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Minimization of Hydrodynamic Pressure Effect on the Ultraprecision Mirror Grinding

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ABSTRACT

This paper describes an investigation about the fluid delivering method that minimizes the generation of hydrodynamic pressure and improves the grinding accuracy. Traditionally, grinding fluid is delivered for the purpose of cooling, chip flushing and lubrication. Hence, a number of conventional investigations are focused on the delivering method to maximize fluid flux into the contact arc between the grinding wheel and the work piece. It is already known that hydrodynamic pressure generates due to this fluid flux, and that it affects the overall grinding resistance and machining accuracy. Especially in the ultra-precision mirror grinding process that requires extremely small amount of cut per pass, its influence on the machining accuracy becomes more significant. Therefore, in this paper, a new delivering method of grinding fluid is proposed with focus on minimizing the hydrodynamic pressure effect. Experimental data indicates that the proposed method is effective not only to minimize the hydrodynamic pressure but also to improve the machining accuracy.

Key words: Ultraprecision grinding, hydrodynamic pressure, resin-bonded wheel, ductile regime grinding, grinding accuracy

Nomenclature

u, v speed in x, y direction
μ fluid viscosity
U wheel speed
Q_x , Q_y volumetric flow rate per unit width in x , y direction
P fluid pressure
$h(x)$ clearance between wheel and work piece along the work distance
h_0 minimum clearance
R wheel radius

1. Introduction

Recently, with the development of information technology, optoelectronic or mechanophotonic devices that are able to transmit a very large number of image data are increasingly needed. Grinding process seems to be most effective method to fulfill those increasing needs for direct machining of the small sized ultra-precision optical parts. In the mirror grinding process of optical material, generally, extremely small depth of cut less than one micrometer should be provided to achieve a ductile regime machining.

Traditionally, in the grinding process, grinding fluid is delivered for the purposes of chip flushing, cooling, lubrication and chemical protection of the work surface[1]. Hence, a number of conventional investigations have been mainly focused on the fluid delivering methods that make large flux into the grinding zone in order to overcome the boundary layer effect of air[1]. However, due to the wedge-effect between the wheel and the work surface, hydrodynamic pressure is generated considerably even in the actual grain cutting process, which affects the actual depth of cut and also the

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grinding resistance increases. Especially, in the mirror grinding process using extremely fine grit resin bonded wheel, the influence of this dynamic pressure on the form accuracy becomes more significant. Some notable and interesting investigations have been presented on the viewpoint of hydrodynamic pressure generating mechanism and measurement in the grinding process. Kuriyagawa[2] pointed out that hydrodynamic pressure-induced resistance is remarkably high in the overall grinding resistance, and suggested that a grooved wheel was effective to release the pressure generation.

Schmack[3] conducted three dimensional analysis with respect to the pressure distribution, Uematsu[4] and Miyaji[5] presented the real pressure distributions based on the measurements. By using the pressure measurement, Furutani[6,7,8] suggested a new in-process method to monitor not only the topographical grinding wheel conditions such as loading or dulling but also the real displacement of wheel spindle caused by the overall grinding resistance. Moreover, noble polishing methods using NC controlled were tried by Sakaya[9] and Mori[10] ,that were based on the polishing grain motion inside the fluid boundary layer.

In this study, authors investigated the effects of the hydrodynamic pressure on the ultraprecision grinding with very small depth of cut, and proposed a fluid delivering method that not only releases the pressure-induced resistance but also produces little effect on the wheel performance. In the experiment, by altering the delivering nozzle location, the hydrodynamic pressure was measured and the actual depth of cut was investigated and compared with the accumulated set depth of cut.

2. Pressure generation

In the grinding process, it is well known that the delivered fluid makes hydrodynamic pressure generation due to the wedge effect between the wheel peripheral surface and the work surface, and that the large magnitude of pressure is especially created in the case of resin bonded wheels. Fluid flow is modeled as shown in Fig.1. Assuming that the fluid is Newtonian and in compressible steady flow, the inertia force is negligibly small compared to viscous force, viscosity change due to temperature and pressure is negligible, there is no slip on the surface of wheel and workpiece, and pressure is constant along the film thickness direction. The velocities and flow rates in x and y direction are given by Eq.(1)~(4) respectively.

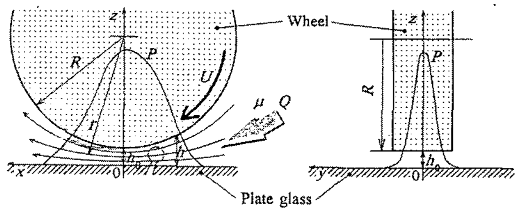

Fig. 1 Fluid around grinding wheel

$$u(x,z) = \frac{1}{2\mu}\frac{dP}{dx}(z^2 - h(x)z) + \frac{U}{h(x)}z \qquad (1)$$

$$v = \frac{1}{2\mu}\frac{dP}{dy}(z^2 - h(x)z) \qquad (2)$$

$$Q_x = -\frac{1}{12\mu}\frac{dP}{dx}h(x)^3 + \frac{U}{2}h(x) \qquad (3)$$

$$Q_y = -\frac{1}{12\mu}(\frac{dP}{dy})h^3 \qquad (4)$$

Considering the clearance configuration between wheel and work piece approximately expressed by Eq.(5), Eq(3) results in Eq.(6).

$$h(x) = h_0\left(1 + \frac{x^2}{2Rh_0}\right) \qquad (5)$$

$$\frac{1}{12\mu}\frac{dP}{dx} = -\frac{Q_x}{h_0^3\left(1+\frac{x^2}{2Rh_0}\right)^3} + \frac{U}{2h_0^2\left(1+\frac{x^2}{2Rh_0}\right)^2} \qquad (6)$$

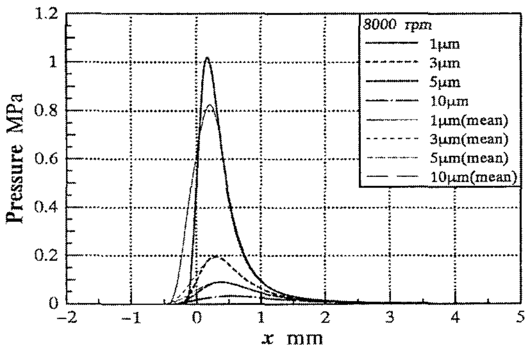

Fig.2 Calculated pressure distribution along x direction (wheel diameter 200mm, 8000 rpm)

Pressure distribution P(x) is obtained by integrating along the x-direction in the pressure generation region. Fig.2 shows a typical calculated pressure distribution along the maximum pressure position for 8000rpm when using 200 mm of wheel diameter, where 'mean' represents the averaged clearance considering grain protrusion of the wheel surface. Negative x represents the position after minimum clearance when the workpiece moves from right to left. It can be noted that the maximum pressure is generated just in front of the minimum clearance position.

3. Experiment

In order to investigate the hydrodynamic pressure in the process of grinding, an experimental set-up schematically shown in Fig.3 was used. Test piece made of optical glass is attached on the fixture, which is fixed on the three axis force transducer. Strain gauge type pressure sensor is installed on the fixture. Pressure measuring hole of 0.5 mm diameter is provided in the test piece that is connected to the pressure sensor through the hole located inside the fixture.

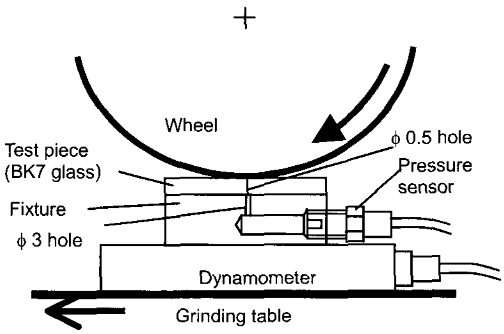

Fig. 3 Schematic diagram of experimental set-up

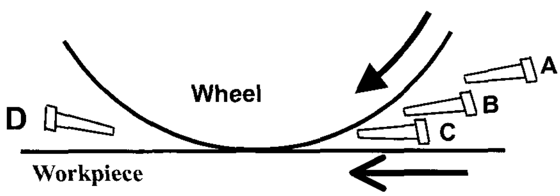

Fig. 4 Grinding fluid delivering method

In the experiment, resin-bonded diamond wheel that makes a large pressure generation compared with other types of wheel was used. Table 1 indicates the experimental conditions used in this study. Limiting this study on the effect of coolant delivering method, single wheel speed of 2880 rpm was applied. In regard to the table speed, 0.1 m/min and 2.0 m/min were applied for pressure measurement and for normal machining respectively. Pressure and force were measured for depth of cuts of 0.1μm, 0.5μm, 1.0μm, 1.5μm and 2.0μm. Grinding fluid was delivered from four positions, three from up-stream side and one from down stream side as shown Fig.4.

Table 1 Experimental conditions

Wheel type	SD1500 N125B Diameter 200mm, width 10mm
Workpiece	Optical glass (BK7) Width 8mm, length 60mm
Coolant type	Chemical Solution (Kurecut ET50X)
Wheel revolution (rpm)	2,880
Table speed (m/mim)	0.1, 2.0
Depth of cut (μm)	0.1, 0.5, 1.0, 1.5, 2.0
Pressure transducer	Strain gauge type (Kyowa PGM-30kH)
Amplifier	Dynamic range 2kHz (Shinko, DSA-603)

4. Results and discussion

Hydrodynamic pressure without machining for each position can be measured by scanning the workpiece in axial and traverse directions with the table speed of 0.1m/min. Then the typical pressure distribution along the wheel axis and the traverse direction can obtained as shown in Fig.5.

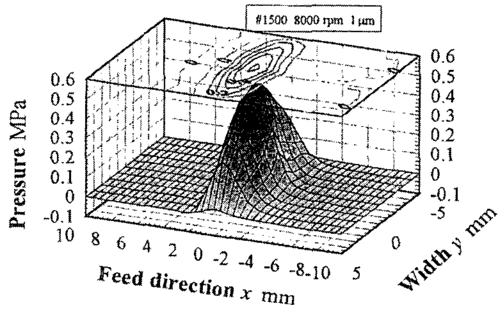

Fig.5 Measured three dimensional pressure distribution (8000 rpm)

The profile of velocity *u*, *v* can be obtained by calculating the pressure gradients (*dP /dx* , *dP /dy*) using the Lagrange Method in 0.5 mm interval, then replace *dP /dx* into Eq.(1) and Eq.(2) at each point. Fig 6 shows the result obtained by following this procedure. In the figure, it can be seen that the small amount of flow enter into the downstream due to the negative pressure.

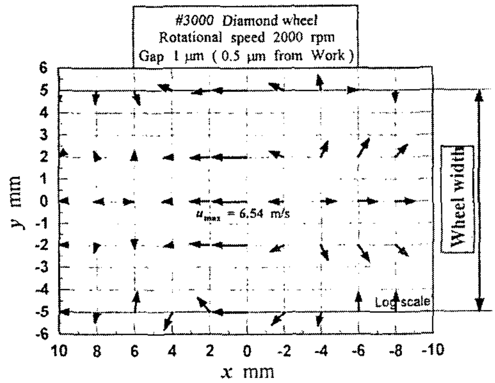

Fig.6 Velocity vector profile based on the measured pressure distribution (2000rpm)

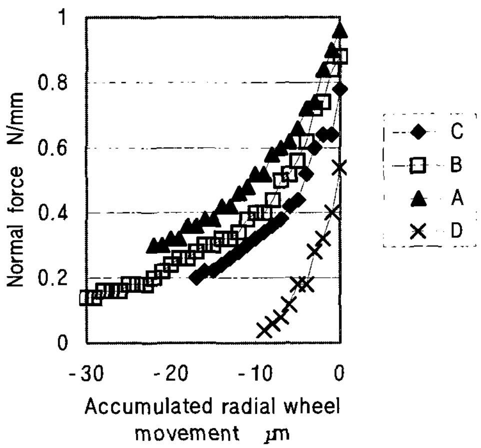

Fig. 7 Normal force generated by dynamic pressure according to nozzle position

Fig.7 shows the normal force generated by dynamic pressure according to the wheel movement. Negative value represents existence of clearance between the wheel and the work surface. In the figure, it can be seen that pressure decreases as the target of delivering nozzle becomes lower in the normal delivering method (A,B,C), and delivery from the opposite side(D) provides remarkable decrease of the pressure generation. These results can be explained by suppression of boundary layer film thickness. For position A that is widely applied and is known to generate a large fluid flux into the grinding region, boundary layer is fully developed, while others suppress the growth of film thickness. For position D that is delivered from the downstream of down-cut, fluid collides with the rotating wheel and very thin film thickness is formulated as shown in Fig.8.

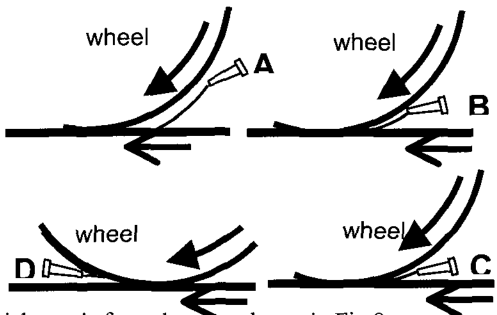

Fig.8 Fluid film thickness according to delivering position

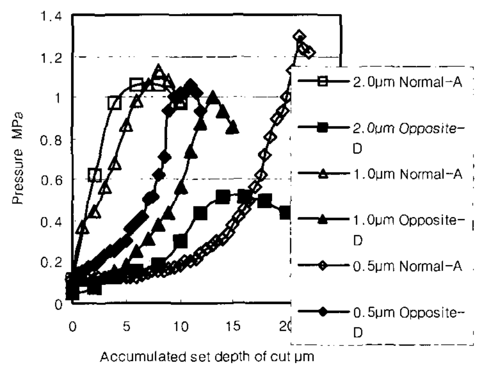

Fig.9 Maximum pressure vs. accumulated set depth of cut

Fig.9 compares the maximum pressures for normal delivery(A) and opposite side delivery(D). In the figure, it can be noted that the pressure reaches about 1.0Mpa during actual cutting process, and that the pressure generation is remarkably suppressed for the case of 2μm.

This pressure effect results in the decrease in the grinding resistance as shown in Fig. 10. In the case of 0.5μm down feed, due to the suppression of hydrodynamic pressure by applying position D, actual machining starts earlier than 1μm and 2μm case since its actual machining resistance is much smaller than others.

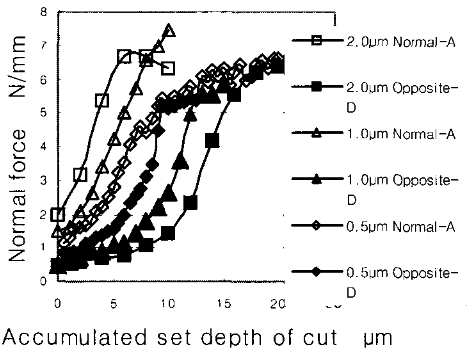

Fig. 10 Normal force of grinding resistance according to accumulated set depth of cut

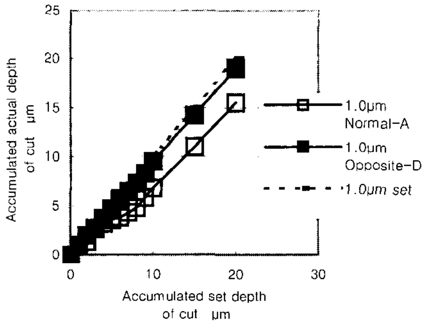

Fig.11 Accumulated actual depth of cut according to accumulated set depth of cut

Eventually, the overall grinding resistance is decreased to 20 percentage of the normal delivery at the early stage of machining as shown in the figure. These effects lead to the improvement of both grinding resistance and actual depth of cut. Fig.11 shows a comparison of the actual grinding ratio for two delivering methods. Due to the smaller resistance of opposite delivering position D, the actual depth of cut is truly improved compared with normal delivering position A.

For the saturated grinding condition that the grinding resistance is almost constant, the ratio of actual depth of cut against the set depth of cut at the saturated condition is shown in Fig.12. In the figure, it can be seen that the machining efficiency significantly improved by applying the delivering position D particularly for the small depth of cut such as 0.5μm or 1.0 μm in the case of resin bonded wheel used in this study. Fig.13 shows a comparison of the grinding resistances according to the down feed. For all cases of 2.0μm, 1.0μm, 0.2μm, it is not to be seen that fluid delivering position D leads to significant wheel deterioration over the long distance of machining. In addition, Fig.14 shows the SEM image of machined surface after reaching the saturated grinding with delivering position D. Grinding traces that were created by ductile regime grinding are apparent. Also, surface roughness and waviness are found to be almost the same as the conventional delivering positions.

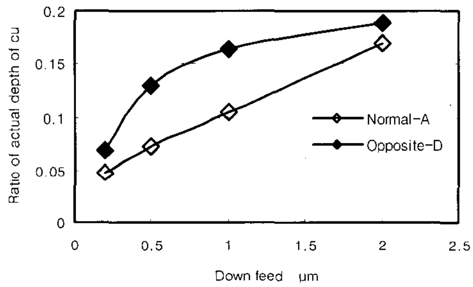

Fig.12 Ratio of actual depth of cut according to down feed

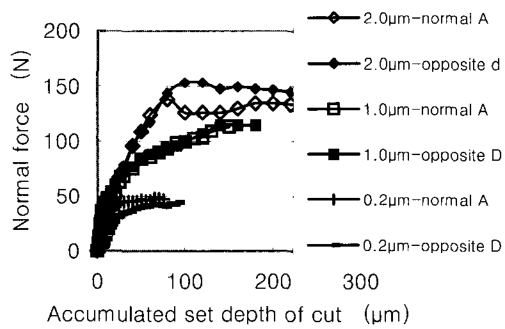

Fig.13 Comparison of grinding resistance

Those results indicate that altering the fluid delivering method can improve the grinding accuracy as well as machining efficiency especially in the ultraprecision mirror grinding process using resin-bonded diamond wheel.

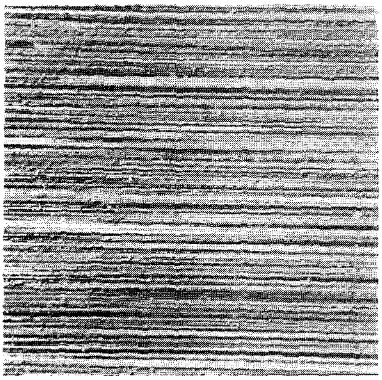

Fig.14 SEM image of ground surface (BK7 Glass, delivering position D)

5. Conclusion

In this paper, authors investigated the effect of hydrodynamic pressure generation on the viewpoint of improving the grinding accuracy and machining efficiency especially in the process of ultra-precision mirror grinding with resin-bonded fine diamond wheel. It is found that hydrodynamic pressure is created in accordance with the boundary film thickness. By altering the location of fluid delivering nozzle, the film thickness can be significantly reduced. It is also found that grinding fluid delivered from the downstream against the wheel rotational direction in the process of down cutting releases the pressure generation and provides a significant effect on the improvement of machining accuracy for the small depth of cut.

For the realization of the proposed method in the practical applications, behavior of overall grinding resistance and wheel conditions over long machining period should be further investigated.

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