Feed Control Based on the Prediction of Workpiece Deflection in Grinding*1

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Grinding is employed as a finishing process for the manufacture of engine parts. Actual depth of cut in grinding lags behind the command value due to workpiece deflection. Therefore, the grinding process has a long finishing time for the demanded form accuracy. In this research, we propose feed control logic (based on the prediction of workpiece deflection in grinding) to achieve both machining time and form accuracy. This report describes the development of a grinding system composed of a standard cylindrical grinder and the proposed feed control logic. A grinding experiment is also carried out for evaluation of the proposed grinding system.

Key Words: *grinding cycle, grinding force, workpiece deflection, feed control*

1. Introduction

Grinding is a removal process which uses super-hard, fine abrasive to achieve a high quality and high accuracy for hardened steel, carbide and other hard-to-cut material. Due to this feature, grinding is often employed as the finish process for engine parts, and in recent years high productivity is also demanded.

Meanwhile, cylindrical workpieces such as shafts are deflected by the grinding force at a high stock removal rate. In transient state of grinding process, the actual cutting depth lags behind command cutting depth1). Therefore, in order to achieve the required form accuracy, the stock removal of the finishing process must be increased, which in turn extends grinding time.

In this research, a grinding system was developed which achieves both short grinding time and stable form accuracy in cylindrical grinding. By predicting workpiece deflection amount and controlling feedrate, control logic was built which settles actual cutting depth to target value in a short time. Moreover, a cylindrical grinding system was developed by equipping this control logic on a standard cylindrical grinder and a grinding experiment was carried out to verify effectiveness. This report provides an overview of this grinding system and the grinding experiment results.

2. Grinding Process

2. 1 Cylindrical Grinding Cycle

Figure 1 shows a conventional cylindrical grinding cycle. Cutting speed is lowered through the various stages of grinding - rough, fine, and micro. In the last grinding process called "spark out", form accuracy is achieved by stopping the infeed motion for a predetermined length of time. This trajectory of the cutting position among whole grinding process is called the grinding cycle. The diameter of workpiece in-process is measured by automatic sizing equipment (hereinafter auto-sizer). The grinding processes are switched at the auto-sizer signal points, which are determined by the preset diameter of workpiece.

Table 1 shows the function of each process2). Rough grinding is required to rapidly remove a large amount of stock in order to shorten grinding time, while in contrast, the finishing processes of fine, micro grinding and spark out must achieve quality aspects such as form accuracy and surface roughness. Increasing the cutting speed of rough grinding is one possible method to shorten grinding time, however the increase in grinding stock removal rate would result in grinding burn. Moreover, increasing the cutting depth would increase the form error such as the step caused by cutting that would need to be removed in the finishing process. Therefore the required form accuracy may not be achieved. For the above reasons, shortening the grinding time is complicated. Moreover, the form error depends on the deflection during grinding, therefore even if the grinding force is the same, the lower the stiffness of a workpiece, the greater the form error will become. In other words, the lower the workpiece stiffness, the longer the grinding time.

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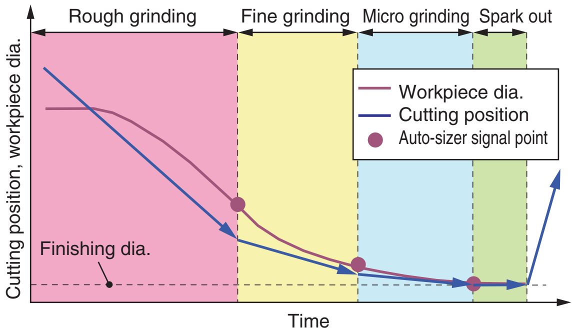


Fig. 1 Conventional cylindrical grinding cycle

Table 1 Functions of grinding processes

	Function
Rough grinding	· Removes the run-out of the previous machining · Grinds as fast as possible (emphasis on speed)
Fine grinding	· Removes form error created at rough grinding · Secures micro grinding stock removal (emphasis on accuracy)
Micro grinding	· Suppresses outer diameter dimension variation · Achieves surface roughness (emphasis on accuracy)
Spark out	· Removes the remaining stock after micro grinding · Improves and stabilizes surface roughness (emphasis on accuracy)

2. 2 The Grinding Model

Figure 2 shows a model of a cylindrical grinding. By infeed motion, the grinding wheel interferes with the workpiece and removes the designated portion. At this time, the grinding force based on the cutting depth is generated. Therefore, the workpiece will deflect by the amount of ε, which is this grinding force divided by workpiece stiffness K. As a result, the actual cutting depth Δ_{actual} will lag behind Δ_{com} given in the position command. This phenomenon is expressed with Formula (1), and the time constant τ is expressed in Formula (2).

$$\Delta_{actual} = \Delta_{com} - \Delta_{com} \cdot e^{-t/\tau} \tag{1}$$

$$\tau = \frac{\alpha \cdot b \cdot \pi \cdot D}{K \cdot V} \tag{2}$$

Here, α is contact stiffness, b is grinding width, D is workpiece diameter, K is workpiece stiffness and V is wheel peripheral speed.

In this way, Δ_{actual} is expressed as a first-order lag of Δ_{com}. α will increase if wheel performance degrades. In Formula (2), the higher the contact stiffness, or the lower the workpiece stiffness, the greater the time constant will be.

2. 3 The Effect of Lag Caused by Deflection

A grinding experiment was carried out to investigate the effect of contact stiffness α and workpiece stiffness K against the lag caused by deflection. **Table 2** shows the grinding conditions and **Fig. 3** shows a schematic of the workpiece, whose stiffness differs according to the portion along the axial direction.

Figure 4 shows the relationship between cutting depth and grinding time. Under the same grinding conditions, the deflection amount upon rough grinding will be greater if workpiece stiffness K is low. Therefore, shows cutting depth must be settled by extension of fine grinding time in order to achieve form accuracy. Also, if the contact stiffness α is high, as shown in **Fig. 4 (b)**, the grinding force will increase and cutting depth is still not settled after the predetermined spark out time. Form measurement results confirmed that, at this time, a step created by cutting remained.

From the above, it was verified that deflection caused by grinding force increases form error and finishing stock removal must be increased for achievement of the required form accuracy.

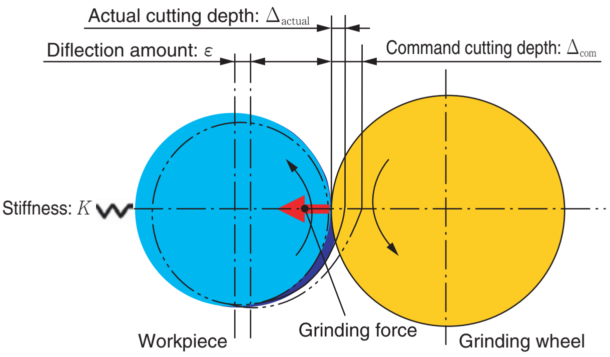


Fig. 2 Cylindrical grinding model

Table 2 Grinding test conditions

Grinder	Cylindrical grinder (JTEKT)
Grinding wheel	Vitrified CBN wheel (#120, Concentration 150) ϕ120mm
Workpiece	Chromium steel (Carburized quenched) ϕ29mm Width: 20mm 4.4 N/μm (Low stiffness portion), 13.8 N/μm (High stiffness portion)
Wheel peripheral speed V	80 m/s
Workpiece peripheral speed v	0.4 m/s
Grinding stock removal rate Z'	8.4 mm^3/ (mm·s) (Rough grinding)
Coolant	Emulsion type (Diluthon rate: x20)

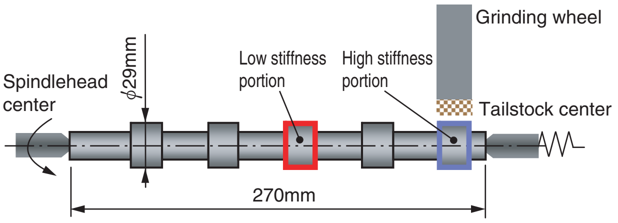
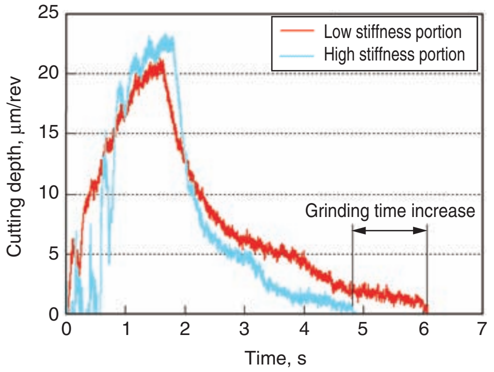
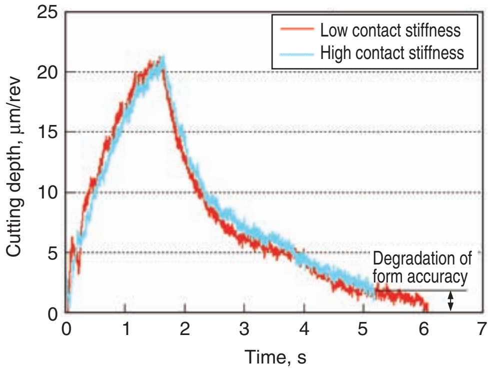


Fig. 3 Workpiece dimensions



(a) Difference in workpiece stiffness



(b) Difference in wheel performance

Fig. 4 Relationship between cutting depth and machining time

3. Grinding System Based on Compensation of Workpiece Deflection

3. 1 Overview

The grinding test confirmed that there was a lag as expressed by Formula (1) in the actual cutting compared with the command cutting in transient state of grinding processes. With a focus on the extension of grinding time in conventional grinding cycles caused by the first-order lag of actual cutting depth due to deflection amount generated during grinding, a grinding cycle which achieves shorter grinding time was developed. **Figure 5** shows the schematic of the developed grinding cycle compared with the conventional one. In the zone (i) until settling to the cutting depth of the rough grinding and the fine grinding of (ii), which is a connection process between rough grinding and micro grinding, grinding time is reduced by settling the deflection amount of each respective zone in a short time.

The settling time in conventional grinding cycle is dependent on the time constant τ, which is determined by workpiece stiffness K and contact stiffness α. In the developed grinding cycle with feed control which settles deflection in a short time, the same grinding time is achieved without depending on workpiece stiffness. Moreover, by stabilizing the deflection amount in micro grinding, cutting depth is stable without depending on contact stiffness. Therefore, the stability of form accuracy is improved.

3. 2 Control Logic

Figure 6 shows the control logic based on compensation of workpiece deflection. This control logic settles deflection amount to targeted value of each process in one rotation of the workpiece by the compensation of infeed amount. The deflection amount during grinding must be known for the proposed control logic. However it is difficult to directly measure the deflection amount of the portions being ground due to chips and coolant. Therefore, control logic was built which predicts the deflection amount from the relationship between the normal grinding force F_n and actual cutting depth Δ_{actual} during grinding. Actual cutting depth and grinding force are proportional3). Therefore, normal grinding force can be expressed by Formula (3), in which the contact stiffness α is used as a proportional constant.

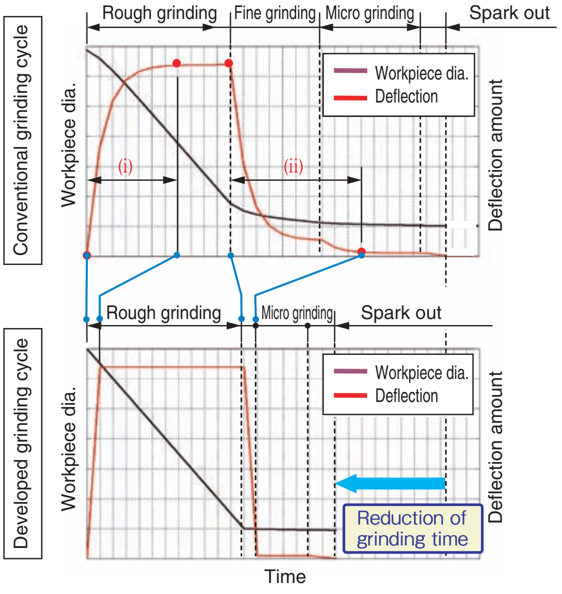


Fig. 5 Schematic of developed grinding cycle

$$F_n = \alpha \cdot \Delta_{\text{actual}} + \beta \tag{3}$$

Here, β is defined as the force caused by dynamic pressure of coolant. From Formula (3), deflection ε during grinding is expressed in Formula (4) using the contact stiffness α and workpiece stiffness K.

$$\varepsilon = (\alpha \cdot \Delta_{\text{actual}} + \beta)/K \tag{4}$$

Force β caused by dynamic pressure is assumed as constant without depending on cutting depth. When the deflection amount at the beginning of rough grinding when the grinding wheel makes contact with the workpiece is established as the reference, the relationship between the command cutting depth Δ_r and the deflection amount ε_r in rough grinding will be expressed in Formula (5). And the relationship in micro grinding will be expressed in Formula (6).

$$\varepsilon_r = \alpha \cdot \Delta_r/K \tag{5}$$

$$\varepsilon_f = \alpha \cdot \Delta_f/K \tag{6}$$

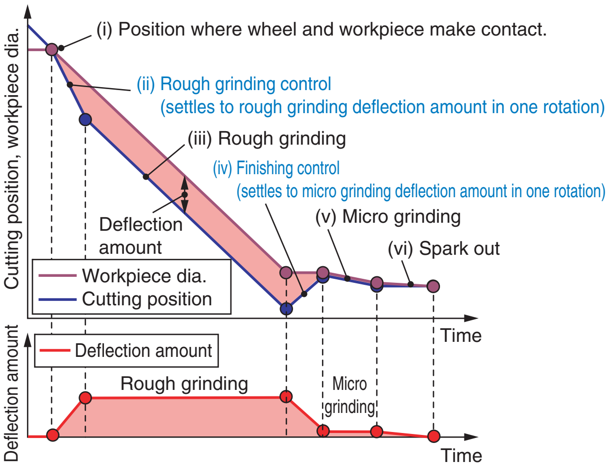


Fig. 6 Feed control logic based on compensation of workpiece deflection

In the rough grinding control shown in (ii) of the figure, the infeed amount per one rotation is expressed by adding rough grinding deflection ε_r to the command cutting depth. After one rotation, the deflection of the workpiece is settled to the targeted value. Moreover, in the finishing control shown in (iv) of the figure, the infeed amount per one rotation is similarly determined by the command cutting depth in micro grinding and the difference between ε_r and ε_f.

3. 3 Grinding System with Feed Control Logic

Figure 7 shows the grinding system based on compensation of workpiece deflection. Normal grinding force F_n is derived from the current of the linear motor, which is the drive unit for an infeed motion of a wheel. Actual cutting depth Δ_{actual} is derived by calculating the output from the auto-sizer. From the relationship between grinding force F_n and actual cutting depth Δ_{actual}, the contact stiffness α and force β caused by dynamic pressure of coolant are predicted.

In actual application, the first workpiece in the dressing interval is ground in the conventional grinding cycle, due to large difference between the contact stiffness α before and after dressing, then α and β are predicted. The developed grinding cycle is used from the second workpiece onwards. Contact stiffness α is renewed at each workpiece and fed back to the grinding of the following workpiece, thereby responding to degradation of wheel performance.

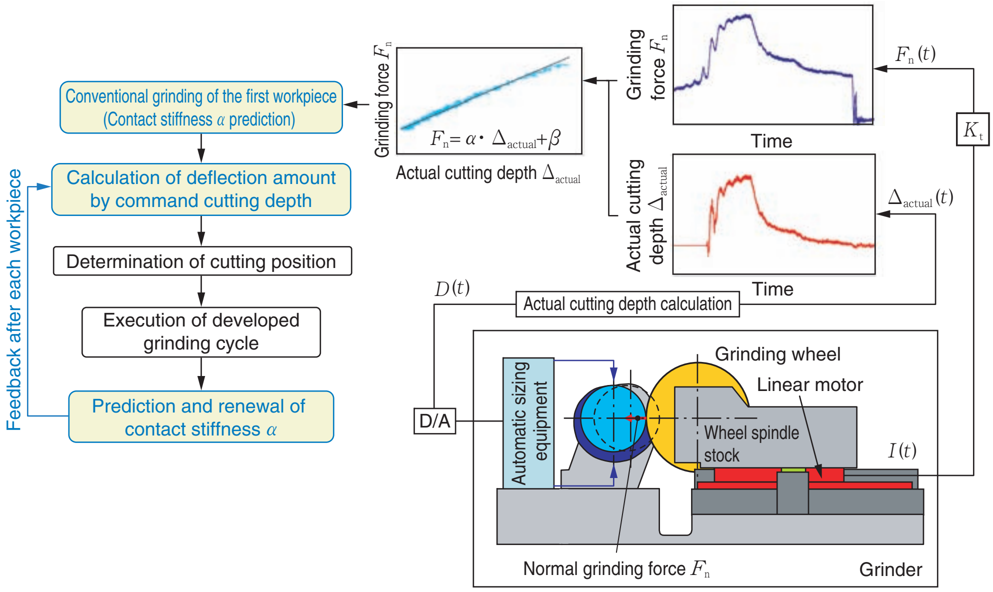


Fig. 7 Grinding system based on compensation of workpiece deflection

4. Test Results

In order to evaluate the basic performance of this system, feed control logic was equipped on a standard cylindrical grinder and a grinding experiment was carried out under the conditions shown in **Table 2**. The grinding results with the conventional grinding cycle and the developed grinding cycle are shown in **Fig. 8** and **Fig. 9** respectively. In the conventional grinding cycle, cutting depth is settled to the targeted value of the micro grinding by extention of fine grinding time, which is dependent on time constant τ determined by workpiece stiffness. Meanwhile, in the developed grinding cycle, cutting depth is settled to the targeted value in one rotation of the workpiece, which is achieved by the feed control based on the prediction of workpiece deflection. The experiment also confirmed that it was possible to grind in around the same time without depending on workpiece stiffness. In the grinding conditions of this experiment, a grinding time with the feed control logic is reduced by over 20% compared with the grinding time of the conventional cycle.

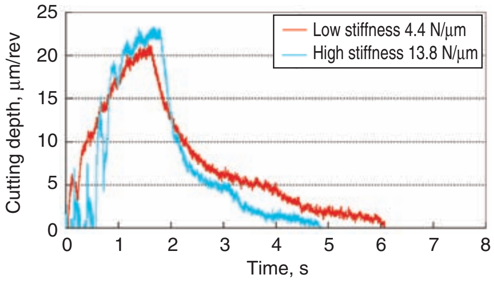


Fig. 8 Grinding experiment results (conventional grinding cycle)

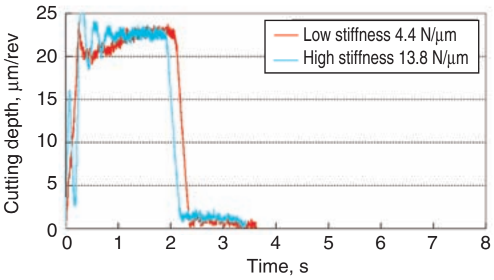


Fig. 9 Grinding experiment results (developed grinding cycle)

5. Conclusion

The grinding system with feed control logic based on the prediction of workpiece deflection, is developed for achievement of both short grinding time and stable form accuracy in cylindrical grinding. The grinding experiment demonstrated that grinding time could be reduced by over 20% compared with the conventional grinding cycle, and it was also confirmed that both grinding time and form accuracy was stable in workpieces of differing stiffness.

By considering the basic principles relating to the effects of workpiece deflection caused by grinding force on grinding time and form accuracy, it was possible to develop a grinding cycle which significantly reduces grinding time. We will continue to develop grinding technologies which improve our product competitive power.

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