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High-speed Internal Finishing of Capillary Tubes by Magnetic Abrasive Finishing

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Abstract

In magnetic abrasive finishing, the development of a multiple pole-tip system using a partially heat-treated magnetic tool allows the finishing of multiple regions simultaneously in capillary tubes and thus improves the finishing efficiency. To further reduce the processing time required, a new high-speed machine is fabricated. This paper describes the development of the high-speed multiple pole-tip finishing equipment, which is capable of rotating the spindle up to 30000 min-1, and the effects of tube rotational speed on abrasive motion during the finishing experiments. Also, the finishing mechanisms of the high-speed machine are clarified.

Keywords: Finishing; Polishing; Magnetic abrasive finishing

1. Introduction

Austenitic stainless steel capillary tubes are widely used in medical devices, including catheter shafts and needles for injection or biopsy procedures. A smooth interior tube surface is required to prevent contamination, but as the tube diameter decreases, the more difficult the internal finishing becomes.

In a magnetic field, magnetic flux flows unimpeded through nonferrous workpiece material, and ferrous material—a component of the magnetic tool—is suspended by magnetic force. It is possible to influence the magnetic tool motion by controlling the magnetic field, thus enabling the finishing operation to be performed not only on easily accessible surfaces but also on areas that are difficult to reach by conventional mechanical techniques. A variety of Magnetic Field-assisted Finishing processes using this principle have been developed for the internal finishing of components [1-11].

The potential of the process using magnetic abrasive [12] for the internal finishing of capillary tubes has been demonstrated for tubes with inner diameters down to 0.4 mm [11]. However, the length of the finishing area is primarily dependent on the width of the magnetic pole tip and the total length of travel of the tip along the tube axis. In practice, difficulties associated with the insertion of the magnetic abrasive into the finishing area have limited the total finished length to just a few times the pole-tip width. To finish the entire surface of a long tube, several short finishing steps are required, leading to a long finishing time. To overcome this limitation, the use of a multiple-pole tip system with a magnetic tool has been devised. This method improves finishing efficiency by allowing for the simultaneous finishing of multiple areas [13, 14, 15]. The feasibility of the concept was demonstrated at a tube revolution rate of 2500 min-1. For further improvement of the finishing efficiency, an increase of the tube rotational speed is necessary.

This paper studies the application of a multiple pole-tip system for high-speed finishing of capillary tubes. Firstly, finishing equipment with double pole-tip sets is developed, which enables a tube to rotate up to 30000 min-1. Secondly, the effects of tube revolution on abrasive motion are investigated through the tube finishing experiments. Finally, the finishing mechanisms of the high-speed finishing are discussed.

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2. Development of high-speed finishing machine

Figure 1 shows a schematic for a method using double pole-tip sets, which generates magnetic fields in two finishing areas, and a photograph of the equipment developed to realize the method. The finishing area is doubled as magnetic abrasive is introduced and pushes against two regions of the tube surface. As the pole-tip sets move along the tube axis, and the finished area is extended. The number of pole-tip sets can be increased if required. For a constant pole-tip width, the finishing area will be a function of the total number of pole-tip sets. The double pole-tip sets require the introduction of a magnetic tool with the mixed-type magnetic abrasive. The tool guides the magnetic abrasive deep into the tube and increases the magnetic force acting on the magnetic abrasive [14].

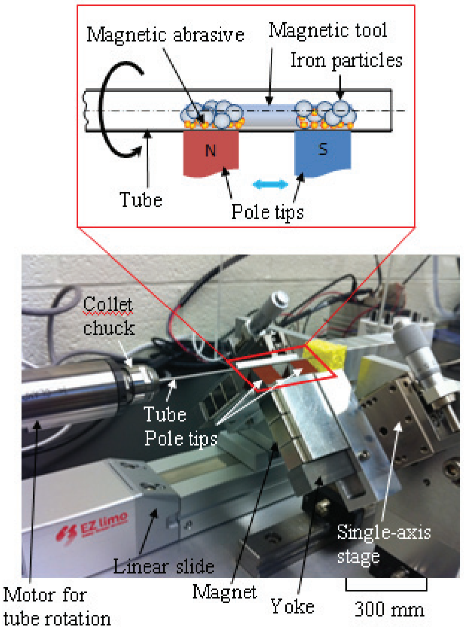


Fig.1 Schematic of processing principle and photograph of experimental setup with double pole-tip sets

The workpiece tube is chucked to a motor (speed range: 5000–30000 min-1). Two pole-tip sets consisting of six neodymium permanent magnets (12.7x12.7x12.7 mm; residual flux density 1.26–1.29 T; coercive force >875 AT/m) are mounted 12.7 mm apart on a single-axis micrometer stage, and their position is adjustable in the tube radial direction. To avoid collision between the rotating tube and pole tips, the pole-tip surfaces are covered by 0.3 mm thick polytetrafluoroethylene (PTFE) tape. The pole-tip sets are mounted on a linear slide so that they can be fed in the tube axial direction. The feed length and speed are adjustable to maximums of 150 mm and 600 mm/s, respectively.

Figure 2 shows changes in magnetic flux density By, measured by a Hall sensor (sensing area: ∅1.0 mm), with distance X for double pole-tip sets. The magnetic flux density and gradient increases from the center toward the edges of pole tip. A particle in the magnetic field is attracted to the pole-tip edges where the magnetic force is higher.

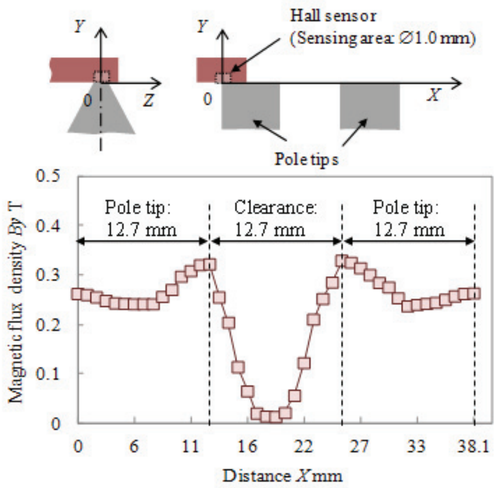


Fig. 2 Changes in magnetic flux density in double pole-tip sets at Y=0 mm

3. Experimental conditions

Table 1 Experimental conditions

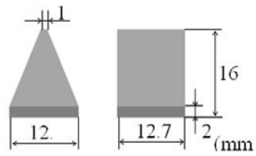
Workpiece	304 Stainless steel tube (Ø1.27x Ø 1.06x100 mm)
Workpiece revolution	500, 5000, 10000, 20000 and 30000 min^{-1}
Mixed-type magnetic abrasive	5 mg (Iron particles (150-300 µm dia.):80 wt%, magnetic abrasive (80 µm mean dia.): 20 wt%)
Magnetic tool	See Fig. 3
Pole-tip geometry	
Pole-tip feed	0.59 mm/s
Pole-tip feed length	12.7 mm
Workpiece-pole-tip clearance	0.3 mm (Polytetrafluoroethylene (PTFE) tape thickness)
Lubricant	Soluble-type barrel finishing compound (pH: 9.5, Viscosity: 755 mPa•s at 30°C)
Processing time	10 and 20 min

Table 1 shows the experimental conditions. Austenitic stainless steel tubes (304 stainless steel, ∅1.27x∅1.06x100 mm; 2–3 μm Rz initial surface roughness) were prepared as workpieces for this study. A 304 stainless steel tool with three heat-treated regions was used as a magnetic tool (see Fig. 3). The heat-treated regions became non-magnetic by reverting from BCC crystalline structure to FCC crystalline structure as a result of the normalization while the four un-treated sections remained magnetic [14]. The mixed-type magnetic abrasive separates as it is attracted to the ends of the four magnetic sections. The four magnetic regions correspond to each edge of the two magnetic pole-tips due to its stronger magnetic force [15]. The pole tip feed length was set to 12.7 mm, and the feed rate was set to 0.59 mm/s.

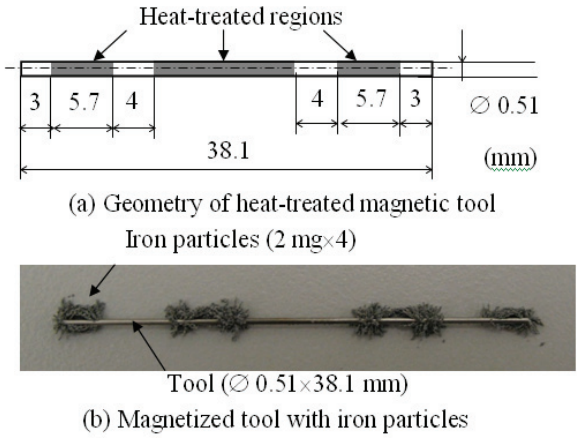


Fig. 3 Tool geometry and magnetized tool with iron particles

For the experiments, 5 mg of mixed-type magnetic abrasive (80 wt% iron particles and 20 wt% magnetic abrasive) [4] was introduced with the magnetic tool. The mixed-type magnetic abrasive and magnetic tool filled 21.4 vol%, and 23.1 vol% inside the tube, respectively. The tube rotational speeds were varied between 5000, 10000, 20000, and 30000 min-1. To encourage uniform internal surface coverage with the mixed-type magnetic abrasive prior to high-speed finishing, the tube was rotated at 500 min-1 with a single pole-tip stroke before finishing.

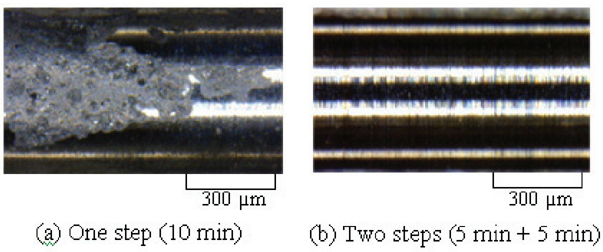


Fig. 4 Micrographs of surface finished for 10 min at 30000 min-1

In high-speed finishing, centrifugal force tends to cause the displacement of the lubricant from the finishing area, which in turn causes the mixed-type magnetic abrasive to adhere to the tube surface due to friction. Adhered material noticeably covered the surface in Figure 4(a), which shows the surface finished continuously for 10 min at a tube revolution rate of 30000 min-1. No adhered material is observed in Figure 4(b), which shows the surface finished for 10 min with lubricant added after 5 min. During the finishing process, the presence of lubricant is crucial to encourage the smooth relative motion between the mixed-type magnetic abrasive and the tube surface that facilitates finishing performance of the abrasive. Accordingly, in the cases of 20000 and 30000 min-1 tube revolution, the finishing experiments were interrupted to inject lubricant every 5 min. For the cases of 5000 and 10000 min-1 tube revolution, the finishing experiments were performed continuously for 10 min without additional lubricant injection. Each experiment was repeated at least three times to ensure the repeatability of the results. Before and after the finishing experiments, the tube was rinsed with ethanol in an ultrasonic cleaner for 1 hr.

4. Effects of tube rotational speed on finishing characteristics

Figures 5 and 6 show intensity maps and oblique plots—measured by an optical profiler at X=13 mm—of the unfinished surface and surfaces finished for 10 and 20 min, respectively. Figure 7 shows changes in material removal with tube revolution and finishing time. The surface finished for 10 min at a tube revolution of 5000 min 1 (Figure 5(b)) has a roughness of 0.15 μm Rz, but multiple irregular asperities from the initial surface remained. However, an extension of the finishing time for another 10 min allowed the abrasive to remove those irregular asperities (Figure 6(a)). The material removal after 20 min was more than twice the removal after 10 min (Figure 7). Although the magnetic abrasive was not exchanged during the interruptions to inject lubricant, the reconfiguration of the magnetic abrasive during these breaks encouraged the relocation of the sharp abrasive cutting edges. The sharp cutting edges and newly added lubricant seemed to refresh the finishing performance after each intermission.

At a tube revolution rate of 10000 min-1, the surface was smoothly finished (0.1 μm Rz) after 10 min, and the roughness value remained constant after 10 min of extra finishing time despite the additional material removal (Figure 6(b)). Compared to 10 min at a tube revolution rate of 10000 min-1, the material removal is drastically increased after finishing for 20 min. Analogous to the case of finishing for 20 min at 5000 min-1, the pauses to add lubricant after 10 min aided the finishing performance.

It was confirmed that the increase in the tube revolution (i.e., cutting speed) improves the material removal rate and finishing efficiency. However, due to the high centrifugal force, the high-speed tube rotation creates more opportunities for the mixed-type magnetic abrasive and magnetic tool to lapse into unstable conditions. The lack of a uniform magnetic abrasive distribution under an unstable rotating magnetic tool may lead to the deep, irregular scratches. This trend was observed in the case of 20000 min-1 (Figure 5 (d)), the finished surface has deep scratches and surface distortions. Extending the finishing time slightly increased the material removal due to the longer duration contact of the magnetic abrasive cutting edges against the tube surface and removed the relatively short-wavelength surface asperities (Figure 6(c)); however, the deep scratches produced by the irregular motion of the magnetic tool and mixed-type magnetic abrasive remained on the surface.

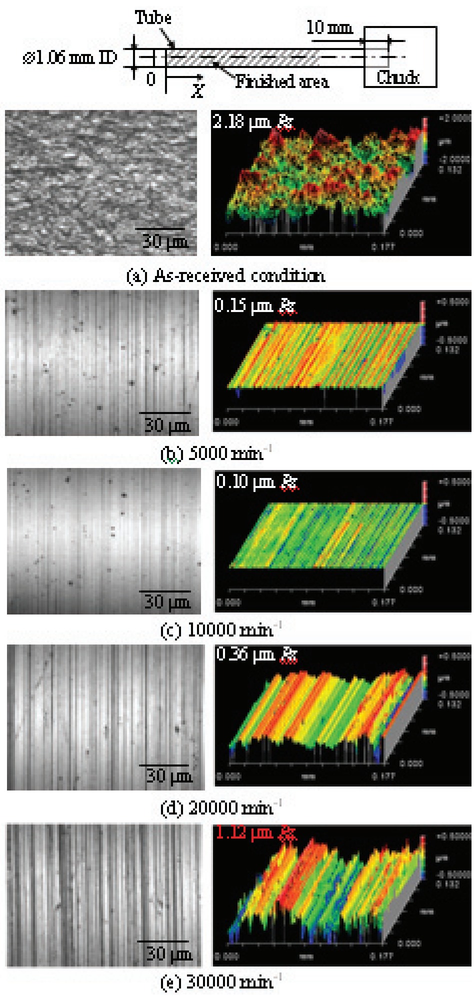


Fig. 5 Intensity maps and oblique plots of surface finished for 10 min

Further increase in the tube revolution, such as the 30000 min-1 test, further enhanced the irregularity of the motion of the magnetic tool and abrasive. The nonuniformly distributed mixed-type magnetic abrasive must be pressed against the surface by a rotating magnetic tool that is unstable due to the centrifugal force. This led to increased material removal and resulted in a surface consisting of deep scratches over long-wavelength asperities, as shown in Figure 5(e).

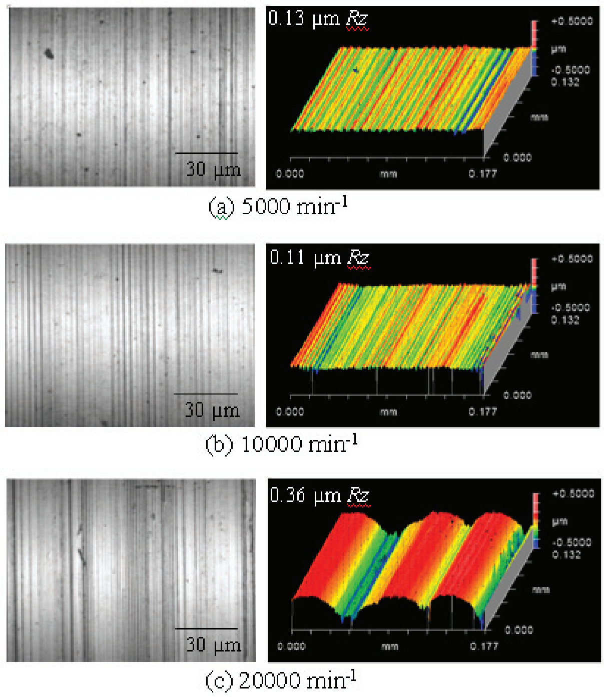


Fig. 6 Intensity maps and oblique plots of surface finished for 20 min

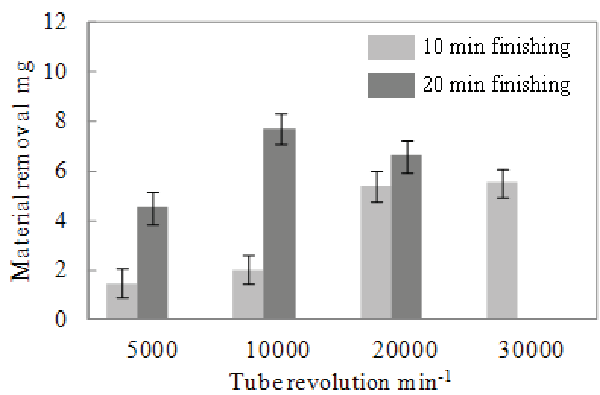


Fig. 7 Changes in material removal with tube revolution in double pole-tip system

Use of the previously developed multiple pole-tip finishing system [15] produced a uniformly finished surface (from 2–3 µm Rz to ~0.2 µm Rz) 72 mm long—

four times the pole-tip width—in 180 min. The high-speed finishing system proposed in this paper can produce a finished surface 50.8 mm long (four times the pole-tip width) in 10 min with a roughness of about 0.1 μm Rz. Thus the proposed high-speed finishing system is twelve times more efficient than its predecessor.

5. Conclusion

The results of this research can be summarized as follows:

1. A high-speed multiple pole-tip finishing system has been developed for finishing capillary tubes, and finishing experiments have been performed with tube revolutions up to 30000 min-1.
2. In the single pole-tip system, the magnetic abrasive is stable and performs efficient surface finishing up to 30000 min-1. Conversely, the magnetic abrasive and tool lapse into unstable conditions in the multiple pole-tip system at high speed due to high centrifugal force. This causes deep scratches and irregular asperities on the finished surface.
3. In this paper, 10000 min-1 is the highest tube revolution rate at which the high-speed internal finishing of a capillary tube using double pole-tip sets is successfully achieved. It produces a smoothly finished surface (≈0.1 μm Rz) and is twelve times more efficient than the previous multiple pole-tip finishing system.

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