Review Article

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Precision injection molding of freeform optics

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Abstract: Precision injection molding is the most efficient mass production technology for manufacturing plastic optics. Applications of plastic optics in field of imaging, illumination, and concentration demonstrate a variety of complex surface forms, developing from conventional plano and spherical surfaces to aspheric and freeform surfaces. It requires high optical quality with high form accuracy and lower residual stresses, which challenges both optical tool inserts machining and precision injection molding process. The present paper reviews recent progress in mold tool machining and precision injection molding, with more emphasis on precision injection molding. The challenges and future development trend are also discussed.

Keywords: freeform; injection molding; optics; ultra-precision machining.

1 Brief history of manufacturing of optics

Manufacturing of optics develops throughout the history of human civilization, experiencing the routines from craftwork, machined-based manufacturing to numerical controlled manufacturing processes. The earliest known lenses were made from polished crystal, often quartz, and have been dated as early as 750 B.C. for Assyrian lenses such as the Nimrud/Layard lens [1]. There are many similar lenses from ancient Egypt, Greece, Babylon, and China. Greek philosopher, Ptolemy, mentioned the general principle of magnification at about 150 A.D., but the lenses then available were unsuitable for use in precise magnification [2]. Ultimately, Italian monks crafted the first semi-shaped ground lenses in the 13th century using a type of quartz called Beryl. Only a few years later, in 1267, Oxford Franciscan monk Roger Bacon provided scientific proof that small letters could be magnified with lenses that were ground in a specific fashion [3]. The first eyeglasses were made in Italy in about 1286. Following this invention, quartz and beryl lenses were replaced by glass lenses because of the increasing demand for eye glasses [4]. In the 17th century, people knew the principle of the concave and convex lenses and had used them for correction of nearsightedness and farsightedness. Bifocal lenses, invented by Benjamin Franklin in 1784, were used to treat nearsightedness and presbyopia. Around the end of the 18th century, spectacles with a single lens called monocles gradually became popular. Nowadays, more than 80% of all eyeglasses worn are made of plastic lenses. Glass lenses remained dominant before the invention of plastic lenses in the 1950s. The plastic lens rapidly became very popular because they were lighter, less prone to breakage, and more comfortable for those who wear eye glasses [4]. Grinding and polishing were used for centuries for machining optical blanks, like glass. Grinding with nanometer precision has not become available before the advent of ultra precision machines [5]. Machining of precision optics started as early as the Second World War [6]. Diamond turning has been successfully performed on plastics, as inspired by the requirement of precision electronic parts of the second industrial revolution [7]. Diamond machining of copper, gold, silver, aluminum, platinum, lead, and nickel, on one hand, provides lenses themselves and, on the other hand, enables the possibility of molding of precision optics. However, at that time, injection molding, extrusion, and compression molding cannot satisfy the precision requirements of lenses and electronics. Diamond turning was used for machining imaging and illumination plastic optics with regular surfaces, such as plano and spherical surfaces with sufficient precision. Since the 1980s, the development of all electrical injection molding machines significantly improved the precision and reliability of injection molding process. Along with

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the development of aspheric machine tools and improvement of precision up to PV 0.3~0.5 μm and Ra 10 nm in the 1970s [8], manufacturing ultra-precision mold insert for aspheric lenses became feasible. Injection molding was gradually used for precision lenses manufacturing and became more and more mature for applications including imaging, illumination, and concentration. It offers benefits of low weight, integration of various optical surfaces and mechanical mounting flange into a single component, ease of mass production, and forming complex form, becoming the major production methods for plastic optics.

This paper reviews the recent progress on optical tool insert machining and precision injection molding for complex form plastic optics. The discussion would be firstly focused on precision mold machining and then concentrated on challenges of precision injection molding and newly developed specific injection molding technologies. The challenges and opportunities for future development are also discussed.

2 Manufacturing process chains for precision plastic optics

In the process of manufacturing precision plastic optics, optical design, tool insert machining, and injection molding are critically important. Design engineers need to work closely with tool development engineers and process engineers to ensure that the product design is feasible for manufacturing and cost effective. Mold design and optical tool machining influence tool precision, and it is critical for injection molding. Injection molding is a high volume production method, offering benefits of forming an enormous variety of complex surface shapes and structures with an integration of several optical and mechanical functions into monolithic devices. The precision molded lenses with acceptable optical aberration dependent on applications require acceptable and controlled PV, less residual stress, high transparency, and high replication fidelity for microstructures, short cycle time, and high production efficiency. Metrology and quality control are essential to guarantee the presentation of products within tolerance and optically acceptable without defects. For high-quality imaging applications, post-processing is necessary to reduce residual stress and improve form accuracy. The process chain for manufacturing an optical product is shown in Figure 1. Although the procedure of precision injection molding of plastic optics is similar to conventional injection molding, it differs itself in some aspects. For example, precision optical injection molding requires high precision tool inserts and mold, strict tolerance, extra form accuracy, dimensional measurement and correction, high process stability and repeatability, strict material preparation, clean production environment, etc.

As precision optical injection molding is the core of this review, basic principle of injection molding process is introduced here. Using a reciprocating injection molding machine as an example, as shown in Figure 2, plastic pellets are firstly fed into the hopper, which delivers the resin to the plasticizing screw. The screw rotates, and the polymer pellets are fed into its channels. Plastic pellets are then heated, mixed, compressed, and melted. When an appropriate amount of material is accumulated in front of the injection nozzle, screw rotation stops. The molten polymer is then injected into the mold through the sprue, runner, and gate by a forward movement of the injection screw. This is followed by packing and cooling stages by pushing more materials into the mold to compensate for material shrinkage due to the solidification process. Once the gate is solidified, the mold cavity is isolated from the melt delivery system. The cavity pressure gradually decreases with the decrease of material temperature. When the temperature of the plastic reaches a level at which it is safe to eject the part without damage, the mold

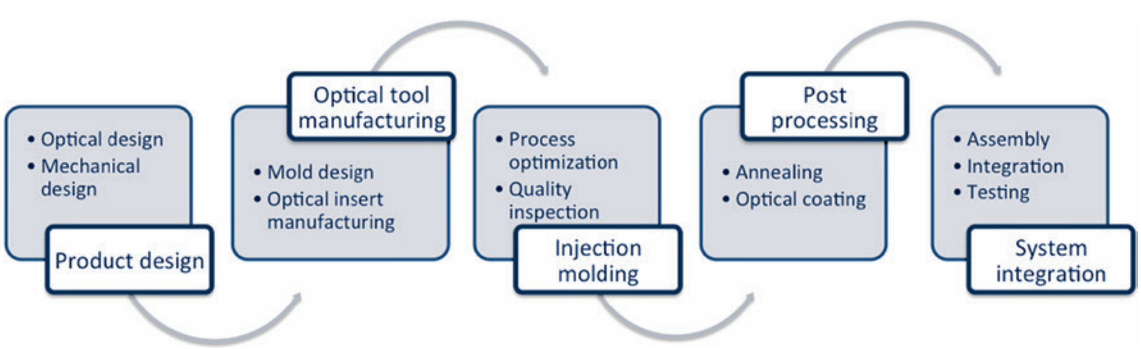

Figure 1: Process chains for manufacturing plastic optics.

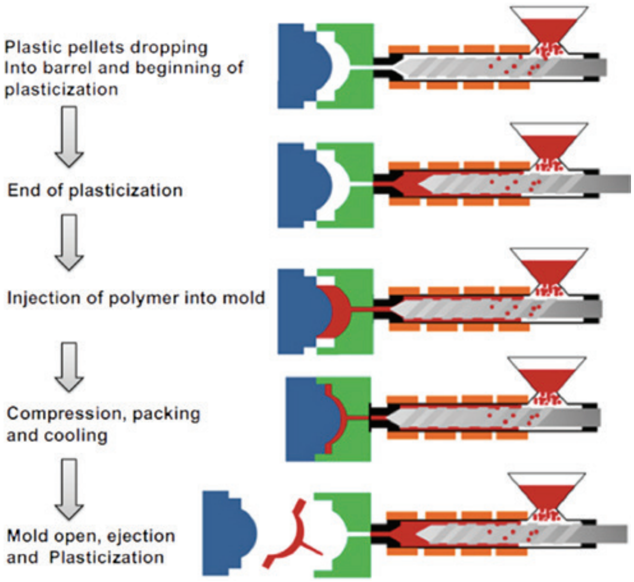

Figure 2: Simplified schematic of injection molding process.

is opened and the part is ejected. Subsequently, the mold is closed again for the next cycle. Process parameters (metering size, injection velocity, mold temperature, melt temperature, holding pressure, holding time, and cooling time, etc.) that control the filling, holding, and cooling stages allow machine operators to alter processing conditions so as to control the quality of finished parts.

3 Ultra-precision machining of optical mold tool insert

Ultra-precision machining technologies have been developed since the 1960s for manufacturing optical surfaces, including mold tool inserts [6]. An optical mold tool insert can be machined by a variety of methods, such as ultra-precision grinding and polishing, single-point diamond turning, and electroforming. Optical surfaces with negative format can be generated with various forms, such as plano, spherical, aspheric, and freeform for injection molding. Compared to directly used surfaces such as optical elements, mold tool surfaces were functionally showed to be less sensitive to subsurface damage. However, tool material is critical, as the mold is subject to cyclic tempering when repeatedly injected with polymer and has to sustain the integrity over tens of thousands of molding cycles. Tool inserts must have sufficient strength, high hardness, and wear/chemical resistance to prevent possible local deformation and wear.

Ultra-precision grinding and polishing are employed for generating optical mold surfaces on hard-to-machine materials for glass molding, such as mold steel, binderless tungsten carbide (WC), silicon carbide (SiC), and silicon nitride (Si_3N_4) [9]. The achievable surface has a low roughness and high form accuracy in nanometer scale with high material hardness, high thermal stability, and corrosion resistance in order to satisfy the harsh requirement of glass molding at high temperature of 400~800°C or even above. As grinding generally cannot meet the optical surface requirement for many applications, ultra-precision polishing is used as a subsequent step for finishing, such as magnetorheological polishing, ion beam figuring, and plasma chemical vapor polishing. Some new polishing methods for manufacturing optical surfaces were developed, such as inclined grinding methods for machine WC tools with aspheric surfaces [10, 11] and slow-tool grinding for grounding mold of cylindrical or toric shapes and lens arrays [12]. More details regarding ultra-precision grinding and polishing can be found in the reviews of references [1] and [9].

Single-point diamond cutting is capable of machining optical surfaces without the subsequent finishing. Generally, the best-fit curve is generated on a mold steel substrate. The substrate is then electrolessly plated by a layer of nickel phosphorus alloy up to 500 μm. It is then machined using single-point diamond turning to produce the final form with nanometer roughness and submicron to nanometer form accuracy. Materials that can be machined by diamond turning are aluminum, copper, copper-nickel alloys, brass, crystals, germanium, calcium fluoride, silicon, and polymers such as acrylics. Conventional tool steel cannot be machined directly by diamond turning because of chemical reactions of all ferrous metal, causing extra wear [13]. However, as stainless steel is a mainstream mold tool material, ultraprecision machining of stainless steel is attractive for optical mold maker. As reviewed in literature [14], wear of diamond tool in machining ferrous metals was mainly attributed to three reasons: (a) adhesion and formation of a built-up edge; (b) abrasion, microchipping, fracture, and fatigue; and (c) tribothermal wear, including graphitization, diffusion, carbide formation, and oxidation. Chemical wear is believed to be dominant in diamond tool wear in machining ferrous metals because of graphitization from high temperature, pressure, and catalytic action. A variety of methods were proposed to reduce tool wear, such as modification of machining processes, use of modified tools, modification of workpiece materials, or use of combinations of above mentioned processes. From a view of the machining processes, cryogenic turning, turning in hydrocarbon gas environment, and ultrasonic vibration assisted cutting or their combination was used for cutting stainless steel. Ultrasonic vibration assisted cutting was found to reduce the cutting energy, cutting force, and temperature by intermittent contact. Meanwhile, it improved machining accuracy, surface finish, and prolonged tool life. The surface roughness could reach 100 nm in Rz using ultrasonic assisted milling process [15]. However, ultrasonic vibration assisted cutting process is slower than conventional cutting and may be not applicable to machining concave surfaces because of interference between work piece and diamond tool. It is worthwhile to notice that modification of workpiece surface is an effective way to improve stainless steel machinability using diamond tool. A plasma nitrided steel was machined using diamond turning; wear of diamond tool was two orders of magnitude less than that of conventional process, and surface roughness reached 4.2–7.5 nm [16]. However, at the moment, nickel phosphorus alloy is still a mainstream material that can be single-point diamond-turned with less wear and amorphous nickel phosphorus can be also polished up to 0.3-nm rms surface roughness [17]. Amorphous nickel phosphorus alloy itself has hardness up to 800 HV, as strong as hardened mold steel, which could be a good mold tool for injection molding over 10 000 molding cycles.

Development of optoelectronic technology inspires the increase of form complexity from conventional plano and spherical to aspheric and freeform. Freeform is categorized into continuous smooth surfaces, discontinuous surfaces including steps and facets, structured surfaces, and multiple surfaces on a single substrate, as shown in Figure 3. Typical machining technologies such as slow slide servo (SSS), fast tool servo, ultra-precision milling, and fly-cutting were presented for manufacturing freeform surfaces are discussed below.

3.1 Slow slide servo for machining optical insert

SSS is a machining process capable of generating freeform optical surfaces at levels of high accuracy and azimuthal height more than 25 mm. In SSS process, the Z-axis oscillates back and forth, while X- and C-axes maintain at the constant speed, which does not need any additional or auxiliary axes [18]. It is not suitable for machining of too steep surface, as tool may interface with workpiece surfaces. Figure 4 demonstrates several examples of

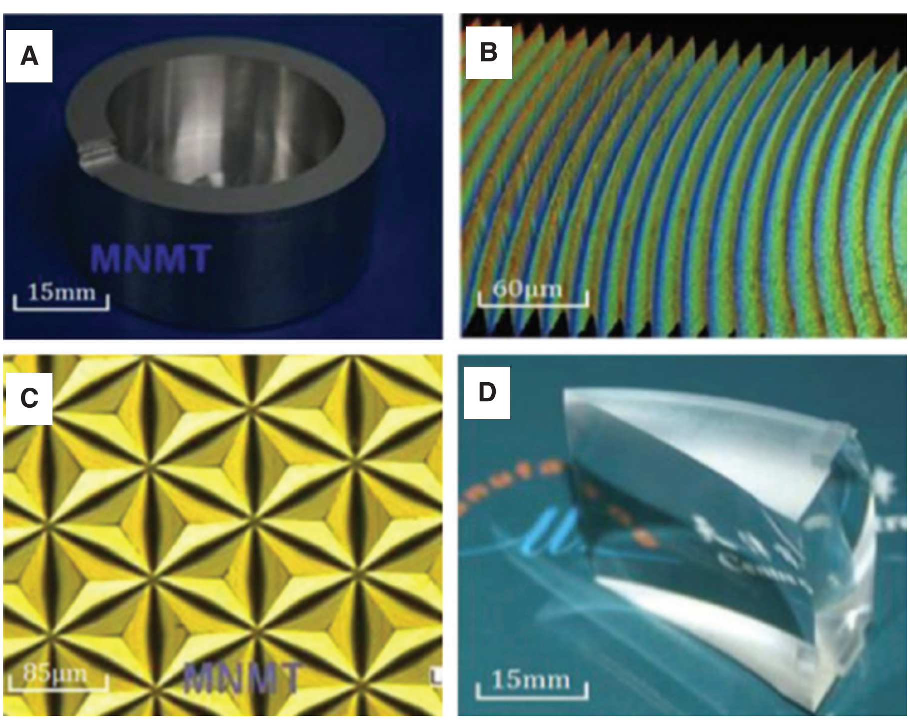

Figure 3: Freeform surfaces: (A) continuous smooth surfaces modeled using a mathematic formula and CAD software, such as spiral mirrors applied to the femto-second (fs) laser scanning; (B) a Fresnel lens with discontinuous surfaces include steps or facets; (C) structured surfaces, which are the arrays of structure for specific function, therefore called functional surfaces; (D) an optical freeform prism with multiple surfaces on a single substrate [5].

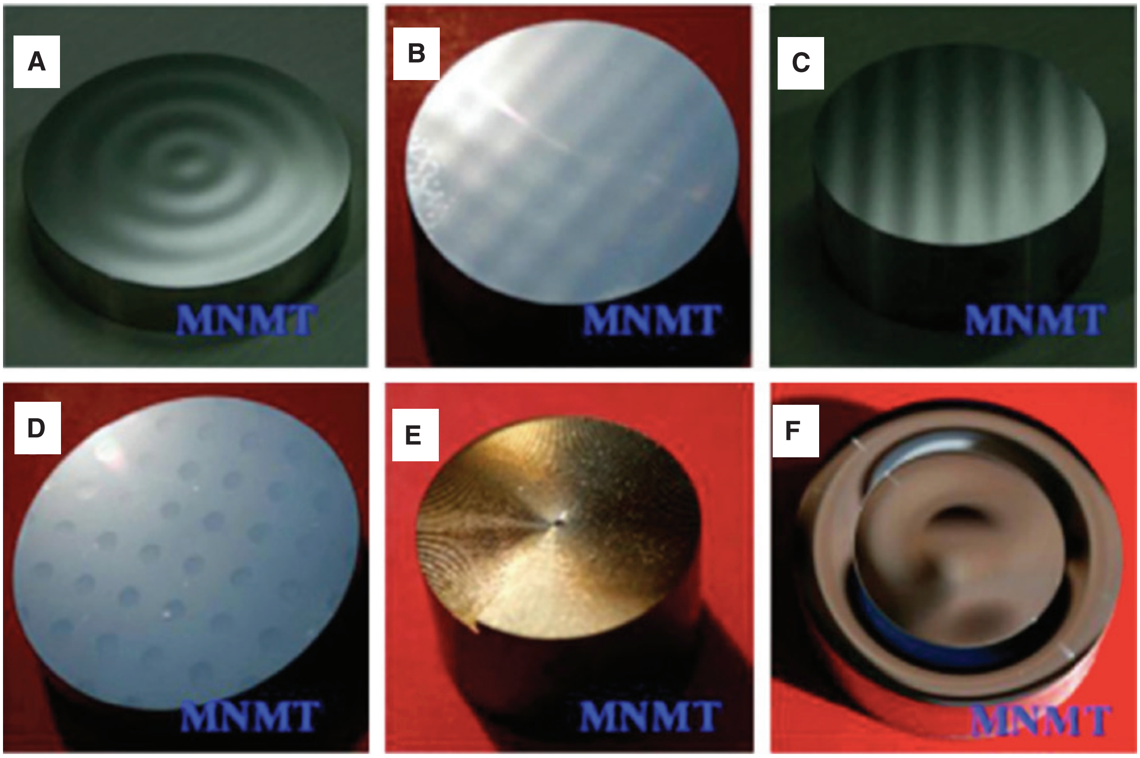

Figure 4: Typical freeform optics fabricated by the cylindrical machining method: (A) water-drop freeform, (B) sinusoidal freeform, (C) cylindrical freeform, (D) aspheric lens arrays, (E) spiral freeform, (F) integrated freeform.

freeform surfaces fabricated by cylindrical machining method based on SSS. Yi and Li [19] machined concave micro lenses arrays (MLAs) mold on 715 copper nickel and 6061 aluminum alloy using SSS diamond turning process, as shown in Figure 5A. The same group subsequently developed 5×5 micro Alvarez lens array mold using 6061 aluminum alloy using SSS diamond turning process (Figure 5B) [20]. Figure 6 shows a 40-mm-diameter freeform tool insert made by hardened steel substrate with nickel phosphorous plating machined by SSS using single-point diamond turning, as reported by Dick et al. [21]. They used a machining process iteration loop to achieve the tool form of PV 0.24 μm with surface roughness of 33.1 nm in rms. Zhang et al. [22] used SSS ultra-precision turning process to fabricate a mold for compound eye lenses. They machined concave compound eye mold based on aluminum alloy and then replicated compound eye structure by microinjection molding process, as shown in Figure 7. Subsequently, they studied the influence of machine errors on form errors of micro arrays and

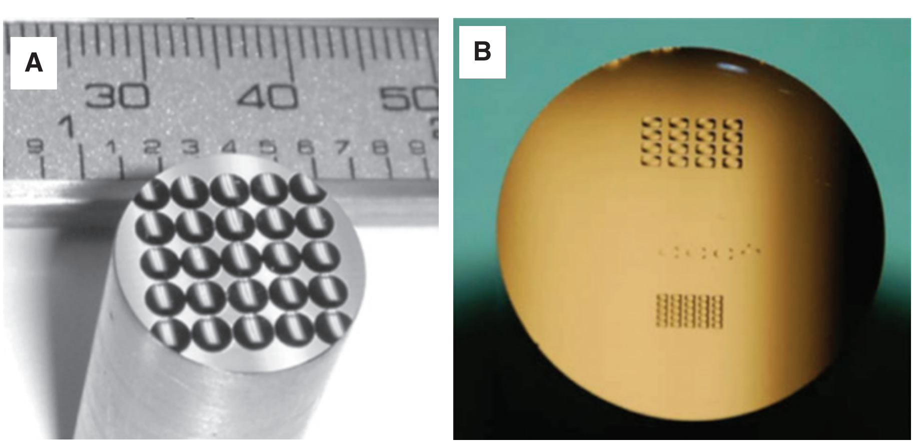

Figure 5: Freeform microlens array (A) and Alvarez lens array [19] (B) machined by SSS ultra-precision turning process [20].

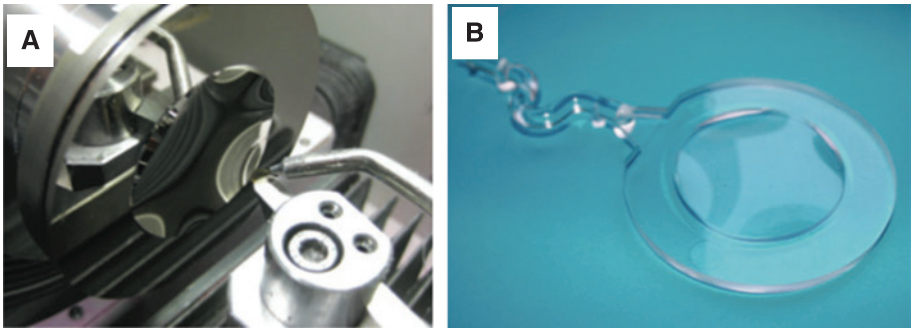

Figure 6: Freeform tool insert positioned at the vacuum chuck on the ultra-precision machine (A) and diamond tool and molded freeform optical element with defined Zernike surface including gate (B) [21].

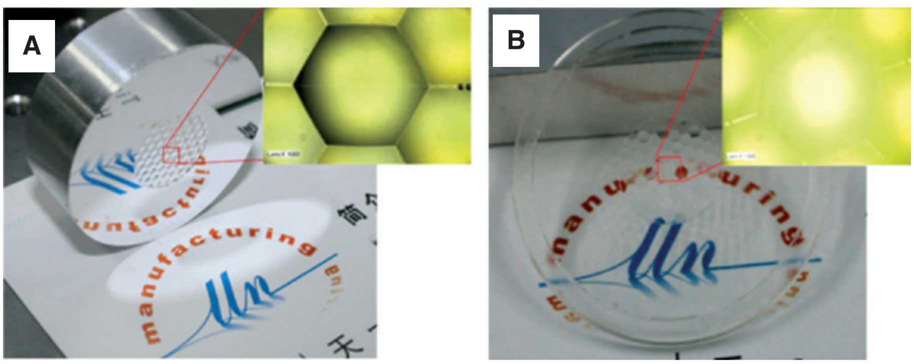

Figure 7: Optical device of the compound eye: (A) fabricated mold using SSS, (B) compound eye lens fabricated by microinjection molding [22].

developed a method based on one plano-spherical surface to separate the main machining errors, which showed significant improvement on machining accuracy [23, 24].

3.2 Fast tool servo for machining optical insert

Fast tool servo generates the high-frequency moment in the Z-axis by driving the tools, instead of the entire slide table in the SSS process. Thus, it gives much higher frequency and suits for machining fine structures. Using slow tool servo technique, complex optical geometries over a large surface area can be created with a surface finish adequate for some optical applications. However, tool marks due to large step size and relatively low production rate because of limitations on slide speed still remain to be resolved [25]. Scheiding et al. [25] used fast tool servo process to machine MLAs on a hemispherical surface using high-strength aluminum for injection molding (Figure 8). The tool surface shows nanometric pits because of high-frequency moment of diamond tool.

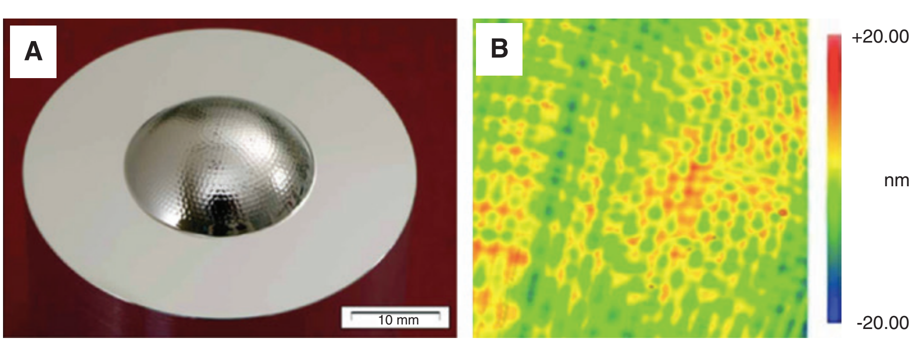

Figure 8: A finished freeform microlens array mold insert containing 1219 single spherical lens lets (A) with clear aperture of the lens area is 19 mm and the outside diameter of the substrate is 40 mm and topography of a single lens surface (B) [25].

Surface roughness turned out to be 3.9 nm (rms) with PV 44 nm for a single lens, which is acceptable for optical lenses injection molding.

3.3 Other ultra-precision machining technologies for mold manufacturing

In addition to SSS and fast tool servo, ultra-precision milling and fly cutting are also used to machine surface patterns, like micro grooves and micro pyramid arrays [26]. Figure 9 demonstrates raster milling of V-grooves (Figure 9A), end milling of rectangular grooves (Figure 9B), and fast tool servo machining of circular grooves for functional surfaces (Figure 9C) [27]. Some special machining processes, such as diamond micro chiseling, have also been developed for generation of micro cube corner retro-reflectors, as shown in Figure 10. In diamond micro chiseling process, the combined movement of axes X, Y, and Z allows the diamond cutter to enter into workpiece to cut a sloped mirror edge, generating cubic hexagon retro-reflector arrays of 100 μm [28].

4 Precision injection molding process

Referring to precision injection molding, form accuracy, residual stress, and transparency are critical factors to influence quality of plastic optics. Nevertheless, such critical factors are determined by product design, mold design, molding machine, mold installation accuracy, selected plastic materials, process parameters, post-processing, etc. This challenges the injection molding of plastic optical products. There has been a large amount of work carried out in the last two decades on precision injection molding of plastic optics. Their main focus can be categorized into three important aspects, such as form accuracy, residual stress, and imaging quality.

4.1 Form accuracy

In the injection molding process, solidification of polymer melts from liquid state to solid state, causing

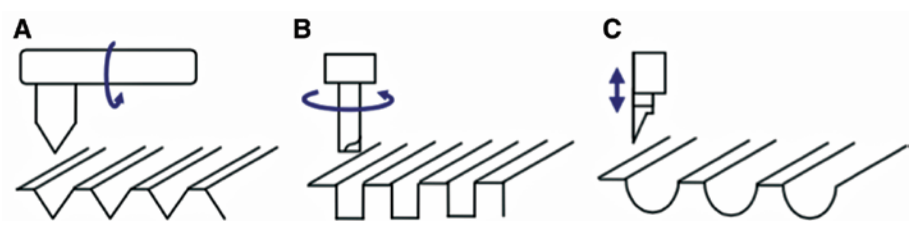

Figure 9: Selection of ultra-precision machining to produce 3D-microstructured surfaces: (A) raster milling, (B) end milling, and (C) FTS machining [27].

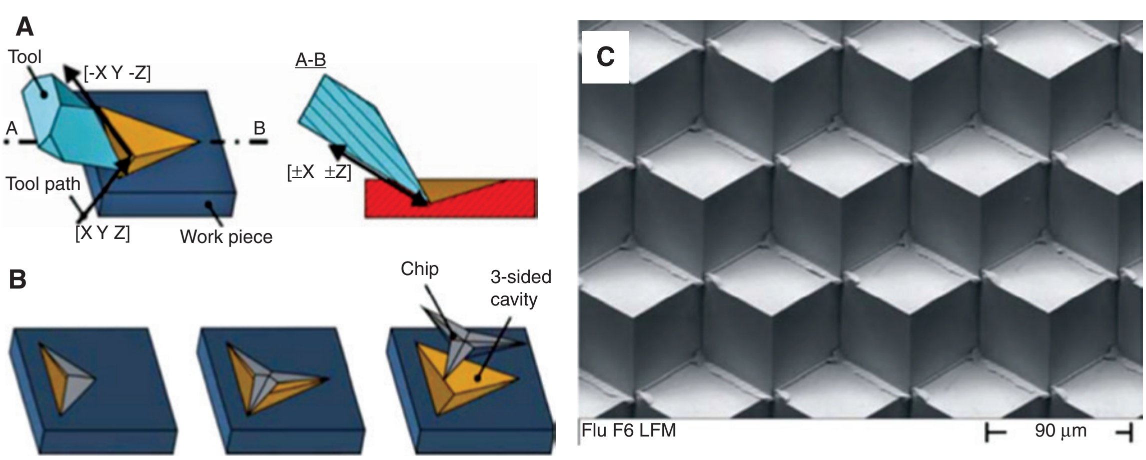

Figure 10: Diamond micro chiseling process for manufacturing cubic hexagon retro-reflector arrays: (A) principle of diamond micro chiseling, (B) cubic hexagon retro-reflector arrays [28], (C) the diamond micro chiseling machined cubic array with an individual circumference diameter of 100 μm on an electroless nickel substrate with intruding edges caused by interactions of set-up accuracy, non-ideal tool geometry and plastic material behavior.

material shrinkage according to a material's P-v-T behavior (pressure-specific volume-temperature), where evolution of product's volume is related to pressure and temperature. Even though more material is injected into the mold for compensation of material shrinkage during packing stage, it still cannot achieve submicron form accuracy because of possible early-stage solidification of product surface layer, non-uniform solidification, and associated shrinkage and warpage. Such form error causes deviation between designed optical performances to real optical performance and consequently influences image quality. Currently, there are mainly three methods available to improve form accuracy: tool insert machining compensation; injection molding process optimization; and specific injection molding processes, such as injection compression molding, multilayer injection molding, etc.

4.1.1 Mold tool insert compensation

Mold tool insert form measurement and correction is commonly used for compensation of lenses shrinkage produced by injection molding process based on close loop iteration. Dick et al. [21] used iteration loop to define a higher accuracy of freeform lenses tools with a diameter of 40 mm: they measured the machined surface with surface deviation map; the deviation surface was superimposed to Zernike surface where a new freeform surface can be calculated in a very high numerical precision; a new tool path was generated and the free mold was corrected, with all the other technological process parameters all the same as the first machining. After one cycle close loop iteration, form accuracy can be reduced from PV 2.27 μm to 0.24 μm. A similar strategy has also been used for compensation of polymer shrinkage in the injection molding process (Figure 11). Injection molding process was optimized to reach a level where the surface deviation was small enough; the surface deviation of molded part was measured and fitted with Fourier function; the deviation of the molded freeform surface was superimposed to Zernike sag itself to form new mold tool surface. In such a way, shrinkage of plastic part was compensated, where all the molding processes should be kept consistent. They reduced form error of 18.2 μm PV from directly molding to 1.57 μm PV after compensation. However, correction of mold tool insert to compensate molded part shrinkage is a slow process and takes several days. In addition, ultraprecision machining and injection molding are influenced by environmental conditions and the compensation is not always effective.

Regarding lenses with top and bottom composed by concave and/or convex surfaces, decentration of two surfaces, due to tool insert offset, leads to optical retardation, causing image defects like coma. In the high-quality imaging application, the centering error should be smaller than 10 μm for lenses with diameter up to 100 mm [29]. Walach [30] developed a micro adjustment system using piezoelectric actuator to compensate tool offset for injection molding of a double convex lens, as shown in Figure 12. The X- and Y-axes have a movement range of 130 μm. For a biconvex lens with a diameter of 50 mm, the initial test showed that the centering error in X and Y directions was -42.49±1.84 μm and -31.26±1.25 μm, respectively. After adjustment, centering error in X and Y directions was reduced to 1.87±3.41 μm and -0.79±2.4 μm, respectively, within the acceptable level. The higher deviation may result from tool insert fine movement due to shear force when polymer is injected into the mold.

The decentration error of molded part may be caused by tool inserts alignment error or mold tool offset/deformation because of high shear and possible non-uniform shrinkage after demolding. Particularly, for some imaging bi-convex MLAs, decentration of single lens is different at various locations. Currently, there are few works on decentration, and these are worthwhile to be studied in order to further improve imaging quality.

4.1.2 Process characterization and optimization

Many studies have been conducted regarding the influence of injection molding process parameters on form accuracy of optical lenses. Lu and Khim et al. [31] studied the influence of injection speed, holding pressure, and mold temperature on form accuracy of polycarbonate (PC) mono-axis spherical lens with a diameter of 50 mm and the minimum thickness of 1.5 mm. They found that mold temperature was most influential and form accuracy increases with an increase in mold temperature, as it promoted lens shrinkage and internal stress; holding pressure did not have significant influence on form accuracy, owning to counterbalance between compensation of part shrinkage and increased difficulty of molecular relaxation; and injection speed only changed residual stress distribution. Tsai et al. [32, 33] optimized injection molding process for a plano-convex lens with a diameter of 14 mm and a thickness of 1 mm; they found packing pressure and melt temperature to be the most influential factors on form accuracy, and part surface roughness was determined more by mold surface roughness; the effect of process parameter on transparency can be ignored.

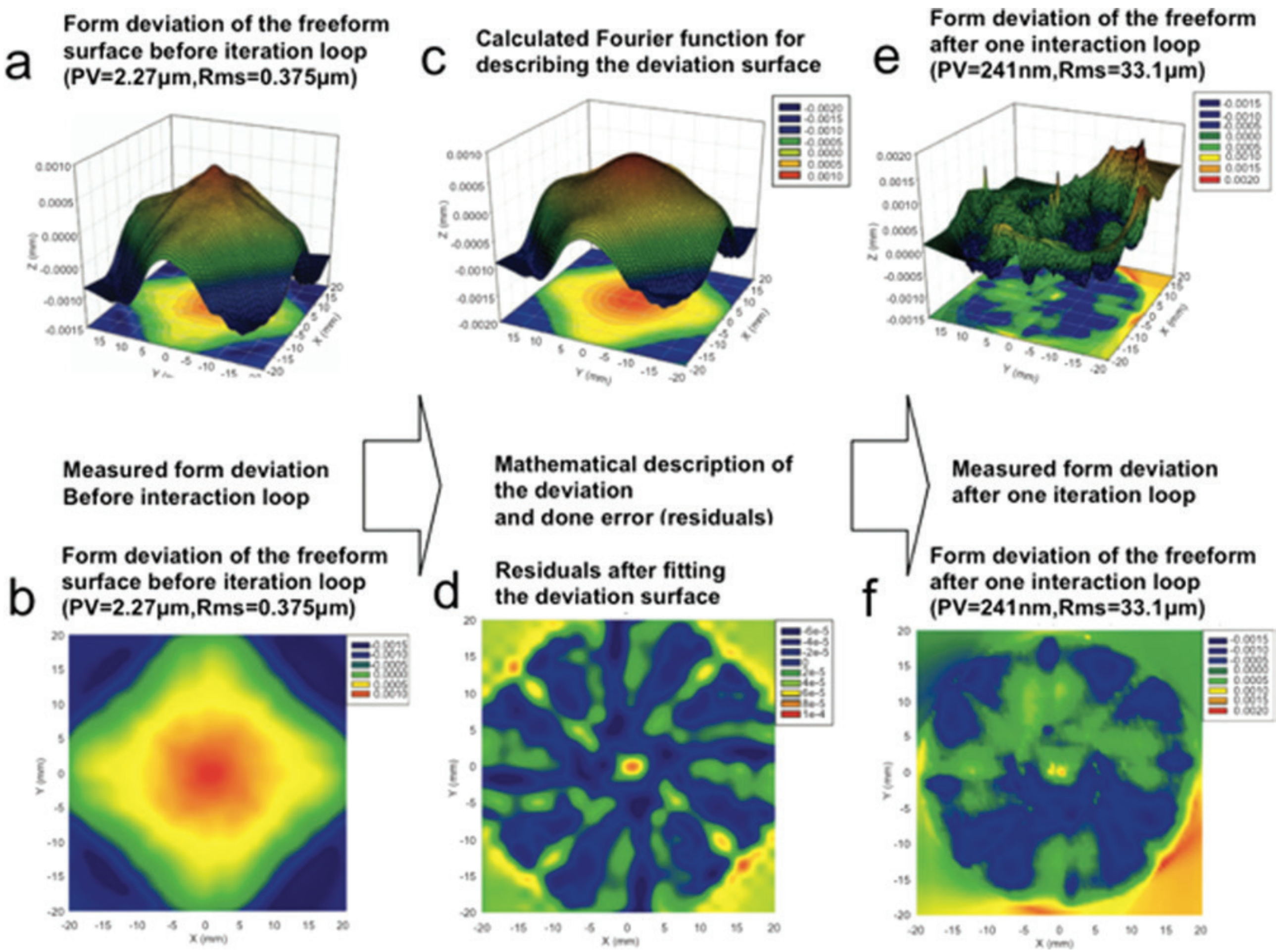

Figure 11: Details of the iteration loop for machining a high precision freeform surface on the mold: (A) Surface deviation before iteration loop, 3D view; (B) surface deviation before iteration loop, top view; (C) Fitted Fourier function as error description of the surface deviation; (D) error between fitted deviation and found mathematical description; (E) surface deviation after one iteration loop, 3D view; (F) surface deviation after one iteration loop, top view [21].

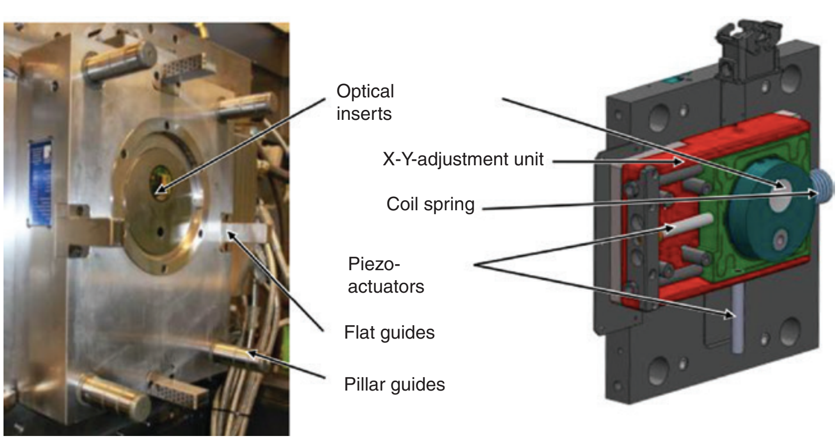

Figure 12: Fixed mold half with integrated adjustment unit using piezoelectric actuator [30].

Additionally, they found that the maximum PV of lenses was reduced from 2.614 µm to 2.577 µm after 6-month storage. Lai and Wang [34] investigated the effect of mold cooling channels and injection molding process on form accuracy of plano-convex lens with a diameter of 25 mm and the maximum thickness of 1.125 mm; cooling channel arrangement influenced mold temperature uniformity and the consequent form accuracy, while increased mold temperature and melt temperature eased filling and improved form accuracy.

However, because of the difference among materials, part geometry and selected processing parameters and their range, the effect of process parameters on form accuracy is not consistent and even contradictive. As a result, process characterization and optimization should rely on a particular product. It relies more on fundamental understanding of polymer material injection molding process and real molding operation practice.

4.1.3 Injection compression molding

Conventional injection molding applies a pressure to polymer melt through a gate. As the pressure distribution is not uniform, it causes problems of non-uniform residual stress, shrinkage, and warpage. Especially for thin wall part, premature solidification causes problem of short shot and much higher pressure is required for fully filling a cavity, leading to high residual stress and associated warpage and birefringence. Injection compression molding has more uniform pressure by adding a compression operation of a mold core, as shown in Figure 13.

The injection compression process can be divided into two separated process steps: melt injection and compression. In the injection stage, the molten polymer is injected into the mold cavity, in an opened state, or free from a clamping force. The mold is then compressed by a clamping force, thereby reducing the cavity thickness to final part thickness. Additional process parameters, e.g. compression stroke, clamping force, and compression velocity, are used to control the compression stage. A machine toggle lever or an externally designed pneumatic system executes the compression action. Injection compression allows increasing the cavity thickness during injection stage by retract mold core. After a certain amount of polymer melts injected into mold, the retracted core moves forward to compress the polymer melts for fully filling of cavity, followed by packing and cooling processes, as shown in Figure 14. As compression occurs when polymer material is still in molten state, the applied pressure is more uniform than a conventional injection molding process.

The early stage of application of injection compression in the fields of lenses concentrated on spectacle lenses. Many patents were disclosed on implementation of compression stroke in mold design, where hydraulic cylinder and compression spring were generally used for compression [36–38]. From the view of processing, Young [39] studied injection compression process of a CD pick-up lens with a diameter of 5 mm; he found that mold temperature, heat transfer, and compression time could influence the distribution of thickness and residual stress; higher mold temperature and slow cooling were useful to obtain uniform shrinkage and residual stress. Michaeli et al. [40] compared injection molding and injection compression molding of a plano-convex lens with a diameter of 50 mm and the minimum thickness of 8 mm; their study indicated that injection compression molding reduced PV of spherical surfaces from 16 µm to 12 µm. Huang et al. [41] compared injection compression molding of rectangular parts with polypropylene (PP) and polystyrene (PS); they found that compression forces had the most significant effect on shrinkage of two materials; compression stroke showed less influence to PS, while it has minor effect on PP, which was attributed to different solidification process. Chen and Kao [42] developed two stages of micro injection

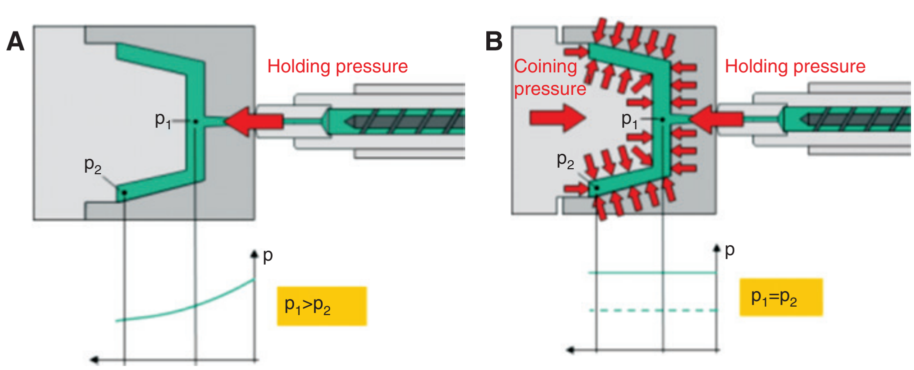

Figure 13: Schematic of injection molding and injection compression molding: (A) pressure distribution of conventional injection molding is related to part geometry and location of injection gate, (B) injection compression molding has more uniform pressure by adding a compression operation of a mold core [35].

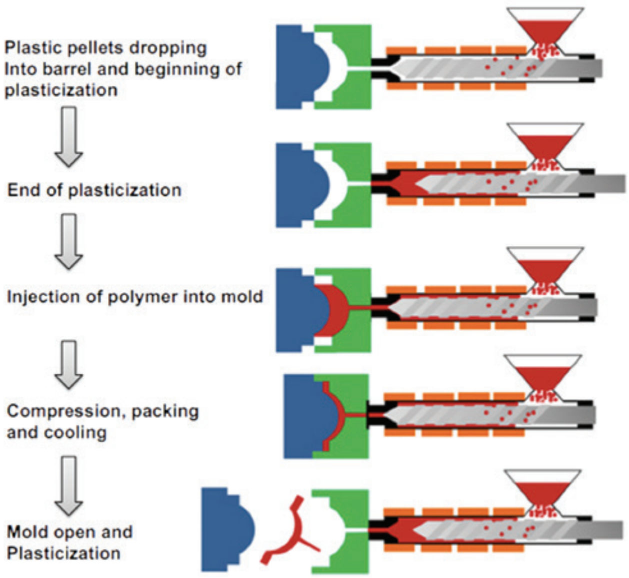

Figure 14: Simplified schematic of injection compression molding process.

compression molding for fabrication of plastic diffractive optical elements. The first compression was implemented similar to conventional injection molding, while the second compression used a piezoelectric actuator for micro compression. Results showed that micro injection compression molding of the diffractive optical elements can obtain the highest transfer ratio of grooves than that of injection molding and conventional injection compression molding processes. Niewels [43] incorporated piezoelectric actuators into an injection mold to improve dimensional accuracy of preform of plastic bottle in order to achieve more uniform thickness. Chen et al. [44] invented a mold apparatus where two piezoelectric actuators were used to vibrate mold material along two directions to improve form error to increase groove filling and reduce residual stress. Chen and Wang [45] simulated injection compression molding of a large thick plano-convex lens with a diameter of 72 mm and the maximum thickness of 8 mm using Moldex3D; it was found that injection compression molding could reduce residual stress and improve form accuracy.

Injection compression molding has some limitations. For lenses with a large thickness variation, thin edge limits the compression stroke of thick part, which may cause non-uniformity compression and restrict improvement of form accuracy via compression operation. Additionally, some complex-form optical products, such as prism, are not possible for injection compression molding because of geometrical limitations.

4.1.4 Multilayer injection molding

Thick lenses injection molding process is a challenge, as part cooling time is proportional to wall thickness and cycle time is too long, causing problem of material degradation. For example, a 30-mm-thick automobile headlight lens takes about 20 min in a molding cycle. Stricker et al. [46] have developed a multilayer injection molding process to reduce cycle time and improve surface quality. The process involves firstly molding a preshot layer and then subsequently overmolding one or more layers of the same material. Overmolded part could effectively

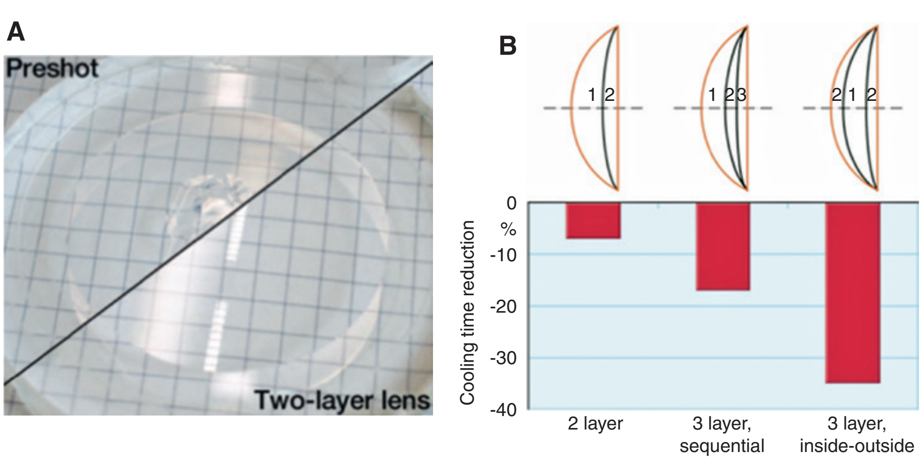

Figure 15: Multi-layer injection molded lens: (A) Preshot with surface defect before and after overmolding of a 2-mm-thick layer of plastic, (B) simulation results for various molding sequences: compared to the single-layer approach, the multi-layer process reduces the cooling time considerably. The cavity wall temperatures are color-coded [46].

compensate shrinkage and surface defects of the preshot (Figure 15A). The cycle time reduction may be achieved from faster solidification of individual layers. Numerical simulation (Figure 15B) indicated that three layers of injection molding could save ~35% cycle time. However, multilayer injection molding requires injection molding machine using a rotary table or a mold with indexing plate. The cycle time reduction depends more on part geometry, layer design, and mold temperature control.

4.2 Residual stress

Residual stress includes flow induced residual stress and thermal induced residual stress. In injection molding process, molecular chains near part surface are significantly oriented along the flow direction because of the high shear rate. However, in the core, shear rate is lower and molecular orientation is not as significant as the skin. Because of fast solidification around the part of skin, molecular orientation freezes immediately before relaxation. While in the core, because of thermal isolation of skin layer and lower thermal conductivity of polymer melts, temperature is still high enough to relax the weakly oriented polymer chains. Once the part cools down, molecular relaxation occurs. Due to diverse distribution of oriented skin and orientation free core, local deformation of skin and core layer is different, causing residual stress [47, 48]. As flow is the only reason for molecular orientation, such residual stress is also called 'flow induced residual stress.' Thermally induced stresses occur during the cooling phase, causing different cooling rate across varying thickness in a part. The rapid cooling and solidification of the surface layer is constrained from shrinkage and, at the same time, restrains the still warm interior from contracting upon further cooling. The result is tensile stresses in the interior and compressive stresses in the exterior layers. This is the so-called thermal induced stress. The total residual stress generated in the parts is the sum of the flow-induced stress and the thermally induced stress. As the residual stresses are associated with local deformation, they would cause problems of warpage, crack, reduction of mechanical properties, and optical birefringence. The relaxation of residual stress of plastic product in service may also induce deformation, caused by problems of assembly and long-term stability, and even local coating delamination. As residual stress is tightly related to form accuracy, it has been discussed in the section of 'form accuracy.' Therefore, here, we only focus on specific processes for relaxation of residual stresses.

4.2.1 Variotherm assisted injection molding

Variotherm mold temperature control has been developed and used in the industry in the last decade. As shown in Figure 16, under variotherm injection molding process, mold temperature at filling and packing stage is elevated over material glass transition temperature/crystalline temperature in order to reduce material viscosity and flow resistance for diminishing weld lines and improvement of micro/nano feature filling. At cooling stage, the mold temperature is decreased to material deflection temperature until material is strong enough for ejection. Chen et al. [50] developed a rapid thermal response (RTR) molding technique using thin metal thermal heating layer where temperature increased from 50 to 250°C in 2 s and cooled to 50°C in 8 s. They found that when mold temperature is close to/higher than material glass transition temperature, birefringence is reduced. When mold temperature reaches 180°C, birefringence totally disappeared, as shown in Figure 17. Yao et al. [51] used high proximity heating to help in the filling of PC rectangular part with a thickness of 0.5 mm. When the mold temperature approached 265°C, mold was fully filled and flow induced molecular orientation and residual stress were significantly reduced. They also reviewed various ways for realization of variotherm injection molding process [52]. In industrial application, variotherm mold temperature system is mainly used to eliminate weld line, increasing flow length and minimizing flow/thermal residual stresses, such as gloss finished thin wall frame of LCD TV [53]. There are still less applications of variotherm system in optical precision injection molding industry.

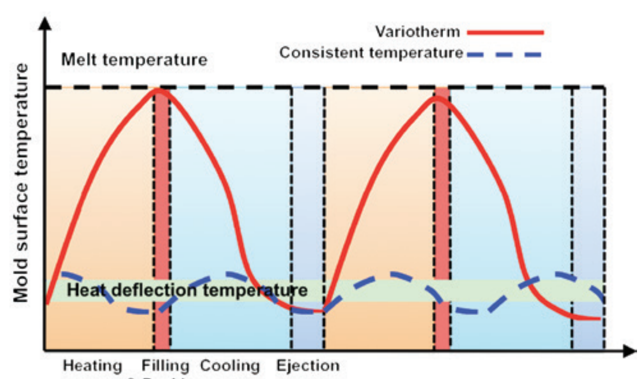

Figure 16: Under variotherm mold temperature control system, mold temperature increases to/over material's glass transition temperature to reduce material viscosity and flow resistance, to diminish welding lines and help surface replication. In cooling stage, mold temperature is reduced to material's deflection temperature in order to eject part out safely [49].

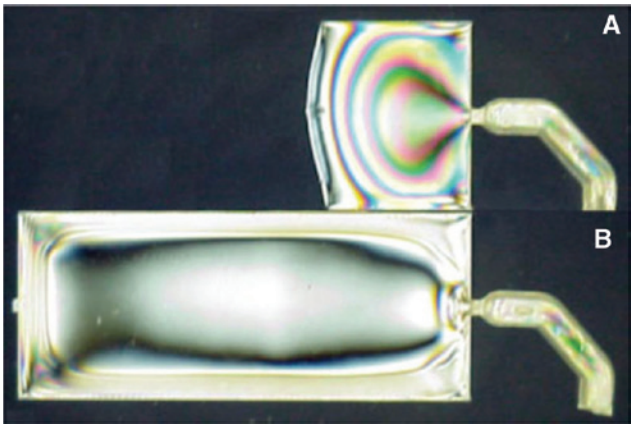

Figure 17: Effect of conventional injection molding (A) and variotherm assisted injection molding (B) on flow length and birefringence of 0.5-mm-thick PC [50], it can be seen that variotherm significantly increases flow length and decreases residual stress.

4.2.2 Ultrasonic assisted injection molding

Ultrasonic vibration present action of reducing apparent friction and causing local heating and have been used for the polymer process since 1970s [54]. It was then used for hot embossing microstructure [55], welding polymer parts [56], and improving filling of injection molding [57]. In injection molding, ultrasonic vibration promotes the apparent fluidity of resin via action of sound pressure and reduction of apparent friction between wall surfaces in the cavity and resin. Sato et al. [57] developed a mold with ultrasonic assisted injection molding system for molding PC aspheric double convex lenses with a diameter of 77 mm and the minimum thickness of 1.3 mm, as shown in Figure 18. They found that ultrasonic molding increased lens weight and improved surface finish; the associated oscillatory flow prevented part shrinkage; and localized heating created by ultrasonic between mold and resin reduced part skin's deformation resistance, leading to better replication on surface features. They also found that ultrasonic vibration can decrease the residual stress due to heating effect. Yang et al. [58] developed a similar ultrasonic system to assist molding of a flat rectangular part (75 mm×47 mm×1 mm) with PC. An ultrasonic oscillation device 45 mm in diameter was placed in the center of the cavity and used to vibrate a PC melt at a frequency of 20 KHz (Figure 19). Their results indicated that oscillation from ultrasonic waves helped to reduce molding pressure up to 29%, due to localized heating. Additionally, direct ultrasonic oscillations destroyed the melt flow and thermal stresses, creating a low stress distribution. Ultrasonic oscillation affected the surface roughness during melt solidification. When the ultrasonic power was <70%, no substantial increase in surface roughness was observed. However, when the ultrasonic power was >70%, the surface roughness was 10 times higher compared with that observed using CIM. Qiu et al. [59] developed a longitudinal ultrasonic vibration core for molding of Fresnel lenses. Their results showed that the filling mold area of the polymer melt was increased by 6.08% to 19.12%, and the symmetric deviation of the Fresnel lens is improved by 15.62% on average.

Although incorporation of ultrasonic system into mold makes a mold design more complex, ultrasonic assisted injection molding shows great potential to improve filling length, reduce residual stress, and improve the part shrinkage, because of oscillation flow and localized heating effect. More works have still not been explored, such as the influence of ultrasonic waves on form accuracy and production cycle time. Process simulation of influence of ultrasonic wave is also potentially important for product design and process development.

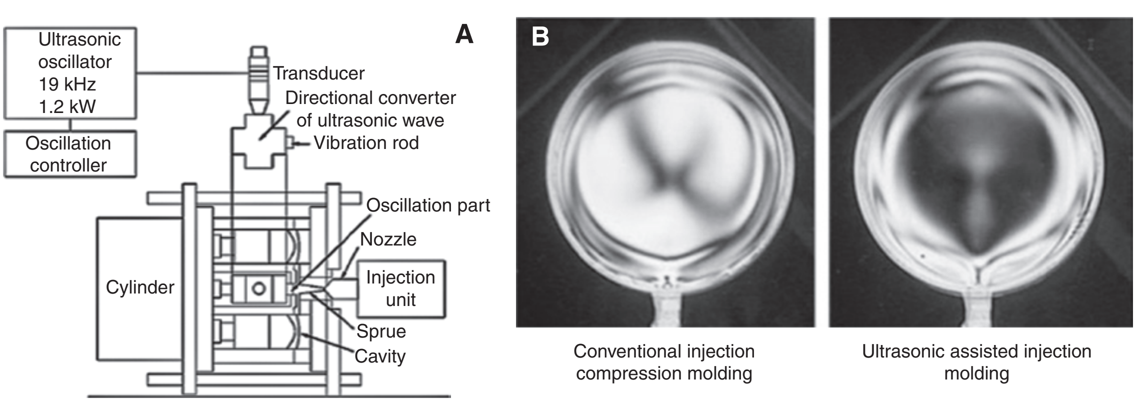

Figure 18: Schematic drawing of ultrasonic assisted injection molding system (A) and comparison of residual stress of conventional injection molded part and ultrasonic assisted injection molded part [57].

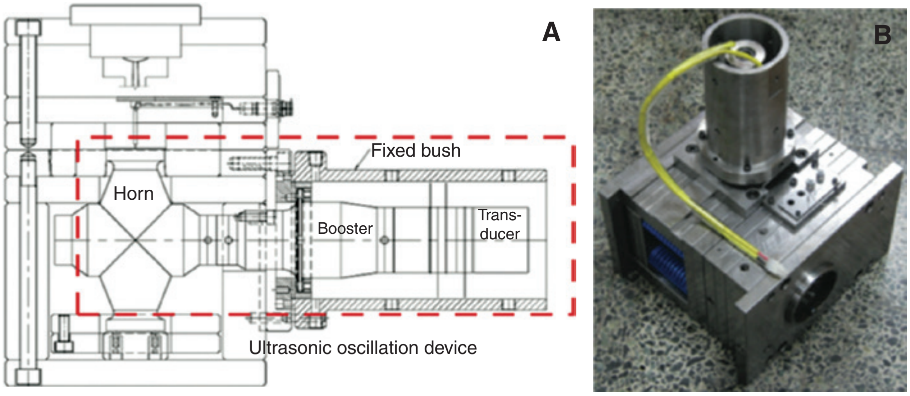

Figure 19: Ultrasonic assisted injection mold [58].

4.2.3 Thermal annealing

Annealing is a common method to release residual stresses. Lai and Wang [34] studied residual stress of a Cylic Olefin Polymer (COP) plano-convex lens with a diameter of 30 mm and thickness of 2 mm. It was found that the distribution of shear stress and residual birefringence was similar to each other. Their experiment indicated that flow induced residual stress accounted 92.3% of overall residual stress. They tried to reduce the residual stress via thermal annealing. After 8-h annealing at 153°C, stress around gate was not totally diminished (Figure 20). They subsequently developed a method to use injection molding to produce a lens preform and use secondary compression molding to release the residual stress and improve form accuracy [60]. After 30-min compression molding, PV of preform reduced from 15.31 μm to 0.693 μm and residual stress was totally diminished (Figure 21). It is seen that conventional annealing may not be able to reduce residual stress, and the associated local deformation is difficult to predict. Compression molding is effective to obtain a high form accuracy and low residual stress. However, it needs additional mold and takes much longer time. Chidley et al. [61] studied performance of injection molded Zeonex E48R aspheric lenses with an outer diameter of 7 mm in the application of disposable endoscope probe with optical system target Strehl Ratio >0.6. They found that flow would induce birefringence influenced optical quality. Subsequent annealing process was used to reduce birefringence. However, it could not improve imaging quality without physical warping. Optimization of molding process was relatively more effective to reduce flow induce birefringence and gave better optical uniformity.

Annealing is a batch of stress relief method and could provide high volume treatment. However, it is difficult to predict and control part deformation because of stress

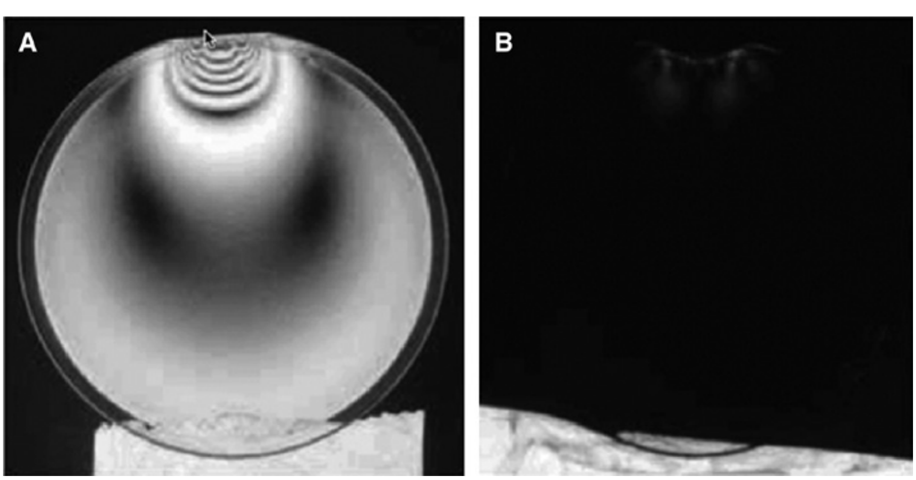

Figure 20: Distribution of residual birefringence of plano-convex lens with a diameter of 50 mm and a thickness of 2 mm: (A) directly injection molded part, (B) part annealed at 153°C for 8 h [34].

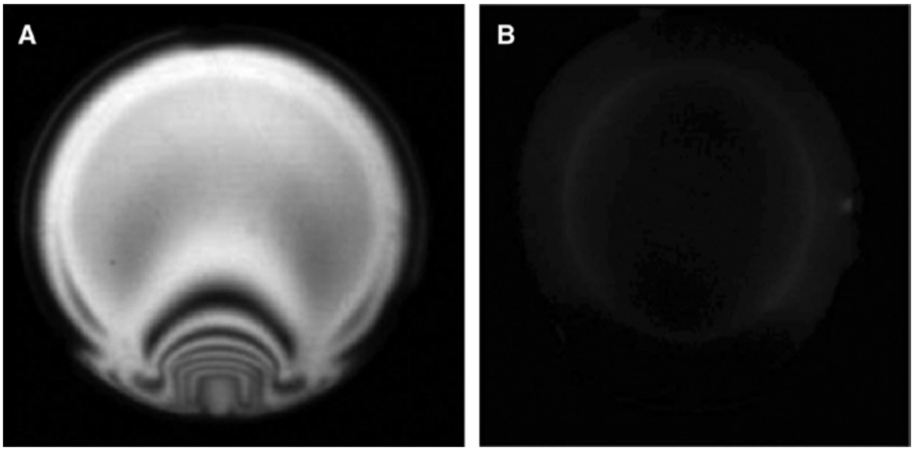

Figure 21: Distribution of residual birefringence: (A) preform with PV 15.31 μm, RMS 3.73 μm, (B) compression molding assisted annealing gives PV 0.693 μm and RMS 0.16 μm [60].

relaxation. Residual stress itself is associated with material molecular structure and thermo mechanical history during processing. Optimization of annealing process is still required to balance residual stress and form accuracy. Injection molding process optimization could decrease residual stress in some degree, but it cannot eliminate stresses totally. As a result, confined geometry stress relaxation process, such as compression molding, benefits more in balance form accuracy and residual stress. However, the efficiency of compression molding is too low.

4.3 Imaging quality assessment

Form accuracy and residual stress both influence imaging quality of plastic optics, causing optical aberrations, such spherical aberration, distortion, coma, and astigmation. Optical transfer function (modulation transfer function and point spread function) is generally used to evaluate imaging quality of plastic optics. Michaeli et al. [40] compared injection molding and injection compression molding of 80-mm-diameter plano-convex lens with a thickness of 8 mm. The aberrations of the injection-compression molded lens were three times lower than that of the injection molded lens but approximately 2.7 times higher as the systematical deformation of the wave-front caused by the plane-convex test geometry (Figure 22A). Injection compression molding shows 10 times higher intensity (Point Spread Function) in the center of lens than that of injection molding (Figure 22B). In comparison to injection-compression molding, the modulation transfer function of injection molded lenses decreases clearly at a low spatial frequency. In spite of similar boundary conditions including machine, mold, and periphery, the optical performance of injection molded lenses is clearly worse than the optical performance of the injection-compression molded lenses. Lai and Wang [34] studied the influence of process on the relationship between form accuracy, residual stress, and image quality. They found that melt temperature and injection speed had the most significant effect on residual stress; mold temperature and interaction between melt temperature and holding pressure directly affected form accuracy. Their statistical study implied that form accuracy and birefringence significantly influenced spherical aberration and astigmation; higher form accuracy and lower residual stress can significant reduce astigmation. Tsai et al. [33] used design of experiments to analyze the influence of process on image quality, including spherical aberration, coma, astigmatism, and illumination. Their result indicated the injection pressure and holding pressure showed the highest impact on spherical aberration. But after a 6-month storage, spherical aberration increased and best processing conditions became different. The mold temperature showed the most significant effect on coma, which increased from 2.09 μm to 2.365 μm after a 6-month storage. Additionally, an increase in injection pressure can improve astigmation and 6-month storage decreased astigmation because of possible stress relaxation. Illumination was related more to holding time. Regarding evaluation of freeform spectacle, Yu et al. [62] used wavefront aberration to evaluate the freeform spectacle lenses based on Hartmann wavefront technology, instead of conventional refractive power evaluation. It provided an effective way to evaluate freeform spectacle lenses.

In addition to form accuracy and residual stress, micro feature replication also shows a significant effect on performance of optical lenses. Shim et al. [63] characterized

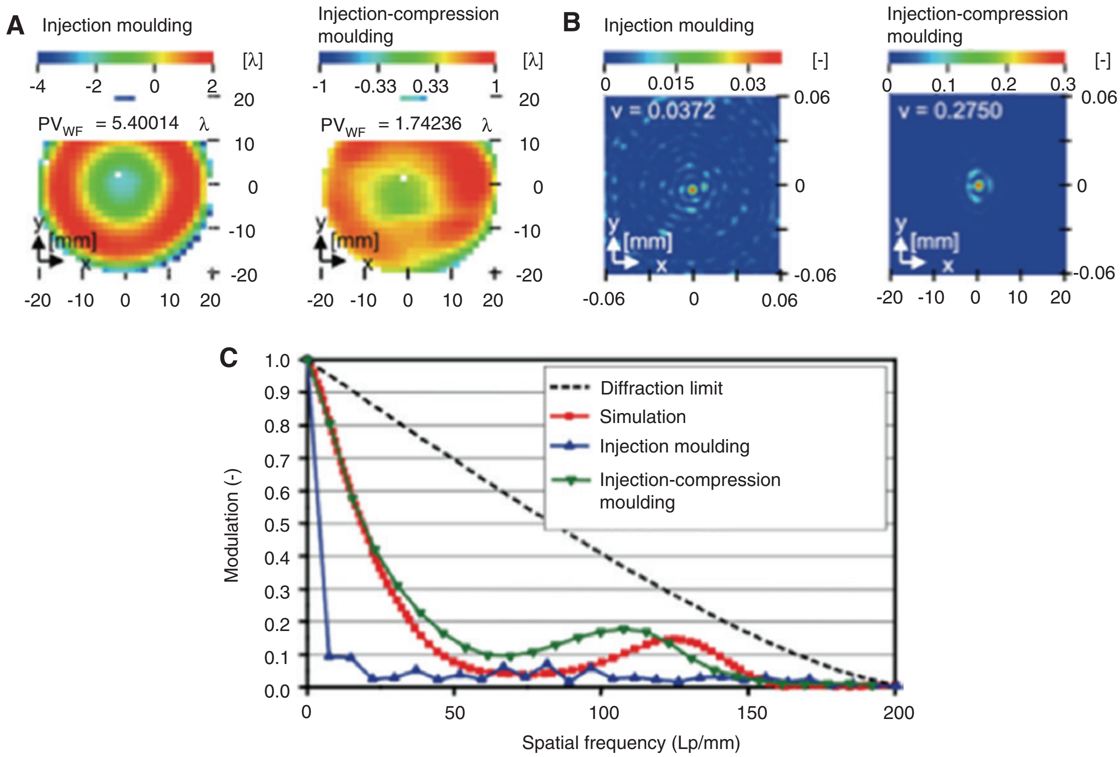

Figure 22: Injection molding and injection compression molding of lens: (A) measured deformation of the wave-front topography, (B) point spread function, and (C) modulation transfer function [40].

effect of fabrication error on performance of a modified Fresnel lenses (MFLs) based on simulation and experiment. An ultraviolet imprinting process and an injection molding process were used to fabricate MFLs. As shown in Figure 23, the measured maximum groove peak radius (GPR) of the UV-imprinted MFL was 6 µm for a groove height of 400 µm. The injection-molded MFL exhibited a maximum GPR of 12 µm at a groove height of 395 µm.

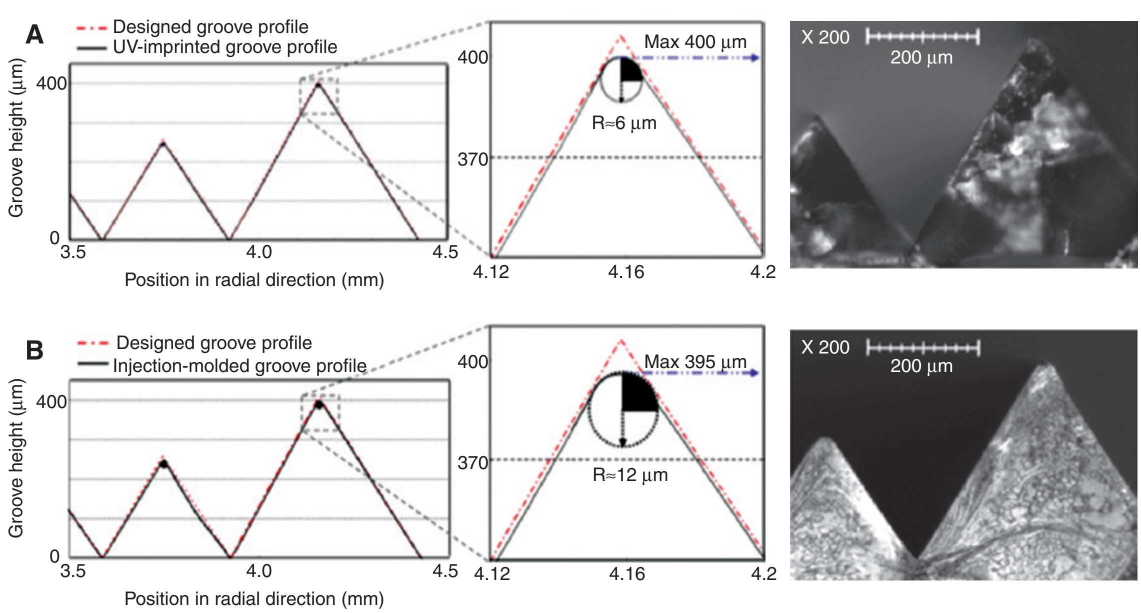

Figure 23: Designed and measured profile and cross-sectional images of (A) a UV-imprinted MFL with a GPR of 6 µm and (B) an injection-molded MFL with a GPR of 12 µm [63].

Simulation results showed that when the GPR was 0, the relative flux efficiency was 91.5% and the illuminance uniformity was 98.4%. However, as the GPR increased from 0 to 6 μm and 12 μm, the relative flux efficiency decreased to 84.5% and 76%, respectively, and the illuminance uniformity decreased to 97% and 95.2%, respectively. Thus, the greater the GPR, the smaller the relative flux efficiency and illuminance uniformity, and the greater the difference from the targeted optical performance. The MFLs fabricated by UV imprinting and injection molding demonstrated GPR values of 6 μm and 12 μm, respectively; measured relative flux efficiencies of 80% and 69%, respectively; and measured illuminance uniformity values of 96.1% and 95%, respectively.

For conventional form optics, form error can be simulated via optical design software, such as Zemax. However, regarding freeform optics, there is no mature algorithm for fitting form deviation and simulation of the form accuracy on imaging quality. There are few studies on residual stress and its influence on imaging quality and effective working area plastic glasses. Exploring relationship between form accuracy and residual stress on imaging quality for freeform optics is useful for product design.

5 Typical applications

Plastic optics has been used in many fields from consumer electronics, green energy, and optical communication to biotechnology and medical devices. There have been several publications that discussed applications of plano, spherical, aspheric plastic optics, and freeform optics [5, 35, 64, 65]. In this paper, we will illustrate some industrial applications of plastic optics according to the research and development conducted in Center of Micro Nano Manufacturing Technology (MNMT) at Tianjin University in recent years.

Figure 24A shows two COC E48R prisms for beam splitter for an Augmented Reality (AR) head mounted system. Figure 24B is a biconvex lens with both its convex surfaces where reflection coating has not been coated yet. Figure 24C and D demonstrates two optical components used in a laser printer, where Figure 24C is a collimator lens and Figure 24D is f-θ scan lenses. F-θ scan lens has two freeform imaging surfaces, and it is used to realize a large field of view, parallel field scanning and elimination of optical aberration. Imaging plastic optics requires high form accuracy and less residual stresses.

Compound eye lens array has been widely used as optical homogenizer. There are two kinds of homogenizers, including non-imaging and imaging homogenizers. Both types are employed to divide the incident beam into small sub-beams and then superimposed by the spherical lens, called Fourier lens, in focal plane, leading to a homogeneously illuminated field. Comparably, non-imaging homogenizers are the first choice for illuminating larger areas, while imaging ones are competent for the small area requiring a very even distribution [6]. Figure 25 displays the optical structure of imaging homogenizer, which has two MLAs.

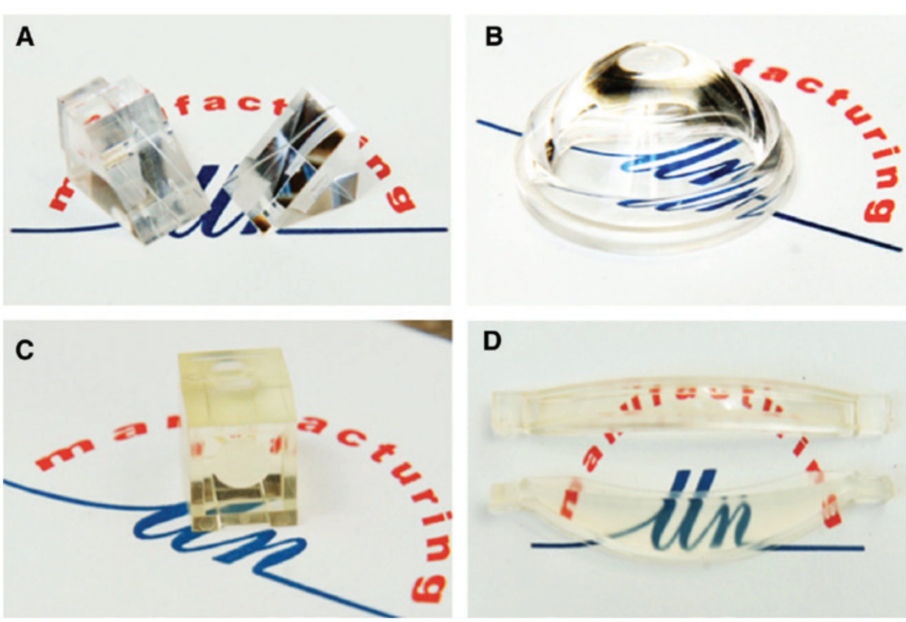

Figure 24: Imaging plastic optics (the maximum side length of the reference logo 55 mm): (A) prism for a beam splitter in augmented reality (AR) systems, (B) biconvex lens, (C) light collimator lenses, (D) f-θ scan lenses with freeform optical surfaces.

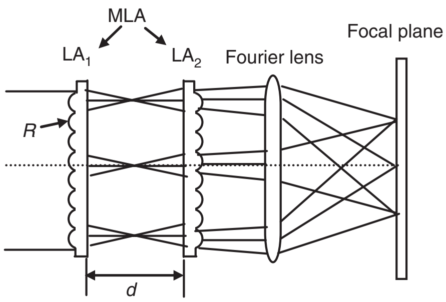

Figure 25: Structure of imaging homogenizer.

MLA is the structured freeform consisting of many patterned micro cells to meet the different illuminating requirements. The types of cell are various, such as aspheric, pyramid, micro-groove, taper, and others. The spherical or aspheric cell is always the selection because it is suitable for fabrication using ultra-precision machining. Here we demonstrate a plano aspheric lens array, double side lenses array, and MLA. Figure 26 shows uniform projection of a laser beam by using double sides MLAs (Figure 27B) as a homogenizer.

Figure 28 shows laser projection system, where the total reflective lens converts a straight laser beam into ring projection on to a wall from side of lens, as indicated by schematic of optical path.

6 Challenges and future development trend

The development of plastic optics is very fast in the recent years, especially with rapid growing of opto-electronics industry. From LED illumination to smart phone lenses and even wearable devices, such as Virtual Reality (VR) and Augmented Reality (AR) systems, optical systems play a particular important role. The surface form of optical elements becomes much more diverse and requires high form accuracy and low residual stress. For example, the optical system of the Google Glass is composed of mini-projector and a beam splitter cube. Virtual images are projected on a human's retina though cubic beam splitter. This beam splitter is composed of a half-silvered prims and concave reflector. Optical plastics have been used for manufacturing the cubic beam splitter using injection molding. As it is used for imaging, form accuracy is critical for high image quality; residual stress determines effective working area. Considering wear comforts, such heads-up display system is inclined to use plastic lenses with small volume to weight ratio. This challenges all manufacturing processes of plastic optics, as it requires specific molding process and high accuracy tool inserts.

Using freeform optics is becoming a future develop trend from the perspective of product design. Conventional optics is generally composed of plano, spherical, or aspheric surfaces. Freeform optics has surfaces with no axis of rotational invariance (within or beyond the part). Freeform optics offers many benefits, such as more design flexibility and freedom for innovation, enhancement of the optical system performance to the maximum extent, and simplifying of system structure with fewer surfaces and ease of integration. In recent years, significant progress has been made on design, machining, and measurement of freeform optics. More and more applications of freeform optics presented and played an important role spanning from optoelectronics to communication, green energy, and life science. However, design of freeform optics is still challenging. The mathematical models for freeform geometric specification and verification are still in the early stage of development.

Although ultra-precision machining of optical tool insert can realize form accuracy of submicron and surface

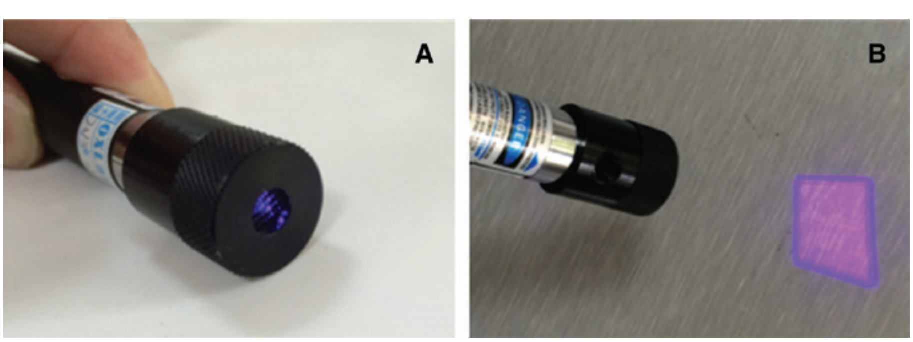

Figure 26: Double side MLAs for uniform illumination: (A) double-sided compound lens arrays assembly into a laser pointer, (B) a laser beam is uniformly projected on to a wall.

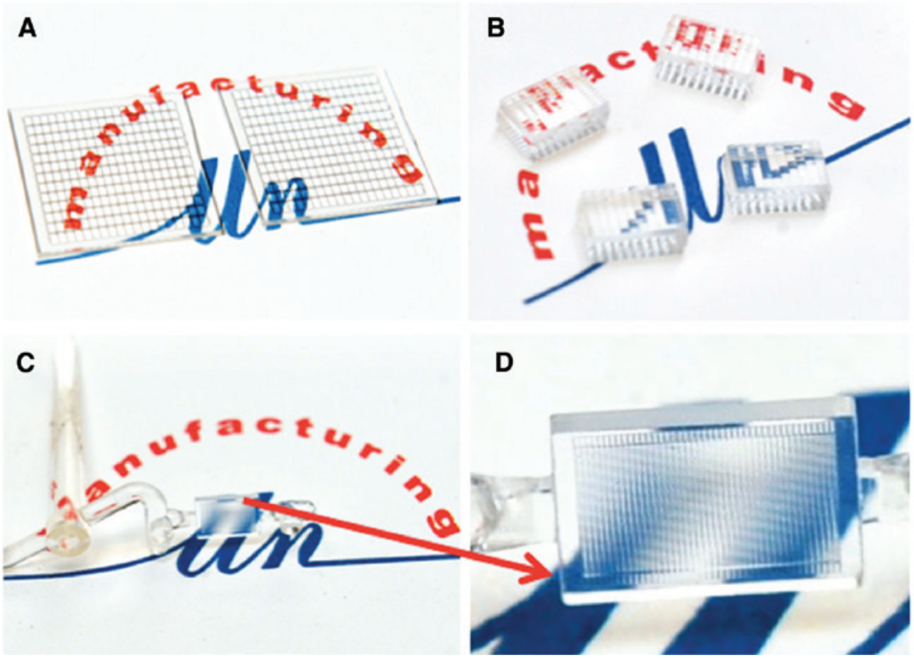

Figure 27: Compound eye lens arrays (the maximum side length of the reference logo 55 mm): (A) plano-aspheric lens arrays, (B) double sided compound lens arrays, (C) double side MLSs, (D) enlarged view of a microlens arrays.

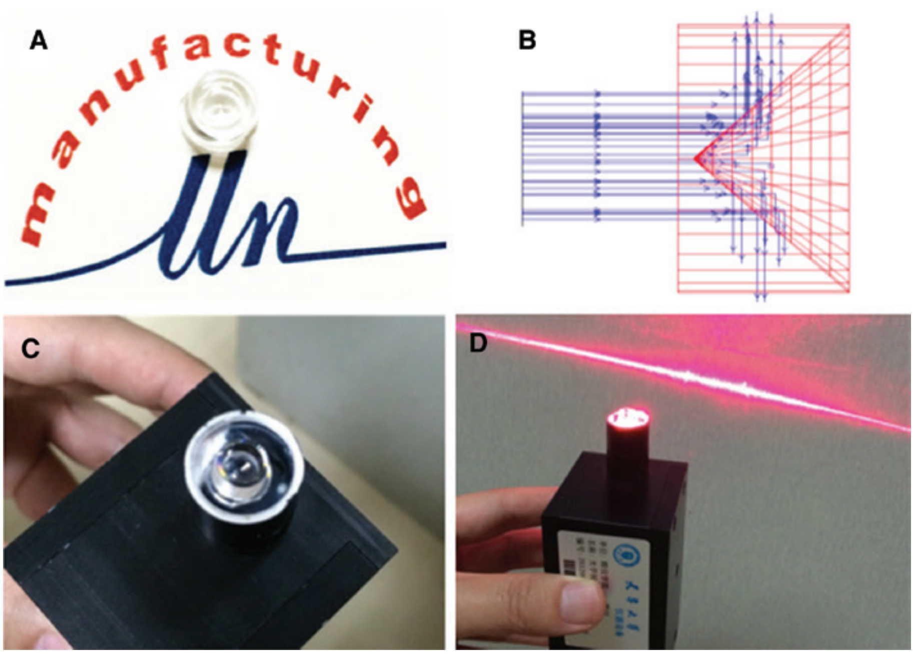

Figure 28: Laser total reflection system: (A) micro injection molded total reflection system, (B) schematic of optical path, (C) lens assembled with a laser beam, (D) laser project from sidewall of lens.

roughness of nanometers, machining accuracy of freeform optics is expected to be improved to nanometer or even sub-nanometer scale. More types of complex surfaces are required to be machined on various mold materials. The currently widely used electroplated nickel phosphate alloy material has better machinability; however, it shows surface scratches in several thousand molding cycles. Electroplating is not an environment friendly process, and it is necessary to explore new optical insert materials with a better machinability in ultra-precision machining.

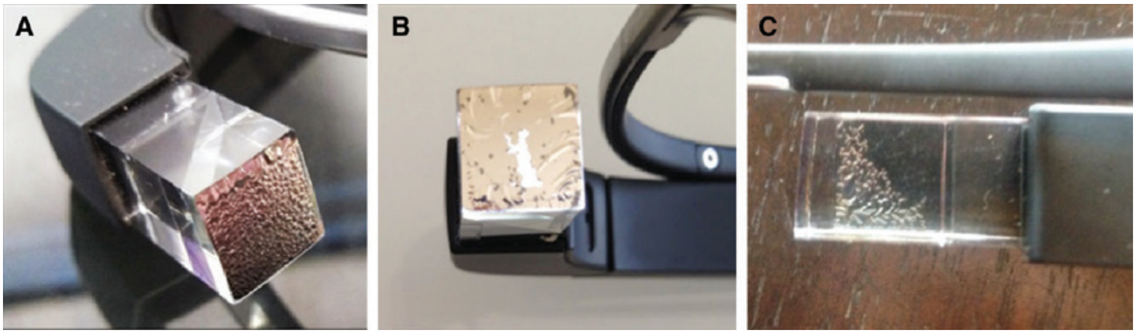

Figure 29: The failure of Google glasses in service: (A) bubbled surface formed on a concave reflector in a humid and hot weather [66], (B) delamination of coatings of concave reflector [67], and (C) breakage between 6-month use [68].

Currently, conventional injection molding of plastic optics can satisfy most of applications for optical industry, although the form accuracy for most of the parts is up to several micrometers. However, for high-end imaging applications, form accuracy and material uniformity are more and more critical. The research published currently is still based much more on plano-spherical lenses and aspheric lenses. Development of freeform lenses injection molding is still less. With the development of miniaturization and bio-inspired engineering, micro lens arrays, such as compound eyes, requires precision not only on overall dimensions but also on each individual lens and their position. For thick lenses, such as prism, non-uniform shrinkage causes difficulty for improvement of form accuracy; residual stress leads to small working area. Future development should be focused on ultra-precision injection molding complex form part with a larger thickness and micro injection molded parts with a form accuracy to submicron with relatively large working area while maintaining high efficiency and low cost.

It is still worthwhile to be noticed that in the long-term service, plastic optics shows defects and failure. For example, because of release of residual stress, humidity, and temperature-varied environment, surface coating of the cubic beam splitter of Google Glasses showed delamination and wrinkling; the two prisms of splitter even broke, as shown in Figure 29. As a result, it is important to study long term behavior of material at actual application environment and optimize processing practice to avoid/reduce risk of long-term failure.

7 Conclusions

The progress in single-point diamond turning in recent years has enabled machining of various surface form tools for precision injection molding. The machining accuracy of freeform optic tool inserts is expected to be improved to sub-micron and even less. However, form accuracy of plastic optics manufactured by precision injection molding process is at least one order of magnitude worse than tool itself. In addition to some unavoidable errors, such as mold installation and environment variation, there are some other important parameters existing for the improvement of plastic optics precision, such as materials, mold design, and process characterization and optimization. Except for compensation based on tool correction, specific molding processes, injection compression molding, multilayer injection molding, ultrasonic assisted injection molding, and variotherm assisted injection molding have used or are potentially useful for improving plastic optics form accuracy and/or minimizing residual stress. Future work in injection molding will focus more on optical performance and manufacturing efficiency of high performance freeform optics.

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