Abstract

This research aims to solve the fabrication issues that restrict the surface quality of freeform optics during ultra-precision diamond turning. Freeform optics is a promising substitute for conventional optics in many applications, such as illumination applications, projection devices, ophthalmic applications, aerospace engineering, etc. The use of freeform optical elements in an optical system provides opportunities for numerous improvements in their optical performance at reduced system size, fabrication effort, and cost. Various fabrication methods viz. Ultra-precision machining, precision grinding, and advanced polishing methods are developed recently to fabricate freeform optical components. Ultra-precision machining is the best-suited method to process complex shapes with nano-metric surface finish and sub-micron profile accuracy. Slow tool servo (STS) configuration of ultra-precision machining is used to develop continuous type freeform surfaces. The low spindle speed of the STS process and involvement of multiple process parameters limit the surface quality. In principle, the optimized STS machining process is capable of developing the surface quality required for optical applications if supported by suitable metrology feedback. The metrology feedback is essential to correct the tool path to compensate for the form error. However, in the absence of a suitable metrology technique, it is not possible to achieve the desired surface quality. The alignment of freeform optics is another challenging task that affects both the fabrication and measurement process. It is essential to mount the freeform surface precisely with some pre-defined references during fabrication and metrology. The misalignment errors mislead the metrology feedback and limit the compensation process. Even if all these issues are resolved, a sustainable approach to fabricate the freeform optics is required. Till now, molding is the most suitable process for mass production of freeform optics. However, it is difficult to cut the hard mold materials in STS configuration due to low cutting speed. Polishing is one of the essential steps in that case, which significantly increases the process cost.

The thesis presents the development of the process for the fabrication of freeform optics by ultra-precision machining and is summarized in the following four major investigations:

a) Optimization of STS process parameters *i.e.*, Machine axis motion increments, tool nose radius, spindle speed and depth of cut.

b) Form error compensation technique for corrective machining of freeform optics.

c) Novel alignment method for freeform optics

d) Development of cost-effective polishing setups for finishing of freeform mold

In the first study, a set of experiments are performed to explore the effects of various process parameters of STS machining. The effects of tool setting in terms of tool overhang on surface quality and the selection of other parameters are studied. Further, the STS machining process parameters are analyzed and optimized. This initial study is helpful to fabricate the freeform optical surface with optimized process parameters.

In the second study, the tool path compensation routine is developed to minimize the form error. The fabrication steps of STS machining are discussed, including fiducial-based alignment of freeform optics, contact profiler based metrology and feedback mechanism to modify the tool path. The simulation study is also performed to understand the effects of alignment errors, which are the main reasons limiting the compensation cycle.

After understanding the reasons behind the saturation of the tool path compensation process, the third study is performed to solve the alignment issues. The sampling moiré based technique is developed to precisely align the freeform optics throughout the fabrication iterations. The proposed alignment technique is better than mechanical probe-based methods, easy to use, and cost-effective. The freeform surface with form accuracy 0.18 µm is developed, which demonstrates the effectiveness of the alignment process. In the end, the overall alignment strategy is formulated to standardize the alignment process.

In the fourth study, the goal was to develop the mold insert for freeform optics. The flexible pad polishing setup is developed to improve the surface finish of freeform surfaces without affecting the profile. The precisely milled freeform surface of mold steel is polished on the developed setup. A significant improvement in the surface finish is achieved. Although the setup is used on a two-axis diamond turning machine, no substantial effect is found on the profile. Hence, the current setup can easily be used with STS configuration and other shape generation platforms also. Further, the magneto-rheological finishing and bonnet based hybrid polishing setup is designed for corrective polishing of the freeform surface. The capability of the setup is demonstrated by initial experiments and proposed as cost-effective solution for corrective polishing of freeform optics in the future.
It is expected that the investigations carried out in the thesis work will help in substantially increasing the accuracy of the production of high-performance freeform optics.

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