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Uniform Internal Finishing of SUS304 Stainless Steel Bent Tube Using a Magnetic Abrasive Finishing Process

This research studies the factors affecting the conditions required for successful uniform internal finishing of SUS304 stainless steel bent tube by a Magnetic abrasive finishing process. In particular, the effects of the magnetic field and ferrous particles were investigated. Local intensification of the magnetic field is accomplished by offsetting the axis of pole rotation from elbow axis. This effect enables local control of the material removal rate, which leads to uniformity in the finished surface regardless of the initial surface conditions. A two-phase finishing process controlling the size of the ferrous particles is proposed to achieve efficient fine surface finishing. [DOI: 10.1115/1.1951786]

Introduction

Magnetic abrasive finishing processes were proposed for the internal finishing of tubes used for high purity gas and liquid piping systems to replace electrolytic polishing or pre-processing [1–5]. Previous research presented the finishing principle, the finishing equipment, and a method to produce nearly uniform finished internal surfaces of SUS304 stainless steel complex shaped tubes, which incorporate straight and bent sections [6]. Due to the geometry at the bend, the positional relationship changes between the pole tip, or magnetic field generator, and the inner surface of the bent tube, or finishing area, depending on the region of the tube surface. As a result, the magnetic field and, therefore, the finishing force are hardly uniform over the entire finishing area. This changes the magnetic abrasive behavior in addition to the finishing force against the inner surface of the tube and thus changes the finishing characteristics.

In the previous research, nonuniformities in surface finish were found to exist at the bent section of the tube (representative of the bent sections of fittings) between the inside, outside, and lateral regions [6]. The unevenness of the finished surface at the bent section was in the range of 0.05–0.15 μm in *Ra*, and the surface roughness in the inside region was about three times rougher than that in the outside and lateral regions. This resulted from not carefully controlling the magnetic force and abrasive behavior for the initial surface conditions, which varied from part to part.

Aluminum oxide (WA) composite magnetic abrasive with a mean diameter of 80 μm is currently the only commercially available magnetic abrasive in Japan and is generally used for this process. It contains aluminum oxide with grain size less than 10 μm sintered with iron in an inert gas atmosphere with high temperature and pressure [7]. This deficiency in the variety of available magnetic abrasive results in a narrow range of finishing performance. So in practical use, a mixture of ferrous particles and WA magnetic abrasive (called "mixed-type magnetic abrasive") is employed for the finishing process [3]. The ferrous particles experience greater magnetic force and play a role in pressing the WA magnetic abrasive and preventing the WA magnetic abrasive from dispersing [3].

The magnetic force acting on the magnetic abrasive is the predominant component of the finishing force, and it is determined by the magnetic field at the finishing area and the material properties and geometry of the ferrous particles mixed with the magnetic abrasive. This paper investigates the effects of these factors on the magnetic force and behavior of the mixed-type magnetic abrasive in addition to the finishing characteristics of SUS304 stainless steel bent tubes. These studies reveal the finishing mechanism and identify the finishing conditions required for successfully diminishing the nonuniformity in the finished surface.

Magnetic Force and Abrasive Behavior

Magnetic Field at the Finishing Area. In the process, the poles, which consist of permanent magnets, are placed outside the bent tube and generate the magnetic field needed for attracting the magnetic abrasive to the finishing area. In a nonuniform magnetic field, a magnetic force F acts on the magnetic abrasive, driving it [8].

$$F = V\chi H \cdot gradH \quad (1)$$

where V is the volume of the magnetic abrasive, χ is the susceptibility, and $H \cdot gradH$ is the intensity and gradient of the magnetic field.

When the poles rotate around the bent tube, the magnetic abrasive rotates along the inner surface of the bent tube along with the poles, and removes material from the surface. Manipulating the rotating poles along the tube axis causes the magnetic abrasive to follow both the poles' rotational and axial motion, finishing the entire inner surface of the tube.

In conditions with weak magnetic force acting on the magnetic abrasive, the abrasive disperses and adheres to the surface of the bent tube because of friction, and it cannot follow the movement of magnetic field regardless of the motion of the poles [9]. This eliminates the relative motion of the magnetic abrasive against the inner surface needed for the finishing operation and results in unsuccessful finishing.

The magnetic field is a predominant factor of the finishing force [Eq. (1)] acting on the magnetic abrasive particles and driving their dynamic behavior. The effects of the magnetic field on the magnetic abrasive behavior in the case of internal finishing of SUS304 stainless steel elbows (10 mm OD, 8 mm ID, and 41 mm radius of curvature) were examined with the finishing unit used in previous research for bent tubes with ID > 13 mm (see Fig. 1) [6]. The experimental conditions are shown in Table 1. Electrolytic iron particles (330 μm mean diameter), which have been intro-

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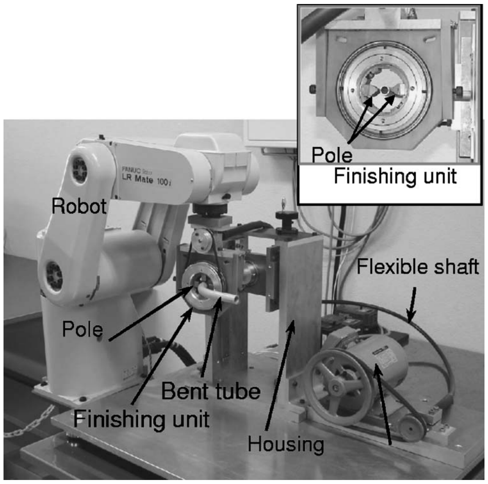
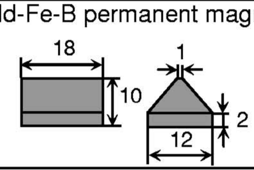
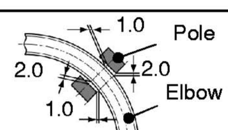


Fig. 1 External view of experimental setup

duced previously as ferrous particles with WA magnetic abrasive for the internal finishing of elbows, were used for the experiments. In the case of diametrically opposed poles, the distance between the parallel pole faces was fixed at 13 mm to avoid any collision between the elbow and poles, as shown in Fig. 1. The driving pass of the finishing unit was determined by the smallest clearance between the pole and elbow at the bent section, and the smallest clearance at the bent section was 1.0 mm while the largest was 2.0 mm.

Table 1 Experimental conditions

Workpiece	SUS304 stainless steel 90° bright annealed elbow: ∅10 × ∅8 mm Radius of curvature: 41 mm
Magnetic abrasive	WA magnetic abrasive: 0.12 g (80 μm mean diameter)
Ferrous particles	Iron particles (330 μm mean diameter) S48C carbon steel pins (∅0.5×2.5 mm) : 0.48 g
Pole	Nd-Fe-B permanent magnet 
Pole revolution	2000 min^{-1}
Pole feed speed	1.0 mm/s
Clearance	 Pole-pole distance: 13 mm
Lubricant	Soluble type barrel finishing compound: 0.26 mL / 16 strokes
Finished length	64.4 mm

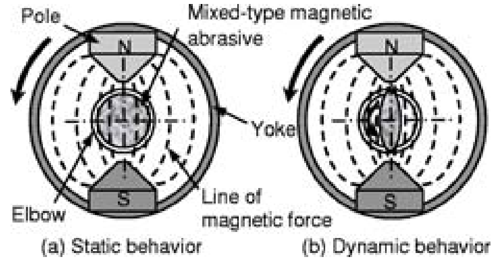


Fig. 2 Two-dimensional schematics of abrasive behavior with N-S 180 deg pole arrangement

Figure 2 shows two-dimensional schematics of the abrasive behavior in a magnetic field. The condition with diametrically opposed poles was called N-S 180°. As Fig. 2(*a*) shows, the electrolytic iron particle mixed-type magnetic abrasive adheres to the surface of the elbow regardless of the rotation of the magnetic field at 2000 min^{-1} due to the lack of the magnetic force acting on it. To achieve internal finishing, the mixed-type magnetic abrasive must be held by magnetic force inside the elbow, but only in the regions corresponding to the pole tips, as shown in Fig. 2(*b*). In this condition, the mass of the mixed-type magnetic abrasive shows dynamic rotational motion following the movement of the magnetic field.

The pole arrangement is a major parameter affecting the magnetic field, and a pair of N and S poles arranged at 90° must generate greater magnetic field intensity than the same pair arranged at 180° (Figs. 2 and 3) [10,11]. Therefore, the finishing unit was modified to accommodate the N-S 90° arrangement, as shown in Fig. 3. In the case of N-S 90 deg, two counterweights were mounted to eliminate vibration caused by the load imbalance. The magnetic flux density, a function of the magnetic field intensity, was measured by a hall device (1.0 × 2.25 mm) to examine the effects of the pole arrangement on the magnetic field in the finishing area.

Figure 4 shows the changes in the magnetic flux density B_y and $B_y(\mathrm{d}B_y/\mathrm{d}y)$ at the center of the pole with distance y. The term $B_y(\mathrm{d}B_y/\mathrm{d}y)$ was calculated based on the measured values of B_y, and the absolute value of $B_y(\mathrm{d}B_y/\mathrm{d}y)$ is considered to be a term of the magnetic force shown in Eq. (1). The N-S 90 deg case shows higher values of $|B_y(\mathrm{d}B_y/\mathrm{d}y)|$ than the N-S 180 deg case. This leads to a higher magnetic force in the N-S 90 deg case acting on the mixed-type magnetic abrasive at the finishing area, as shown by Eq. (1).

With the N-S 90 deg configuration, the mixed-type magnetic abrasive showed smooth rotational motion following the poles' rotation at 2000 min^{-1}, as shown in Fig. 3(*a*). This indicated that,

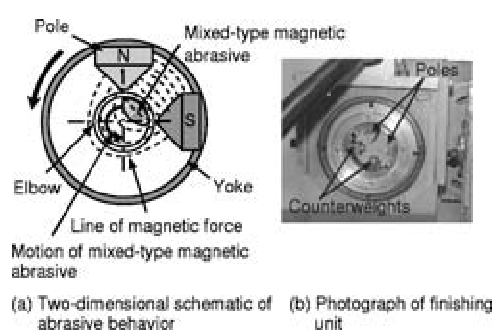


Fig. 3 Two-dimensional schematics of abrasive behavior and photograph of finishing unit with N-S 90 deg pole arrangement

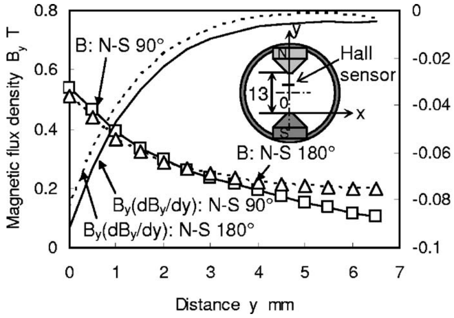


Fig. 4 Changes in magnetic flux density B_y and $B_y(dB_y/dy)$ at center of magnetic pole with distance from pole tip

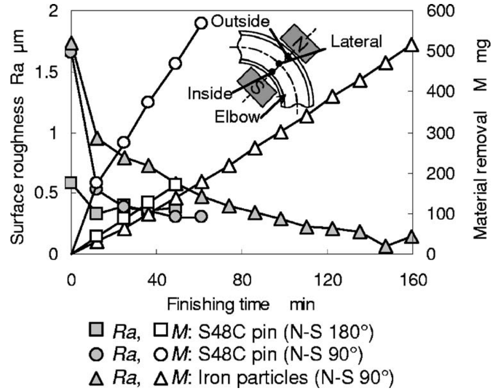


Fig. 5 Changes in surface roughness at outside of elbow and material removal with finishing time

using this finishing unit, the magnetic field can be controlled by adjusting the pole arrangement to intensify the magnetic field and its gradient at the finishing area.

Ferrous Particles Mixed with Magnetic Abrasive. As Eq. (1) shows, the magnetic force acting on a ferrous particle is a function of the particle's volume V and the susceptibility χ of the material. S48C carbon steel pins have greater susceptibility and produce higher magnetic force in the magnetic field than electrolytic iron particles [12], and S48C carbon steel pins ($\varnothing 0.5 \times 2.5$ mm) were introduced into the elbow in place of electrolytic iron particles. The other conditions were as listed in Table 1.

The S48C carbon steel pin mixed-type magnetic abrasive showed smooth rotation along the inner surface of the elbow following the movement of the magnetic field, as shown in Fig. 2(*b*). The existence of the S48C carbon steel pins in the magnetic field distorts the magnetic field around the pins, generating enough magnetic force for them to follow the magnetic field rotation.

Introducing the S48C carbon steel pins as well as employing the N-S 90 deg arrangement should encourage the finishing operation by causing higher magnetic force to act on the mixed-type magnetic abrasive. The effects on the finishing characteristics of the magnetic field resulting from the N-S 90 deg pole arrangement and of the ferrous particles were examined through the internal finishing of the SUS304 stainless steel bright annealed elbows.

Discussion of Finishing Characteristics

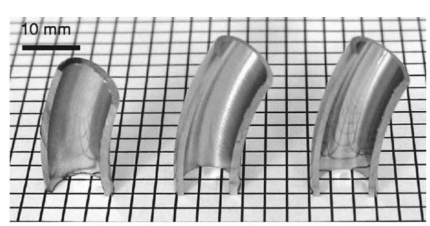
The finishing conditions followed Table 1 except where noted below. The pass length was 64.4 mm along the centerline of the elbow. The experimental period was determined by the reciprocating cycle (consisting of one stroke in each direction) of the finishing unit over the finishing area, and the period was 46 s per stroke. The surface roughness was measured in the axial direction of the elbow by a surface roughness profilometer using a contact stylus method. It and material removal were measured every 16 strokes of the finishing unit. The lubricant was mixed with the mixed-type magnetic abrasive at a rate of 0.26 mL every 16 strokes of the finishing unit. In each experiment, the finishing was stopped when the surface roughness improvement became negligible between measurements.

As representative of the finishing trend, Fig. 5 shows changes in surface roughness *Ra* at the outside of the elbow and material removal with finishing time. The material removal of the N-S 90 deg case with S48C carbon steel pins was about three times higher than the N-S 180 deg arrangement. This resulted from the higher magnetic force acting on the mixed-type magnetic abrasive in the N-S 90 deg case than in the N-S 180 deg case. The surfaces, however, showed similar roughness in both cases. The surfaces must be finished by severe contacts of the magnetic abrasive pressed by the pins against the target surface, generating deep scratches. This indicates the existence of a limitation of the surface roughness improvement using S48C carbon steel pin mixed-type magnetic abrasive.

In the N-S 90 deg case, the material removal rate of the abrasive mixed with electrolytic iron particles was slightly less than the S48C carbon steel pin mixture. While the abrasive mixture with S48C carbon steel pins reached the limitation of the surface roughness improvement in 80 strokes (61 min 20 s), the condition with the electrolytic iron particles continuously improved the surface roughness until 208 strokes (159 min 24 s) had been completed. The conditions with the S48C carbon steel pins in N-S 180 deg and N-S 90 deg achieved 0.38 μm *Ra* in 64 strokes (49 min 4 s) and 0.30 μm *Ra* in 80 strokes, respectively. In contrast, the condition with the 330 μm electrolytic iron particles in N-S 90 deg achieved 0.48 μm *Ra* in 80 strokes and 0.15 μm *Ra* in 208 strokes.

Figure 6 provides a comparison of the inner surfaces of elbows (a) unfinished and finished by the N-S 90 deg pole arrangement with (b) S48C carbon steel pin (after 80 strokes) and (c) 330 μm electrolytic iron particle (208 strokes) mixed-type magnetic abrasive. The finished surface clearly reflects the lattice under the bends only with the electrolytic iron particle mixed-type magnetic abrasive (c).

An obvious major difference between the electrolytic iron particles (330 μm mean particle size) and the S48C carbon steel pins ($\varnothing 0.5 \times 2.5$ mm) is geometry. This changes the magnetic force acting on the particles and the conformity at the finishing area. The abrasive mass consisting of the densely packed smaller-sized electrolytic iron particles must closely press the magnetic abrasive against the surface. In turn, the magnetic force acting on the electrolytic iron particles is transferred to the larger number of magnetic abrasive particles. This reduces the finishing force and depth of cut of each cutting edge of the magnetic abrasive. For electro-



(a) Unfinished surface (b) Surface finished with S48C carbon steel pin mixed- type magnetic abrasive (80 strokes) (c) Surface finished with Electrolytic iron particle mixed- type magnetic abrasive (208 strokes)

Fig. 6 Photograph of inner surface of elbows (*a*) unfinished and finished by N-S 90 deg arrangement with (*b*) S48C carbon steel pin and (*c*) electrolytic iron particle mixed-type magnetic abrasive

lytic iron particles, this resulted in an accumulation of microscratches with smaller depths of cut and achieved finer surface finishing.

These experiments show that the finishing characteristics are controlled by the relationship between the magnetic field, ferrous particles, and magnetic force; which together determine the magnetic abrasive behavior. The iron particle mixed-type magnetic abrasive in the N-S 90 deg configuration improved the inner surface the most from 1.00 μm *Ra* to 0.05 μm *Ra* in the inside region, from 1.73 μm *Ra* to 0.15 μm *Ra* in the outside region, and from 0.47 μm *Ra* to 0.16 μm *Ra* in the lateral region of the elbow. Accordingly, the magnetic field generated by the N-S 90 deg pole arrangement was sufficient to finish the elbow with the finishing equipment shown in Fig. 1.

The next chapter discusses the finishing mechanism in view of the relationship between the ferrous particles, magnetic force, and magnetic abrasive behavior in detail with the N-S 90° pole arrangement. The discussion will include the proposal of methods for uniform fine finishing.

Achievement of Uniform Fine Finishing

Discussion of the Finishing Mechanism. The relationship between the geometry of ferrous particles and dynamic behavior of the mixed-type magnetic abrasive are discussed with respect to the experimental observations. In addition to 330 μm mean diameter iron particles and S48C steel pins ($\varnothing 0.5 \times 2.5$ mm), 150 and 510 μm mean diameter iron particles were prepared for the experiments. The other conditions were the same as in Table 1.

Except for the 150 μm iron particle mixed-type magnetic abrasive, the abrasive showed smooth rotational motion following the poles' rotation. A fixed amount of mixed-type magnetic abrasive was supplied into the elbow, so the smaller that the ferrous particles are, the more particles are present. With a greater number of particles, the magnetic force acting on each particle is smaller. If the tangential component of the magnetic force is larger than the friction force between the particles and the inner surface of the elbow, the particles show smooth relative motion against the inner surface of the elbow, removing the material. With a smaller magnetic force, the ratio of the sum of the gravitational force and centrifugal force to the magnetic force in the radial direction on each particle is increased. This increases the ratio of the friction forces to the tangential component of the magnetic force acting on the mixed-type magnetic abrasive. This must inhibit the dynamic motion of the 150 μm iron particle mixed-type magnetic abrasive.

As shown in Fig. 4, the magnetic field is weaker toward the center of the elbow. In the case of larger supply of 150 μm iron particle mixed-type magnetic abrasive, the weak magnetic force toward the center of the elbow is insufficient to hold the particle in position. Elimination of the unstable excess abrasive results in the smooth rotational motion of the entire abrasive mass. The reduction from 0.6 to 0.2 g induced smooth rotation along the inner surface of the elbow.

Based on this observation, the finishing experiments were performed with 330 and 510 μm iron particles and S48C steel pins, because 150 μm iron particles required different conditions than the other ferrous particles for adequate finishing performance. The other experimental conditions followed Table 1. The magnetic flux density at the clearance between the elbow and pole tip was measured since the shape of the elbow prevents accurately measuring the finishing force, pressure, and torque under finishing conditions.

Figure 7 shows the magnetic flux density at the clearance between the elbow and pole tip for the three kinds of mixed-type magnetic abrasive. Larger ferrous particles lead to slightly higher magnetic flux densities. As mentioned above, a reduction in the particle size increases the number of particles in the process. Therefore, the magnetic force transferred from the ferrous particles to each magnetic abrasive particle must be smaller when smaller ferrous particles are used.

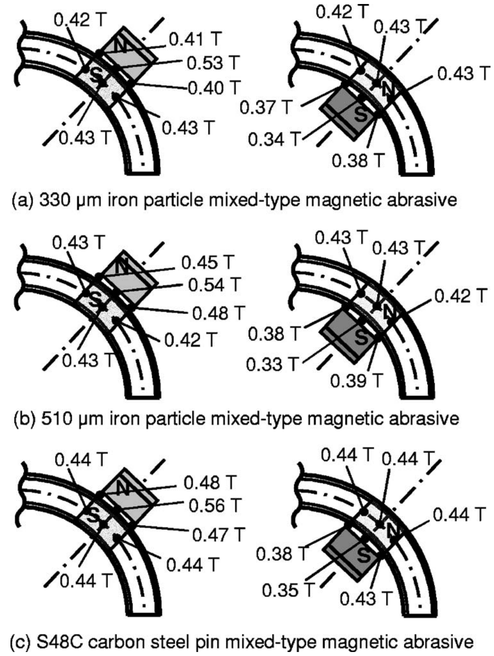


Fig. 7 Magnetic flux density at clearance between elbow and pole tip under the finishing conditions with mixed-type magnetic abrasive

Figure 8 shows changes in material removal and surface roughness at the outside with finishing time for iron particles of 330 and 510 μm mean diameter and S48C steel pins. The flexibility in the configuration of the mixed-type magnetic abrasive mass is a function of the stiffness of its component chains controlled by the magnetic force. In the case of the 330 μm iron particle mixed-type magnetic abrasive, the mass shows lower stiffness relative to the other mixed-type magnetic abrasives. As a result, the relatively longer wavelength components of the roughness profiles remain on the surface after the finishing process. The larger the ferrous particle, the greater is the magnetic force pressing each magnetic abrasive. This increases the depth of cut of the abrasive as well as the stiffness of the mixed-type magnetic abrasive. The material is more efficiently removed, but the surface roughness profiles show greater irregularities with increasing particle size, as shown in Fig. 9.

Figure 10 shows scanning electron microscope (SEM) photographs of the inner surface at the outside of the unfinished elbow and elbows finished by electrolytic iron particle and S48C steel pin mixed-type magnetic abrasive. The surfaces show deeper scratches and dents made as the ferrous particles pressing the

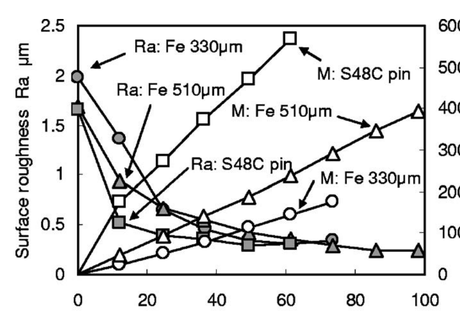


Fig. 8 Changes in surface roughness at outside the elbow and material removal with finishing time

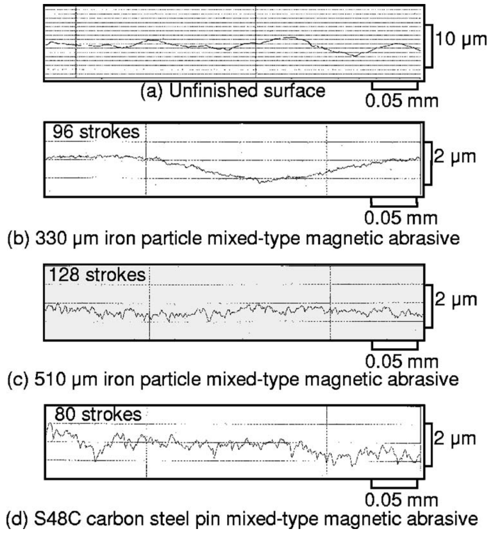


Fig. 9 Surface roughness profiles of unfinished and finished by mixed-type magnetic abrasive with iron particles, 330 and 510 μm, and S48C carbon steel pins

magnetic abrasive become larger. This also explains the irregularities shown in the profiles of Fig. 9. The magnetic force generated with 330 μm iron particles is sufficient to remove the relatively higher frequency components of the surface but is insufficient to remove the longer wavelength components. Therefore, the surface finished with 330 μm iron particles and abrasive showed less damage, as shown in Fig. 9(*b*), but with a higher roughness value, as shown in Fig. 8, than the 510 μm iron particles.

In the process, the mass of S48C carbon steel pins must have difficulty in conforming to the shape of the elbow due to the geometric relationship between the pins and the elbow surface. This causes irregular motion of the pins and the magnetic abrasive under the finishing process. In contrast, the mass of iron particles and magnetic abrasive easily conforms its shape to the inner surface of the elbow. The magnetic abrasive pressed by the pins showing irregular motion strikes the target surface with stronger magnetic force, generating the deep gouges shown in Fig. 10(*d*). This suggests that the additional magnetic force and irregular motion of the magnetic abrasive must over-remove the material from the surface by generating gouges and disturbing the surface roughness improvement.

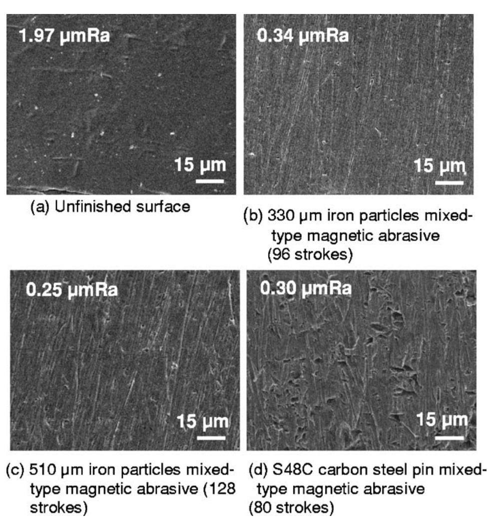


Fig. 10 SEM microscopy of inner surface of elbow at outside (*a*) unfinished; finished by electrolytic iron particle (*b*) 330 μm and (*c*) 510 μm; and (*d*) S48C carbon steel pin mixed-type magnetic abrasive

Of the three conditions, the 510 μm iron particles achieved the smallest surface roughness value, 0.25 μm *Ra*, at the outside region of the inner surface of elbow. The lateral and inside regions were 0.22 and 0.16 μm *Ra*, respectively. While the 330 μm iron particles produced 0.34, 0.10, and 0.09 μm *Ra* in the outside, lateral, and inside regions, respectively; the S48C steel pins showed 0.30, 0.45, and 0.20 μm *Ra*. As the ferrous particle size becomes smaller, the better the mass of the mixed-type magnetic abrasive conforms to the surface of the elbow at the finishing area. This promotes the fine contacts of the magnetic abrasive with the surface, performing fine finishing along the inner surface of the elbow.

Consequently, it was found that the geometry of the ferrous particles mixed with the abrasive changes the magnetic force as well as conformity of the mixed-type magnetic abrasive to the inner surface of the elbow. These factors affected the dynamic behavior of the mixed-type magnetic abrasive against the inner surface, and thereby controlled the finishing characteristics. The magnetic abrasive pressed against the inner surface of the elbow with greater finishing force by larger ferrous particles efficiently removes material but generates irregularities on the surface due to the uneven contacts of the magnetic abrasive with the surface, especially in the inside region. In these experiments, the 330 μm iron particle mixed-type magnetic abrasive generated the least damage to the finished surface while better following the inside shape of the elbow.

The elbows used in this research initially have deep scratches in the outside region due to the mandrel used in the bending process. This causes nonuniformity in the surface roughness in the initial condition and increases the difficulty of achieving uniform fine finishing. In order to diminish the unevenness in the finished elbows, more material must be removed from the outside region to remove the deep scratches, which is necessary to obtain a mirror finished surface. The next section will propose methods to satisfy this requirement.

Two-Phase Finishing Process. The size reduction of the ferrous particles to less than 330 μm was expected to promote finer finishing. As mentioned above, the 150 μm iron particle mixed-type magnetic abrasive could be made to experience smooth rotation along the inner surface of the elbow with 0.2 g supplied. With these points considered, a two-phase finishing process was introduced to improve the surface smoothness. Experiments were performed using either 330 or 510 μm iron particle mixed-type magnetic abrasive in the first phase. When the improvement of the surface roughness diminished, the mixed-type magnetic abrasive was switched to the 150 μm iron particle mixed-type magnetic abrasive with the supplied amount of lubricant reduced from 0.26 to 0.09 mL. The finishing experiments were terminated when the process ceased to significantly affect the surface roughness.

Figure 11 shows the changes in the surface roughness and material removal with finishing time. The change in the slope of the material removal rate corresponds to the point between the first and second phases. The differences in surface roughness with finishing time were hardly detected after finishing for 112 strokes (85 min 52 s) in the case of 330 μm iron particles and 146 strokes (110 min 24 s) for 510 μm iron particles. In each case, the difference between the final surface roughness measurement and the previous measurement was 0.1% or less and was, therefore, considered to be negligible. At those points in the experiments the iron particles were switched to 150 μm in both cases.

The case of 330 μm iron particles show final surface roughness values of 0.20, 0.08, and 0.03 μm *Ra* in the outside, lateral, and inside regions, respectively, after 160 strokes (122 min 40 s). The 510 μm iron particle case shows 0.16, 0.08, and 0.03 μm *Ra*, respectively, for 224 strokes (171 min 44 s). This experiment

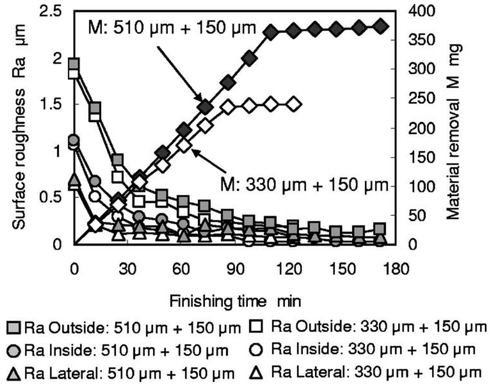


Fig. 11 Changes in surface roughness and material removal with finishing time

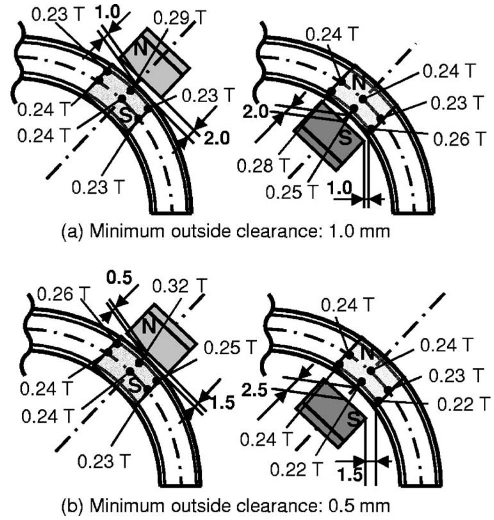


Fig. 12 Magnetic flux density at finishing area in cases of minimum outside clearance 1.0 and 0.5 mm.

showed the effectiveness of the application of smaller ferrous particles and the feasibility of a two-phase finishing operation for improving the surface roughness. Because of the elbow geometry, the inside region has overlapping finishing marks to a greater extent than the other regions, promoting the finishing performance at the inside region. This resulted in the relatively better finished surface than the other regions, so unevenness of the surface remained.

Offset of Pole Rotation Axis From Elbow Axis. The smaller the clearance between the inner surface and pole tip, the higher is the magnetic force acting on the magnetic abrasive. Therefore, the offset of the pole rotation axis from the elbow axis must locally control the magnetic field intensity, and experiments were performed to utilize this effect. The experimental conditions followed Table 1. Without exception, the elbows as received have large nonuniformities and deviations in surface roughness. The surface as received was 1.9, 0.56, and 1.0 μm *Ra* in the outside, lateral, and inside regions, respectively. The surface roughness was measured in each region after 16 strokes of the finishing unit. Using the measured values as a guide, the pole axis was offset to intensify the field in the rougher regions as the need arose. In addition, two-phase finishing with 330 and 150 μm iron particle mixed-type magnetic abrasive was employed.

After the first period of finishing with the standard coaxial setting, the surface was finished to 0.81, 0.26, 0.46 μm *Ra* in the outside, lateral, and inside regions, respectively. In this case, the outside region needed to be finished the most. Therefore, the pole axis was offset in the radial direction to reduce the clearance at the outside region. Figure 12 shows the magnetic flux density at selected positions (without any abrasive at finishing area) in cases of minimum outside clearance of 1.0 and 0.5 mm. Since the distance between the parallel pole faces was set at 13 mm, offsetting of the pole rotation axis from the elbow axis by 0.5 mm results in a minimum clearance of 0.5 mm in the outside region and 1.5 mm in the inside and lateral regions. The offset of 0.5 mm was chosen as the largest that could be made without causing a collision between the elbow and poles. Such an offset of the pole rotation axis intensified the magnetic field in the outside region and reduced it in the inside region.

Figure 13 shows the changes in surface roughness and material removal with finishing time. The resulting finished surface showed only small deviations between the outside, lateral, and inside regions, which were 40, 47, 34 nm *Ra*, respectively. This method successfully diminished the nonuniformity in the finished surface, although the inside region showed a relatively smaller value than the others.

Conclusions

This research studied the factors affecting the finishing conditions required for successful uniform internal finishing of SUS304 stainless steel elbows. In particular, the effects of the magnetic field and ferrous particles were investigated. The results of this research can be summarized as follows:

(1) The pole arrangement can be adjusted to control the strength of the magnetic field, and a stronger field results in the proper rotation of more types of mixed-type magnetic abrasive. The size of the ferrous particles mixed with the magnetic abrasive changes the force and conformity of the abrasive to the inner elbow surface. By affecting the dynamic behavior of the mixed-type magnetic abrasive against the inner surface, these factors contribute to the control of the finishing characteristics;

(2) a two-phase finishing process controlling the size of the ferrous particles was proposed to achieve efficient fine surface finishing. In particular, the use of 150 μm iron particles after 330 μm iron particles was found to be effective;

(3) local intensification of the magnetic field was accomplished by offsetting the axis of pole rotation from elbow axis. This effect enables local control of the material removal rate. Furthermore, this control of the material removal rate leads to uniformity in the finished surface regardless of the initial surface conditions.

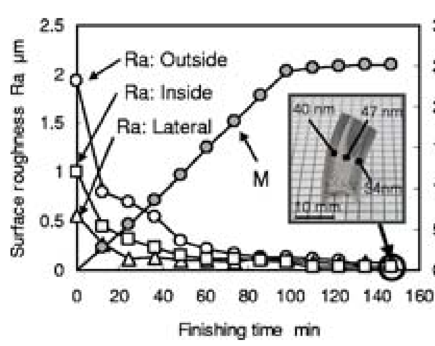


Fig. 13 Changes in surface roughness in outside region and material removal with finishing time

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