Topical Review

A review of the techniques for the mold manufacturing of micro/nanostructures for precision glass molding

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Abstract

Micro/nanostructured components play an important role in micro-optics and optical engineering, tribology and surface engineering, and biological and biomedical engineering, among other fields. Precision glass molding technology is the most efficient method of manufacturing micro/nanostructured glass components, the premise of which is mold manufacturing with complementary micro/nanostructures. Numerous mold manufacturing methods have been developed to fabricate extremely small and high-quality micro/nanostructures to satisfy the demands of functional micro/nanostructured glass components for various applications. Moreover, the service performance of the mold should also be carefully considered. This paper reviews a variety of technologies for manufacturing micro/nanostructured molds. The authors begin with an introduction of the extreme requirements of mold materials. The following section provides a detailed survey of the existing micro/nanostructured mold manufacturing techniques and their corresponding mold materials, including nonmechanical and mechanical methods. This paper concludes with a detailed discussion of the authors recent research on nickel-phosphorus (Ni-P) mold manufacturing and its service performance.

Keywords: precision glass molding, mold manufacturing, micro/nanostructure, mold material, extreme features

(Some figures may appear in colour only in the online journal)
1. Introduction

Due to their significant functions in hydrophobicity [1–3], friction reduction [4], and optical reflection and diffraction [5], micro/nanostructures are widely applied in the fields of optical imaging and sensing, biomedicine, etc. A micro/nanostructure array is composed of many geometric units on the micro/nanometer scale. Commonly used micro/nanoarrays include lens arrays, columnar arrays, groove arrays, and pyramid arrays, as shown in figure 1. In addition, some other nonconventional micro/nanoarrays have been designed and manufactured to meet the needs of uniquely designed functional surfaces [5, 6]. Micro/nanostructured glass components have the advantages of miniaturization, integration, and being lightweight, which are in line with the development direction of microsystems. As a result, micro/nanostructured glass components are widely used in the microsystems. Microlens array structured glass is used in integrated cameras to improve imaging quality and achieve refocusing and three-dimensional imaging functions. Benefiting from its high diffraction efficiency, micro/nanostructured glass is applied in optical information processing, structural coloration, anti-counterfeiting, etc [7–9]. The scale reduction and performance improvement of these microsystems are largely determined by the quality of the micro/nanostructured glass components, which requires overcoming the challenge of manufacturing micro/nanostructures with the features of both extremely small size and high quality. Considering the broad application prospects and extreme features of small scale and high quality, ultra-precision manufacturing technology for the fabrication of micro/nanostructured glass components has become a strategic development field in many countries.

Micro/nanostructures are produced by generating a series of geometric units on a surface at the micro/nanometer scale via certain methods. Attempts are currently underway to advance the extreme manufacturing ability of these methods in terms of size, accuracy, consistency, and efficiency. Glass molding has been creatively and innovatively used to efficiently manufacture micro/nanostructure arrays on glass surfaces, which is deemed as the best technology to fabricate micro/nanostructures on glass surfaces. The concept of glass molding technologies involves inducing the proper pressure at a high temperature to copy the micro/nanostructure array from a mold onto a glass. During the molding process, glass is softened via heating and then solidified via annealing. Glass molding has the advantages of high forming accuracy, efficiency, good consistency, and low processing costs, and is therefore suitable for the mass production of micro/nanostructure arrays. It should be noted that the micro/nanostructure generated on the glass surface is completely copied from the mold surface during the molding process, so the precise manufacturing of the micro/nanostructure with extreme features of small size and high quality on the mold is the premise of glass molding. Recently, many methods, including both mechanical and nonmechanical methods, have been rapidly developed to overcome the challenge of manufacturing small, high-quality micro/nanostructures. These novel methods have been successfully applied to mold manufacturing. Etching technology can achieve material removal at the atomic scale, so the produced micro/nanostructure molds have high precision. However, this technology is limited by its low manufacturing efficiency and complex process. Laser technology is also widely applied in surface engineering. Femtosecond laser-induced periodic surface structures (FLIPSSs) display high efficiency in micro/nanostructure mold manufacturing. Micro-electrical discharge machining (μEDM) and electrochemical machining technologies have also been investigated for micro/nanostructure manufacturing and are especially dominant in the fabrication of microstructures with complex shapes and high aspect ratios. In addition, ultra-precision cutting technologies and micro/nanogrinding technologies have been widely used to machine micro/nanostructures. These mechanical methods use diamond cutting tools to remove mold materials at the micro/nanoscale and fabricate the desired structure [10, 11]. Compared with those manufactured by nonmechanical methods, micro/nanostructures molds machined by mechanical machining technology can directly reach nanometer precision.

This paper explores the key technologies of mold manufacturing. As a typical example of molding technologies, the precision glass molding (PGM) process is first introduced and analyzed, as are the extreme requirements of the mold materials. Subsequently, the newest nonmechanical technologies, including etching, laser machining, and electrical discharge machining (EDM), are introduced and explained in detail. The newest micro/nanostructure processing methods that use mechanical methods, including turning, milling, fly cutting, grinding, and lapping, are then explained. Next, compound technologies that combine conventional mechanical machining the ultrasonic vibration are also introduced and described in detail. Finally, the authors’ recent study on the service performance of a nickel-phosphorus (Ni-P) micro/nanostructured mold is presented in detail.

2. Mold materials for glass molding

Glass molding has become the most effective and efficient method for the high-precision manufacturing of
micro/nanostructures on glass surfaces and is implemented on a molding machine. For instance, as shown in figure 2, the PFLF7-60A molding machine (produced by SYS, Japan) consists of a heating module, pressurizing module, and automatic conveyor. The glass is processed into the desired shape after undergoing four processes in the molding machine, including heating and maintaining, pressurizing at high temperature, annealing at low pressure, and cooling and demolding, as shown in figure 3. The micro/nanostructured mold can be divided into the upper mold, lower mold, and sleeve. The vertical distance between the upper and lower molds is aligned with the designed micro/nanostructures, and it can be controlled by regulating the sleeve height. The glass preform is placed into the mold core and then transferred into the mold chamber for heating. A protective gas (such as nitrogen) fills the mold chamber to prevent the glass and mold from oxidizing under the high temperature. When the glass preform is heated 30 °C–40 °C above the glass softening point, the upper and lower molds are closed and loaded to compress the glass preform to achieve complete filling and replication of the micro/nanostructures. The mold temperature is slowly reduced to approximately 200 °C, during which a small load is still applied. Finally, the mold leaves the mold chamber and is taken out after being cooled to room temperature.

The main component of glass is silicon dioxide ($\text{SiO}_2$), which is brittle at normal temperatures but exhibits viscoelastic characteristics at high temperatures. The temperature is subdivided into the strain point ($S_P$), annealing point (AP), transition point ($T_g$), yield point ($A_t$), and softening point (SP) according to the expansion coefficient characteristics of glass. The glass used for molding must have a low transition point, which can extend the mold life and shorten the processing cycle [12, 13].

According to the mechanism of glass molding, the mold material has a substantial influence on the interface condition between the mold and glass, which also affects the precision of the fabricated glass components. To suppress the forming error resulting from high-temperature deformation, a mold material with low thermal expansion and high-temperature resistance
should be selected. In addition, under the action of the heating-cooling temperature cycle and the mold clamping-releasing pressure cycle, thermal fatigue and stress fatigue will occur in the microlens mold, which will cause mold wear and failure. Therefore, the selection of the mold material and mold manufacturing technology is essential to the glass molding process. The materials used for glass molding must have the following characteristics: (a) high hardness and strength at high temperatures, a low thermal expansion coefficient, and excellent stability of the chemical properties at high temperatures; (b) good material consistency, meaning that it can be processed to meet the requirements of an optical-grade surface; (c) inert adhesion and reaction with glass [13, 14]. It is important to note that ideal mold materials with extremely high hardness, such as silicon carbide (SiC) and tungsten carbide (WC), usually cannot be micro/nanotextured via mechanical methods due to serious tool wear and the affinity reaction between the materials and the carbon atoms in the diamond tool during the cutting process. Therefore, machining large-area micro/nanostructures requires frequent tool changing, which inevitably results in errors. Therefore, plating and developing new mold materials with low hardness are necessary for mold manufacturing. Nickel phosphorus (Ni-P), has a hardness (500–600 HV) less than that of WC, SiC, and other super-hard materials. Ni-P can meet the hardness requirements of glass molding. Ni-P exhibits relatively good cutting performance, which makes it more suitable for single-point diamond cutting and use as an ideal mold material for glass molding [12, 13, 15]. In addition, it has been demonstrated that Ni-based materials have excellent lubrication and antiadhesive properties when used with glass at high temperatures [16]. The plating thickness of Ni-P can reach more than 100 µm. To improve the mechanical properties of Ni-P plating molds, graphene and graphene oxide were added and co-deposited with the Ni-P plating on the substrate, acting as reinforcement phases to generate a composite plating. Figure 4 shows the graphene-nickel-phosphorus (G-Ni-P) plating generated by Yu et al [15], the Young’s modulus and hardness of which before and after heat treatment were demonstrated to be higher than those of Ni-P.

3. Mold manufacturing of micro/nanostructures via nonmechanical methods

3.1. Micro/nano-etching

Etching is a pattern transfer technology that has been widely used in semiconductor manufacturing. Patterns can be transferred from a mask to a substrate by selectively etching an uncovered part of a layer. Etching processes include wet and dry etching, such as plasma etching, reactive ion etching, and ion-beam etching (IBE). Wet etching always takes place in a liquid environment where chemical solutions can react with the materials to be etched, thereby generating easily removable reaction products. However, the ‘undercutting’ effect in wet etching can reduce the precision of the etching pattern. Thus, dry etching, which can achieve high anisotropy via plasma-assisted material removal, has rapidly been developed to achieve high-accuracy pattern transfer. Thus far, etching has been studied in the fabrication of various microstructures with unique functions on molds for optical and biology fields.

3.1.1. Wet etching. Wet etching has been studied to obtain functional surfaces. It can achieve the isotropic etching of amorphous and polycrystalline materials, which can produce not only trenches and cavities but also microlens structures on mold materials, as shown in figure 5. Zhang et al produced a honeycomb-like textured surface with a pitch of 18 µm on multi-crystalline Si via a masked wet etching process [17]. Sood et al created deep Ta film trenches with widths ranging from 10 to 200 µm via hot NaOH/H2O2 and KOH/H2O2-based solutions [18]. By investigating the influences of various masks and solutions on the etching process, researchers have found ways to achieve deep etching and have produced cavities on the order of hundreds of microns. Chen et al and Tong et al produced both closely packed hexagonal and rectangular
concave microlens arrays with diameters less than 100 µm on silica via the femtosecond-laser-enhanced local wet etching method, in which the femtosecond laser induces craters on transparent materials, the chemical etching process is then accelerated in the laser-induced craters, and then the concave spherical surfaces begin to form [19, 20]. For single-crystal mold materials, such as Si and GaN, the crystal is etched at various rates in different crystallographic directions due to the various arrangements of bonds and atoms. Thus, wet anisotropic etching is used to manufacture spatial shapes on these materials. Based on this, both concave and convex pyramidal structures [21, 22] and microtip arrays [23] have been formed on Si wafers. Additionally, structures such as hexagonal pyramids and hillocks have been formed on certain crystal planes of GaN [24] and AlN [25].

3.1.2. Dry etching. Different from wet etching, dry etching covers plasma-driven chemical reactions and energetic ion beams aimed at removing the material in a gaseous environment, which can yield highly anisotropic etch profiles [27]. Some functional surfaces, such as antireflective ‘moth-eye’ surfaces [28], low-reflectivity pyramid-like surfaces [29], and lamellar-patterned surfaces [30], have been investigated and produced by the dry etching process. By combining dry etching with advanced mask fabrication techniques, researchers have also produced 2D and 3D microstructure arrays on various mold materials. 2D structures, such as microgrooves [31], cylindrical arrays [32], and gratings [33] with vertical walls, have been fabricated by lithography and dry etching processes. To obtain 3D structures, researchers have also investigated novel methods by which to first produce 3D masks and then transfer them to the substrates via the dry etching process. Greyscale lithography [34] and thermal scanning probe lithography [35] have been studied for the fabrication of 3D microstructures, such as microlenses, v-grooves, and pyramids. The direct production of microstructures on photoresist [36] and metal [37] masks via single-point diamond cutting has been proposed, and microlens structures have been successfully produced on Si via dry etching pattern transfer, as shown in figure 6.
Lasers. LIPSSs are usually regular grooves with a period equivalent to the laser wavelength and are oriented perpendicularly to the laser polarization direction. The generation of these LIPSSs on metals is attributed to the interference between the incident laser light and the excited surface plasmon polaritons (SPPs), which leads to the periodic energy distribution on the surface.

3.2. Laser processing

3.2.1. Conventional laser processing. Due to the high brightness, directionality, monochromaticity, and coherence of lasers, laser processing is characterized by high precision and efficiency in the micro/nano-processing of various materials. Laser processing technologies can be classified according to the lasers’ pulse widths, into conventional laser processing (with a pulse width greater than 10 ps) or ultrafast laser processing (with a pulse width less than 10 ps). Since the duration of the laser pulse exceeds the electron-lattice heat transfer time, thermal processing is the main mechanism of conventional laser processing. In contrast, in ultrafast laser processing, the pulse width of the laser is far less than the electron-lattice heat transfer time, which means that it is a non-thermal processing method.

In conventional laser processing, laser ablation, multi-beam interference, and laser-induced periodic surface structures (LIPSSs) are the primary methods for creating structures. In laser ablation, high-intensity lasers incrementally ablate the mold materials to fabricate the desired structures with typical sizes on the order of 10 µm to 10 mm. However, conventional laser ablation is a spot-focused process, which has extremely low efficiency for large-area processing. High-efficiency techniques, including line-focused laser machining, multi-laser interference, and diffraction-based laser micromachining, have been proposed. Regarding two-beam interference, the periodicity of the line-like surface topography is determined by the laser wavelength and the angle between the interfering sub-beams. In addition, as shown in figure 7, by conducting direct laser interference patterning, line-like grooves can be superimposed on pre-machined microstructures, which may be generated by other technologies.

LIPSSs were first investigated via the use of long-pulsed lasers. LIPSSs are usually regular grooves with a period equivalent to the laser wavelength and are oriented perpendicularly to the laser polarization direction. The generation of these LIPSSs on metals is attributed to the interference between the incident laser light and the excited surface plasmon polaritons (SPPs), which leads to the periodic energy distribution on the surface.

3.2.2. Ultrafast laser processing. An ultrafast laser, which has a pulse width that is far less than the electron-lattice heat transfer time, allows the process to be finished before lattice heating. Due to the advantages of a minimized heat-affected zone and ultrahigh power, ultrafast laser processing enables smaller-scale and higher quality processing of micro/nanostructures for almost all types of mold materials, including metals and semiconductors.

Femtosecond lasers are the most advanced due to their extremely short pulse width (10^-15 s). When a femtosecond laser pulse strikes a metal surface, the electrons initially absorb the laser’s pulse energy through the inverse bremsstrahlung mechanism over a skin layer with a thickness of about 10 nm. Since the electron interaction time is usually short, it is assumed that the heat that excites the electrons occurs instantaneously. Therefore, the entire nonequilibrium system in metals is described as constituting two sub-equilibrium systems, namely the hot electrons and cold lattice. Figure 8 shows a typical experimental setup of direct femtosecond processing for the creation of micro/nanostructures. Pulses generated by femtosecond lasers are focused onto a sample mounted on a computer controlled XY translation stage through a lens. A focused line can be obtained through a cylindrical lens. This femtosecond laser setup is suitable for constructing a single spot on the sample when the translation stage sits stationary, constructing a single line when translating the sample along the X-axis or Y-axis, or constructing a larger area when rastering a sample. Regular micro/nanostructures that can be created by direct femtosecond laser processing are classified as LIPSSs, nanohole arrays, and nanostructure-textured microstructures.

It has been found that LIPSSs generated using long-pulse lasers can also be produced by femtosecond laser pulses on metals. Similarly, FLIPSSs are commonly produced by multi-pulse ablation in a range of laser fluences.
slightly above the ablation threshold. FLIPSSs are more densely covered by nanostructures [45, 49], in contrast to the smooth LIPSSs produced by long-pulse lasers. Figure 9 depicts FLIPSSs induced on W and stainless steel (SS) covered with ridge and valley nanostructures. In addition, the period $d$ of these FLIPSSs is significantly smaller than that of regular LIPSSs, which attributes to the change in the effective refractive index of the air-metal interface, affecting the propagation of excited SPPs [45, 49]. To improve the manufacturing efficiency of surface texturing, microlens arrays are used to split the laser beam into several sub-beams so that several rows of periodic structures can be induced simultaneously [50]. In addition, as shown in figure 10, via cylindrical focusing and scanning the femtosecond laser pulses, Sun et al successfully manufactured large-area gratings on a Si wafer. The manufacturing efficiency improved by at least two orders of magnitude as compared to conventional line-scanning.

The period of FLIPSSs can be controlled by changing the laser wavelength, incidence angle, and laser fluence [54–56]. The ablation environment is another factor that affects the period of fabricated FLIPSSs. Liquids have larger refractive indexes than air, which significantly decreases the period of the FLIPSSs [57]. Currently, observed FLIPSSs can be classified as either low-spatial-frequency LIPSSs (LSFLs) or high-spatial-frequency LIPSSs (HSFLs). LSFLs have a period close to the laser wavelength, which is explained by the classical interference model. HSFLs have a period much smaller than the laser wavelength and are usually produced following several hundreds to thousands of laser irradiations with laser fluence lower than the single pulse ablation threshold [60].

Due to the Gaussian beam profile of the laser beam, only the central part of the irradiated spot can be ablated, thereby
generating nanoholes on mold materials, such as Si. Furthermore, by scanning the laser beam, surface nanomilling on a metal surface has been proposed via the use of near-threshold femtosecond laser pulses [61]. By irradiating gold nanospheres deposited on a Si surface, the plasmonic laser nano-ablation technique has been proposed and used for the fabrication of nanoholes in Si [62]. Micro/nanohole arrays can be fabricated by interferometric femtosecond laser ablation [63].

Direct femtosecond laser ablation can produce both nanostructures and hierarchies by varying the laser beam parameters. Microstructures with some nanostructures were formed in irradiated areas at a high laser fluence with large numbers of laser shots. Microspikes covered by irregular nanostructures with a size of 10–50 nm were produced on Si [64]. Columnar microstructures fabricated on titanium by a femtosecond laser were covered by nano-secondary structures [45, 65], as shown in figure 11(a).

FLIPSSs provide an effective way to produce nanostructure-textured microgrooves (hierarchical grooves) on mold surfaces. By scanning the focused laser beam across the workpiece surface, a single microgroove or a microgroove array can be produced on many materials. Nanostructure-textured microgrooves can be fabricated not only on the mold surface, as shown in figure 11(b). Both the valleys and ridges of the generated microgrooves are extensively covered with a variety of irregular nanostructures. Recently, an efficient approach was demonstrated to fabricate highly nanograting-textured lines on Si via combining the chemical etching and femtosecond laser. First, amorphous-crystalline nanofringes are fabricated after femtosecond laser scanning over a line on the Si surface, which creates almost no material removal. In the subsequent auxiliary chemical etching, nanograting structures are obtained and form the hierarchical line, as shown in figure 12 [66].

3.3. Micro-EDM

EDM is capable of machining all concave and convex microstructures, including complex 3D structures with high aspect ratios. It can be used to process conductive materials, regardless of their hardness.

Based on EDM technology, µEDM has been proposed and employed to machine microstructures. The processing mechanism of µEDM is the same as that of EDM. This process utilizes sequential spark energy in the form of the pulse between the tool and the workpiece, which are all immersed in dielectric fluids. However, the erosion rate is much lower than that in
conventional EDM because of the small pulse energy involved. The micromachining performance depends on the melting point, thermal conductivity, and electrical conductivity of the materials. A low melting point and electrical conductivity result in a good micro-machined shape with a low relative wear rate. High electrical conductivity and a low melting point produce low surface roughness, high micro-removal rate, and high discharge energy efficiency. Low thermal conductivity leads to a high aspect ratio and low micro-removal rate [68].

To improve the manufacturing efficiency, electrodes with micro-tip arrays have been extensively applied. He et al. fabricated a concave micro-array using an electrode with a micro-tip array to investigate the batch micro-machinability of metallic materials, such as die steel cemented carbide, as shown in figure 13. An electrode with a micro-tip array was generated by creating a pyramid micro-tip array on the electrode surface using a microdiamond grinding wheel [68]. Tong et al. analyzed the processing errors that resulted from the
offline-fabricated micro-electrode arrays, and then proposed an array servo-scanning µEDM process with on-machine fabricated micro-electrode arrays [69]. In µEDM, the minimum machinable size determines the extreme scale of the machined microstructure and is defined as the material removal per pulse discharge. To minimize the material removal per pulse discharge, researchers have utilized new electrode materials with high electrical resistivity. Koyano et al. found that the peak discharge current decreases with increasing electrical resistivity of the tool electrode. During the fabrication of microrod array, single-crystal Si tool electrodes with high electrical resistivity can reduce the average diameter of discharge craters generated on the microrods to approximately 0.4 µm. However, the Si tool electrode is also characterized by a tool wear ratio higher than that of copper, which may attribute to the brittleness of Si [70].

In recent years, reverse micro-electro-discharge machining (R-µEDM) has been proposed and has become a promising technology for the fabrication of precise components and microstructures with high aspect ratios, as shown in figure 14. R-µEDM is a noncontact thermal micromachining process that is extensively used to fabricate single and multiple 2.5-D features with high aspect ratios and different cross-sections, such as square, circular, and triangular cross-sections. The feed rate voltage and capacitance are the process parameters [71].

During the machining of a high-aspect-ratio microprobe array by µEDM, heat accumulation and heat deformation may occur in the microprobe array due to the poor debris expulsion in such a narrow spark-gap. It has been demonstrated that the use of ultrasonic vibration assistance is beneficial to debris removal in µEDM [72, 73]. It was found that when using vibration assistance during µEDM, bubbles are quickly driven out of the machining gap [74] and the processing efficiency significantly improves [75]. In addition, Lin et al. reported that the quantity of effective discharge of magnetic force assisted EDM was greater than that of conventional EDM [76], and the machined structure’s quality and manufacturing efficiency improved with the assistance of the magnetic force. Adding a rotating magnetic field perpendicularly to the electric arc enhances the material removal rate (MRR) as the debris is expelled from the machining gap [77]. When added tangentially to the electric field, the pulsating magnetic field helps facilitate the transfer of electrons and the degree of ionization, which improves the MRR and dimensional accuracy. Singh et al. investigated the combined effect of the application of a magnetic field and ultrasonic vibrations to the machining zone in µEDM and found that it resulted in a higher MRR and less taper for semicircular microfeatures, as well as higher machining efficiency [78].

Although R-µEDM is suitable for the manufacturing of microrods of various shapes with high aspect ratios, its process capability is limited by the difficulty of debris ejection, which causes debris to stick to the electrodes and creates secondary and higher-order erosion. Therefore, converting this disadvantageous phenomenon into a beneficial process is significant. According to the influence law of the secondary and higher-order erosion of debris, the electrode shape can be correspondingly designed to obtain the objective microstructure. Roy et al. studied the relationship between the material removed by secondary and higher-order erosion and that removed by primary erosion during machining. They found that secondary and higher-order erosion is five times more material than primary erosion [79].

The above examples illustrate the principle details and latest progress of several nonmechanical methods. Table 1 summarizes the processing characteristics and capabilities of nonmechanical methods for micro/nanostructure manufacturing.

4. Mold manufacturing of micro/nanostructures via mechanical machining

The previously discussed nonmechanical methods can achieve the micro/nanoscale manufacturing, but some resistance exists in the conductivity and magnetism of the materials. The cross-sections of the micro/nanostructures cannot be precisely regulated. In contrast, mechanical methods are available for most workpiece materials, and can achieve micro/nanostructures with superior geometric freedom and lower surface roughness.

4.1. Micro/nano-cutting

Ultra-precision cutting technologies via the use of diamond tools have become very important for the manufacturing of micro/nanostructured molds, as they can directly produce surfaces with nanometer precision without the need for subsequent processes [80]. Cutting technologies for micro/nanostructure manufacturing include diamond turning, diamond milling, fly cutting, and vibration-assisted cutting technologies.

4.1.1. Single-point diamond turning. Single-point diamond turning (SPDT) can manufacture micro/nanostructures with high machining speed and accuracy. The most basic
configuration of the diamond turning machine is based on only two controlled axes and a spindle. Therefore, rotationally symmetric structures, including Fresnel lens and aspheric Fresnel lenses, are the typical micro/nanostructures machined by turning. During microstructure cutting, the relative trajectory of the cutting tool to the workpiece is created by coupling the rotation of the workpiece and the feed motion of the diamond tool. The cross-section profiles of the structures are determined by both the diamond tool geometry and the modulation of the infeed depth. Contouring the desired shape by controlling both linear axes, easily generates more microstructures with complex shapes [81]. As a typical microstructure with a rotationally symmetric surface, Fresnel lenses can be machined by coupling the spindle rotation and the feed motion of the X-axis and Z-axis. Li et al. proposed a true circle processing method with SPDT to promote the machining precision of a Fresnel lens mold. The arc-curved surface of the Fresnel lens was machined with B-axis rotation instead of the frequent servo feed of each axis, which is utilized in the traditional interpolation method [82]. Moreover, the combination of ultraprecision machining technology and micro-indentation was proposed to machine high-accuracy microlenses. The proposed method achieved the array machining of microlenses with complex cross-sectional profile [83].

To extend the machinability of the diamond turning of more complex structures, modulated depth-of-cut (DOC) turning according to the radial and angular positions of the cutting tool on the surface has been proposed. According to the modulation frequency, these processes are called slow tool servo (STS) turning or fast tool servo (FTS) turning. An STS is driven by a table of the machine tool, while an FTS is driven by a piezo-electric actuator and the machine tool itself. Normally, an STS is used for machining surface structures with large amplitudes and freeform surfaces with high-aspect-ratio [84]. An FTS is suitable for generating small-amplitude microstructures on flat or axially symmetric surfaces.

STS turning has recently attracted significant interest because it is an economical machining method with no extra machine for tool drive, compared with FTS turning. Unlike the conventional process in which a single diamond tool is used to machine one lens at a time, researchers have developed an innovative diamond tool trajectory that allows the entire microlens array to be machined in a single operation using an STS [85]. Kong et al. proposed the orthogonal STS (OSTS) process to machine wavy microstructure patterns on precision rollers [86], as shown in figure 15.

Zhang et al. proposed a path strategy called the grid machining method to fabricate a compound eye lens (CEL) mold using STS technology. The off-centered machining configuration was proposed to prevent shape distortion caused by tool misalignment. This method was also proven to improve the form accuracy. The machined CEL mold was ultimately used in molding technologies [87], and it was proved that the CEL can machined both on planar surface and aspheric surface, as shown in figure 16. Spherical concave microlens arrays are usually fabricated on a single-crystal Si wafer for performance improvement in infrared optics via STS diamond turning [88]. Hexagonal microlens arrays offer higher optical efficiency than spherical lenses since the tight arrangement of hexagons makes the microlenses on the surface denser than the spherical lenses. The tool servo-driven segment turning method has also been utilized to reduce the dynamic error of the machine tool induced by lenslet edges during the cutting of hexagonal lens arrays. A measured peak-to-valley (PV) error of $\sim 300 \text{ nm}$ and a surface roughness of $\sim 5 \text{ nm Sa}$ were successfully achieved [89].

The virtual spindle-based tool servo (VSTS) diamond turning method has been proposed to generate discontinuously
structured micro-optics arrays. The VSTS is advanced in that the virtual spindle axis (VSA) can be constructed at any specified position during VSTS diamond turning via the multiple translational and rotational servo motions of the machine tool, as shown in figure 17. Based on the VSTS, microstructure cell arrays with specific shapes can be generated by FTS or STS turning by sequentially passing the VSA through the center of each microstructure cell. These discontinuous micro-optics arrays can be created on both planar and freeform surfaces [91].

FTS diamond turning is a promising machining process for generating microstructure surfaces that is widely used in the optics industry. Many researchers have focused on the development of FTS devices to improve their performance. The bandwidth, stroke, acceleration, stiffness, and accuracy of FTS devices significantly influence the final quality of the machined micro/nanostructures [92]. Moreover, the tool path strategy of FTS diamond turning is the key factor that influences the quality of the machined surface. The tool path generation for the machining of micro/nanostructures can be described by either analytical description or nonuniform rational B-spline description. The form error resulting from the tool nose radius cannot be ignored in FTS turning. Therefore, a stable compensation strategy for the tool nose radius should be implemented to optimize the tool path. In addition, because the dynamics of machine axes affect the surface quality of micro/nanostructures, they must be controlled to be consistent with the tool path strategy to minimize the form error [93, 94]. With the urgent demand for bulk metallic glasses (BMGs) with microstructure surfaces in micro/nano-electromechanical systems, a sinusoidal grid surface has been created on BMGs, which verifies that FTS technology is a very promising method of fabricating microstructure surfaces on BMGs [95].

Ultraprecision microstructure functional surfaces on hard and brittle materials (e.g. ceramic and glass) face the challenges of both a high surface finish and complex surface shapes due to their tendency to become damaged in the form of brittle fractures during machining. For highly brittle materials, ductile-regime machining is the only method by which to manufacture high precision micro/nanostructures. FTS diamond turning has been utilized to achieve the ductile-regime machining of these brittle materials, in which plastic deformation and brittle fracture are the main methods of material removal. Moreover, this method prevents the cracks produced during material removal from extending into the finished surface [96].
Ultrasonic vibration-assisted cutting (UVC) was initially proposed for machining difficult-to-cut materials (e.g., hardened steel and WC) to overcome the challenges of tool wear and processing inefficiency [97, 98]. UVC is achieved by integrating ultrasonic vibration motion into conventional diamond machining methods [99] (e.g., turning, milling [100, 101], grinding, and planing [102]). Structures are created after material removal by a tool edge at high speed. There are typically two types of vibration modes, namely the reciprocating and elliptical vibration modes. According to the generation mechanism of the elliptical trajectory of the tool tip, elliptical vibrators can be categorized as nonresonant and resonant elliptical vibrators. In a nonresonant vibrator, the tool is vibrated by two separate piezoelectric actuators (PZT) arranged with a right angle, and the working frequency is continuous but cannot be high due to the low stiffness of the mechanical structure [97, 103–105]. Regarding resonant vibrators, researchers have synthesized the resonant vibration of either the longitudinal vibration or bending vibration with a certain order to generate elliptical vibration [106, 107]. The vibration frequency of the designed device can be greater than 20 kHz by exciting the actuators. Unlike nonresonant vibrators, the vibration frequency of the resonant vibration is fixed and cannot be changed.

Figure 17. Illustration of the VSTS [91]. Reprinted from [91]. Copyright (2016), with permission from Elsevier.

Figure 18 illustrates the reciprocating UVC method with vibration in the nominal cutting direction. It should be noted that the nominal cutting speed is lower than the maximum vibration speed in the nominal cutting direction, so that the tool can be separated from the workpiece in each vibration cycle. This type of UVC results in smaller cutting forces, a longer tool life, higher cutting stability, and better surface finishing when machining micro/nanostructures on difficult-to-cut materials [108]. Regarding microstructure machining, this type of UVC can only be used to fabricate groove-like microstructures, as shown in figure 20. However, to avoid the interference between the tool tip and machined surface when the tool moves back, the tool vibration direction is inclined with respect to the nominal cutting direction to prevent chipping the tool, which can create a vibration mark on the finished surface [109].

To solve these problems in the reciprocating UVC method, elliptical vibration cutting (EVC) has been proposed [110–112] and proven to achieve better performance in machining difficult-to-cut materials [110, 111]. As shown in figure 19, during EVC, the cutting tool is fed in the nominal cutting direction, and the tool tip is simultaneously modulated by the vibration in both the nominal cutting and DOC directions to elliptically vibrate. In each elliptical vibration cycle,
The EVC process leaves periodic cusps on the machined surface due to the overlapping tool trajectory in each vibration cycle. A slow cutting speed is therefore utilized to improve the processed surface with a low cusp amplitude. In contrast to the general EVC process, large cusps left on the surface are treated as the texture by using a higher nominal cutting speed and a constant elliptical vibration amplitude, which is called elliptical vibration texturing (EVT). Figure 23 presents the cutting process of EVT. Via the EVT method, Guo and Ehmann fabricated a series of dimples [121, 122] and grooves for hydrophobicity and structural coloration applications [123, 124].

According to the processing mechanism of EVT, one structure is created during every vibration cycle [125]; the high frequency of the ultrasonic vibration dramatically improves the processing efficiency of the micro/nanostructure. With the decrease of the DOC, noncontinuous dimples are fabricated, as shown in figure 24. In addition, the overlapping of the generated dimples in a certain direction can create channels [126]. Although the EVT process is highly efficient for micro/nanostructure manufacturing, it has not been applied to difficult-to-cut materials due to severe tool wear and the large cutting force required for these materials.

A novel rotary ultrasonic texturing (RUT) technique has been developed for the efficient fabrication of precision micro/nanostructures [127], as shown in figure 25. The ultrasonic vibration, feed motion, and rotation are combined to generate high-frequency periodic changes in the cutting motion, which are used to fabricate micro/nano-textured surfaces [127, 128]. The diamond tool can vibrate in 3D space, and the tool locus can be flexibly obtained, which enables the generation of a variety of microstructures.

### 4.1.2. Micro/nano-milling

In micro/nano-milling processes, a monocrystalline diamond tool rotates on a spindle and moves along the surface of the fixed workpiece. During milling operations, the tool rotates along the axis perpendicular to the workpiece. At least three numerically controlled axes are used in this process, and micro/nanostructures with almost any specific cross-section shape, such as microlens arrays, compound eyes, and groove arrays [80, 129], can be machined with optical quality. The final surface quality of the machined micro/nanostructures is directly dependent on the corner radius of the milling tool. A matter of general importance in the diamond milling of complex structures is the generation of an optimized tool path [130], and the micro/nano-milling processing time is also a vital factor. To machine a large area of microstructures, the required processing time is usually several days. Therefore, the tool wear and machining efficiency should also be regarded. Wilson et al used a micro-scale milling tool to fabricate semicircular patterns on a metallic surface as the mold [131]. Wan et al generated microgrooves on titanium (Ti) alloy via micro-milling technology, and TiO₂ nanotubes were then generated on the machined microgrooves via anodic oxidation to form a novel hierarchical micro/nano-topography composed of microgrooves of 40 μm in depth and TiO₂ nanotubes of 70 nm in diameter [132].
During micro-milling, the cutter axis is usually inclined to prevent a cutting point with a speed of 0. The inclined axis helps improve the machined surface quality. In addition, to machining micro/nanostructures with various shapes, the spindle and tool are tilted at inclined angles to create periodic patterns on workpiece surfaces by adjusting the spindle speed and feed rate. To machine microdimples on a cylindrical surface, Matsumura and Takahashi used a two-flute ball-end mill inclined with respect to the tangential direction [133]. Graham et al. fabricated microdimple patterns by tilting the spindle and tool at an inclined angle and developed efficient surface pattern algorithms to generate different dimple geometries [134]. Researchers have investigated the application of ultra-precision multi-axis machining technology in the fabrication of v-groove components. Ultra-precision side milling
(UPSM) has been proposed to generate infrared hybrid micro-optics in a single-step ductile mode. In UPSM, the primary surface of the hybrid micro-optics is constructed via the removal of the workpiece material, and high-frequency secondary micro/nanostructures are simultaneously formed by the interference of the diamond tool edge between two neighboring raster cutting trajectories. During the machining process, the rotating spindle feeds horizontally in the X-direction, and the diamond tool intermittently cuts in and out of the workpiece surface with a specific DOC. In the meantime, the
workpiece performs the transitional servo motions in the Z-direction, just like the STS, to deterministically generate the desired primary surface. After finishing one cutting profile, a step motion along the raster direction (Y-direction) is carried out on the diamond tool so that the entire workpiece can undergo material removal [135]. Figure 26 presents the schematic diagram of the UPSM process.

Similarly, ultra-precision raster milling (UPRM) has been proposed to produce v-grooves and provides more freedom to produce v-groove structures as compared to precision grinding technology [136, 137]. There are two possible cutting strategies in UPRM, namely horizontal and vertical cutting, as shown in figure 27. During horizontal cutting, the cutting tool is fed horizontally. After finishing one cutting step, the diamond tool moves one step vertically. During vertical cutting, the cutting tool is fed in vertically direction while the diamond tool moves one step horizontally. After finishing one cutting step, the workpiece performs the transitional servo motions in the Z-direction, just like the STS, to deterministically generate the desired primary surface. After finishing one cutting profile, a step motion along the raster direction (Y-direction) is carried out on the diamond tool so that the entire workpiece can undergo material removal [135]. Figure 26 presents the schematic diagram of the UPSM process.

During the RFC process, the spindle mounted with the cutting tool rotates at high speeds, and the workpiece can be fed either axially (ARFC) or horizontally (HRFC) to the spindle. The feed motion of the workpiece is completed at a relatively slow speed, and the two motions of the spindle rotation and feed motion are coupled to form various features. The arrangement of the fly-cutting setup makes it more flexible for the fabrication of microgrooves [151]. Guo et al investigated the cutting force model used in microgroove fly cutting and considered the cutting-edge radius of a single crystal diamond tool [152]. This method can be used in the ultra-precision machining of difficult-to-machine materials, such as potassium dihydrogen phosphate crystals [153] and single-crystal Si [154].

Figure 29(a) illustrates the material removal mechanism during the HRFC process. HRFC can only generate parallel grooves with cross-sections consistent with the tool geometry. The shaded area is the shape of the material removed during a single fly cutting rotation. The thickness of the removed material first increases from 0 at the cut-in side to the maximum value $d_{\text{max}}$ and then decreases to 0 at the cut-out side. The maximum thickness of the removed material is given by

$$d_{\text{max}} = R - \sqrt{(R - D_x)^2 + \left(\sqrt{R^2 - (R - D_y)^2} - f\right)^2},$$

where $R$ is the swing radius of the cutting tool, $f$ is the feed rate per rotation circle, and $D_x$ is the nominal DOC. Figure 29(b) illustrates grooves machined by RFC by continuously feeding the workpiece in the horizontal direction perpendicular to the spindle. It is evident that the geometry of the cutting edge is directly copied onto the cross-section profile of the fabricated grooves. Nearly any type of groove-like structure is machinable via the use of shaped cutting tools. Furthermore, even prismatic features, such as pyramids and triangular pyramid arrays, can be generated by intersecting several of these

![Figure 26. Schematic diagram of the UPSM approach for hybrid surfaces with secondary micro/nanostructures [135]. Reprinted with permission from [135] © The Optical Society.](image-url)
Figure 27. Illustrations of (a) the horizontal cutting strategy of UPRM and (b) the vertical cutting strategy of UPRM [137]. Reprinted from [137]. Copyright (2013), with permission from Elsevier.

Figure 28. Hierarchical ribs fabricated by (a) the horizontal cutting strategy of UPRM and (b) the vertical cutting strategy of UPRM. [138] (2016) Copyright © 2015, Springer-Verlag London. With permission of Springer.

Figure 29. (a) Mechanism of HRFC and schematic diagram of grooves machined by HRFC [143]. Reproduced from [143]. © IOP Publishing Ltd All rights reserved.
grooves [155]. To achieve this, a rotational axis must be mounted on the moving axis so that the workpiece can be aligned in an angular and lateral position relative to the rotating plane of the cutting tool [80]. Before a triangular pyramid array is cut, the tool alignment with respect to the workpiece is very important, as the groove at the third angle must intersect at the same point where the grooves at the first two angles intersect with each other. A deviation of only a few micrometers will lead to deformation, and, therefore, unusable structures. The sizes of the workpiece and structure as well as the feeding speed primarily affect the processing time for fly cutting. Generally, the machining of miniaturized prismatic structures requires a processing time of several days.

ARFC, which is similar to the vertical machining of raster milling, is a novel method that uses the existing fly cutting device. During ARFC, the workpiece is fed along the spindle axis. One groove is generated per rotation of the cutting tool, and grooves are parallelly arrayed while the workpiece is fed along the spindle axis. Figure 30(a) presents a schematic diagram of the ARFC method and the corresponding grooves generated on the surface. The grooves have very high aspect ratios, and the depth of the grooves increases from 0 on both ends to the maximum in the middle.

In this method, parallel submicron grooves are produced, which are similar with those created by diffraction grating. On both sides of the structure, the distance between the grooves differs from that in the middle, as the cutting depth is low at the groove tips. ARFC has the advantage of the flexible regulation of groove spacing by controlling the feed rate.

To meet the demands of generating hierarchical structures for applications in optics [157], tribology and hydrophobicity [144, 145], and biology [146], modulated flycutting technology has been proposed for the machining of micro/nanostructures. By vibrating the workpiece in the DOC direction during ARFC, two-level structures composed of a first-order geometry feature and second-order submicron structures can be generated. Figure 30(b) shows the schematic diagram of the vibration assisted ARFC method and the corresponding two-level structures. The geometric shape of the first-order microfeature can easily be controlled by the processing parameters (e.g. the vibration frequency, amplitude, and offset distance). The cross-section of the second-order submicron grooves is determined only by the tool geometry. Groove spacing, which is the key factor for functionality, can also be flexibly regulated by the feed rate during processing [5].

Figure 30. Schematic diagrams of (a) the ARFC method and the corresponding grooves [156] and (b) vibration assisted ARFC and the corresponding two-level structures [5], [156] (2020) Copyright © 2020, International Society for Nanomanufacturing and Tianjin University and Springer Nature Singapore Pte Ltd With permission of Springer. Reproduced from [5], CC BY-NC-ND 4.0. With permission.
In EFC, because the cutting tool is mounted on the spindle with the rake face parallel to the spindle axis, a ring groove is created on the workpiece during each rotation cycle of the spindle. As shown in figure 31(a), the offset of the diamond tool with respect to the spindle center is the swing radius of the cutting tool, which is also equal to the radius of the generated ring groove. Side-feeding along the surface of the workpiece causes the cutting to cover the entire surface. Changing the angle of the workpiece relative to the translational axis can generate approximately orthogonal intersections of grooves, thereby creating pyramid structures. EFC is a highly efficient method of manufacturing micro/nanostructures.

Inspired by the STS/FTS, the end-fly-cutting servo (EFCS) has been proposed for the deterministic generation of hierarchical micro/nanostructures. Translational servo motions along the Z-axis are used to form primary desired surfaces with intricate shapes. Similarly to EFC, the secondary nanostructures in EFCS are generated by actively controlling the tool mark residuals [158, 159]. The hierarchical micro/nanostructures machined by EFC are shown in figure 31(b).

The DOC of fly cutting during the machining of high-hardness materials is generally several microns, which leads to low machining efficiency and severe tool wear. To overcome this problem, fly cutting has also been combined with other ultra-precision machining technologies, such as precision grinding [160] and laser etching, to fabricate complicated structures. Although fly-cutting technology can generate high-quality micro/nanogrooves at high cutting speeds, the curvature and slope angle of suitable structures remain limited due to the large swing radius [151, 161].

4.2. Micro/nano grinding and lapping

4.2.1. Micro grinding. Due to the enhanced optical performance requirements of molded components and molding temperature, the development of mold materials aims at
improving the service life and accuracy of the mold [162, 163]. Mold materials, such as SiC, WC [164], and silicon nitride, are must exhibit good performance in terms of high hardness, high temperature resistance, good wear resistance, and good chemical stability. Currently, micro-grinding is also the best method by which to fabricate microstructures on mold materials. It has received significant attention in the field of microstructure mold manufacturing and has been applied to the processing of microstructures such as diffractive optical elements, microgrooves [164–166], microlens arrays, pyramid microstructures, and anti-reflective moth-eye gratings [167], among others.

Diamond wheels are commonly utilized for micro-grinding because they exhibit superior cutting performance when cutting mold materials; they can produce lower surface roughness so that the surface accuracy of the microstructure surface can be ensured. Profile grinding is commonly used to machine microstructures and indicates that the cross-section profile of the machined structure is consistent with the wheel shape [167]. As shown in figure 32, a diamond wheel with the same shape as the desired microstructures rotates at a very high speed, and the bonded diamond abrasives act as many microcutters for material removal. Figure 33 presents microgrooves fabricated by profile micro-grinding on WC. Generally, the processing accuracy and surface roughness can reach 0.1 and 0.025 µm, respectively.

To fabricate smaller microstructures with more complicated shapes on molds, the microdiamond wheel has been proposed and utilized in microstructure surface machining. Aurich et al proposed the concept of superabrasive electroplated grinding wheels based on defined grain structures [168, 169]. Because the strength and impact resistance of a grinding wheel are mainly determined by the bonding agent, metal bonds are predominantly employed in the fabrication of superabrasive grinding wheels due to their excellent formability and high strength compared to resin bonds and vitrified bonds [168, 170]. Electroplating and electroless plating methods can be used to fabricate superabrasive microgrinding wheels with metal bonds. The electro-plating method has been widely used to fabricate micro-grinding wheels due to its low cost. Onikura et al conducted the fabrication of micro-cylindrical diamond grinding wheels with diameters from 100 to 500 µm via the electroplating of diamond grits in a Watts bath [168, 171], and the fabricated microdiamond wheel was then utilized to fabricate grooves on Tungsten carbide (WC) and cemented carbide [172], as shown in figure 34.

However, only a single layer of abrasives can be embedded in a metal bond with high residual stress, resulting in the short life of the grinding wheel [168]. The uniformity of abrasives on the grinding wheel is also limited by the distribution of the current, which may reduce the shape accuracy of the microwheel [168]. It has been found that electroless plating has the ability to create uniform coatings on complex shapes [168, 173]. The generated composite platings exhibit excellent functional performance due to the corresponding embedded particles. Composite platings with good wear and abrasion resistance have been fabricated by embedding hard particles, such as diamond particles [168]. Compared with the electroplating method, the electroless composite plating method can be used to prepare uniform composite platings with well-distributed abrasive grains for the fabrication of micro-grinding wheels [168], as shown in figure 35.

Although disc-shaped diamond grinding wheels are not as flexible as diamond pens, they can achieve better surface quality and higher processing efficiency. Moreover, disc-shaped diamond grinding wheels exhibit higher rigidity and better wear resistance when processing the microstructure surface. Because the machining scale is on the order of micrometers, only a small part with a size of several micrometers is used to grind the microstructures. Therefore, the grinding wheel easily becomes worn during grinding, which causes large errors at the edges and internal corners of the microstructure surface. In addition, under the same processing conditions, the MRR of the current, which may reduce the shape accuracy of the grinding wheel is also limited by the distribution of the current, which may reduce the shape accuracy of the microwheel. In UVG, the uniformity of abrasives on the grinding wheel is also limited by the distribution of the current, which may reduce the shape accuracy of the microwheel. In UVG, the uniformity of abrasives on the grinding wheel is also limited by the distribution of the current, which may reduce the shape accuracy of the microwheel. In UVG, the uniformity of abrasives on the grinding wheel is also limited by the distribution of the current, which may reduce the shape accuracy of the microwheel. In UVG, the uniformity of abrasives on the grinding wheel is also limited by the distribution of the current, which may reduce the shape accuracy of the microwheel.
In UVG, the cavitation effect resulting from ultrasonic vibration emulsifies the cutting fluid into particles so that the cutting fluid can easily infiltrate the contact surface between the grinding wheel and the workpiece. The infiltrating cutting fluid helps fully cool and lubricate the surface, thereby preventing surface burns on the workpiece [174].

4.2.2. Ultra-precision lapping. Lapping is a method of processing microstructures via the micro-cutting action of abrasives on workpieces. The abrasive is added between the tool and the workpiece. When pressure is applied, the relative movement of the tool and the workpiece causes a small amount of cutting so that a very thin metal layer of the surface of the
workpiece is evenly cut off. To improve the machined surface quality, the material used as the lapping tool (lapping head) is softer than the workpiece; thus, the abrasive embeds in the surface of the lapping tool under the effect of pressure.

The lapping process can produce an optically finished surface during Si wafer production; it is widely used for microlens fabrication. However, it is not suitable for the groove-like microstructure fabrication. Liu et al proposed a lapping-based process to create evenly distributed microlens arrays on Si mold surfaces using steel balls and diamond slurries, as shown in figure 36. To obtain a high-quality microlens with a highly accurate geometry and surface finish, the material selection of the lapping ball and the lapping time were carefully investigated. They fabricated a microcavity with a $\sim 10$ nm surface roughness in 30 s, which improved both the processing efficiency and surface quality [177]. A $5 \times 5$ microlens array was fabricated on a Si wafer, as shown in figure 37.

Liu et al further developed a lapping system for the precision fabrication of 3D microlens arrays on nonplanar silica surfaces. With the assistance of the stage movement, the 3D microlens arrays were precisely fabricated on both concave and convex surfaces via the developed experiment setup, as shown in figure 38. To achieve micropatterns by properly arranging microlenses on a curved surface, a microwear model was also established to calculate the relationships between the microlens sag height and the lapping parameters, such as the downward force, relative sliding velocity, and lapping time. Specifically, two groups of microlens arrays with different apertures were produced on concave and convex silica surfaces, respectively [178].

Although the section above introduces many typical mechanical machining methods for the fabrication of micro/nanostructured molds, these methods are suitable for different processing requirements when considering factors including the micro/nanostructure size, processing accuracy and environment, because of their different processing principles. Table 2 shows the characteristics capabilities of these mechanical methods for micro/nanostructure manufacturing.

## 5. Service performance of micro/nanostructure molds in glass molding

### 5.1. Surface evolution of molds under high temperatures

In micro/nanostructure glass molding, the working temperature of the mold is higher than 500 °C. When general amorphous Ni-P is used as the mold material under high-temperature conditions, the Ni-P in the mold material undergoes an amorphous-to-crystalline transition, causing the mold to deform, which, in turn, affects the precision of the glass micro/nanostructure molded product.

To investigate the influence of high-temperature molding conditions on the accuracy of the micro/nanostructure molds, a flat mold made of amorphous Ni-P material was used for glass molding. First, the plate mold was polished and marked along the centerline of the mold. The marked mold was then used for glass molding at a temperature of 550 °C, molding time of
10 min, and \( N_2 \) as the shielding gas. The surface shapes before and after the molding process were measured using a VK-100 laser confocal microscope.

As shown in figure 39, the straight line in the figure is the surface shape of the flat mold before the experiment, and the curve is the deformation of the mold surface measured along the measurement reference line after the molding process. It was found that although only one molding cycle was performed, the maximum amount of deformation of the mold surface caused by the crystallization transformation of the Ni-P material reached to 0.6 \( \mu \text{m} \). During glass molding, this deformation affects the molding accuracy of the micro/nanostructures and shortens the service life of the mold.

### Table 2. Characteristics and capabilities of the mechanical methods for micro/nanostructure manufacturing.

| Methods    | Surface finishes Within ~ | Achievable accuracy within ~ | Typical feature size range | Advantages                                                                 | Limitations                                                                 |
|------------|---------------------------|------------------------------|---------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------|
| SPDT       | 5 nm                      | 100 nm                       | 10 \( \mu \text{m} \)-1000 \( \mu \text{m} \) | • High-speed cutting  
• Low cost  
• High accuracy | • Limited to rotationally symmetric structures |
| STS        | 5 nm                      | 100 nm                       | 10 \( \mu \text{m} \)-1000 \( \mu \text{m} \) | • Available for complex structures  
• High accuracy  
• Low cost | • Limited to large-amplitude surface structures |
| FTS        | 10 nm                     | 100 nm                       | 1 \( \mu \text{m} \)-100 \( \mu \text{m} \) | • High efficiency  
• High accuracy | • Limited to small-amplitude microstructures on flat or axially symmetric surfaces |
| EVC        | 10 nm                     | 100 nm                       | 10 \( \mu \text{m} \)-1000 \( \mu \text{m} \) | • Available for difficult-to-cut materials  
• High response frequency | • Complicated to control the structure shape |
| EVT        | 10 nm                     | 100 nm                       | 100 nm-10 \( \mu \text{m} \) | • High accuracy  
• High efficiency  
• High accuracy | • Powerless to high-hardness materials  
• Complicated to control the structure shape |
| UPSM       | 10 nm                     | 100 \( \mu \text{m} \)       | 100 \( \mu \text{m} \)-1000 \( \mu \text{m} \) | • High accuracy  
• Low cost | • Powerless to high-hardness materials |
| UPRM / UPFC| 10 nm                     | 100 nm                       | 100 nm-1000 \( \mu \text{m} \) | • High accuracy  
• Low cost  
• Extreme small size structure | • Powerless to high-hardness materials |
| Micro-grinding | 100 nm                | 10 \( \mu \text{m} \)       | 100 \( \mu \text{m} \)-1000 \( \mu \text{m} \) | • Available for high-hard and brittle materials  
• Low cost | • Severe wheel wear  
• Potential fluid contamination  
• Powerless to large-area arrays |
| Lapping    | 10 nm                     | 10 \( \mu \text{m} \)        | 500 \( \mu \text{m} \)-1000 \( \mu \text{m} \) | • High surface finishes  
• High accuracy | • Rotationally symmetrical structure  
• Low efficiency  
• Limited to brittle materials |
To eliminate the mold deformation caused by the crystallization transformation of Ni-P at high temperatures, the Ni-P material was first subjected to a high-temperature heat treatment to complete the crystallization transformation, then the micro/nanostructure was machined on the crystallized Ni-P material. The heat treatment was conducted with a temperature of 580 °C, treatment time of 2 h, and N₂ as the shielding gas. X-ray diffraction (XRD) analysis was carried out for the Ni-P material before and after treatment, and it was found that the material was completely transformed into a crystal structure dominated by the Ni₃P phase after high-temperature heat treatment, as shown in figure 40.

To investigate the service performance, 500 glass molding tests were carried out on the crystalline flat plate, and the results are shown in figure 41. Compared with the amorphous Ni-P materials, crystalline Ni-P material fabricated by heat treatment performs better since its shape deformation is 0.05 µm after 500 molding processes.

It was found that the crystalline Ni-P material is more suitable for mold for glass molding since it can achieve higher accuracy and a longer service life [179]. The specific processing method is shown in figure 42. First, the amorphous Ni-P material mold was heat-treated at a high temperature to complete the crystallization transformation. A circular diamond tool was used to cut the mold with surface deformation after crystallization to achieve a surface roughness $R_a < 1$ nm. Then the micro/nanostructures were machined on the flat crystalline Ni-P mold surface.
5.2. Controlling the microdeformation of micro/nanostructure molds

To investigate the service performance of the micro/nanostructured mold, both the amorphous and crystalline Ni-P material molds were structured with grooves with period of 20 µm, and the changes of the mold form accuracy before and after glass molding were compared. For the amorphous Ni-P microstructure mold, the PV value of the mold increases from 0.37 µm to 0.58 µm after one glass molding cycle, and the change rate was greater than 50%. In addition, as shown in figure 43, it was found that the surface roughness $R_a$ increased 25% from 82 nm to 104 nm, which indicates that the amorphous micro/nanostructure mold deteriorated after the molding. This occurs because the amorphous material undergoes a crystallization transformation at high temperatures, resulting in the change of the microscopic volume and the deformation of the processed mold surface. The deformation not only affect the precision of the mold surface but shorten the mold life.

After 500 pressing tests, the PV values of the crystalline micro/nanogroove mold were kept at around 0.34. And the surface roughness $R_a$ increased slightly from 2 nm to 2.1 nm, as shown in figure 44. It demonstrates that the crystal Ni-P material shows a better service performance than amorphous Ni-P under high-temperature molding conditions. A longer service life of the mold can also be achieved by using crystalline Ni-P material for the ultra-precision molding process.

6. Conclusions and outlook

Because micro/nanostructures have numerous special functions and have been widely used in various applications, the manufacturing of micro/nanostructures on molds plays a vital role in the mass production of micro/nanostructured components. PGM technology contributes to the mass production of micro/nanostructured components with high efficiency and precision, which requires that the mold materials exhibit good high-temperature resistance and that the micro/nanostructured mold exhibit high accuracy. Mold materials should have high hardness, high-temperature resistance, and inert adhesion and reaction with glass. In addition, to overcome the challenges of manufacturing micro/nanostructures on difficult-to-cut molds, plating generation, the surface treatment of the mold, and the development of new mold materials with low hardness have been conducted.

The manufacturing accuracy of the mold affects the final accuracy of the molded components; therefore, many methods, including both mechanical and nonmechanical methods, have been investigated for the fabrication of various
micro/nanostructure surfaces. Etching is a pattern transfer technology that can be categorized as either wet or dry etching. By selectively etching the uncovered part of the layer, the patterns can be transferred from a mask to a substrate. Regarding laser manufacturing, femtosecond laser technology can induce periodic solid micro/nanostructures (FLIPSSs) on the surface, the period of which is determined by the wavelength of the laser and the processed materials. EDM is a good method for manufacturing concave and convex microstructures, including complex 3D structures with high aspect ratios. Moreover, µEDM and R-µEDM have been proposed and employed to remove materials with a low pulse energy. These methods have been found to improve manufacturing accuracy. Additionally, the utilization of an array electrode can enhance processing efficiency. Although nonmechanical methods can manufacture micro/nanoscale materials, they are limited in terms of the materials’ conductivity and magnetism. Moreover, the cross-sections of the micro/nanostructures cannot be precisely regulated. In contrast, mechanical methods are available for most workpiece materials and can achieve improved geometric freedom and lower surface roughness of micro/nanostructures as compared to nonmechanical methods.

While only rotationally symmetric structures can be obtained by conventional turning, STS and FTS extend the machinability of micro/nanostructures with various shapes. STS turning is suitable for machining large-amplitude surface structures and high-aspect-ratio freeform surfaces, while FTS turning can only generate small-amplitude microstructures on flat or axially symmetric surfaces. Suitable machining strategies have been constructed and optimized to form various types of micro/nanostructures. Micro/nano-milling is usually used in the fabrication of microlenses and grooves. Additionally, the application of ultra-precision multi-axis machining technologies, namely UPSM and raster milling, have demonstrated for the ability to fabricate hierarchical structures. Fly-cutting technology has demonstrated substantial advantages in high-accuracy groove fabrication due to the high-speed cutting process. Change in the feed direction of the fly-cutting tool is used to fabricate different structures; moreover, the processing efficiency is greatly improved. Ultrasonic vibration assisted cutting (UVC) is a promising technology for the fabrication of micro/nanostructures on difficult-to-cut materials. In addition, the amplitude-controlled EVC and EVT methods have been developed and used in the high-efficiency fabrication of micro/nanostructures. Diamond grinding and UVG are widely applied in the machining of high-hardness materials. Due to the development of the micro-diamond wheel via both the electroplating and electroless plating methods, the machinable scale can be further reduced. Additionally, because of the resulting high-quality machined surface, the lapping process has been used as a method for the ultra-precision machining of microlenses on both 2D planes and 3D surfaces.

Regarding the service performance of Ni-P microstructure molds, it has been demonstrated that the mold deformation and surface quality are substantially different before and after the glass molding process, which is caused by the crystal transition of Ni-P from the amorphous to the crystalline state. The crystal transition of the micro/nanostructured mold severely deteriorates the PV value and surface roughness; thus, the mold life is greatly reduced if amorphous Ni-P is used. To prevent the mold deformation caused by the crystallization transformation of the Ni-P material at high temperatures, the Ni-P material is first subjected to high-temperature heat treatment to complete the crystallization transformation, and the micro/nanostructure is then machined on the crystal Ni-P material.

In the future, the techniques to manufacture micro/nanostructure molds and the extreme features of micro/nanostructures, including the realization of extremely small sizes and high quality, will remain the study focus. A greater expectation of the component performance makes the large-area processing another extreme feature of the micro/nanostructured molds, which will require high efficiency and low-cost manufacturing. In addition, due to the upgrading of mold materials, research on the most suitable processing methods and techniques will always be a hot spot in micro/nano mold manufacturing. Meanwhile, the compound technology, such as the combination of etching and micro/nano cutting, will receive more attention.

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