INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING Vol. 15, No. 7, pp. 1275-1281 JULY 2014 / 1275
DOI: 10.1007/s12541-014-0467-x

Effect of the Magnetic Pole Arrangement on the Surface Roughness of STS 304 by Magnetic Abrasive Machining

Sung Yoon[1], Juei-Feng Tu[2], Jun Ho Lee[3], Gyun Eui Yang[1], and Sang Don Mun[3,#]

1 Division of Mechanical Engineering, Chonbuk National University, 664-14, Duckjin-dong, Duckjin-gu, Jeonju, Seoul, South Korea, 561-756
2 Department of Mechanical and Aerospace Engineering, North Carolina State University, 911 Oval Drive, Raleigh, USA, 27695-7910
3 Division of Mechanical Design Engineering, Chonbuk National University, 664-14, Duckjin-dong, Duckjin-gu, Jeonju, Seoul, South Korea, 561-756
Corresponding Author / E-mail: msd@jbnu.ac.kr, TEL: +82-63-270-4762, FAX: +82-63-270-2460

KEYWORDS: Magnetic pole arrangement, Inner surface roughness, Magnetic pole vibration device, Proximity sensor, Removed weight

In this study, a magnetic pole vibration device that uses a proximity sensor for magnetic abrasive finishing equipment using a permanent magnet was developed, and the performance of this system was proved, focusing on how the surface roughness of STS 304 pipes is affected by the magnetic pole arrangement. The results of this study confirm that the resulting magnetic fields of different magnetic pole arrangements change the behavior of the magnetic abrasive mixture, thus impacting the abrasion effect. Among the four different pole arrangements investigated, the M-S-N magnetic pole arrangement provides the best surface finish. A mixture of iron particles and magnetic abrasive materials in a 3 to 1 ratio is found to be the most advantageous in terms of surface roughness and material removal rate. In addition, the wet processing, in which light oil is added to the magnetic abrasion mixture, is more effective than the dry processing. Finally, the effect of the spindle speed was also investigated for speeds from 200 to 1,400 rpm. At 1,400 rpm, the surface roughness shows approximately 76.1% improvement over that at 200 rpm.

Manuscript received: March 8, 2013 / Revised: March 13, 2013 / Accepted: March 18, 2014

1. Introduction

Because various equipment and devices of high precision and compactness are required in medical, aerospace, and nuclear industries, research in precision machining technology has been received intensive attention.[1-6] The Magnetic Abrasive Machining (MAM) is a ultra-finishing process, which uses magnetic abrasive particles as a tool to abrade workpiece surface to achieve extremely high quality surface finish. Because this method can be applied to any workpiece shapes, it offers the advantage for abrading parts which cannot be easily machined, such as the inner face of a long pipe with a small diameter. For this reason, many studies on the magnetic abrasive finishing process have been carried out.[7-20] One critical process parameter for the magnetic abrasive machining is the intensity of the magnetic field which can affect the abrasiveness of the magnetic abrasive particles. However, if the intensity of the magnetic field is increased by increasing the current through the electric coils, the number of coils must also be increased in order to prevent excessive heat generation around the coils. With an increased number of coils, the equipment becomes larger, which results in higher difficulty in disassembling, assembling, and transportation.[21-24]

In this study, a magnetic pole vibration device that uses a proximity sensor for magnetic abrasive equipment using a permanent magnet was developed with the goal of analyzing the performance of the magnetic abrasive machining equipment, focusing on how the surface roughness of STS 304 pipes is affected by the magnetic pole arrangement.

2. Experimental Investigation

2.1 Specimen and experimental setup

In this study, STS 304 pipes, which are used to feed highly purified materials for LED and semi-conductor production, were used as specimens. Fig. 1 shows the schematic of the pipe specimen. Table 1 and 2 list the chemical composition and mechanical properties of the specimen, respectively. Due to the miniature size of the experimental device and the consideration of the ease of magnetic pole arrangement, an Fe-Nd-B type permanent magnet was used for the experiment. Fig. 2 shows a schematic view of the magnetic abrasive equipment. In Fig. 2(a), the workpiece is fixed by a chuck on the spindle, and it rotates as the spindle rotates. A magnetic tool is supplied to inside the workpiece and a permanent magnet pole is arranged outside the workpiece. Fig.

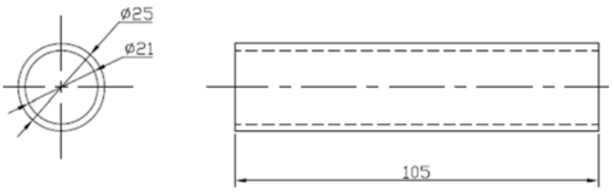


Fig. 1 Schematic of STS 304 pipe setup

Table 1 Chemical composition of STS 304

Ingredients	C	Si	S	Ni	Cr	Mn	P
Content	0.08	1.00	0.03	8.0~ 10.5	18~ 20	1.00	0.04

Table 2 Mechanical properties of STS 304

Young's modulus (Gpa)	Tensile strength (Mpa)	Yield strength (Mpa)	Elongation (%)
203.2	720	60	7

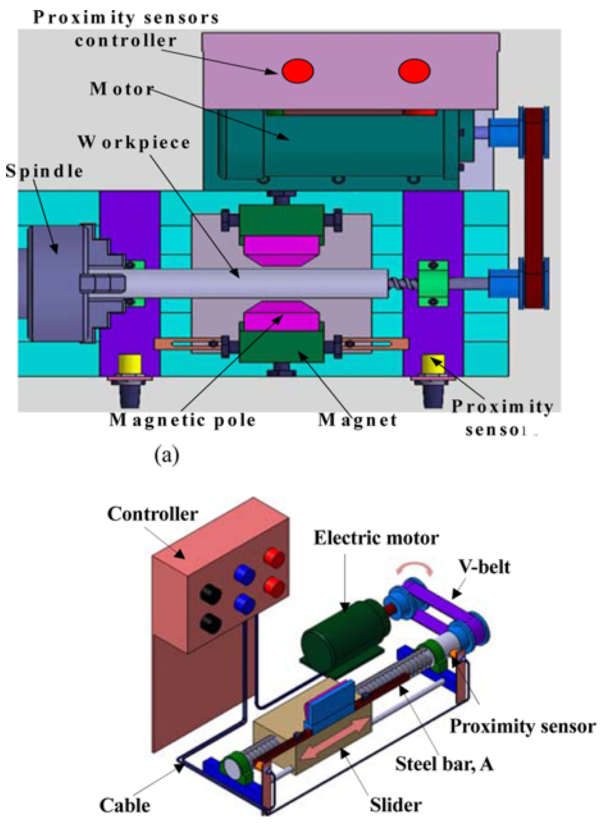


Fig. 2 Schematic of the experimental setup

2(b) shows a schematic view of the equipment used to add vibration to the magnetic pole. The magnetic vibration device consists of proximity sensors, slider, electric motor, and control system. A proximity sensor with the detection distance of 8mm and a normal and reverse rotational 25w-rated electric motor with an electro-magnetic brake were used for this equipment. When steel bar approaches the proximity sensors on the left and right, these proximity sensors detect that the steel bar approaches and the detection signal leads the direction of the motor in

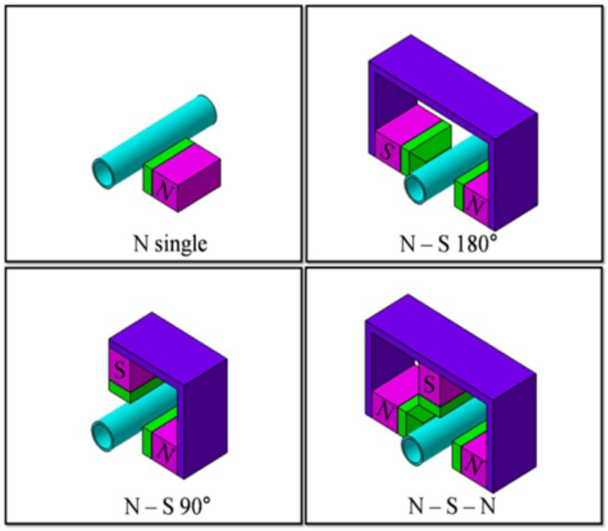


Fig. 3 Schematic of magnetic pole arrangements

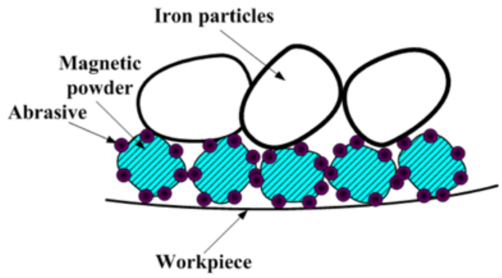


Fig. 4 Machining principles of magnetic abrasive finishing process

Table 3 Mechanical properties of STS 304 pipe

Spindle speeds	200, 600, 1000 , 1400 (rpm)
Workpiece	STS 304 stainless steel pipe (od: 25 mm, l: 105 mm, t: 2 mm)
Processing time	10(min)
Vibration of magnetic poles	Amplitude: 5 mm Frequency: 1
Mixed ratios	Iron : magnetic abrasive (1:1, 3:1, 6:1)
Processing conditions	Wet (0.5 ml light oil), Dry
Magnetic pole arrangement	N single, N-S 90°, N-S 180°, N-S-N

the opposite way, which results in the transfer of magnet. In this system, the transfer amount can be adjusted by adjusting the distance between the steel bar and the proximity sensor. In this experiment, this distance was set to be 2 mm.

2.2 Experimental procedures

In the magnetic abrasive finishing of the inner face of the pipe, the magnitude and direction of the magnetic force acting on the magnetic abrasive particles depend on the magnetic pole arrangement. The abrasion effect on the workpiece, therefore, is affected by the pole arrangement. Four magnetic pole arrangements were investigated in this study, which included N single, N-S 90º, N-S 180º, and N-S-N arrangements (Fig. 3). The #320 magnetic abrasive materials and the #200 iron particles were mechanically mixed in a specific ratio to form

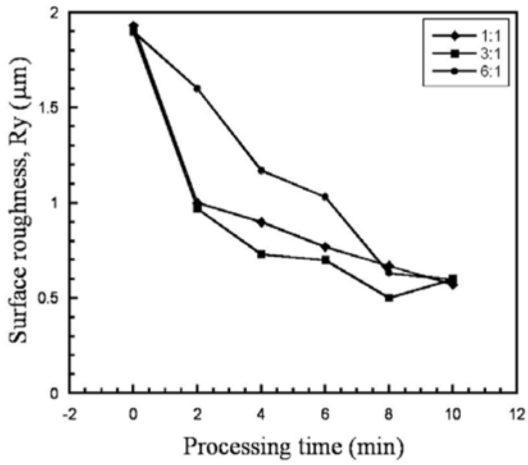


Fig. 5 Surface roughness (Ry) by abrasive mixed ratio (pole arrangement: N-S 90°, rotational speed: 1000 rpm, wet condition)

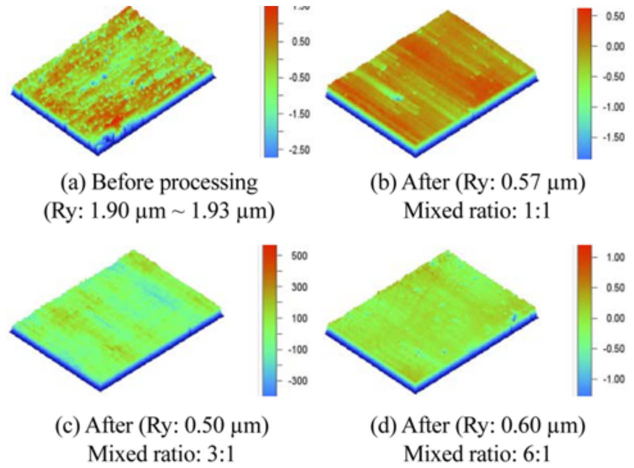


Fig. 6 Surface states of workpiece by abrasive mixed ratio

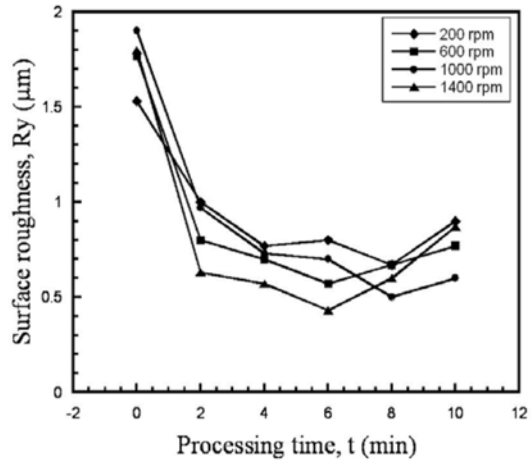


Fig. 7 Surface roughness (Ry) vs. rotational speeds with a pole arrangement: N-S 90°, abrasive mixing ratio: 3:1, and wet condition

the abrasive mixture with a total weight of 10 g, as shown in Fig. 4. Three abrasive mixtures, with a magnetic abrasive materials to iron particles ratio at 1:1, 3:1 and 6:1, were used in the experiment for four different spindle speeds at 200 rpm, 600 rpm, 1,000 rpm, and 1,400 rpm. The experimental conditions are shown in Table 3.

3. Experimental Results and Discussions

3.1 Surface roughness vs. abrasive mixed ratio

Fig. 5 shows the relationship between surface roughness measurements with different processing time for abrasive mixtures at different mixing ratios. This experiment was conducted using a magnetic pole arrangement of N-S 90°, a rotational speed of 1000 rpm, and 10 g of abrasive mixtures. The weight ratios of iron particles to magnetic abrasive materials were 1:1, 3:1, and 6:1. In general, surface roughness improves with a longer processing time, and the most improvement occur within the first two minutes. The best surface roughness values with abrasive mixing ratios of 1:1, 3:1, and 6:1 were 0.57 μm, 0.50 μm, and 0.6 μm, respectively. Fig. 6 shows the optical microscope images of three-dimensional surface textures of the workpiece before (Fig. 6(a)) and after processing (Figs. 6(b)~(d)). Apparently, the surface roughness shown in Fig. 6(a) is worse than those shown in Fig. 6(b)~(d). The workpiece of Fig. 6(c) was processed by an abrasive mixture with a mixing ratio of 3:1. The surface roughness improvement of the workpiece in Fig. 6(c) shows an improvement of 73.7% over that of Fig. 6(a) in terms of the Ry value of surface roughness, superior to the other two cases in Figs. 6(b) and 6(d). It is likely that the abrasive mixture with a 3:1 mixing ratio is more effective than the one with a 1:1 ratio because, at the mixing ratio 1:1, even though more abrasive particles are available for the abrading action but the force against the workpiece surface generated by the iron particles is small; therefore, it is less effective.

On the other hand, when the mixing ratio of iron particles to magnetic particles is 6:1, even though the force against the workpiece surface could become higher, but the number of abrasive particles available for abrasion is less to reduce the abrasion effect. In conclusion, the mixing ratio is an important process parameter for the magnetic abrasive finishing process.

3.2 Surface roughness vs. spindle speeds

To investigate how surface roughness is affected by the spindle speed, we employed a magnetic pole arrangement of N-S 90° and 10 g of abrasive mixture with a mixting ratio 3:1. The spindle speeds used were 200 rpm, 600 rpm, 1,000 rpm, and 1,400 rpm. Fig. 7 illustrates the relationship between the surface roughness and processing time at different spindle speeds. The surface roughness value in Ry were found to improve from 1.53 to 0.67 μm, 1.77 to 0.57 μm, 1.73 to 0.50 μm, and 1.80 to 0.43 μm for speeds of 200, 600, 1,000, and 1400 rpm, respectively. The best surface finish was achieved with 1,400 rpm, a 76.1% improvement, while the improvement was 71.1%, at 1,000 rpm.

3.3 Surface roughness vs. wet or dry processing conditions

To observe the variation in surface roughness using wet or dry processing conditions, we used a magnetic pole arrangement of N-S 90° and a spindle speed of 1,000 rpm. The mixing ratio was 3:1 for both processing conditions. In the wet condition, 0.5 ml of light oil was

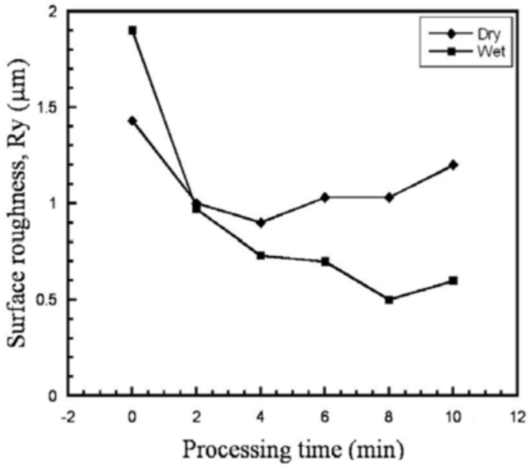


Fig. 8 Surface roughness (Ry) under dry and wet conditions (pole arrangement: N-S 90°, abrasive mixed ratio: 3:1, rotational speed: 1000 rpm)

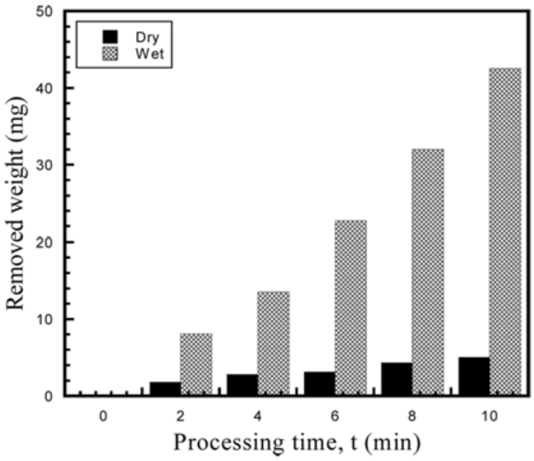
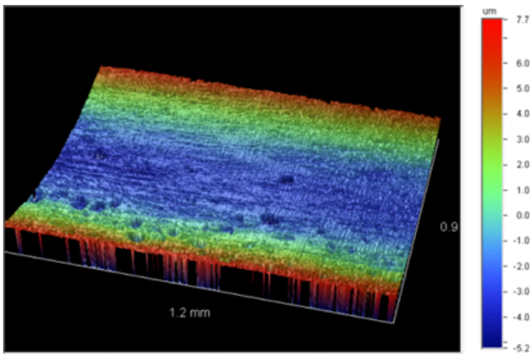
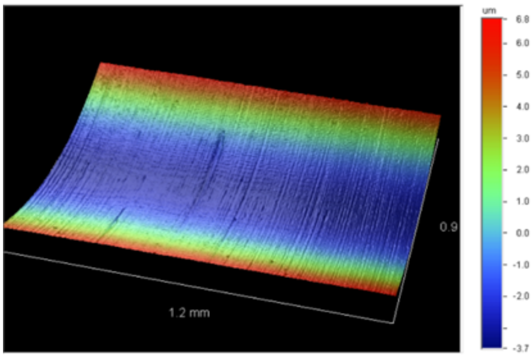


Fig. 10 Removed material in weight under dry and wet conditions (pole arrangement: N-S 90°, abrasive mixing ratio: 3:1, rotational speed: 1000 rpm)



(a) Dry condition (Ry: 0.90 μm)



(b) Wet condition (Ry: 0.50 μm)

Fig. 9 Three-dimensional surface shape by optical profiler

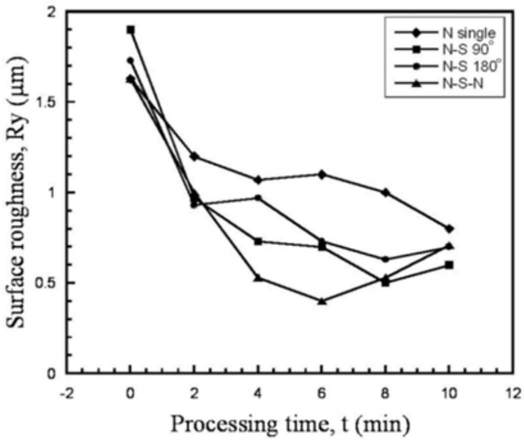


Fig. 11 Surface roughness (Ry) for different pole arrangements (rotational speed: 1000 rpm, abrasive mixing ratio: 3:1, light oil: 0.5 ml)

added to the abrasive mixture. No light oil was used in the dry condition.

Fig. 8 shows the trend in the variation in surface roughness depending on whether the condition was dry or wet. The rate of improvement in surface roughness was approximately 73.7% in the case of the wet condition, which is significantly higher than the 37.1% improvement achieved with the dry condition. It was also observed that the surface finish no longer improves after four minutes of processing.

Fig. 9 shows the three-dimensional images of the specimens after processed by the wet (Fig. 9(a)) and dry conditions (Fig. 9(b)). These images were obtained using a non-contact type optical microscope. The surface roughness was 0.90 μm for the dry condition and 0.50 μm for the wet condition, which difference is so obvious that it could be easily distinguished with naked eyes.

Fig. 10 shows the removed weight by the wet and dry conditions. After 10 min of magnetic abrasion on the inner face of the pipe, the total removed weight by abrasion was 42.5 mg in the wet condition and 5 mg in the dry condition. Therefore, it is concluded that the addition of light oil to the mixing abrasive powders could significantly affect the abrasion amount and the surface roughness. Therefore, it is desirable to use the wet processing condition by adding light oil to the abrasive mixture.

3.4 Surface roughness vs. magnetic pole arrangements

To study the effect of the magnetic pole arrangement on the surface roughness, we conduct experiments using a rotational speed of 1,000 rpm and a mixing ratio of 3:1 for four different pole arrangements at the wet processing condition. The magnetic pole arrangements used were N

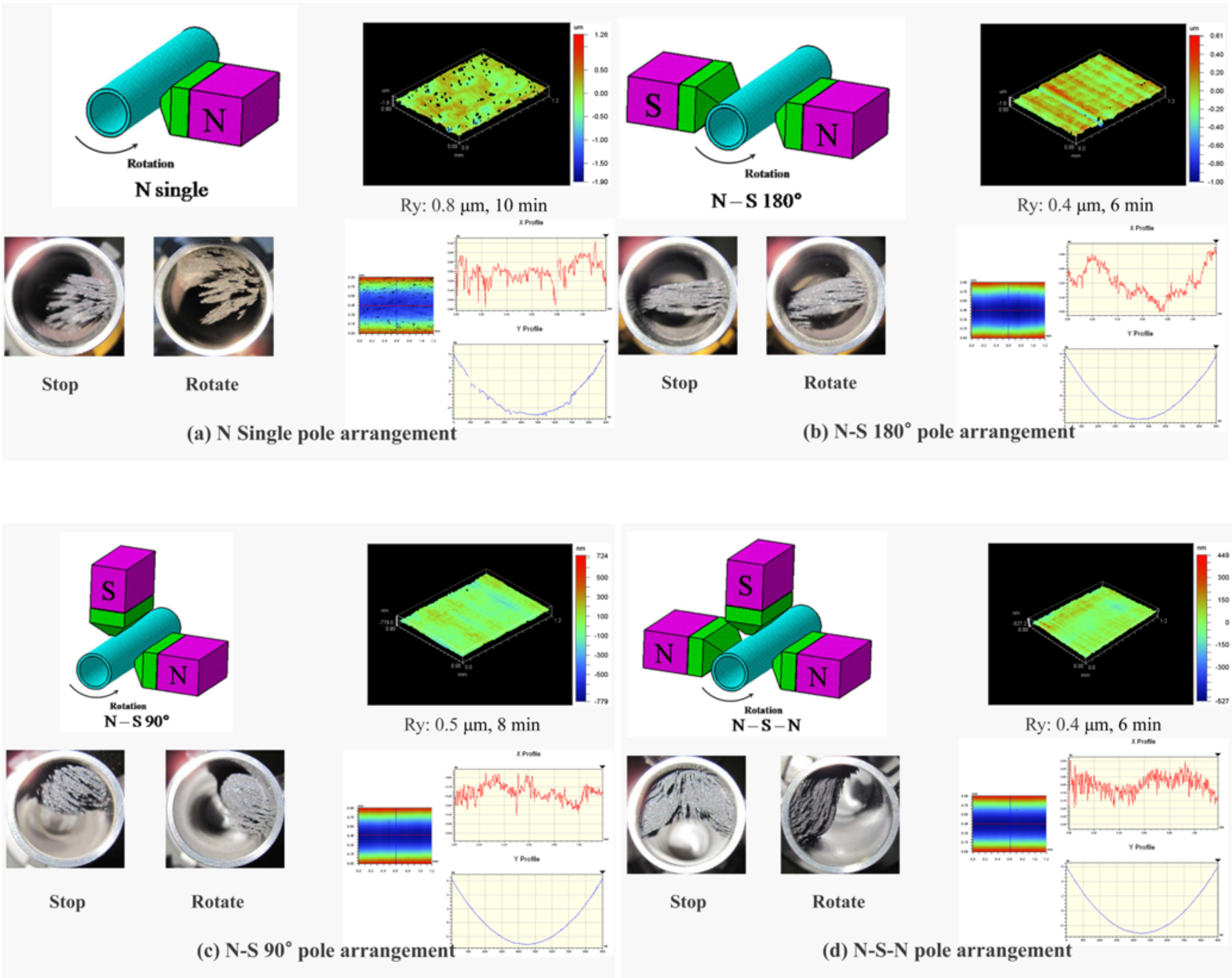


Fig. 12 Photo of magnetic abrasive behavior

single, N-S 90°, N-S 180°, and N-S-N. Fig. 11 shows the variation in surface roughness for different magnetic pole arrangements. The surface roughness measured by Ry of the inner face of the pipe shows improvement in all four magnetic pole arrangements. The best surface roughness was achieved after 10 min using the N single arrangement, after 8 minutes using the N-S 90° arrangement, after 8 min using the N-S 180° arrangement, and after 6 min using the N-S-N arrangement.

The surface roughness improvements were 50.9%, 70.6%, 63.6% and 75.5%, respectively. It can be seen that the magnetic pole arrangement of N-S-N offers the best surface finish. Fig. 12 shows the inner pipe surfaces before and after processing and the behaviors of the magnetic abrasive mixtures for different magnetic pole arrangements. In the case of N single magnetic pole arrangement, it covers a smaller area of the inner face of the pipe than those of the other three pole arrangements; therefore, the removal rate and surface roughness improvement rate for the N single pole arrangement are the lowest (Fig. 13). For the case of N-S 180° and N-S 90° arrangements, which use a pair of magnetic poles, have a larger abrasion area. The surface roughness improvement rates for these two conditions were 63.6% and 70.6%, respectively. In the case of the N-S-N magnetic pole arrangement, the magnetic abrasive materials were arranged in the form of a "八" in the left and right of

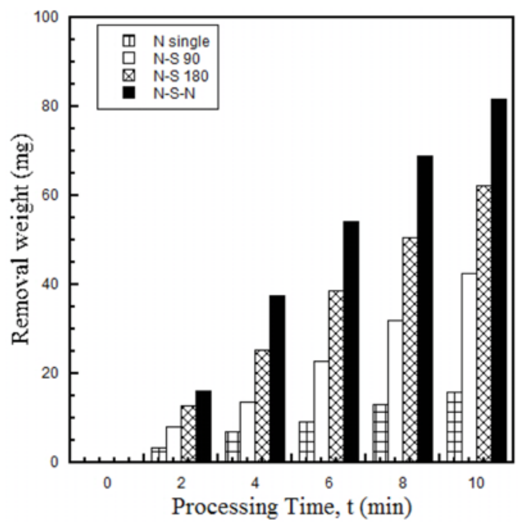
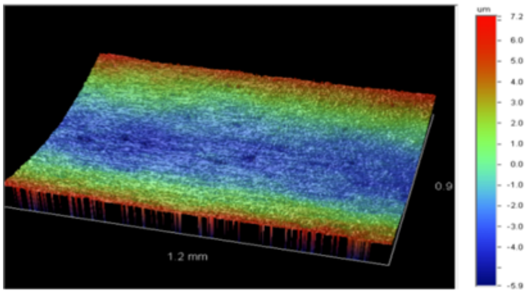
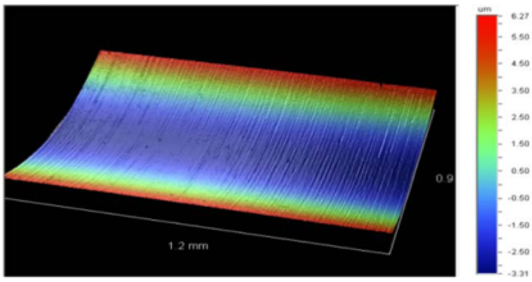


Fig. 13 Removed weight by pole arrangement (abrasive mixed ratio: 3:1, rotational speed: 1000 rpm, wet condition, light oil: 0.5 ml)

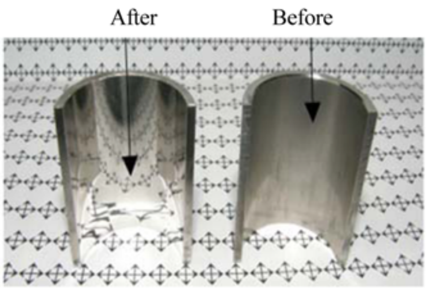
the pipe's inner face, with the S pole placed in the center. In this arrangement, when the pipe rotates, the abrasive materials accumulate



(a) Before Ry: 1.63 μm, Ra: 0.19 μm



(b) After Ry: 0.40 μm Ra: 0.052 μm



(c) Photo of inner face after magnetic abrasive finishing

Fig. 14 Three dimensional surface shape

at locations between about 90° (where the right side of the N pole is 0°) and 225°, with the particles leaning into the direction of rotation. Furthermore, the magnetic field of the N pole in the 0° direction formed a reactive magnetic field against the magnetic pole in the 180° direction to exert a force pressing on the abrasive materials. Therefore, the effectiveness of the N-S-N arrangement is likely due to the fact that it offers a larger abrasion area and a higher pressing force.

Fig. 14 shows the result of abrasion on the inner face of the pipe after six minutes of abrasion processing when the best processing of the inner face of STS 304 pipe was achieved using the N-S-N magnetic pole arrangement. This result was measured using a non-contact type optical microscope and digital camera. The surface roughness was 0.4 μm (Ra: 0.052 μm and Ry: 0.4 μm), and the roughness on the processing face was uniform in the direction of the rotation of the workpiece. Fig. 14(c) shows a comparison of the reflectivity of the workpiece. A mirror finish is confirmed if all the symbols at the bottom can be projected onto the finished surface.

4. Conclusions

A vibration device which makes the magnetic pole vibrate using proximity sensors was applied to the magnetic abrasive finishing equipment, and STS pipes were machined in various conditions. As a result, following conclusions were obtained.

1) The abrasive mixture with a mixing ratio of 3:1 weight ratio offers the best surface finish with an improvement 73.7%.

2) It appears that higher spindle speeds offers higher surface finish. At 1,400 rpm, the highest speed tested, the improvement is 76.1%.

3) The wet processing, in which lubrication fluid is added to abrasive particles, has advantage over the dry processing in terms of material removal and surface roughness improvement.

4) The magnetic fields of different magnetic pole arrangements change the behavior of the magnetic abrasive mixture, thus impacting the abrasion effect. Among the four different pole arrangements investigated, the M-S-N magnetic pole arrangement provides the best surface finish with a surface finish improvement of 75.5% and a surface roughness of 0.4 μm in the Ry value.

ACKNOWLEDGEMENT

"This paper was supported by research funds of Chonbuk National University in 2011."

REFERENCES

1. Song, J. H. and Mun S. D., "Research Papers: Materials Processing; Machinability of CBN Tools in Interrupted Milling Process of Die & Mold Steels with High Hardness," Korean Journal of Metals and Materials, Vol. 48, No. 7, pp. 651-659, 2010.
2. Yamaguchi, H. and Shinmura, T., "Study of the Surface Modification Resulting from an Internal Magnetic Abrasive Finishing Process," Wear, Vol. 225, No. 1, pp. 246-255, 1999.
3. Mun, S. D., "Micro Machining of High-Hardness Materials using Magnetic Abrasive Grains," Int. J. Precis. Eng. Manuf., Vol. 11, No. 5, pp. 763-770, 2010.
4. Shinmura, T. and Yamaguchi, H., "Precision Surface Finishing of Si3N4 Fine Ceramic Components by the Application of Magnetic Abrasive Machining Process," Journal-Japan Society for Precision Engineering, Vol. 67, No. 12, pp. 1986-1990, 2001.
5. Chen, W., "Cutting Forces and Surface Finish when Machining Medium Hardness Steel using CBN Tools," International Journal of Machine Tools and Manufacture, Vol. 40, No. 3, pp. 455-466, 2000.
6. Wang, Y., Zhao, Q., Shang, Y., Lv, P., Guo, B., and Zhao, L., "Ultra-Precision Machining of Fresnel Microstructure on Die Steel using Single Crystal Diamond Tool," Journal of Materials Processing Technology, Vol. 211, No. 12, pp. 2152-2159, 2011.
7. Zareena, A. R. and Veldhuis, S. C., "Tool Wear Mechanisms and Tool Life Enhancement in Ultra-Precision Machining of Titanium," Journal of Materials Processing Technology, Vol. 212, No. 3, pp. 560-570, 2012.

8. Sato, T., Yamaguchi, H., Shinmura, T., and Okazaki, T., “Study of Internal Finishing Process for Capillary using Magneto-rheological Fluid,” Journal of the Japan Society for Precision Engineering, Vol. 75, No. 5, pp. 612-616, 2009.

9. Kwak, T., “Machining Properties to Nano-Level Mirror Surface Finishing for Fine Grained WC-Co 18% Alloy using Magnetic Polishing Slurry,” Journal of the Korean Ceramic Society, Vol. 46, No. 1, pp. 102-107, 2009.

10. Jain, V., “Magnetic Field Assisted Abrasive based Micro-/Nano-Finishing,” Journal of Materials Processing Technology, Vol. 209, No. 20, pp. 6022-6038, 2009.

11. Judal, K .B. and Yadava, V., “Electrochemical Magnetic Abrasive Machining of AISI304 Stainless Steel Tubes,” Int. J. Precis. Eng. Manuf., Vol. 14, No. 1, pp. 37-43, 2013.

12. Im, I. T., Mun, S. D., and Oh, S. M., “Micro Machining of an STS 304 Bar by Magnetic Abrasive Finishing,” Journal of Mechanical Science and Technology, Vol. 23, No. 7, pp. 1982-1988, 2009.

13. Kang, J. and Yamaguchi, H., “Internal Finishing of Capillary Tubes by Magnetic Abrasive Finishing using a Multiple Pole-Tip System,” Precision Engineering, Vol. 36, No. 3, pp. 510-516, 2012.

14. Yamaguchi, H., Srivastava, A. K., Tan, M. A., Riveros, R. E., and Hashimoto, F., “Magnetic Abrasive Finishing of Cutting Tools for Machining of Titanium Alloys,” CIRP Annals-Manufacturing Technology, Vol. 61, No. 1, pp. 311-314, 2012.

15. Yamaguchi, H., Kang, J., and Hashimoto, F., “Metastable Austenitic Stainless Steel Tool for Magnetic Abrasive Finishing,” CIRP Annals-Manufacturing Technology, Vol. 60, No. 1, pp. 339-342, 2011.

16. Yamaguchi, H. and Shinmura, T., “Study of an Internal Magnetic Abrasive Finishing using a Pole Rotation System: Discussion of the Characteristic Abrasive Behavior,” Precision Engineering, Vol. 24, No. 3, pp. 237-244, 2000.

17. Das, M., Jain, V., and Ghoshdastidar, P., “Nano-Finishing of Stainless-Steel Tubes using Rotational Magnetorheological Abrasive Flow Finishing Process,” Machining Science and Technology, Vol. 14, No. 3, pp. 365-389, 2010.

18. Das, M., Jain, V., and Ghoshdastidar, P., “Nanofinishing of Flat Workpieces using Rotational-Magnetorheological Abrasive Flow Finishing (R-MRAFF) Process,” The International Journal of Advanced Manufacturing Technology, Vol. 62, No. 1-4, pp. 405-420, 2012.

19. Shinmura, T. and Yamaguchi, H., “Study on a New Internal Finishing Process by Applying Magnetic Abrasive Machining. Internal Finishing of Stainless Steel Tubings and Clean Gas Bombs,” Transactions of the Japan Society of Mechanical Engineers Series C, Vol. 59, No. 560, pp. 1261-1267, 1993.

20. Sato, T., Yamaguchi, H., Shinmura, T., and Okazaki, T., “Study of Internal Finishing Process for Capillary using Magneto-rheological Fluid,” Journal of the Japan Society for Precision Engineering, Vol. 75, No. 5, pp. 612-616, 2009.

21. Yamaguchi, H., Shinmura, T., and Takenaga, M., “Development of a New Precision Internal Machining Process using an Alternating Magnetic Field,” Precision Engineering, Vol. 27, No. 1, pp. 51-58, 2003.

22. Yan, B. H., Chang, G. W., Cheng, T. J., and Hsu, R. T., “Electrolytic Magnetic Abrasive Finishing,” International Journal of Machine Tools and Manufacture, Vol. 43, No. 13, pp. 1355-1366, 2003.

23. Chang, G., Yan, B., and Hsu, R., “Study on Cylindrical Magnetic Abrasive Finishing using Unbonded Magnetic Abrasives,” International Journal of Machine Tools and Manufacture, Vol. 42, No. 5, pp. 575-583, 2002.

24. Yin, S. and Shinmura, T., “A Comparative Study: Polishing Characteristics and its Mechanisms of Three Vibration Modes in Vibration-Assisted Magnetic Abrasive Polishing,” International Journal of Machine Tools and Manufacture, Vol. 44, No. 4, pp. 383-390, 2004.