing surface roughness, temperature, and geometric error were used. The instruments used were the MITUTOYO SURFTEST-301, the CA type thermocouples with a diameter of 3mm, and the Tayrond-252 made in Rank-Taylor Hobson. The testing results were analyzed in the following.

4.2 Experimental results and discussion

Figure 6 presents the surface roughness obtained by the surface profile tests. The value of the surface roughness deteriorates generally, according to the increase in the depth of the cuts. It is evident that the ground surface roughness, with the intermittent wheels, grows from bad to worse in surface quality, in comparison to the conventional wheel. The higher the intermittent ratio is, the more deterioration is generated in the surface roughness. It causes the intermittent wheel to contact with a discontinuous process on the workpiece surface and the wheel oscillates in the direction of the radial axes.

Figure 7 shows the change of the grinding temperature obtained through the thermocouple

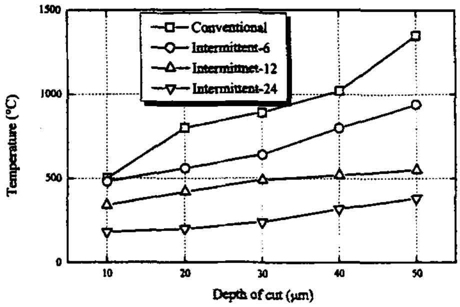


Fig. 7 Grinding temperature of the conventional and intermittent wheels

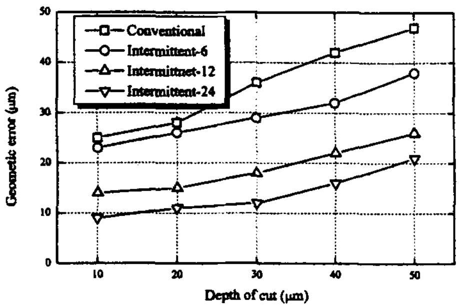


Fig. 8 Geometric error of the conventional and intermittent wheels

method. This method uses the CA type materials submerged in specimens. Although the temperature increases with various depths of the cut, the reduction effect of the temperature was identified with the intermittent wheel. That is the reason there appears to be a reduction. There can be a more effective supply of the coolant through the grooves of the intermittent wheel than through the conventional wheel.

A geometric error on the ground surface gives a definition of difference between the horizontal datum line on the free surface of the workpiece and the bottom of the concave made by the thermal deformation. A numerical value of geometric error indicates how much a part produced in the grinding operation suffers from thermal damage.

Figure 8 presents that by using the intermittent wheel there is an improvement in the geometric error. The more grooves are, the smaller geometric errors generate. Those phenomena are due to the sufficient supply of the coolant through the grooves of the intermittent grinding wheel and to the decrease of the grinding temperature in the grinding zone.

As the previous test results, it is seen that the intermittent wheel has excellent characteristics in view of surface roughness, grinding temperature, and geometric error.

5. Conclusion

In order to introduce the grinding force model and verify superiority of the intermittent wheel, the simulation and the experimentation were conducted in the surface grinding. Based on these results, the conclusions can be drawn as following:

(1) Based on the introduction to the simulation model with the SIMULAB program for estimating the force in the surface grinding, the grinding force could be predicted by using this model and an availability of the simulation model was verified by numerous experiments.

(2) From the results of the experiments for a conventional and intermittent wheels, it was proven that the intermittent wheel appeared to be superior in various aspects such as grinding force, temperature, and geometric error with little deterioration of the surface roughness.

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