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Research Article

Optimization Of Aspheric Surface Fabrication Through Sequential Bonnet And Pitch Polishing

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ABSTRACT

The fabrication of high-precision aspheric surfaces is vital for advanced optical systems. This study investigates the efficacy of sequential bonnet and pitch polishing techniques in improving the surface quality of aspheric optical components. Initial bonnet polishing achieved a PV value of approximately λ/2, with subsequent measurements showing a PV value of 403 nm, radius of 135.72 mm, and surface roughness (Ra) of 6.9 nm. Pitch polishing further refined these metrics, resulting in a PV value of 256 nm, radius of 135.78 mm, and Ra of 5.4 nm. A final iteration combining both methods reduced the PV value to 210 nm, maintained a radius of 135.77 mm, and achieved an Ra of 3.9 nm. The results indicate significant improvements in surface form values (47%) and roughness (43%) through the sequential polishing process. These findings demonstrate the potential of integrated polishing techniques to enhance the precision and quality of aspheric optical components, meeting the stringent requirements of modern optical applications.

Keywords: Aspheric, bonnet polishing, pitch polishing, surface finish

1. Introduction

The fabrication of precise aspheric surfaces is a crucial area of research and development in the field of optical engineering, driven by the demand for high-quality optical components in advanced optical systems. This literature survey examines various methodologies and advancements reported in the field, highlighting significant contributions from numerous studies.Jones [1] pioneered the use of computer control for grinding and polishing, laying the groundwork for subsequent developments in precision optics. This early work emphasized the potential of automated systems to achieve high levels of accuracy and repeatability, which have since become cornerstones of modern optical fabrication techniques. Cheng et al. [2] designed a six-axis high-precision machine tool specifically for machining aspherical optical mirrors. Their work demonstrated the importance of multi-axis control in achieving the complex geometries required for aspheric surfaces, highlighting how advancements in CNC (Computer Numerical Control) technology significantly enhance the precision and efficiency of optical manufacturing processes. Kordonski and Golini [3] provided a substantial progress update on magnetorheological finishing (MRF), a technique that uses a magnetic field to control abrasive particles in a fluid medium. MRF has been shown to achieve ultra-smooth surfaces, making it a valuable method for polishing optical components, emphasizing the flexibility and precision of MRF in correcting surface imperfections and achieving high-quality finishes.Shanbhag et al. [4] explored ion-beam machining for millimeter-scale optics, demonstrating its effectiveness in achieving precise material removal at a micro-scale, particularly useful for applications requiring extremely fine surface finishes and precise control over the removal process. Walker et al. [5] introduced the 'Precessions' tooling for polishing and figuring flat, spherical, and aspheric surfaces, utilizing a precessing motion to enhance the uniformity and precision of material removal, making it highly effective for achieving the desired surface quality in optical components. Subsequent studies by Walker et al. [9,11,12] further refined this process, demonstrating its scalability and effectiveness in various applications, including the removal of mid-spatial frequency features and edge control in CNC polishing. Kordonski et al. [6] described a new magnetically assisted finishing method using a magnetorheological fluid jet, combining the benefits of fluid jet polishing with magnetic field control, offering improved material removal rates and surface finishes.Hinn and Alex [7] discussed efficient grinding and polishing processes for asphere manufacturing, emphasizing the importance of process optimization in achieving high precision and quality. Their work highlighted advancements in tool design and process control that contribute to the efficiency and effectiveness of optical fabrication. Fähnle et al. [8] detailed the use of fluid jet polishing for optical surfaces, a technique that utilizes a high-velocity jet of abrasive fluid to remove material, proving effective in achieving high-quality finishes on complex optical surfaces. Yu et al. [10] and Li et al. [13] focused on the removal of mid-spatial frequency features and edge control in CNC polishing, demonstrating the importance of advanced tool path strategies, such as pseudo-random tool paths, in enhancing the uniformity of material removal and achieving superior surface quality.Tesar and Fuchs [15] investigated the removal rates of fused silica with cerium oxide/pitch polishing, providing valuable insights into the material removal mechanisms and the optimization of polishing parameters. Yu et al. [16] studied ultrasonic vibration-assisted polishing of optical glass lenses, highlighting the benefits of ultrasonic vibration in improving polishing efficiency and surface finish, reducing processing time and achieving high-quality optical surfaces. Ikeda and Akagami [17] introduced tribo-chemical polishing with electrically controlled slurry, combining chemical and mechanical polishing actions to achieve highly efficient and precise polishing of glass substrates. Liao et al. [18] addressed the improvement of surface shape error in pitch lap polishing, focusing on deterministic continuous polishing processes, emphasizing accurate tool control and process optimization in achieving high-precision optical surfaces. Pan et al. [19] explored control optimization for bonnet polishing systems, highlighting advancements in process control and tool design that enhance the precision and efficiency of bonnet polishing.Despite significant advancements in precision polishing techniques for aspheric surfaces, there remains a need for comprehensive studies that integrate multiple polishing methods to optimize both surface form and roughness. Existing research often focuses on single-method approaches, leaving room for improvement through combined polishing techniques.

This paper investigates the sequential application of bonnet and pitch polishing techniques to enhance the precision and quality of aspheric surfaces. By integrating these methods, we achieved substantial improvements in surface form and roughness, demonstrating the effectiveness of a combined polishing approach for high-precision optical fabrication.

2. Materials and Method

In this study, we aimed to fabricate a precise aspheric surface using a BK7 glass substrate with a diameter of 60 mm. BK7 was chosen for its good optical properties, including high transparency and low refractive index variations, making it ideal for precision optical applications. The substrate was securely mounted using wax on a precision runner, which ensured stability throughout the entire polishing process and minimized any potential distortions or vibrations that could affect the quality of the surface.The initial stage of the process involved rough grinding to remove excess material from the substrate. This was achieved using a cup wheel on an MCG150 5-axis CNC machine and following the suitable tool path, as shown in Figure 1(a-b).

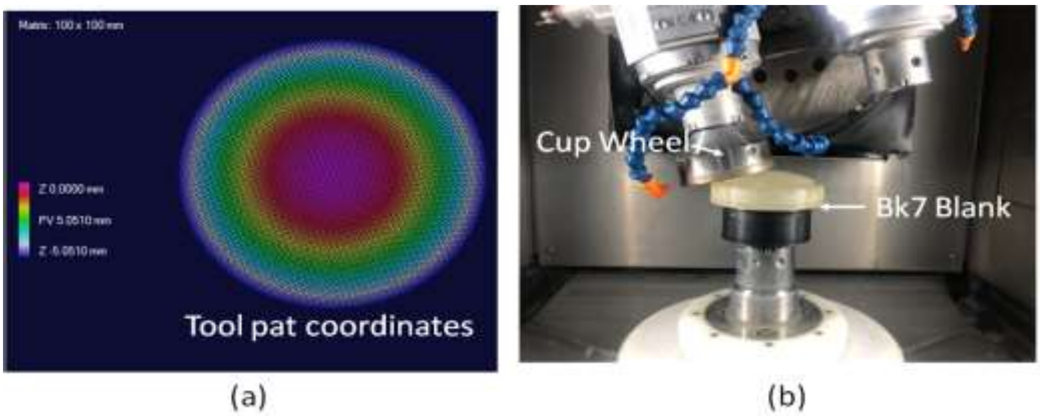

Figure 1: (a) Tool path for grinding (b) Photo of grinding machine setup

The polishing phase commenced with bonnet polishing, which was conducted on an MCP 250 6-axis CNC polishing machine as shown in Figure 2 (a-b). A GR-35 polishing pad with Zirconium oxide filler was utilized for its effectiveness in achieving fine surface finishes. The choice of a flower-shaped polyurethane pad was strategic, as it facilitated the efficient flow of slurry and removal of glass particles during the polishing process as shown in Figure 3a.

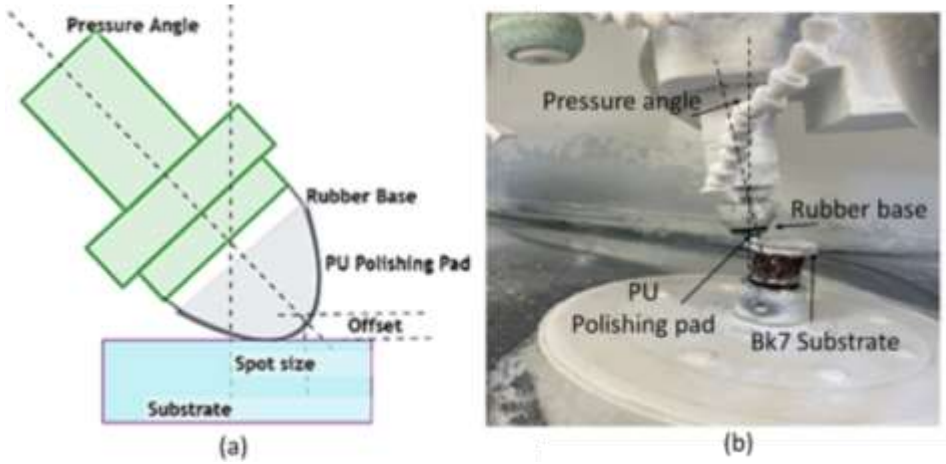

Figure 2: (a) Schematic of bonnet polishing (b) photo of actual polishing process

The slurry, composed of cerium oxide mixed with water, served dual purposes as both a coolant and an abrasive. This combination was essential in maintaining the temperature of the substrate and preventing any thermal damage while simultaneously providing the abrasive action necessary for polishing. The bonnet tool used for stage-I polishing had a radius of 20 mm and employed a spot size of 5 mm. A spiral spindle tool path was implemented, in which both the bonnet tool and the substrate rotated on their respective axes. This rotation, combined with linear movement, enabled the tool to traverse from the center to the periphery of the substrate, ensuring a uniform and thorough polishing. The stage-II polishing was performed by pitch polishing tool having suitable slots for abrasive slurry flow, as shown in Figure 3b. A pitch lap with a diameter of 30 mm was prepared and used on the same MCP 250 Polishing CNC machine. The polishing slurry consisted of Cerium oxide and water, similar to the bonnet polishing phase. The pitch tool followed a spiral axis path, rotating in a spiral motion, while the substrate maintained a circular rotation. This technique ensured a consistent application of the polishing medium and an evenly polished surface. The careful control of these movements was vital in achieving the desired surface quality.

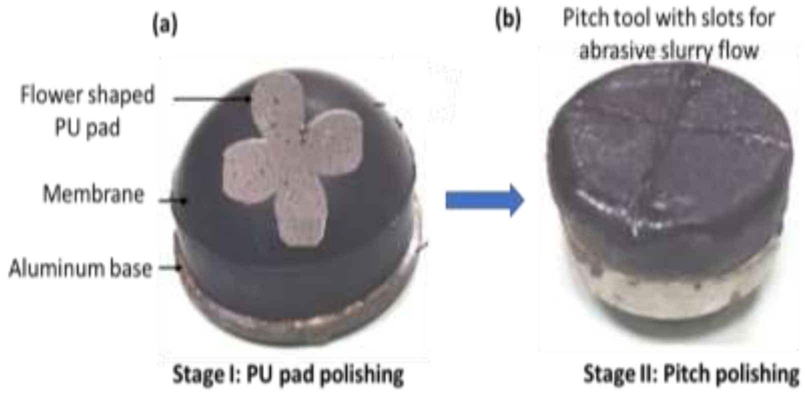

Figure 3: (a) Bonnet polishing tool (b) Pitch polishing tool

At each stage of processing surface was measured with Mahr MFU 200 profiler to ensure the profile accuracy. Profilometer measurements provided precise data on the surface form and any deviations from the desired aspheric profile.

3. Result and discussion

The precision fabrication of the BK7 aspheric glass substrate involved several iterative steps of grinding and polishing to achieve the desired surface quality. The results after each significant phase i.e. grinding, bonnet polishing, pitch polishing, and final are discussed in detail below.

The primary objective at grinding stage was to achieve a preliminary shape that was close to the desired aspheric profile. This rough grinding step laid the groundwork for more precise subsequent operations by significantly reducing the amount of material that needed to be removed during finer grinding and polishing stages.Following the rough grinding, aspheric grinding was conducted using a toric shape grinding tool on the same machine. The toric tool was selected for its capability to achieve the precise asphericity required for the substrate. Multiple iterative grinding sessions were performed, each iteration progressively refining the surface to closely match the desired aspheric profile. These iterations were critical in achieving a high level of precision, ultimately reaching a form value of approximately 1μm as shown in Figure 4. This grinding stage optimization approach ensured that the substrate was adequately prepared for the polishing phase, minimizing the risk of introducing significant surface deviations.

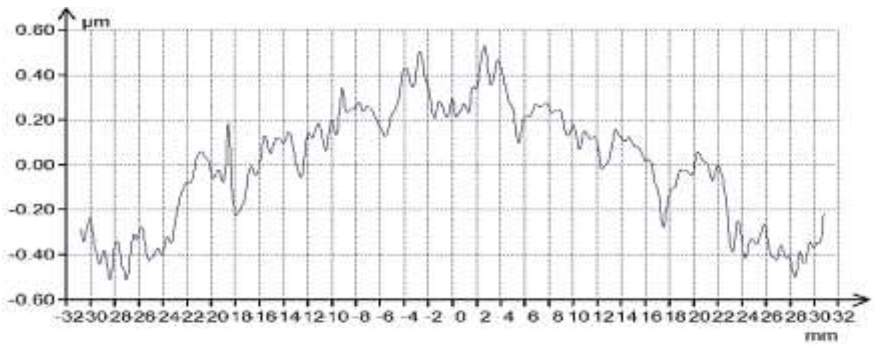

Figure 4: Residual form error after grinding stage

The initial polishing phase using the bonnet polishing technique produced notable improvements in the substrate's surface quality. The PV value, which is a critical indicator of the surface's deviation from the ideal aspheric form, was approximately 403 nm, corresponding to slightly higher than a λ/2 precision for a visible light. This demonstrates that the bonnet polishing method effectively reduced significant surface irregularities, bringing the form error within a moderate range. The radius of curvature (R0) was measured at 135.72 mm, closely aligning with the targeted specifications. The surface roughness (Ra) of 6.9 nm indicates that while the bonnet polishing improved the surface, there were still residual roughness and micro-defects present.

The bonnet polishing process effectively reduced larger form errors of grinding process and prepared the surface for finer polishing. The use of a GR-35 pad with Zirconium oxide filler and a spiral spindle tool path ensured uniform material removal and addressed major surface deviations. However, this stage alone was insufficient to achieve the highest surface quality, as evidenced by the remaining roughness and PV values. Due to spiral tool path motion and overlapping region of bonnet, the surface is degraded and circular mid-spatial frequency errors are left in surface. The mid-spatial frequency errors (circular ripples) can be found in Figure 5(a-b). Following the bonnet polishing, the substrate underwent pitch polishing, which further refined the surface. Pitch polishing significantly improved the surface quality, with the PV value reduced to 256 nm. This represents a 36% improvement from the initial bonnet polishing stage. The slight adjustment in the radius to 135.78 mm indicates a more precise alignment with the desired curvature

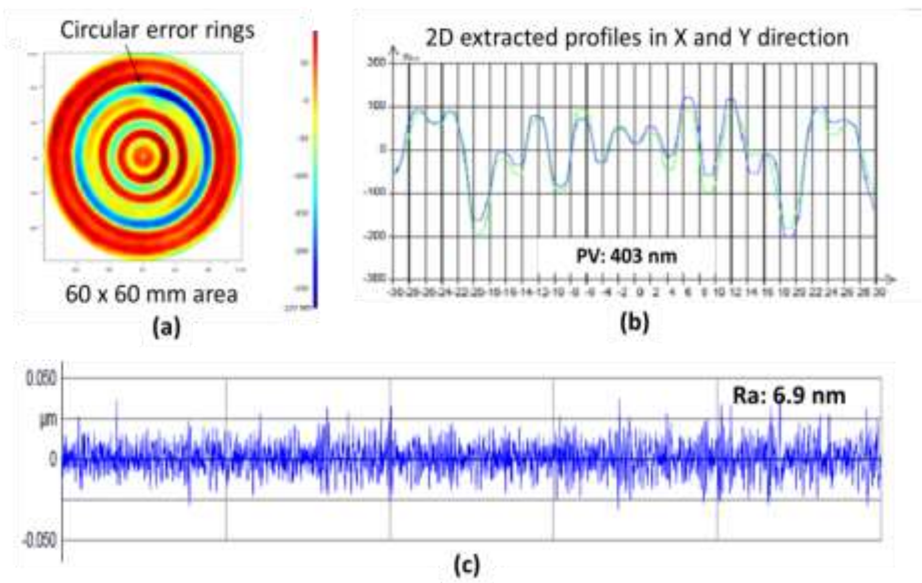

Figure 5: polishing results after bonnet polishing (a) 3D residual error map (b) Extracted 2D profiles in X and Y directions (c) Surface roughness

The roughness (Ra) further decreased to 5.4 nm, highlighting the pitch polishing's effectiveness in smoothing the surface and removing finer defects that the bonnet polishing could not eliminate. The use of a spiral path motion during pitch polishing was crucial in breaking up the circular lines left by the bonnet tool, resulting in a more uniform and smoother surface. The polishing results at pitch polishing are shown in Figure 6 (a-c).

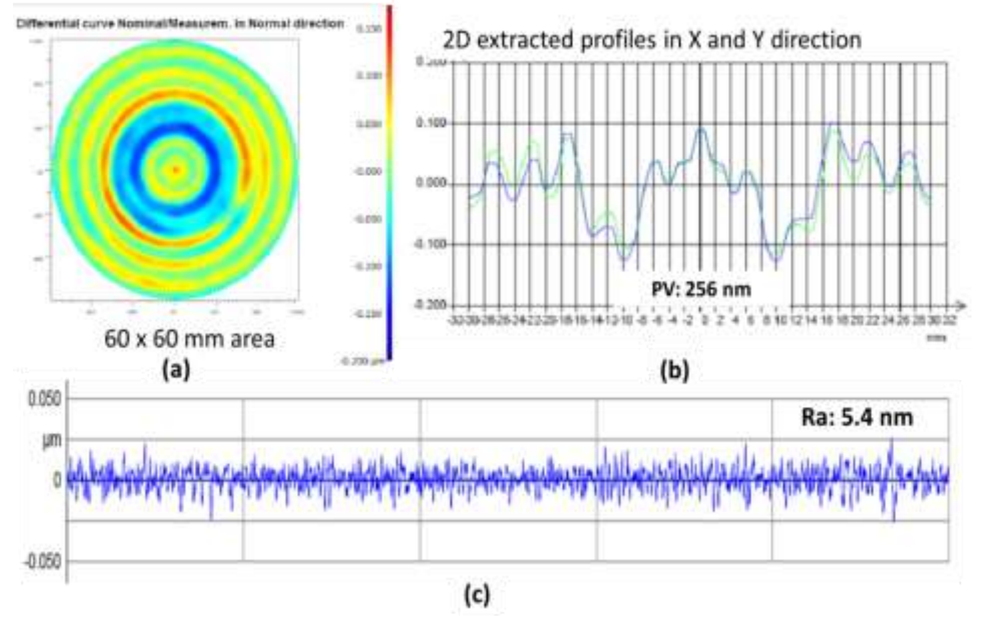

Figure 6: Pitch polishing results (a) 3D residual error map (b) Extracted 2D profiles in X and Y directions (c) Surface roughness

The form error left after first polishing cycle is utilized for form error correction. The error map was imported in tool path generation software and modified toolpath is generated. A final iteration of polishing was performed to achieve the optimal surface quality. The final PV value of 210 nm marks a substantial overall improvement of 47% from the initial post-bonnet value, underscoring the effectiveness of the sequential polishing approach. The radius of curvature remained consistent at 135.77 mm, ensuring the substrate's shape met the precise optical specifications required. The roughness value (Ra) reached 3.9 nm, a 43% improvement from the post-bonnet polishing stage, indicating a high-quality, smooth optical surface suitable for advanced applications. The results after final ittration of pitch polishing are shown in Figure 7 (a-c)

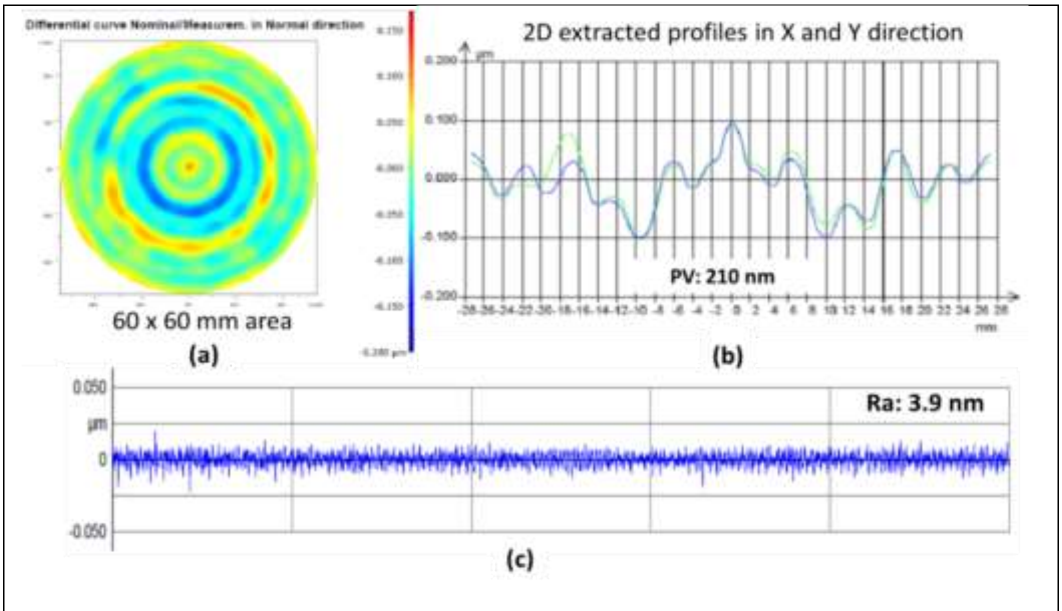

Figure 7: 2nd iteration of pitch polishing results (a) 3D residual error map (b) Extracted 2D profiles in X and Y directions (c) Surface roughness

the results validate the effectiveness of using a combination of bonnet and pitch polishing techniques for the precision fabrication of aspheric surfaces. The significant improvements in PV values and surface roughness achieved through sequential polishing highlight the potential of these methods to meet stringent optical specifications. The comparative results are summarised in Table 1.

Table 1: Comparison of results at different stages of optical polishing

Parameters	Design/ required results	After grinding	Bonnet polishing	Pitch polishing	2^{nd} iteration of pitch polishing
PV (Peak to valley form value), nm	< 250	1040	403	256	210
R0 (Radius), mm	135.75 +/- 0.05	135.76	135.72	135.78	135.77
Ra (Roughness), nm	< 5	-	6.9	5.4	3.9

This study contributes to the ongoing development of advanced optical fabrication technique. The photo of fabricated precise aspheric surface is shown in Figure 8.

Figure 8: Photo of fabricated precise BK7 aspheric lens

4. Conclusion

The sequential application of bonnet and pitch polishing techniques has proven highly effective in enhancing the surface quality of aspheric optical components. The study achieved a 47% improvement in surface form values and a 43% reduction in surface roughness. The bonnet polishing effectively addressed initial surface irregularities, while pitch polishing smoothed out the remaining imperfections, including circular lines. The final surface quality, with a PV value of 210 nm and Ra of 3.9 nm, underscores the efficacy of this integrated approach. These results highlight the importance of combining different polishing techniques to meet the demanding standards of contemporary optical engineering, offering a viable pathway for the production of high-precision aspheric surfaces.

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