Study on a New Internal Finishing Process by the Application of Magnetic Abrasive Machining*  
(Internal Finishing of Stainless Steel Tube and Clean Gas Bomb)  

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In magnetic abrasive machining, the internal finishing of a nonferromagnetic tube is performed by means of the magnetic force generated between magnetic abrasive and the N-S magnetic poles. In this experiment, "mixed-type magnetic abrasive" are applied to finish the internal surface of a tube, in which large iron particles, generating a high finishing pressure, are mixed with magnetic abrasive resulting in finishing. By this new process using the mixed-type magnetic abrasive, the finishing efficiency is increased markedly. In this paper we describe the effects of both the size and the mixed weight percentage of iron particles on the surface roughness of a stainless steel tube. We also describe the application of the new process to the internal finishing of the bottom of a clean gas bomb for practical use. As a result, the surface roughness before finishing, 7 μm $R_{\text{max}}$, was reduced to 0.2 μm $R_{\text{max}}$ over the entire inner surface of the bottom.

**Key Words:** Polishing, Abrasive Grain, Surface Roughness, Internal Finishing, Magnetic Abrasive Machining, Magnetic Abrasive, Iron Particle, Stainless Steel Tube, Clean Gas Bomb, Magnetic Force

1. Introduction

Currently, a high-precision inner surface (less than 0.2 μm $R_{\text{max}}$) is required for a clean gas bomb and a clean gas piping system to prevent deposition of material such as dust. In the past, a high-precision surface has generally been produced by electrolytic polishing. This polishing process, however, involves problems such as high cost for deposition of the electrolyte and the need for a controlled atmosphere during polishing. Therefore, a new internal finishing process without the requirements of strict conditions and high cost is considered in place of electrolytic polishing. We have carried out research and development of a high-efficiency and high-precision internal finishing process, magnetic field-assisted finishing\(^{(1,2)}\).

We succeeded in increasing the finishing efficiency markedly by the utilization of "mixed-type magnetic abrasive" in which large iron particles, generating high finishing pressure, are mixed with magnetic abrasive, resulting in finishing. The finishing characteristics of this process are affected by the size and mixed weight percentage of iron particles. In this paper we describe the effects of these factors on the finishing characteristics.

Moreover, it was confirmed that this new finishing process using mixed-type magnetic abrasive is applicable to the internal finishing of the bottom of a clean gas bomb with a narrow opening which is hard to finish by the conventional finishing process. As an experimental result, a fine finished surface, 0.2 μm $R_{\text{max}}$, was obtained from a rough surface, 7 μm $R_{\text{max}}$, by the application of the new finishing process proposed in the present paper.

2. Magnetic Abrasive Machining Using Mixed-Type Magnetic Abrasive

2.1 Magnetic force acting on magnetic abrasive

Figure 1 shows a two-dimensional schematic view of the magnetic abrasive machining. Magnetic abrasive supplied into the tube are conglomerated at the finishing zone by the magnetic field, generating the finishing pressure. When the tube rotates at a high
speed, the relative motion between the tube and the magnetic abrasive makes the inner surface smooth.

As shown in Fig. 1, a nonuniform magnetic field is ordinarily generated at the finishing zone. As a result, the magnetic abrasive at position “A” is affected by the magnetic forces $F_x$ and $F_y$ ($F$: resultant force) given by Eq. (1). The magnetic abrasive particles become concentrated toward the finishing zone in which there exists a higher magnetic field strength, and exert pressure on the inner surface of the tube (2). The magnetic forces in Eq. (1) also prevent the dispersion of the magnetic abrasive particles.

$$F_x = kD^2 \chi H(\partial H/\partial x)$$
$$F_y = kD^2 \chi H(\partial H/\partial y)$$

Equation (1)

where $k$: coefficient, $D$: diameter of magnetic abrasive particle, $\chi$: susceptibility of particle, $H$: magnetic field strength, $(\partial H/\partial x)$, $(\partial H/\partial y)$: gradients of the magnetic field strengths in the directions of the equipotential line and magnetic line of force, respectively.

The distance between the poles is quite large in the internal finishing process of a tube shown in Fig. 1. Thus the magnitude of the magnetic field strength $H$ and its gradients $(\partial H/\partial x)$ and $(\partial H/\partial y)$ may have upper limits. The susceptibility $\chi$ of the magnetic abrasive particles is also constant during the production sequence. As a result of these factors, the magnitude of magnetic force should be increased by increasing the diameter $D$ in Eq. (1). Furthermore, magnitude of magnetic force is proportional to the cube of the diameter $D$.

2.2 Original idea of magnetic abrasive machining using mixed-type magnetic abrasive

As mentioned above, the magnetic force is affected by the diameter of the magnetic abrasive particles. However, magnetic abrasive is not common and is expensive due to the unique production process (3). Hence, we decided to mix large iron particles, generating a high finishing pressure, with small magnetic abrasive, resulting in finishing, shown in Fig. 2. The magnetic abrasive is magnetically attracted to the surface of the iron particles, effectively forming large magnetic abrasive particles, namely “mixed-type magnetic abrasive”. Conventional iron particles with various diameters are economically prepared, and it is expected that the diameter of the mixed-type magnetic abrasive particles can be controlled by changing the diameter of the iron particles. Forming various magnetic abrasive by the combination of small magnetic abrasive and various large iron particles in a magnetic field helps to reduce the production cost considerably.

The magnetic forces acting on the iron particles to exert pressure on the inner surface of the tube were first compared with those on the magnetic abrasive. The magnetic abrasive, 80 μm in mean diameter, and five kinds of electrolytic iron particles (Fe: 99%) with different diameters in the 75 to 1 680 μm range were prepared. As Fig. 3 shows, the magnetic forces were detected by strain gages fixed on the outer surface of the tube (using the equipment shown in Fig. 5). Figure 3 also shows the variation of the magnetic forces acting on the magnetic abrasive and the iron particles.

Although there is some dispersion, five kinds of iron particles show almost the same magnitude of the magnetic forces. It can be concluded that the magnitude of the magnetic forces generated by the iron particles are not appreciably dependent on the diameter. Moreover, these magnetic forces are about five times larger than that of the magnetic abrasive.

The finding that the magnetic forces of the iron particles are almost independent of the particle diameter is explained as follows. The magnitude of
the magnetic force acting on an iron particle is directly proportional to the cube of the diameter as mentioned before. The magnitude of the resultant force of the iron particles acting on the inner surface of the tube is obtained as the product of the number of the particles and the magnitude of the magnetic force of the particle given by Eq. (1). On the other hand, the number of particles supplied into the finishing area is inversely proportional to the cube of the diameter. It is, therefore, considered that the magnitude of the resultant force of the iron particles acting on the inner surface is independent of the diameter, as confirmed in Fig. 3.

The content of nonferromagnetic WA grains in a magnetic abrasive is 50% by volume. Hence, the susceptibility $\chi$ of the magnetic abrasive particles is much lower than that of the iron particles. Therefore, the magnetic force acting on the magnetic abrasive is much smaller than that of the iron particles.

It is expected from Fig. 3 that the magnitude of the magnetic force of the mixed-type magnetic abrasive takes the median value between those of the magnetic abrasive and iron particles. The magnetic force of the mixed-type magnetic abrasive may depend on the mixed weight percentage of the iron particles.

Figure 4 shows the variation of the magnetic forces of the mixed-type magnetic abrasive in the case that the iron particles are 330 $\mu$m in diameter. The measuring method was the same as that for Fig. 3. In Fig. 4 0 wt% means the case of magnetic abrasive only, and 100 wt% means the case of iron particles only. The case of using only the magnetic abrasive shows the smallest magnitude of magnetic force because of the highest percentage content of the nonferromagnetic WA grains. Conversely, the highest magnetic force is obtained in the experiment using only ferromagnetic iron particles. It was confirmed from Fig. 4 that the mixed-type magnetic abrasive generates the median value of the magnetic force between the value for the magnetic abrasive only and that for the iron particles only. The magnitude of the magnetic force increases with increasing mixed weight percentage of the ferromagnetic iron particles.

The increase of the mixed weight percentage of iron particles decreases the number of the cutting edges which cause the finishing. In consequence, it can be considered that the amount of material removal decreases, that is, the initial surface cannot be removed rapidly. In lapping, the finishing characteristics are considerably affected by the diameter of abrasive grains even under constant finishing pressure. Similarly, both the size and the mixed weight percentage of iron particles of mixed-type magnetic abrasive will probably affect the finishing characteristics predominantly under constant finishing pressure.

3. Experimental Setup and Conditions

Figure 5 is a photograph of the experimental setup of the magnetic abrasive machining for the internal finishing. The eccentric cam system enables the tube (SUS 304 clean pipe, 50.8 mm in outer diameter, 4 mm in thickness) to vibrate in the axial direction (frequency: 10 Hz, amplitude: 5 mm) along with a rotatory motion at the same time. The combination of the rotation and axial vibration facilitates achievement of a smooth surface rapidly by crossing the finishing locus of the abrasive. The experimental conditions are given in Table 1.
Table 1  Experimental conditions

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>SUS304 stainless steel tube ( \phi \ 50.8 \times \phi \ 42.8 \times 500 \text{mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic abrasive</td>
<td>WA grains (10µm under in dia.) sintered with iron particles, mean dia.: 80µm</td>
</tr>
<tr>
<td>Magnetic flux density</td>
<td>0.8T</td>
</tr>
<tr>
<td>Workpiece revolution</td>
<td>645rpm</td>
</tr>
<tr>
<td>Axial vibration of workpiece</td>
<td>Frequency: 10 Hz  \quad \text{Amplitude: 5 mm}</td>
</tr>
<tr>
<td>Supplied amount of mixed-type magnetic abrasive</td>
<td>40g</td>
</tr>
<tr>
<td>Lubricant</td>
<td>Straight oil type grinding fluid, 7 wt% supplied</td>
</tr>
</tbody>
</table>

![Fig. 5  External view of experimental setup](image)

**Fig. 5  External view of experimental setup**

4. Experimental Results and Discussions

Figure 6 shows the variation of the surface roughness with finishing time in the case of 60 wt% mixed weight of iron particles. The mixed-type magnetic abrasive consisted of five kinds of iron particles, from 75 to 1,680 µm in diameter. It is evident from Fig. 6 that 330 µm iron particles can reduce the surface roughness of the inner surface of the tube in the shortest time. It took only 4 minutes to reach a saturation level. The mechanism of this result is explained by the application of lapping theory as follows.

As mentioned before, the finishing pressure generated by the magnetic force is independent of the diameter of the iron particles. Using large abrasive makes the number of acting abrasive particles per finishing zone small and the finishing pressure per abrasive particle becomes large. Therefore, cutting depth of each abrasive particle becomes large and the amount of material removal increases. A smooth surface can thus be obtained. On the other hand, using small abrasive makes the number of acting abrasive particles per finishing zone large. The smaller the finishing pressure per abrasive particle, the less material removal occurs. Then, the initial rough surface is not appreciably removed. The same phenomenon will occur in internal finishing by magnetic abrasive machining using mixed-type magnetic abrasive. The diameter of the mixed-type magnetic abrasive should be defined by the diameter of the iron particles shown in Fig. 2. Although it is not shown here, when using large iron particles, 1,680 µm, the amount of material removal was large. Although the deep cutting depth caused by a large abrasive is effective in removing an initial surface, it cannot help to make a smooth surface as shown in Fig. 6. Conversely, in the case of 75 µm iron particles, the amount of material removal was small, and the initial rough surface remained. Accordingly, it can be concluded that 330 µm iron particles are the most suitable for high-efficiency finishing under the present conditions.

The effects of varying the mixed weight percentage of iron particles on surface roughness were investigated. Figure 7 shows the changes in surface roughness with finishing time in the case of 330 µm iron particles. It can be seen that using mixed-type magnetic abrasive can improve the surface roughness in much less time compared with using the magnetic abrasive or iron particles alone. By using only magnetic abrasive, less finishing pressure can be generated. Using only iron particles will result in shortage of abrasive grains to cause finishing. It can be concluded that a smooth surface can be obtained more rapidly with an optimal mixed weight percentage of iron particles. The case of 80 wt% iron particles can produce a smooth surface in least time as seen in Fig. 7. This experiment shows that the finishing characteristics are controlled by the interrelationship between the finishing pressure and the number of the cutting
edges of the abrasive grains.

When evaluating the experimental results, it was verified that using the mixed-type magnetic abrasive can accomplish high-efficiency internal finishing of a tube. Additionally, the finishing characteristics are controlled by the interrelationship of the size of iron particles, the finishing pressure, and the number of the cutting edges of the abrasive grains.

5. Application to the Internal Finishing of a Clean Gas Bomb

5.1 Experimental setup

Since the head of a clean gas bomb is made by hot forming (plastic deformation), the internal surface is rough, generally in the 60 to 70 μm $R_{\text{max}}$ range. Moreover, it is impossible to insert a conventional finishing tool into a clean gas bomb through the narrow opening. Until now, it is estimated that the internal finishing of the head of a clean gas bomb probably depends on barrel finishing and hand finishing. Therefore, development of a new precision internal finishing process of the head of a clean gas bomb is strongly required.

We applied the new high-efficiency internal finishing process using mixed-type magnetic abrasive proposed in this paper to the internal finishing of a clean gas bomb. Granular mixed-type magnetic abrasive can be easily inserted into and removed from a gas bomb through the narrow opening. The strategy used to generate magnetic force acting on mixed-type magnetic abrasive supplied into the workpiece from the magnetic poles placed outside the workpiece is applicable to the case of a bomb. The bottom of a bomb can be considered as a model of the head of the bomb due to the similar shapes. The technique proposed in this paper was applied to the internal finishing of the bottom of a bomb of 80 mm outer diameter and 5 mm thickness, instead of the head, for practical use.

Figure 8 shows the schematic view of the experimental setup. The bomb and the poles were rotated in opposite directions simultaneously to encourage the
relative motion between the tube and mixed-type magnetic abrasive. Figure 9 shows the arrangement of the rare-earth permanent magnets which generate a magnetic field at the finishing zone. Since the magnets are set on the turntable with different heights, the mixed-type magnetic abrasive attracted by the magnets can exert pressure over the entire inner surface at the bottom of the bomb, while the tube and poles rotate. This leads to finishing of the entire inner surface.

5.2 Experimental results

Figure 10 shows the experimental conditions and the variation of the surface roughness with mixed weight percentage after finishing for 40 minutes in the case of 330 μm iron particles. The initial surface roughness of the inner face of the bottom of a bomb was 7 μm $R_{\text{max}}$. It is observed from Fig. 10 that using either magnetic abrasive only (0 wt%) or iron particles only (100 wt%), does not result in a smooth surface. Even with longer finishing time, a smooth finished surface could not be obtained in both cases. Use of 50 wt% iron particles can achieve a smooth surface, 0.2 μm $R_{\text{max}}$, or even a mirror-finished surface. It was found that the interrelationship between the finishing pressure and the content of the abrasive affects the surface finishing. These results are similar to those in the case of the tube. Here, 50 wt% is the optimum value for obtaining a smooth surface, in constant to 60 wt% to 80 wt% for the case of the tube shown in Fig. 7. Although the exact reason for the difference between the two values was not obvious, the necessity of a suitable value of mixed weight percentage of iron particles to accomplish high-efficiency finishing was demonstrated. This value may depend on the shape, size, and material of the workpiece and the finishing conditions.

The effects of the diameter of iron particles on the surface roughness were investigated using three kinds of iron particles, 75, 330, and 1 680 μm in diameter, at the constant mixed weight percentage 50 wt%. Figure 11 shows the variation of the surface roughness with finishing time. Use of the 330 μm iron particles resulted in a smooth finished surface in the least amount of time, as in the case of a tube (see Fig. 6). This also shows the existence of an optimum diameter of iron particles for efficient smooth finishing of the bomb.

Fig. 10 Changes in surface roughness with mixed weight percentage of iron particles
[Conditions] Workpiece: SUS 304 spherical shape (see Fig. 9), workpiece revolution: 400 rpm, pole revolution: 400 rpm, mixed type magnetic abrasive: WA magnetic abrasive (mean dia.=50 μm) and iron particles (mean dia.=330 μm), supplied total weight of mixed type magnetic abrasive: 20 g, magnetic flux density: 0.64 T, lubricant: light oil (7 wt% supplied), finishing time: 40 min

Fig. 11 Changes in surface roughness with finishing time
[Conditions] Mixed weight percentage of iron particles: 50 wt%, other conditions: see Fig. 10

Fig. 12 Profiles of surface roughness and photograph of inner surface of bomb
[Conditions] Mixed weight percentage of iron particles: 50 wt%, other conditions: see Fig. 10
Accordingly, the most efficient smooth internal finishing of a bomb was realized with 50 wt% content of 330 μm iron particles. Figure 12 shows the profiles of the surface roughness and photographs of the internal surface of the bottom of the bomb before and after finishing. It is confirmed that a surface with a 7 μm \( R_{\text{max}} \) initial roughness could be finished to 0.2 μm \( R_{\text{max}} \) all over in 40 minutes.

6. Conclusions

The results obtained in this paper can be summarized as follows:

(1) A new efficient internal finishing process by magnetic abrasive machining, utilizing "mixed-type magnetic abrasive" in which large iron particles are mixed with magnetic abrasive, was proposed. The finishing mechanism was verified.

(2) The necessity of a suitable diameter and mixed weight percentage of iron particles to accomplish the efficient finishing was verified. In the case of the internal finishing of a tube, 330 μm iron particles in the content range of 60 to 80 wt% is a suitable condition.

(3) It was confirmed that the new finishing process using the mixed-type magnetic abrasive is applicable to the internal finishing of a clean gas bomb. Using this process, a smooth finished surface of 0.2 μm \( R_{\text{max}} \) could be obtained from a surface with initial roughness of 7 μm \( R_{\text{max}} \).

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