Improvement of shape accuracy in internal grinding with slender grinding wheel

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Abstract. The shape error of the ground workpiece worsens in case of internal grinding with a slender grinding wheel. In this study, we propose a new grinding system to improve the shape accuracy of the ground workpiece, where the grinding force was estimated previously to minimize the shape error. Considering the effect of wheel wear and wheel run-out on the shape error, the optimized grinding force was obtained by simulating the wheel wear before grinding. Grinding experiments were carried out to verify the proposed system which successfully reduced shape error of the workpiece.

Introduction

Recently, there is necessity to finish a slender hole by internal grinding[1]. In internal grinding of a slender hole, the shape error of the finished hole due to the low stiffness of slender grinding wheel. As shown in Fig.1, the grinding wheel is bended by the normal grinding force during the grinding process. Therefore, there is a risk that diameter of finished hole is uneven. According to our previous study[2], the main cause of shape error is elastic deformation of the grinding wheel. Fig.2 shows an example of measured normal grinding force. As the spark-out duration is longer, the normal grinding force decreases because the residual stock removal decreases during the spark-out process. Therefore, extension of the spark-out duration is considered to be effective to improve the shape accuracy. Fig.3 shows the measured shape of the surface finished in several conditions with changing the spark-out duration. It is found that the shape accuracy is improved by extending the spark-out duration.

However extension of the spark-out duration increases grinding cycle time and leads to low productivity. To solve this problem, we proposed a new method to optimize the spark-out duration.

Considered causes of shape error

In the proposed method, the elastic deformation of the grinding wheel is considered to be the main cause of the shape error. Furthermore wheel wear and wheel run-out are considered to be the causes
of shape error as shown in Fig.4. It is possible to estimate the elastic deformation of the workpiece by measuring the normal grinding force during grinding process. The effect of wheel wear is calculated from the shape error of the workpiece measured before a grinding experiment. As the stock removal increases, the wheel wear also increases. Therefore, the amount of wheel wear is estimated using the grinding rate between the volume of stock removal and wheel wear. Supposing that there is no shape error of finished workpiece, the stock removal of the workpiece is proportional to the shape error measured in each positions of the axial coordinate before grinding.

\[ \frac{d_{r}}{d_{w}} = \frac{P / k_s}{d_{w0}} \]

\[ d_{1} = d_{1} + d_{w} - e_{s} \]  

Equation (1) \[ d_{1} = d_{1} + d_{w} - e_{s} \]

In equation (1), \( d_{1}, d_{w}, e_{s} \) are the shape errors caused by elastic deformation, wheel wear, wheel run-out, respectively. \( d_{1} \) is calculated from the measured normal grinding force \( P \) and the spring rate of grinding wheel \( k_s \) by the following equation.

\[ d_{1} = P / k_s \]  

Equation (2) \[ d_{1} = P / k_s \]

The wheel wear \( d_{w0}(z) \) at an arbitrary point of the axial coordinate \( z \) is described in equation (3) [3].

\[ d_{w0}(z) = K_r S_s(z) / G \]  

Equation (3) \[ d_{w0}(z) = K_r S_s(z) / G \]

Where \( K_r \) is a radius ratio between a wheel and a workpiece, \( S_s(z) \) stock removal, and \( G \) grinding ratio. From equation (3), the wheel wear \( d_{w} \) after grinding is calculated by the following equation.

\[ d_{w} = d_{w0} + K_r (d_{d0} - d_{r}) / G \]  

Equation (4) \[ d_{w} = d_{w0} + K_r (d_{d0} - d_{r}) / G \]

In the above, \( d_{w0} \) is the shape error of the grinding wheel measured before grinding. \( d_{d0} \) and \( d_{r} \) are shape errors measured before and after grinding, respectively. In equation (4), the shape error caused by the difference of wheel wear at \( z = 0 \) mm (front end of the wheel) and \( z = 50 \) mm (rear end of the wheel) is proportional to the distance of shape error measured before and after grinding. This means that the shape error caused by the wheel wear becomes larger as the difference of the shape error increases before and after grinding because the difference of stock removal changed remarkably at each positions of axial coordinate. From equations (1), (2) and (4), \( d_{r} \) obtained after grinding is expressed in the following equation.

\[ d_{r} = P / k_s + d_{w0} + K_r (d_{d0} - d_{r}) / G - e_{s} \]  

Equation (5) \[ d_{r} = P / k_s + d_{w0} + K_r (d_{d0} - d_{r}) / G - e_{s} \]

In the above, \( d_{r} \) is put to be zero because the purpose of this study is to minimize the shape error of the workpiece.

\[ 0 = P / k_s + d_{w0} + K_r d_{d0} / G - e_{s} \]  

Equation (6) \[ 0 = P / k_s + d_{w0} + K_r d_{d0} / G - e_{s} \]

From the above equation, at the moment when the shape error is minimized the normal grinding force \( P \) is given by the following equation.

\[ P = k_s (- d_{w0} - K_r d_{d0} / G + e_{s}) \]  

Equation (7) \[ P = k_s (- d_{w0} - K_r d_{d0} / G + e_{s}) \]

By use of equation (7), the optimized grinding force is calculated from the shape error of the workpiece \( d_{d0} \) and that of grinding wheel \( d_{w0} \) measured before grinding.
Grinding experiment to verify the proposed method

Table 1 shows the main grinding conditions in the present experiment. Fig.5 shows the positional relation between the workpiece and grinding wheel. On-machine measurement of the workpiece was performed to estimate the internal shape of the ground workpiece. The shape of the grinding wheel was also measured by copying the wheel shape to the acrylic plate.

Fig.6 shows the measured shape error of the workpiece and grinding wheel before grinding, and that, shape errors are determined as follows: \( d_{w0} = -0.2 \mu m \), \( d_{r0} = -3.8 \mu m \). The radius of ground hole at \( z = 0 \)mm is larger than that measured at \( z = 50 \)mm. The reason of this difference was caused by the wheel run-out. The effect of the wheel run-out increases as the spark-out duration becomes longer, while the effect of elastic deformation of the wheel decreases. The optimized normal grinding force \( P \) was calculated using these measured results. Values assigned in equation (7) are as follows: \( k_s = 4.59 \text{N/}\mu \text{m} \), \( K_r = 1.3 \), \( G = 65 \), \( e_s = 3.0 \mu \text{m}[^3] \). The optimized normal grinding force \( P \) was determined as 15N from equation (7). Based on the calculated result, the grinding machine was controlled to retract the wheel when the normal grinding force was reduced to 15N during the spark-out process.

![Fig.5 Positional relation of workpiece and wheel](image)

![Fig.6 Shape error measured before grinding](image)

Fig.7 shows the measured grinding force during the grinding process, where the wheel was retracted when the normal grinding force reduced to 20N that was close to the target value 15N. Fig.8 shows the shape error of the workpiece measured after grinding. The shape error was reduced close to 2\( \mu \text{m} \) at the front end of grinding wheel. Fig.9 gives the measured and simulated results of wheel shape. The wheel shape obtained by the simulations before grinding with considering wheel wear was in good agreement with measured result. From these results, it was found that the shape error of the workpiece could be reduced by the proposed estimation method for optimized normal grinding force.
Summary

In this study, a new estimation method of optimized normal grinding force was proposed to improve the shape accuracy in internal grinding by slender grinding wheel. Main conclusions obtained in this study are as follows:

(1) Calculation method of optimized normal grinding force was proposed. During the grinding process, it is expected that the shape error was minimized if the wheel is retracted at the moment when the normal grinding force is reached to optimized normal grinding force.

(2) The shape error of the ground workpiece was reduced with controlling the grinding machine by proposed method.

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References

