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A Review on Micro Hot Embossed Fresnel Lenses

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Abstract

Background: *Micro replication techniques like HE allows for the large-scale manufacturing of the micro components which use polymers like Polymethyle methacrylate, Polycarbonate, polystyrene as the work material. In the hot embossing process, key parameters include applied pressure, temperature during heating, duration of embossing, and temperature during demolding.* ***Research Objectives:*** *Developing straightforward and affordable methods to produce the micro featured molds needed for the hot embossing is a significant research goal. Fresnel lenses, made up of concentric ringed facets, are important compact optical elements with advantages over traditional spherical and aspherical lenses, including thinner form factors and using less material.* ***Significance of the Study:*** *Generally, Fresnel lens fabrication falls into two main categories: subtractive methods and precision methods for forming similar moulding and embossing. For mass manufacturing the latter are frequently employed, employing molds created through subtractive processes. This review summarizes research on hot embossing of Fresnel lenses, aiming to provide a consolidated information source for new researchers entering this field. It offers an overview of work already done in Fresnel lens hot embossing fabrication.* ***Scope and Organization****: Following this introduction and overview, Application of Micro Fresnel Lens, Summary of previous works done on fabrication Fresnel Lens in a table form, Possible defects in embossed Fresnel lenses after Micro Hot Embossing with Conclusion.*

Keywords: HE-Hot embossing, fresnel lens, optical devices, epoxy, resin, pmma-polymethylemethacrylate, polycarbonate, silicone rubber, polyethylene terephthalate

INTRODUCTION AND OVERVIEW

Fresnel lenses require precise control of parameters for large-scale, low-cost mass production. Their thin, lightweight design with concentric ring microstructures provides capabilities akin to bulkier conventional lenses. Applications include LEDs, security systems, concentrating solar energy, thermal imaging, automobile lighting, cell phone flashes, X-rays, satellites, optics, and astronomy. Among replication techniques for micro diffractive polymer optics, microinjection molding is common, but micro hot embossing offers competitive advantages like lower costs, simpler operation with few process variables, and excellent replication fidelity for high aspect ratios when small batches are needed. Micro hot embossing thermoplastics is emerging for optical and micro structured components. Compared to other methods, hot embossed parts see lower residual stresses because the polymer deforms over a smaller distance from the substrate. The relatively narrow temperature range also decreases shrinkage and friction during cooling and de-embossing [1, 2].

Two major challenges in hot embossing are determining optimal process parameters to completely fill embossing tool cavity through polymer and attain extreme accuracy and applying the right demolding force during cooling to separate the tool and polymer without impacting the structure of the replicated polymer [3-5]. Careful control and observation of these critical steps in the

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hot embossing process is key [6, 7]. The conventional hot embossing setup and variations in temperature and pressure during process is depicted in shown in **Figure 1(a) and 1(b)**, respectively. Thermoplastic polymers are often used as work pieces in hot embossing micro-patterning due to qualities like low cost, Light weight, versatile thermal, chemical, and optical characteristics, with low molding temperatures. For optical applications transparency is essential. In semi crystalline polymers, transparency reductions take place because crystalline regions cause more refraction than amorphous regions. Thus, amorphous polymers such as PC and PMMA are better suited for optics compared to semi-crystalline polymers [8].

In 1822, the Engineer and Physicist designed a new type of lens for lighthouses whose name was Augustin Jean Fresnel. Fresnel's lens design allowed the lighthouse to project light much farther out to sea. This improved navigation for ships by increasing the visibility of the lighthouse beam. Fresnel's lens design, sometimes called the "echelon" lens, was compact and had a short focal length. The design also reduced weight and light absorption compared to conventional lenses. A Fresnel lens can focus sunlight to generate a lot of heat. The lens's size, material, and quality of the lens, as well as the sunlight's intensity, all affect how much heat is produced. The key feature of a Fresnel lens is its ability to focus sunlight efficiently onto a small area. It does this using a series of concentric grooves instead of a continuous curved surface like a traditional lens. A high-quality Fresnel lens can focus sunlight to reach temperatures between 400°C and 800°C (752°F to 1472°F). In ideal conditions, temperatures over 1000°C (1832°F) are possible. For instance a 1 m^2 Fresnel lens with the concentration ratio of 1000:1 can theoretically concentrate 1000 W of solar power onto a small focal area, generating extremely high temperatures, limited by the efficiency and heat dissipation of the target material. The construction of fresnel lenses is shown in **Figure 2**. This allowed the lens to fit in tight spaces like lighthouses while improving light transmission over long distances. Like spherical and aspherical lenses, Fresnel lenses collimate and concentrate light by refractive principles described by Snell's law [9]. Fresnel lenses have gained popularity in various applications including lighting systems, solar concentration, and imaging systems due to properties like compact size, light weight, and cost efficiency compared to conventional lenses. Their unique capabilities have led to increased use across many areas like lighting structures [10, 11]. Traditional Fresnel lenses have a grooved profile that revolves around a principal axis. On the other hand, optical designers have created profiles for non-conventional Fresnel lenses in order to maximize optical performance for particular applications. These specialized designs maximize the optical capabilities of Fresnel lenses beyond what is possible with the conventional revolving groove profile. Fresnel lenses can concentrate infrared radiation in infrared detectors, increasing sensitivity. They can also collimate radiation for spectrometers [12-15]. Fresnel lenses can be used to focus sunlight onto a solar cell or thermal receiver in solar power plants. This allows the sunlight to be concentrated, increasing efficiency [16, 17]. Microstructures in Fresnel lenses have feature heights ranging from hundreds of microns to nanometers.

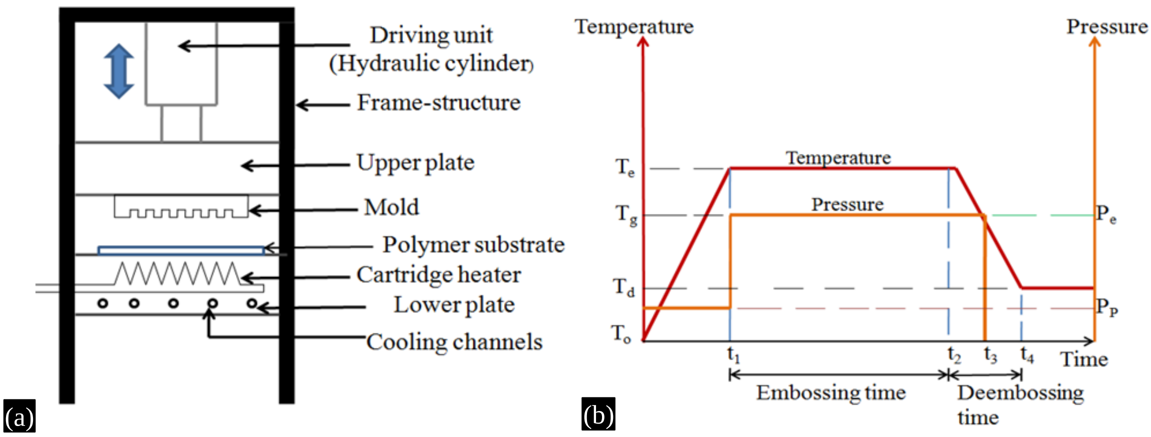

Figure 1. (a) Conventional Hot Embossing Setup (b) Variations in Temperature and Pressure During Process is Being Embossed [39].

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The groove-like profiles diffract light, concentrating or collimating beams. Beyond solar uses, Fresnel lens arrays are essential parts of infrared detection systems, which use them in anything from complex thermal photography for security identification purpose to energy-saving switches. Given their thin, lightweight nature, Fresnel lenses also see widespread use in ophthalmology as intraocular lenses (IOLs). IOLs are polymer lenses implanted to swap out the crystalline lens of the eye in treating cataracts. Harold Ridley developed and carried out the first IOL in London in 1949 [18]. Originally made of PMMA, today's IOLs use more flexible polymers to meet surgical needs. The largest Fresnel lens in the world is at the Makapuu Point Lighthouse in Hawaii. Here are some key details about it. This lens is a hyper-radial Fresnel lens, which is bigger than the usual first-order Fresnel lenses found in lighthouses. Dimensions: The lens at Makapuu Point Lighthouse has a diameter of about 12 feet (3.66 meters). It was Installed in 1893, it is one of only 16 hyper-radial lenses ever made. It was crafted by the French company Barbier, Benard, and Turenne. This lens has an amazing ability to gather and focus light, which was crucial for helping ships navigate safely.

Micro HE is a precision manufacturing method employed to replicate microscale features onto a substrate, typically made of polymers or other materials. It involves heating a mold (typically made of metal or silicon) with microscale features to temperature that is higher than glass transition or softening the substrate material's temperature. Once heated, mold is pressed against substrate with a controlled force, transferring the microscale features onto the substrate's surface. This process is used in fabrication of microfluidic devices, optical components, micro-electromechanical systems (MEMS), and other microscale structures. Micro hot embossing offers several advantages, including high replication fidelity, low cost per part, high throughput, and compatibility with a wide range of materials [19].

Micro hot embossing of thermoplastics is an affordable replication method for transferring patterns of microstructure from the master mould to a polymer substrate using appropriate pressures with temperatures. This technology allows cost-effective production of precision polymer micro structures. One of the more intriguing techniques is micro hot embossing. for fabricating high precision along with high quality micro/nano scale features in the both academic and industrial settings. This replication method enables precise production of micro and nano structures with excellent quality [20]. There are four basic phases in a standard micro hot embossing procedure [21-24]: (1) Giving heat to a mould and polymer substrate up to the moulding temperature, (2) using the embossing temperature to create microstructure patterns, (3) bringing the substrate and mold down to demoulding temperature and (4) demoulding the component by separating the mold tools. Throughout the process, there are two phases of deformation for thermoplastic polymers. First stage during heating and embossing involves. concentration of stress and hardening of strain. The second stages during cooling and demoulding involves stress relaxation and deformation recovery [25]. The general steps involved in micro-HE is depicted in **Figure 3**. Glass transition temperatures, the amount of pressure used, and the holding duration are three most significant variables for the micro HE. A summary of previous works done on fabrication Fresnel Lens by differrnt reseacher is given in **Table 1**.

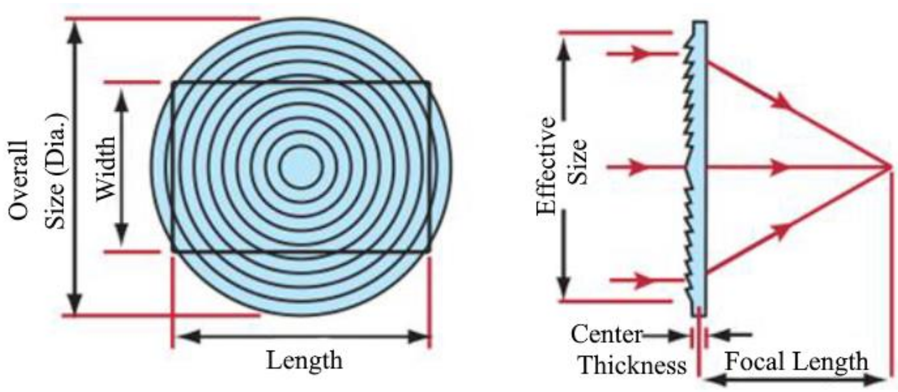

Figure 2. Construction of fresnel lenses [42].

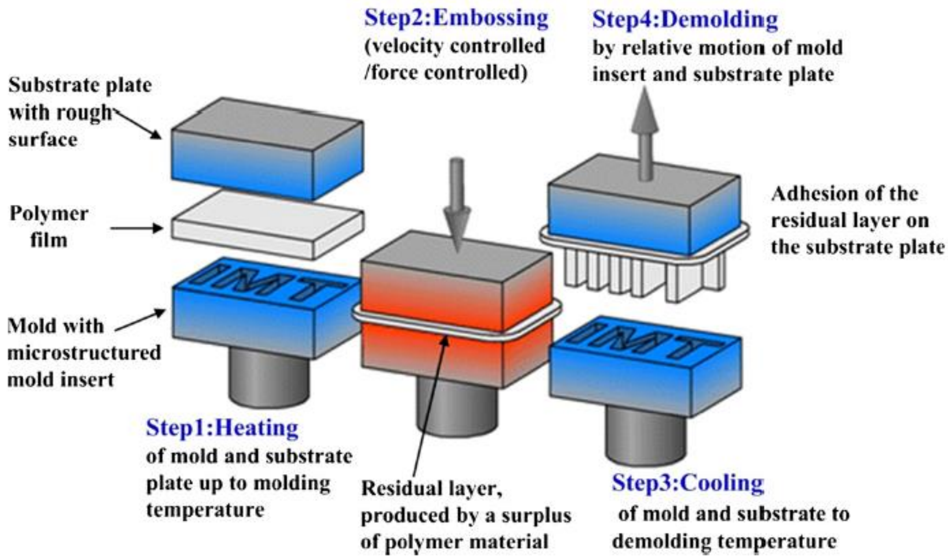

Figure 3. Diagram showing the general steps involved in micro HE [44].

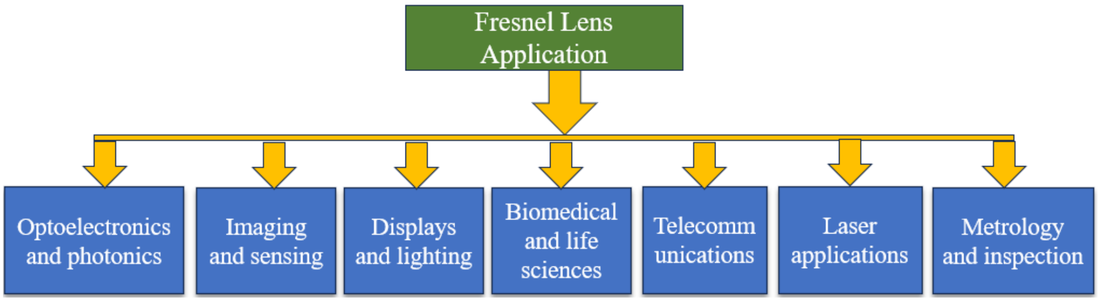

Figure 4. Application of micro fresnel lens.

APPLICATION OF MICRO FRESNEL LENS

Micro Fresnel lenses, renowned for their diminutive dimensions and distinctive optical characteristics, serve diverse purposes in sectors prioritizing compactness and precision. These scaled-down adaptations of conventional Fresnel lenses have been instrumental across multiple domains owing to their small form factor and adeptness in light manipulation. Below are highlighted some noteworthy implementations of micro Fresnel lens (**Figure 4**).

In optoelectronics and photonics, micro Fresnel lenses play pivotal roles in several key areas. They facilitate the coupling of light into and out of optical fibres, aid in collimating and focusing light within optical interconnects, and serve as integral components in optical switching and routing systems. In imaging and sensing applications, micro Fresnel lenses find wide utility. They contribute to the functionality of microlens arrays used in imaging and light field cameras, enable miniaturized cameras and sensors through micro-optics, and support integrated optics in lab-on-a-chip devices. In displays and lighting technologies, micro Fresnel lenses are indispensable. They assist in illumination and light extraction for micro-displays and micro-LED displays, aid in coupling of the light into and out of the waveguides, and enhance performance of augmented reality (AR) and virtual reality (VR) displays. In Biomedical and life sciences, micro Fresnel lenses offer significant benefits. They are utilized in endoscopes and minimally invasive surgical instruments, enable optical tweezers for the manipulation of micro-particles, and enhance fluorescence microscopy and bio-imaging through micro-lenses. In Telecommunications, micro Fresnel lenses play crucial roles in optical coupling and collimation within fibre-optic communication systems, as well as in optical interconnects for data centres and high-speed communication networks. Moreover, in laser applications, micro Fresnel lenses are instrumental in beam shaping and focusing within micro-lasers, as well as in laser printing and lithography systems. In

Metrology and inspection, micro Fresnel lenses contribute to structured illumination and 3D surface profiling through micro-lens arrays, and enhance high-resolution inspection and metrology systems through micro-optics. Overall, micro Fresnel lenses offer significant advantages in applications where the miniaturization and integration of optical components are paramount, making them invaluable in various emerging technologies [26]. Fresnel lenses can be relatively expensive for several reasons:

- *Manufacturing Complexity:* Fresnel lenses consist of many precisely aligned concentric rings or grooves that act as individual refracting prisms. Creating these intricate patterns with optical precision requires advanced manufacturing techniques, making them more difficult and costly to produce compared to simple lenses.
- *Optical Quality Requirements:* For applications like concentrating sunlight, Fresnel lenses need to have very high optical quality. This means accurate groove shapes, minimal defects, and good transparency. Achieving this level of quality control increases manufacturing costs.
- *Large Aperture Sizes:* Many Fresnel lenses, especially those used for solar power concentration, need to be made with large aperture diameters (over 1 meter). Manufacturing large, high-precision optics is inherently more challenging and expensive.
- *Specialized Materials:* While some Fresnel lenses use common polymers like acrylic, others require specialized plastic or glass materials that can withstand high temperatures and concentrated solar radiation without degrading. These specialty materials add to the cost.
- *Niche Applications:* Fresnel lenses are often produced for niche scientific, industrial, and renewable energy applications rather than mass-market consumer products. The smaller production volumes lead to higher per-unit costs.

EFFECTIVENESS OF A FRESNEL LENS

Fresnel lenses are special optical devices known for their ability to focus light efficiently while being lighter and thinner than regular lenses. Here are some key points about their effectiveness:

1. Light Focusing and Magnification
    - *High Concentration:* They can focus light to a small point, making them perfect for applications like solar energy concentration.
    - *Magnification:* They are used to magnify images in devices such as overhead projectors, magnifying glasses, and lighthouses.
2. Thin and Lightweight
    - Fresnel lenses are much thinner with lighter than traditional lenses with similar aperture and focal length. This makes them easier to handle, transport, and install.
3. Versatility
    - *Wide Range of Applications:* They are used in many fields, including lighthouses, solar energy systems, photography, stage lighting, and augmented reality displays. Their precise light-focusing ability makes them useful in both industrial and consumer applications.
4. Manufacturing Efficiency
    - *Cost-Effective Production:* Despite the need for precision molds and quality materials, the manufacturing process of Fresnel lenses is efficient, allowing for the production of large, lightweight lenses that are often more cost-effective than traditional lenses.
5. Material Reduction
    - By dividing lens into a series of concentric rings. Fresnel lenses use less material while still focusing light effectively. This design reduces optical aberrations to some extent, though not entirely.

POSSIBLE DEFECTS IN EMBOSSED FRESNEL LENSES AFTER MICRO HOT EMBOSSING

Micro hot embossing is the primary method for producing micro-scale Fresnel lenses, but it can introduce several defects into the final product, impacting its quality and performance. These potential defects include:

- *Incomplete Filling:* Insufficient material flow or pressure during embossing may result in unfilled mold cavities, leading to missing or distorted features in the lens structure.

- *Surface Roughness:* Variations in temperature, pressure, or mold quality can cause rough surfaces on the lens, reducing optical clarity and efficiency.
- *Mold Damage:* Wear and tear on the embossing mold can cause scratches, dents, or deformations on the lens surface.
- *Dimensional Inaccuracies:* Variations in process parameters or material properties can cause dimensional inaccuracies in the lens, deviating from the desired shape, curvature, or focal length.
- *Warpage:* Non-uniform cooling or mold release can cause warpage in the lens, distorting its shape and optical properties.
- *Flow Lines:* Inadequate material flow or cooling can result in flow lines or streaks on the lens surface, affecting appearance and optical performance.
- *Bubble Formation:* Air bubbles trapped during embossing can create voids or bubbles in the lens structure, compromising integrity and optical properties.
- *Delamination:* Poor adhesion between layers or materials can lead to delamination, causing cracks or peeling. Manufacturers can mitigate these defects by optimizing process parameters, maintaining mold quality, ensuring uniform material distribution, and implementing quality control measures.

Advancements in materials and processes can further improve the quality and consistency of embossed Fresnel lenses [44, 45, 50, 51]. Below figures indicating different defects produced in hot embossing **Figure 5** showing that the characteristics of hot-embossed Fresnel lenses vary depending on the level of material coalescence during manufacturing. In a fully coalesced lens **Figure 5(a)**, the material seamlessly merges, resulting in a smooth and intact structure. Conversely, an incompletely coalesced lens **Figure 5(b)** exhibits areas where material fusion is lacking, leading to irregularities or gaps within the lens. SEM analysis **Figure 5(c)** offers detailed insight, revealing cracks between Fresnel zones due to insufficient material coalescence, which can compromise the lens's integrity and optical performance. Ensuring complete coalescence is essential to guarantee the functionality and quality of hot-embossed Fresnel lenses [45].

Figure 6 indicates that surface roughness plays a pivotal role in optical components and necessitates thorough characterization. Surface topography of newly manufactured aspherical microlens was characterized by using Atomic Force Microscope (AFM Model SPA-400, manufactured by Seiko Instruments Inc., Tokyo, Japan). The AFM scan was performed over a 15 μm × 15 μm area located at the central region of lens. The AFM data revealed that Ra the average surface roughness of lens was approximately 2 nm. This low roughness value indicates that the lens surface exhibits an extremely smooth, mirro like finish [50].

Figure 7 illustrates the forming defects observed during HE process of a glass microprism array. At temperatures near the glass softening point (T_f) of 714°C - sticky glass debris adhered to tip of the die core microgroove, as depicted in Figure 10a. This phenomenon is likely attributable to the heightened adhesion of glass materials at elevated temperatures.

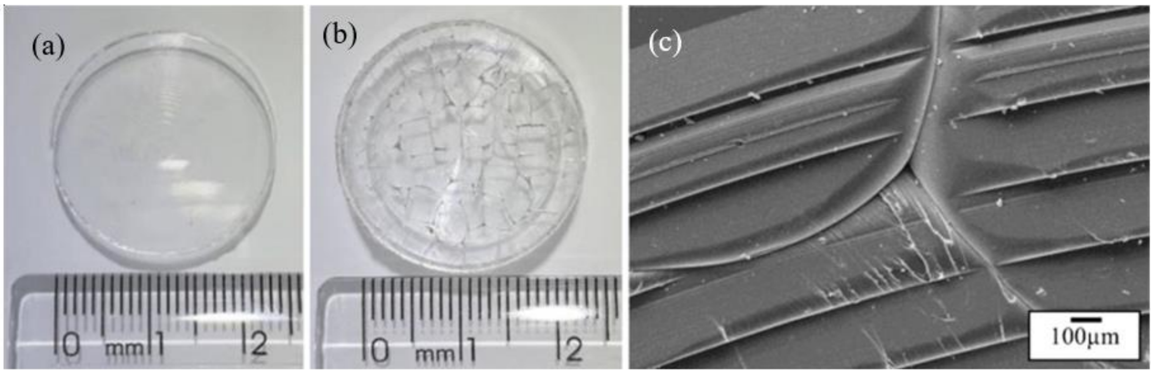

Figure 5. (a) Fully Coalesced Lens (b) An Incomplete Coalesced Lens (c) SEM Analysis [45].

Table 1. Summary of previous works done on fabrication of fresnel lens.

Sl. No	Author & Year	Paper Title	Contribution with Substrate and the mold used	Process and the parameters used	Findings
1	Chil-Chyuan Kuo et al, 2013 [27]	Micro-Hot Embossing of Fresnel Lens Using Precision Micro-Featured Mold.	Examined were the impacts of the micro HE procedure variables on the accuracy of micro feature embossing. A micro feature mold insert was created by using epoxy resin composite with PMMA film serving as substrate.	Until saturation value is achieved, the embossing load from 40 to 70 kg and embossing temperature from 150 to 180 degrees Celsius improved the depth and width of the microgroove's embossed accuracy	The element has been replicated with a 55 kgf embossing load and a 170 C embossing temperature, taking into account cycling time. Improved surface flatness and decreased residual stress were noted.
2	R. Kasztelanic et al, 2013 [28]	Fresnel lens fabrication for broadband IR optics using hot embossing process	A element of fused silica that was developed via ion etching technique was utilized as the mold. Glasses made of tellurium with lead bismuth gallium oxides were utilized as the substrate. A single mold has 64 (8X8) arrays, each with a 750 micrometer diameter.	Low pressure was used in a static procedure to produce the elements. Process parameters included force, temperature, and time. White light interferometer was utilized to assess the quality of the manufactured components.	The ideal values were Fs = 1.02N for force, Ts = 518 C for molding temperature, and 120 min for molding duration. Observations for a 1300 nm light wave length and a 10 mm focal distance.
3	R. Stepien et al, 2013 [29]	Fabrication and characterization of microlenses made of tellurite and heavy metal oxide glass developed with hot embossing technology.	Using ion etching technique, quartz glass was used to fabricate the molds. A single mold held 64 (8 × 8) lenses array, each measuring 750 μm in diameter. The substrate was made of tellurite glasses and lead bismuth gallium oxide .	At a wavelength of 1,300 nm, measurements of the curvature in mm and focal length in mm were made. A precisely regulated temperature, the force of pressure and dynamics, the time it takes to stop the stamp and the rate at which it retracts from the surface are among the important process characteristics.	For PBG08 and TWPN/I/6 glass, an optimum emboss temperature was determined to be 544 ◦C and 446 ◦C, respectively. In both of the cases, a constant imprinting pressure of 32 bar was applied. Extending the Hot Embossing process duration beyond two hours results in the sample sticking to the mold, making it impossible to separate.
4	Hsiu-Ju Hsu et al., 2013 [30]	Fabrication of High Resolution Microstructures Using Micro Hot Embossing with a Precision Rapid Tooling.	The epoxy resin mold was made using epoxy resin composite, and the substrate was commercially available Polymethylemethacrylate. The experiment's Rapid Tooling material was at room temperature vulcanization - silicon rubber .	For two hours, the temperature in the part that was green was raised to 79 °C. After temperature was raised from 79 °C - 149 °C, it maintained there for three hours. At last, a completely dense hybrid RT has been developed. To form a silicone rubber mold free of bubbles, air bubbles created during mixing of the silicone rubber with the curing agent were extracted using a handmade vacuum machine.	In the quick tooling production process, the transcription rate is around 92.5%. In the molded component, the transcription rate is around 95.1%.Using a combination of rapid tooling technique can result in a 60.4% cost decrease when compared to the standard way for creating one pair of rapid tools of a new DOE.

5	Kui Liu et al, 2014 [31]	Roll-to-roll embossing of optical linear Fresnel lens polymer film for solar concentration	The brass roller mold measures 235 mm length and Ø170 diameter. The substrate was polycarbonate, and it was processed employing a tool made from a single natural diamond crystal having a 40þ included angle and a nose radius = 12.7 µm.	The high-precision roller mold that was manufactured was put on a Roller to roller ultraviolet embossing equipment that the researcher had created. Tungsten carbide is utilized to make stylus tip, It has an included angle of 45p and a tip radius of 20µm. , which is utilized to determine lens profile.	In this test, four distinct pneumatic pressures—0.5, 0.6, 0.65, and 0.35 bars—were used to determine the optimum pressure. The Fresnel lens was developed. to feature 166 number (2 × 83) prismatic rings with an average Width of 55.6mm and a uniform ring height 100µm.Focal distance of 82.5 mm was designed.
6	Ying Jie Wang et al, 2014 [32]	Development of a Micro-Hot-Embossing Mold with High Replication Fidelity Using Surface Modification	With the use of a low temperatures plasma system and a Polymethylemethacrylate substrate, The first mold for silicone rubber was surface modified with goal of creating a precise epoxy resin mold that may be manufactured without the need of a releasing agent	The silicone rubber mold's surface was effectively altered using low-temperature plasma, and The silicone rubber mold's surface was modified using an 80W power source and a 5-minute exposure period. The epoxy resin used in the mold was cured for. 3 hour at 149 C after 2 hour at 79 C.	By using this finding, a Fresnel lens capable of up to 99% transcription rate may be produced. With a precise epoxy resin mold, surface roughness may be improved by up to 46.2%. The transcription rate that is as high as one hundred percent cannot be achieved due to the estimated 0.2–0.6% shrinking of PMMA films.
7	Ireneus Kujawa et al, 2014 [33]	Optimization of hot embossing method for development of soft glass microcomponents for infrared optics	For metal stamps, brass 58 & steel 1H18N9T were utilized, while glass made by fused silica s was employed for non-metallic stamps. Lead-silicate was used to create 1.7 millimeter diameter and 10 millimeter focal length lenses. glass LW-1 in a duration of one minute.	Following heating rates were used: 9.5 C/min (with the temperatures ranging from 22 to 455 C) along with 5.0 C/min (with the temperature ranging from 456 to 590 C), and 3.0 C/min (with temperature ranging 591 to 605 C/min). Piston's pressure force was 1.47 kN, or 150 kG. About 120 minutes were spent cooling in total."	The outcomes at a rate of heating of 5 C/min and a rate of cooling of 1.5 C/min. Outer layer of the material was first heated to 460 C over 90 minutes prior to testing. Glass that is both mechanically and thermally stable and has a broad transmission range of visible to up to the mid infrared 6 µm, has been successfully created.
8	B.-C. Chen et al, 2015 [34]	Optimization of hot embossing molding process parameters of Fresnel lens using Taguchi method.	The molding material consisted of 0.8-mm-thick PMMA (Polymethylemethacrylate) sheets measuring 3 cm by 3 cm. Silicone rubber and epoxy resins packed with aluminum were used as the substrate. The manufactured hot embossing tool has an exact replication quality of around 98%.	In order to examine how HE process parameters, affect the Fresnel lens transcription rate, a L9 (34) orthogonal array was created using the Taguchi approach. Four variables were employed as control factors: pressure holding duration, demolding temperature, hot embossing temperature, and hot embossing pressure.	HE pressure equal to 83 kgf/cm2, hot embossing temperature that is 155 °C, hot embossing duration of 6 min, and demolding temperature that is 55 °C are the ideal hot embossing moulding parameters for the process. With the ideal hot embossing molding process parameters, the depth of transcription rate of the embossed component may be increased by around 7.8%."

9	X. Q. Zhang et al., 2015 [35]	Fabrication of linear Fresnel lens using UV embossing and a micromachined roller mold.	By employing roll to roll Ultraviolet embossing to transfer features from mold to plastic flexible substrate and ultra-precision diamond tuning machine for the mould manufacturing, optic film containing linear arrays of Fresnel lens have been created.	Each Fresnel lens was made up of 166 small prisms with an identical 0.1 mm feature height to the design of the roller mould used to create the Fresnel lens array, which produced 82.5 mm of focal length.	Using a solar simulator system, the lens film created across a vast area showed a significant concentrated light effect, increasing light intensity by more than six times. A tool known as a profilometry is used to measure the lens profile on optical film and assess the light concentration impact.
10	H. Ottevaere et al, 2015 [36]	Optical quality study of refractive lenses made out of oxide glass using hot embossing.	The adoption of a both side hot embossing technology enables lower cost and lower volume lens reproduction. From commercially available concave lenses, the necessary mold shape that is, negative of the each lens surface was chosen, and oxide glasses are utilized as the substrate.	In Process 1, the optimum process parameters were the temperature of molding was 468 C, rate of heating was 5 C/min, with a force of 1.22 N along with molding time of 80 minutes. Secondly, to continue with Process 2 and lower the forming time was 5 minutes by the applying pressure equivalent to 200 N. Additionally, the production time is cut in half, from 210 to 135 minutes.	Under typical operating circumstances, lenses having radii of curvature as big as 8 mm but an overall Dia measuring 4.5 mm may be produced (without vacuum). The temperature at which the glass element was formed was the most crucial aspect. relative to the surface that is more convex, the flatter surface has been replicated with better repeatability (the FWHM is equal to 0.076 millimeter and the FWHM is equal to 0.125 millimeter, respectively).
11	I. Kujawa et al, 2016 [37]	Fresnel lens fabrication for MidIR optics and fiberoptic technique by using hot embossing process	Tellurite glasses and lead-bismuth-gallium oxide were utilized as substrates, while fused silica was employed as a mold.	used the HE technique and repeated element replication experiments at varying pressures which is 1.02N to 1.34N and processing times that is up to 2 hours with temperature changes.	Method at 518°C with an embossing force of 1.02 N, working for 120 minutes, yielded the best replication results out of the 6 types of glasses examined. 5 component lead bismuth gallium glass, designated PBG08 was the selection.
12	Giuseppe A. Cirino et al., 2016 [38]	Assessment of replication fidelity of optical microstructures by hot embossing.	Optical component was replicated using PMMA, Plexiglas® V825 is the commercial name and mold insert was made on nonferrous 99.9% pure electro less copper using a single point diamond turning equipment.	A concentrative, closed-loop Cyl MLA design has been used. Optic lens was intended to have an f-number of 6.67, a diameter of DL is equal to 3 mm, and a focal length of FL is equal to 20 mm. While hot embossing, pressure, temperature, and time were used as the process variables.	Regarding applications in the spectrum of visible light, surface optical quality with a resultant root mean square roughness of the surface per a minimum of a tenth of wavelength was found. At 150 bar of pressure, the best replication outcomes in both micro and Nano scaling were achieved. Regarding mold measurements, The width of the ring and the height of the lens varies by 0.45% and 1.08%, respectively, between mold & the replica.

13	A. J. Waddie et al, 2016 [39]	Development of glass microoptics for MidIR with hot embossing technology	Selected steel and brass molds, pure silica molds, and specially made heavy metal oxides glasses with a large transmission range that were utilized as substrate all performed at their best. Created 200µm-diameter Fresnel micro lenses and one-dimensional and two-dimensional diffractive gratings having a minimal feature size of 5µm.	a number of Heavy Metallic Oxide glasses varieties that are appropriate for infrared and visible wavelengths, and confirm that they are suited for the hot embossing technique. Temperature: 607°C, Warming Time: 85', Force: ~1.47 kN, Stamping Time: 2x30"	Replication technique for diffractive Fresnel optics was enhanced through the creation of diffractive as well as refract micro optical components for Mid-IR applications. That resulted in a shrinking of less than 10% with extremely acceptable surface profile replication.
14	M. Worgull et al, 2016 [40]	Replication of optical components by hot embossing	HE produces microstructures with reduced internal stress, making it ideal for replicating components that are sensitive to stress when needed, such as in optical applications. Granules of polymer are utilized as the substrate in place of a polymer film.	Using combined hot embossing and thermoforming to achieve a prominent structure offers an innovative opportunity for micro replication. Optical wave guides having a cross area of around 10x10µm² were created in PMMA.	Low shear velocities in the compression phase lead to reduced shear stresses and little residual stress in the molded components. The compression stage is characterized by low molding velocities. It has been noted that buildings with a high aspect ratio work well with this method.
15	Teng-Sheng Chiang et al, 2016 [41]	Development of a precision hot embossing tool with microstructures for microfabrication.	It is possible to acquire transcription rates that have the breadth and depth of around 97.3 and 95.7%., Composites constructed of epoxy resin used as the hot embossing tool. while the elastomeric mold was made of silicone rubber.	The master model chosen to create. The plastic Fresnel lens used for hot embossing .Embossed temperature had been fixed at 120 °C, the embossing force was 900 N, the holding duration of 10 minutes are the process conditions for micro HE molding.	The HE tool's surface flatness may be increased by about 46.38%, and costs can be decreased by about 69.61%. The main model, initial silicone based rubber mold, following silicone rubber mold, the HE tool, and their corresponding Ra values are 1.52, 3.45, 11.9, and 59.9 nm.
16	Xinquan Zhang et al, 2017 [42]	Rotating-tool diamond turning of Fresnel lenses on a roller mold for manufacturing of functional optical film.	Flexible polyethylene terephthalate sheets are utilized as the substrate, and both the linear as well as radial lens arrays on brass roller serves as a mould. In the Roller to roller embossing method, material shrinking throughout UV curing is taken into account and compensated for.	Surface finish and facet angle deviation are measured using Roller to roller UV embossing. When it comes to diamond turning, feed rate and nose radius are considered to be the key process parameters that determine surface finish.	The length of the arc and lens diameter are the two machining parameters indicated to be crucial in influencing the integrity of the surface and finish of a the diamond turning procedure using a 4 axis rotating tool after theoretical analysis of the dynamic issue.
17	C.-C. Kuo et al, 2019 [43]	A cost-effective method to fabricate micro-featured mold for microstructures replication.	A micro featured mold insert measuring 70 mm by 70 mm and 15 mm thick was manufactured. PMMA was employed as the substrate, and silicone rubber served as the mold.	When using a hybrid approach to create a micro feature mold insert, thermal conductivity is greater than when using conventional techniques. Replication takes total 5 hours at a	The embossed portion has a transcription rate of around 95.1%. A 60.4% cost decrease over the conventional technique was attained. Using this method, superior accuracy optical elements with the roughness measurement

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				maximum temperature of 149 °C.	of 1.5 micrometers are produced.
18	Manfeng Hu et al, 2020 [44]	Theoretical and Experimental Study on Hot-Embossing of Glass-Microprism Array without Online Cooling Process.	Between the theoretical and experimental values, there was a good agreement, with the difference of 12% and the standard deviation of 7%, respectively. K9 optical glass, measuring 15 x 15 x 1 mm, was utilized as the substrate, while silicon carbide served as the mold.	Low strain rates were obtained without the need for an online cooling procedure. The parameters that were established were the embossing force of the 0.335–0.835 N and holding time duration of 8–12 minutes, and embossing temperature of 560 to 710 centigrade.	The optic glass substrate cracked when the, force and temperature of embossing were high. possibly as a result of uneven thermal stress. Using an embossing temperature equal to 630 C, an embossed force equal to 0.335 N with a holding period equal to 12 minutes, 66.56% was the highest experimental formation rate.
19	joão Paulo Colafemina et al, 2021 [45]	Hot embossing of aspherical Fresnel microlenses: design, process, and characterization.	A specialized single point diamond turning process crafted the mold used in the experiment. A copper mold was produced and a Polymethyle methacrylate substrate served as the workpiece.	A micro hot embossing process was conducted utilizing a micro machined mold to replicate convex-plane PMMA lenses. Measurements found the areal average surface roughness (Sa) of the lenses produced to be 4.92 nm. Additionally, the areal root-mean-squared roughness (Sq) was quantified at 6.04 nm.	Replicating high-fidelity complex microstructures required minimal surface roughness outcomes, recover of viscoelasticity is a characteristic inherent to the polymers which was difficult to regulate or eliminate.
20	Ai Jiang SEXTON et al, 2021 [46]	Investigation of non-imaging Fresnel lens prototyping with different manufacturing methods for solar energy application.	A PMMA acrylic sheet and a steel masters mold were utilized. A linear lens measuring 90 mm by 120 mm was created, including a 5 mm average thickness and 38 grooves with the 3 mm width difference, and a 240 mm of focal length.	A steady temperature of 193°C and 10 to 15 tons of pressure were employed in this process, which was then cooled to a temperature of between 66 and 82°C with 10 tons' constant pressure. The lens took ten hours to fabricate in total.	A 40% improvement in efficiency was attained, and total efficiencies exceeded 1.84% when contrasted with other methods. The performance of hot-embossed Fresnel lenses in terms of solar concentration may also be impacted by the variation in geometry.
21	Swarup S. Deshmukh et al, 2022 [47]	Microlens array through induction-aided hot embossing: fabrication, optimization, and characterization.	For manufacturing, a hot embossing setup with induction assistance was developed. A mold was created using a PMMA sheet as the substrate and a laser-engraved, P20 steel plate polished by diamond, measuring 50 x 50 mm in front and 15 mm thick.	HE temperature, pressure with embossing time, and de-embossing temperature are examples of the process parameters. A laser engraving procedure was used to create a 30 x 30 array of micro holes with an 250 µm outer diameter and 400 µm pitch on a top of P20 plate of steel	It was shown that as Te rises from 120^{o}C to 130^{o}C, the diameter deviation decreases form the 27.12 µm to the 23.63 µm. Te's contribution is 44.63%. The ultimate optimization outcome shows that TLBO outperforms the CD. The TLBO approach predicts a deviation in diameter of 15.83 µm at optimal conditions, this is consistent with the experimental findings of 16.57 µm at optimal conditions.

22	Bruno M. C. Oliveiral et al, 2022 [48]	PMMA Lens Arrays for Micro Concentrator Solar Cells Produced by Hot Embossing.	low-cost array manufacture of spherical lenses with a diameter of 1 mm in accordance with the specifications of micro concentrator solar cells. In this study work, three distinct molds, including Brass, DIN H56-5-3-8, and DIN 1.2083 were utilized with PMMA substrate.	PMMA disks were embossed using a basic compression technique and an infrared light heat chamber. After applying the heating rate of 10 °C per minute, the arrays of lenses were hot embossed about 170 °C Over 20 min of holding times. System was subsequently allowed to cool over 10 minutes before the lens array was demoulded.	Using a mould insert created via micro Electro Discharge Machining (with the Ra & the Rz readings of 0.6 and 4.58μm respectively), an especially acceptable lens array was obtained. The most dimensionally exact cavities could be produced with micro-EDM, with a maximum depth variation of only a few micrometers.
23	Rafal Kasztelanic et al, 2023 [49]	Mid-infrared ZBLAN glass optical components made by hot embossing technique	ZBLAN was employed for a substrate in hot embossing for the first time, and M58 brass was utilized as the mold. ZBLAN fluorite glass may be used to create reasonably priced passive optical components that have a large transmission window spanning from the ultraviolet to the mid-infrared spectrum.	The glass's adhesion to stamp was eliminated by ZBLAN glass's low transition temperature. The plan convex lens is obtained with a sag of s = 1.143 mm, a useful diameter of 10 mm, and a curve radius of 11.50 mm. by forming the lens curvature using diamond turning.	The ideal hot embossing methods were achieved in about 3 seconds at the 449°C with an applied force equal to 33,85 N. Ra = 77 nm was the lower value of surface roughness. With a 10 mm diameter and a 30.0 mm (f#=3) focal length, the test lenses may attain resolutions equal to 23 lp/mm for 1.5 μm and 8 lp/mm with broadband heat sources radiating in 3–5 μm range.

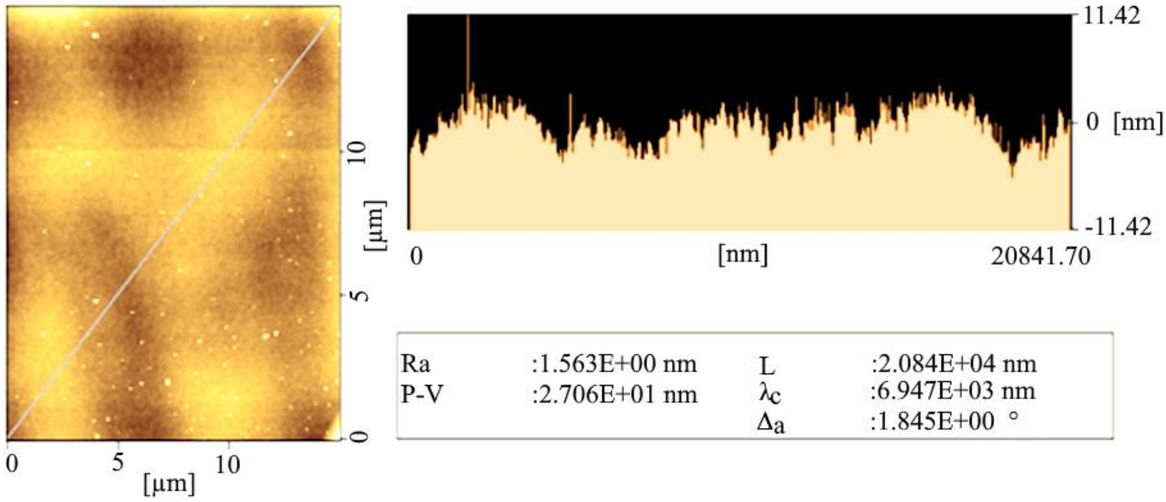

Figure 6. Surface Roughness of Manufactured Micro-Optic Surface Profile [50].

The microscopic image in the Figure 7b reveals the presence of small crater-like deformations called pit and debris and scattered particulate matter on surface of glass microprism array. Deformations appear to have a circular morphology at their central regions, while exhibiting irregular shapes along their outer edges on the glass microstructure. Copypotentially resulting from uneven thermal stress. Previous research indicates that the excessive forming stress and the residual stress can lead to development of the glass cracking. Precise control over embossing temperature and force is crucial for mitigating these defects [44].

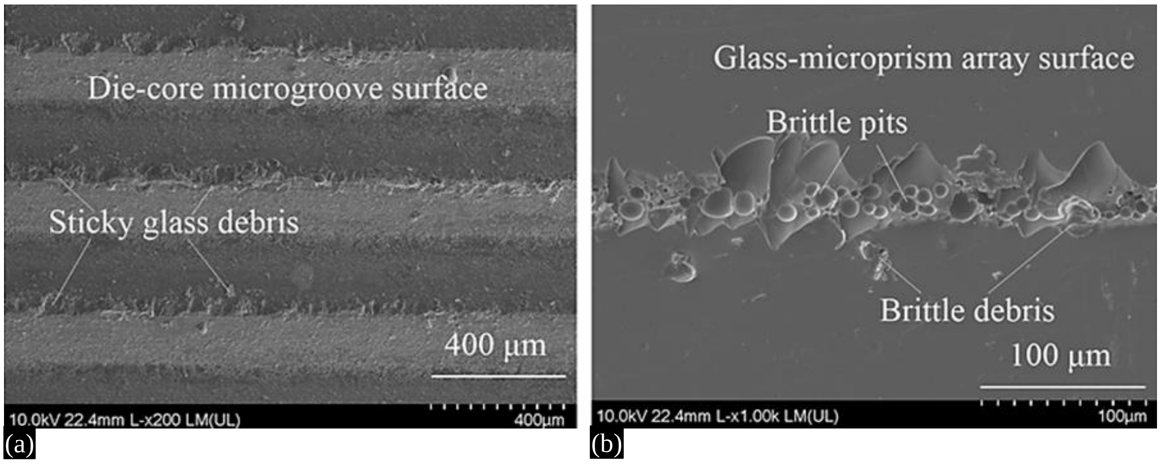

Figure 7. Forming defects during the HE Glas microprism array process: (a) Glass debris (b) Brittle Pits [44].

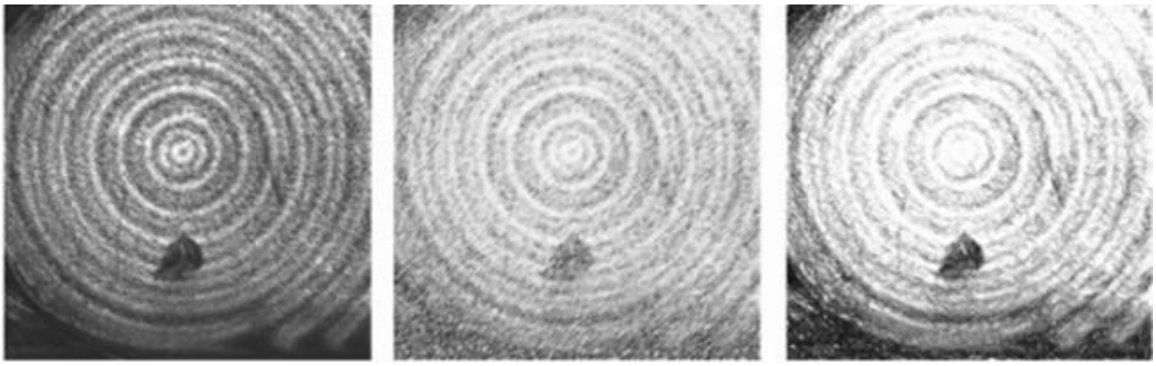

Figure 8. Defect images of various contrast and texture generated with Cycle GAN [51].

Figure 8 displays a selection of images produced using Cycle GAN. By incorporating images generated through Hybrid Cycle GAN and geometric augmentation techniques, the image dataset can be significantly expanded. This expansion enables a broader range of images to be provided as input to the deep convolutional neural network during the training process, enhancing its ability to learn and generalize effectively [51].

CONCLUSION

As discussed, micro hot embossing shows potential as a technique for fabricating complex micro-optics such as Fresnel lenses. The process can replicate precise, tiny grooved patterns from a master mold into optical thermoplastics accurately and cost-effectively for small batches. Key strengths over alternatives are lowered residual stresses and distortions. However, there are still opportunities for better grasping how parameters around heating, pressure, timing, cooling and tool design affect replication fidelity, as this method transitions from academic research toward industry adoption. Ongoing progress in optimizing processes, materials and applications will enhance micro hot embossing capabilities and flexibility for advanced optics manufacturing. By building on current understanding and pushing innovations in this emerging fabrication approach, researchers can unlock further versatility in producing intricate, high-performance diffractive optics. The key aspects of this topic that warrant attention are:

- *Diverse Substrates and Molds:* The studies highlight the use of various substrates and molds, including tellurite glass, lead-bismuth-gallium oxide, silicon rubber, and ZBLAN fluorite glass, showcasing the adaptability of hot embossing for different materials and applications. While PMMA was commonly used, there's potential to expand research into other polymers and glass types, especially for specialized applications like mid-infrared optics.

- *Optimal Process Parameters:* Various studies have determined the optimal process parameters for HE, including temperature, pressure, and embossing time. For instance, the ideal hot embossing temperature ranges from 150°C to 710°C, depending on the substrate and mold used.
- *High Replication Fidelity:* The replication fidelity of microstructures is a critical factor. Several studies achieved high transcription rates, such as 95.1% to 99%, indicating the efficiency of the HE process in accurately replicating intricate microstructures. but there's still room for improvement, especially for more complex microstructures.
- *Surface Quality and Stress Reduction:* The research highlights the importance of achieving excellent surface quality with minimal residual stress. For example, using combined hot embossing and thermoforming can lead to low residual stress, and adopting techniques like UV embossing can further enhance surface finish.
- *Cost-Effectiveness:* Several studies focus on the cost-effectiveness of the HE process. For instance, rapid tooling techniques and hybrid approaches can lead to significant cost reductions compared to traditional methods.
- *Challenges and Optimization:* Issues such as material shrinkage, sticking to molds, and the need for precise temperature control are noted as challenges. Optimization of parameters like embossing temperature and pressure is crucial to mitigate these issues.
- *Innovative Techniques:* The development of new methods, such as roll-to-roll embossing, UV embossing, and induction-aided hot embossing, showcases the continuous innovation in the field to improve efficiency and quality.

Scope of Future Work Areas

Future research should focus on further improving replication fidelity, reducing material shrinkage, exploring new materials and substrates, and enhancing the cost-effectiveness and scalability of the HE process. Further work could explore adaptive or AI-driven optimization techniques. Some other points are also mentioned here.

- *Focus on Mid-IR Applications:* The use of materials like ZBLAN and heavy metal oxide glasses indicates a growing interest in mid-infrared optics, expanding the application range of hot embossing techniques, more works are needed on this area.
- *Scale-up and mass production:* Most studies focused on small-scale production. More research is needed on scaling up to industrial levels while maintaining quality.
- *Novel applications:* While many studies focused on Fresnel lenses, there's potential to explore other optical components and applications, particularly in emerging fields.
- *Characterization techniques:* Some studies combined HE with other techniques (e.g., UV curing, thermoforming). Further exploration of hybrid processes could yield innovative manufacturing methods.
- *Simulation and modeling:* More sophisticated models to predict embossing outcomes could help streamline the optimization process.
- *Sustainability:* Future research could focus on making the hot embossing process more environmentally friendly, including the use of biodegradable materials and energy-efficient methods.

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