論文の内容の要旨
Abstract of Dissertation

Research on Ultraprecision Finishing of Micro-Optic Mold by Vibration-Assisted Polishing

（マイクロ光学素子用金型の振動援用精密研磨に関する研究）

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Recently, demands for micro-optical lenses with high optical performance are increasing in various optical and electrical systems, such as blue-ray players, micro probe and compact digital cameras. Besides that, micro-optical lenses are widely used in medical applications such as endoscopes and ophthalmic systems; and in industrial applications such as inspection and other tasks where their small size and their renowned high-quality optical imaging are so important. Moreover, new applications of micro-structured lenses in the fields such as Micro channel for Blood analysis, Fresnel lenses for solar panels, LED lighting lens, Microprobe for IC testing and micro array for Wafer Level Cameras (WLC) are highly required.

Under these circumstances, the preferred manufacturing method for many micro-optical lenses is quickly evolving from direct lens generation process to molding process because of the large amount of requirement and the complexity of structure of optical lenses. The main manufacturing process of micro-optical lenses is followed by cutting or grinding, polishing and molding. As the final process, the molding is used to do the mass production or batch production. To generate optical lenses with high-performance, the molds are required with high form accuracy and surface quality. Therefore, these molds are mostly machined by diamond cutting or precision grinding with resinoid bonded diamond wheels on an ultra-precision machine tool. Diamond cutting or precision grinding can remove materials fast and high form accuracy can be obtained, but cracks or fractures are induced on top of surface or subsurface of workpiece due to the fact that material is removed due to brittle fracture. Moreover, in some cases the replicated optical elements are not sufficient to meet the increasing demands concerning surface roughness and form accuracy. Therefore, a subsequent polishing process with loose super abrasives is required to guarantee manufactured optics usable. In polishing process, since the material is removed plastically/elastically, the scratches on the surface and residual defective layer which leads to subsurface damage generated by cutting or grinding could be eliminated or reduced, and good

surface roughness and high surface quality could be obtained.

In traditional polishing, a soft rotating polishing tool, such as a rubber tool is used to polish the workpiece. The polishing tool usually with the angle of 45 degree applies a constant polishing force against the workpiece surface, while loose abrasives are supplied. But when the shape of the workpiece and the radius of curvature become smaller typically less than 5 mm in diameter, the polishing mechanism is led to complex due to the requirement of precise control in position and polishing pressure. And also the polishing tool cannot be miniaturized with tool diameter less than Φ2 mm, otherwise the polishing efficiency will be reduced because the radius of polishing tool affects polishing efficiency. Additionally, due to the vibration from rotator, the polishing pressure becomes poor to control, so it is difficult to apply this polishing method.

To solve these problems, the vibration-assisted polishing (VAP) method has been proposed. In this method, the polishing tools can be miniaturized because the polishing efficiency doesn't depends on polishing tool, and it can be focused on polishing very small area (under 0.2 mm^2) with high removal efficiency and the scratches generated by cutting or grinding are removed, so better surface roughness can be obtained. And as the tool is not rotated, the polishing force can be kept constant easily.

The aim of this research is through developing simple and feasible methods which are practical to be used in industry to time-efficiently finish the mico-optical molds used in replication of the micro-optical lenses with good surface quality and high form accuracy. The workpiece is made of cemented carbide which is hard and brittle ceramics (WC) such as tungsten carbide and the diameter is less than 5 mm. The shape of surface is aspheric with high numerical aperture (NA) which means the lens has a steep angle. It is to meet the requirements of some optics such as the pickup lens in a blu-ray player. Surface roughness after finishing process is required as Rz < 10 nm and Ra < 2 nm with the form accuracy should be lower than 0.2 µm P-V.

The thesis is composed of 6 chapters and begins with the introduction of research. Secondly, some new vibrating polishing tools are fabricated. Then the polishing force control systems are developed. Based on the developed vibrating polishing tools and polishing force control systems, the polishing systems are setup. After that, the polishing experiments are conducted. Finally, some conclusions are obtained and the future work is well planned.

Chapter 1 introduces the background of this research. The basis of polishing and state-of-the-art of polishing methods are reviewed. Then the vibration-assisted polishing method is proposed. At last, the research aim and structure of the thesis are summarized.

Chapter 2 explains the developments of vibrating polishing tools. The 2D micro-vibration stage based on piezoelectric effect composes of four PZT actuators and a flexure hinge. The characteristics are evaluated and the driving circuit is developed by following the measured characteristics. The vibration control system is also proposed to control the micro-vibration stage. According to the measurement results, it can generate large amplitude of vibration up to 100 μm in two orthogonal directions independently at a frequency around 1100 Hz and 2D vibration traces like line, circle and ellipse are acquired. The magnetostrictive vibrating polisher is developed basing on magnetostriction effect. The actuation principle is illustrated and vibration mode is analyzed. The characteristics are also evaluated. It is composed of a vibrator made of a giant magnetostrictive material and a small polishing tool, which is screwed into the head of the magnetostrictive vibrator. Coils are wound around four legs of the vibrator, and the legs can be individually pushed (expansion) or pulled (contraction) by controlling the input currents. It has the advantages of compact structure, low voltage driving and high power, and can generate a radius of 30 μm circular vibrating motion at frequency 9.2 kHz. Some other types of magnetostrictive vibrating polishers are also developed based on the size change of the polishing tool and vibrator.

Chapter 3 describes the polishing force control system. Three kinds of polishing force control system are proposed to improve the polishing stabilty. The balancing adjustment mechanism is firstly introduced. The balancing adjustment mechanism based on the principle of mechanical lever has a simple structure and the polishing force is controllable within a range of 0-20 mN with a resolution of 2 mN. It is easy to be fabricated with low cost but it is not stable due to no force feedback. To realize the force feedback, and improve the force control range and resolution, the real-time polishing force control system which mainly composed of a load cell and a piezo stage enables a stable polishing and the polishing force is controllable within a range of 0-200 mN with a resolution of 0.1 mN. However, the system leads to a high cost. Moreover, to assist the polishing of micro-structured molds like fresnel shapes, the constant polishing force control system by a VCM and a linear stage is developed. The polishing force can be controlled with a wide range of 0 -10N (resolution: 2 mN - 20mN) depending on the force range and sensitivity of VCM.

Chapter 4 illustrates the development of vibration-assisted polishing systems. Two kinds of vibration-assisted polishing systems are setup by using the developed vibration polishing tools and polishing force control systems. One is composed of the micro-vibration stage and the real-time polishing force control system, and the other is developed by using the magnetostrictive vibrating polisher with polishing force control systems on a 5-axis NC controlled machine. Concerning about the practical application in industry, a desktop polishing system for micro-optical mold is proposed to cut the cost and downsize the vibration-assist polishing system. Then the tool dwell time control methods are proposed to meet the requirement of polishing experiments for the different shapes of molds. After that, control method of B-axis workpiece tilting table is illustrated and polishing process is descriped.

Chapter 5 conducts some polishing experiments by using the developed polishing system and discusses the experiments results. Some basic polishing characteristics and relationships between parameters have been acquired. The results show that the circular vibrating motion is the best vibrating motion to get high polishing efficiency and generate good shape of material removal function. Concerning about the removal depth and surface roughness, the diamond slurries with grain size of 0.5 μm and 0.25μm are more competitive to meet the requirements. Polisher's radius of 1 mm is more suitable as considering about the practical polishing for micro-optical mold with size between 1-5 mm. The relationship between polishing parameters are tested. The result reveals that material removal rate decreases with the increasing of polishing pressure from a certain value of polishing pressure which will be a great complement to the Preston’s equation. It is also proved that the polishing efficiency is mainly decided by the relative velocity and polishing pressure, and also polishing time if necessarily, whereas the surface roughness is mainly depends on the material of polisher and grain size of slurry. The results of micro-aspheric polishing experiments for Electroless nickel plating show that the form accuracy was improved to 200 nm P-V and the surface roughness was reduced to 8 nm Rz (1 nm Ra) by lateral vibrating motion. The results of micro-aspheric polishing experiments for Binderless tungsten carbide demonstrated that the form accuracy was improved to less than 100 nm P‑V and the surface roughness to 3.3 nm Rz (0.4 nm Ra), this implies that the present work can successfully meet the requirement of the research aim. By using the basic polishing characteristics acquired in this paper, the polishing performance will be well controlled. The wear model of polyurethane polisher’s head has been proposed and analyzed. Some polishing experiments are conducted to preliminary verified with experimentally verification.

Chapter 6 summarizes the work of this research and some conclusions are acquired. Then some challenges are proposed for the future work.