Improvement of form accuracy in cylindrical traverse grinding with steady rest by controlling traverse speed

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Received: 29 November 2020; Revised: 5 March 2021; Accepted: 28 May 2021

Abstract

In cylindrical traverse grinding, a slender workpiece is bent by the normal grinding force due to its low stiffness. Consequently, a form error is generated by the elastic deformation of the workpiece during the grinding process. To prevent such deformation of the workpiece, a steady rest is generally used. However, when the contact point between the workpiece and the steady rest is ground, the pushing force of the steady rest is lost, and the elastic deformation of the workpiece is increased immediately. As a result, a step shape error is generated at the contact point. To improve the use of the steady rest, the elastic deformation of the workpiece during the grinding process is simulated using the beam model considering the steady rest in this study. From the analysis results, it was determined that placing the steady rest outside the grinding part can reduce the elastic deformation of the workpiece. In addition, the traverse speed was controlled to maintain a constant elastic deformation. Through grinding experiments, it was confirmed that the form accuracy of the slender workpiece was improved by setting the steady rest outside the grinding part and adjusting the traverse speed.

Keywords : Traverse grinding, Slender workpiece, Steady rest, Normal grinding force, Beam model

1. Introduction

In cylindrical traverse grinding, the normal grinding force is larger than the tangential grinding force (Nakajima et al., 1978, Park et al., 1999). A slender workpiece is bent by the normal grinding force during the grinding process as shown in Fig.1(a). Consequently, a form error is generated owing to the elastic deformation (Okamura et al., 1980). At the middle of the workpiece, the radial stock removal decreases with the increase in the elastic deformation of the workpiece (Gao and Foster, 1991). The change in elastic deformation causes the form error as shown in Fig. 1(b).

Fig. 1 (a) Elastic deformation of a slender workpiece during grinding and (b) form error of the ground workpiece. The slender workpiece is bent by the normal grinding force and the elastic deformation of the workpiece generates the form error.

To prevent the form error, a steady rest is used in cylindrical traverse grinding of a slender workpiece (Kounosu, 1984, Swic and Taranenko, 2015). Figure 2 shows the steady rest mounted on the cylindrical grinding machine used in this study. The slender workpiece is supported by both centers, and the steady rest pushes the surface of the workpiece to be grinded. Figure 3 shows the measured form of the ground workpiece when the steady rest is used to exert a pushing force at the central point of the grinding part. As shown in this figure, a stepped shape was observed at the contact point between the steady rest and the workpiece. Figure 4 illustrates the mechanism by which the stepped shape is generated. The gap between the workpiece and the steady rest, caused by material removal, increases the elastic deformation of the workpiece, resulting in excessive residual stock removal. The increased residual stock removal leads to the stepped shape of the workpiece. To remove the associated step shape error, additional traverse grinding with lower depth of cut is required.

The purpose of this study is to develop a grinding process that does not generate the step shape error during a traverse grinding operation. In this study, we propose a new beam model to represent the slender workpiece with the steady rest. Using this model, simulation analysis of the form error of the workpiece is performed. In addition, a new method of using the steady rest is proposed, to prevent the generation of the stepped shape. In this method, the contact point between the steady rest and the workpiece is changed from the ground part to outside the ground part, as shown in Fig. 5. The effect of the position of the steady rest is evaluated through simulation analysis and grinding experiments. Furthermore, the traverse speed of the workpiece is adjusted during the grinding process to reduce the elastic deformation of the workpiece, as shown in Fig. 5. The traverse speed is determined based on the proposed beam model.

Fig. 2 Steady rest, mounted on the grinding machine, pushes the workpiece to prevent the elastic deformation caused by the normal grinding force. Strain gauges, mounted on both the centers, measure the normal grinding force during the grinding process.

Fig. 3 Stepped shape observed at the contact point of the steady rest and the workpiece. The red dashed line indicates the contact point. Each colored line represents the profile measured at every 90° on the ground surface, shown in the inset figure.

Fig. 4 Mechanism by which the stepped shape is generated: The gap between the workpiece and a steady rest caused by material removal generates the stepped shape.

Fig. 5 Proposed method of using the steady rest along with controlling the traverse speed: The steady rest pushes the workpiece at a point outside the grinding part and the traverse speed is controlled to maintain the elastic deformation of the workpiece constant.

2. Experimental setup and grinding conditions

Figure 6 shows the schematic of the slender workpiece used in this study. The material of the workpiece is S45C, and its aspect ratio is approximately 15. The central part with a length of 120 mm is the grinding part of the workpiece. As shown in Fig.7, the contact point of the steady rest and the central position of the grinding wheel were defined as Z_s and Z_g respectively.

Table 1 lists the main grinding conditions for the experiments. In this study, only one traverse grinding pass was performed, as shown in Fig.7. In addition, the traverse speed V_f was controlled to maintain a constant elastic deformation of the workpiece during the grinding process. To prevent the stepped shape, the steady rest was set to push the workpiece in an area that was not ground. The contact point of the steady rest Z_s was set to 220 mm.

Fig. 6 Schematic of the slender workpiece with the steady rest. The thicker central area of the workpiece is the grinding part. The contact point of the steady rest is defined as Z_s .

Fig. 7 Relative motion of the grinding wheel with respect to the workpiece. The depth of cut was applied at a point outside the grinding part for one traverse grinding pass.

Table 1 Main grinding conditions for the experiments.

Grinding machine	GE-4P CNC machine (JTEKT)
Grinding wheel	WA80H8VSK-1 ϕ 390 x 50 mm Peripheral speed $V_s = 24.6$ m/s
Workpiece	S45C ϕ 20 x L 300 mm Peripheral speed $V_w = 9.0 \times 10^{-2}$ m/s Grinding part $90 < Z < 210$ mm
Machine motion	Traverse speed $V_f = 2, 8, 14$ mm/s Depth of cut $\Delta = 5 \mu\text{m} \times 1$ pass
Grinding fluid	Soluble type, Flow rate $Q = 20$ ℓ/min
Steady rest	Pushing depth $1 \mu\text{m}$ $Z_s = 220$ mm

3. Simulation of elastic deformation of workpiece using beam model

3.1 Beam model without steady rest

Figure 8 shows the beam model of the slender workpiece without the steady rest. The workpiece was supported by the centers at both ends. Using this model, the elastic deformation of the workpiece during grinding was calculated. The calculated elastic deformation agreed well with the measured form error after the grinding process (Onishi et al., 2014a). The Young's modulus E of the solid cylindrical workpiece is 206 GPa. The diameters of the beams are denoted by d_1 , d_2 and d_3 and are equal to 16 mm, 20 mm, and 16 mm, respectively. The second moment of area I_i in each area was calculated using Equation (1).

$$I_i = \frac{\pi d_i^4}{64} \quad (i = 1, 2, 3) \quad (1)$$

L , L_1 and L_2 are the lengths of the workpiece parts and are equal to 300 mm, 90 mm, 210 mm, respectively, as shown in Fig.6. A normal grinding force was applied to the workpiece at the center of the grinding wheel Z_g (Sakamoto et al., 2018).

Fig. 8 Beam model of the workpiece without the steady rest. The workpiece is supported at both ends (Onishi et al., 2014a).

Figure 9 shows the measured normal grinding force during grinding. The normal grinding force was measured using strain gauges mounted on both centers, as shown in Fig. 2. The elastic deformation of the ground workpiece was calculated by assigning the same amount of normal grinding force in the beam model. Figure 10 shows the measured profile and the calculated elastic deformation. From this figure, it was confirmed that the main cause of the form error was the elastic deformation of the workpiece. Significant over-grinding was observed toward the right end of the grinding part.

Fig. 9 Normal grinding force measured by strain gauges located at both centers during grinding without the steady rest.

Fig. 10 Measured profile of the ground workpiece (green line) and elastic deformation of the workpiece (red dashes line) estimated through simulating the grinding process using the beam model.

Figure 11 shows the mechanism by which over-grinding occurs at the end of the grinding part (Onishi et al., 2014b). When the material at the end of the grinding part was removed, the normal grinding force decreased as the grinding width became narrower. Consequently, elastic recovery of the workpiece occurs, resulting in over-grinding at the end of the grinding part (Okamura et al., 1983). To suppress this, it is necessary to move the grinding wheel away from the grinding part quickly.

Fig. 11 Over-grinding occurring at the end of the workpiece. The over-grinding is the result of elastic recovery of the workpiece due to the decrease of the normal grinding force.

3.2 Beam model with steady rest

3.2.1 Case of steady rest placed at grinding part

As mentioned before, the elastic deformation of the workpiece during the grinding process was simulated using the beam model without a steady rest in our previous study (Onishi et al., 2014a). In this study, a new beam model that considers the effect of steady rest is proposed. Figure 12 shows the workpiece and the steady rest mounted on the cylindrical grinding machine. The steady rest pushes the workpiece at the central point of the grinding part.

Fig. 12 Workpiece and the steady rest mounted on the grinding machine. The steady rest pushes the workpiece at the central point of the grinding part.

Fig. 13 Beam model of the ground workpiece with steady rest. The steady rest supports the workpiece at the center of the grinding part.

Figure 13 shows the beam model of the slender workpiece with steady rest. The workpiece was supported by both centers at the ends of the workpiece and by the steady rest at the grinding part. The central part of the workpiece ($90 \text{ mm} < Z < 210 \text{ mm}$) is ground. We formulated the differential Equation (2) – (6) based on the beam model. These equations hold under the conditions when the grinding wheel is located at the right side of the steady rest ($Z_g < Z_s$).

Fig. 14 Results of stiffness measurement of the steady rest (brown round markers) and the workpiece (gray square markers).

Elastic deformations were measured using an electric micrometer when a load was applied to the objects under study. Figure 14 shows the stiffness of the steady rest and the workpiece. the stiffness values were $41.5 \text{ N}/\mu\text{m}$ and $1.88 \text{ N}/\mu\text{m}$ respectively. Therefore, the rigidity of the steady rest was determined to be sufficiently large compared to that of the workpiece at the fixed point.

We formulated the differential Equations (2) – (6) based on Fig. 13. I_1 , I_2 , and I_3 are the second moments of the three areas of the workpiece.

In $0 \leq Z \leq L_1$

$$EI_1 \frac{d^2y}{dZ^2} = -R_A Z \quad (2)$$

In $L_1 \leq Z \leq Z_g$

$$EI_2 \frac{d^2y}{dZ^2} = -R_A Z \quad (3)$$

In $Z_g \leq Z \leq Z_s$

$$EI_2 \frac{d^2y}{dZ^2} = -R_A Z + P(Z - Z_g) \quad (4)$$

In $Z_s \leq Z \leq L_2$

$$EI_2 \frac{d^2y}{dZ^2} = -R_A Z + P(Z - Z_g) - R_s(Z - Z_s) \quad (5)$$

In $L_2 \leq Z \leq L$

$$EI_3 \frac{d^2y}{dZ^2} = -R_A Z + P(Z - Z_g) - R_s(Z - Z_s) \quad (6)$$

The boundary conditions are given as follows:

$$y = 0 \text{ at } Z = 0 \text{ (Left center)} \quad (7)$$

$$y = 0 \text{ at } Z = Z_s \text{ (Steady rest)} \quad (8)$$

$$y = 0 \text{ at } Z = L \text{ (Right center)} \quad (9)$$

$$\text{In Equation(2),(3), } dy/dZ \text{ and } y \text{ are continuous at } Z = L_1 \quad (10)$$

$$\text{In Equation(3),(4), } dy/dZ \text{ and } y \text{ are continuous at } Z = Z_g \quad (11)$$

$$\text{In Equation(4),(5), } dy/dZ \text{ and } y \text{ are continuous at } Z = Z_s \quad (12)$$

$$\text{In Equation(5),(6), } dy/dZ \text{ and } y \text{ are continuous at } Z = L_2 \quad (13)$$

The elastic deformation of the workpiece was calculated from these differential equations and the boundary conditions. The elastic deformation of the workpiece at the grinding point with the steady rest δ was calculated by inserting $Z = Z_g$ in Equation (3).

The normal grinding force P was measured using strain gauges fixed at both centers (Kodani et al., 2013). Figure 15 shows the measured profiles of the workpiece before and after grinding. In this figure, the profile of the non-ground part was defined as the reference plane. By comparing the heights of the profiles in the radial direction, measured before and after grinding, the stock removal could be calculated. From these results, it was found that the stock removal generated was between 8 and 13 μm . As the pushing depth of the steady rest was 3 μm , the measured stock removal was large enough to cause a gap between the workpiece and the steady rest. The profile height at the right side of the steady rest increased because the elastic deformation of the ground workpiece increased owing to the generated gap.

Fig. 15 Measured profiles of the workpiece before grinding (green broken line) and after grinding (green line). The distance between the two lines gives the residual stock removal of the workpiece during the grinding process.

Fig. 16 Bending moment diagrams calculated using the beam model during grinding process. The normal grinding forces applied to each grinding point were based on the measured values shown in Fig. 9. The bending moment in (a) was calculated using Equations (2) – (6), while in (b) and (c), it was calculated based on Fig. 9 as the workpiece was no longer supported by the steady rest.

Figure 16 shows the bending moment diagrams (BMDs) calculated using the beam model with the steady rest mounted at $Z = 150$ mm. The bending moment is negative at the left end of the grinding part owing to the reaction force from the steady rest. After the grinding point passed the point where the steady rest was mounted, the workpiece lost the support of the steady rest because of the gap generated between the workpiece and the steady rest. This is reflected by the non-negative bending moment values observed when the grinding wheel passed the point $Z_g = 150$ mm. From this result, the elastic deformation of the workpiece was found to be large at the right side of the part close to the center of the workpiece.

Figure 17 shows the measured normal grinding force during grinding. The measured force is the total of the forces applied to both centers. Therefore, the normal grinding force applied to the steady rest increased as the grinding point Z_g was close to the contact point of the workpiece and the steady rest. After the grinding wheel passes the contact point, the normal grinding force increases because a gap is generated between the workpiece and the steady rest. Owing to this gap, the pushing force of the steady rest was lost, and the steady rest could not support the workpiece. Consequently, a step shape was generated owing to the rapid increase in the elastic deformation of the workpiece at the contact point. In this study, it was impossible to directly measure the normal grinding force applied to the steady rest. The change in the normal force applied to the center was estimated through simulation analysis using the beam model. The measured normal grinding force shown in Fig. 9 was plugged into Equation (3) to estimate the elastic deformation of the workpiece during the grinding process. The contact point of the steady rest Z_s was 150 mm. Before the grinding wheel passed the contact point ($Z_g < 150$ mm), the elastic deformation of the workpiece was estimated using Equations (3). After the grinding wheel passed the point ($Z_g > 150$ mm), the elastic deformation of the workpiece was estimated based on a previous study (Onishi et al., 2014a) as shown in Fig. 6, because the workpiece was no longer supported by the steady rest.

Fig. 17 Normal grinding force during grinding process with steady rest. The normal grinding force applied to both centers rapidly changed when the contact point was ground.

Fig. 18 Measured profile of ground workpiece and estimated elastic deformation. The change in elastic deformation occurring at contact point of steady rest agreed well with the measured profile.

Figure 18 shows the estimated elastic deformation and the measured profile of the ground workpiece. The elastic deformation was calculated using Equation (3). Using the beam model, the form error and the step shape error of the ground workpiece were simulated successfully.

3.2.2 Case of steady rest placed outside grinding part

Figure 19 shows the workpiece and the steady rest mounted on the grinding machine. The steady rest pushes the workpiece at a point outside the grinding part. The gap between the steady rest and the workpiece is not generated during the grinding process. This is expected to prevent the generation of the stepped shape.

Figure 20 illustrates the beam model of the workpiece representing the above-mentioned method.

Fig. 19 Workpiece pushed by the steady rest at a point outside of the grinding part to suppress the stepped shape.

Fig. 20 Beam model of the ground workpiece with the steady rest supporting the workpiece at a point outside the grinding part.

We formulated differential Equations (7) – (11) based on the beam model.

In $0 \leq Z \leq L_1$

$$EI_1 \frac{d^2y}{dZ^2} = -R_A Z \quad (14)$$

In $L_1 \leq Z \leq Z_g$

$$EI_2 \frac{d^2y}{dZ^2} = -R_A Z \quad (15)$$

In $Z_g \leq Z \leq L_2$

$$EI_2 \frac{d^2y}{dZ^2} = -R_A Z + P(Z - Z_g) \quad (16)$$

In $L_2 \leq Z \leq Z_s$

$$EI_3 \frac{d^2y}{dZ^2} = -R_A Z + P(Z - Z_g) \quad (17)$$

In $Z_s \leq Z \leq L$

$$EI_3 \frac{d^2y}{dZ^2} = -R_A Z + P(Z - Z_g) - R_s(Z - Z_s) \quad (18)$$

The boundary conditions are given as follows:

$$y = 0 \text{ at } Z = 0 \text{ (Left center)} \quad (19)$$

$$y = 0 \text{ at } Z = Z_s \text{ (Steady rest)} \quad (20)$$

$$y = 0 \text{ at } Z = L \text{ (Right center)} \quad (21)$$

$$\text{In Equation(14),(15), } dy/dZ \text{ and } y \text{ are continuous at } Z = L_1 \quad (22)$$

$$\text{In Equation(15),(16), } dy/dZ \text{ and } y \text{ are continuous at } Z = Z_g \quad (23)$$

$$\text{In Equation(16),(17), } dy/dZ \text{ and } y \text{ are continuous at } Z = L_2 \quad (24)$$

$$\text{In Equation(17),(18), } dy/dZ \text{ and } y \text{ are continuous at } Z = Z_s \quad (25)$$

The elastic deformation of the workpiece was calculated from these differential equations and the boundary conditions. The elastic deformation of the workpiece at the grinding point with the steady rest δ was calculated by inserting $Z = Z_g$ in Equation (15).

Fig. 21 Bending moment diagrams calculated using the beam model during grinding process. The normal grinding force applied to each grinding point were based on the measured values shown in Fig. 9. The bending moment was calculated using Equations (14) - (18).

Figure 21 shows the calculated BMD. The value of the bending moment in the grinding part was lower compared to the calculated results shown in Fig.16. Therefore, it is expected that the elastic deformation of the workpiece can be reduced by mounting the steady rest at a point nearest to but outside the grinding part.

Figure 22 shows that the normal grinding force did not undergo rapid change because the steady rest was located outside the grinding part.

Fig. 22 Normal grinding force measured during the grinding process. As the steady rest was mounted outside the grinding part ($Z = 220$ mm), the normal grinding force applied to both centers did not change rapidly.

Fig. 23 Comparison of displacements of workpiece obtained from simulation considering different steady rest conditions: (a) without steady rest (gray line), (b) with steady rest at $Z_s = 150$ mm, and (c) with steady rest at $Z_s = 220$ mm. The normal grinding force applied at each grinding point was based on the measured values shown in Fig. 10. The displacement of the workpiece due to the elastic deformation decreased by using the steady rest. In (b), after the wheel passed the contact point between the workpiece and the steady rest ($150 \leq Z_g$), the workpiece is not supported by the steady rest.

Figure 23 shows the calculated elastic deformations of the ground workpiece with and without the steady rest. The displacement of the workpiece was calculated using beam models, as mentioned before. The displacement of the workpiece, supported at both ends by centers ($Z = 0, 300 \text{ mm}$), was $0 \text{ }\mu\text{m}$. The ground part was located between $Z = 90 \text{ mm}$ and 210 mm . When using the steady rest, the axial position of the contact point Z_s was 150 mm or 220 mm . In this calculation, the measured normal grinding force shown in Fig. 9 was applied to the beam model. From these results, it was confirmed that the elastic deformation of the workpiece could be decreased significantly using a steady rest. Further, it was expected that the step shape would not be generated if the steady rest was located outside the grinding part, even with the reduced elastic deformation.

Fig. 24 Comparison of elastic deformations of workpiece obtained from simulation. The blue and gray lines show the elastic deformation of the workpiece with and without the steady rest, respectively.

Figure 24 shows the comparison of elastic deformations of the grinding part. In this figure, the elastic deformation generated at $Z = 90 \text{ mm}$ is defined as 0. The elastic deformation of the grinding part during the grinding process was decreased using the steady rest.

Figure 25 shows the measured profile of the ground workpiece and the estimated elastic deformation using the beam model. By using the beam model, the elastic deformation and the form error of the ground workpiece were recorded and simulated successfully.

Fig. 25 Measured profile of ground workpiece (green line) and estimated elastic deformation of the workpiece (red dashed line) simulated using the beam model.

4. Grinding experiments

4.1 Improvement of form accuracy by controlling traverse speed

Figure 26 shows the normal grinding force required to maintain a constant elastic deformation of the workpiece during grinding. At the right part of the workpiece, a larger normal grinding force is required because the steady rest is located at a point close to the right end. In our previous study (Takashima et al., 2016), it was confirmed that the normal grinding force P was proportional to the traverse speed V_f , as shown in Equation (26).

$$P = 0.950 V_f + 0.205 \quad (26)$$

The relationship between the traverse speed V_f and the normal grinding force P can also be expressed as shown in Equation (27).

$$V_f = 1.05P - 0.216 \quad (27)$$

Fig. 26 Normal grinding force (red line) required to maintain a constant elastic deformation (blue line).

Figure 27 shows the calculated traverse speed required to maintain the elastic deformation constant. The traverse speed V_f was determined using Equation (27). The grinding machine used in this study could not change the traverse speed continuously. Therefore, the traverse speed was changed in stages, as shown in Fig. 26 (Onishi et al., 2019).

Fig. 27 Traverse speed required to maintain a constant elastic deformation. The red line shows the traverse speed that was calculated using the beam model and the green line shows the actual traverse speed in the grinding experiment.

4.2 Result of experiments

Figure 28 shows the measured profiles of the ground workpiece. The form error of the ground workpiece was decreased by changing the position of the steady rest and controlling the traverse speed. Over-grinding was not observed at the end of the grinding part. Figure 29 shows the comparison of the measured profiles. In this figure, the profiles are averaged values from four profiles measured at every 90°. In our previous study (Onishi et al., 2019), the profile of the workpiece ground without a steady rest had a large form error in the middle of the grinding part. The form error was successfully reduced using the grinding method proposed in this study.

Fig. 28 Measured profiles of the ground workpiece. The stepped shape and the over-grinding were not observed using the proposed grinding method.

Fig. 29 Comparison of profiles of the workpiece ground using conventional method without steady rest (black line) and using the proposed method (red line). The form accuracy is improved using the proposed method.

Conclusions

In this study, with the aim of decreasing the form error of the slender workpiece in cylindrical traverse grinding, a new method was proposed, which involved setting the steady rest outside the grinding part and adjusting the traverse speed. The main conclusions of this study are as follows:

- 1) The elastic deformation of the slender workpiece during the grinding process with a steady rest was simulated using the beam model.
- 2) The cause of the generation of the step shape at the contact point of the steady rest can be determined using the beam model. The simulation results confirmed that the step shape was generated by the gap between the workpiece and the steady rest owing to material removal of the workpiece at the contact point.
- 3) The form error of the ground workpiece was successfully decreased by setting the steady rest outside the grinding part and by controlling the traverse speed.

Acknowledgement

We wish to thank Mr. Ryohei Mukai in Mitsui Seiki Kogyo Co., Ltd. for his kind assistance in providing the steady rest used in this study. This study was supported by JSPS KAKENHI (Grant Number 20K04194).

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