euspen's 26th International Conference & Exhibition, Krakow, PL, June 2026
www.euspen.eu

Magnetically driven internal finishing of stainless steel tubes by a novel electrostatic flocking and drum-shaped polishing tool

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Abstract

High-quality internal surface finishing is essential for components used in critical industries such as aerospace and medical devices. Compared to conventional magnetic abrasive finishing (MAF), magnetically driven internal finishing (MDIF) represents a more flexible, controllable, and promising processing technology. However, the MDIF technique is constrained by the utilization of fixed-abrasive tools, which limit the attainable surface roughness to above 100 nm Ra. This study proposes a new MDIF tool that uses electrostatic flocking to coat a specially designed drum magnet with a flocking layer. Compared to manual flocking, this technique can more easily build a more uniform and directional flocking layer, improving material removal efficiency. Experimental results demonstrate that this method can reduce the internal surface roughness Ra of 316L stainless steel tubes from an initial average of 265 nm to 29 nm within 10 minutes, improving surface quality by over 89 %. Furthermore, repeatability experiments have shown tool performance to be highly consistent. Experiments on a larger-diameter tube verified the tool's dimensional versatility. This novel approach markedly advances the MDIF process and attains high efficiency nanofinishing, demonstrating substantial potential for precision internal finishing applications in high-demand industries.

KEYWORDS: Magnetically driven internal finishing, Magnetic polishing tool, Electrostatic flocking, Surface roughness

1. Introduction

The integrity of internal surfaces in tubular components is a critical determinant of the operational efficiency and fatigue lifespan of essential systems in aerospace, semiconductor fabrication, and biomedical engineering. Even minor bumps or damage to the surface or below it can cause flow turbulence, corrosion buildup, or catastrophic material failure [1, 2]. Researchers and practitioners use traditional finishing methods, such as abrasive flow machining (AFM) and magnetic abrasive finishing (MAF), to solve these problems. However, these methods often have issues with process flexibility and the inability to achieve deterministic control over material removal on complex internal geometries [3, 4].

Magnetically driven internal finishing (MDIF) has come up as a promising alternative to traditional methods. Zhang et al. were the first to utilize MDIF, which employs externally rotating magnetic fields to position polishing tools precisely inside the tubular components [5-7]. This is a non-contact, adaptive method for polishing long, thin tubes. Although the existing MDIF process is flexible, it typically utilizes magnetic tools coated with fixed abrasives or bonded magnetic abrasive powders, limiting the final surface roughness above 100 nm Ra [8].

Recently, Zhang et. al. proposed a new approach by using a magnetic tool with flocking fibers [9]. This preliminary investigation indicated that soft nylon fibers, when used for transporting abrasive slurry, could generate a finer workpiece surface compared to fixed abrasive tools. However, this manual fabrication of the tool poses challenges in uncontrollable fiber density, fiber oritentation and uniformity.

To address the above issue, this paper proposed a new process to fabricate the MDIF polishing tool, transitioning from a manually created design to one that utilizes an electrostatic flocking method on a drum-shaped magnet. Using high-voltage electrostatics makes sure that the fibers are lined up perpendicular to the tool substrate, creating a dense, directed, and even polishing layer. Repeatability experiments were conducted to compare two adhesive coating strategies. A larger-diameter 316L stainless steel tube is polished to confirm the versatility. The successful development of this tool is expected to establish a foundation for automated tool fabrication, highlighting its potential as a scalable solution for the ultra-precision finishing of critical components.

2. Experiment

2.1. Workpiece preparation

This study employed 316L stainless steel tubes with two dimensions. The two types of tubes were both 100 mm long and 2 mm thick, but they had different inner diameters (ID): 15 mm and 20 mm. The tubes were cut into the shape shown in Fig. 1(a) using a sawing machine to facilitate the following experiments. A Taylor Hobson Talysurf profilometer (PGI) was used to measure the initial surface roughness. To ensure consistency, three closely spaced measurement lines were taken axially at the geometric center of the polished region, where the tool's dwell time was longest (Cut-off: 0.25 mm, evaluation length: 4.75 mm). The tubes with a 15 mm ID had a roughness range of 250 nm–290 nm Ra (average: 265 nm Ra), and the tubes with a 20 mm ID had a range of 270 nm–290 nm Ra (average: 280 nm Ra). Figures 1(b) and 1(c) display the microscopic profile height graphs corresponding to this.

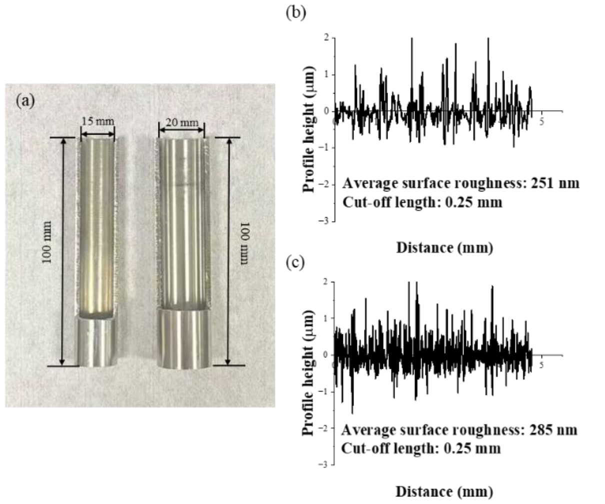

Figure 1. Two 316L stainless steel tubes before polishing (a), microscopic profile height graph (b) of ID15 mm tube, and microscopic profile height graph (c) of ID20 mm tube

2.2. Fabrication process of novel magnetic polishing tools

Figure 2 illustrates the fabrication process of the magnetic tool with flocking fibers. The procedure is meticulously controlled to ensure geometric precision and surface uniformity.

Stage I: Preparing the Substrate. A drum-shaped N35-grade NdFeB magnet is utilized, with a 1.2 mm central hole drilled to facilitate mounting and rotation. To remove all dirt from the surface, the drum magnet is washed with 99.9 % ethanol and then air-dried before the adhesive is put on, which ensures the binding is as strong as possible where it contacts the substrate. Then, a pin is placed through the hole in the middle to keep the magnet in place.

Stage II: Applying the Adhesive. To ensure proper fiber density, achieving a homogeneous adhesive coating is crucial. The pinned magnet is connected to a high-concentricity collet driven by a horizontal motor (Fig. 2(II)) at a constant 30 rpm. A specifically designed flocking glue with high flowability is utilized, which is crucial for maintaining an even film thickness across the curved surface. Following a brief immersion in the adhesive reservoir, the magnet continues rotating for 2–3 minutes to allow for partial curing and leveling before flocking.

Stage III: Flocking with Electricity. Figure 2(III) shows that a high-voltage electrostatic flocking machine (output voltage: 30 kV) is employed to generate the flocking layer. The square metal collecting plate is connected to the positive electrode of the generator, while the flocking barrel is connected to the negative electrode. Nylon fibers with a length of approximately 0.6 mm are used as the flocking medium, pre-dried and passed through a 40-mesh screen to prevent agglomeration. The setup requires precise geometric alignment: both the positive and negative electrodes are positioned 100 mm from the center of the spinning magnet. After the electric field is set up, the flocking barrel is shaken gently and uniformly for approximately 90 seconds. To maintain a constant electric field strength, the distance between the barrel and the magnet remains the same during this phase.

Stage IV: Curing and Post-Processing. The voltage is gently decreased to zero after the flocking phase is over. The magnet continues to spin at 30 rpm for an additional five minutes to facilitate initial air drying. After that, the magnet assembly is removed from the motor and set in an oven for two hours at 55 °C to harden. Finally, it is left at room temperature for 12 hours to fully cross-linked. The diameter of the flocking-treated drum magnet is 8.3 mm ± 0.1 mm, with a magnetic flux density of 0.48 mT ± 0.01 mT.

As illustrated in the schematic diagram in Fig. 2(IV), two distinct fabrication strategies were explored to address edge stability. The first method (full adhesive coated) involves coating the whole surface of the drum, followed by using a blade to cut off the flocking layer from the top and bottom planar faces. This step is critical because it removes irregular fiber clusters on the edges that could render the tool unstable during polishing. The second method (half adhesive coated) utilizes a controlled immersion depth in Stage II to coat only the curved surface, eliminating the need for trimming after treatment. The rationale for evaluating the half-coated strategy is that if it proves to be highly effective, the time-consuming post-trimming step can be completely omitted, which would significantly improve manufacturing efficiency. The original manual coating method [9] was excluded from this specific comparison. While our previous work successfully established the foundational feasibility of fiber-coated magnetic tools, its inherent limitations in fiber uniformity and minimum attainable roughness (>70 nm Ra) are already understood. Consequently, the present study advances this concept by focusing entirely on optimizing the manufacturing strategies within the upgraded electrostatic flocking paradigm to achieve ultra-precision nanofinishing.

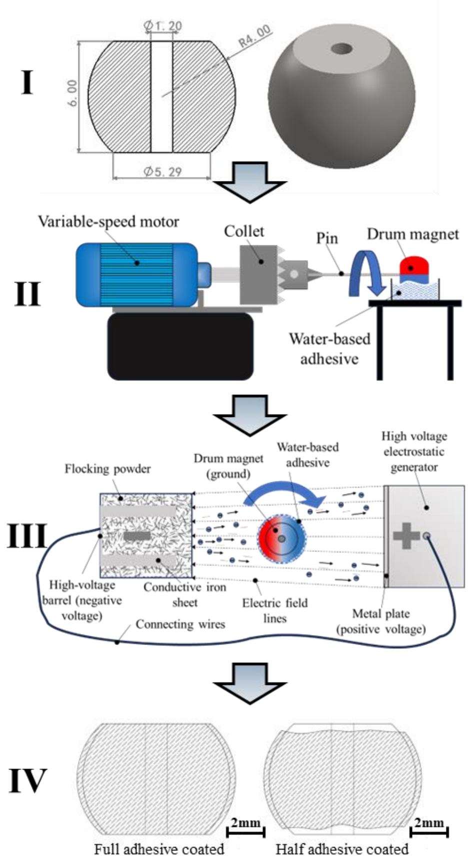

Figure 2. Electrostatic flocking process flowchart

2.3. Polishing setup

The polishing setup of MDIF is shown in Figure 3. The external magnetic field is created by placing four N52-grade cuboid NdFeB magnets on an aluminum prism and arranging their poles in an alternating pattern (N-S-N-S). The spindle of a high-precision CNC machine (Datros-V260) is connected to providing rotation of the external magnetic field. A three-jaw chuck, located on top of a dynamometer, holds the workpiece in place. The dynamometer is fastened to the machine table. A peristaltic pump sends the polishing slurry. And a magnetic stirrer keeps the slurry reservoir mixed up so that it stays uniform and does not settle out.

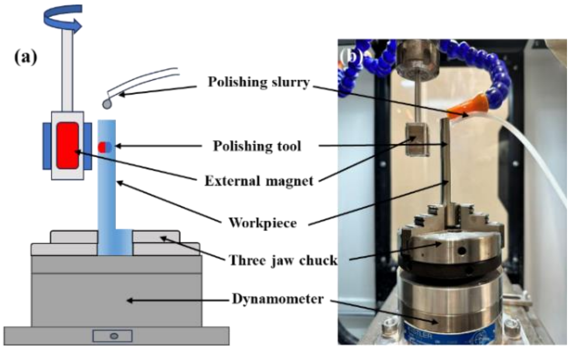

Figure 3. Polishing setup (a) schematic diagram, and (b) actual apparatus

2.4. Experimental procedure

Phase I: The first step was to conduct repeatability tests to compare the two different methods of tool production. Each strategy made three polishing tools. We used these tools to polish the interior of 316L stainless steel tubes (ID: 15 mm, wall thickness: 2 mm) at different locations. The external magnetic field was maintained at 1800 rpm for these tests, with a 10 mm working gap between the external magnet and the outer wall of the tube. Each tool took 10 minutes to process workpiece. The abrasive slurry consisted of 1 μm aluminum oxide (Al_2O_3) particles suspended in deionized water with a mass fraction of 10 %. A peristaltic pump delivered it at a steady flow rate of 5 mL/min.

Phase II: In the second Phase, polishing tools made using the method that worked best and was most stable in Phase I were used to test the tool's versatility. Single-point polishing was performed on larger-bore 316L stainless steel tubes (ID: 20 mm, wall thickness: 2 mm). Three separate tools were used to polish various locations of the same tube. For this test, the rotational speed was set to 2000 rpm, and the working gap was cut to 8 mm. The slurry composition, flow rate, and processing duration (10 minutes) stayed the same as in Phase I. The operational settings were slightly modified from the first group, as using the same parameters on the larger diameter tube made the tool less stable. Fine-tuning was necessary to determine the optimal operating range for the new geometry.

3. Results and discussion

3.1. Repeatability experiment

To determine the most effective method for making tools, we compared the "full adhesive coated" method (which requires edge trimming) with the "half adhesive coated" process (which controls immersion). We measured the surface roughness (Ra) and material removal depth of the workpiece tube for the six polishing tools. Tools 1–3 were used with the full-coating strategy, while Tools 4–6 were used with the half-coating strategy.

Table 1 Summary of repeatable experiments

Polishing tool	Ra / nm	Depth / μm
1	29.3	17.5
2	36.5	16.2
3	41.7	16.5
Average	35.8	16.7
Standard deviation	5.1	0.5
Coefficient of variation	14.2 %	3.3 %
4	59.3	19.5
5	43.8	18.1
6	56.7	17.0
Average	53.3	18.2
Standard deviation	6.8	1.0
Coefficient of variation	12.7 %	5.7 %

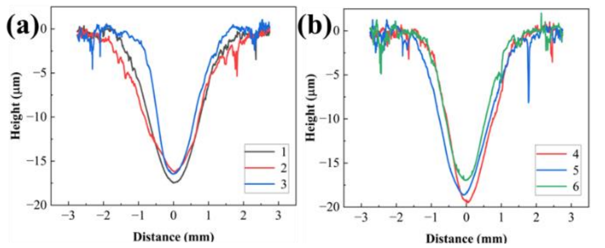

Figure 4. The polished profiles comparison (a) full adhesive coated, and (b) half adhesive coated

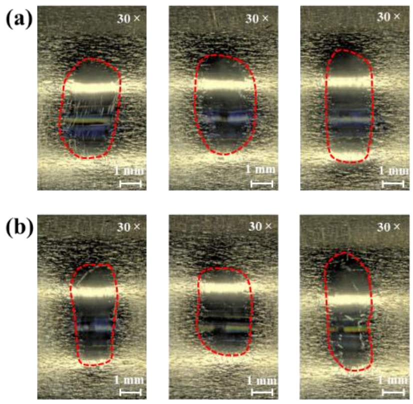

Figure 5. Optical images of polishing marks from three replicate experiments (a) Full adhesive coated, and (b) half adhesive coated

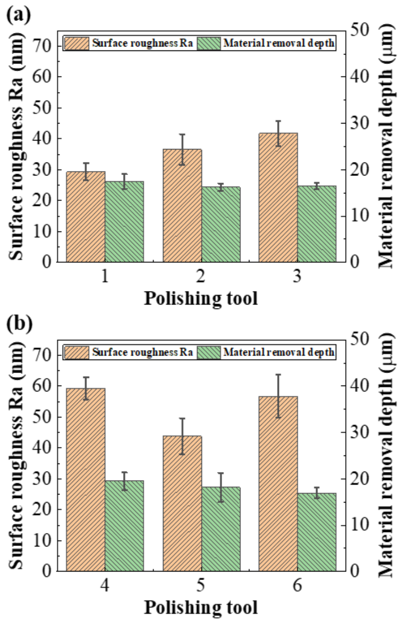

Figure 6. Summary of surface roughness and material removal depth in repeatable experiments (a) full adhesive coated, and (b) half adhesive coated

Table 1 and Figure 6 show that the full adhesive coated strategy (Tools 1-3) demonstrates better finishing capabilities. Figure 6(a) shows that these tools achieved an average surface roughness of Ra 35.8 nm, representing a significant improvement over their original rough state. For this group, the average depth of material removal is 16.7 μm. The optical images in Fig. 5(a) show that the polishing marks are consistent and oriented in a single direction.

On the other hand, the tools made using the half-coating method (Tools 4–6) had an average surface roughness of Ra 53.3 nm and an average material removal depth of 18.2 μm. The half-coated tools did not produce a surface as good as the former, despite similar material removal rates. Figures 4(b) and 5(b) show that the polishing profiles and marks for this group were not as even as those for the trimmed tools.

For all these tools, the material removal mechanism relies on the dense nylon fibers acting as a flexible brush, retaining the slurry and softly transferring magnetic forces to shear off micro-peaks. While comprehensive lifetime testing is reserved for future work, visual inspections confirmed no noticeable fiber degradation after these 10-minute cycles.

The difference in performance can be traced back to the edge conditions of the flocking layer. As mentioned in the manufacturing process, the full-coating method involves trimming the top and bottom edges of the material. This eliminates the uneven fiber clusters and edge effects that can occur during electrostatic flocking. The half-coating method eliminates steps that need to be performed after the coating. Still, it relies on the adhesive's ability to naturally wet itself during immersion, which is influenced by surface tension. It can be hard to control this wetting all the time, which could cause the fiber density to change at the edges. As a result, the full adhesive coated strategy was chosen for the following versatility experiments because it could create a better surface finish (Ra < 40 nm).

3.2. Large-diameter tubes polishing experiment

To prove that the proposed tool is useful in various situations, the optimized polishing tool (made using a full-coating strategy) was applied to a 316L stainless steel tube with an inner diameter of 20 mm. To make up for the larger aperture size and make sure the tool moved smoothly, the experimental parameters were adjusted to a rotational speed of 2000 rpm and a working gap of 8 mm, as explained in Section 2.4.

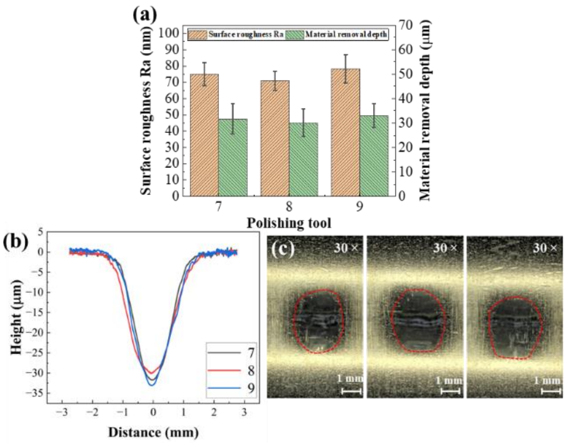

Figure 7. Polishing results of tools manufactured using the full adhesive coated method (a) summary of surface roughness and material removal depth, (b) the polished profiles comparison, and (c) optical images of polishing marks

Table 2 Summary of large-bore tube experiment data

Polishing tool	Ra / nm	Depth / µm
7	74.9	31.7
8	70.8	30.1
9	78.3	33.1
Average	74.7	31.6
Standard deviation	3.1	1.2
Coefficient of variation	4.1 %	3.9 %

The results from the large-diameter tube experiments (Tools 7-9) are shown in Figure 7 and Table 2. The system demonstrated high efficiency in removing material, with an average removal depth of 31.6 µm in just 10 minutes. The significant increase in polishing depth compared to the ID15-mm tube experiments may be attributed to the more stable rotation motion of the tool on the workpiece tube, as evidenced by the small polishing marks in Figure 7(c).

This tool reduced the average internal roughness to 74.7 nm Ra, achieving a ~73.3 % reduction from the initial state. This final Ra is higher than that of the ID 15 mm tube due to two main factors. First, the larger tube had a higher initial surface roughness (280 nm Ra). Second, the reduced working gap generated a stronger magnetic normal force that doubled the material removal depth (31.6 µm), which likely deepened individual abrasive indentations. Nevertheless, the low coefficient of variation (3.9 %) indicates excellent process stability. These results confirm the tool's dimensional adaptability, though further magnetic field optimization is required to match the nanometer-level finish of smaller tubes.

4. Conclusion

This study introduces an innovative Magnetically Driven Internal Finishing (MDIF) tool created using electrostatic flocking to overcome the constraints of conventional fixed-abrasive polishing. Experimental comparisons showed that the full adhesive coating technique with edge trimming gives better performance. This new polishing tool reduces the internal roughness of ID 15 mm 316L stainless steel tubes from 265 nm to 29 nm Ra. Additionally, versatility tests on tubes with a 20 mm inner diameter demonstrated that the tool was capable of removing a substantial amount of material (31.6 µm) with minimal process variation (coefficient of variation 3.9%). These results demonstrate that the tool can achieve high-efficiency nanofinishing, making it a promising and versatile choice for precise internal surface machining in key industries.

Acknowledgements

JZ acknowledges the support of the start-up fund at the City University of Hong Kong with the grant number of 9610646, and National Natural Science Foundation of China with the grant number of 52505524.

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