Design and fabrication of micro imaging lens for biomedical applications

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Design and Fabrication of Micro Imaging Lens for Biomedical Applications

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Abstract

In this research, a hot compression molding apparatus was designed and fabricated for production of polymer micro stand-alone lens. The fabricated lens can be installed easily on the tip of a fiber optic for imaging purposes. FEM (Finite Element Method) simulation of the forming process was conducted to optimize the processing parameters and to predict the behavior of polycarbonate (PC) under different molding temperatures. The results of FEM simulation were then used to compare with actual experimental results. Design of experiments was used to locate the actual feasible molding window. After the set of process parameters was found, a statistical model was used to study the effect of processing parameters on the optical and geometrical properties of the molded lens. The lenses were put through a series of optical characterization tests to examine whether the lenses are suitable for the intended applications. The optical characterization include: (1) focal length and focal spot size, (2) the white light imaging efficiency and (3) the fluorescence collection efficiency and fluorescence imaging ability.

It was found that the best lens can be molded at temperatures slightly above T_g (e.g. 170°C), with high compression velocity of $300\text{ }\mu\text{m/s}$ and demolding temperatures of 50°C . The fabricated lens has focal length of 1.3mm and focal spot size of $25\mu\text{m}$ which is suitable for probe imaging and microscopy. The lens is also able to image the micro spheres with approximate size of $4\text{ }\mu\text{m}$ which make it suitable to image human epithelial cells which are usually $5\text{--}15\text{ }\mu\text{m}$ in diameter.

Dedicated to my wife and my parents

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List of symbols

Symbol	Description	Page
ε	Strain	23
$\dot{\varepsilon}$	Strain rate	23
σ	Stress	23
E	Elastic modulus	23
η	Viscosity	23
t	Time	24
τ_{∞}	Stress relaxation time coefficient	24
ω_i	Weighing factor for each Maxwell element	24
a	Distance between the centre of the cooling hole and mold surface	40
b	Diameter of the cooling hole	40
d	Distance between the cooling tubes and the mold cavity wall	40
$\dot{m}$	Water mass flow rate	40
$\dot{V}$	Water volume flow rate	40
$\Delta\theta_w$	Water temperature change in the mold	40
ρ	Density of the water	40
c_w	Heat capacity of water	40
$\dot{Q}$	Heat transfer rate in the mold	40
M	Mass of the die	41
C	Heat capacity of the mold material	41
$\Delta\theta_m$	Mold temperature change(difference between molding temperature and de-molding temperature)	41
V	Velocity of the compression test device grippers	56
L	Length of the compression samples	56
U	Strain energy per unit of reference volume	60
C_{i0}	First temperature dependent Yeoh parameter	60
D_i	Second temperature dependent Yeoh parameter	60
$\bar{\lambda}_i$	Deviatoric strain	60
λ_i	principal stretch	61
J	Total volume ratio	61
J^{el}	Elastic volume ratio	61
J^{th}	Thermal volume ratio	61
ε^{th}	Linear thermal expansion strain	61
$G_R(t)$	Shear modulus	63
G_0	Initial shear Modulus	63
$\bar{g}_i^p$	Material relaxation constant	63

S/N	Signal to noise ratio	90
n	Number of total experiments	90
μ	Average of one response variable	90
y_i	The value of the variable “ y ”at step “ i ”	90
σ	Standard deviation of the results	90
S_T	Total variation of response variable “ Y ”	90
X_k	sum of result when parameter “ X ” is at level “ k ”	90
S_x	Change of one response variable with respect to the particular factor “ X ”	90
N_{X_k}	Number of results when parameter “ X ” is at level “ k ”	90
f	The focal distance	103
R	The radius of curvature	103
n	Refractive index of the lens	128
C	Stress-optic coefficient	128
I	Intensity of light wave	129
Δ	The phase retardation between two polarized light	129
α	The angle between axis of polarizer(or analyzer) and direction of principal stresses	129

List of Abbreviations

Abbreviations	Explanations	Page
FEM	Finite Element Method	2
DOE	Design of experiments	5
PC	Polycarbonate	6
PMMA	Poly(methyl methacrylate)	6
RMS	Root mean square	7
HPHT	high pressure high temperature	10
TIR	Total internal reflection	13
OA	Orthogonal array	19
T_g	Transition temperature	20
MIT	Massachusetts Institute of Technology	24
SEM	Scanning electron microscopy	26
AFM	Atomic force microscopy	26
SAN	Styrene acrylonitrile	33
TPX	methylpentene	33
WC	tungsten carbide	35
SiC	silicon carbide	35
AlN	aluminum nitride	35
TiN	titanium nitride	35
Al ₂ O ₃	aluminum oxide	35
TiC	titanium carbide	35
T_m	Melting temperature	43
NA	Numerical aperture	49
WLF	Williams-Landel-Ferry	63
FES	Finite element simulation	82
PC	Personal computer	109

CHAPTER 1

INTRODUCTION

1.1. Motivation

Over recent years, micro devices have been widely used in many industries and researches. In medical field, desire of surgical operations with minimal pain and also need for micro imaging devices such as endoscopes made many researchers work on design and fabrication of micro optical elements. The need for finer structures makes researchers look for new fabrication techniques. Micron size lenses and microlens arrays are also new products attracting the attention of the scientific community for their possible outstanding applications. Wide applications of microlens arrays and stand-alone microlens for arrayed device coupling and parallel optical image processing have been developed. The arrayed micro optics technology would be very helpful for advanced ultra-parallel optical systems. Although there are a large number of literatures on microlens array fabrication and characterization, fabrication of stand-alone microlens is not studied widely.

In this study, the fabricated micro imaging lens is to be installed on the tip of an imaging fiber for biomedical applications. In most cases, ball lenses fabricated by liquid techniques are micro-assembled and glued onto the V-groove of a fiber optic for such purpose[1]. There are studies on fabrication of micro imaging lens on the tip of an imaging fiber by lithographic techniques[2],[3] and Laser[4], However, both methods are slow and unreliable. Some researchers have studied hot compression molding of polymer powders[5], compression molding of glass lens[6] and injection molding of polymer lens[7].

Nevertheless, production of polymer stand-alone microlens which can be assembled easily on the tip of an imaging fiber remains a challenge for researcher.

1.2. Objectives

The main objectives of this project are:

- (i) Design and fabrication of a hot compression molding set-up for the fabrication of stand-alone microlens and
- (ii) Optimization of stand-alone microlens fabrication parameters for optical fiber probe application

1.3. Scope

The scope of the works in this study includes:

- State-of-the-art literature review on lens fabrication techniques and related concepts.
- Development of hot compression molding set-up.
- Material characterization and FEM (Finite Element Method) simulation to find optimum processing condition (better replication, lower residual stress).
- Design of experiments: experimental investigation to fabricate the best possible lens and find the optimum process conditions.
- Geometrical and optical characterization of molded microlens.
- Study on the imaging applications of the molded microlens.
- Comparison of the developed compression molding method to often utilized fabrication methodologies.

1.4. Research road map

In this research, a compression molding machine suitable to fabricate stand-alone microlens will be designed and developed. Parallel to this work, material characterization of the molding material will be conducted. Material characterization and simulation of deformation behavior under different molding conditions form the theoretical part of this research. The design and development of the machine, samples preparation, lens fabrication, optimization and characterization of the microlens form the experimental part of this research work. These two parts are connected together when the results of the simulations are verified by experimental results. Figure 1-1 shows the research road map of this study.

Figure 1-1: Research road map of this study

1.5. Thesis organization

This thesis covers a complete study on the fabrication, analysis and characterization of stand-alone microlens. This chapter contains motivation, objectives, scope of work and the research road map. Chapter two covers literature review on microlens fabrication techniques,

CHAPTER ONE

thermoforming process simulations and characterization techniques. Chapter three discusses the design and development of the micro molding machine. Chapter four discusses the fabrication mechanism and operation sequences. Chapter five covers FEM simulation of thermoforming of stand-alone polymer microlens under different processing conditions and its optimization. Design of experiments was performed to optimize the process experimentally and a statistical model was used to analyze the effect of processing variables on lens quality. These works are reported in chapter six. Chapter seven covers lens characterization. Chapter eight concludes the research work and provides suggestion for future work.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction to microlenses and fabrication techniques

This chapter surveys microlens fabrication techniques, fiber optics, DOE (Design Of Experiments) technique, characterization of the molding material, FEM simulation of thermoforming processes and microlens characterization techniques.

Although there are many techniques to fabricate microlenses, all these techniques fall into four major categories: (1) Direct machining, (2) Molding techniques, (3) Lithographic techniques and (4) Direct printing. The following sections survey these methods and discusses on their advantages and disadvantages.

2.1.1. Direct Machining of lenses

Traditional lens fabrication methods have been utilized to fabricate very accurate microlenses in different sizes. Machining of brittle materials such as glass and silicon is possible today by mean of ductile mode machining of brittle materials first established in the United States[8].

Machining of optical element is a multi-step method briefly described below:

- Rough shaping: the initial blank is manufactured to a size within the few hundred micrometer of the final dimension.

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- Support: the optic must be held for subsequent operations. Many difficulties arise here related to the equipments required, make it very difficult to fabricate microlens.
- Generating: The blank is machined to within 100- 500 micrometers of the final dimensions.
- Fining: the optical surfaces are ground to improve surface quality.
- Polishing: the optical surfaces are polished providing a very smooth surface suitable for optical applications. It has been shown that extremely precise surfaces with an accuracy of approximately 7 nm and surface finish in the range of 0.5-2 nm can be generated using Ion beam polishing[9].

Although glass was commonly used for more accurate optical devices, recently polymer lenses have become more popular, simply because they are lighter, cheaper, and easier to process. Polymers such as PMMA(Poly(methyl methacrylate)) and polycarbonates(PCs)[10], with very high refractive index, have been developed. Moreover, an aspherical surface is often used to achieve better imaging performance and to reduce number of elements in an optical system. Aspherical optics can be fabricated with polymers relatively easy.

One of the weaknesses of direct machining is that it's not suitable for polymer lenses as the heat generated by machining is too high for polymers to withstand. Another disadvantage is that it's an expensive and also time consuming process. In addition to the complexity of the machining process, direct machining is highly sensitive to the manufacturing environment, with strong dependence on the positioning accuracy of the machine, the condition of the grinding wheel and vibrations in the system. All these factors result in an increase in process time which is sometimes estimated to be days and even weeks[11], but they are good for machining of glass as long as very accurate surface texture and smooth surface are needed.

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Micro machining of lenses suffer from weaknesses such as limited flexibility, low production rate and high cost. For instance, the price of the product would be twice if a high precision lens with RMS (Root Mean Square) roughness of less than 5 angstrom is required.

2.1.2. Micro molding

Polymer molding processes can be categorized into the following four major groups: injection molding, reaction injection molding, hot embossing and injection compression molding[12]. The injection molding process involves the injection of molten polymer into a mold where the melt cools and solidifies to form a plastic part. It is generally a three-phase process including filling, packing and cooling phase. After the cavity becomes stable, the product is ejected from the mold. Injection molding of lenses is not widely studied but there are reported experimental studies and stress analysis [7].

Despite many advantages, the injection molding process experiences some inherent problems in molding micro-features. The main difficulty is that the molten polymer in a tiny cavity instantaneously solidifies upon touching the relatively cold cavity wall. The problem gets worse when micro-features with high aspect ratios are to be molded. The best replication results were achieved when melt and mold temperatures were higher than normal values.

Reaction injection molding is a process exactly like injection molding except that the material is a thermoplastic which require a curing reaction which occurs inside the mold[13]. First, the two parts of the polymer are mixed and then are injected into the mold under high pressure. A device called impinging mixer is used for such purpose. The mixture remains in the mold long enough for it to expand and cure[14]. This process also suffers from inherent problems of injection molding process mentioned above.

In hot embossing method, a sheet of thermoplastic material suitable for optical use such as polycarbonate or PMMA is heated so that it softens sufficiently to allow it to be permanently deformed (Figure 2-1). The heated sheet is then pressed against a material that has one or more apertures, such that the softened lens material forms a protrusion at each aperture. Hence an individual lens or lens array can be made, and by changing the embossing temperature, pressure, and holding time, the radius of curvature of the lenses can be controlled [15, 16]. Recent development in hot embossing mechanisms results in fabrication of high precision diffraction optical elements with features smaller than 400nm[17].

Figure 2-1: Schematic representation of hot embossing process

The sequence of injection compression molding process is similar to that of injection molding except that it involves additional stroke of clamping unit after mold filling stage. At first, the mold closes. The material is then injected to 80-85% of the cavity which is equal or more than the final volume of the finished product. The mold is then further compressed simultaneously or sequentially. It follows a post compression (if required), cooling, opening and ejection. This process has several qualitative advantages over injection molding such as reduction in injection pressure, clamping force and cycle time and improved hold pressure effect which often reduces sink marks and warpage. This process finds applications in thin walled packaging, optical parts and foam products [18].

2.1.2.1. Micro mold

Although stainless steel can't be used as mold material for glass molding because iron may diffuse from mold to material and reduce the optical performance of the product as well as mold life time, advantage of stainless steel is that it does not adhere to polycarbonate, so that the molded part can simply be de-molded from the die without damage. In hot embossing, the curved surfaces of the lenses have not been in contact with any solid surface and surface tension is what controls the lens profile[16].

Many different processes have been utilized to produce micro molds. Methods such as micro machining, different lithographic processes such as X-ray and electron beam lithography and UV lithography, Dry etching, plasma etching, deep electron irradiation, ion beam assisted radical etching and also EDM processes[12].

One widely used technique to produce micro molds of injection molding is lithography. Lithography is a three steps process. The first step in most of lithographic processes is exposing a thick layer of resist, through a patterned mask, to some kind of energy (can be photons, electrons or ion beams). Chemical changes into the resist make it possible to etch the patterns into the resist substrate by the use of chemical etchants or different energy sources.

The pattern or negative image of the pattern is replicated (depending on whether the resist is negative or positive). Certain metals or other materials are then electroplated onto the resist mold[19]. After removing of the resist material a free standing metal structure is produced. The structure can be used as a mold in injection molding. The product has the same shape, size and form of the original resist or deposited metal structure but is produced much faster

and cheaper. Most of lithographic processes made mention above are also utilized to produce microlenses directly and will be discussed below.

2.1.3. Lithographic techniques

The principle of fabrication of optical elements by lithographic techniques is the same as mentioned above. Some works on the feasibility of electron beam lithography to produce microlenses have been conducted by Fujita and Borelli[20, 21]. They show that this technique can be used for fabrication of even special types of lenses.

The feasibility of producing microlenses via lithography by ion beam milling has been studied by Xin Jian et al. [22]. Preparing a photoresist shape by melting process or any other process and transferring the shape onto a substrate (usually silicon) using wet or dry etching is the principle of the process.

Deep proton irradiation is the other famous method utilized by Kufner et al. [23]. The process consists of these basic steps: PMMA substrate is irradiated and then the irradiated area is developed or swelled by organic vapor. The original development step can be combined with a swelling procedure to fabricate microlenses. The substrate is subjected to both techniques to achieve high mechanical stability and high accuracy of alignment.

Different lithographic techniques mentioned above have been mostly utilized to produce micro insert dies for micro injection process but lithography and also etching processes could be used to produce directly the final product such as producing diamond lenses through etching which was done by Lee et al. [24] for the first time and briefly described here.

Etching of micro diamond lenses resulted in only a small deviation from a perfect spherical surface and the RMS (root mean square) roughness of the lens surface is 15 nm in a

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3*3mm area. This is due to the intrinsic defects in the HPHT (high pressure high temperature) diamond. These intrinsic defects made the etching non-uniform. It is expected that the surface quality of the microlens will be greatly improved using high quality diamonds.

Laser beam machining of micro optics is the other challenging method which consists of three stages.

- Radiation of laser beam to the samples which are moved by a computer controlled XYZ stage.
- Heat treatment followed by chemical processing for about 1 hour.
- Finally, the samples are rinsed in the distilled water and are dried with nitrogen gas flow.

The critical doses of the photoreaction and the scanning speed are the most important factors. Figure 2-2 shows the experimental set up of the process.

Sugioka[25] has studied the feasibility of true 3-D micro structuring in the photosensitive glass using femtosecond laser. 3-D micro mirror was formed inside the photosensitive glass using this method.

Figure 2-2: Experimental set up for Laser beam machining of micro optics[25]

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Reflow method is the other method recently developed which can be sub-categorized into Lithographic techniques as long as the base cylinders, which are melt to produce lenses, are fabricated by lithographic techniques. This process consists of melting photoresist structures to form small lenses shaped by the surface tension of the liquid resist[26]. This method is mainly used to fabricate microlens arrays and to my knowledge, the application for production of large or stand-alone lenses is not studied yet. The surface profile of the lenses can be much more complicated than simple spherical shape and is determined through surface energy minimization[27].

2.1.4. Direct printing methods

Micro-inkjet printing is a relatively new method used for fabrication of stand-alone lens as well as lens arrays[28, 29]. Micro-inkjet printing methods are used for fabrication of different optical elements such as refractive lenslet arrays, multimode waveguides and stand-alone lenses deposited onto the tips of optical fibers. Optical adhesives and index-tuned thermoplastic are the materials used for micro-inkjet printing of micro optics. These materials are dispensed at temperatures up to 200 °C onto optical substrates and components. The processing parameters include numbers and locations of deposited droplets, print head temperature and orifice size, and target substrate temperature and surface wettability. By varying such process parameters different sizes of arrays of spherical and cylindrical plano-convex microlenses ranging from 40 μm to 1 mm is achievable. Sub-micron precision of such optical elements fabricated by this technique was reported[30]. Recently, fabrication of GRIN lenses using this technique was reported[31].

Figure 2-3 shows the schematic of the system used for micro-inkjet printing of plano convex microlens arrays. The similar set up can be used to print the microlenses directly on the polished tip of the optical fibers.

Figure 2-3: Schematic of the system used for micro-inkjet printing of plano convex microlens arrays[30]

2.2. Introduction to fiber optics

As mentioned before the lens fabricated via hot compression molding can be easily mounted onto fiber optics and this gives them superiority to other stand-alone lenses. In order to better understand the importance of this research, a brief introduction of fiber optics and its role in imaging optics is needed.

An optical fiber is an optic device consists of two parts: core and cladding. The main duty is to transfer imaging signals. The concept is based on total internal reflection (TIR) phenomena to guide light through the core which is transparent. As shown in the Figure 2-4 core is the inner part of an optical fiber which has the ability to guide light to an interested zone. As for the cladding, it surrounds the core completely. Refractive index of the core will be higher than that of the cladding so as to confine the light in the core when it strikes the interface with the cladding. It is not only depends on difference in refractive index but also incident angle[32].

Figure 2-4: (a) Cross-sectional of an optical fiber (b) Light guiding in an optical fiber [33]

When the incident angle (θ_1) is sufficiently large, the whole incoming light is reflected from core-cladding interface. This is called total reflection phenomenon. When it's low, a fraction of light is refracted into the cladding. That's the reason why intensity of the guided wave is not good when fiber is bent. Illustration of total internal reflection as light beam strikes the medium at initial angle θ_2 is shown in Figure 2-5.

Figure 2-5: Illustration of total internal reflection as light beam (blue) strikes the medium at θ_2

2.3. DOE (Design Of Experiments)

Design of experiments (also called designed experimentation or planned experimentation) refers to of collection of useful, powerful organizational or analytical methods to search for knowledge to solve problems and improve or understand a process[34]. In this research, the

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method is used to identify the important factors and their effect on the process. The molding conditions are optimized using design of experiments methodology.

2.3.1. Rules and Methods of Analysis

Generally, Design of experiments is divided into two major types depending on the type of action taken:

- An enumerative study is one in which the action will be taken on the whole universe of study.
- An analytical study is one in which the action will be taken on a cause system to improve performance of a product, a process or a system in the future.

In this study, an analytical study will be conducted in order to study the process, important factors and answer cause and effect questions.

There are many different types of experimental patterns in the literature which are trying to satisfy all the principles of design of experiments [34, 35]. One of the experimental patterns which have become very famous is factorial design. In factorial design, tests are arranged in such a way to analyze multiple factors in each test.

2.3.2. Factorial designs

To set up a factorial design, the experimenter should determine all the factors and levels of each factor. A full factorial design consists of all possible combinations of factors and levels. For example if the experiment has 3 factors and each factor has 4 levels, 4^3 runs are required for a complete factorial experimentation.

Number of runs required can be easily calculated as follows (equation 2-1):

$$\text{No. of experimental runs} = a^k \quad (2-1)$$

where “ a ” is the no. of levels and k is the no. of factors.

Many designs use factors with two levels because it makes the problem much easier. It also makes the pattern easier to be shown and also satisfy many practical problems[36].

There are many ways to display the factorial design of experiments. Matrix display, tabular display, and geometric display are common examples. Matrix display is shown in Figure 2-6.

Figure 2-6: Geometrical display of a factorial 2^4 design [34]

The most important considerations in a factorial design are: choosing number of factors, the level for each factor, consideration of background variables¹, selecting the amount of replication and randomization and the order of test which are essential in assurance of getting good result as well as determining cost and time required.

¹ Background variable sometimes called noise variable or blocking variable is a variable that can affect the response variable in the experiment but is not of interest as a factor. Time, operator, lot and instrument are common background variables.(the objective differentiate between factors and response variables)

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2.3.3. Fractional factorial and one factor at a time design of experiments

Suppose that in one experiment the effect of time, temperature and pressure on response variables are the subjects of study. If two values for each of the factors are considered, a complete factorial design will consist of 8 experiments. In order to lessen the number of experiments, several designs of experiment can be considered. Suppose that only one factor is changed at each time (Table 2-1). This design (Table 2-1) is usually called “one at the time” design. The number of experiments reduced to 4 (+ represents higher level, – represent the lower level). Now, suppose another design of experiments shown in Table 2-2 which also considered of 4 tests called fractional factorial design. Fractional factorial design has several advantages over other experimental procedures with the same number of experiments.

Table 2-1: “One factor at a time” design for 3 factor each has 2 level

Factor Exp. Nom.	1	2	3
1	-	-	-
2	+	-	-
3	+	+	-
4	+	+	+

Table 2-2: Orthogonal fractional factorial design for 3 factor each has 2 level

Factor Exp. Nom.	1	2	3
1	+	-	-
2	-	+	-
3	-	-	+
4	+	+	+

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This design is orthogonal which means that the design is balanced in a very specific way, each column has the same number of low levels and high levels, and any combination of two columns has both a low level and a high level of one factor for each low level and high level of other factor. The orthogonality of the test gives each factor a fair test against the other factors[35].

There are also lots of other designs of experiments. Some of them can be considered as a subdivision of fractional factorial designs. Methods such as Hadarmand designs, geometrical packet Burman designs, 2^k designs, certain Taguchi L-type orthogonal arrays (L8 or L10 designs) and certain Latin square designs which are to some extent equivalent designs known by different names.

2.3.4. Taguchi L-type orthogonal arrays

Taguchi L-type orthogonal arrays (i.e. L4, L8 and L16) are very famous designs. The reason is not only because the number of experiments is much less than factorial designs especially when the number of factors is high but also because of their efficiency in determining the effect of factors on each other. Taguchi arrays are mostly used for factors with two levels but there is no limitation on number of factors. The main parameter in choosing type of Taguchi array is the degree of freedom which is the sum of DOF for each factor.

Degree of freedom for each factor = Number of levels for the factor – 1

In experiments in which interaction between factors play an important role in the result of the experiment, levels of interaction is also important in determining the type of orthogonal array which can be used for design of experiments. The total degree of freedom of the result (the sum of degrees of freedom for each factor) must be less than the array total degree of the

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freedom. An L_4 OA (orthogonal array) has three degree of freedom where for example L_8 OA has seven and so on[37].

In this study the effect of molding temperature, molding pressure (velocity of compaction), and time for each sequence (especially compression time which is in a direct relation with cooling rate) and de-molding temperature will be studied. Beside the effect of each factor combination of different temperature and pressure values influence the results which mean that the interaction between the factors should be also taken into consideration.

2.3.5. Strategies for Choosing the method and number of factors

Beside full factorial and fractional factorial designs there are some other methods such as screening designs, box behnken designs, central composite designs, rotatable designs, mixture designs, nested designs, blocking designs, d-optimal designs and evolutionary operation designs which are suitable for some specific kinds of experimentation.

For experiments in which there is a high level of interaction between most of factors, the full factorial design maybe the best choice because it goes through all possible combination of factors which result in possibility of determining whether different factors have interaction or different combination of them influence the results or not, But it's usually very rare and most of the times, it's not necessary to explore between all different combination and a good fractional factorial design should be sufficient. The choice of the type of factorial design is also related to the level of experimenter knowledge about the nature of the experiment.

The best strategy to choose the factors in one study is to identify as many factors as possible, and then choosing the factors that have the biggest impact on the outcome of the

process. Only the factors that have the biggest effect on the experiment are included in the experiment.

There are several reasons for limiting the number of factors. One reason is economics. When the effect of powerful factors overwhelms the effect of weak factors, there is no reason to waste time, money and effort, testing for effects that don't really matter in the final process. The other reason relates to a principle in design of experiments called "scarcity of effects" saying that there are usually few of the many factors involved in a process that have a large effect on the outcome of the process.

2.4. Rheology of polycarbonate

The rheological behavior and important processing parameters of glassy polymers such as PMMA or PC at temperatures far below and well above the glass transition temperature (T_g) have been widely studied. At temperatures far below T_g , many studies have been done and tensile test can give lots of useful information about the elastic and plastic behavior of polymers deformation in that range[38].

Rheological behavior at processing temperatures well above the T_g is also studied widely[39], but not much has been done in temperatures around T_g . The working temperature of most of the polymer molding processes such as injection molding is relatively high and that's why the behavior of material in temperatures around T_g has not been studied widely. Recently the applications of hot embossing method made researchers study polymers at temperatures slightly above their glass transition temperature because the processing temperature in this process is slightly above the transition temperature of the material.

Tensile test has been applied for temperatures slightly above T_g with test samples marked with grids [40]. Beside tensile test, other characterization techniques such as biaxial stretching, plane strain compression, uniaxial compression and shear test have also been applied. A study on rheological characterization near T_g has been investigated by Jain [11]. It is mentioned that several characterization methods can be used to obtain the material properties in temperatures around T_g . At low strain and strain rates, the transient shear viscosity measurement can be used. At low temperatures, the tensile test is a good method to obtain the strain-hardening effect at large strains. At higher temperatures, compression test or shear and extensional rheometers can be used[41].

Typical stress-finite strain curve which can be obtained from compression uniaxial test and also shear test in low strain rates is shown in Figure 2-7.

Figure 2-7: Typical stress strain relationship

Tensile test and compression test beds as well as different rheometer devices are the equipments mostly utilized for polymer rheology characterization. The results of previous studies show that polymers mostly act like visco-plastic material which means they show elastic behavior in low temperature and low pressure condition and show viscous behavior in higher temperatures or pressures. At temperatures below T_g , the material is rigid for shear

stress τ , less than a critical value τ_0 . In higher stresses, the material flows as a Newtonian or non-Newtonian fluid with incremental shear stress proportional to shear stress divided by viscosity or a power of that.

2.4.1. Mechanical models of Polymers

There are many mechanical models used to describe viscoelastic behavior of materials. These models consist of a combination of linear elastic elements and dashpots. Using these elements, it's easier to determine the relation between stress and strain using the particular method. Some of these combinations which are used to describe viscoelastic behavior are shown in Figure 2-8.

Figure 2-8: Some of different mechanical models used to describe viscoelasticity; (a)Maxwell model; (b)Kelvin model and (c)burger model

Although Maxwell model seems to be simple to characterize all different properties of material behavior, it's still able to show both viscous and elastic properties of viscoelastic materials. Generalized Maxwell model is also proposed to fit the experimental data better as long as it has more coefficients which can be determined to fit the data better. In this study a Maxwell model is also used to simulate the elastic behavior of material in linear viscoelastic model.

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Maxwell model is one the oldest models has been proposed for viscoelastic material and has been widely accepted. As shown in Figure 2-8, Maxwell element consists of a linear elastic component and a dashpot in a line. Stress-strain relation can be easily derived as follows (equation 2-2 and equation 2-3):

$$\dot{\varepsilon}(t) = \dot{\varepsilon}(t) + \dot{\varepsilon}(t) \quad (2-2)$$

total elastic viscous

$$\dot{\varepsilon}(t) = \frac{\dot{\sigma}(t)}{E} + \frac{\sigma(t)}{\eta} \quad (2-3)$$

Considering a constant strain rate ($\dot{\varepsilon}(t) = \dot{\varepsilon}$) and solving the first order differential equation, we have (equation 2-4):

$$\sigma(t) = \eta \dot{\varepsilon} (1 - e^{-\frac{E}{\eta} t}) = \eta \dot{\varepsilon} (1 - e^{-\frac{t}{\eta/E}}) \quad (2-4)$$

Solving equation 2-3 for $\varepsilon(t) = \varepsilon_0 = cte$ results in stress relaxation prediction with Maxwell model. Considering $\dot{\varepsilon}(t) = 0$, we have (equation 2-5):

$$\sigma(t) = E \varepsilon_0 \exp\left(-\frac{t}{\eta/E}\right) \quad (2-5)$$

where η is viscosity of dashpot, E is modulus of elasticity of spring, $\dot{\varepsilon}$ is constant strain rate and $\frac{\eta}{E}$ which is also shown by τ_s is called stress relaxation time coefficient. A generalized Maxwell model which basically consists of several Maxwell elements placed in series is used to model the stress relaxation behavior. For n elements placed in parallel stress is sum of the stresses in each element (equation 2-6).

$$\sigma(t) = E \varepsilon_0 \sum_{i=1}^n w_i e^{\frac{-t}{\tau_i}} \quad (2-6)$$

where w_i is the weighing factor for each Maxwell element where $\sum_{i=1}^n w_i = 1$

Equation below is also proposed to investigate stress-strain relationship in PC ($T_g=145-150$) at temperatures from room temperature to temperatures slightly above its transition temperature (equation 2-7) [38].

$$\sigma = K(1 - \exp(-w\xi)) \exp(h\xi^2) \dot{\xi}^m \quad (2-7)$$

Where σ is stress, ξ is strain, $\dot{\xi}$ is strain rate, K and h and w are constants function of temperature and m is the strain rate index.

Equation above is hard to work with. Determination of the parameters in equation 2-7 can be done by some reasonable assumptions which is not going to be discussed here and completely discussed by Juang et al. [41]. There are many other models which try to simulate stress- strain behavior of polymers. Most of them are only appropriate for a specific range of temperature and there is still a big challenge to find a model which can predict stress- strain behavior in wide range of temperatures from far below T_g to above melting temperature. Some works recently are conducted at MIT (Massachusetts Institute of Technology) to propose such a model and it's shown that the experimental results fit the their proposed model very good[42].

2.4.2. Important parameters in rheological characterization

Behavior of polymers are strongly temperature and pressure dependent to the extent of undergoing completely inverse phenomena when the temperature or pressure changes. Although it's obvious that polymer characteristics are extremely temperature and pressure

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dependant, the details of its functionality is not accurately investigated in some particular range of temperature including temperatures around glass transition temperature and this make it hard to simulate the processes when the working temperature is in that range. One other thing make it very hard to simulate the processes in that range of temperature is the high sensitivity of the material behavior to temperature as even changing 5°C in temperature can cause material to greatly lose elastic properties.

2.5. Lens characterization methods

There are many different approaches to characterize lenses but all of them can be categorized into two major categories: (1) Metrological tests that measure geometrical characteristics such as height of the profile or surface texture and (2) Tests which measure optical performance of the elements such as focal length, imaging efficiency, amount of diffraction or different aberrations[43].

Different optical characteristics of lenses fabricated in different molding conditions can be the result of geometrical differences between them, different residual stresses, and also change of material in terms of changes in material crystallinity and phases. A brief background of the geometrical and optical characterization techniques are presented in the following sections.

2.5.1 Geometrical Characterization

Geometrical characterization of the lenses fabricated by compaction molding in this study mainly consist of measurement of the surface profile, surface roughness and lens sag height deviation from mold sag height in different molding conditions. There is variety of tests used to measure geometrical characteristics of optical elements including lenses. Methods such as

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optical microscopy, mechanical profilometry, scanning electron microscopy (SEM), atomic force microscopy (AFM) and interferometry are all well utilized in lens characterization. Each of these methods has advantages and disadvantages relative to the other.

As mechanical profilometry suffer from tip problems which make the measurement not accurate, scanning electron microscopy cannot give the exact position of the points. Although the image taken from SEM can be analyzed by any of image processor softwares but this takes time and extra effort. SEM is also a destructive test for lenses as long as the sample must be coated with a conductive material which is generally not transparent. Atomic force microscopy is generally used for determination of surface roughness and is a powerful technique to get the profile of very tiny features, and interferometry methods need accurate set up which should be set by experimenter most of the times. As there are advantages as well as disadvantages for all the methods mentioned above, most of these methods have been used in this study in order to have a complete data on geometrical testing of new lenses.

2.5.1.1. SEM (Scanning Electron Microscopy)

Although further processing of the data obtained from SEM is required to get the profile of the lens, it's a very good way to recognize defects on the lens surface.

2.5.1.2. White light confocal microscopy

White light confocal microscopy is based on processing the reflected light beam from the surface of the sample. The initial light beam is emitted from a point light source and the reflected light imaged into the object focal plane of the microscope objective. Imaging are then taken point by point and analyzed into the computer to generate a 3-D pattern of the lens. Choosing a suitable objective lens for the microscope is critical. The size of the

fabricated lens is around 1mm in this study so the 20X objective lens is chosen. Although the number of data points for this objective is less than that for other objectives, the resolution is sufficient to provide good surface profile image and surface defects. The surface roughness can also be studied.

2.5.1.3. Contact profilometry

Contact profilometry is a simple method of profilometry using a sensitive stylus to measure 2D and 3D profiles of the lens. Detection of the bending moment applied to the cantilever is related to the height of the points and by performing multiple scans, a 3D image of the surface can be obtained. The accuracy of the measurement is related to the size and shape of the stylus[33]. The shape of the stylus may influence the results specially when the lens is steep and tangential angle at the surface is more than half of the stylus angle. In this case the side walls of the stylus contact with the surface of the lens at the edges and it influences the results as shown in figure 2-9. In this study the lenses were shallow enough to be accurately measured. The other problem with the contact method is that it may destroy the samples.

Figure 2-9: The effect of stylus geometry on the results

2.5.2. Optical characterization

Optical measurements have been reported by variety of techniques from each some particular information about optical performance of lenses can be obtained. Devices such as

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interferometers, scatterometer, charged coupled devices and rotating slit scanners are utilized to measure optical performance of lenses. In order to have a complete characterization of optical performance of the fabricated lens, chapter 7 discusses the focal length and focal spot size of the microlens followed by investigation into the normal imaging efficiency, fluorescence collection efficiency and imaging.

2.6. Potential research area

The literature review shows that fabrication of polymer stand-alone microlens which can be mounted easily on the tip of an imaging fiber has not been studied widely. Hot-compression process seem to be a promising area, in this process, the material is not injected but placed into the hot compression press and material is just softened slightly above transition temperature and then compressed (formed). The advantages of this process will be discussed in chapter 4.

The process can be optimized theoretically as well as experimentally. FEM (Finite element method) simulation of the process would be conducted in different process conditions (chapter 5) to analyze the effect of different parameters on the lens performance. The experimental study based on DOE principals would also been conducted (chapter 6) and the theoretical results verified.

In order to have a complete characterization of the performance of the fabricated microlens, geometrical characterization as well as optical characterization of the lens would be conducted and is covered in chapter 7. Geometrical characterization includes defect analysis, lens surface curvature and surface roughness characterization. Optical characterization includes: (1) Focal length and focal spot size characterization, (2) Normal

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imaging power characterization of lenses, (3) fluorescence collection efficiency and (4) fluorescence imaging ability of the microlens.

CHAPTER 3

DESIGN OF HOT COMPRESSION MOLDING SET UP FOR POLYMER STAND-ALONE MICROLENS FABRICATION

3.1. Introduction

A compression molding set up has been utilized in this study to satisfy these two main objectives.

- To study the feasibility of fabrication of polymer microlenses via hot compression molding.
- Optimization of the process through experimental design to satisfy the optical requirements of the product.

While there are commercial machines available, most of these machines don't offer the capability and flexibility required for scientific research in size and temperature range similar to this study. Therefore it is desirable to construct a custom machine, which enables precise control over the mold position and temperature.

Design of the molding apparatus can be divided into three main steps: lens design, mold design and machine design. In general, requirements of the lens size and surface quality determine the requirements of the mold design. The accuracy of the moving elements is the controlling parameter for the accuracy of the machine design.

3.2. Lens Design**3.2.1. Conceptual design of lens**

The lens was designed such that it can be installed directly onto the tip of an optical fiber for imaging purposes (Figure 3-1). The use of individual lens on each imaging fiber enhances the overall imaging power as it allows imaging of individual point under a particular fiber in the fiber bundle [44].

Figure 3-1: Molded lens and imaging fiber

The lens designed and fabricated with the molding apparatus consists of a spherical part and a cylindrical part. The clear aperture of the lens is ≈ 1 mm with a total dimension of 1.4mm including the side wall which is used to secure the stand-alone lens on the fiber tip as shown in figure 3-1. The extended side wall shown in figure 3-2 is to enable the snap fit to take place. The size and shape of lens can be changed easily by changing the upper and lower mold inserts and the ejector sleeve.

Figure 3-2: Desired shape of the lens

Design process for lens consists of several steps as shown in Figure 3-3. The first step is to determine the specification of the optical system such as the shape of the lens, field of view, focal distance and the magnification factor. The next step is to determine what fabrication procedure is suitable to satisfy the specification required which is also dependent on geometrical specification. Optical devices using aspherical elements can reduce optical aberrations, alleviate internal reflection, reduce lens count, and subsequently minimize assembly requirements. Demands on cheaper, better, and smaller optical devices require use of more aspherical lenses[45]. The fabricated lenses are characterized and the processing parameters are optimized to fabricate the best possible lens.

Figure 3-3: Steps for integrated design and fabrication process

3.2.2. Lens material

Glasses and different polymers have been widely used in lens production. Each has its relative weaknesses and strengths. While polymers are lighter and easier to fabricate, glasses are generally more heat resistant and more resistant to scratches. These particular characteristics give each of them special applications. Polymer was chosen as a molding material for this study.

Polymers are a class of versatile materials comprised of macromolecular chains (each link is a repeating unit) that can be configured (Figure 3-4) to form a virtually endless variety of compounds. There are many different applications for polymers including the world of micro optics where they are used for different purposes.

(a)linear

(b)branched

(c)cross linked

Figure 3-4: Different types of polymer chains; (a) linear, (b) branched, (c) cross linked

There are about eight thermoplastic polymers that have been most commonly used to make plastic precision products. These are normally amorphous thermoplastics and include: polycarbonate (PC), Polymethyl methacrylate (PMMA), acrylate and acrylic copolymers, polystyrene, methyl methacrylate-styrene copolymer, styrene acrylonitrile (SAN), methylpentene (TPX), ABS or nylon.

Polycarbonate is the most commonly used optical material. It's commonly used for optical discs including CD-ROM[10]. The chemical structure is as follows (Figure 3-5).

Figure 3-5: Chemical structure of PC

It's necessary to dry the polycarbonate at 120°C for a few hours prior to hot pressing as polycarbonate can absorb water moisture up to about 0.15% of its weight. This drying stage avoided formation of small bubbles in the finished product. The most important advantage of polycarbonate is its transparency and high refractive index[46]. (See Appendix A for further information on mechanical and thermal properties of the material provided by the supplier). The other important characteristics of polycarbonate that make it an appropriate choice in optics are:

- low levels of impurities
- transparency
- high scattering
- heat resistance
- moldability (Transferability)
- high intensity

3.3. Mold design

As mentioned in previous chapter, in every molding process, design and fabrication of mold inserts is a challenge. In many cases, ultraprecision machining of mold inserts is required. Recently many studies also use lithographic techniques to fabricate molds or master parts but single point diamond turning machines are mostly used for this purpose when the mold material is stainless steel. In order to obtain better results from molding process, design consideration such as materials which can be used, surface quality required and fabrication

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techniques which can be used to satisfy optic requirement should be taken into consideration. In mold insert fabrication, surface roughness is the most important factor which affects the quality of the product and even feasibility of the process. Surface roughness of the mold inserts should be in the range of 7-10 nm for imaging applications.

Mold inserts material is of a great importance as it directly affect the quality of the molded parts. The material chosen for optic inserts should have the following properties:

- Sufficient hardness,
- Sufficient heat resistant,
- Chemically and physically stable at high temperature.
- Low adhesion between materials and die.

Some of the materials that have been tested as mold materials include tungsten carbide (WC), silicon carbide (SiC), aluminum nitride (AlN), titanium nitride (TiN), aluminum oxide (Al₂O₃), titanium carbide (TiC), and stainless steel. Stainless steel is not considered as a good mold material for glass molding anymore because of diffusion of iron to the glass at high temperatures which causes low hardness, poor heat resistance and colorization of glass[45].

Reducing the probability of adhesion between mold and polymer is another issue which should be considered. Surface roughness is the most important parameter which should be reduced in mold insert fabrication to reduce adhesion between mold and material. Choosing the right material is also very crucial simply because the material can get changed easier in comparison to other parameters and several alternatives can be used to reduce adhesion probability. As viewed from energy point of view, molecule interaction at the contact surface between the mold and the polymer may induce surface adhesion, particularly when the

surface energy of the mold is high[47]. The surface energy of the mold material (high chrome steel hardened to 54 HRC) and PC are almost equal to each other and is about 46 dynes/cm. It means that this steel doesn't adhere to polycarbonate as long as its surface energy is not higher than that of PC.

The guide pins play an important role in horizontal positioning accuracy. Standard part from HASCO company has been utilized as guide pins. Z00 standard part for the guide pins and Z10 for guide bushing have been used. The stated tolerance for this set is 10 micron. The vertical positioning is related to accuracy of the stepper motor which is 0.003mm/pulse considering gear ratio and resolution of 0.72 degree per step.

Figure 3-6: Upper and Lower Mold inserts; (a) picture of the mold, (b) schematic diagram of the mold

Lower mold insert (ejector pin) is also chosen from standard parts of HASCO company. The stiffness of ejector pin also plays an important role in design because it may affect the quality of the products over a long period of time. A picture of the mold inserts and a schematic of that is shown in Figure 3-6. The detailed engineering drawing of the mold inserts parts are included in Appendix B.

3.4. Machine design

The objective here is to have a very compact design. As shown in Figure 3-7, the machine designed for this study has a footprint of 55cm × 55cm and a height of 120cm. The feeding system is currently manual and cylindrical parts with the volume same as the final product volume is placed on the lower part where ejector pin is placed.

Figure 3-7: Compression set up for hot compression of microlenses

There are some important characteristics of the machine which influences the minimum size and accuracy of the parts which can be fabricated. It seems that the most important ones related to resolution of the stepper motors and accuracy of the guide pins, its tolerances and

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the accuracy of fabrication of mold insert as well as the assembly process which can be considered as the most important factor in design and fabrication of micro fabrication dies.

As mentioned above, resolution of stepper motor is the controlling parameter for the vertical positioning accuracy of the mold but it may have an ignorable effect on the controllability of the forming process. Here, controllability means that the higher resolution may help the experimenter to define more exact steps in forming process and also provide less vertical positioning error.

Assembly is the last most important step of production which plays an important role in product tolerances. In other words, a good assembly is essential for micro production system while a bad one may result in failure of the whole system.

3.4.1. Heating system

Heating elements (300Watt at 250Volt) are placed in the upper and lower mold inserts. The heating cartridges are placed in pre-drilled holes in both mold bases. A total of 4 elements are used. A temperature sensor is placed on the lower mold to control the die temperature and a feedback system is used to maintain the temperature during molding. Two heat insulators are placed on both sides of the mold in order to prevent heat lost.

3.4.2. Cooling system

Heat transfer mechanism for different molding processes such as injection molding has been studied widely and several studies on optimization of these mechanisms have been conducted. The cooling system efficiency is very important issue as long as it directly influences the production time and also has severe influence on reproducibility of the process. The cost-efficiency of the process is also dependent on the time spent in the molding cycle

and many studies has been done to increase the efficiency of cooling systems and decrease the cooling time[48, 49]. Correspondingly, the cooling phase is the most significant step among the steps as it determines the production rate. As in most modern industries, time and costs are strongly linked, the longer is the time to produce parts, and the more is the costs. Reducing the cooling time would effectively increase the production rate and hence reduce cost. Uniform heating of the molded part is also an important issue as long as it directly influence the quality of the product and reproducibility[50].

There are many factors affecting the working performance of a cooling system. For a given mold base material, the type of coolant, geometry of the product, environmental condition and processing requirements would have the most dominant effect on the design and the arrange of a well-performed cooling circuit.

A simple way to control temperature and heat exchange is to create several channels inside the mold where a cooler liquid is forced to circulate. In this study a very simple but efficient cooling system is designed. Two channels on each lower and upper part are machined in order to let the cold water circulate in both of the mold assemblies. It's suggested that the suitable temperature range of cooling water should be 20–60°C .

Figure 3-8: Schematic configuration of cooling channels

There are some considerations in placing the cooling channels for optimization of cooling system for an injection molding process[51]. Rules such as the cooling tubes should be

located as close as possible to the mold cavity and “a” (in Figure 3-8) should be small are taken into consideration. However, the strength of the mold should be taken into consideration. Strength of the mold require “a” and “d” (shown in figure 3-8) follow equation3-1[51].

$$0.01 < a - \frac{d}{2} < 0.02 \quad (3-1)$$

Where “a” is distance between the centre of the hole and mold surface and “d” is diameter of the hole. The distance between the cooling tubes and the mold cavity wall “b” must be greater than the diameter of the cooling tubes d (b > d). Also, for easiness in machining and maintenance of the cooling tubes, the diameter d (m) is required to be in the range of 8mm to 12mm. In this study “d” is chosen to be 9mm, “a” is 5.5mm and “b” is 38mm. Figure 3-9 Shows the picture of the mold assembly indicating the heating and cooling systems.

Figure 3-9: Mold assembly indicating the heating and cooling systems

The calculation of water flow rate required to have an efficient cooling system is shown in equation3-2.

$$\dot{Q} = \dot{m} c_w \Delta\theta_w = \rho \dot{V} c_w \Delta\theta_w \quad (3-2)$$

Where $\dot{V}$ is the water flow rate and $\Delta\theta_w$ is the difference in temperature in water.

The heat transfer should be also equal to (equation3-3):

$$\dot{Q} = M C \frac{\Delta\theta_m}{t} \quad (3-3)$$

where M is the equivalent mass of the whole die, C is the heat capacitance of the die material, $\Delta\theta_m$ is mold temperature difference before and after cooling stage and t is the time for cooling stage.

The location of heating element is some centimeters above the upper mold insert in the upper mold assembly and some centimeters below the lower mold insert in the lower mold assembly. Cavities of the cooling system for water flow are also near heating elements.

3.4.3. Drive system

As shown in figure 3-10, drive system of the mold consists of two Micom 5-phase, 5-lead stepper motors operating at 4.37 Volt (DC) and 1.4 Ampere of which one drives the upper mold assembly and the other drives the ejector system. Torque is transmitted through a gearing system and a ball screw to the upper mold assembly. The vertical feedrate of the upper mold assembly determines the strain rate of the material during molding.[44]. The strain rate affects both the forming process and the results.

After lens is fabricated, the formed material must be ejected from the lower mold insert. The ejector system consists of a stripper sleeve which is installed into a holder, the holder is connected to the stepper motor by two pins. The pins are responsible for transferring the linear motion of the lower plate to stripper sleeve.

Figure 3-10: Transmission system to maneuver upper mold assemble. (b) Transmission system to elevate stripper sleeve during extraction phase, (c) CAD drawing of the drive system for the upper mold assembly, (d) CAD drawing of the drive system for ejector system

CHAPTER 4

LENS FABRICATION

4.1. Sample preparation

Sample preparation consists of several steps; the material is first dried at 120°C for several hours and made ready for extrusion, then a simple extrusion die is used to extrude long string of Polycarbonate with the diameter of 1.5mm. The string is then stretched to a diameter of 1.4mm and cut into cylindrical gobs having the height of 0.4mm. A diamond cutter with positioning accuracy of 0.01mm was used to cut the samples. These gobs are then annealed at 160°C for two hours to reduce the residual stresses before it is placed into the molding press.

4.2. Sequences in Compression Molding

The whole process of compression molding can be summarized in 5 steps:

1. Heat the die and polymer to 170°C which is between material transition temperature and melting temperature ($145^{\circ}\text{C} < T_{\text{molding}} < 267^{\circ}\text{C}$). This temperature seems to be more suitable as it minimized the amount of material springback and reduce the amount of adhesion to the mold inserts. The springback of the material is more than permissible if it is molded at around T_g . Excessive adhesion to the upper mold insert occurs when it is molded well above T_g .
2. The upper mold insert which is controlled by stepper motor then moves down to hold the PC tablet which is placed on top of the lower mold insert. The springs are

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compressed and forming occurs after the PC tablet is softened and the temperature is stable.

3. The heaters are turned off and the cooling system begins to work.
4. Wait until the suitable temperature for de-molding process is reached then the injector which is controlled by the other servo motor moves up to de-mold the fabricated lens.
5. The lens reaches the room temperature when it's de-molded.

Pressure and temperature cycle curves are similar to a typical process of compression molding or hot embossing and are shown in figure 4-1. Figure 4-1 shows the sequences of the process, time of each sequence as well as compression and de-molding temperature.

Figure 4-1: Pressure and temperature history in a cycle time

4.2.1. Compression molding mechanism

The following illustrate the whole process of compression molding with diagrams

1. Heat the die to 170°C (figure 4-2) which is between the material transition temperature ($T_g = 148^{\circ}\text{C}$) and melting temperature ($T_m = 267^{\circ}\text{C}$). This temperature seems to be more suitable as it minimized the amount of material springback and reduce the amount of adhesion to the mold inserts. The springback of the material is

more than permissible if it is molded at around T_g . Excessive adhesion to the upper mold insert occurs when it is molded well above T_g .

2. The upper mold insert which is controlled by stepper motor then moves down to hold the PC tablet which is placed on top of the lower mold insert (figure 4-3).
3. The springs are compressed and forming occurs after the PC tablet is softened and the temperature is stable (figure 4-4)
4. The heaters are turned off and the cooling begins. When the suitable temperature for de-molding process is reached, the ejector which is controlled by another stepper motor moves up to de-mold the fabricated lens. The lens reaches the room temperature when it's demolded (figure 4-5).

Figure 4-2: Schematic of two mold insert before compaction[44]

Figure 4-3: PC tablet is softened and is ready to be formed[44]

Figure 4-4: Upper mold undergo further compression to form the PC tablets[44]

Figure 4-5: Ejector pin eject the molded lens

4.2.2. De-molding process

In most of molding processes when tiny features are involved, the success of de-molding step will determines the success of whole molding process. In de-molding, different defects may occur. Micro structures may be torn apart, deformed and even destroyed. In order to have a successful molding process, there should be a proper ejection system design. During the initial trial, parts did not adhere to the lower mold insert and in most cases, it adhered to the upper mold when the mold was opening. The other problem was that at some molding conditions, the spherical parts remain in the upper mold insert where the cylindrical part remains in the lower mold assembly. That's why the temperature where the die opens plays a much more important role than de-molding temperature in this particular case. (De-molding temperature by definition is the temperature at which the lens is ejected from the lower mold insert)

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There are some important factors should be considered in design of micro mold to have a successful de-molding step:

- Suitable ejector which does not contact the important surfaces.
- Adequate angle that reduces the de-molding forces.
- De-molding system should be placed on the side of the mold that the material is more likely to adhere.
- The product should be symmetrical or the designer should enforce symmetry with neighboring auxiliary structures in order to prevent tilting of the mold due to the shrinkage force.

4.3. Advantages and limitations

Every fabrication technique has its own unique characteristics which bring that special advantages and superiorities to other techniques. Each technique also suffers from particular weaknesses in comparison to the other ones. Some of the advantages and limitations of this process can be listed as follows:

Advantages:

- Mass production of stand-alone lens.
- Possibility to change the size of the lenses easily.
- Not very expensive. In comparison to injection molding, the device is much less complicated.
- Very good surface roughness(according to the inserts being optical finished) and extremely accurate texture.
- Suitable for producing individual lenses with special features which make the assembly (installation on optical fibers) easier.

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- The residual stress is much lower than that of injection molding processes as polymer flow a much shorter distance in this method, so lower birefringence and better quality is possible.
- Lower forming temperature.
- In hot embossing method, it's the surface tension which defines the surface texture but in this method the texture doesn't depend on material properties.

There are some restrictions for this production technique which limit the size of the lenses that can be fabricated. All these restrictions can be divided into two groups: (1) factors which limit the minimum size of the lens and (2) the factors which limit the maximum size of the lens.

(1) Factors which limit the maximum size of the lens:

- In larger diameters, the deviation from the die size is larger so the need for compensation in size arises.
- Non uniformity of cooling plays a more important role in larger lenses and may cause distortion of the lens.

(2) Restrictions for the minimum size of the lens:

- Fabrication of tiny aspherical or spherical dies for optic purposes becomes harder as the diameter decreases.
- As the diameter of lenses decreases, the accuracy of the whole die such as accuracy of stepper motors and guide pin should increase.

4.4. First results of the compression molding

In every experimental procedure the processing parameters in which the experiments begin with is one of the most important steps as it may help to find the optimum processing

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parameters very soon if it's chosen correctly. It may also confuse the experimenter if it's chosen far away from the optimum point of processing conditions. As the first step three different temperatures, one below T_g , one around that and one well above that were chosen. The results show that the forming is impossible in temperatures well above T_g as the material is too soft to be formed and flow downward inside the mold cavity. The adhesion of material to the die is also another big problem which may eventually cause the mold insert to lose its surface quality. It was also impossible to get good results when the temperature was well below T_g as the material was too hard to be formed and the probability of crack formation was high. As it was predictable, the range of temperatures where the process was successful is from T_g to temperatures about $T_g + 50^\circ\text{C}$. It shows that the nature of the process is somehow like hot embossing.

4.5. Processing parameters in compression molding

As mentioned in previous chapter, forming temperature and pressure, number of sequences, time of each sequence, de-molding temperature and heat transfer rate could possibly be some dominant factors which affect total performance of micro optical lens produced. Although some of the factors above such as molding temperature are much more important than the others, all factors should be taken into consideration in the first step.

In order to analyze the effect of factors on the total performance of the fabricated lens, optic variables such as numerical aperture (NA), refractive index as well as geometrical variables such as base diameter, sag height, radius of curvature, and pitch must be studied.

CHAPTER 5

FEM SIMULATION

5.1. Introduction

The performance of an optical lens depends on its physical profile (i.e. radius of curvature and sag height) and its optical properties (e.g. numerical aperture and refractive index). In any forming process, the profile of the lens deviates from the mold profile because of springback due to internal stresses (the stresses which are not relaxed at the end of each step) and curve shift due to shrinkage in cooling step. The change in the shape due to shrinkage especially the change in the radius and the sag height are responsible for the change of focal length and wavefront error. The internal stresses built-up during the process also affect the numerical aperture and refractive index of lenses.

Choosing the right material with suitable refractive index is the first step in process optimization. PC (Polycarbonate Lexan 123R), which is used in this study, has the refractive index ≈ 1.56 . The refractive index of material matches closely with that of the imaging fiber. The molded stand alone lens is designed so as to attach onto the end-facet of the image fiber. In order to optimize the fabrication process in any lens fabrication technique, fabrication parameters in which the lens with least deviation from the designed profile (whether it's spherical or aspherical) and also with least residual stress should be determined.

There are theoretical approaches such as FEM simulation models[52, 53], Newtonian and non-Newtonian fluid models[54] as well as experimental and statistical analysis[55] on the optimization of thermoforming processes. As hot embossing has become a very well-known

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production technique for polymers and is going to be very popular in the field of lens production, there are many studies on forming of polymers in temperatures slightly above T_g [53]. In this section, FEM simulation analyses as well as experimental analysis were conducted to find the optimum process parameters. A good simulation can also be helpful in determining the initial volume needed to reduce the formation of sharp edges as it can be harmful to the tissues. The formation of sharp edges is mainly due to exceed materials used. Comparison of simulation results and experimental results with different molding parameters helps to optimize the fabrication process.

Although there are many studies on FEM simulation of polymer forming in temperature slightly above T_g , only a few of them consider the effect of stress relaxation of material due to viscoelastic properties in the cooling stage[56]. Though there are also reported studies on FEM simulation of glass lens forming[6], there are very few studies reported on modeling the effect of temperature and strain rate on the part quality[54]. It should be also mentioned that most of these reported studies did not consider the history of stresses and strains and concentrated only on one-stage simulation of the molding process.

Certain reported work concentrated on mold filling stage and investigated the forming behavior of material without considering the effect of stress relaxation due to viscoelastic properties of material[57]. Others concentrated on cooling and de-molding stages[58] assuming that the stress has already been relaxed at the end of molding stage[59]. This is because of the complexity involved in simulating the process at all stages. It involves the use of complicated material properties under different stages, changes in contact behavior, boundary conditions and loading conditions.

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Based on the above context, a reliable simulation model of polymer lens molding is needed to predict the final lens performance (which is dependent on lens curvature, residual stresses, etc). In this study, the whole process of lens compression molding in different molding conditions considering the effect of stress relaxation due to the effect of both viscoelastic and volumetric response of the material was simulated. Compression test is simulated as the first step for two reasons: (1) In order to have better understanding of material behavior under compression force and (2) In order to see how accurate FEM simulation can predict the stress history of the material, compression test is simulated with two material models which will be discussed below.

5.2. Compression test

5.2.1. Theory

Compression test is utilized to characterize material behavior under conditions similar to that of lens compression molding. Although in most of studies conducted on polymer characterization shear and extensional viscosity measurement are quite routine, compression test was preferred in this study because it was easier to gain stress strain curve under compression conditions and the data could be fitted to different models proposed for viscoelastic materials. The results of fitting can be used in different finite element packages to define linear or nonlinear viscoelastic material models.

5.2.2. Experiments

In order to perform compression test on material, cylindrical parts of the diameter and height of 25mm were machined and prepared for the testing. As the material supplier didn't supply material in cylindrical shape, PC rods with mechanical and optical properties very similar to the PC used in lens making with diameter of 25mm were bought and used in

compression test device to characterize the material (Please see Appendix C for the mechanical and thermal properties of the compression test sample material). These samples were then machined to proper length of 25cm and were put into the oven in temperature $T_g + 10^\circ\text{C}$ for 5 hours for two reasons. Firstly to anneal the samples and reduce the effect of residual stresses resulted from previous molding and machining and secondly to increase the core temperature to temperatures up to T_g before putting it into the test device. The “INSTRON 5500R” compression test bed was used for the tests. Figure 5-1 shows the picture and a schematic of the compression test set up used for the compression test experiments on PC samples.

Figure 5-1: Compression test set up used for the compression tests on PC samples; (a) picture, (b) schematic

Stress-strain of the material was obtained under wide range of temperatures and strain rates. Temperature ranges from $T_g + 10^\circ\text{C}$ to $T_g + 50^\circ\text{C}$ and strain rate ranges from 0.001 1/s to 0.1 1/s. Results of such experiments were then used to model the process in different temperatures and strain rates and to compare the results of the simulation with experimental results. Details of the temperatures and strain rates used in compression test are shown in table 5-1.

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Table 5-1: Different temperatures and strain rates used in compression test

Number of experimental set	Temperature (°C)	Strain rates (1/s)
1	160	0.001 , 0.01 , 0.1
2	170	0.001 , 0.01 , 0.1
3	180	0.001 , 0.01 , 0.1
4	190	0.001 , 0.01 , 0.1
5	200	0.001 , 0.01 , 0.1

Figure 5-2 shows stress strain curve obtained under compression in different temperatures and strain rates. In each of the tests, a constant strain rate is applied to the sample. The change in stress is due to both elastic response of the material and viscoelastic relaxation properties. The slope of the curves decreases as the time increases because of stress relaxation effect.

Figure 5-2(a) shows stress-strain at high strain rate of $0.1 \frac{1}{s}$ and different temperatures. It shows that the response of material in temperatures slightly above T_g is highly temperature dependent and stress decreases much as the temperature increases. Strain hardening effect disappears as temperature increases and that's because of the priority of viscous effect in higher temperatures.

Figure 5-2(b) and Figure 5-2(c) show the results of compression test at strain rates of $0.01 \frac{1}{s}$ and $0.001 \frac{1}{s}$ respectively. Same effects can be seen in these strain rates although there are differences in magnitude and slope of the curves. These changes can be the result of stress relaxation in lower strain rates. In lower strain rates, the material has sufficient time to relax so the slope of the curves is less than that for higher strain rates. Comparing the results of

tests performed in different temperatures and strain rates, it can be seen that difference between curves for different strain rates increases as the temperature increases. It shows that the effect of relaxation is more dominant in higher temperatures.

Figure 5-2: Results of the compression test in different temperatures (All temperatures are in °C) and strain rates; (a) 0.1 1/s , (b) 0.01 1/s , (c) 0.001 1/s

5.2.3. Determination of the elastic modulus for linear viscoelastic model

Different methods have been applied in determination of elastic modulus of polymers in elevated temperatures. In some studies, elastic modulus of the material in temperatures above T_g is obtained through optic techniques such as Brillouin light scattering measurements which takes much effort and time to determine the elastic response of material[60]. In some other studies the uniaxial test data of the material is fitted to a strain energy potential and the

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equivalent initial elastic or shear modulus is used for simulation which is not wise as long as hyperelastic material models cannot be used to determine the elastic modulus of material[57]. Some research groups curve fit the test data to a generalized Maxwell model which requires going through a complete dynamic mechanical analysis[61]. The material can also be modeled as a Non-Newtonian fluid[54] and the coefficient for the power law model is obtained by Juang et al.[62]. In this study, the elastic modulus was obtained simply by curve fitting the test data to Maxwell model (equation 5-1).

$$\sigma(t) = \eta \dot{\varepsilon} (1 - e^{-\frac{E}{\eta} t}) = \eta \dot{\varepsilon} (1 - e^{-\frac{t}{\eta/E}}) \quad (5-1)$$

It's also easy to obtain stress strain curve as long as strain rate is constant.(equation 5-2)

$$\dot{\varepsilon}(t) = \frac{V}{L} \quad (5-2)$$

$$t = \frac{\varepsilon(t)}{\dot{\varepsilon}(t)} = \frac{\varepsilon(t) * L}{V} \quad (5-3)$$

So equation 5-1 Can be written as follows (equation 5-4):

$$\sigma(t) = \eta \dot{\varepsilon} (1 - e^{-\frac{E}{\eta} t}) = \eta \dot{\varepsilon} (1 - e^{-\frac{E * L}{\eta * V} \varepsilon(t)}) \quad (5-4)$$

It's important to maintain a constant strain rate as equation 5-4 is derived on the condition of constant strain rate ($\dot{\varepsilon} = cte$). Strain rate can be calculated having the height of the polymer gob and speed of compression (equation 5-2). Nonlinear curve fitting procedure based on least square method has been conducted with MATLAB and it was observed that data fits the model (equation5-4) well at temperatures above $T_g + 10^\circ\text{C}$. So at the first stage instantaneous elastic modulus which is obtained from stress-strain curve was used to define

elastic properties into commercial FEM code ABAQUS 6.7-2 standard solver. Figure 5-3 shows the results of curve fitting in different temperature at a fixed strain rate of $0.1 \text{ } \frac{1}{\text{s}}$.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 5-3: Results of curve fitting with Maxwell model;(a)150°C, (b)160°C, (c)170°C (d)180°C, (e)190°C, (f)200°C

It can be seen that Maxwell model fits the experimental data at temperatures above $T_g + 10^\circ\text{C}$.

Elastic modulus obtained from curve fitting for different temperatures are listed in Table 5-2.

Table 5-2: Elastic modulus obtained from curve fitting with Maxwell model for different temperatures

Temperature ($^\circ\text{C}$)	Elastic Modulus(MPa)
150	88.4
160	9.64
170	6.45
180	4.95
190	2.71
200	1.33

5.2.4. Determination of the instantaneous response for hyperelastic-viscoelastic model

In the second approach, material is modeled as a hyperelastic material which also undergoes stress relaxation[41, 42]. The stress- strain curve in high strain rate is used as input to solver. Stress-finite strain curve is fitted to different strain energy potential of hyperelastic

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materials to see which theory fits the curve better. The results of compression test were fitted to different strain energy potentials and it was seen that for some strain energy potentials although model fitted data good, the material was stable just in a particular range of strains. In most cases, Ogden model (N=1), Arruda-Boyce and Reduced polynomial (N=1, N=3) were properly fitted to data. There are generally three considerations in choosing the strain energy potentials; the first is the goodness of fitting, the second is the stability of the material which ABAQUS always check it, and the third is the suitability of nature of test data to define coefficients for different strain energy potentials. In general, Ogden and van der Waals strain energy potentials are good when multiple experimental test data are available and Polynomial, Marlow and Arruda-Boyce Options are good when limited test data is available[63]. Based on all the above considerations, reduced polynomial (N=3, Yeoh's Model) is used for all the simulations above 150 °C. For Yeoh's Model the strain energy can be written as equation 5-5[64, 65].

$$U = \sum_{i=1}^3 C_{i0} \left(\bar{I}_1 - 3 \right)^i + \sum_{i=1}^3 \frac{1}{D_i} \left(J^{el} - 3 \right)^{2i} \quad (5-5)$$

Where U is the strain energy per unit of reference volume; C_{i0} and D_i are temperature dependent material parameters; $\bar{I}_1$ is the first deviatoric strain invariant defined as (equation 5-6):

$$\bar{I}_1 = \bar{\lambda}_1 + \bar{\lambda}_2 + \bar{\lambda}_3 \quad (5-6)$$

Where deviatoric strain is defined as: (equation 5-7)

$$\bar{\lambda}_i = J^{-\frac{1}{3}} \lambda_i \quad (5-7)$$

Where J is the total volume ratio, λ_i are the principal stretches. J^{el} in equation 5-5 is the elastic volume ratio as defined as: (equation 5-8)

$$J^{el} = \frac{J}{J^{th}} \quad (5-8)$$

J^{th} is thermal volume ratio and is defined as (equation 5-9):

$$J^{th} = (1 + \varepsilon^{th})^3 \quad (5-9)$$

Where ε^{th} is linear thermal expansion strain that is obtained from the temperature and the isotropic thermal expansion coefficient.

The results of curve fitting of compression test results in 160 °C with different models are shown in figure 5-4. The same trend is observed in all different temperatures.

Figure 5-4: Results of curve fitting of compression test results in 160 °C with different strain energy potentials; (Red: test data, Blue: Polynomial (N=1), Green: Ogden(N=2), Yellow: Arruda Boyce, Orange: Reduced Polynomial(N=3 Yeoh model))

Initial shear Modulus of material is defined as $\mu_0 = 2C_{10}$. The values of μ_0 obtained in different temperatures are listed in table 5-3.

Table 5-3: Initial shear Modulus based on Yeoh Model

Temperature (°C)	Initial shear modulus(Pa)
160	3464097
170	2186813
180	1758540
190	1060369
200	565649.9

5.2.5. Determination of Viscous response of material for both of the models

Compression relaxation test was conducted to obtain the viscous behavior of material. Although it's possible to obtain the relaxation behavior material from the compression test in different strain rates but the objective here was to check whether viscous behavior obtained from compression relaxation test is able to predict the strain rate dependent behavior of the material. Samples were compressed to 30% of their height and the history of compression stress was recorded for almost 10 minutes. The results are shown in figure 5-5.

Figure 5-5: Relaxation curves for PC in different temperatures (All temperatures are in °C)

All the stresses are normalized with respect to the stress at the maximum strain in each experiment so that the results could be compared. ABAQUS performs a nonlinear least-

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square fit of the relaxation test data to a Prony series (equation 5-10) for each temperature as it's required for simulation of compression test. For lens compression simulations, WLF (Williams-Landel-Ferry) equation which will be discussed later is used to define temperature dependent viscous behavior of material.

$$G_R(t) = G_0 \left(1 - \sum_{i=1}^N \bar{g}_i^p \left(1 - e^{-t/\tau_i} \right) \right) \quad (5-10)$$

Where $G_R(t)$ is the shear modulus at time t ; G_0 is the initial shear Modulus of material and $\bar{g}_i^p$ and τ_i are material constants. Data obtained for values of relaxation time coefficient and $\bar{g}_i^p$ for the material are listed in table 5-4.

Table 5-4: Relaxation coefficients of the material

Temperature (°C)	Relaxation Time coefficients(τ_i (s))(s)	($\bar{g}_i^p$)
160	1.9735	0.24583
	24.295	0.37356
	189.72	0.30132
170	0.0039	0.0740
	12.595	0.47236
	119.58	0.38721
180	4.0544	-2.2946
	4.0508	2.8845
	38.964	0.3974
190	1.2433	-160.59
	1.2434	161.16
	8.4934	0.42678
200	0.5299	-38.857
	0.5358	-96.362
	0.5352	135.64
	4.3119	0.5749

5.3. Volumetric response of material

PVT curve of the material was obtained from Moldflow databases. Volumetric test data and coefficient of thermal expansion required for modeling were obtained from the PVT curve below (Figure 5-6).

Figure 5-6: PC Lexan-123 PVT curve

5.4. FEM Simulation of Compression test

As mentioned above, the main objective in this part is to simulate a less complicated problem of simple compression test for two main reasons; Firstly, it acts as a tool to study the simulation process and secondly it helps to see if the results obtained from simulations are close to actual results of experiments. It is also possible to compare results of simulation with linear viscoelastic and hyperelastic-viscoelastic material models and experimental results of stress history. This provides an insight into why nonlinear viscoelastic material model is more accurate in predicting the material behavior. Simulation of compression test was also a very good starting point to see the effect of different parameters in simulation of polymer deformation.

5.4.1. Geometry, boundary conditions, Meshing and Material properties

Figure 5-7 shows a 2-D axisymmetric simulation model of compression test. Test specimens were 25mm in diameter and 25mm in height. The Polymer test specimen is meshed with 1250 Quadratic four node axisymmetric elements with 25 elements along the radius and 50 Elements along the height. Elastic modulus of test device grippers was much higher than polymers in high temperatures so that upper and lower surfaces were simulated as rigid surfaces. No change in temperature was assumed and no-slip boundary condition was applied to the upper and lower surfaces of the model. Simulations were performed using commercial FEM code ABAQUS 6.7-2 standard solver. Comparison between figure 5-1 and figure 5-7 shows that the geometry and the boundary conditions applied to the model match well with the actual test conditions. Relaxation behavior of material was defined through definition of Prony series. As tests were performed at a fixed temperature point, data input didn't include temperature dependent properties of material. The data obtained from all 18 compression tests resulted in similar simulation input parameters so as an instance, the data obtained from compression test in 160 °C and used in simulation are listed respectively in table 5-5.

Table 5-5: Input data for compression test simulation in 160 °C (a) simulation using linear viscoelastic model; (b) simulation using rubber like material model

Density(kg/m ³)	1190
Elastic modulus(Pa)	9.64e6
Characteristic Relaxation time coefficients (s)	1.9735 24.295 189.72
Volumetric response	PVT data

(a)

Density (kg/m ³)	1190
Initial shear Modulus(Pa)	Yeoh Hyperelastic model 3.464e6
Characteristic Relaxation time coefficients (s)	1.9735 24.295 189.72
Volumetric response	PVT data

(b)

Figure 5-7: 2-D axisymmetric simulation model of compression test; (a)undeformed model (b) deformed model

5.4.2. Results of compression test simulation

One of the shortcomings of both of ABAQUS linear viscoelastic and hyperelastic-viscoelastic material models is that none of them is able to predict the yield behavior of

material in temperatures below T_g . Although high order strain energy potentials fit the experimental data very well and are able to predict the yield behavior, the material model is unstable for temperatures below T_g . That's why the simulations are performed only in temperatures above T_g . Figure 5-8 shows the result of compression test in temperature of 160°C and strain rate of $0.1/\text{s}$ and compares that to predicted FEM simulation results of stress versus strain obtained from linear viscoelastic and hyperelastic-viscoelastic models.

Figure 5-8: Comparison of the FEM predicted force and the actual force in compression test of samples in 160°C and $0.1/\text{s}$

As shown in Figure 5-8 forces obtained from FEM analysis are exactly similar to the actual forces of the experiment for high strain rates although in lower strain rates and higher temperatures there are some differences in slope of the curves. That difference could be due to the effect of relaxation which increases when the temperature increases or strain rate decreases. Simulating the process for different temperatures and strain rates shows that hyperelastic-viscoelastic model is good for modeling of polymers in temperatures slightly above T_g . The predicted stress strain curves and actual ones for different temperatures and strain rates are shown in following figures (figure 5-9 to figure 5-12).

Figure 5-9: Comparison of the FEM predicted force and the actual force in compression test of samples in 160 °C
(a) 0.01 1/s, (b) 0.001 1/s

Figure 5-10: Comparison of the FEM predicted force and the actual force in compression test of samples in 170°C ; (a)0.1 1/s, (b)0.01 1/s, (c)0.001 1/s

Figure 5-11: Comparison of the FEM predicted force and the actual force in compression test of samples in 180°C; (a) 0.1 1/s, (b) 0.01 1/s, (c) 0.001 1/s

Figure 5-12: Comparison of the FEM predicted force and the actual force in compression test of samples in 190 °C ; (a) 0.1 1/s, (b) 0.01 1/s, (c) 0.001 1/s

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The results show that both linear viscoelastic and hyperelastic-viscoelastic models can predict the history of stress in temperatures above $T_g + 10^\circ\text{C}$ but as the temperature goes higher or the strain rate decreases, the results of linear viscoelastic material show more deviation from the actual results and this shows that instantaneous behavior of material cannot be considered as linear and polymers are more likely to be rubberlike materials which also exhibit high rate of stress relaxation in high temperatures.

The definition of instantaneous response of material in higher temperatures is not accurate as the relaxation time coefficient reduces drastically in very high temperatures. The stress strain relationship of material at strain rate of 0.1s^{-1} can be a good approximation of instantaneous response of material when the temperature is around T_g or slightly higher than that. It's because the relaxation time of the material is much higher than the time of the compression test in temperatures around T_g . In higher temperatures around 190°C ($T_g + 40^\circ\text{C}$) the stress-strain curve obtained in strain rate of 0.1s^{-1} is not a good approximation of the instantaneous response as the relaxation time of the material and time of compression are comparable to each other. As it was impossible to do compression test in higher strain rates, the stress-strain curve in 0.1s^{-1} was used for temperatures of 190°C and higher as an approximation of instantaneous response of material.

Main results of this part can be summarized as:

1. Simple way of determining the elastic modulus of material in temperatures above $T_g + 10^\circ\text{C}$ is proposed.
2. The results show that both hyperelastic-viscoelastic and linear viscoelastic material models are able to predict the behavior of polymers in temperatures above $T_g + 10^\circ\text{C}$ in

high strain rates but as the temperature increases or strain rate decreases, hyperelastic viscoelastic material model show better agreement with the experiments.

5.5. FEM modeling of lens compression molding

As mentioned above, simulation process consists of four steps as the experiment also is composed of four main stages. Mold filling stage, cooling stage, de-molding stage, and cooling to room temperature after de-molding. In order to model the molding step, rheological behavior of material under molding condition should be studied. As there were insufficient databases to get the required information, compression tests were designed and performed on material to derive stress strain relation and also the time dependent characteristics of material. Some of the data also obtained from databases available and previous studies. PVT curve of the material was obtained from “Moldflow” databases. Similar studies were done on glass compression simulation using poisson’s ratio of glass[6].

5.5.1. Geometry, boundary conditions, Meshing and Material properties

User controlled inputs to FEM Model include: instantaneous response and relaxation time coefficient of material in molding temperature, PVT relation of material, contact behavior of mold and polymer and boundary conditions in Molding step, temperature dependent mechanical and thermal properties of material, contact behavior and heat transfer mechanism in cooling stage, friction and adhesion forces and change in boundary conditions in de-molding stage.

Molding experiments composed of three main stages. Mold filling stage, cooling stage and de-molding stage. De-molding stage is divided into two steps in the simulations: Release of the upper mold insert, and de-molding from the lower mold insert following cooling to

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room temperature. Details of the timing, mechanical and thermal boundary conditions for these four steps when the molding temperature is 160°C are summarized in table 5-6. In higher molding temperatures the time of the cooling step has been increased while other conditions are identical.

Table 5-6: Details of the timing, mechanical and thermal boundary conditions for all four steps of simulations

Step		Mold filling	Cooling	Upper mold insert release	De-molding and cooling to room temperature
Time(s)		0.5	400	1	600
Boundary condition	Mechanical	No slip	Simple shear friction	Simple shear friction	Free
	Thermal	Isolated	Uniform cooling	Isolated	Uniform Cooling

Figure 5-13 shows a 2-D axisymmetric simulation model of lens compression molding. Initial polymer gob is 1.4mm in diameter and 0.4mm in height. The Polymer gob is meshed with 1120 Quadratic four node axisymmetric elements with 20 elements along its height and 56 Elements along its radius. The upper and lower mold inserts were modeled as rigid bodies as the elastic modulus of stainless steel is much higher than the polymer in high processing temperatures.

Figure 5-13: 2-D axisymmetric simulation model of lens compression molding

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Material was modeled as a hyperelastic viscoelastic material undergoing stress relaxation. Determination of instantaneous and time dependent behavior of material are described in section 5.2.4 and 5.2.5. Material was modeled as a thermo-rheologically simple material and temperature dependent viscous behavior of that was considered as a shift factor which can be expressed by Williams-Landel-Ferry (WLF) equation (equation 5-11). The parameters for the WLF equation were obtained from the literature[41].

$$\text{Log}(A) = -\frac{C1(\theta - \theta_0)}{C2 + (\theta - \theta_0)} \quad (5-11)$$

$$C1=13.21, C2=48.79, \theta_0 = T_g + 10 = 158^\circ\text{C}$$

Thermal properties of polycarbonate such as heat transfer coefficient and coefficient of thermal expansion were obtained from the material supplier[66]. Contact behavior consists of adhesion and friction properties of touching surfaces which should be determined as input into the FEM simulation solver. In molding stage, no slip boundary condition was applied to the model but in cooling and de-molding a simple shear friction model was applied. The coefficient of friction was set to 0.3 which is identical to most of the studies done on de-molding of polymers[67]. Data input for simulation of Lens molding is summarized in table 5-7.

Table 5-7: Data input for lens compression simulation

Density(kg/m ³)	1190
Initial shear Modulus(Pa)	3.464e6
Characteristic Relaxation time coefficients(s)	1.9735 24.295 189.72
Friction coefficient	0.3
Constant for WLF equation	C1=13.21 C2=48.79 Reference Temperature= 160 °C

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In this study, a uniform change in temperature was assumed in the cooling stage. This is due to the fact that (i) it was hard to determine the exact heat transfer mechanism in the mold lens interface, and (ii) the part is so tiny and temperature gradient in the lens was expected to be minute (volume of the whole lens is only 0.62mm^3).

5.5.2. Material definition

As mentioned above, deformation of polymers which are known as viscoelastic materials can be explained by isothermal non-linear elasticity theory[68]. In this study, time and temperature dependent behavior of the material are determined from the experiments and material is modeled as a hyperelastic-viscoelastic material. Uniaxial compression test is used to characterize the strain stress behavior of material. Data obtained from the experiments are then curve fitted to different strain energy potential models. Time dependent characteristics of material are defined independently from temperature and strain rate characteristics of that.

Using strain separable model has several advantages. First, a rubber-like constitutive model such as the van der Waals, Ogden, Polynomial or Mooney-Rivlin models which are also available models in ABAQUS can be used to describe the nonlinear instantaneous stress strain behavior of material, and Second, the stress relaxation behavior is only a function of time and does not vary with strain or strain rate, and thus can be characterized using standardized viscoelastic stress relaxation tests. This stress relaxation behavior can be characterized by the Prony series which is also available in ABAQUS[69].

The change in instantaneous response of material with temperature in the cooling stage is not considered. This may not influence the results much as long as internal stresses after molding step is less than 5% of the maximum stress in all the simulations.

5.5.3. Results of lens compression simulation and discussion

The maximum in-plane, minimum in-plane and out of plane principal residual stress distribution of the molded lenses in different molding temperatures are shown in figure 5-14. The principal residual stresses are of great importance as the amount of birefringence is a function difference between principal stresses within the material. It can be seen that amount of predicted residual stress and consequently the difference between them decreases as the molding temperature increases.

Figure 5-14: Max. in-plane, Min. in-plane and out of plane principal residual stresses in different molding temperatures; (a)160 °C, (b)170 °C, (c)180 °C, (d)190 °C, (e)200 °C (Note that the color scale is different in each figure)

It can be seen that amount of predicted von-Mises residual stress decreases as the molding temperature increases (Table 5-8). It can also be seen that the amount of spring back is more for temperatures around T_g and the deviation of the profile from spherical profile decrease as the temperature increases to temperatures around $T_g+20\text{ }^{\circ}\text{C}$. If the temperature is further increased, the radius of curvature decreases to less than that of the mold because the effect of shrinkage.

Table 5-8: Maximum residual stress at different molding temperatures

Molding temperature (°C)	Maximum residual stress(Pa)
160	1.792e6
170	5.254e5
180	7.018e4
190	6.81e4
200	8.79e3

Figure 5-15 shows the distribution of von-Mises stress at the end of different stages in 160°C. Similar results for distribution of stress are obtained for different temperatures.

Figure 5-15: Distribution of von-Mises stress at the end of different steps; (a) Molding, (b) Cooling, (c) De-molding and (d) De-molding and cooling to room temperature

Figure 5-16 shows the difference between the predicted curves in different molding temperatures. The results show that the lower layers of the material has compression residual stress and intend to bring the material back to its initial condition where the upper layers of that have tensile residual stress which makes the part maintain its shape. The balance between

the forces of upper and lower layers and the stresses resulted from cooling of material determine the amount of springback.

Figure 5-16: Comparison of the profiles of the lenses molded in different temperatures
(All temperatures are in °C)

Briefly, There are two important factors that determine the final shape of the lens: (1) The amount of internal stresses at the end of molding and cooling stages and (2) shrinkage of material. In temperatures around T_g , The effect of internal stresses is more dominant and that's the why the final radius of curvature of the lens is more than that of the die. In higher temperatures of $T_g + 30^\circ\text{C}$ and higher, the effect of shrinkage is more dominant thus reducing the resultant lens curvature.

It also can be seen that maximum residual stress occurred at the edge where spherical part attaches to the cylindrical part. This shows why de-molding step is very critical as in many of the experiments the parts are torn from the connection of cylindrical and spherical parts when de-molding temperature wasn't low enough. At last the actual result of lens compression in 170°C was compared to the FEM simulation results. Good agreement between FEM predicted curve and actual lens profile in different temperatures from $T_g + 10^\circ\text{C}$ to $T_g + 50^\circ\text{C}$

could be obtained showing that FEM simulation is a suitable tool to predict the nonlinear viscoelastic behavior of polymers. Figure 5-17 shows the comparison between the mold profile, FEM simulation results and actual lens profile molded in different temperatures.

(a)

(b)

(c)

Figure 5-17: Comparison of profiles of simulation, Mold and molded lens in different molding temperatures; (a)160 °C, (b)170 °C, (c)180 °C, (d)190 °C, (e)200 °C

Comparison between finite element simulation (FES) and experimental results in high strain rates shows that the effect of molding temperature on lens profile can be predicted through FEM simulation generally, although the exact profile of the lenses is not predicted. FEM results show that in temperatures from 180 °C and above, the radius of curvature of the lenses doesn't change much. Experimental results also show the same trend. In experimental results in high strain rates, it can be seen that the radius of curvature of the lenses molded in temperatures from T_g to $T_g+20^\circ\text{C}$ is more than that of the mold where in higher temperatures it reduces to lower than 0.7mm and it doesn't change much in temperatures above 180 °C. The process is not successful in temperatures above 200 °C because the mold doesn't fill completely as the material is too soft.

CHAPTER 6

STATISTICAL STUDY ON THE EFFECT OF DIFFERENT MOLDING PARAMETERS

6.1. Design of experiments

Taguchi orthogonal array (L_9) was used to analyze the effect of molding temperature, molding velocity and de-molding temperature on the variation of radius of curvature, focal length and lens surface roughness. Each factor has three levels and the levels are coded 1, 2 and 3. Table 6-1 shows the values of each factor. 9 set of factors shown in Table 6-2 are required for L_9 orthogonal array where a total of 27 sets are required for a full factorial design. If each experiment is to be repeated 3 times, 27 runs are required for Taguchi method where 81 runs are required for full factorial design.

The main advantage of Taguchi method is the possibility of analyzing interactions between factors. The numbers of runs are reduced significantly as compared to factorial design but it carries the risk of missing important data when there is high level interaction between factors. However this is rarely happens in practice[37]. In hot embossing, embossing temperature, compression time, compression force and de-molding temperature have the most dominant effect on the sample profile[70]. In injection molding and injection compression molding, temperature, packing pressure and holding time have the most dominant effects[71] but injection speed and de-molding temperature also affect the process.

Table 6-1: Levels of each factor and their labels

Factor \ Table	1	2	3
Molding temperature (°C)	150	170	190
molding velocity (μm/s)	100	200	300
De-molding temperature (°C)	50	70	90

Table 6-2: L₉ orthogonal array for design of experiments of hot compression molding of lenses

Factors Exp. Nom.	Molding temperature	Molding Velocity	De-molding temperature
1	1	1	2
2	2	1	3
3	3	1	1
4	1	2	3
5	2	2	1
6	3	2	2
7	1	3	1
8	2	3	2
9	3	3	3

Figure 6-1(a) to figure 6-1(i) show the SEM picture of these 9 lenses.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

As shown in figure 6-1, Surface roughness and the profile of the lenses molded in 190 °C (figure 6-1(a), figure 6-1(b) and figure 6-1(d)) were not always satisfactory. The process has not always been successful when the molding temperature is 190 °C. In molding temperatures above 200 °C, the process is more likely to be unsuccessful.

6.2. Effect of processing variables

The effect of processing factors on three main characteristics of lenses, focal length, radius of curvature and lens surface roughness, was analyzed. It could be seen that in high strain rates the radius of curvature of the lens profile reduces as the molding temperature increases. This is due to the higher spring back of material in lower temperatures because the

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relatively strong elastic response of the material. In lower strain rates, this variance seems to vanish and even it could be seen that in very low strain rates the radius of curvature increases as the temperature increases. There are two explanations for that. The first is that in high temperatures well above the transition temperature of material, material is so soft and flow downward easily and may not fill the mold cavity completely when the strain rate is small. The other reason may be the presence of air which may not let the material fill the mold cavity specially when the material is too soft. These two effects may evolve in changing the effect of temperature on radius of curvature in different strain rates.

In this study, Each experiment was repeated three times and the standard deviation of the results of radius of curvature was found to be less than 10%. The average of response variables in each experimental set was used for analysis. The results of lens curvature, lens surface roughness, theoretical and experimental focal length are summarized in table 6-3.

Table 6-3: Response factors for different fabrications parameters

Response Factors Exp. Nom.	Radius of curvature(μm)	Surface roughness(μm)	Theoretical Focal length(mm)	Experimental focal length(mm)
1	734.65	0.967	1.312	1.44
2	714.45	1.27	1.276	1.35
3	702.96	2.85	1.255	1.24
4	710.34	1.82	1.268	1.27
5	692.67	1.12	1.237	1.24
6	687.23	3.1	1.227	1.21
7	682.54	0.892	1.219	1.29
8	672.23	1.23	1.200	1.26
9	678.12	3.85	1.211	1.21

Qualitative analysis of the effect of each factor on the response variable can be shown by charts and diagrams made mention in literature review. The qualitative analyze of the effect of control factors on the response variables is shown in figure 6-2. Figure 6-2a, 6-2b and 6-2c show the effect of control factors on the radius of curvature, surface roughness and experimental focal length respectively.

Figure 6-2: Effect of control factors on the response variables

One quantitative approach in determining the effect of different variables on response variables is analyzing the signal to noise ratio (S/N) meaning that a big S/N represent a high level of effect for one factor where a low S/N represent a low effect[70]. Equation 6-1 to 6-3 Show how signal to noise ratio is calculated[71].

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$$S/N = 10 \log \left(\frac{\mu^2}{\sigma^2} \right) \quad (6-1)$$

Where

$$\mu = \frac{1}{n} \sum_{i=1}^n y_i \quad (6-2)$$

And

$$\sigma^2 = \frac{1}{n-1} \sum_{i=1}^n (y_i - \mu)^2 \quad (6-3)$$

Another quantitative view of the contribution of each factor in change of response variable which is used in this study is as follows. In this approach the fraction of the change of one response variable with respect to the particular factor (S_x) to the total variation of that response variable is determined [37, 72] by (equation 6-4 to 6-6).

$$S_T = \sum_{i=1}^n y_i^2 - \frac{\left(\sum_{i=1}^n y_i \right)^2}{n} \quad (6-4)$$

Where S_T is the total variation of response variable Y , and n represent the number of total experiments.

Variation of response factor Y due to the effect of factor X can be determined as follows (equation 6-5):

$$S_x = \sum_{k=1}^n \frac{X_k^2}{N_{X_k}} - \frac{\left(\sum_{i=1}^n y_i \right)^2}{n} \quad (6-5)$$

Where X_k is the sum of result when parameter X is at level k and N_{X_k} is the number of results when parameter X is at level k

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The percentage contribution of each variable to the total variation of the results can be calculated as follows (equation 6-6):

$$P_x = \frac{S_x}{S_T} \times 100 \quad (6-6)$$

Table 6-4 shows the values of total variation, variation due to the effect of one factor and percentage contribution of each factor on the total variation of the results. (1, 2 and 3 represent molding temperature, molding velocity and de-molding temperature respectively)

Table 6-4: Total variation, variation due to the effect of one factor and percentage contribution of each factor on the total variation of the results

Response Factors Results	Radius of curvature	Surface roughness	Focal length(experimental)
S_T	3228.27	9.50	0.0441
S_1	661.13	8.41	0.0194
S_2	2368.02	0.19	0.0189
S_3	199.11	0.9	0.0058
P_1	20.2%	88.5%	44%
P_2	73.6%	2%	42.8%
P_3	6.2%	9.5%	13.2%

As shown in table 6-4 the effect of molding velocity and molding temperature is more dominant on the lens surface profile than the effect of de-molding temperature. The effect of molding velocity is very high because it directly affects the mold filling stage. As shown in table 6-3 lenses molded in higher velocities have generally lower radius of curvature which means that the mold filling was better in higher strain rates. The effect of molding temperature on the lens radius of curvature is predicted in FEM simulation analysis and as it was expected, the radius of curvature decreases as the molding temperature increases. It's due

to elastic spring-back of the material in de-molding stage. The effect of de-molding temperature on lens curvature is not dominant statistically.

The percentage contribution of different factors on focal length variation also shows a similar trend as the focal lens of the lenses is directly affected by lens radius of curvature. But the effect of molding temperature has higher value. This is because the lenses are not completely symmetrical (due to the effect of non symmetrical cooling and distortion after de-molding) and it's hard to determine the average radius of curvature but the focal length of the lens is a unique character for the lens which gives a better idea of the radius of curvature.

The results of surface roughness analysis show that the molding temperature has the greatest and the most dominant effect on surface roughness of lenses which has great impact on the lens quality. The results show that lower molding temperature will results in higher surface quality in compression molding. The effect of de-molding temperature is also significant as in higher de-molding temperatures, the surface roughness trends to increase. Figure 6-3 shows the image surface profile of the molded lenses sorted by Taguchi L9 orthogonal array obtained from confocal microscopy.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i)

Figure 6-3: Image surface profile of the lenses molded in different processing parameters sorted by Taguchi L9 orthogonal array

After optimization of the process based on both the theoretical results of simulations and experimental results of DOE, It was found that lenses molded in temperatures slightly above T_g (e.g. 170 °C), with high compression velocity of almost 300 $\mu\text{m/s}$ and demolded in relatively low temperatures of almost 50 °C generally show lower surface roughness and less deviation from spherical profile. Figure 6-4 shows the SEM picture of the lens fabricated using these parameters.

Figure 6-4: Fabricated lens after Process optimization

CHAPTER 7

LENS CHARACTERIZATION

7.1. Geometrical characterization

Geometrical characterization techniques are the techniques which determine the geometrical characteristics of lenses such as lens diameter, sag height, radius of curvature. The methods used in this study are scanning electron microscopy (SEM), white light confocal microscopy and contact profilometry.

7.1.1. SEM

Scanning electron microscopy (SEM) is used in this study mainly to get the picture of the lenses and the defect analysis. Although surface profile of the lenses could be obtained by SEM microscopy, it has not been utilized for that purpose as long as there are more convenient ways to study that. Top, bottom and side portions of the microlens were coated with a 30nm layer of gold and the SEM pictures are shown in Figure 7-1.

SEM pictures indicate that most of the defects are more likely to be the effect of remaining material from the previous molding cycles. In order to avoid such problems lower molding temperatures were preferred.

(a)

(b)

(c)

Figure 7-1: SEM Picture of the first molded lens; (a)top view, (b)bottom view and (c) side view.

7.1.2. White light confocal microscopy

In this research, White light confocal microscopy was used mainly to obtain the surface roughness of the lenses as the resolution of confocal microscopy is higher than other microscopic techniques. The value for R_a was found to be almost $2\mu\text{m}$ for lenses molded in temperatures around 190°C . The picture and the profile obtained from confocal microscopy are shown in Figure 7-2.

Figure 7-2: White light confocal microscopy; (a) 3D view, (b) Profile

The main difficulty here was the poor reflection of light beam from the defects which make it very hard to get complete image of the lens. Loss of data points at the edges of the lens where the surfaces are too steep was also a problem. Coating the sample with a layer of metal could solve the problem but it suffers from the problem of destroying the samples as they lose their transparency. Root mean square roughness of the 25nm could be achieved for

this process (figure 7-3) using low molding temperature (150 °C), high molding velocity (1 mm/sec) and low de-molding temperature (50 °C).

Figure 7-3: White light confocal microscopy of a good lens having the surface roughness of 25 nm

7.1.3. Contact profilometry

Contact profilometry was used to determine the surface profile (if the lenses are shadow enough) and sag height of the lenses accurately. Figure 7-4 shows 3D image and profile of the lens obtained from contact profilometry.

Figure 7-4: Shape and profile of the lens obtained from contact profilometry

Studying the surface profile of the lenses molded in different molding temperatures shows that at Temperatures from T_g to $T_g + 50\text{ }^{\circ}\text{C}$, increasing the molding temperatures results in decreasing the lens surface profile. In higher temperatures, either the process was unsuccessful or radius of curvature increases as temperature increases. This is mainly because the material is too soft at temperatures higher than $T_g + 50\text{ }^{\circ}\text{C}$ and flow downward causing inappropriate mold filling in the molding stage.

7.2. Optical characterization

The feasibility of thermoforming of polymer stand-alone lenses with size of almost 1mm has been studied. The results of compression molding show that a good replication of mold surface profile can be obtained through thermoforming at temperatures above T_g . FEM simulation of the process also conducted and helped me to gain an idea of predicting the deviation of profile of the lenses from spherical profile due to the effects of residual stresses and shrinkage of material in cooling stage. Beside all these works, the main problem which is whether the fabricated lens is suitable for the desired applications is remained open. To answer this, optical properties and real applications of the lenses are discussed in this section.

Optical measurements have been done by variety of techniques. From each of the techniques, some particular information about optical performance of lenses can be obtained. Devices such as interferometers, scatterometer, charged coupled devices and rotating slit scanners are utilized to measure optical performance of lenses. In order to have a complete characterization of optical performance of the lenses, the following four aspect were covered: (1) Focal length and focal spot size characterization, (2) Normal imaging (3) fluorescence collection efficiency and fluorescence imaging ability of the lenses (the ability of the lens to

image fluorescent micro spheres) and (4) real endoscopic probe applications and depth sensitive imaging power of the microlenses.

7.2.1. Focal length characterization

Studies on microlens fabrication usually determine the focal length and focal spot size of the lenses as the first crucial factor for them. An identical experimental concept is utilized in most of these studies to measure such characteristics([73],[74]). In this study, a similar set up is designed for the purpose. The set up consists of a laser source(473nm laser), a translator with the accuracy of $10\mu\text{m}$ which is very good in comparison with the range of focal length (almost 1.3mm), an objective lens, a CCD camera and a lens holder which all are placed on an optical table as shown in Figure 7-5. The idea behind such a set up can be stated as: the distance the stage travels to change the focus from the surface of the lens to the focal point is the focal distance of the lens.

Figure 7-5: Set up for focal length characterization

Figure 7-6 shows the experimental set up used for focal length and focal spot size characterization. The objective lens and the CCD camera work as the imaging unit which is used for imaging the focal point and surface of the lens and connected to a computer. A coherent light beam is passed and collimated through the microlens. The imaging unit is moved horizontally to image the smallest spot point of light formed by the microlens. The smallest spot seen on the monitor is the image of focal plane of the lens. The stage is then

moved to focus on the surface of the lens. The distance which stage travels is the focal length of the lens.

Figure 7-6: Experimental set up used for focal length and focal spot size characterization

The focal length is measured to be 1.34mm which is more than its theoretical value. The theoretical value of the microlens found to be 1.298mm based on the following formula (equation 7-1) obtained from ray tracing method.

$$f = \frac{R}{n-1} \quad (7-1)$$

Where f is the focal distance, R is the radius of curvature and n is the refractive index of the lens. Radius of curvature of the lens can be calculated having the sag height and diameter of that. These characteristics are the results of geometrical characterization of the lenses. Figure 7-7 shows the image of the focal point and the surface of lens. Light distribution at the focal point and the focal spot size of the lenses are analyzed through the software “Image J”. Figure 7-8 shows the light distribution of the microlens output at the focal plane. The diagram was almost the same for lenses molded in different processing conditions.

Figure 7-7: Images of the focal point and surface of the lens; (a) focal point, (b) surface of the lens

Figure 7-8: Light distribution at the focal spot.

The focal spot size is calculated based on $1/e^2$ of the maximum intensity and is found to be $38\mu\text{m}$. The focal spot size of the microlens is calculated based on the pixel size of the camera and the magnification of the imaging lens. Figure 7-9 shows how the size of the focal spot of

the lens is measured. The value of focal distance shows that the molded lens can be used in fiber probe focusing applications. Also, the focal spot size of the lens shows that the lens is suitable for imaging applications.

Figure 7-9: Focal spot size of the microlens

In order to gain a better understanding of the focusing ability of the lens, planes with different distances from the lens surface are imaged. The images are then analyzed and the intensity profile is extracted. Figure 7-10 shows the images of the different planes where the first one is at 100 μm distance from lens surface and the last one is the focal plane image of the lens (1340 μm distance from the lens surface). The pictures shown in figure 7-10 are then analyzed and the profile is extracted as shown in figure 7-11.

(a)

(b)

(c)

(d)

Figure 7-10: Images taken at different distances from lens surface; (a) at 100 μm distance form lens surface, (b) at 600 μm distance form lens surface (c) at 1000 μm distance form lens surface (c) at focal point(at 1340 μm distance from lens surface)

Figure 7-11: Light distribution at different distances from lens surface; (a) at 100 μ m distance form lens surface, (b) at 600 μ m distance form lens surface (c) at 1000 μ m distance form lens surface (d) at focal point (at 1340 μ m distance from lens surface)

The capability of the lens for real endoscopic applications is discussed in following sections. The studies consist of: (1) Investigating the finest feature of the USAF test chart

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which can be resolved by the microlens, (2) The effect of microlens of the fluorescence collection behavior of the fiber system, (3) the ability of the lens to image micro spheres with the size of almost $4\mu\text{m}$ which is less than the approximate size of human epithelial cells which are usually $5\text{--}15\mu\text{m}$ in diameter.

7.2.2. While light imaging power and fluorescence collection efficiency characterization

There are two general applications for the lens ended fibers : (1) Optical communication application and data storage devices which also include applications such as pick up heads in computer technology, (2) biomedical application which involve surgical application as well as imaging applications for disease recognition. The main objective in this study is to use the lens ended fiber as an endoscope to image the inner tissues of the human body for tissue inflation or other disorders detection. In order to determine the imaging power of the system containing the fabricated microlens, a way to characterize the spatial resolution of the imaging system must be sought.

Theoretical resolution of the fiber optic system is dependent on the magnification of the lens installed at the fiber tip and number of fibers along the fiber diameter (number of pixels) and can be calculated as : $\text{Theoretical resolution} = \text{Fiber spacing} / \text{lens magnification}$. Where fiber spacing is diameter of the fiber bundle divided to the number of fibers. However the experimental resolution of the system is not exactly the same as the theoretical value and resolution test charts are normally used for such purpose in white light microscopy. For the fiber used in this study the number of fibers along the fiber bundle found to be 267/mm. considering the lens magnification for the object distance as 0.7mm, the theoretical lateral resolution of the system is almost $5.35\mu\text{m}$.

USAF Resolution Test Chart is a resolution test pattern conforms to MIL-STD-150A standard, set by US air force in 1951 and similar charts are still widely accepted to test the resolving power of optical imaging systems such as microscopes, cameras and endoscopic set ups. As shown in Figure 7-12, the pattern consists of groups of three bars with dimensions from big to small. Instead of the old pattern modern patterns which are suitable for modern lens analysis are recently used.

Figure 7-12: 1951 USAF resolution test chart[75]

As it's obvious from the name of the chart, it's used to measure the highest resolution of an optical system. Working principle is determining the ability of the system to produce image of different patterns on the chart with different sizes of columns[76]. Because of several reasons such as complex numbering system and use of a look-up chart, 1951 resolution test chart is not used widely and modern charts such as T21 and T22 as shown in figure 7-13 are used widely to determine the resolution power of imaging systems.

The actual lateral resolution of the optic system can be determined using table 7-1. The resolution is the size of the smallest pattern which the optical system is capable of imaging. The size of patterns on USAF test chart is determined by: $\text{Resolution} = 2^{\left(\text{Group} + \frac{(\text{element}-1)}{6}\right)}$.

portion of the fiber so as to match the diameter of 1mm for perfect fit. The lens is attached to the fiber end in a way that the centre of fiber facet is located at the centre of the lens.

Figure 7-15: Experimental set up for imaging efficiency characterization of the microlenses

The images were taken with and without the lens attached to end facet of the fiber and are compared to each other. Figure 7-16 shows the image obtained for the sixth element of the group number 1 of the USAF resolution test chart.

Figure 7-16: Image obtained for the sixth element of the group number 1 of the USAF resolution test chart; (a) without the microlens, (b) with the microlens

Other pictures are also taken to see the change in the imaging capability of the fiber when the microlens is attached to the fiber facet. Figure 7-17 and figure 7-18 show the images of the third element of the group number 2 and first element of group number 4 respectively.

Figure 7-17: Images of the third element of the group number 2; (a) without the microlens, (b) with the microlens

Figure 7-18: Images of the first element of the group number 4; (a) without the microlens, (b) with the microlens

The actual resolution of the system consisting the microlens and the fiber bundle is characterized by the smallest feature of the resolution test chart which the lens ended fiber can image. Figure 7-19 shows that the lens ended fiber is able to image the fifth element of the group number 4 but the image of the sixth element is not clear at all. This shows that the actual resolution of the system in white light imaging is almost $35\mu\text{m}$.

The image of the last four elements of the group number 4 when the microlens is not attached to the fiber end is shown in figure 7-20. It is quite obvious that the fabricated microlens enhances the imaging power of the fiber. Collection power of the fiber is also modified.

Figure 7-19: Image of the last four element of group number 4

Figure 7-20: Image of the last four elements of the group number 4 when the microlens is not attached to the fiber end

7.2.3. Fluorescence collection and imaging efficiency characterization of microlenses

The next step to characterize the optical performance of the optical system which consists of the lens and optical fiber is measuring the fluorescence collection efficiency of the microlens. The incoming photons of light are collected and transferred to measure the intensity and the total number of photons collected. The spatial distribution of photons can also be measured. The fluorescence collection is measured two times once when the microlens is attached to the fiber facet and once when the lens is not attached. The comparison between the two distributions shows the effect of the microlens and distribution efficiency of that. Figure 7-21 shows the schematic of the set up used for fluorescence collection efficiency measurement of the microlens.

Figure 7-21: Schematic of the set up used for fluorescence collection efficiency measurement of the microlens

A 473nm laser light (blue light) is allowed to excite the fluorescent sample which emits green light. The emitted fluorescence light is collected by the same fiber. The microlens is attached to the fiber facet to enhance the collection of fluorescence light. The collected fluorescence light is guided to optical spectrometer as shown in figure 7-21. The spectrometer is connected to the computer to analyze the collected fluorescence spectrum. Figure 7-22 shows the actual set up used for determining the fluorescence collection efficiency of the microlenses.

Figure 7-22: Set up used for determining the collection efficiency of the microlenses

Figure 7-23 shows the comparison between spectrum of the collected light from the fluorescent target when the microlens is attached to the fiber and when it's not attached.

Figure 7-23: Comparison between spectrum of the collected light from the fluorescent target when the microlens is attached to the fiber and when it's not attached

The comparison shows that the collection of the fluorescence light is enhanced well when the fabricated microlens is attached to the fiber. The comparison between the fluorescence collection efficiency when the lens is attached and when is not attached indicate that the lens modify the collection power of the endoscopic system. Figure 7-24 shows the spectrum collected by four different lenses. The results show that the lenses enhance the collection behavior of the fiber well.

Figure 7-24: The spectrum collected by four different lenses

The distance between the fiber and the fluorescent target is almost 3mm where the distance between the fiber end facet and the microlens plane is almost 1mm. The effect of “d”

(the distance between the fiber end facet and lens plane) is also studied. “d” has been changed from zero to 2mm in 0.5mm steps and the fluorescence spectrum is collected in each step. Figure 7-25 shows the effect of “d” on the fluorescence collection of the lens ended fiber.

Figure 7-25: The spectrum collected in different “d” values

It can be seen that the collection efficiency enhances as “d” decreases from 2mm to 1.5mm. It can be seen that the collection of the fluorescence again decreases as the distance reduces more. The highest fluorescence pick could be obtained at $d \approx 1.5\text{mm}$.

In order to characterize the imaging power of the microlens in the fluorescence mode, fluorescent micro spheres are imaged through the lens ended fiber. The approximate size of micro spheres is $4\mu\text{m}$. These micro spheres provide a good sample for testing the microlens ended fiber performance as the size of the nuclei of human epithelial cells are usually $5\text{--}15\mu\text{m}$ in diameter. The image shows the capability of microlens to resolve the micro spheres satisfactorily.

The schematic diagram and the actual set up utilized for the fluorescence imaging characterization, as shown in figure 7-26, is much similar to the set up used for characterization of fluorescence spectrum analysis. The only differences are that the sample

is replaced by prepared micro spheres sample and a color CCD camera is used as the detector.

Figure 7-26: Set up for micro sphere resolving power characterization of the microlenses

For proper imaging of the micro spheres, the distance between lens and the fiber was optimized to be 2mm and the working distance was set at 2.5mm. The image of the micro spheres using the fiber probe with the molded lens is shown in figure 7-27.

Figure 7-27: Image of the micro spheres obtained through the lens-ended fiber

The images are obtained in different working distances of the microlens is characterized. Figure 7-28 shows the images of the micro spheres at different planes. Figure 7-28a shows

the image of the sample places at 1.7mm distance from the lens ended fiber. It can be inferred from the figure that the micro spheres are in focus when the distance is increased to 2.8mm as shown in figure 7.28k. Figures 7-28a to 7-28j show images taken at steps of 100 μ m till 2.8mm and figures 7-28j to 7-28s show images taken beyond 2.8mm till 3.3mm (figure 7-28s) with equal steps as in the previous case. It should be note that the quality of the image is

Figure 7-28: Images of the micro sphere sample at different working distances; (a)1.8mm, (b)1.9mm, (c)2mm, (d)2.1mm, (e)2.2mm, (f)2.3mm, (g)2.4mm, (h)2.5mm, (i)2.6mm, (j)2.7mm, (k)2.8mm, (l)2.9mm, (m)3 mm, (n)3.1mm, (o)3.2mm, (p)3.3mm, (q)3.4mm, (r)3.5mm, (s)3.6mm

7.2.4. Endoscopic probe using the fabricated microlens

Fiber-optic probes are widely used in optical microscopy and spectroscopy of biological tissues. Many studies of the Microlens-ended fibers have been reported in the recent years. Many studies concentrate on the fabrication of such systems[77, 78] while others concentrate on the imaging and collection behaviour of them[79] [3]. One of the crucial components in all such systems is a refractive microlens, which is integrated with the fiber to improve the optical efficiency. The fabrication process for such stand-alone lenses for fiber optic applications fall into four major groups; (1)Molding techniques [80, 81], (2)lithographic techniques[2, 82, 83], (3)laser machining techniques[4] and (4)direct printing techniques[29,

30]. In this section an endoscope probe using the particular molded stand-alone lens is designed. The lens is used as the imaging unit on the head of probe. The whole system consists of a coherent light source (473nm laser), intermediate optical elements, tissue sample and the detector (high resolution color CCD). The schematic of the set up is shown in figure 7-29a. Figure 7-29b shows the experimental set up using the fiber probe and utilized for micro spheres imaging.

Figure 7-29: The imaging system using the microlens ended fiber; (a) schematic diagram, (b) actual set up

The endoscope probe consists of a rigid distal end and a flexible part which guides two illumination fiber and one imaging fiber through the distal end. The schematic of this probe is shown in figure 7-30.

Figure 7-30: Schematic of the endoscopic probe

As shown in figure 7-30, the probe consists of two illumination fibers and one imaging fiber. The total diameter of the probe is 1.4mm and its total length is 140mm. The length is designed so that the probe can be used for inspection of the colon up to cecum. The main consideration in designing the probe are : choice of the light source and the sample, distal end design considerations, choice of the imaging fiber and illumination fibers and the position of the microlens.

The crucial factors which one needs to consider in design of the distal end are: the working distance of the lens ended fiber, the suitable distance between the illumination fibers and the imaging fiber considering the geometry and machining restrictions and the required illumination angle to provide a good illumination over the working range of the optical system. The distal end is designed so that it can be used for the working distances raging from 1.3mm to several millimeters. The distance between the microlens and the fiber is adjustable as the position of the distal end fitted on the flexible part of the probe is changeable. The details of the distal end design are shown in figure 7-31.

Figure 7-31: Details of the distal end design

The images of the micro sphere with the size of almost $4\text{ }\mu\text{m}$ are shown in figure 7-32. Figure 7-32a shows the image of the micro sphere at working distance (distance between the distal end and the sample) of 10mm when the lens is attached to the fiber where figure 7-32b shows the results at the same working distance when the lens is not attached. The results show how the microlens modifies the imaging ability of the fiber optic system. The possible large working distance shows the suitability of the microlens to be used for in-vivo endoscopic application where a safety factor for the working distance of the system should be considered.

Figure 7-32: Images taken from the micro sphere sample at working distance of 10 mm; (a) with lens, (b) without lens

The comparison between the images taken when the lens ended fiber when it is at focus and when the fiber without lens is at focus are shown in figure 7-33. The results show that although the images taken without lens are clearer, there are several advantages for using the microlens in the setup. First, the working distance of the system can be significantly increased to more than 10mm. Second, the magnification of the system has been significantly increased using the microlenses.

Figure 7-33: Images of the micro spheres; (a) without lens, (b) with lens

Figure 7-34 shows the images of the micro spheres taken at different focal planes. The planes differ by 100 μ m in each step and the distance is varied from 11.2mm (figure 7-34a) to 7.2mm (figure 7-34 c). Figure 7-34b show the image when the object plane is at 9.2mm distance from the probe. These results show the suitability of the microlens for intended imaging applications.

Figure 7-34: Images of the micro spheres at different planes differ by 2mm; (a) at 11.2mm distance from the probe, (b) at 9.2mm distance from the probe, (c) at 7.2mm distance from the probe

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1. Conclusions

This M. Eng. Dissertation research addressed the fabrication of stand-alone micro imaging lens for biomedical applications. The feasibility of thermoforming of polymer stand-alone lenses with size of almost 1mm has been proven. The results of compression molding showed that a good replication can be obtained through thermoforming in temperatures above T_g . Optimization of the process was done experimentally as well as theoretically. FEM simulation and design of experiments were used as tools for process optimization. Good agreement between simulation results of lens surface profile and experimental results have been obtained.

The results show poor replication when the molding temperature is above $T_g + 50^\circ\text{C}$. The best molding temperature is $T_g + 20^\circ\text{C}$ and the best de-molding temperature is 70°C . The profile of the lenses has low deviation from the mold spherical profile and low residual stresses. Lower de-molding temperature generally results in better surface roughness. Higher molding speed results in better mold replication especially when the molding temperature is high.

Optical performance of the lenses was also studied and the results show that the molded lenses are suitable for the required applications. The focal length of almost 1.3mm and the focal spot size of $25\mu\text{m}$ show the propriety of the molded lens for probe imaging and

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microscopy. The experimental resolution of $35\mu\text{m}$ shows that the fabricated lens is suitable for endoscopic application. The ability of the lens to image the micro spheres with approximate size of $4\mu\text{m}$ shows that the microlens can be used to image human epithelial cells which are usually $5\text{--}15\mu\text{m}$ in diameter.

8.2. Future Work

8.2.1. Size limitations

It's of academic interest to investigate the ultimate limit of the smallest possible lens which can be fabricated by the proposed method. This is limited by how small one can fabricate the mold and the mold inserts. Simulations and mathematical models can also be very helpful in predicting various molding stages of very tiny mold cavity. It's also of interest to fabricate multiple lenses on a curved surface. This modifies the imaging behavior of the microlens significantly.

8.2.2. Process control and robustness of the results

The other possible interesting research area is the process control and robustness of the results. Identifying the sources of variation of the results under same processing conditions has not been thoroughly investigated so far. My experience shows that standard deviation of the radius of curvature and the sag height of the lenses molded under the same processing condition can be as high as 13%. It means that a thorough study on the process control is required. Studying the effect of cooling rate and design of cooling channels on the similarity of the results seems to be interesting. There are many theoretical and experimental studies on the effect of cooling rate on the process success, geometrical characteristics of the products and residual stresses but there is little effort on the effect of design of the cooling channels on similarity of the symmetry of the products and similarity of results.

8.2.3. Experimental stress analysis

Experimental stress analysis by photoelasticity is a common way of determining the residual stresses of the transparent molded structures. The residual stresses impact the optical behavior of the lenses in two ways. The first one is that residual stresses cause distortion of the product after de-molding and reduce the quality. The other problem is that residual stress causes birefringence meaning that the light travels at different speeds in different polarities and this causes wavefront error.

Measurement of stresses can be done experimentally as well as analytically. Theoretical investigation of the residual stresses has been included in chapter 5 and FEM analysis has been conducted to predict the amount of residual stresses. Experimental stress analysis has been reported by a variety of techniques. Methods such as hole drilling, optical birefringence, layer removal and X-ray diffraction are used firstly to determine stresses in metals and then systems are adapted to measure stresses in polymer structures. Among all these methods, photoelasticity is generally preferred for the analysis of distribution of residual stresses quantitatively as well as qualitatively for transparent materials. Photoelasticity is widely used and developed due to availability of high resolution CCD cameras, high speed computers and several image processing softwares. In this section a brief overview of this technique is included.

Many non-crystalline materials such as PC which are ordinary optically isotropic become anisotropic when they are stressed[84]. The calculation of stress distribution in material using photoelasticity is based on the effect of different stresses in different directions on the velocity of light (which also can be represented as refractive index) in those directions. This phenomenon is first observed by David Brewster in 1816.

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Stress optic law is the first proposed by Maxwell in 1852 and tries to show the relation between optical properties of material and stress which is applied on that. It shows that there is a relation between refractive index of material and principal stresses (equation8-1):

$$(n_1 - n_0) = a\sigma_1 + b(\sigma_2 + \sigma_3) \quad (8-1)$$

Where n_0 is refractive index of the unstressed material. The similar equation can be written for two other directions thus difference between principal stresses can be written as follow (equation8-2):

$$(\sigma_1 - \sigma_2) = \frac{1}{C} (n_1 - n_2) \quad (8-2)$$

where C is known as stress-optic coefficient.

There are many methods utilize the simple equation above to quantitatively investigate the stress distribution into the material as well as qualitatively [85]. Two well-known set ups that have been used for photoelasticity analysis are: (1) photoelasticity using plane polarized light and (2) photoelasticity using circular polarized light. These techniques utilize the polar properties of light as when light ray with a certain polarity travels through the stresses material is split into two waves with two different polarities travel with different velocities and directions coincide with the principal stress directions, cause the phase shift between the two components. These two waves are then interfere and produce fringes .stress distribution in material can be qualitatively analyzed from the shape of fringes. The intensity of light in each point of image can be used to quantitatively analyze the principal stresses in the material.

The set up for photoelasticity using plane polarized light consists of a light source, a couple of plane polarizer and a screen which can be replaced by a CCD camera and computers.(figure 8-1) The light travel from the light source is polarized by the first polarizer.

The polarized light is then enters the stressed material and because of existence of stress is resolved into two components vibrating parallel to the principal stress directions. After leaving the specimen there is a phase change between two components due to different refractive indices in two directions. The second polarizer which is known as analyzer is used to emerge the components into one plane so that the effect produced by the model can be measured from the resulting interference of waves.

Figure 8-1: The schematic of the set up for stress analysis using plane polarized light [85]

The intensity of the emerging light can be determined as a function of intensity of the first wave(K), the angle between axis of polarizer(or analyzer) and direction of σ_1 (or σ_2) which is called “ α ” (equation 8-3) and the phase retardation “ Δ ”.

$$I = K \sin^2 2\alpha \sin^2 \frac{\Delta}{2} \quad (8-3)$$

The problem now is that the intensity of the light is dependent on the angle between polarizers and principle stresses, in order to solve the problem stress analysis using circular polarizer is proposed.

The principal of photoelasticity using plane polarized light is the same as mentioned for the previous method but here a circular polarized light is used. After light is emerged from the first polarizer, a quarter wave plate is used to develop two waves with phase shift of $\pi/2$.

These waves are then going through the sample and the same story happens. Two components of light are then pass through another quarter wave plate and a relative phase shift of $\pi/2$ is again developed. The components are then pass through the analyzer and can be interpreted as they interfere. Figure 8-2 shows the schematic of the set up for stress analysis using circularly polarized light.

Figure 8-2: The schematic of the set up for stress analysis using circularly polarized light [85]

The intensity of light in each point can be determined as follows (equation8-4):

$$I = K \sin^2 \frac{\Delta}{2} \quad (8-4)$$

The advantage here is that the intensity of light is not affected by angle between polarizers and principal stresses so interpretation of the results is easier. Δ is the amount of phase retardation between two polarized light beams, I is the intensity of the emerging light and K is the intensity of the initial light beam. “ Δ ” depends on the difference between normal stresses in a specific point and thickness of the layer (equation8-5).

$$\Delta = \frac{2 \pi h c}{\lambda} (\sigma_1 - \sigma_2) \quad (8-5)$$

σ_1 and σ_2 are the principal residual stresses, h is the thickness of the layer, c is the stress-optic coefficient and λ is the wavelength of the light. Measuring the intensity of light passed

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through the set up for circular birefringence and the stressed model, it's possible to determine the phase retardation and consequently the difference between principal residual stresses and the results can be compared to FEM predicted results of residual stresses.

8.2.4. Aberration Analysis

Aberration analysis of the molded lenses is required for further study on the lens quality. Aberration of the lenses is commonly studied by measuring the wavefront profile. This wavefront data is then curve fitted to the Zernike polynomials. The order of Zernike polynomials determine the kind of lens aberration. Further study can also be done on the effect of processing parameters, material characteristics and 3D lens surface profile on lens aberrations.

Aberration results in blurring of the image formed by the imperfect optical system. All different types of aberrations fall into two major categories: (1) Monochromatic aberrations which produced without dispersion and (2) chromatic aberration which are produced by dispersion of light into different wavelengths[86]. In most of studies done on lens optical characterization monochromatic aberration are studied measuring the wavefront profile of the outcome light beam and curve fitting Zernike polynomials to wavefront data[73]. The order of fitted Zernike polynomial determines the aberration exist in the lens.

Monochromatic aberrations can be categorized into spherical aberration, coma, and curvature of field, image distortion and tilt. Geometrical differences in between a perfect spherical shape and the actual lens can be responsible for each of these aberrations which cause blurring of the image. Fitted Zernike polynomial determines which geometrical imperfections exist in the lens and thus determines the types of existing aberrations.

From all the methods to measure the wave front data, two well-known interferometry techniques called Mach–Zehnder and Twyman–Green interferometry are the most widely used for lens characterization [80, 87]. These interferometers and the attached analyzing software are available to characterize the optical aberrations of the lenses.

8.2.5. Endoscopic confocal probe application of the microlenses

Slicing ability of the microlens and the lens confocality has not been studied deeply in this work because of lack of time. Some works has been conducted to determine the axial resolution of the system. The axial resolution of the lens ended fiber was measured by moving the sample in 100 μ m steps through the focus of the system. The quality of this result has not been satisfactory because of the Numerical aperture of the lenses and further study on the confocal imaging ability of the lenses is required.

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Appendices

Appendices

Appendix A

Mechanical and thermal properties of PC grade lexan 123R

SABIC
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Lexan® Resin 123R

Americas: COMMERCIAL

UL rated HB as of 10/87. 200 series recommended when V-2 rating required. Nonhalogenated. 17.5 MFR, for small, intricate parts. UV stabilized. Internal mold release.

TYPICAL PROPERTIES ¹	TYPICAL VALUE	UNIT	STANDARD
MECHANICAL			
Tensile Stress, yld, Type I, 50 mm/min	630	kgf/cm ²	ASTM D 638
Tensile Stress, brk, Type I, 50 mm/min	680	kgf/cm ²	ASTM D 638
Tensile Strain, yld, Type I, 50 mm/min	7	%	ASTM D 638
Tensile Strain, brk, Type I, 50 mm/min	110	%	ASTM D 638
Flexural Stress, yld, 1.3 mm/min, 50 mm span	940	kgf/cm ²	ASTM D 790
Flexural Modulus, 1.3 mm/min, 50 mm span	23900	kgf/cm ²	ASTM D 790
Hardness, Rockwell M	70	-	ASTM D 785
Hardness, Rockwell R	118	-	ASTM D 785
Taper Abrasion, CS-17, 1 kg	10	mg/1000cy	ASTM D 1044
IMPACT			
Izod Impact, unnotched, 23°C	328	cm-kgf/cm	ASTM D 4812
Izod Impact, notched, 23°C	70	cm-kgf/cm	ASTM D 256
Tensile Impact, Type I ²	557	cm-kgf/cm ²	ASTM D 1822
Falling Dart Impact (D 3026), 23°C	1728	cm-kgf	ASTM D 3026
THERMAL			
Vicat Softening Temp, Rate B/50	154	°C	ASTM D 1525
HDT, 0.45 MPa, 6.4 mm, unannealed	137	°C	ASTM D 648
HDT, 1.82 MPa, 6.4 mm, unannealed	132	°C	ASTM D 648
CTE, -40°C to 95°C, flow	6.84E-05	1/°C	ASTM E 831
Specific Heat	1.25	J/g-°C	ASTM C 351
Thermal Conductivity	0.19	W/m-°C	ASTM C 177
Relative Temp Index, Elec	100	°C	UL 746B
Relative Temp Index, Mech w/impact	100	°C	UL 746B
Relative Temp Index, Mech w/o impact	100	°C	UL 746B
PHYSICAL			
Specific Gravity	1.2	-	ASTM D 792
Specific Volume	0.83	cm ³ /g	ASTM D 792
Density	1.19	g/cm ³	ASTM D 792

¹ Typical values only. Variations within normal tolerances are possible for various products. All values are measured at standard test conditions of 23°C/50% relative humidity.
² Properties reported on impact values are determined on impactor modulus samples.
All properties are reported according to ISO 704.

³ Only typical data for material selection purposes. Not to be used for part or tool design.
⁴ The rating is not intended to reflect hazards presented by this or any other material under actual fire conditions.
⁵ Data measurement according to UL.

Source: SABIC, last update 04/14/2005

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Appendices

Lexan® Resin 123R

Americas: COMMERCIAL

TYPICAL PROPERTIES ¹	TYPICAL VALUE	UNIT	STANDARD
PHYSICAL			
Water Absorption, 24 hours	0.15	%	ASTM D 570
Water Absorption, equilibrium, 23C	0.35	%	ASTM D 570
Water Absorption, equilibrium, 100°C	0.58	%	ASTM D 570
Mold Shrinkage, flow, 3.2 mm	0.5 - 0.7	%	GE Method
Melt Flow Rate, 300°C/1.2 kgf	17.5	g/10 min	ASTM D 1238
OPTICAL			
Light Transmission	88	%	ASTM D 1003
Haze	1	%	ASTM D 1003
Refractive Index	1.598	-	ASTM D 542
ELECTRICAL			
Volume Resistivity	>1 E+17	Ohm-cm	ASTM D 257
Dielectric Strength, in air, 3.2 mm	14.9	kV/mm	ASTM D 149
Relative Permittivity, 50/60 Hz	3.17	-	ASTM D 150
Relative Permittivity, 1 MHz	2.98	-	ASTM D 150
Dissipation Factor, 50/60 Hz	0.0009	-	ASTM D 150
Dissipation Factor, 1 MHz	0.01	-	ASTM D 150
Hot Wire Ignition (PLC)	4	PLC Code	UL 746A
High Voltage Arc Track Rate (PLC)	2	PLC Code	UL 746A
High Ampere Arc Ign. surface (PLC)	1	PLC Code	UL 746A
Comparative Tracking Index (UL) (PLC)	2	PLC Code	UL 746A
FLAME CHARACTERISTICS			
UL Recognized, 94HB Flame Class Rating (3)	0.78	mm	UL 94
UV-light, water exposure/immersion	F1	-	UL 748C

1) Typical values only. Variations within normal tolerances are possible for various colours. All values are measured at least after 48 hours storage at 23°C/50% relative humidity.
All properties, except the melt volume rate are measured on injection-moulded samples.
All samples are prepared according to ISO 294.

2) Only typical data for material selection purposes. Not to be used for part or tool design.
3) This rating is not intended to reflect hazards presented by this or any other material under actual fire conditions.
4) Chen measurement according to UL.

Source: OEM, Last Update: 04/14/2003

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Appendices

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Lexan® Resin 123R

Americas: COMMERCIAL

PROCESSING PARAMETERS	TYPICAL VALUE	UNIT
Injection Molding		
Drying Temperature	120	°C
Drying Time	3 - 4	hrs
Drying Time (Cumulative)	48	hrs
Maximum Moisture Content	0.02	%
Melt Temperature	280 - 305	°C
Nozzle Temperature	275 - 300	°C
Front - Zone 3 Temperature	280 - 305	°C
Middle - Zone 2 Temperature	270 - 285	°C
Rear - Zone 1 Temperature	280 - 280	°C
Mold Temperature	70 - 95	°C
Back Pressure	0.3 - 0.7	MPa
Screw Speed	40 - 70	rpm
Shot to Cylinder Size	40 - 80	%
Vent Depth	0.025 - 0.075	mm

NOTE: Back Pressure, Screw Speed, Shot to Cylinder Size and Vent Depth are only mentioned as general guidelines. These may not apply or need adjustment in specific situations such as low shot sizes, thin wall molding and gas-assist molding.

1) Typical values only. Variations within stated parameters are possible for various resins. All values are measured at a weight of 100 g and storage at 23°C/50% relative humidity.
All properties except the melt viscosity are measured on injection molded samples.
All numbers are prepared according to ISO 527.

2) Only typical data for material selection purposes. Not to be used for part or tool design.
3) The value is not intended to reflect hazards presented by this or any other material under actual fire conditions.
4) Own measurement according to UL.

Source: GMD Last Update: 04/16/2005

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Appendix B

Engineering drawing of the mold parts

Appendices

1	2	3	4	5	6

<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p>STANDARD SPECIFICATIONS</p> <p>1. MATERIAL: E-Nickel</p> <p>2. FINISH: RA 0.1</p> <p>3. TOLERANCES:</p> <p>4. DIMENSIONS:</p> <p>5. WEIGHT:</p> </div> <div style="width: 45%;"> <p>REVISIONS</p> <p>1. REVISION: 1</p> <p>2. REVISION: 2</p> <p>3. REVISION: 3</p> <p>4. REVISION: 4</p> <p>5. REVISION: 5</p> <p>6. REVISION: 6</p> <p>7. REVISION: 7</p> <p>8. REVISION: 8</p> <p>9. REVISION: 9</p> <p>10. REVISION: 10</p> </div> </div>					
<p>Notes:</p> <ul style="list-style-type: none"> • Debur all sharp edges unless otherwise stated • All fillets unless otherwise stated are R0.1 					
<p>Particulars:</p> <p>NAME: _____</p> <p>DATE: _____</p> <p>MATERIAL: E-Nickel</p> <p>WEIGHT: _____</p> <p>DATE: _____</p> <p>L6</p> <p>A4</p>

Appendices

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH TOLERANCES: LINEAR: ANGULAR:				FINISH 		DEBUR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
								<ul style="list-style-type: none"> • Deburr all sharp edges unless otherwise stated • All fillets unless otherwise stated are R0.1 			
NAME		SIGNATURE		DATE				TITLE			
DRAWN								Pin			
CHECKED											
APPROVED											
MFG											
G.A.						MATERIAL: E - Nickel		DWG NO. L11		A4	
						WEIGHT		SCALE: 1		SHEET 1 OF 1

Appendix C:**Mechanical and thermal properties of the PC used in compression test**25. Aug. 2008 10:00
DatenblattENSINGER INTERNATIONAL GMBH - SG
ENSINGER INTL GMBHNo. 0266 P. 2
Page 1 of 2 **Material Data Sheet****TECANAT**Chemical Designation
DIN-Abbreviation:
Colors, fillersPolycarbonat
PC
transparent**Main features**

tough	easily welded and bonded
good electrical insulation	good heat deformation resistance
easily machined and polished	sensitive to stress cracking

Applications

mechanical engineering	food technology
medical technology	transport and conveyor technology
electrical engineering	automotive engineering
model construction	precision engineering
lighting technology	domestic appliance
construction industry	

Preferred Fields

Transparent working models, housing parts, insulators, plugs, plug strips, sight glasses, masking covers, optical components, photo couplers, weather protection

Properties**Material Data Sheet****TECANAT**

Mechanical	dry / moist		standard
Tensile strength at yield	60	MPa	DIN EN ISO 527
Elongation at yield	6	%	DIN EN ISO 527
Tensile strength at break		MPa	
Elongation at break		%	
Modulus of elasticity in tension	2300	MPa	DIN EN ISO 527
Modulus of elasticity after flexural test		MPa	
Hardness	100		DIN 53 456
Impact strength 25° C (Charpy)	n.b.	KJ/m ²	DIN EN ISO 179 (Charpy)
Creep rupture strength	48	MPa	

<http://www.ensinger-online.com/suche/gb/datenblatt.php?ID=00500>

09/12/2003

25. Aug. 2008 10:00
DatenblattENSINGER INTERNATIONAL GMBH - SG
ENSINGER INTL GMBHNo. 0266 P. 3
Page 2 of 2

after 1000 h with static load

Time yield limit 18 MPa
for 1% elongation after 1000 hCo-efficient of friction 0,52-0,58
 $p = 0,05 \text{ N/mm}^2 v = 0,6 \text{ m/s}$
on steel, hardened and groundWear 22 $\mu\text{m/km}$
 $p = 0,05 \text{ N/mm}^2 v = 0,6 \text{ m/s}$
on steel, hardened and ground

Material Data Sheet

TECANAT

Thermal	dry / moist		standard
Crystalline melting point		°C	
Glass transition temperature	148	°C	DIN 53 765
Heat distortion temperature HDT, Method A	135	°C	ISO-R 75 Verfahren A (DIN 53 461)
Heat distortion temperature HDT, Method B	140	°C	ISO-R 75 Verfahren B (DIN 53 461)
Max. service temperature			
short term	140	°C	
long term	120	°C	
Thermal conductivity (23° C)	0,19	W/(K·m)	
Specific heat (23° C)	1,2	J/g·K	
Coefficient of thermal expansion (23-55°C)	7	$10^{-5}/K$	DIN 53 752

Material Data Sheet

TECANAT

Electrical	dry / moist		standard
Dielectric constant (10 ⁶ Hz)	3		DIN 53 483, IEC-250
Dielectric loss factor (10 ⁶ Hz)	0,006		DIN 53 483, IEC-250
Specific volume resistance	10^{13}	$\Omega \cdot \text{cm}$	DIN IEC 60093
Surface resistance	10^{15}	Ω	DIN IEC 60093
Dielectric strength	27	kV/mm	DIN 53 481, IEC-243, VDE 0303 Teil 2
Resistance to tracking	KA 1		DIN 53 480, VDE 0303 Teil 1

Material Data Sheet

TECANAT

Miscellaneous	dry / moist		standard
Density	1,20	g/cm^3	DIN 53 479
Moisture absorption (23°C/50RH)	0,15	%	DIN EN ISO 62
Water absorption to equilibrium	0,36	%	DIN EN ISO 62
Flammability acc. to UL standard 94	V2		

- (1) Testing of compression moulded plates
(2) Testing of semi-finished products
(3) Literature

The above information corresponds with our current knowledge and indicates our products and possible applications. We cannot give a legally binding guarantee of chemical resistance, of certain properties and the suitability of our products and their applications. Our products are not destined for use in medical and dental implants. Existing commercial patents must be observed. Unless otherwise stated, these values represent averages taken from injection moulding samples, dry as moulded. We reserve the right to make technical alterations.

List of publications

1. M. Mirkhalaf , S. B. Tor, V. M. Murukeshan, N. H. Loh, S. W. Lye, Fabrication of Stand-alone Polymer Microlens: Design of Molding Apparatus, Simulation and Experimental Results, *Journal of Micromechanics and Microengineering* 19 (2009) 095005
2. M. Mirkhalaf , S. B. Tor , V. M. Murukeshan, N. H. Loh and S. W. Lye, Optimization of compression molding of Stand-alone Microlenses: simulation and experimental results, *Polymer engineering and science*, DOI 10.1002/pen.21738 (2010) (in press)
3. M. Mirkhalaf, V. M. Murukeshan, S. B. Tor, V. K. Shinoj and K. Sathiyamoorthy, Stand-alone Microlenses for probe imaging applications: Measurement and characterization, *Journal of Measurement Science and Technology* (in preparation)