euspen's 24th International Conference & Exhibition, Dublin, IE, June 2024
www.euspen.eu

New shape profiling polishing method for diffuser microstructured surface

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Abstract

Diffusers are integral components in projection, lighting, and imaging systems, prized for their superior beam diffusion capabilities. Polishing is a critical process for enhancing the performance of diffusers by removing tool marks on the mold surface. However, traditional polishing methods often struggle to improve surface quality without compromising shape accuracy. Addressing this challenge, this study introduces a novel non-contact shape profiling polishing method utilizing non-Newtonian fluids, designed for ultra-precision processing of array microstructured surface molds. Our findings demonstrate that this innovative polishing method significantly enhances diffuser performance, achieving remarkable improvements in mold precision. Notably, after the application of this polishing method, the surface roughness of the diffuser mold sees a remarkable reduction from an initial roughness average Ra of 164.2 nm to a mere 8.1 nm, concurrently preserving shape accuracy to an exceptional degree of less than 0.8 µm.

Keywords: Microstructud surface; Diffusers mold; Shape profiling polishing; Tool mark removal; Shape accuracy

1. Introduction

Diffusers play an important role in optical lighting, projection, and imaging systems [1], mainly used for diffusing and unifying point laser sources, improving the brightness, color, and light source uniformity of projection and LCD backlight module systems [2].

In order to meet the requirements of mass production of diffusers, injection molding technology is generally used for manufacturing. As the core component in the injection molding process, the shape accuracy and surface quality of the mold have a crucial impact on the optical performance of the diffusers. At present, high-quality diffusers molds mainly rely on single point diamond turning technology (SPDT)for manufacturing. Guo et al. used SPDT technology to prepare V-shaped groove microstructure surfaces. [3]. However, due to cutting, it is inevitable to produce defects such as tool marks and burrs on the surface of the mold, which seriously affects the performance of the replicated optical components.

Polishing is the main way to improve the surface quality after machining. However, existing polishing methods for micro structured surfaces have certain limitations. The contact polishing method is prone to poor surface quality of the workpiece due to direct contact between the tool and the workpiece [4]. Jet or magnetic field assisted polishing methods are affected by the fluid flow state, which can lead to poor shape accuracy and ultimately affect the performance of the terminal components [5,6]. Non-contact polishing methods leveraging shear thickening principles have gained prominence for their process flexibility, ease of setup, and cost efficiency. Li et al. [7] achieved Ultra-precision polishing using a weak chemical shear thickening polishing (STP) process. Additionally, Zhang et al. [8] established a damping tool specifically for polishing aspherical surfaces that achieved very low surface roughness on nickel-phosphorus (NiP) alloy surfaces. Leveraging non-Newtonian fluids' flexibility enhances polishing of microstructured surfaces, necessitating approaches for sub-10 nm roughness and shape accuracy due to unique geometric characteristics.

To address the issues of suboptimal surface quality and inaccuracies in the shape of polished array microstructured surface, this research presents a solution through the implementation of a non-contact profiling polishing technique, specifically tailored for the conformal polishing of diffuser molds. The efficacy and superior performance of this innovative processing method were validated via a series of meticulous polishing tests, underscoring its capability to enhance the quality and precision of microstructured surfaces significantly.

2. Method and principle

This study utilizes the shear thickening effect of non Newtonian fluid polishing solution to shear remove the surface material of the mold by forming particle clusters wrapped in abrasive particles, achieving the polishing effect (Figure 1). In order to achieve uniform polishing of the mold surface, a contour polishing tool is prepared using the principle of film replication. The base of the profiling tool is cylindrical in shape, with a diameter of 30 mm. The height of the profiling part of the tool is 380 µm. In order to enhance the shear thickening effect of the polishing solution, the damping polishing pad is adhered to the surface of the non-contact profiling tool.

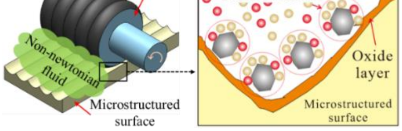

Figure 1. Diagram of the non-contact shape profiling polishing method

3. Experimental details

3.1 Workpiece

In this study, the microstructurd surface mold samples used for polishing were obtained through the previous ultra precision milling process, and the mold material was nickel phosphorus alloy. The mold is 15 mm long and 16.9 mm wide, with 13 grooves arranged on the surface. As depicted in Figure 2, the initial state of the mold sample, which was utilized in the polishing test, is presented. Figure 2(a) shows the mold obtained by ultra precision milling, and Figure 2(b) shows the measured geometric dimension of the mold.

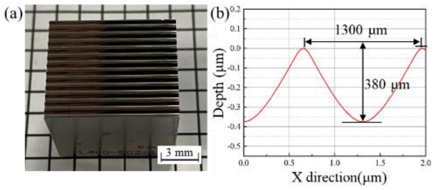

Figure 2. The diffuser mold (a) sample and (b) geometric dimension

3.2 Experimental setup

The polishing experiment is carried out on a custom-developed 5-degree-of-freedom precision machining platform, as illustrated in Fig. 3. During polishing, the tool axis is aligned parallel to the workpiece surface, then adjusted to maintain a 0.2 mm gap above the workpiece for the profiling procedure. The tool position can be adjusted by setting the profile damping tool to the same 0.2 mm gap above the workpiece. The slurry utilized for this experiment is a mixture of non-Newtonian fluid and silica sol. Specifically, the non-Newtonian slurry is composed of a polyhydroxyl polymer and deionized water, with SiO_2 abrasive particles having a size of 50 nm and a concentration of 10% by weight.

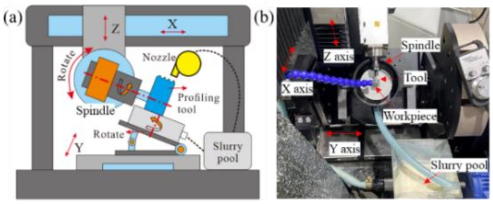

Figure 3. Experimental setup (a) diagram and (b) practical device

Figure 4 shows the prepared profiling damping tool. The tool consists of a tool base, a duplicated film and a damping pad. The duplicated film is made by replicating the contour of the workpiece surface, and the damping pad is to better drive the polishing fluid.

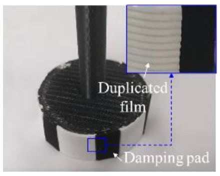

Figure 4. The profiling damping tool developed for polishing experiments

4. Results and discussion

4.1 Surface defects

Figure 5 shows the surface morphology results of the array microstructure mold before and after polishing. Figure 5(a) and (b) respectively show the surface morphology of the workpiece before and after polishing. It can be seen from the images that there are more defects such as spiral tool marks and burrs on the surface of the mold before polishing, and most of defects on the surface after polishing are eliminated.

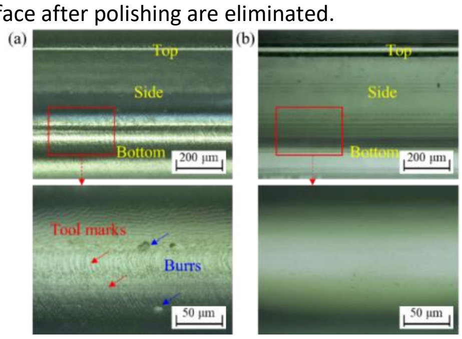

Figure 5. Comparison of the surface defects (a) before and (b) after polishing

4.2 Surface roughness

Figure 6 shows the results of diffuser mold surface roughness before and after polishing. It can be seen from Figure 6 that the surface roughness before polishing is 164.2 nm Ra, and the surface roughness converges to 8.1 nm Ra after polishing for 1 h. The rough peak of the mold surface is effectively eliminated after polishing, and the surface becomes smooth.

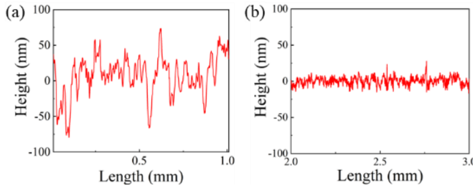

Figure 6. The rough peaks distribution (b) before and (c) after polishing

4.3 Shape accuracy

Figure 7 provides an analysis of the diffuser mold's shape change before and after polishing. The figure reveals that the most significant material removal occurred at the top of the mold groove, with minimal material removal at the bottom. The experimental results indicate the shape change is 0.8 μm.

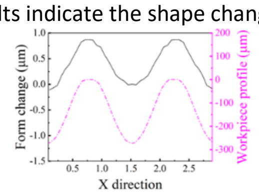

Figure 7. Surface shape change of diffuser after polishing

5. Conclusions

In this study, we present a non-contact profiling polishing method that utilizes non-Newtonian fluid, achieving conformal polishing of the diffuser mold. The key findings can be summarized as follows:

1. The polishing process successfully eliminates tool marks and burrs from the diffuser mold, thereby rendering the surface of the mold significantly smoother.

2. The surface roughness significantly decreases from an initial value of Ra 164.2 nm to 8.1 nm, effectively eliminating the rough peaks on the mold.

3. The geometry and depth of the mold features are preserved with high fidelity, with the form error resulting from the polishing process maintained below 1 μm.

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