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Technical note

Internal finishing of capillary tubes by magnetic abrasive finishing using a multiple pole-tip system

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ABSTRACT

Due to difficulties in controlling magnetic abrasive in the finishing area during internal magnetic abrasive finishing (MAF) of capillary tubes, the finished length is limited in practice to just a few times the pole-tip width. The accumulation of multiple short finishing passes is necessary for long-tube finishing, which results in excessive finishing times. The use of a multiple pole-tip system with a tool, a solid rod consisting of alternating magnetic and nonmagnetic regions, was proposed to overcome this issue. The tool enables multiple finishing regions to be engaged simultaneously. This paper clarifies the finishing characteristics and mechanism and shows the effects of the tool's magnetic properties (including the intervals between magnetic and non-magnetic regions) on the tool and abrasive motion and the interior finishing characteristics of capillary tubes. This paper also proposes a simple method to determine the pole-tip feed length, which allows the MAF process to achieve a uniformly finished surface in half the time of the existing single pole-tip system.

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1. Introduction

In the magnetic abrasive finishing process, material is removed as a result of the relative motion between the workpiece surface and magnetic abrasive under the influence of a magnetic field. Control of the magnetic field at the finishing area is required in order to generate the magnetic force necessary for finishing. The smaller the tube diameter (e.g., capillary tubes), the more critical is the control of the magnetic field. A simple method to adjust the magnetic field without modifying the finishing equipment is to change (1) magnetic properties or geometry of the magnetic abrasive [1–3] or (2) magnetic properties, geometry, or concentration of magnetic tools (such as ferrous particles, a ferrous rod, or a permanent magnet) inserted with the magnetic abrasive or conventional abrasive slurry [4–11]. The effectiveness of these techniques have been demonstrated for capillary tubes, widely used in medical applications and in precision analytical instruments [12,13]. However, the default finished length in the tube axial direction is limited by the pole-tip width. For example, a pole-tip width of 4 mm has been considered adequate for capillary tubes with inner diameters (ID) between 0.4 mm and 1 mm [12]. Feeding the pole tip in the tube axial direction theoretically allows the entire internal surface of a long tube to be finished. However, difficulties associated with the insertion of the magnetic abrasive into the finishing area limit the total finished length in practice to just a few times the pole-tip width. To finish the entire surface of a long tube, several short finishing steps are required, and this approach leads to a long finishing time.

To overcome this issue, an MAF process using a multiple pole-tip system has been proposed [14]. Magnetic properties of a metastable austenitic stainless steel tool can be changed by heat treatment, and multiple partial heat-treatments on a single tool can provide alternating magnetic and non-magnetic regions. The insertion of such a tool into a capillary tube with the magnetic abrasive generates multiple finishing regions as the magnetic abrasive is attracted to the border between the magnetic and non-magnetic regions on the single tool. This (1) facilitates the delivery of the magnetic abrasive deep into the tube and (2) realizes the simultaneous finishing of multiple regions.

The objectives of this paper are (1) to clarify the finishing characteristics and mechanism that control the multiple pole-tip system and improve the finishing efficiency and (2) to achieve a uniformly finished surface over the entire finished area. First, this paper will study the design of alternating magnetic properties (e.g., lengths of magnetic and non-magnetic regions) of the tool. Second, the interior finishing experiments of capillary tubes (1.06 mm ID) will show the key parameter—the relationship between the intervals between magnetic and non-magnetic regions of the tool and pole-tip geometry—to realize the multiple pole-tip system. The experimental results will clarify the finishing mechanism. Finally, a simple method is proposed to determine the pole-tip feed length to control the roughness uniformity over the entire finished area.

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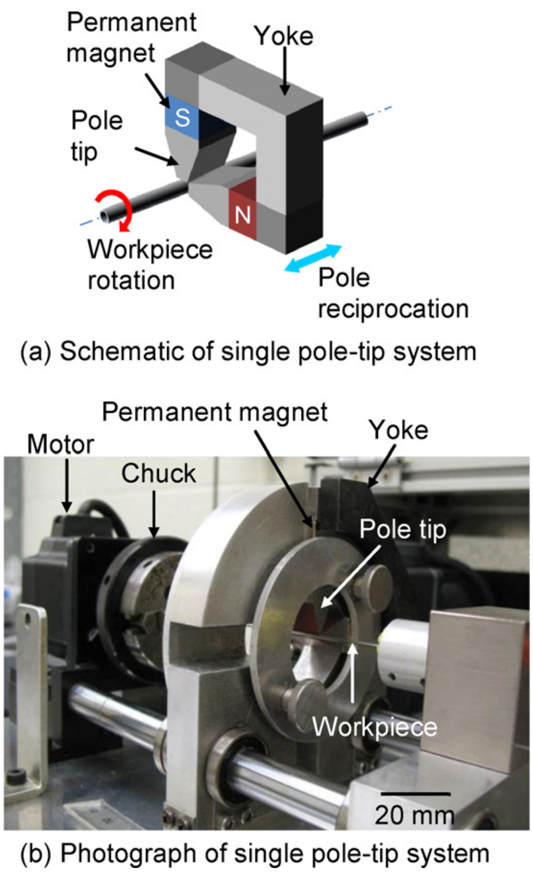

Fig. 1. Schematic and photograph of single pole-tip system.

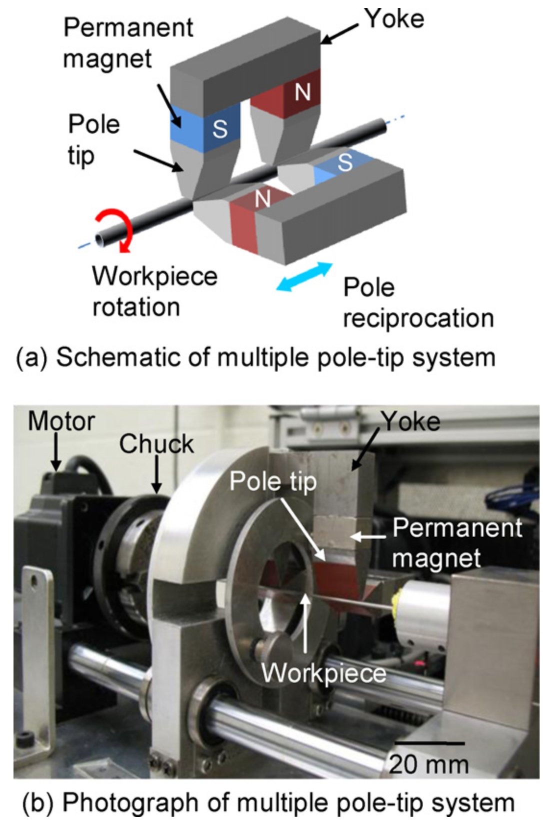

Fig. 2. Schematic and photograph of multiple pole-tip system.

2. Processing principles of single-pole tip and multiple-pole tip systems

Fig. 1 shows a schematic of a magnetic abrasive finishing process with a single pair of pole tips (hereafter called a *single pole-tip system*) and a photograph of the finishing machine. The desired magnetic field in the finishing area is generated by two permanent magnets attached to a steel yoke. Magnetic abrasive in the tube is magnetized, and it is pushed against the tube surface by magnetic force. As the tube is rotated at high speed, the magnetic abrasive exhibits relative motion against the tube surface and thus removes material from the tube surface. The default finished length is determined by the pole-tip width in the tube axial direction, and motion of the pole tip along the tube axis extends the finished area.

Reduction of the tube ID makes this approach difficult. For example, magnetic abrasive tends to build up in the area corresponding to the entry side of the pole-tip edges—instead of being distributed at the region corresponding to the pole tip with following the line of magnetic force—and plugs the tube. Regardless of the pole-tip motion, the magnetic abrasive remains at the initial position and finishing is not performed. This is due to a lack of magnetic force acting on the magnetic abrasive, and the magnetic force yields to friction between the magnetic abrasive and tube inner surface. Since the magnetic force is a function of magnetic field strength and its gradient, it can be controlled by the geometry and magnetic property of the pole-tip or the magnetic tool inserted with magnetic abrasive.

Fig. 2 shows a schematic and a photograph of a method using a *multiple pole-tip system*. In this study, a pair of pole tips is added to a single pole-tip system and yoked together to generate magnetic fields in two finishing areas. The finishing area is doubled as magnetic abrasive is introduced into two regions of the tube and pushes against the tube surface. Analogous to the single pole-tip system, rotating the tube enables the relative motion between the magnetic abrasive and tube inner surface, resulting in an efficient surface finishing. The number of pole-tip sets can be increased if needed. For a constant pole-tip width, the finishing area will be a function of the total number of pole-tip sets.

The geometry of pole-tip sets in both single and multiple pole-tip systems used in this paper are shown in Fig. 3. The width of the pole tip, which defines the default finished length, is 18 mm. The pole-tip set for the single pole-tip system has two magnets. In the case of the multiple pole-tip system, each pole tip has one magnet, and the two magnets are coupled by a steel yoke, which is 54 mm long (parallel to the workpiece axis).

Fig. 4 shows changes in magnetic flux density B_y, measured by a Hall sensor (sensing area: ⌀1.0 mm), with distance X in both pole-tip systems. There is no significant difference in the magnetic flux density B_y between the two systems. Both systems show a similar trend: the magnetic flux density and its gradient increase from the center toward the edges of pole tips. The magnetic abrasive is attracted by magnetic force toward the pole-tip edges. Without assistance of a magnetic tool, this trend encourages the plugging of

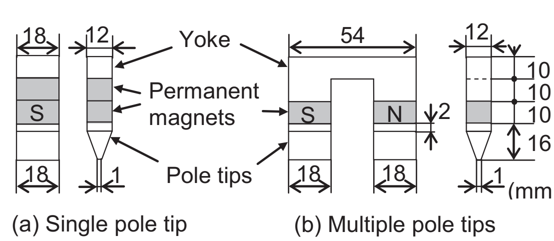

Fig. 3. Geometry of single and multiple pole-tip sets.

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