1. Introduction

In a centerless grinding operation the workpiece rounding mechanism is very complicated, and it is difficult to optimize the grinding conditions for minimizing the workpiece roundness error. Authors had proposed the optimum grinding conditions [1]. However, the selected process parameters based on the proposed optimum grinding conditions might become unsuitable as the grinding wheel and regulating wheel are wore down during grinding. Consequently, in order to re-setup the optimum grinding conditions efficiently and certainly, automatically selecting the process parameters are necessary. For this purpose, an evaluation function of grinding conditions called the waviness decrease rate had also been provided [2].

To build the closed-loop control system for the process parameters, however, it is necessary to find a practical way to measure the waviness decrease rate. In this paper, a relationship between the waviness decrease rate and the dynamic components of grinding force was investigated analytically. It was found that the frequency characteristics of the waviness decrease rate shows a similar tendency to that of the dynamic components of grinding force. Then, a grinding force measurement system was built and measurement and evaluation of the grinding force were carried out. As a result, it was confirmed that the grinding conditions could be evaluated using the dynamic components of grinding force.

2. Principle of obtaining the waviness decrease rate from the dynamic components of grinding force

Fig.1 shows the geometrical arrangement of centerless grinding. \( R_w \) is the radius of the workpiece average circle. Let a waviness component on the workpiece ground for \( i \) revolutions at frequency \( n \) be a vector \( r(i n) \) on the complex number plane, the component on the initial workpiece \((i=0)\) and that on one ground for \( N \) revolutions \((i=N)\) can be expressed as \( r_0(i n) \) and \( r_N(i n) \), respectively. Then a relationship between \( r_0(i n) \) and \( r_N(i n) \) will be as follows [2].

\[
\kappa(i n) = \frac{r_N(i n)}{r_0(i n)}
\]

(1)

Where \( \kappa(i n) \) is called the waviness decrease rate [2], and \( \kappa = K_m/(K_m + K_s) \) the machine stiffness and \( K_s \), the grinding stiffness[3].

Generally the amplitudes of waviness on initial workpiece in low frequency region are bigger than that in high frequency region. Therefore, in order to decrease roundness error the grinding conditions must be set-up so that the waviness decrease rate \( \kappa(i n) \) in low frequency region becomes as smaller as possible according to Eq.(1). Thus, if frequency characteristics of \( \kappa(i n) \) has been obtained in practice, the grinding conditions could be evaluated with this standard.

To find a practical way for obtaining the frequency characteristics of \( \kappa(i n) \), a relation of it to the frequency characteristics of the dynamic component of grinding force was discussed as bellow.

First, assuming the grinding force is proportional to the depth of cut gives a relationship between the dynamic component of grinding force and the waviness component as Eq.(3) [2].
\[ F_{G_n}(jn) = K_s\Delta_i(jn) = K_s\{r_i(jn) - r_{i-1}(jn)\} \quad (3) \]

where \( F_{G_n}(jn) \) is the dynamic component of grinding force at frequency \( n \) in the \( i \)th revolution of grinding, and \( r_i(jn) \), \( r_{i-1}(jn) \) are the waviness components at frequency \( n \) in \( i \)th and \( (i-1) \)th revolution of grinding respectively. Then, next formula can be obtained from Eq. (3).

\[ r_i(jn) = r_0(jn) + F_{G_n}(jn)/K_s \quad (4) \]

where \( F_{G_n}(jn) = \sum_{j=1}^{N} F_{G_n}(jn) \) (5)

Substituting Eq.(1) in Eq.(4) and arranging it, an equation is obtained as Eq.(6).

\[ \kappa_i^n(jn) = 1 + \frac{F_{G_n}(jn)}{K_s - r_0(jn)} \quad (6) \]

Eq. (6) shows that on the complex number plane the vector \( \kappa_i^n(jn) \) is obtained by moving only 1 parallel along the real axis, after the vector \( F_{G_n}(jn)/r_0(jn) \) is expanded (or reduce) in magnification of \( 1/K_s \), as \( K_s \) is a real number.

Therefore, according to the mapping principle of the complex number [4], the frequency characteristics of \( F_{G_n}(jn)/r_0(jn) \) will be same as that of \( \kappa_i^n(jn) \). Consequently, when the initial workpiece waviness \( r_0(jn) \) has been known, the frequency characteristics of \( \kappa_i^n(jn) \) can be obtained by measuring \( F_{G_n}(jn) \).

3. Measuring method of dynamic components of grinding force

As above mentioned, the waviness decrease rate \( \kappa_i(jn) \) can be obtained from the dynamic component of normal grinding force \( F_{G_n} \). However in centerless grinding, it is very difficult to measure \( F_{G_n} \). In this work, instead of \( F_{G_n} \) the force on the blade is used to obtain \( \kappa_i(jn) \) in a way as bellow.

Figure 2 shows the forces on the workpiece. Let the vertical (X direction) component of the force \( F_B \) on the blade be \( F_{B_0}(\theta) \), a relationship between \( F_{G_n}(\theta) \) and \( F_{B_0}(\theta) \) is obtained from the equilibrium of forces on workpiece as bellow [5].

\[ F_{G_n}(\theta) = K_B F_{B_0}(\theta) - K_w W \quad (7) \]

where

\[ K_B = \frac{\sin(\epsilon_B - \epsilon_C + \phi + \beta) \cos \epsilon_G}{\sin(\epsilon_G + \epsilon_C - \gamma) \sin(\epsilon_B + \phi)} \quad , \quad K_w = \frac{\cos(\epsilon_C - \beta) \cos \epsilon_G}{\sin(\epsilon_G + \epsilon_C - \gamma)} \]

and \( \theta \) is the workpiece rotation angle measured from the grinding start point. The angles \( \epsilon_B \) and \( \epsilon_C \) depend on the friction coefficients between the workpiece and the blade, the regulating wheel, respectively. The angle \( \epsilon_G \) is determined by the ratio of normal component of grinding force to its tangential component. Because the geometrical arrangement (\( \beta, \gamma, \phi \)) and the angles \( \epsilon_{in}, \epsilon_C, \epsilon_G \) are independent of the grinding time in a grinding cycle, the coefficients \( K_B, K_w \) can be regarded as constant.

As the workpiece rotation angle \( \theta \) is proportional to the grinding time, doing Laplace transform of Eq.(7) on \( i \)th revolution of grinding (\( 2\pi(i-1) \leq \theta \leq 2\pi i \)) gives a relationship between \( F_{G_n}(jn) \) and \( F_{B_0}(jn) \) at frequency \( n \) as bellow.

\[ F_{G_n}(jn) = K_B F_{B_0}(jn) \quad (8) \]

Then substituting Eq.(8) in Eq.(5) and arranging it, an equation is obtained as following.
where $i = 1, 2, \ldots, N$.

As $K_B$ is a real number, the frequency characteristics of $F_{R_0}(jn)$ should be equal to that of $F_{G_0}(jn)$ according to the mapping principle of complex number. Consequently, we know from Eq.(9) and Eq.(6) that the frequency characteristics of $\kappa(jn)$ can be obtained by measuring $F_{R_0}(jn)$. A measuring system for $F_{R_0}(jn)$ was produced as shown in Fig. 3. The output signal of the dynamometer is used to obtain $F_{R_0}(jn)$ ($i=1,2,\ldots,N$). To extract the signal every revolution of workpiece, a trigger signal is necessary to divide the signal for each revolution. In this system, the trigger signal is obtained by detecting the position of a small iron piece (the sensor target) stuck on the workpiece with an eddy type proximity sensor. The analog signal of dynamometer is sampled through an A/D board by a personal computer. The sampling rate was set at 400Hz.

4. Measurement of frequency characteristics of force on blade

Ferrite rings (36mm in outer diameter, 16mm in inside diameter 12mm in width) were ground on the produced experimental system, and the frequency characteristics of the output signal of dynamometer are calculated. Experimental procedures are as follows.

To begin with, the initial workpieces with a flat (see Fig. 4) are prepared. Next, centerless infed grinding operations are carried out under the given grinding conditions, and the output signal of dynamometer and proximity sensor are incorporated into the computer. Then, the output signal is treated by FFT method to obtain the dynamic components for every revolution of workpiece, $F_{R_0}(jn)(i=1,2,3,\ldots)$ responding to the trigger signal from proximity sensor. Thus, the parameter $F_{R_0}(jn)/r_0(jn)$ can be calculated using Eq.(10) and data in Fig. 4. Changing the center height by using different liners, the experiment on the above procedure was repeated. Fig.5 (a) and (b) show an example for the outputs of dynamometer and proximity sensor, respectively.

Figure 6 shows the frequency characteristics of parameter $F_{R_0}(jn)/r_0(jn)$ obtained experimentally. Obviously, the frequency components of $F_{R_0}(jn)/r_0(jn)$ in low-frequency region of
N=3-7 are comparatively bigger than others at $\gamma=3.2^\circ$ (see Fig.6(a)). In the meantime, in the case of $\gamma=6.2^\circ$ (see Fig.6(b)), the high frequency components such as in 28-32Hz, especially at 30Hz are bigger than others. Furthermore, as the center height increase to $\gamma=8.8^\circ$(see Fig.6(c)), the component at 20Hz is biggest.

To confirm the supposition mentioned in section 3 that the $\kappa(jn)$ can be obtained from the vertical component $F_{BxS}(jn)/r_{0}(jn)$ of force on the blade, the calculated results of $\kappa_{r}(jn)$ (here $N=10$) with Eq.(2) are shown in Fig. 7. In comparison with Fig.6 and Fig.7, it is obvious that frequency characteristics of $F_{BxS}(jn)/r_{0}(jn)$ and $\kappa_{r}(jn)$ agree with each other for all of the center height angle. Like this, it is confirmed experimentally that the grinding conditions can be evaluated by obtaining the frequency characteristics of the waviness decrease rate, which can be obtained by measuring dynamic component of vertical component of force on blade.

5. Summary

The evaluation of grinding conditions in centerless grinding was attempted by measuring the dynamic components of grinding force. The obtained results can be summarized as: (1) the frequency characteristics of the waviness decrease rate can be obtained by measuring that of the dynamic components of grinding force, (2) the frequency characteristics of the dynamic components of grinding force can be specified by measuring that of the dynamic component of vertical force on the blade, (3) the measuring system, which is mainly composed of a thin-type dynamometer was produced, and measurement experiments were carried out, as the result, it was confirmed that the grinding conditions can be evaluated using the dynamic components of vertical force on the blade.

Reference