Surface Quality Enhancement of Metallic Tubes by A Novel Flocking-Fiber Coated Magnetic Tool

Zhanjie Zhang, Chongrui Wang and Jiong Zhang#

Department of Mechanical Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon Tong, Kowloon, Hong Kong SAR
Corresponding Author / Email: jiong.zhang@cityu.edu.hk, TEL: +852-3442 7345, FAX: +852 3442 0235

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High-quality internal surfaces are critical in aerospace, medical devices, and precision engineering industries. Internal polishing is generally employed to enhance the performance and longevity of components with such surfaces by minimizing friction, wear, and corrosion. Magnetically driven internal finishing (MDIF) is a promising technique for improving surface quality of internal surfaces. However, the fixed-abrasive tools used in MDIF limit its best achievable surface roughness to >100 nm Ra. Hence, this study proposed an innovative method employing magnetic tools coated with flocking fibers to achieve a more flexible and gentle polishing process compared to the existing MDIF. With the assistance of abrasive slurries, the new magnetic tool achieves a surface roughness of approximately 60 nm Ra on a 316L stainless steel tube. The repeatability of the newly-developed tools was validated. And the evolution of material removal depth and surface roughness against the polishing time was investigated. A section polishing experiment was also conducted to explore the possibility of polishing larger surfaces by the new polishing tool. The proposed method expands the boundary of MDIF techniques and may find potential applications in aerospace and optical industries.

1. Introduction

The pursuit of high-quality internal surface finishes has become increasingly critical in industries such as aerospace, medical devices, and precision engineering, where surface integrity directly influences product performance and durability. Traditional internal finishing techniques, such as abrasive flow machining (AFM) and magnetic abrasive finishing (MAF), have been widely used for their ability to handle complex geometries and achieve fine surface finishes [1]. However, these methods often suffer from limitations, including uneven material removal, complexity in setup, or challenges in scaling for industrial applications, particularly when dealing with long or intricately shaped tubes [2].

Recent advancements in finishing technologies have sought to overcome these challenges by developing more flexible and adaptive methods. Magnetically driven internal finishing (MDIF) has emerged as a promising alternative, offering the advantage of high flexibility and efficiency, which enhances precision and control during the polishing process [3-5]. However, MDIF employs magnetic polishing tools coated with fixed abrasive particles, leading to the fact that the surface roughness cannot be reduced to below 100 nm Ra even using the 3-μm Al_2O_3 abrasive particles [6].

To further enhance the surface quality of metallic internal surfaces, this paper proposed an innovative approach that utilizes flocking materials to create a new type of magnetic polishing tool. This novel tool is driven by an external rotating magnetic field, enabling it to achieve precise and consistent polishing of internal surfaces, with effectiveness in reducing surface roughness to approximately 60 nm Ra. The method expands the potential applications of magnetically driven internal finishing (MDIF) techniques, especially in high-precision industries such as semiconductor manufacturing and optical engineering, where internal surface quality is paramount.

2. Experiments

2.1. Workpiece Preparation

This study employs 316L stainless-steel tubes with dimensions of 65 mm in length, 15 mm in inner diameter, and 2 mm in wall thickness. Fig. 1 illustrates the as-received stainless-steel tube and its surface roughness profile. Part of the 316L stainless-steel tubes were halved by the wire electrical discharge machining (wire-EDM) process to facilitate subsequent internal surface structure measurements. The initial surface roughness was measured using a Taylor Hobson Talysurf profilometer (PGI) along the axial direction of the tube. Measurements were taken thrice at different positions, yielding a roughness distribution between 250–290 nm Ra, with an average of 265 nm Ra (with a cut-off distance of 0.25 mm), as depicted in Fig. 1 (b).

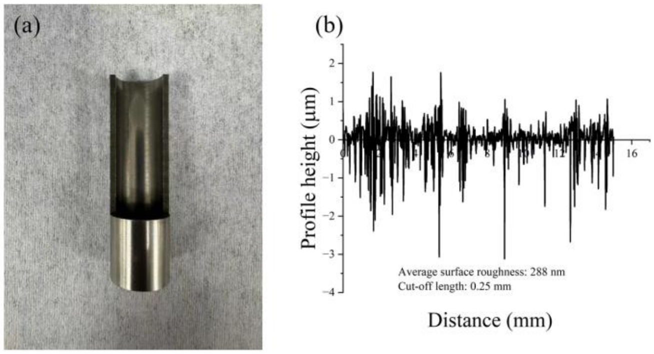

Fig. 1 The original 316L stainless-steel tube (a) and the corresponding microscopic profile height graph (b)

2.2. Fabrication Process of the Novel Magnetic Tool

The fabrication process of the novel magnetic tool involves several precise steps to ensure optimal performance for the targeted polishing of internal surfaces. First, a spherical N35-grade NdFeB magnet with an diameter of 8 mm and a surface magnetic flux density of 4.3 ± 0.1 kGs is immersed in a silicone adhesive to create a uniform adhesive layer. The magnet together is then rolled between two rough acrylic discs to facilitate an even coating of flocking fiber. This process results in a dense layer of the flocking fiber with a thickness of approximately 0.60 ± 0.05 mm. The specific flocking material used is short-flocked nylon, with the average fiber lengths of approximately 1 mm. Nylon is chosen for its excellent mechanical properties, including high strength, wear resistance, and chemical stability, making it particularly suitable for polishing applications [7].

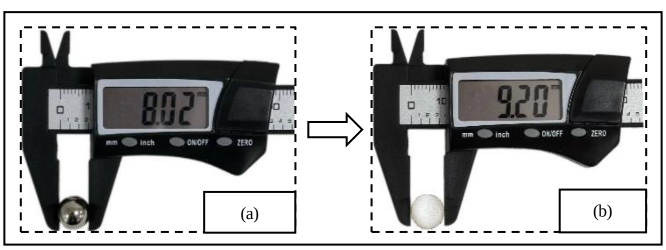

Fig. 2 The raw magnetic ball (a) and the fabricated polishing tool (b)

Once the coating process is complete, the tool undergoes a curing phase at room temperature for 24 hours. This duration allows the adhesive to be fully set, ensuring the flocking fibers adhere firmly to the magnet's surface. After applying the flocking coating, the diameter of the magnetic tool increases to 9.2 ± 0.1 mm, with a reduced magnetic flux density of 3.6 ± 0.1 kGs, as illustrated in Fig. 2.

2.3. Polishing Setup

The experiment utilized a high-precision CNC machine tool (Datros-V260) as the power and motion source for the external magnetic field. The top of the external magnetic field was designed cylindrically for better clamping by the machine tool's holder, as shown in Fig. 3. The 316L stainless-steel tube was placed on a dynamometer and secured with a special clamp. As the polishing tool in this experiment lacked fixed abrasives, abrasive slurries (with 1-μm Al_2O_3 particles) were supplied by a peristaltic pump during the polishing process.

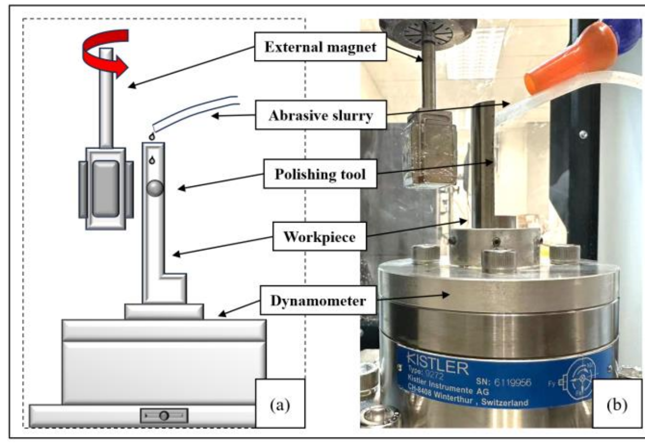

Fig. 3 Schematic (a) and photo (b) of the polishing setup

2.4. Experiment Protocol

Three sets of polishing experiments were designed to verify the performance of the new polishing tool. Some parameters for these experiments were consistent, namely, the rotation speed of the external magnetic field as 1800 rpm, the distance between the external magnetic field and the outer wall of the stainless-steel tube as 7.5 mm, the flow rate of the abrasive slurry as 2.0 mL/min. This parameter set was identified as the most stable configuration for the polishing tool.

The first set of experiments aimed to verify the consistency and repeatability of the polishing tool in terms of surface roughness and material removal rate. Three new polishing tools were used to polish the internal surfaces of three stainless-steel tubes for 20 minutes separately. The second set of experiments explored the variation of surface roughness and material removal with the polishing time. The same polishing tool was used to perform continuous polishing at the same position on the same stainless-steel tube (single-point polishing experiment). Each polishing session lasted 3 minutes until no change of the surface roughness. At the end of each session, the polished footprint was measured at least three times using the profilometer. The third set of experiments aimed to verify the tool's ability to polish a large area (section polishing). The CNC machine tool controls the external magnetic field, moving it up and down over a total length of 20 mm while rotating to drive the polishing tool. The feed rate is 200 mm/min. This experiment was divided into two stages, both with an external magnetic field speed of 1800 rpm and a magnetic field spacing of 7.5 mm. In the first stage, aluminum oxide with a particle size of 5 μm was used as the abrasive, while aluminum oxide with a particle size of 1 μm was used in the second stage. The processing time for both parts was 20 minutes.

3. Results and Discussion

3.1. Repeatability Experiment

Fig. 4 presents the polishing profiles from three repeatability tests. These profiles provide a detailed visualization of the surface roughness and material removal characteristics of the internal surfaces after polishing. The depth, shape, and concave areas of the three test groups are remarkably consistent, indicating the high precision and repeatability of the new polishing tool. The consistency across these profiles suggests that the tool can deliver uniform polishing results, a crucial factor in applications where consistent surface quality is required.

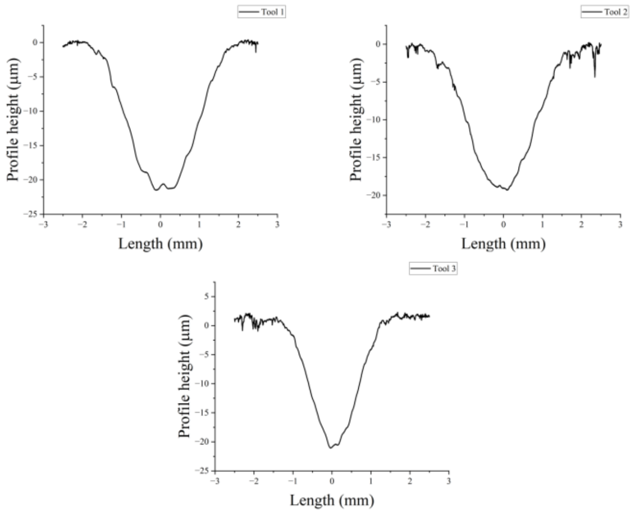

Fig. 4 The polished profiles of three polishing tools

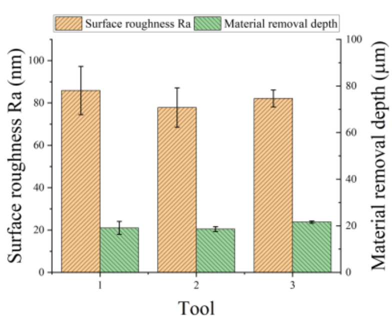

Fig. 5 Summary of the surface roughness and material removal depth of the repeatability experiment

The surface roughness and the material removal depth of the polished footprint are summarized in Fig. 5. The average surface roughness (Ra) achieved across the three tests is 82.0 nm, while the average material removal depth is 19.8 µm. This value corresponds to a material removal rate of approximately 0.988 µm/min, which is a significant indicator of the tool's polishing efficiency.

Table 1 Repeatability test summary

Test	Ra (nm)	Depth (µm)
1	85.9	19.1
2	77.9	18.6
3	82.2	21.6
Average	82.0	19.8
Standard deviation	3.3	1.3
Percentage error (%)	5.0	9.3

Moreover, the low percentage errors, i.e., 5.0% for surface roughness and 9.3% for material removal depth, demonstrate the tool's good repeatability. One can conclude that the polishing process is stable and predictable. This level of stability is particularly important in industrial settings where precision and repeatability are critical for maintaining high standards of product quality.

3.2. Single-point Polishing Experiment

The single-point polishing experiment, as illustrated in Fig. 6, offers visual image into the performance of the new polishing tool over time. Fig. 6 (a) highlights the initial condition of the internal surface of the tube, characterized by numerous uneven and elongated grooves. These grooves are indicative of the inherent roughness and imperfections that exist before the polishing process begins.

Upon the first application of the polishing tool, a small, elliptical bright area emerges in the center of the internal surface. This bright area signifies the initial stage of surface polishing, where the tool begins to smooth out the rough surface. As polishing continues, this bright area progressively expands, reaching its maximum size around the 15-minute mark.

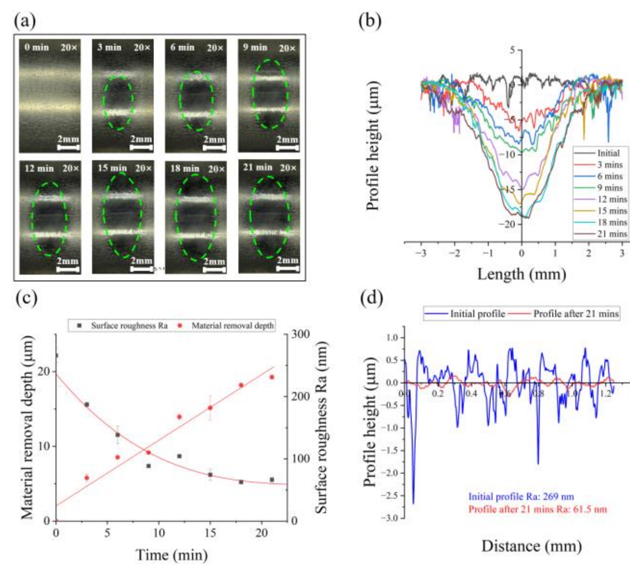

Fig. 6 Results of the single-point polishing experiments: (a) optical images of the polished footprints at different polishing time; (b) polished profile against the polishing time; (c) surface roughness Ra and material removal depth against the polishing time; and (d) surface roughness profile of the initial surface and the polished surface

Fig. 6 (b) provides a more detailed view of how the depth of the grooves in this central bright area change as polishing progresses. The profile shows a gradual increase in the depth of the valleys, indicating that the polishing tool is effectively removing material from the surface in a controlled manner. This consistent reduction in depth highlights the tool's capability to perform precise material removal, which is crucial for achieving a high-quality finish.

Fig. 6 (c) shows the surface roughness (Ra) evolution against the polishing time. Initially, the surface roughness decreases significantly as the polish tool smooths out the larger imperfections. However, the rate of decrease in surface roughness begins to taper off after 15 minutes of polishing. By 18 minutes, the surface roughness value stabilizes. This plateau suggests that the polishing process reaches a point where further reduction in roughness becomes difficult, possibly because the surface has approached its optimal smoothness which the new polish tool can reach.

Furthermore, the material removal depth, as illustrated by the fitted curve in Fig. 6 (c), exhibits a linear positive correlation with the polishing time. This linear relationship indicates the tool maintains a steady and predictable rate of material removal throughout the polishing process. The stability in the removal rate is a critical feature, as it ensures that the tool can deliver consistent results over time, making it suitable for applications where precise control over material removal is essential.

3.3. Section Polishing Experiment

Fig. 7 provides a microscopic profile comparison between the section polishing area and the original internal surface of the tube, offering a detailed look at the improvements brought about by the new polishing tool. Unlike the shorter measurement length presented in Fig. 6 (d), which focuses on a localized area, Fig. 7 extends the measurement across a longer section of the internal surface. This broader view allows for a more comprehensive assessment of the polish tool's effectiveness in processing larger areas of the tube.

The comparison reveals a significant transformation in the surface profile after polishing. The original internal surface, as observed in the pre-polished state, is characterized by pronounced peaks and valleys, indicative of substantial surface roughness.

In contrast, the profile of the sectioned polishing area, as depicted in Fig. 7, shows a much smoother and more uniform surface. The peaks have been significantly reduced, and the valleys have been filled in, resulting in a lower and more consistent profile. This substantial reduction in surface irregularities highlights the polish tool's capability to achieve a high degree of surface smoothness.

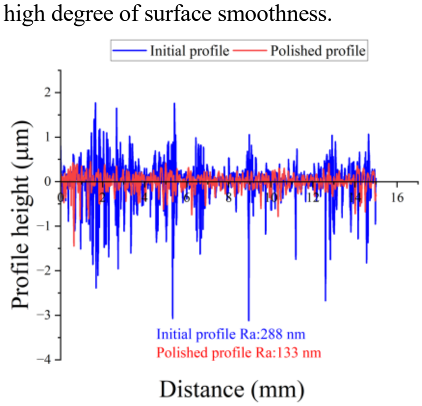

Fig. 7 Surface roughness profile of the initial and polished surfaces

Quantitatively, the roughness of the sectioned polishing area is reduced by 155 nm, representing a 54% decrease from the original surface roughness. The roughness of this area did not reach ~60 nm, which may be related to insufficient polishing time. The width of the trace formed by single-point polishing for 20 mins is about 4 mm, while the width of the cross-section is 20 mm, which is five times the former, which means it takes more than five times the time (100 mins) to achieve a surface roughness of 60 nm. This dramatic reduction underscores the tool's effectiveness not only in localized polishing but also in processing larger areas, where maintaining uniformity and consistency across the entire surface is often challenging [9].

4. Conclusions

In conclusion, this study proposed a new flocking-fiber-coated magnetic tool for polishing the internal surfaces of 316L stainless steel tubes in MDIF process. The research demonstrates significant improvements in surface roughness, achieving approximately 60 nm Ra in single-point polishing experiment, which surpasses the performance of existing MDIF. The innovative use of flocking material on the magnetic tool enhances both the adaptability and durability of the polishing process, making it particularly effective for applications requiring high precision and consistency. The repeatability, single-point, and section polishing tests validate the stability and efficiency of the tool, suggesting its potential for broader adoption in high-precision industries such as semiconductor manufacturing and optical engineering. Future work could explore further optimization of the magnetic tool's design and aim for sub-10 nm surface roughness generation.

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