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Optimization of grinding conditions for small diameter hole to achieve higher performance of linear solenoid

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Abstract
On deep cylindrical inner surface with a small diameter, diameter of the grinding wheel and tool shaft are restricted by the inner diameter. Larger grinding wheel diameter leads to longer contact arc length between the grinding wheel and workpiece, then it brings higher grinding force and causes the deflection of tool shaft and grinding burn or clogging of the grinding wheel. In order to solve these problems, a new grinding wheel was developed, which was capable of supplying grinding fluid from the inner side of the grinding wheel. Vitrified bonded Cubic Boron Nitride (CBN) grinding wheel with grain size of #60 was used. The grade of the grinding wheel was "N", which means the moderate hardness of the bond. So it is rather porous comparing with conventional CBN grinding wheels. Workpiece material was electromagnetic soft iron (SUY1) used for a linear solenoid of AT transmission. As the grinding wheel diameter became large, contact arc length and grinding force became larger. On the contrary, when the grinding wheel diameter became small, grinding force became smaller. But the tool shaft diameter should be smaller than the grinding wheel diameter, which leads to lower stiffness and poor machining accuracy. Then the simulation was developed to estimate the inner diameter error based on the size of the grinding wheel diameter and the shaft diameter. The simulation showed that there was a point where the deflection of the shaft is minimized under the restriction of constant difference between the wheel diameter and the shaft diameter. From the grinding experiment, it was shown that the error of inner diameter was improved by 2.5 µm when the wheel diameter was changed from 9.3 mm to 8.3 mm. The error was also improved by 5.5 µm when the shaft diameter was changed from 7.0 mm to 8.0 mm.

Key Words: grinding, deflection, grinding wheel, tool shaft, deep and small inner surface

1. Introduction

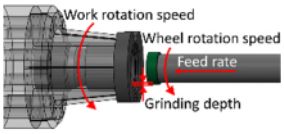
As the performance of linear solenoid valve for AT transmission is directly related to the fuel consumption of the automobile, high accuracy is required on its manufacturing process. The linear solenoid valve has a deep cylindrical inner surface with a small diameter, and it is generally finished by grinding. However, non-uniformity of the inner surface of the cylinder due to the deflection of the tool shaft and grinding burn or clogging of the grinding wheel is a big problem.

Recommended dressing conditions for grinding the cylindrical inner surface with the small vitrified grinding wheels was described by Daneshi et al. [1]. They showed that a finer workpiece surface was achieved when dressed by up-dressing compared to the case of down-dressing. Pereverzev et al. showed the model of cutting force while managing two regime parameter in the process of internal grinding and this model allows calculating the changes of the grinding force depending on variable values of infeeds [2]. Biermann et al. showed the process simulation with the general thermos-mechanical process characteristics and developed compensation strategies to minimise the dimensional error of the resulting workpiece inner cylindrical shape after grinding [3].

In the grinding of the deep cylindrical inner surface with a small diameter, the diameter of the wheel and the tool shaft are limited by the diameter of the hole. In this paper, we developed a simulation that is able to predict the grinding force depending on the grinding conditions and the amount of shaft deflection depending on tool shaft diameter and the grinding wheel diameter. Then in the experiments, the conditions of the wheel diameter and the shaft diameter to reduce the deflection of the tool shaft was clarified.

2. Experimental method

Generally, on the inner surface grinding, a plunge grinding with feeding a wheel vertical to the workpiece surface or a traverse grinding with feeding a wheel in the axial direction of the workpiece is adopted. In this experiment, traverse grinding was employed because better surface roughness can be obtained. Figure 1 (a) and (b) shows the diagram of experimental device. Grinding was done by down cutting, and the tool feeding direction is z direction. After the preliminary machining with a reamer to the inner diameter *d* of 10.07mm, finish grinding was performed with the grinding depth *t* 2.5 × 10^{-3} mm × 4 passes and 1.0 × 10^{-3} mm × 1 pass. The target inner diameter *d* was 10.092mm, which is based on the actual product.



(a) Schematic diagram (b) Experimental set up
Figure 1 Diagram of experimental device

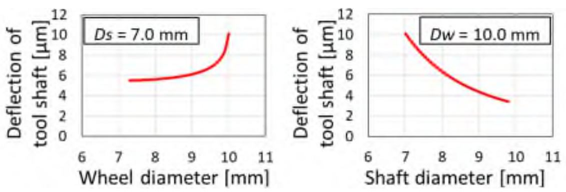
Wheel rotation speed S_t and workpiece rotation speed S_w were 40000 min^{-1} and 1500 min^{-1} respectively, and feed rate *f* was 100 mm/min. Workpiece material was electromagnetic soft iron (SUY1) which is used for linear solenoid of AT transmission. A vitrified bonded CBN grinding wheel was used and its grade was N, which is rather porous compared to the conventional CBN wheels. The grain mesh size was #60 and wheel width *w* was 1.5 mm. Experiments were conducted with wheel diameter *Dw* [mm] and tool shaft diameter *Ds* [mm]. Grinding fluid was supplied from three ways, the inner side of the grinding wheel, the outer nozzle and the exit side of the workpiece from the chucking system.

3. Prediction on tool shaft deflection affected by wheel diameter and shaft diameter

A prediction procedure on the grinding force and the amount of the shaft deflection depending on the wheel diameter and tool shaft diameter was developed. The radial grinding force can be estimated from the following equation (1) [4]. The symbol k and ε are constants obtained from experiment, F [N] is grinding force, v [mm/min] and V [mm/min] are circumferential speed of the workpiece inner surface and the grinding wheel respectively.

$$F = k\frac{f}{S_t}\left(\frac{v}{V}\right)^{1-\varepsilon} t^{1-\frac{\varepsilon}{2}}\left(\frac{1}{Dw}-\frac{1}{d}\right)^{-\frac{\varepsilon}{2}} \qquad (1)$$

In this paper, it is assumed that $k = 2.0\times10^6$ and $\varepsilon = 0.4$ for mild steel which is close to the target material of SUY1 [4]. The amount of tool shaft deflection was simulated on the spread sheet software based on the numerical model on the bending deflection of column beam. Figure 2 (a) shows the deflection of tool shaft when the wheel diameter is changed from 7.3 mm to 10.0 mm keeping the shaft diameter as 7.0 mm. On the other hand, figure 2 (b) shows the deflection of tool shaft when the shaft diameter is changed from 7.0 mm to 9.7 mm keeping the wheel diameter as 10.0 mm. As the shaft diameter becomes smaller, the deflection becomes larger. When the wheel diameter becomes large, although the cutting speed increases, the contact arc length increases and the grinding force becomes large. On inner grinding, the relationship between the wheel diameter and the shaft diameter is important to reduce the machining error.



(a) Change in wheel diameter (b) Change in shaft diameter

Figure 2 Prediction of tool shaft deflection

Figure 3 shows the deflection of the shaft when the wheel diameter is changed from 7.3 mm to 10.0 mm, while the difference between the wheel diameter and the shaft diameter is kept constant 0.3 mm. It can be seen that there is a point where the amount of deflection becomes a minimum. It is very important to determine this point to improve accuracy of inner surface.

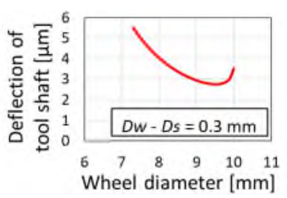
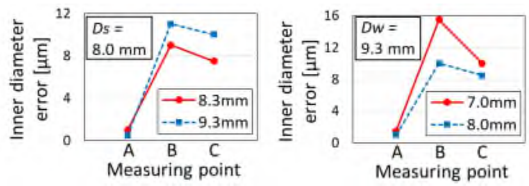


Figure 3 Prediction of tool shaft deflection considering shaft diameter and wheel diameter

4. Experiment on the effect of wheel diameter and shaft diameter on grinding error

After grinding, the inner diameter of the workpiece was measured and compared for each grinding condition. The point 2mm from the entry of hole is defined as A, the point 2mm from the end of hole is defined as C and the middle of A and C is defined as B.

Experiments were carried out while changing the wheel diameter and the shaft diameter. Figure 4 (a) shows the error from the target value of the inner diameter when the shaft diameter *Ds* was 7.0 mm and the wheel diameter *Dw* was set 8.3 mm and 9.3 mm. When the wheel diameter *Dw* was 8.3 mm, the error was improved by 2 µm at point B and 2.5µm at point C. Figure 4 (b) shows the error from the target value of the inner diameter when the wheel diameter *Dw* was 9.3mm and the shaft diameter *Ds* was set 7.0 mm and 8.0 mm. When the shaft diameter was 8.0 mm, the error was improved by 5.5 µm at point B and 1.5 µm at point C. These results show that the same tendency as the result shown in figure 2(a) and (b).



(a) Effect of wheel diameter (b) Effect of shaft diameter

Figure 4 Inner diameter error affected by wheel diameter and shaft diameter

Figure 5 shows the comparison of inner diameter error for each wheel width. When the wheel width was 1.5 mm, the inner diameter increased 3.5 µm at point B and 2.0 µm at point C. The traverse grinding seems to have no relation with width of wheel because grinding is performed at the corner of the wheel, however, it is thought that the contact area increases when wheel width is wide because the tool shaft is deflected.

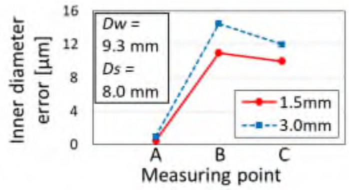


Figure 5 Effect of wheel width on inner diameter error

5. Conclusions

In this paper, it was shown that the wheel diameter and the shaft diameter are large error factors.

1) The developed simulation showed that there was a point where the deflection of the shaft is minimized under the restriction of constant difference between the wheel diameter and the shaft diameter.
2) Error of inner diameter was improved by 2.5 µm when the shaft diameter was changed from 8.3 mm to 9.3 mm. The error was also improved by 5.5 µm when the wheel diameter was changed from 7.0 mm to 8.0 mm.
3) In traverse grinding, it was shown that the width of the wheel affects the tool shaft deflection and hole diameter error.

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