Ultra-Precision Machining Technologies

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In order to reduce the surface/subsurface damage of soft-brittle optical materials and improve their surface quality, it is necessary to carry out ultra-precision machining of soft-brittle optical materials. Common ultra-precision machining techniques for soft-brittle optical materials include abrasive-free deliquescent polishing, single-point diamond turning (SPDT), chemical mechanical polishing (CMP), ultra-precision grinding, micro-milling, ion beam figuring (IBF) and magnetorheological finishing (MRF).

Keywords: Ultra-precision machining technologies ; Soft-brittle optical materials ; Abrasive-free deliquescent polishing ; Single-point diamond turning ; Chemical mechanical polishing ; Ultra-precision grinding ; Micro-milling ; Ion beam figuring ; Magnetorheological finishing

1. Introduction

Generally speaking, brittle materials with low Mohs hardness and whose elastic limit is very close to the strength limit are called soft-brittle materials [1][2]. Common soft-brittle optical materials include potassium dihydrogen phosphate (KDP), mercury cadmium telluride (MCT), FCD1 optical materials, etc. Soft-brittle optical materials have the advantages of excellent optical characteristics and good temperature stability, so they have extremely broad application prospects in the fields of optics, microelectronics, aerospace, instrumentation, laser nuclear fusion and other fields [1][3][4]. However, soft-brittle optical materials also have the characteristics of soft texture, high brittleness, low fracture toughness, strong anisotropy and low resistance to thermal shock, which increases the processing difficulty of soft-brittle optical materials.

2. Major Ultra-Precision Machining Technologies

Abrasive-free deliquescent polishing is a new ultra-precision processing technology proposed for easily deliquescent materials. This technology is a new flattening polishing technology formed by removing the solid abrasive in the solution based on the traditional chemical mechanical polishing technology, which avoids the embedding of the abrasive. The deliquescent polishing liquid mixed with water can deliquesce the undulating layer, and then remove the deliquescent layer by the mechanical action of the polishing pad [5][6][7]. It imposes no mechanical stress during polishing and does not damage a polished surface. This method is a soft-brittle optical material processing technology with great potential.

SPDT is the most important method for processing large optical elements. During the fly cutting process, the spindle drives the fly cutting disk to rotate rapidly, the diamond tool installed on the edge of the fly cutting disk completes the main cutting movement, while the substrate fixed by the vacuum chuck moves in the feed direction [8]. In order to improve the processing quality, it is necessary to pay special attention to the brittle to ductile transition depth of the material [9]. This technology can obtain a very smooth surface, but higher processing requirements are required for its surface accuracy, surface roughness and surface waviness [10]. SPDT is mainly used for soft-brittle optical devices, especially for precision manufacturing of large-diameter KDP devices. The disadvantage is that they will form cutting marks, which will adversely affect the optical performance.

CMP is a widely used process for ultra-smooth surface polishing, which can remove materials at the atomic level [11]. It utilizes the dual action of chemistry and machinery to make the polished surface reaches the required flatness and roughness [12]. The material removal mechanism of the polished surface is that the polishing liquid reacts with the active atomic layer on the surface of the polished material to form a transitional soft layer. The soft layer is removed by the way of the action of the abrasive or the drag of the polishing disc, and then taken away by the flowing liquid. With this method, the surface of the polishing plate can be planarized globally without damaging the surface. However, the value of PH of the polishing fluid has a great influence on the material removal rate and surface roughness. In addition, the chemical composition of the polishing fluid will cause some damage to the environment.

Ultra-precision grinding is a common method to obtain high quality surfaces. It is widely used in the area of large wafer thinning and optical elements manufacturing. The working principle of ultra-precision grinding is removing the material by means of rotation motion and axial feed motion of the grinding wheel [13]. It is found that ultra-precision grinding can obtain nano-level surface roughness [14]. However, the ultra-precision grinding technology is affected by the falling off of abrasive particles of the grinding wheel, which will lead to abrasive embedding, scratches and other defects [15]. These marks and damages will affect the optical performance of soft-brittle optical materials.

Micro-milling is used to repair the micro defects on the surface of soft-brittle optical materials in laser target shooting and processing because it can flexibly process complex 3D geometric shapes. This technique is considered to be a useful method for repairing micro-defects on the surface of soft-brittle optical materials during laser target shooting or processing [16][17]. The results show that micro-milling can repair the surface damage of soft-brittle optical materials with high efficiency and high quality. In addition, it can improve the resistance of optical materials to laser damage, and can increase its service life to a certain extent [18].

IBF is a non-contact optical manufacturing technology. It uses the ion beam emitted by the ion source to bombard the workpiece surface to produce physical sputtering effect and remove the material of the soft-brittle optical elements. In this way, the workpiece surface material at atomic level is removed [1]. IBF is characterized by high machining precision and low force on the workpiece. Moreover, the surface quality of workpiece can get a good protection in a vacuum [19]. During processing, the workpiece is not subjected to pressure and does not produce the subsurface damage. Theoretically, IBF can realize the non-damage ultra-precision surface, which can be widely used if the cost is reduced and the material removal rate is improved.

MRF is an indispensable ultra-precision processing technology in the optical manufacturing industry. It is especially suitable for the polishing of optical elements with complex shapes, which can obtain good surface finish without introducing any surface/subsurface damage [20]. When a magnetic field is applied in the working gap, the magnetorheological fluid hardens and then rotates to the finishing area through a rotating bearing wheel and grinds the workpiece. Because the contact area between magnetorheological fluid and the workpiece is limited to one point, so MRF is very suitable for polishing workpieces with complex surfaces [21]. The technique has obvious advantages in improving surface accuracy, but it has disadvantages such as surface scraping and abrasive embedding.

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