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Micro machining of an STS 304 bar by magnetic abrasive finishing †

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Abstract

A magnetic abrasive finishing process is a method of non-traditional precision machining in which the finishing process is completed using magnetic force and magnetic abrasives. In this research, a STS 304 cylindrical workpiece was finished using a magnetic abrasive finishing process at 30,000 rpm, and the roughness, roundness, and changes in the micro-diameter were investigated. The study showed that it is possible to control the micro-diameter and weight of the STS 304 cylindrical workpiece by using a near linear approach. Surface roughness as fine as 0.06 ㎛ (Ry) and roundness as fine as 0.12 ㎛ (LZS) were achievable by using a diamond paste with 1 ㎛ particles. Vibrational motion applied to the workpiece improved the surface roughness. The improvement of the surface roughness was achieved because the vibrational motion effectively removes unevenness in the rotational direction and the direction orthogonal to it.

Keywords: Magnetic abrasive finishing process; Non-traditional precision machining; Magnetic abrasives; Micro-diameter; Surface roughness; Roundness

1. Introduction

A variety of techniques exist for machining three-dimensional workpieces freely. Cutting and grinding methods have been employed with improved precision. However, such mechanical techniques have certain limitations regarding surface roughness, precision, and processing time. A magnetic abrasive finishing process is a non-traditional process that employs magnetic field action and mixed magnetic abrasives [1-4]. Studies on this method have focused on improvement of surface roughness [5-9]; the control of roundness, diameter, and other parameters has been somewhat neglected.

In this research, an STS 304 cylindrical workpiece which had been ground by a centerless grinder was machined further using a magnetic abrasive finishing process and then surface roughness, roundness, micro-diameter change, and weight change were analyzed. The potential for control of micro-diameter, weight change, and roundness of the micro-machined workpiece was explored.

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2. Principle of the magnetic abrasive finishing process

Fig. 1 is a schematic of the magnetic abrasive finishing process. Magnetic abrasives of unbonded type (a mixture of strong magnetic particles and magnetic abrasives with polishing capability) are supplied between the N-pole and the S-pole; mixed type magnetic abrasives form a particulate brush along the magnetic flux. A workpiece is inserted inside the particulate brush and then rotated at a high speed. It is possible to apply vibrational action in the longitudinal direction. Here, distance between the workpiece and the magnetic pole is a few millimeters. In Fig. 2, processing forces comprise a force (Fx) in the direction of the magnetic line pressing onto the surface of the workpiece continuously as the strongly magnetic particles are pulled along the magnetic lines, and a force (Fy) is generated when the workpiece pushes out bridges formed in the direction of magnetic equipotential lines. The two forces work on the piece which results in a grinding effect. Here, particle brushes have many degrees of freedom, and become flexible enough to accommodate the surface conditions of the workpiece.

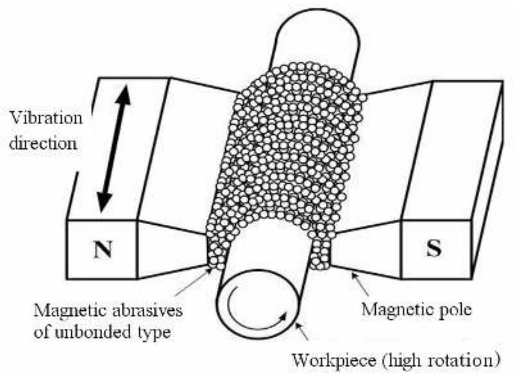


Fig. 1. Machining principle of the micro-magnetic abrasive finishing process.

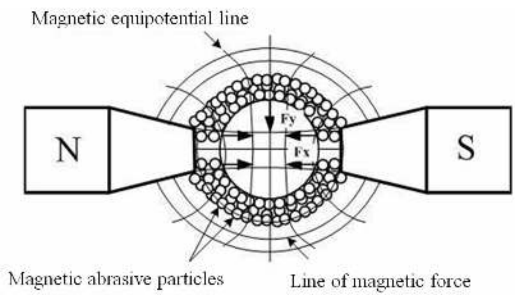


Fig. 2. Two dimensional magnetic forces operating on the workpiece.

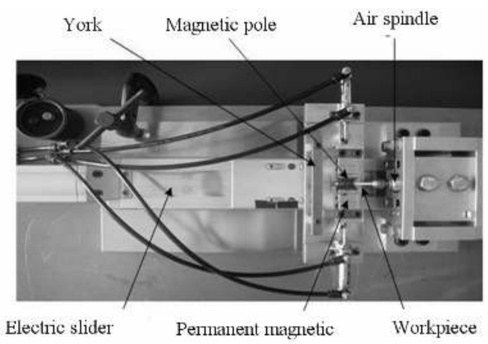


Fig. 3. Photograph showing the magnetic abrasive finishing process apparatus.

3. Experimental apparatus and method

A micro-diameter controlled magnetic abrasive finishing process in Fig. 3 is composed of a high-speed spindle, an electromotive slider, and permanent magnet and poles.

The high-speed spindle is operated by pneumatic pressure, and the workpiece is mounted by the collet of the high-speed spindle. The magnetic pole area is composed of permanent magnets and magnetic poles, and the magnetic brush is formed between the magnetic poles. The STS 304 bar is machined by a magnetic abrasive finishing process aided by magnetic abrasives of unbonded type. Magnetic poles are configured as shown in Fig. 4 so as to increase grinding efficiency. Permanent magnets are of the Fe-Nd-B type. A york part is added to induce continuous flow of the magnetic field. York parts and magnetic poles are made of SS41 steel.

A micro magnetic abrasive finishing process experiment was conducted in the following sequence. A workpiece was mounted on the high-speed spindle, and magnetic abrasives of unbonded type were in-

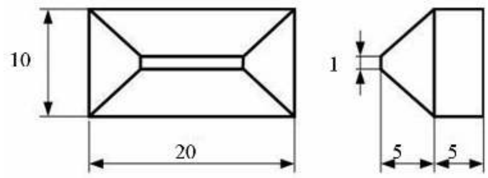
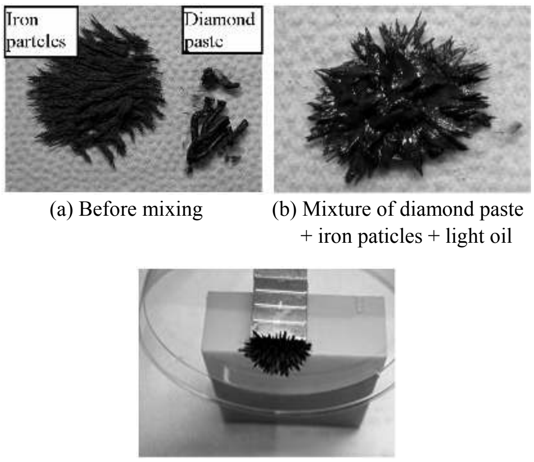


Fig. 4. Shape of magnetic pole.



(a) Before mixing (b) Mixture of diamond paste + iron paticles + light oil

(c) Mixture lifted by 90 degree
(Diamond grain size: 1 ㎛)

Fig. 5. Photographs of mechanical mixture of unbonded type magnetic abrasives.

serted into the magnetic pole area. The workpiece was rotated at a high speed and was subject to vibrational motion by placing the magnetic poles close to the workpiece by using an electromotive slider control.

After the magnetic abrasive finishing process was done as described above, the minute amount of weight removed from the workpiece, micro-diameter changes, surface roughness, and roundness were measured. In the experiment, an STS 304 bar with a 3 mm diameter and 60 mm length was used. The vibration frequency of the magnetic poles was 12 Hz and 0 Hz, with an amplitude of 2 mm. The magnetic abrasives of unbonded type were composed of a mixture of iron particles (mean diameter 75 ㎛) 0.8 g, diamond paste (mean diameter 1 ㎛, 3 ㎛, 9 ㎛) 0.2 g (or 0.05 or 0.4 g), and grinding fluid 0.2ml. Photographs in Fig. 5 show that the magnetic abrasives of unbonded type are mixed mechanically. (a) shows the photograph before the mechanical mixing of iron particles and diamond pastes. (b) shows the mechanical mixture of iron particles, diamond paste and light oil. As shown in the photographs, the mixtures have adhesiveness. And when these mixtures are put on the permanent magnet as shown on (c), the particles form get hard while forming brush, and diamond particles also do not fall off due to adhesiveness. Process clearance was 1 mm, and process duration was 60 seconds. Detailed experimental conditions are listed in Table 1.

Table 1. Experimental conditions.

Magnet	Nd-Fe-B permanent magnet: 20x10x12 mm
Magnetic pole	Material: SS400
Magnetic flux density	0.52 T
Workpiece	STS 304 stainless steel bar ϕ 3 × 60 mm
Vibration of magnetic poles	Amplitude: 2 mm Frequency (f): 0, 12 Hz
Revolution	30,000 rpm (workpiece)
Magnetic abrasives of unbonded type	- Iron particles: 0.8 g Mean diameter: 75 ㎛ - Diamond paste: 0.2 g Diamond grain size (DP): 1, 3, 9 ㎛ - Lubricant (light oil): 0.2 ml
Clearance	1 mm

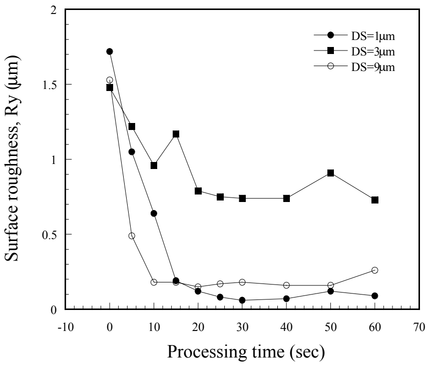


Fig. 6. Variations of surface roughness vs. processing time. (Workpiece: STS 304 bar, Frequency (f): 12 Hz, Rotational speed: 30,000 rpm, Clearance: 1mm).

4. Experimental results and analysis

Fig. 6 shows the relationship between the magnetic abrasive finishing processing time and the surface roughness (maximum height of the profile, Ry). Diamond pastes with diameters of 1, 3, and 9 ㎛ were used as a parameter, and the workpiece was rotated at 30,000 rpm. Magnetic poles were vibrated at 12 Hz. The surface roughness improves rapidly during the initial process period. The slope of improvement slows with time, and becomes zero after 20 seconds. Regarding the relation between surface roughness and the diamond grain size, the roughness (Ry) was 0.06 ㎛ for 1 ㎛ abrasive and it was 0.16 ㎛ when a 3 ㎛ abrasive was used. The surface roughness was 0.73 ㎛ at best when the 9 ㎛ abrasive was used. The reason why the roughness did not improve after 20 seconds and stayed constant after the duration is probably the large size of the abrasive used.

Fig. 7 shows the largely linear relationship between micro-diameter and processing time. This linear relationship is attributed to the fact that the process pres-

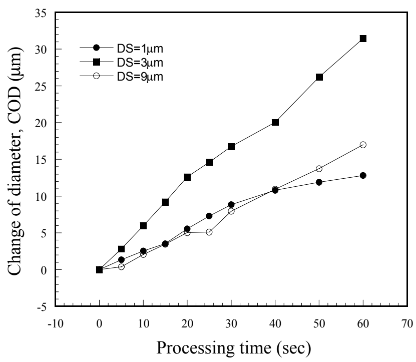


Fig. 7. Variations of micro-diameter vs. processing time. (Frequency: 12 Hz, Diamond grain size: 1 ㎛, 3 ㎛, 9 ㎛)

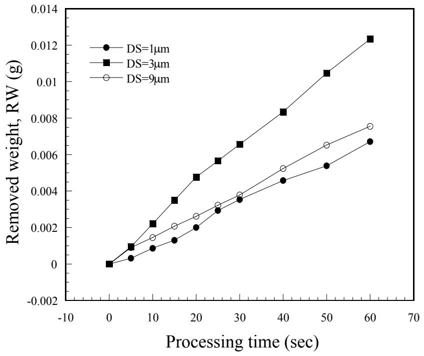


Fig. 8. Variations in removed weight vs. processing time. (Frequency: 12 Hz, Diamond grain size: 1 ㎛, 3 ㎛, 9 ㎛)

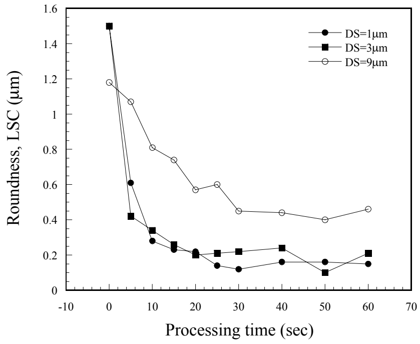


Fig. 9. Variations in roundness (LSC) vs. processing time. (Frequency: 12 Hz)

sure working on the workpiece remained constant, and that the diamond particles remained the same size throughout the processing time due to their hardness.

Fig. 8 shows the relationship between processing time and the weight removed from the workpiece. The removed weight shows a largely linear relationship. It has the largest slope for 3 ㎛, and the smallest slope for 1 ㎛. The 3 ㎛ diamond grain is particularly effective in this regard. The results as shown in Figs. 7 and 8 indicate that it is possible to linearly control processing with the magnetic abrasive finishing process using a rather simple apparatus.

Fig. 9 shows the progress of roundness with respect to processing time (least square circle method: LSC). The improvement is rapid during the initial processing period because the original surface unevenness is removed rapidly in the initial period. The improvement rates with the 1 ㎛ and the 3 ㎛ cases are largely the same, and remain approximately constant after 20 seconds. According to the graphs, the best roundness was achieved with the 1 ㎛ abrasive, and it reached 0.12 ㎛ after 30 seconds of processing.

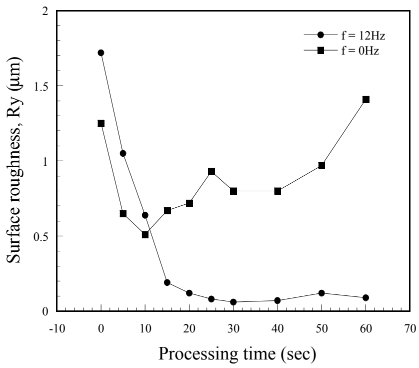
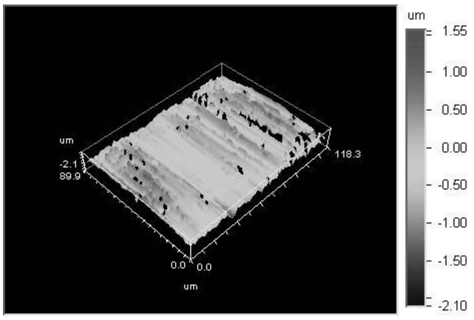


Fig. 10. Variations in surface roughness vs. processing time. (Workpiece: STS 304 bar, Diamond grain size: 1 ㎛, Rotational speed: 30,000 rpm, Clearance: 1mm)

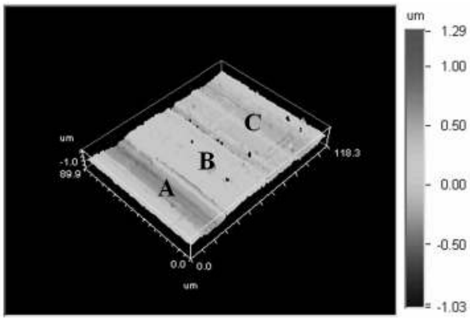
Fig. 10 shows variations in surface roughness (Ry) versus processing time with 0 Hz and 12 Hz of vibration applied in the longitudinal direction. In the case of 0 Hz vibration, the surface roughness improved drastically in the initial phase of processing, and then got worse until it became worse than the initial condition after about 60 seconds of processing. The best result obtained was 0.51 ㎛ (Ry). In the case of 12 Hz vibration, the surface roughness improved until the 30 second time point after which it remained about the same.

Fig. 11 shows the surface condition of the original workpiece and that of the workpiece processed over 60 seconds. (a) shows the surface condition prior to the process, and (b) shows the surface condition processed at 0 Hz. The surface condition was fair in the direction of the rotation while it was different in different areas A, B, and C, as noted by different colors in Fig. 11(b), along the direction orthogonal to the rotation direction. This variation along A, B, and C is judged to cause the deterioration in the surface roughness measurement result. Fig. 11(c) and (d) show the surface processed at 12 Hz. The surface condition is relatively good not only in the rotational direction but also in the orthogonal direction.

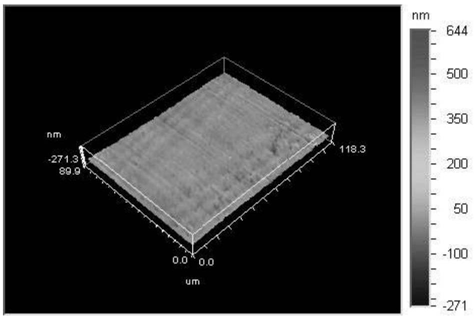
The images in Fig. 11(b) and (c) allowed us to determine that just by varying the vibration condition while keeping other parameters the same, the vibrational motion removes the unevenness effectively in the direction orthogonal to the rotational direction. Due to the improvement in the roughness, the surface roughness value (Ry) was enhanced to 0.06, far better than 0.51, and the removal rate of the material was also enhanced.



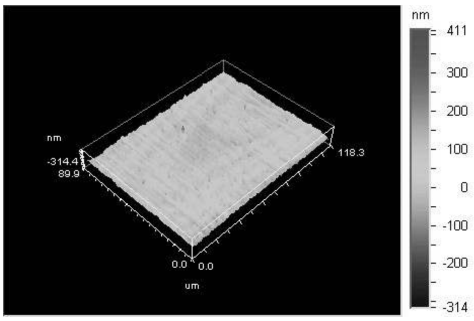
(a) Before abrasive. (0 sec)



(b) After abrasive (Frequency: 0 Hz, Diamond grain size: 1 ㎛, Processing time: 60 sec)



(c) After abrasive (Frequency: 12 Hz, Diamond grain size: 1 ㎛, Processing time: 60 sec)



(d) After abrasive (Frequency: 12 Hz, Diamond grain size: 3 ㎛, Processing time: 60 sec)

Fig. 11. Three dimensional surface conditions before and after processing.

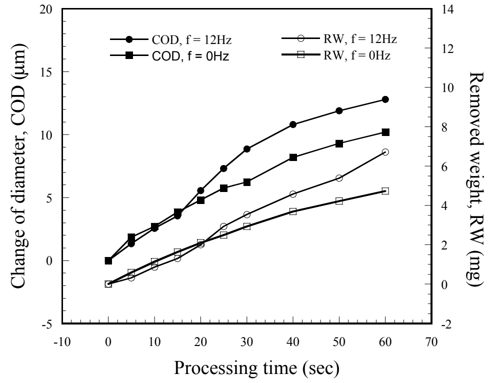


Fig. 12. Variations in micro-diameter and removed material vs. processing time. (Diamond grain size: 1 ㎛)

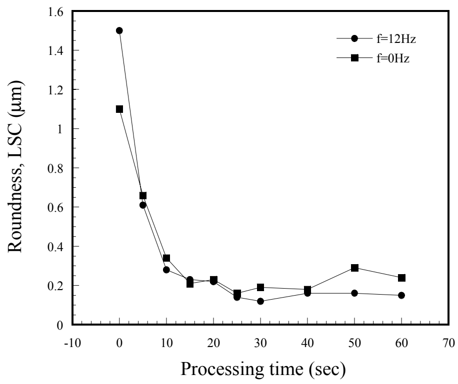
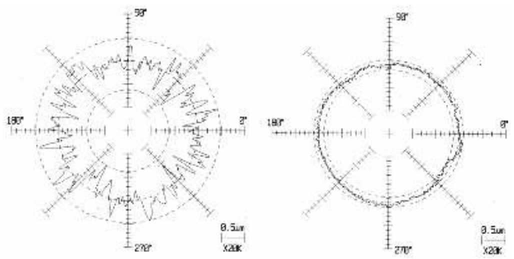


Fig. 13. Variations in roundness vs. rocessing time. (Diamond grain size: 1 ㎛)

Fig. 12 shows the relationship between micro-diameter change, removed weight, and processing time. As for 12 Hz versus 0 Hz, the micro-change in diameter was about the same for both cases during the initial phase, but it became larger for the 12 Hz case after 20 seconds. This is because the removed weight was larger in the 12 Hz case.

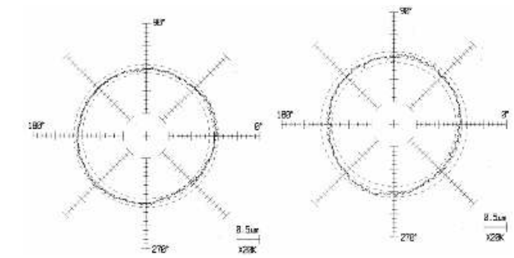
Fig. 13 shows roundness versus processing time. The roundness shows rapid improvement during the initial phase of the processing and then does not improve further after about 20 seconds. Unlike the surface roughness, it does not show much difference between 0 Hz and 12 Hz cases.

Fig. 14 shows changes in the roundness at 0, 15, 30, and 60 second points. The two graphs do not show much difference between the 0 Hz and 12 Hz cases. In the experiments at different vibration frequencies, the surface roughness condition of the workpiece could be improved greatly by vibrational motion. The



(a) Time: 0sec
Roundness: 1.10 ㎛

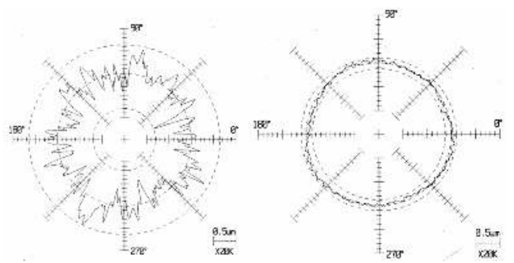
(b) Time: 15sec
Roundness: 0.21 ㎛



(c) Time: 30 sec
Roundness: 0.19 ㎛

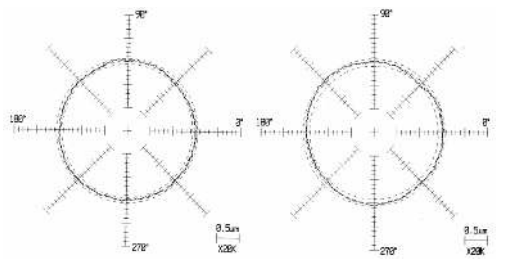
(d) Time: 60 sec
Roundness: 0.24 ㎛

(A) Changes in roundness. (Frequency: 0 Hz, Diamond grain size: 1 ㎛, Processing time: 60 sec)



(a) Time: 0sec
Roundness: 1.5 ㎛

(b) Time: 15sec
Roundness: 0.23 ㎛



(a) Time: 30sec
Roundness: 0.12 ㎛

(b) Time: 60sec
Roundness: 0.15 ㎛

(B) Changes in roundness. (Frequency: 12 Hz, Diamond grain size: 1 ㎛, Processing time: 60 sec)

Fig. 14. Roundness changes in relation to processing time.

roundness, unlike the surface roughness condition, showed improvements at a similar rate.

5. Conclusions

A STS 304 bar was micro machined using a magnetic abrasive finishing process, and then surface roughness, roundness, micro-diameter change, and removed weight were investigated and analyzed, yielding the following conclusions.

(1) Micro-diameter and weight can be controlled using a simple apparatus and magnetic abrasive finishing processing.

(2) Surface roughness (Ry) and roundness improved most when 1 ㎛ diamond abrasive particles were used, with results as good as 0.06 ㎛ and 0.12 ㎛, respectively. However, in terms of the rate of weight removal, the best result was obtained with 3 ㎛ diamond particles.

(3) Roundness improved most in the initial processing phase, similar to surface roughness.

(4) Substantial improvement in surface roughness occurred when vibrational motion was induced on the workpiece. This improvement was achieved because the vibrational motion effectively removed the unevenness in the direction orthogonal to the rotational direction.

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