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On the Superfinishing of the Convex Surface with Newly Developed MPR Stones*

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The experiments have been carried out in order to examine if it is possible to superfinish the whole convex surface smooth with newly developed MPR stones without changing the profile of the convex surface. MPR stones consist of abrasive particles, copper powders sustaining abrasive particles and synthetic rubber as a bonding material.

The results are as follows:

The convex surface can be finished smooth with an MPR stone No. 1 without changing the profile of the convex surface if the height at the center of the convex surface is less than $13.8\ \mu$ in case of 11 mm in width, and with an MPR stone No. 2 if the height is less than $11.9\ \mu$. These values become larger as the surface irregularities of the abrasive stone become larger.

1. Introduction

The slightly undulating surface (*e.g.* the flat face of a spinning yarn nozzle made of stainless steel) must be finished smooth along the contour. In such a case, the cutting surface of an abrasive stone should follow the contour of the work piece surface.

For this purpose the authors have developed MPR stones, the elastic modulus of which is less than that of an MP stone⁽¹⁾. This paper reports the finishing characteristics of the undulating surface with the above stone.

2. Apparatus and abrasive stone

The superfinishing machine used in this experiment is an SF 615 Type Micro Polisher of Koganei Co. make. Figure 1 shows the shape and size of the abrasive stone used.

Table 1 The elastic modulus of the abrasive stone used in the experiment

Abrasive stone	Elastic modulus kg/cm ²	
	In the dry state	In the wet state
MPR stone No. 1	8 200	7 600
MPR stone No. 2	14 000	12 000
MP stone	53 000	16 000

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MPR (Elastic Micro Polishing) stones consist of abrasive particles, copper powders sustaining abrasive particles and synthetic rubber as a bonding material. MPR stones have two merits. First, it can finish the surface smooth without any serial scratch because the abrasive grain is elas-

Fig. 1 The shape and size of the abrasive stone

Fig. 2 The compressive stress-strain diagram of the stone specimen

tically and plastically buried in a copper powder surface in operation and the cutting edges are distributed uniformly on the stone surface. Second, it has a remarkably long life because of very stable rubber used as the bonding material.

Table 1 shows the elastic moduli of MPR stones made by changing the percentage of the bonding material. In addition, the elastic modulus of the MP stone is also shown in Table 1 for comparison. The abrasive grain of the stones is a white fused alumina grain of grain size # 600. The elastic moduli of the above stones are determined by a compression test on the specimen of 30 mm in diameter and 6 mm in length both in a dry state and in a wet state. For the compression test in the wet state, the specimen was dipped for 50 hours in kerosene which was used as cutting fluid.

Figure 2 shows the compressive stress-strain diagrams of the stone specimen. The stress increases in proportion to the strain up to 50 kg/cm² in every specimen, and the elastic modulus of MPR stone No. 1 is the least and that of MP stone is the largest. The elastic modulus of the stone in the wet state is slightly less than that of the stone in the dry state. Therefore, it is recognized that these stones are easily deformed when they are dipped in kerosene.

3. Experimental methods

The material of work pieces used is stainless steel (SUS 29B). The following three kinds of work pieces are used according to the experimental purposes.

(i) In order to examine if it is possible to make the whole surface irregularities smooth with MPR stones, a cylindrical piece of 12 mm in diameter is used as the work piece. It has a convex surface wet-lapped with WA 600 grains. Several kinds of work pieces having various curvatures were prepared.

(ii) In order to examine if the stock removal and the surface roughness differ by the finishing conditions, a cylindrical piece of 10 mm in diameter is used as the work piece, the end surface of which is finished flat with a WA 400 MP stone.

(iii) In order to observe the surface profile around holes finished with MPR stones, a cylindrical piece of 12 mm in diameter is used as the work piece. It has the hole of 0.5 mm in diameter in the center of the end, and is finished flat with the WA 400 MP stone.

The work pieces are superfinished under the

following conditions both with MPR stones and the MP stone.

Finishing conditions are;

Rotational speed of stone: 80 rpm,

Number of vibrations of work piece: 1500°

C/min

Amplitude of vibration: 2.5 mm

Crosshatch angle: 25°

Stone pressure: 0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4 ton/cm²

Finishing time: 2.5, 5, 7.5, 10 min

Cutting fluid: kerosene No. 1

The profiles of convex surface of the work piece before and after finishing are recorded with a Kosaka Roughness Tester at a vertical magnification of 1000 and a horizontal magnification of 10. Surface profile is obtained for the central 11 mm, excluding the circumferential 0.5 mm. The recording is done in a lapping direction before finishing and in a vibrational direction of the work piece after finishing. The vibrational direction of the work piece is taken to be identical with the lapping direction. The recorded profiles of the convex surface before and after finishing are shown respectively in Fig. 3(a) and (b). In order to examine if the convex surface can be finished smooth without changing the profile of the convex surface by comparing the

Fig. 3 The recorded profile of the convex surface before and after finishing (abrasive stone: MPR stone No. 1, stone pressure: 0.5 kg/cm², finishing time: 10 min)

Fig. 4 The surface roughness curve of the work piece before finishing

profile curve of the convex surface before and after finishing, the height at the center of the convex surface H is discussed as a numerical indication of the convex surface which can be finished with MPR stones without changing the profile of the convex surface.

The stock removal is designated by a weight loss of the work piece. The surface roughness is measured with the Kosaka Roughness Tester at a vertical magnification of 10 000 and a horizontal magnification of 50. Figure 4 shows the roughness curves of work pieces before finishing. Figure 4(a) shows that of the work piece which is used for examining the convex surface, and Fig. 4(b) shows that of the work piece which is used for examining the stock removal and the surface roughness. The surface profile around the hole after finishing is observed with a reflected-light interference microscope ($\lambda=0.6$ mm, one division of scale=0.1 mm). Figure 5 shows a micrograph of the interference pattern of surface around the hole before finishing.

4. Experimental results

On finishing the convex surface, it is supposed

Fig. 5 A micrograph of the interference pattern of surface around the hole before finishing

that the H value varies by the conditions of the stone surface, because the conditions of the stone surface may affect the contact between the cutting surface of the abrasive stone and the convex surface of the work piece. So it is examined if the conditions of the stone surface which are made by changing the dressing method and the dressing condition influence the H value. Two kinds of dressing methods are adopted. One uses a mesh-dresser, and the other uses a WA 600 MP stone which is 40 mm in outer diameter and 20 mm in inner diameter. From now on, we call the former a mesh-dressing method and the latter a rotary dressing method. As to the mesh-dressing method, the feed of 3, 18, 36 cm/min, the rotational speed of stone of 600 rpm and the depth of cut of 0.05 mm are used. As to the rotary dressing method, MPR stones are revolved at 80 rpm, and the rotary dresser is revolved at 30 rpm and is pressed onto the rotating MPR stone surface under the pressure of 0.2 kg. Figure 6 shows the surface profile of the dressed MPR stone No. 1 which is measured in a radial direction with the Kosaka Roughness Tester at a vertical magnification of 1 000 and a horizontal magnification of 50. It is recognized that the stone surface dressed by the rotary dressing method has smaller irregularities and is smoother than that by the mesh-dressing method. The surface irregularities of the stone by the mesh-dressing method become larger as the feed becomes larger.

Table 2 shows the H value obtained after finishing with the abrasive stone dressed under the above dressing conditions by the above dressing methods. The right part of Fig. 6 shows the surface irregularities which are measured in the radial direction after finishing. The H value is

Fig. 6 The profile of the surface irregularities of MPR stone No. 1 after dressing and after superfinishing

5.6 μ for the rotary dressing method, which is remarkably small compared with the mesh-dressing method, that is, 8.2 μ in case of the feed of 3 cm/min and 11.0 μ in case of the feed of 18 cm/min and 36 cm/min. Therefore, it is recognized that the H value varies with the dressing method and the dressing conditions even if the same stone is used. In other words, the H value becomes larger with the increase of the surface irregularities of the stone which is dressed within the limits of this experiment. Figure 6 shows that the surface irregularities of the stone before and after finishing are hardly changed. From this fact, it is recognized that the contact between MPR stones and the work piece is similar to an elastic contact.

It is examined if the stock removal changes with the dressing method and the dressing conditions when the work piece is finished with the MPR stone No. 1 under ten levels of pressure keeping other conditions constant. Figure 7 shows the relation between the stock removal and the stone pressure. The stock removal is the smallest in case of the abrasive stone dressed by the rotary dressing method with which the smallest surface irregularities are produced in every stone. The stock removal varies remarkably with the

Table 2 The influence of the dressing method on the maximum height at the center of the convex surface which can be finished without changing the profile of the convex surface (Abrasive stone: MPR stone No. 1, Stone pressure: 0.5 kg/cm², Finishing time: 10 min)

Dressing method	Feed cm/min	H μ
Mesh-dressing method	36	11.0
	18	11.0
	3	8.2
Rotary dressing method	—	5.6

Fig. 7 The influence of the dressing method and the dressing condition on the stock removal (abrasive stone: MPR stone No. 1, finishing time: 10 min)

feed of dressing in case of the mesh-dressing method. The stock removal becomes larger up to the stone pressure of 1 kg/cm² as the feed becomes larger, that is, as the surface irregularities of the stone become larger. The stock removal is the largest at the feed of 18 cm/min for the stone pressure more than 1 kg/cm². In case of the feed of 36 cm/min, the stock removal reaches a maximum value under the stone pressure of 1 kg/cm², and then begins to decrease with the increase of the stone pressure, and takes a minimum value under 1.5 kg/cm², and later begins to increase again. The reason why the stock removal differs with the surface conditions of the stone and the stone pressure, may be that the abrasive grains are bonded by elastic material. That is, when the work piece is simply pressed against the stone, the abrasive grain penetrates the work piece up to the depth of δ_1 as shown in Fig. 8(a), but in process of finishing the abrasive grain which is bonded by elastic material is turned in the cutting direction shown in Fig. 8(b) by a torque arising from a tangential force, so the depth to which the abrasive grain penetrates the work piece becomes δ_2 . $\delta_1 > \delta_2$ means that the stock removal decreases. The turning of the abrasive grain is caused not only by the deformation of elastic material bonding the abrasive grain, but also by the deformation of the surface irregularities of the stone. Therefore, the turning of the abrasive grain becomes larger as the surface irregularities of the stone become larger. In other words, the reason why the stock removal decreases is because the turning of the abrasive grain becomes remarkably large at the feed of 36 cm/min and under the pressure of more than 1 kg/cm². On the other hand, with the MPR stone No. 2 which has a larger elastic modulus than the MPR stone No. 1, the maximum value of the stock removal can not be obtained under the above experimental conditions. This may show that the turning of the abrasive grain of this stone does not increase even if the stone pressure increases.

From the above experimental results, the mesh-dressing method at the feed of 18 cm/min

Fig. 8 Movement of the abrasive particle of the elastic stone

is taken in the following experiments. With this method and this condition, a large H value is obtained and the stock removal increases with the increase of the stone pressure.

The experiment is carried out to examine if the H value is affected by the elastic modulus of the stones which are dressed under the conditions explained above. Table 3 shows the results obtained. The smaller is the elastic modulus, the larger is the H value. Moreover the H value becomes larger with the increase of the stone pressure. On the other hand, there is little difference in the H value when changing the finishing time. With the MP stone, very small convex surface can not be finished without changing the profile of the convex surface.

Figures 9 and 10 show the influence of the

Table 3 The maximum height at the center of the convex surface which can be finished without changing the profile of the convex surface with MPR stones

Stone pressure kg/cm ²	$H \mu$	
	MPR stone No. 1	MPR stone No. 2
0.5	11.0	9.2
1	11.6	9.5
2	12.3	10.1
4	13.8	11.9

In case of the finishing time of 10 min		
Finishing time min	$H \mu$	
	MPR stone No. 1	MPR stone No. 2
5	11.4	9.2
10	11.6	9.5
20	11.8	9.6
30	11.8	9.8

In case of the stone pressure of 1 kg/cm²

Fig. 9 The relation between the stock removal and the stone pressure in case of the finishing time of 5 min

elastic modulus on the stock removal under various stone pressures and various finishing times. The stock removal with the MPR stone of small elastic modulus is remarkably smaller than that with the MP stone of large elastic modulus. Moreover the stock removal is larger with the MPR stone No. 2 of larger elastic modulus than with the MPR stone No. 1. From these facts, it can be concluded that the abrasive stone of larger elastic modulus can produce a larger stock removal. This is because in the stone of larger elastic modulus, the abrasive grain is hardly turned by the tangential force as mentioned above.

Figure 11 shows an example of the surface roughness curve. The finishing is carried out under the stone pressure of 0.5 kg/cm² and the finishing time of 10 min. The surface roughness

Fig. 10 The relation between the stock removal and the finishing time in case of the stone pressure of 2 kg/cm²

(c) In case of MPR stone No. 2
Fig. 11 The surface roughness with the abrasive stone in case of the stone pressure of 0.5 kg/cm² and the finishing time of 10 min

value with the MPR stone No. 1 and No. 2 is less than $0.1 R_{\max}$. But with the MP stone, the surface roughness value is about $0.1 R_{\max}$ and is larger than that with MPR stones. The surface roughness value is not different by stone pressures or finishing times.

Figure 12 shows the micrograph of the interference pattern of surface around the hole. The portion of hole is rounded by finishing with every stone. The degree of edge roundness is almost equal in every stone under various stone pressures. On the other hand, the degree of edge roundness is not equal around the hole, that is, the degree of edge roundness of the portion which always opposes the cutting edge of the

stone surface, is $0.6 \sim 0.9 \mu$ in depth and about 0.2 mm in width after finishing. Therefore the width of edge roundness increases and the depth of edge roundness is hardly changed by finishing with the MPR stone No. 1 and No. 2. On the other hand, the degree of edge roundness of the portion which leaves the cutting edge of the stone surface, is hardly changed or becomes small after finishing.

5. Considerations on finishing the whole convex surface smooth

It might be possible to consider the reason why MPR stones can finish the surface irregularities smooth without changing the contour of the

Fig. 12 Micrograph of the interference pattern of surface around the hole after finishing

convex surface of the work piece. In the super-finishing machine, a small clearance exists between the bearing of the oscillating arm which holds the work piece and the shaft on which the oscillating arm vibrates. Thereby, the convex surface with a very small curvature may be finished smooth with the non elastic abrasive stone without changing the contour of the convex surface.

Table 4 shows the H value with a WA 1500 Lapo stone which is a stiff one. In this experiment, the stone surface is carefully kept flat with dressing every one minute in order to avoid the influence of the stone wear on the H value. The value which can be obtained by subtracting this H value from the H value explained in the former section, is the maximum value of the height at the center of the convex surface which can be finished smooth by the deformation of the cutting surface of stone. This may be due to the following two deformations of the abrasive

Table 4 The maximum height at the center of the convex surface which can be finished without changing the profile of the convex surface with the stiff Lapo stone.
(Abrasive stone: WA 1500 Lapo stone, Finishing time: 10 min)

Stone pressure kg/cm ²	$H \mu$
0.5	3.5
1	2.5
2	2
4	2

Table 5 The maximum height at the center of the convex surface which can be finished without changing the profile of the convex surface in case of giving the vibration or not
(Abrasive stone: MPR stone No. 1, Finishing time: 10 min)

Stone pressure kg/cm ²	$H \mu$	
	In case of giving the vibration	In case of no giving the vibration
0.5	11.0	4.0
1	11.6	4.5
2	12.3	4.5
4	13.8	5.5

Fig. 13

stone. That is, (i) the deformation of the bulk of the abrasive stone except the surface irregularities, and (ii) the deformation of the surface irregularities caused by dressing. The vibration of the work piece is added to the revolution of the abrasive stone during super-finishing, therefore the influence of the vibration on the H value is examined in the following. Table 5 shows the H value of both cases where a vibration is given or not. The H value obtained by superfinishing is remarkably large compared with the H value obtained by conventional finishing without the vibration of the work piece. This may be due to the difference in contact condition between the abrasive stone and the work piece in the process of finishing. In other words, in case of giving the vibration the work piece having the convex surface can be finished up to the height corresponding to the depth of stone deformation as shown in Fig. 13(a), even if the stone surface does not contact perfectly with the work piece. In case of giving no vibration, the work piece can be finished up to the depth of pressing into the stone which contacts perfectly with the work piece as shown in Fig. 13(b).

When the work piece, of which the radius of curvature of the asperity is R , contacts elastically with the abrasive stone on the assumption that the stone surface is perfectly smooth and flat, the distance δ to which the work piece approaches the abrasive stone is given by the next equation.

$$\delta = \sqrt[3]{\frac{9}{16} \frac{P^2}{R} \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^2}$$

where,

E_1, E_2 : the elastic moduli for the work piece and the stone

ν_1, ν_2 : poisson's ratios for the work piece and the stone

P : normal force

and $E_1 \gg E_2$

Hence, the above equation becomes

$$\delta = \sqrt{\frac{9}{16} \frac{P^2}{R} \left(\frac{1-\nu_2^2}{E_2} \right)^2} \dots \dots \dots (1)$$

Where, it is supposed that δ is equal to the depth of the stone deformation caused when the work piece is pressed into the abrasive stone with pressure P . The following equation holds good geometrically among the radius of cylindrical piece r , the radius of spherical surface R and the height h , as shown in Fig. 14.

$$h(2h-r) = r^2$$

where

$$2R \gg h$$

Fig. 14 The work piece

hence

$$2Rh=r \quad (2)$$

When the depth of the stone deformation becomes equal to the height of the convex surface of the work piece by contacting elastically, that is,

$$\delta = h$$

the distance δ to which the work piece approaches the abrasive stone, is given by the next equation from Eqs. (1) and (2).

$$\delta = \frac{3\sqrt{2}}{4} \frac{P}{r E_2} \frac{1-\nu_2^2}{E_2}$$

Substituting $r=5.5$ mm, $\nu_2=0.2$, then

$$\delta = 0.185 \frac{P}{E_2}$$

From the above equation, the H value is proportional to the normal force which acts on the work piece. Substituting the elastic modulus E_2 of the abrasive stone in the wet state into this equation for δ , the δ value is obtained as shown in Fig. 15. Figure 15(a) shows the case of the MPR stone No. 1 and Fig. 15(b) shows the case of the MPR stone No. 2.

In order to compare the δ value with the experimental value, the value which can be obtained by subtracting the value shown in Table 4 from the H value is shown in Fig. 15(a) and (b). The finishing is carried out with the abrasive stone dressed by the mesh-dressing method at the feed of 18 cm/min and by the rotary dressing method. The H value obtained by the above experiment is larger than the δ value to which the work piece approaches the abrasive stone in both the dressing methods. The difference between both the value is larger in case of the mesh-dressing method than in case of the rotary dressing method, and decreases with the increase of the stone pressure. The difference in both the dressing methods is due to the deformation of the surface irregularities of the abrasive stone caused by dressing. This might suggest the following facts. The deformation of the surface irregularities of the abrasive stone becomes large as the surface irregularities become large, and this deformation is added to

(a) In case of MPR stone No. 1

(b) In case of MPR stone No. 2

Fig. 15 Distance to which the work piece approaches to the abrasive stone, and the maximum height at the center of the convex surface which can be finished without changing the profile of the convex surface

the distance δ to which the work piece approaches the abrasive stone.

6. Conclusions

The results obtained are summarized as follows:

(1) The compressive stress-strain diagrams of MPR stones are almost straight lines up to 50 kg/cm². The elastic modulus is 8 200 kg/cm² for the MPR stone No. 1 and 14 000 kg/cm² for the MPR stone No. 2.

(2) The convex surface can be superfinished smooth with MPR stones without changing the profile of the convex surface of the work piece. The maximum value of the height at the center of the convex surface varies remarkably with the dressing method and the dressing conditions even if the same stone is used. This value becomes remarkably larger by vibrating the work piece.

(3) The above value is 13.8 μ for the MPR stone No. 1 and 11.9 μ for the MPR stone No. 2 under the stone pressure of 4 kg/cm². This stone is dressed by the mesh-dressing method at the feed of 18 cm/min.

Reference

- (1) Asaeda, T., et al.: *Bull. of TIT*, 100 (1970), p. 15.