euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

Replication fidelity of concave and convex Fresnel lenses in Poly(dimethylsiloxane)

Marcel H. M. Dib[1]; Ronaldo Ariati[2], Débora V.Pacheco[2], João Eduardo Ribeiro[2]; Renato G. Jasinevicius[3]

[1]Inst. Federal de Educ. Ciência e Tecnologia de São Paulo, CEP 14801-600 Araraquara – SP, Brazil
[2]. Instituto Politécnico de Bragança, Campus Santa Apolônia, Bragança, Portugal
[3]. Depto Eng. Mecânica, EESC, USP, C.P. 359, CEP 13566-590, São Carlos, São Paulo, Brazil

renatogj@sc.usp.br

Abstract

A small Fresnel lens machined into a soft semiconductor crystal was used as mold for experimental replication using poly(dimethylsiloxane) (PDMS). The replication fidelity of convex and concave Fresnel molds was analysed by measuring characteristic geometrical dimensions of the replicated microfeatures from the machined microcavity. Nano and micro-features were probed by optical profilometry to explore the replication accuracy of this polymer. Nano features were assessed using surface roughness replication fidelity. The variations in surface roughness Rrms between the mold and the PDMS replica were within ± 0.2 nm. The average surface roughness Rq of the mold and the replica were about 6.7 and 7.0 nm (λ/100), respectively. Micro features were assessed through sharp crest edge height and width of Fresnel zones. Results from the difference in zone crest height and zone width between the mold and the replica are considerably small and are found in the range of hundreds of nanometers. It was found that the height and width transfer rates for the concave Fresnel mold to the PDMS samples were about 95% and 99.75%, respectively. The height and width transfer rates for the convex Fresnel mold to the PDMS sample were about 94.5% and 99.6%, respectively.

ultraprecision machining, replication fidelity, Indium Antimonide; Fresnel Lens, PDMS

1. Introduction

Single point diamond turning process has proven to be a suitable technique for fabricating optical mirrors as well as three-dimensional microstructures, with applications in diffractive optical elements and micro mirrors arrays [1]. Diamond turning is a more accurate and faster method than abrasive machining processes and is particularly suitable for generating microstructures with sharp or straight edges in semiconductor crystals [2]. Because of the lowest transition pressure value, Indium antimonide (InSb) is considered one of the semiconductor crystals with high potential to be applied in the fabrication of microstructures with diamond turning [3].

Replication processes are always considered an alternative when large quantities and low cost are required. Poly(dimethylsiloxane) (PDMS) is an elastomeric polymer and is not considered a machinable material because of the difficulty in precisely generating surface microfeatures by micromachining using mechanical material removal processes. Conversely, promising results concerning precise micro-end milling of micro channels in PDMS were achieved with cryogenic cooling. Nevertheless, PDMS shows advantages including simple fabrication by replica moulding and optical transparency [5].

In this paper, we describe the replication of kinoform structures machined in a soft semiconductor crystal based on PDMS material. The performance evaluation of a low-cost low-temperature embossing process of fine three-dimensional microstructures, namely (i) plano-convex aspheric Fresnel lens, and (ii) plano-concave aspheric Fresnel lens replicated by an optical quality silicon-based organic polymer.

2. Experimental details

The workpiece was approximately 10 mm x 10 mm cut by cleaving from a 0.5 mm thick, 50 mm diameter wafer polished single crystal Indium Antimonide (100). The sample was glued with bee wax to a diamond turned aluminium blank with 20 mm diameter and 18 mm height then vacuum chucked to the machine spindle. The samples were machined on the ASG 2500 2-axis ultraprecision machine using a single-point half-radit diamond tool. In this process, it was used a half radius diamond tool with a cutting radius of 0. 100 mm, 0º rake an 10º clearance primary and waviness < 0.25 μm over 130º excluding elliptical form. The tool was tilted -37.5º so a negative rake was established. The surface finish was assessed as a function of rake angle to avoid brittle damage formed on the machined surface due to the anisotropic behavior of single-crystal machining. Surface roughness and ductile response as a function of tool rake angle were tested on the sample before the machining of the convex mold lens using a 0.762 mm nose radius, 0º rake and 12º clearance. The tool tilted -10º, -30º and -45º. The feedrate and depth of cut were kept constant f= 1.8 μm/rev and 20 μm, respectively.

Each lens was designed to have a diameter D_L=3 mm and a focal length f_L = 30 mm, with a corresponding f-number f/# = 10. Concave and convex Fresnel lenses were machined with a cutting depth fixed in 7 μm and feedrate of 0.250 μm/rev based upon cutting tests prior made with a half radius tool; two passes using these cutting conditions were carried out.

The surface finish analysis and replication fidelity of machined mold and PDMS replicas were assessed using a VEECO non-contact highresolutionprofiler Wyko NT 1100. The scanning areas for replication fidelity were kept constant at 184 x 242 μm^2. The scanning areas for surface finish measurements were kept constant at 462 x 608 μm². Four measurements of roughness and zone heights were taken, both on the lenses and on the replicas, every 90° and an average of the values is plotted.

Each lens was designed to have a diameter D_L=3 mm and a focal length f_L = 30 mm, with a corresponding f-number f/# = 10. Concave and convex Fresnel lenses were machined with a cutting depth fixed in 7 μm and a feedrate of 0.250 μm/rev based upon cutting tests prior made with a half radius tool; two passes using these cutting conditions were carried out.

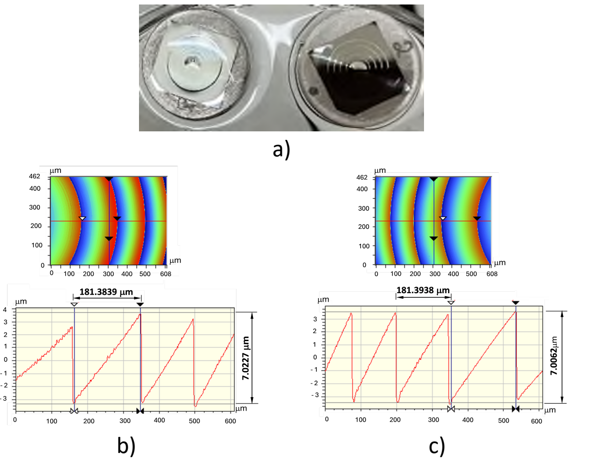


Figure 1. PDMS cladding layer poured onto a) 2D profile Concave and b) 2D profile Convex molds.

The PDMS used was Sylgard 184 ® from Dow Corning. To obtain the PDMS resin, it was necessary to mix the curing agent with the prepolymer; for each 10 g of a prepolymer, 1 g of the curing agent was added (10:1). The obtained mixture is deposited on the face of the machined sample used as the mold. To eliminate any air bubbles in the uncured PDMS mixture, it was left to rest for about 40 minutes in a desiccator connected to a vacuum pump. Next, the molds with the cladding layer were put in an oven that controlled temperature and time. The mixture was then cured at 80ºC for 45 minutes. Finally, the molds' parts were separated, and the PDMS specimens were obtained *(Fig.1a)*.

In order to quantitatively evaluate the characteristics of the replication process at the nanometer level, comparative measurements on the mold and replica, considering the R_{RMS} values, were carried out. To this end, a figure of merit called roughness transfer ratio, TR_{ROUGH}, was introduced, which is defined as:

$$TR_{rough} = \left\{1 - \left(\frac{|R_{q\,mold} - R_{q\,PDMS}|}{R_{q\,mold}}\right)\right\} \times 100 \quad (1)$$

where $R_{q\,mold}$ is the *root mean square* roughness of the mold insert and $R_{q\,PDMS}$ is the *root mean square* roughness of the PMMA replica [1].

Considering the Fresnel lens, the replication process was also evaluated in terms of the dimensional variations of the replica for the mold. To this end, two other figures of merit were introduced, namely, the height transfer ratio of the Fresnel structure, TR_{height}, and the width transfer ratio of the Fresnel structure, TR_{WIDTH}, and the width transfer ratio of the Fresnel structure, TR_{WIDTH}, defined as the absolute difference between mold and replica characteristic dimensions, concerning mold:

$$TR_{height} = \left\{1 - \left(\frac{|h_{mold\ Max,\ FZ} - h_{repl.PDMS\ Max,\ FZ}|}{h_{mold\ Max,\ FZ}}\right)\right\} \times 100,\quad (1 < FZ < 10) \quad (2)$$

$$TR_{width} = \left\{1 - \left(\frac{|W_{mold\ Max,\ FZ} - W_{repl.PDMS\ Max,\ FZ}|}{W_{mold\ Max,\ FZ}}\right)\right\} \times 100,\quad (1 < FZ < 10) \quad (3)$$

where $h_{mold\ Max,\ FZ}$ is the h_{MAX} of the FZ_{th} Fresnel zone (ring) of the mold insert, $h_{repl.PDMS,\ FZ}$ is the h_{MAX} of the FZ_{th} ring of the PDMS replica, $W_{MOLD\ Max,}$ is the width of the FZ_{th} ring of the mold insert, and $W_{replic.\ PDMS,\ FZ}$ is the width of the FZ_{th} ring of the PDMS replica [1]. Both h_{MAX} and W are measured at their correspondent FZ_{th} zone, as shown in Fig. 1 b) and 1c).

3. Results and Discussion

Figure 2 summarizes the results from the machining test carried out to assess the replication fidelity of surface roughness obtained by machining an InSb (100) sample under different Rake angle values. The roughness level of R_q ~(λ/100) was registered under different rake angle conditions in both, mold and PDMS replica. This level os surface roughness is also acceptable to be used in most visible range applications.

Figure 3 shows $h_{mold\ Max,\ FZ}$, $h_{repl.PDMS,\ FZ}$, and TR_{HEIGHT} for each of the ten zones of the Concave and Convex Fresnel lens. From Fig. 3a, one can observe that h_{MAX} initially increases and then decreases slightly as the Fresnel annular zone location gets farther from the center. This is due to the highest aspect ratio of the annular zone when distancing from the lens center, this turns more difficult with the tool nose half radius employed since the annular zone becomes narrower: ~98.6 μm at zone 5th down to 70.5 μm at the 10th zone. For all zones, TR_{HEIGHT} remains approximately constant between 95 and 99 %. Fig. 3b, it is noticed that h_{MAX} decreases slightly, lens than 1 μm, as the Fresnel annular zone location is distancing from the lens center zone. Nevertheless, TR_{HEIGHT} decreases from approximately 94 % up to about 100%.

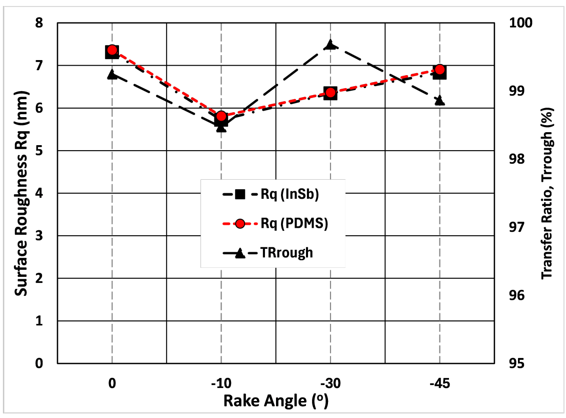
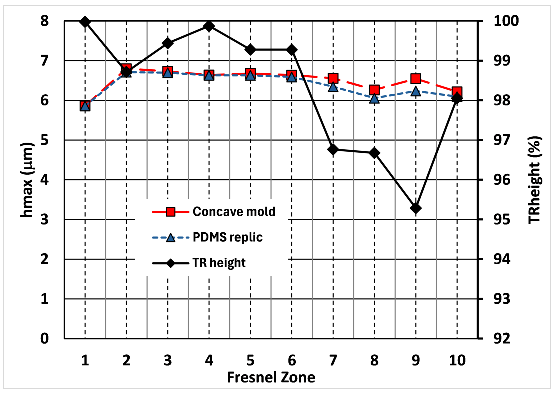


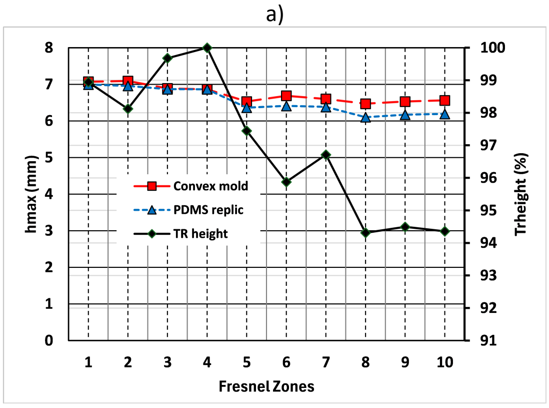
Figure 2. Results for the surface quality and replication fidelity of PDMS replica obtained from the machined sample cut under the same cutting conditions and different rake angles. a TR_{ROUGH} and Rq as a function of rake angles.

From Fig. 4a, the TR_{WIDTH} decreases as a Fresnel zone approaches the periphery of the lens. From the measurements of the annular distance and maximum height, one can note a very good agreement between InSb (100) mold and PDMS replica. The high quality of the replication process is clear. TR_{WIDTH} is constant and equals to 100% for both, mold and replica. Error bars were not considered in the graphs because the standard deviation values were calculated and are in the range of ± 0.2-0.5 nm for both the mold and the replicas.

Fig. 5 a) and 5 b) show the results for the aspheric Fresnel lens molds and PDMS replicas. Figures 5a and 5b show the mold insert with a 2D cross-section a concave aspheric Fresnel profile mold and a replica respectively. Figures 5c and 5d show the images and profile cross sections of mold and replica with a convex profile, obtained by the embossing process described in section 2.

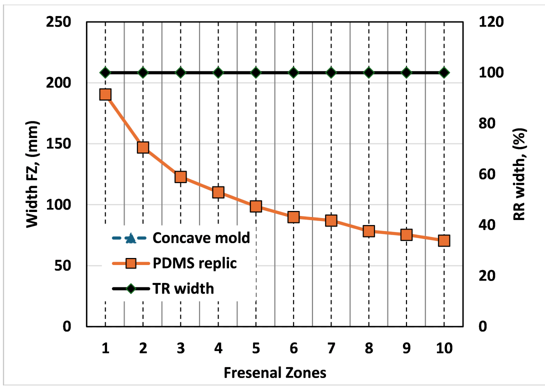


a)

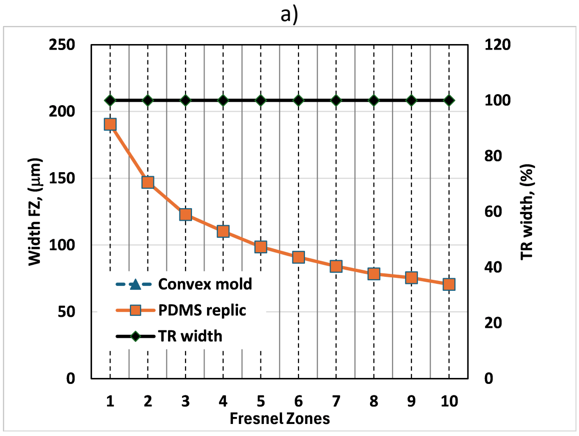


b)

Figure 3. Fresnel lens characterization as a function of Fresnel annular zones. a $h_{MAX,FZ\ MOLD}$, $h_{MAX,FZ\ REPLIC}$, and TR_{height} as a function of Fresnel annular zones (FZ). a) Concave mold/Replica PDMS, b) Convex mold/Replica PDMS.



a)



b)

Figure 4. Fresnel lens characterization as a function of Fresnel annular zones. a $W_{mold\ Max,P\ MOLD}$, $h_{Repl,\ PDMS,FZ}$, and TR_{width} as a function of Fresnel annular zones (FZ). a) Concave mold/Replica PDMS, b) Convex mold/Replica PDMS.

In the case of heights, the average standard deviation was only ± 0.1 µm. In this case, as well as for the roughness Rq, the error bars would not possibly be visible plotted over the points shown in the graph. In the case of width of Fresnel zones, no deviation were probed, so the replication fidelity was 100%.

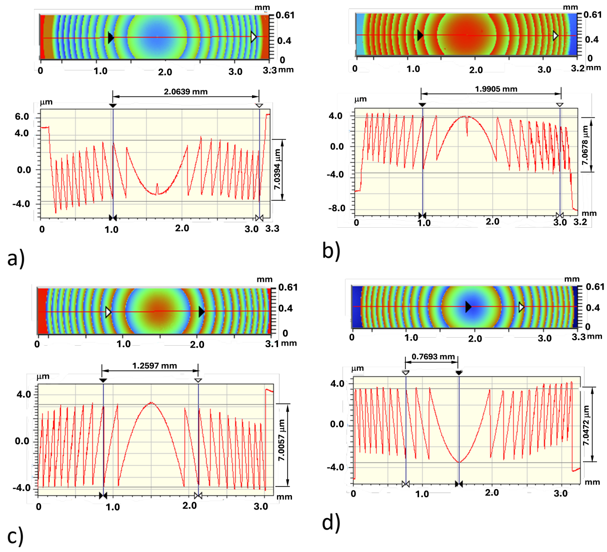


Figure 5. Characterization of the aspheric Fresnel lens mold and replica. a SEM of the concave mold insert and b its respective 3D images and cross section profile; c SEM of the convex PMMA replica and d its respective 3D images and cross section profile.

4. Concluding Remarks

Small Fresnel lenses machined into a soft semiconductor crystal were used as mold for experimental replication using poly(dimethylsiloxane) (PDMS).

Nano features were assessed by means of surface roughness replication fidelity. The variations in surface roughness Rrms between the mold and the PDMS replica were within ± 0.2 nm. The average surface roughness R_q of the mold and the replica were about 6.7 and 7.0 nm (λ/100), respectively.

Micro features were assessed through sharp crest edge height and width of Fresnel zones. The mold and the replica show an extremely small difference in zone crest height and zone width, measured in the range of hundreds of nanometers.

It was found that the height and width transfer rates for the concave Fresnel mold to the PDMS samples were about 95% and 99.75%, respectively. The height and width transfer rates for the convex Fresnel mold to the PDMS sample were about 94.5% and 99.6%, respectively. It is worth noticing that the height of the zone crests was compromised as the Fresnel annular zone location is getting farther from the center. This is due to the highest aspect ratio of the annular zone when distancing from the lens center, this turns more difficult with the tool nose half radius (0.100 mm) employed since the annular zone becomes narrower: ~98.6 µm at the 5^{th} zone down to 70.5 µm at 10^{th} zone,

Results from zone width replication were found to be constant and equal to 100% for both, concave and convex replicas.

Finally, the presented results demonstrated that PDMS is a suitable material for replicating microfeatures and nanofeatures from diamond-turned molds. Future studies are being carried out for nonferrous metallic materials such as RSA6061-T6 alloy and electrolytic copper. Results presented in previous articles [6-10] showed high fidelity replication results for PMMA through hot embossing and microinjection. In the future, lens replicated in PDMS will be evaluated by MTF (Modulation Transfer Function). MTF is a metric used to evaluate how well an optical system transfers contrast from an object to an image. It's a key parameter for measuring image quality.

References

[1] Jasinevicius, R. G.; Duduch, J. G. ; Cirino, G. A. ; Pizani, P. S. 2013 Diamond turning of small Fresnel lens array in single crystal InSb. *Journal of Micromechanics and Microengineering*, **23**, 055025.

[2] Peng He, Likai Li, Hui Li, Jianfeng Yu, L. James Lee, Allen Y. Yi, 2014 Compression molding of glass freeform optics using diamond machined silicon mold, *Manufacturing Letters*, **2**, 17-20

[3] Jasinevicius, R. G. ; Pizani, P. S. On the ductile response dependence upon phase transformation in diamond turning of semiconductors. *Physica Status Solidi. B, Basic Research*, 244, p. 261-265, 2007

[4] Kakinuma, Y., Yasuda, N., Aoyama, T. 2008 Micromachining of Soft Polymer Material applying Cryogenic Cooling. **2**, *J Adv Mech Des Syst Manuf*, 560-569

[5] Kuo, CC., Lin, JX. 2019 Fabrication of the Fresnel lens with liquid silicone rubber using rapid injection mold. *Int J Adv Manuf Technol* **101**, 615–625.

[6] Cirino, G. A.; Bereczki, Allan ; Morato, Spero Penha ; Jasinevicius, R. G. ; Neto, L.G. . Fresnel Infrared Radiation Concentrator Fabricated in Polymeric Material. In: 25th Symposium on Microelectronics Technology and Devices, 2010, Sao Paulo. Proceedings of the Electrochemical Society. Pennington, NJ, USA: Electrochemical Society, 2010. v. 31. p. 281-288.

[7] Cirino, G.A.; Mansano, R.D.; Verdonck, P.; Jasinevicius, R. G. ; Neto, L.G. . Diffraction gratings fabricated in DLC thin films. Surface & Coatings Technology, v. 204, p. 2966-2970, 2010.

[8] Granado, R.M.; Cirino, G. ;Jasinevicius, R G; DUDUCH, J.G.. Evaluation of replication performance in the nanometer range by hot molding of Diffractive Optical Elements. In: 12th euspen International Conference, 2012, Estocolmo. Proceedings of the 12th euspen International Conference Stockholm June 2012. Delft: Sieca Repro, 2012. v. 2. p. 173-176.

[9] Granado,R.M. Jasinevicius,R.G. Cirino, G.A. Camilo J.R. Micro Injection Molding Polimeric Difracttion Grating In: 17th euspen International Conference, 2017, Hannover Alemanha. Proceedings of the 17h euspen International Conference Leuven June 2017. Delft Holanda: Sieca Repro, 2017, PP.503-504.

[10] Cirino, G.; Granado, R. M. ; Mohammed-Brahim, T. ; Jasinevicius, R.G. . Assessment of replication fidelity of optical microstructures by hot embossing. International Journal, Advanced Manufacturing Technology, v. 88, p. 303, 2017.