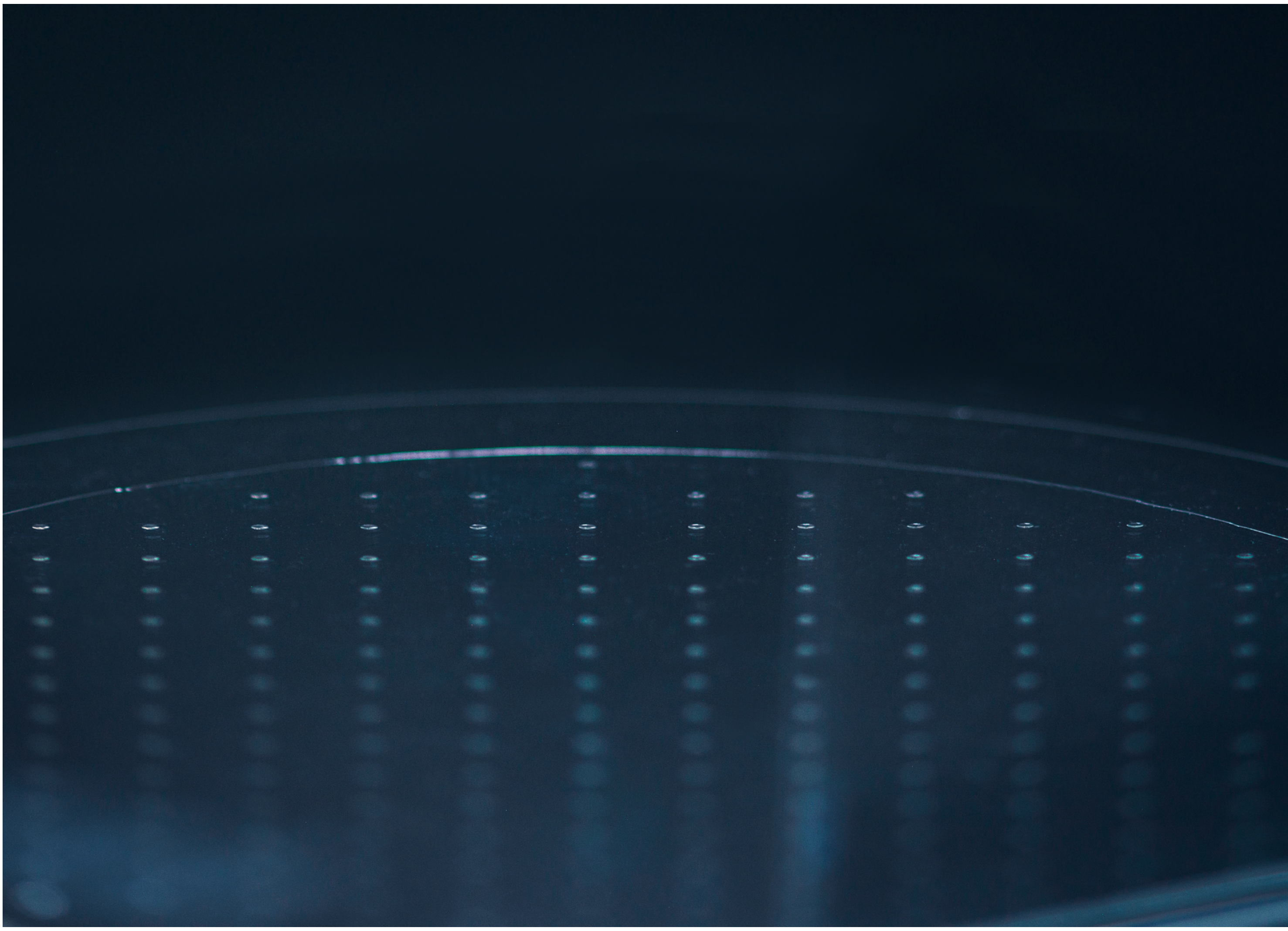
EV GROUP® | Technologies

Wafer-level micro-optics fabrication by lens molding using UV-curable polymers



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Introduction

Today, polymer refractive microlenses are the core of micro-optical modules. For small form factor modules, the manufacturing process is based on UV lens molding at wafer level. Whereas alternative lithography methods are limited in their ability to manufacture complex optical structures at wafer level, nanoimprint lithography (NIL) and lens molding are insensitive to shape and complexity, rendering them suitable for high-volume production. The highly parallel nature of these processes allows for added complexity without incurring additional manufacturing costs. This whitepaper presents an overview of the current status of lens molding technology and its associated materials.

Technology and Applications

Wafer-level lens molding is the technology of choice for the manufacturing of micro-optical components and modules to support new devices and applications across a wide range of markets. The technology allows mass production in industries that demand high performance and specialized design—particularly the manufacturing of multi-functional wafer-level optics (WLO) or advanced freeform structures with excellent pattern fidelity. This technology holds promise in emerging applications such as optical sensors or LiDAR modules designed for autonomous driving, microlens arrays and projectors intended for automotive lighting, microlenses positioned on bio-medical devices, miniaturized multi-lens vision systems for endoscope cameras, as well as sophisticated structures developed for silicon photonics.

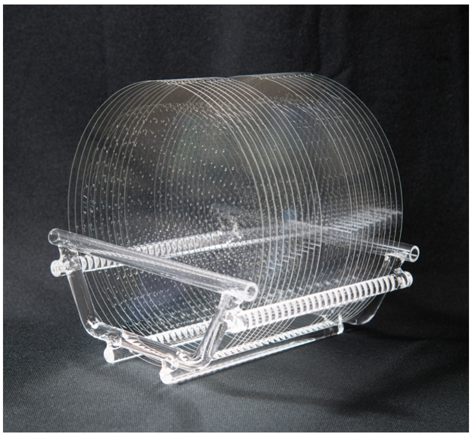
Equipment

EVG provides industry-leading lens molding equipment as a turnkey solution with an advanced, controlled process. Supporting wafer sizes from 150 mm up to 300 mm and featuring live alignment down to 300 nm, the EVG®7300 meets the high-volume manufacturing (HVM) needs for a variety of high-precision nano and micro-optical components and devices. Designed to provide the highest flexibility in most use cases, EVG process equipment can be used with manual to fully automated operation, which comes with easy and fast automatic demolding.

Optical Material

Advanced resists play a pivotal role in enabling wafer-level production of next-generation optical devices for mass markets. The development of advanced optical UV-curable polymer materials requires extensive characterization of chemical, mechanical, and optical properties, as well as proven scalability for high-volume manufacturing (HVM). While working stamp materials primarily provide process stability and increase the overall process quality, high-purity lens materials ultimately determine the optical performance and ensure a high product quality over lifetime. Particular knowledge of material requirements for automated molding and demolding processes, as well as excellent material compatibility of working stamps and resists, are important, as they enable optimal WLO performance at the smallest form factors.

This joint effort between EV Group and DELO Industrial Adhesives brings a proven industrial solution for wafer-level lens molding to address current and future market requirements, significantly shortening transfer times from prototyping to mass production.



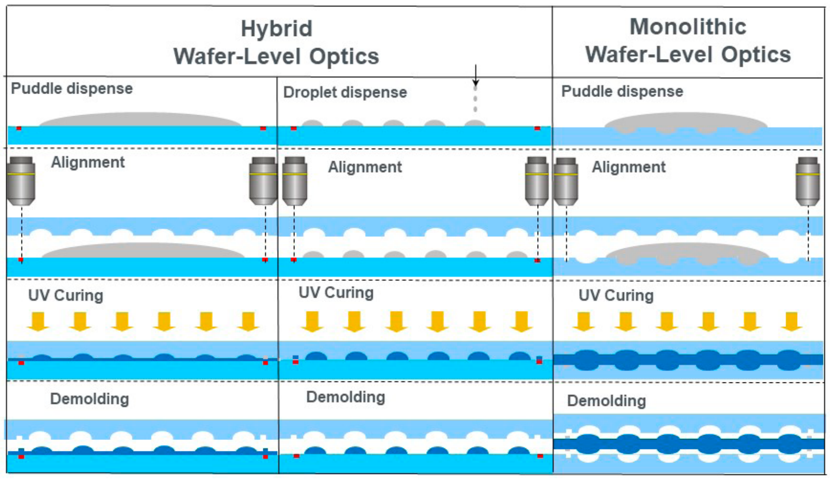
Key Aspects

1. Industrial solution for wafer level lens molding
2. Parallel and automated process enables high volume production
3. Excellent and reproducible pattern fidelity along the whole process
4. Precisely controlled multistep process including alignment, contacting and UV-curing
5. Exceptional compatibility of working stamp and lens material
6. UV-curable transparent lens material with outstanding reliability and processability

Lens Molding: Wafer-Level Optics Fabrication

UV lens molding is used to manufacture high-quality lenses on wafer level. This technique uses transparent working stamps to replicate defined lens shapes into UV-curable polymers, directly deposited onto substrates, e.g., glass or silicone. To deposit the polymer, either puddle or droplet dispensing is used. Subsequently, the working stamp (on a rigid backplane) is brought into contact with the substrate using a linear force. Due to the backplane's rigidity, very high alignment accuracies can be achieved. The polymer is cured with UV light to form a solid lens with glass-like properties. Afterwards, the working stamp is released and reused for the next imprints. The imprinted wafer—comprised of hundreds to thousands of optical elements—can now be further processed.

The figure below shows a schematic illustration of the typical processes of wafer-level optics manufacturing. EV Group offers hybrid and monolithic wafer-level molding processes, depending on the required residual layer thickness.



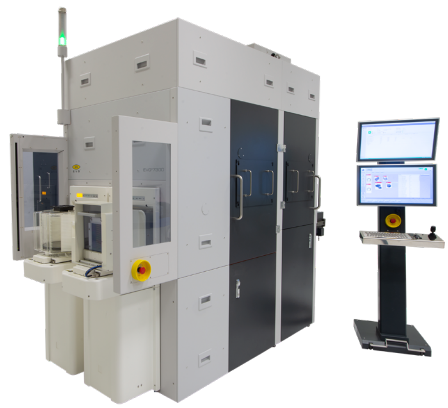


Figure 1: Lens Molding Process Flow on EVG®7300 UV Nanoimprint Lithography (NIL) System

The EVG®7300 UV Nanoimprint Lithography System is dedicated for WLO production. This molding equipment features industry-leading alignment accuracy down to 300 nm live alignment, which is enabled by a combination of alignment-stage improvements, high accuracy, and fast alignment optics, as well as gap and force-control molding. The system allows relatively easy production scaling, from 150 mm to 300 mm wafer-level imprinting. Consequently, this tool provides the most advanced nanoimprinting capabilities on the market, including conformal imprinting, fast curing times with a high-power lamp (up to intensities > 500 mW/cm²), and automated low-force stamp detachment.

It is particularly advantageous that working stamps and imprints are produced in the same system, as it eliminates the need for multiple tools and the requirement to move the wafer outside the system environment. The degree of automation, encompassing the handling of stamps and substrates, can be customized per user preferences, with the option of selecting manual, semi-automated, or fully automated modes. For applications demanding pre- and post-processing, the modular system is designed to be fully integrated into the HERCULES® NIL system.

More information on the EVG®7300 UV Nanoimprint Lithography (NIL) System can be found here.

Dedicated Optical Material and Suitable Working Stamp

For a successful lens molding process, as well as for optimal performance of the manufactured optical element, the right choice of materials is essential. Only a perfect match of working stamp materials and UV-curable lens materials can enable efficient processes and yield reproducible results with high optical quality. DELO has developed a set of epoxy-based imprint resins optimized to work in tandem with the EVGNIL UV/AF7 working stamp. DELO KATIOBOND OM6611 is one of the latest developments in this field and was selected due to its outstanding optical and mechanical properties, as well as exceptional reliability, which benefits final product performance. Table 1 provides an overview over the most important parameters for working stamp and lens material.

Table 1: Overview of used materials

Working stamp EVGNIL UV/AF7	**Chemical basis**	solvent-free
	Index of refraction (@589 nm) - liquid	1.34
	Viscosity (10/s)	200 - 500 mPas
	Typical irradiation time (LED 365 nm, 340 mW/cm²) – O2 free	200 s
	Index of refraction (@589 nm) - cured	1.35
	Transmission	100%
	Young's modulus	130 MPa
	Shore hardness	5 MPa
	Volume shrinkage	4 - 5 vol%
	Contact angle (H2O)	109°
	EVGNIL UV/AF7 is a UV-curable material for soft-working stamp fabrication in UV-based nanoimprint lithography	

Lens material DELO KATIOBOND OM6611	**Chemical basis**	Modified epoxy resin, solvent-free
	Typical irradiation time (LED 365 nm, 200 mW/cm²)	60 s
	Color	Colorless, transparent
	Index of refraction (@589 nm)	1.50
	Abbe number	53
	Viscosity (10/s)	300 mPas
	Compression shear strength	Glass/Glass: > 20 MPa PC/PC: 16 MPa
	Young's modulus	2150 MPa
	Shore hardness	D 81
	Glass transition temperature	120 °C
	Volume shrinkage	2,4 vol%

DELO KATIOBOND OM6611 is a fast-curing epoxy-based polymer which can be utilized universally for lens molding of single lenses or micro-lens arrays (MLA), as well as for replication of nanostructured diffractive optical elements (DOE), e.g., with the EVG SmartNIL® technology. In combination with the EVGNIL UV/AF7 working stamp, DELO KATIOBOND OM6611 shows minimal stamp interaction and low detachment force, which enables a long stamp lifetime and automated separation. A very low volume shrinkage of only 2.4 % allows for the exact reproduction of master geometries and smooth optical surfaces in the lens molding process.

DELO KATIOBOND OM6611 shows high transmission values close to 100% over the entire visible spectral range with no scattering and is thus perfectly optically clear. The excellent optical stability of the material is shown in Figure 2; high transmission is maintained even after the most challenging reliability tests, e.g., 3x reflow test according to JEDEC standard J-STD-020D.1 with 260°C peak temperature, 1,000-hour storage at high temperature/high humidity (85°C/85% r.h.), 1,000-hour storage at 125°C, and 1000 h storage under simulated sunlight (Q-Sun).

DELO KATIOBOND OM6611's high level of adhesion to typical substrates like glass and PC is proven by high compression shear strength values >15 MPa, without using any pretreatment or primer. Like the transmission, adhesion stays high, even after high-temperature/high-humidity testing, underlining its mechanical stability. It should be noted that, at compression shear strength values of >20 MPa for glass, substrate failure is observed rather than adhesive failure. Consequently, DELO KATIOBOND OM6611 shows a higher mechanical strength than typical glass substrates.

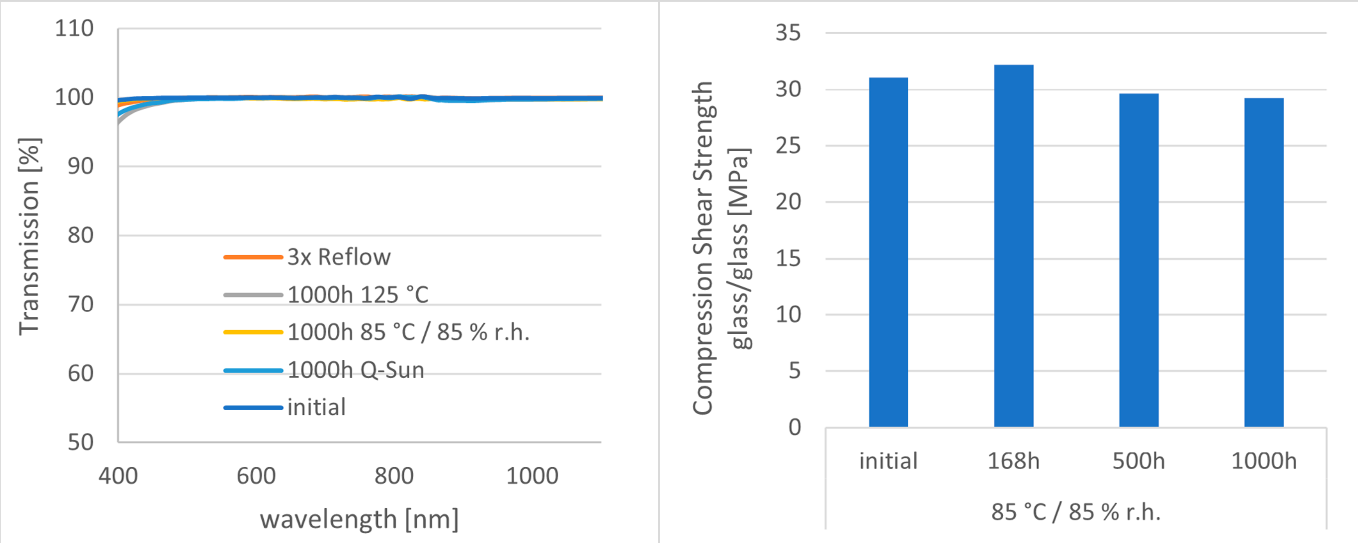


Figure 2: Left: Transmission of DELO KATIOBOND OM6611 after typical reliability testing, characterized in 100 µm layer thickness. Right: Compression shear strength on glass/glass of DELO KATIOBOND OM6611 initially and after storage at 85 °C / 85 % r.h.

Exceptional optical properties and well-balanced mechanical properties, combined with outstanding reliability, makes DELO KATIOBOND OM6611 a superb candidate for fabrication of optical elements with the best possible quality.

Process Results

For the replication tests, a fully populated master with EVG standard lenses was utilized (see Figure 3). As a substrate material, standard glass substrates with a thickness of 500 µm, commonly employed in Wafer-Level Optics (WLO) area, were utilized.

EVGNIL UV/AF7 was selected for the fabrication of the working stamp (WS), which was applied via puddle dispensing using EVG®7300, following the same process depicted in Figure 1. No extra treatment, such as anti-sticking treatments, were performed for the WS. No extra steps, such as baking with heated chuck, were necessary to achieve good imprint quality with the above-mentioned DELO material.

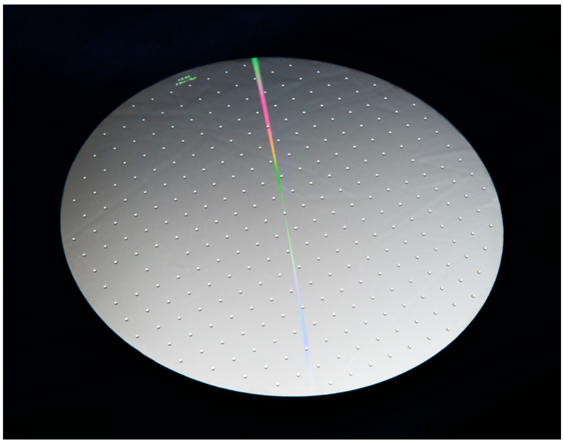


Figure 3: Fully Populated Master with Standard EVG Lenses

For achieving high-quality optical devices, stable pattern fidelity and low surface roughness are of primary importance. Consequently, a thorough analysis of the resulting imprints and individual lenses was conducted to evaluate their replication quality.

Included are:

1. Optical Quality Inspection and 3D Measurement
2. Roughness
3. Lens Shape Peak-to-Valley (PV) and Root Mean Square (RMS)
    a. Lens Profiles
    b. Residual Error Plots, Calculated Peak-to-Valley (PV) and Root Mean Square (RMS) Values
4. Reliability
5. Conclusion

Below, we present the detailed results.

1. Optical Quality Inspection and 3D Measurement

An optical microscope in bright field mode was utilized to inspect the fabricated WS and imprints. The quality of the molded lenses was investigated for possible cracks, bubbles or shrinkage defects (like e.g. dendrites), and compared to the lenses on the master.

Master | **WS EVGNIL UV/AF7** | **Imp DELO KATIOBOND OM 6611**

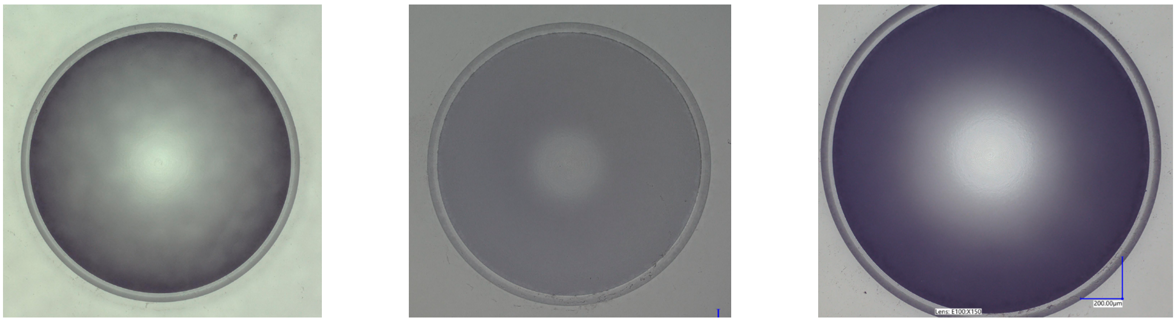


Figure 4: Fully Populated Master with Standard EVG Lenses

It can be seen on the pictures in Figure 4 that the replication process worked out without any issues. No bubbles, cracks, or any shrinkage effects can be observed in or on the imprinted lenses. The surface of the molded lenses did not change across all replication steps, from master to final imprint. No uncured material or residue can be observed on the lenses, which means that the curing is complete.

The volumetric shape fidelity of the molded lenses was investigated using 3D measurements made with a white light interferometer. The results of measurements are shown below in Figure 5.

Master | **WS EVGNIL UV/AF7** | **Imp DELO KATIOBOND OM 6611**

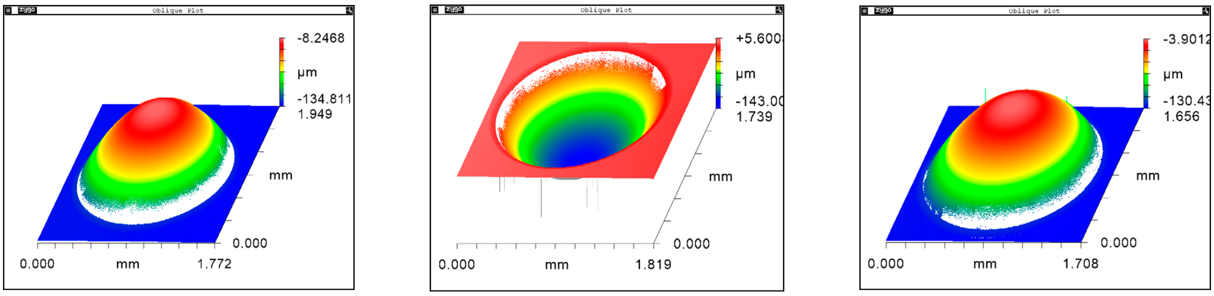


Figure 5: Inspection of the Lenses with a White Light Interferometer

Comparable to the optical inspection above, no defects due to bubbles or shrinkage can be observed in the 3D measurements. The lenses are well-shaped without dents or major deformities like dendrites or swirls.

Based on the above measurements, DELO KATIOBOND OM6611 proves to be well-suited for the EVG WLO process without creating any visible deformation, residue, or defects in the finished molded lenses. The filling behavior of the EVGNIL UV/AF7 WS works without issues, verified by the absence of any bubbles. The material can be fully cured without creating shrinkage defects of the imprints.

2. Roughness

It is necessary for optically active surfaces to have sufficiently low roughness to achieve optimal performance in a variety of different applications. Hence, a crucial parameter for WLO processes is the change in lens surface roughness over the course of the entire process, from master to final imprint. It is important to control the process and material parameters to keep this change as low as possible.

The potential change in surface roughness of the imprinted lenses was measured with a white light interferometer. To measure the roughness values ($RMS_{surface}$), the curvature of the lens was subtracted and a low-pass filter was applied. The resulting values can be seen in Figure 6 below. Five lenses from each step were measured: center, left, right, top and bottom. The graph below shows the average values.

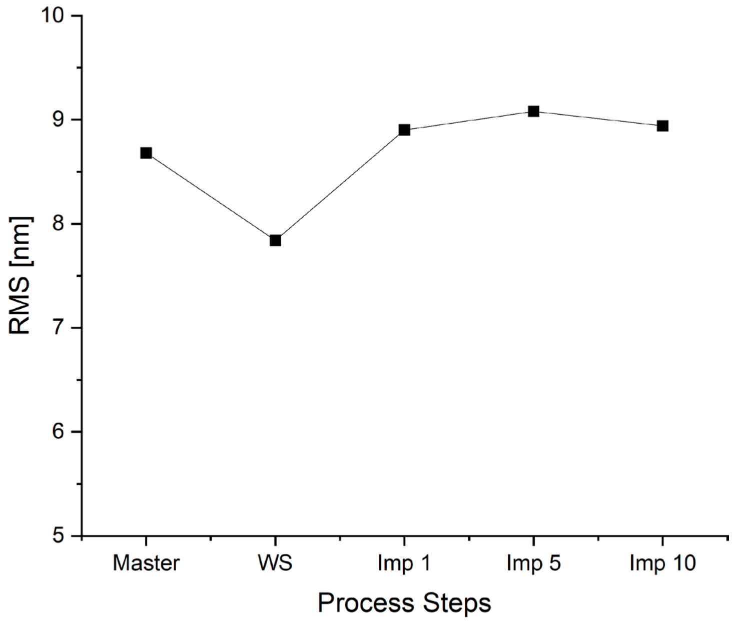


Figure 6: Lens Roughness ($RMS_{surface}$) from the Surface of the Master to Final Multiple Imprints

The average roughness ($RMS_{surface}$) of the lens surfaces is below 10 nm. This is a common requirement for optical active surfaces. The average surface roughness shows almost no change from master to imprints and over multiple imprints. This is a strong indicator of process stability. Lenses molded with DELO KATIOBOND OM6611 show constant surface roughness over the whole imprint series on a low absolute level. The material cures evenly, fully replicating the surface shape of the master without adding additional defects or deformities. The curing and detachment of the material does not influence the surface quality of the WS mold, as seen in the stable roughness values of the imprint series.

3. Lens Shape Peak-to-Valley and Root Mean Square

Based on the ISO 10110-12 standard, the way to qualify lens shape and the stability of lens shape replication is to compare the measured profile of the molded lens to the lens design equation. The comparison of the profile to the equation results in a residual error plot. The two main parameters that are derived from this residual error plot are:

- PV/Pt
- RMS (Root Mean Square), in the following for better understanding: $RMS_{residual\ error}$

PV (peak-to-valley) is the difference in height between the highest and lowest points in the residual error plot. PV represents the worst-case scenario, so to speak, for the surface. $RMS_{residual\ error}$ is a method for describing the average deviation of the surface figure from the desired surface. $RMS_{residual\ error}$ describes the overall surface variation.

a. Lens Profiles

The molded lenses were measured with an industry-standard tactile profilometer and analyzed for shape PV stability. Five lenses in total were measured from each step (master, WS and imprint up to the 10th): center, left, right, top, bottom. The graph below shows the average values.

The measured profiles were overlaid and compared with the profiles from the metal master and WS, see Figure 7.

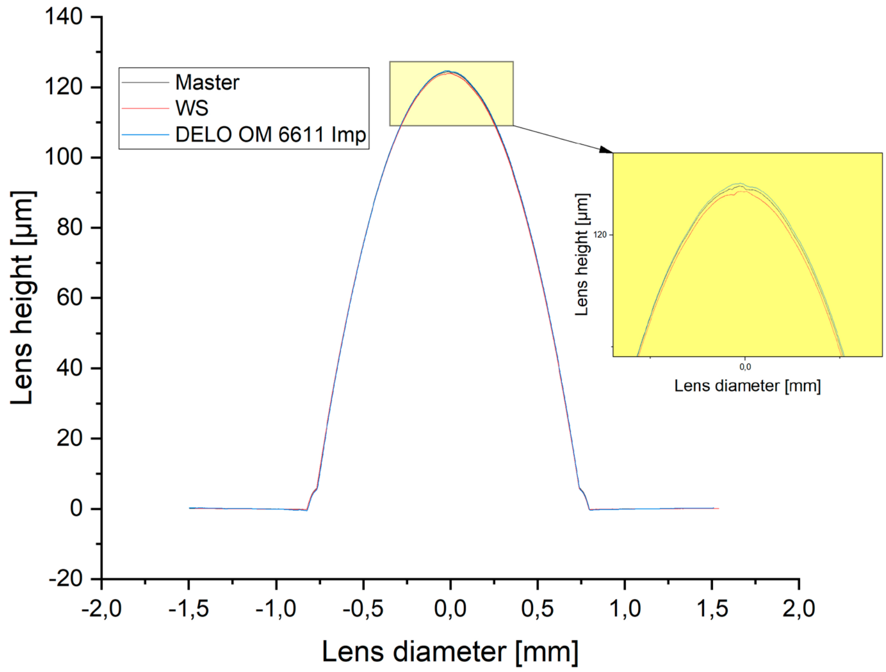


Figure 7: Lens Profiles

All the measured profiles show a very uniform shape without any discrepancies. The lens profiles resulting from the imprint series with DELO KATIOBOND OM6611 can be perfectly laid over each other. No change in shape is observed between the 1st and 10th imprint, indicating a stable process and no deformations in the WS mold.

b. Residual Error Plots, calculated PV and $RMS_{residual\ error}$ values

The residual error plots of the master, WS, and imprint were calculated and compared to each other by overlaying the plots. It is clearly recognizable in Figure 8 that the plots are almost identical. This points to very high fidelity in the replication throughout the whole process, resulting in good correlation to the above overlayed raw lens profiles.

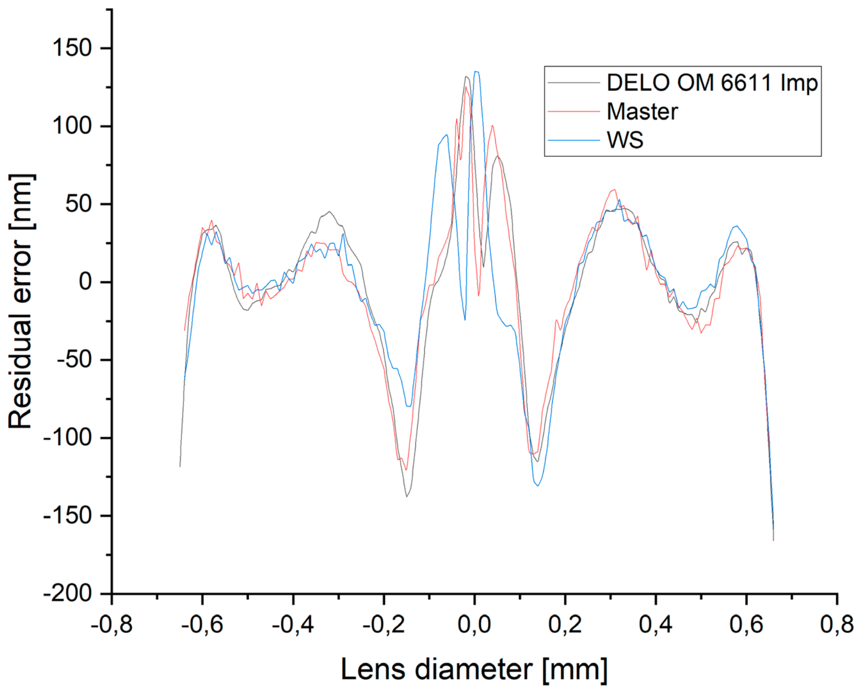


Figure 8: Residual Error Plots from Master, Working Stamp and Imprint

Additionally, the residual error plots of the 1st, 5th, and 10th imprints were compared to see if the imprint process itself is stable, see Figure 9 below.

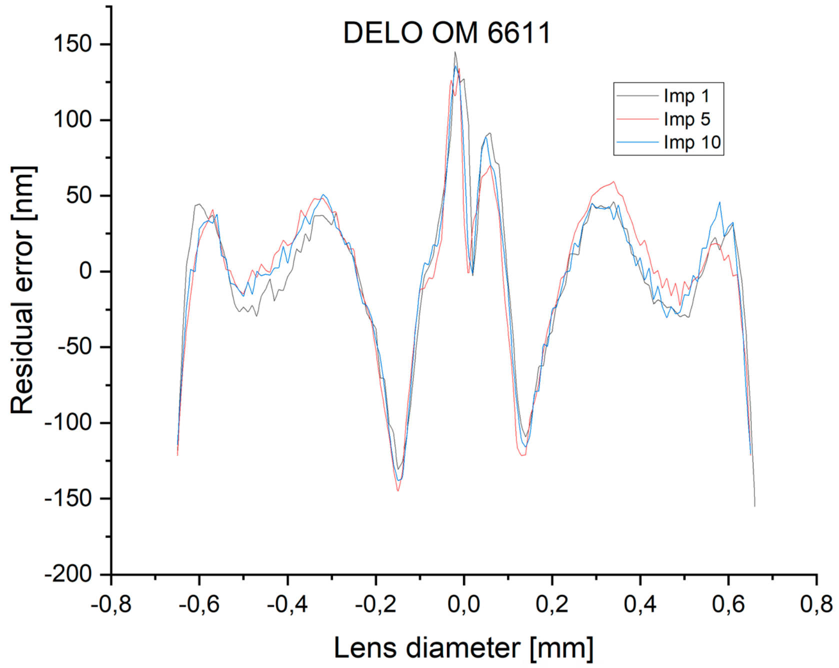


Figure 9: Residual Error Plots of the Manufactured Lenses Measured on the first, 5th and 10th Imprinted Wafer

Comparing the residual error plots from the 1st and 10th imprint shows almost no difference in the shape of the profile. That means there is no significant change in the molded lenses between the start and the end of the automatic molding process, underlining their excellent reproducibility. The precise PV and $RMS_{residual\ error}$ values calculated from the residual error plots can be seen below (Figure 10).

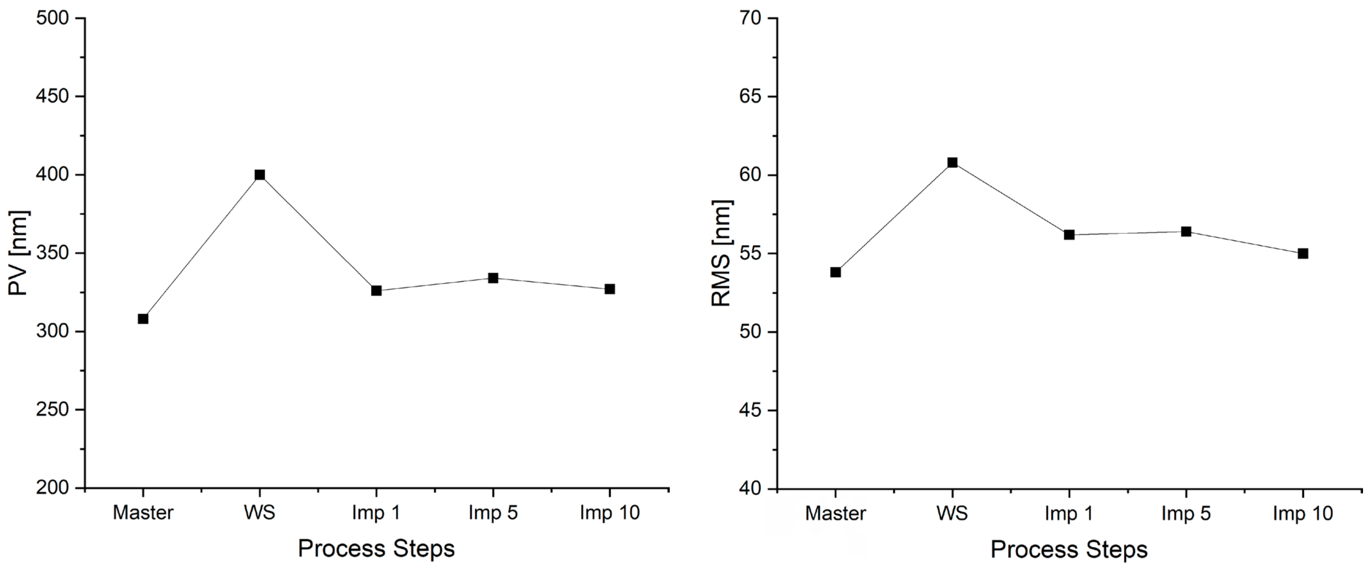


Figure 10: PV and $RMS_{residual\ error}$ Values Over 10 Imprints

The increase and subsequent reduction of the PV and $RMS_{residual\ error}$ value from master over WS to the imprint is due to the reversed polarity of the molded cavity and change in residual error.

It is shown that the average absolute PV value of the imprint series with DELO KATIOBOND OM6611 is as low as 330 nm with a stable $RMS_{residual\ error}$ of approximately 55 nm, which is close to the value of the master. The minimal deviation observed is a result of material shrinkage. This value can be easily considered in the master design and therefore compensated.

Both the PV and the $RMS_{residual\ error}$ values remain on a constant level over all imprints. The deviation range of the PV is well below 100 nm and for $RMS_{residual\ error}$ below 10 nm. Both minimum deviation ranges are an indicator for a stable and reproducible process.

4. Reliability

To test the form stability of the imprinted lenses, the wafers were subjected to a reflow process three times in accordance with JEDEC standard J-STD-020D.1 at a peak temperature of 260°C.

As can be seen in Figure 11 visually and optically, the lenses show no changes after the reflow process compared to the imprint series. No yellowing or cracking of the lenses even after three rounds of reflow are visible.

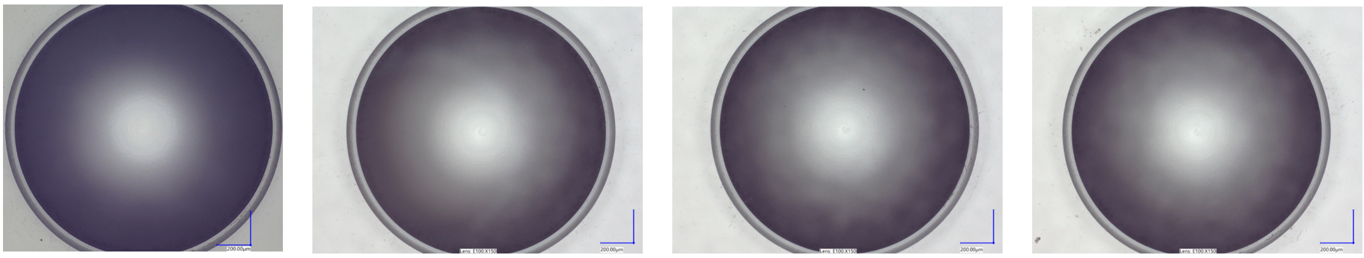


Figure 11: Imp 10 (first picture on the left), Reflow x1 (second picture), Reflow x2 (third picture, Reflow x3 (right picture

The lens shapes after reflowing were measured by a profilometer via the same procedure as described in Chapter 3. Figure 12 shows the overlaid profiles of the measured lenses after the reflow process compared to the profiles after 10 imprints. As shown, the shape of the lenses is almost identical between the reflow steps and imprints. No deformation or deviation from the original shape can be observed. Also, no significant change in height or diameter of the lenses can be seen. Overall, the lenses show high stability during the reflow process.

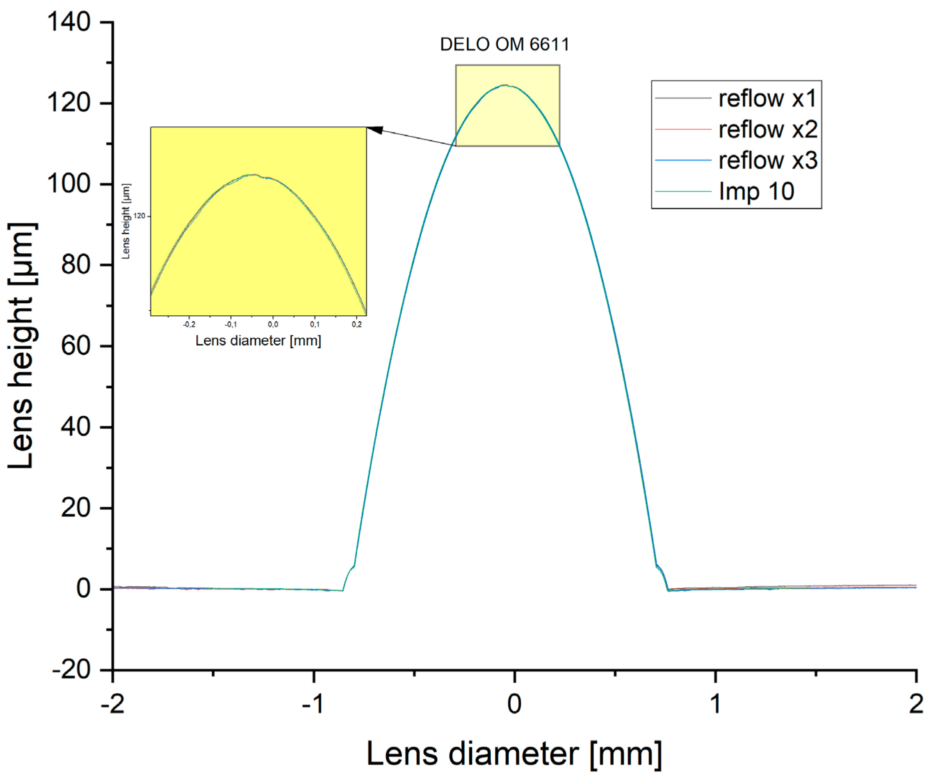


Figure 12: Lens Profiles after Reflow in Comparison with the Imprints

Like before, the shape of the lenses after the reflow process was analyzed using the lens equation to create a residual error plot ($RMS_{residual\ error}$). The overlaid residual error plots of the reflow lenses can be seen in Figure 13. The three residual error plots are similar to each other.

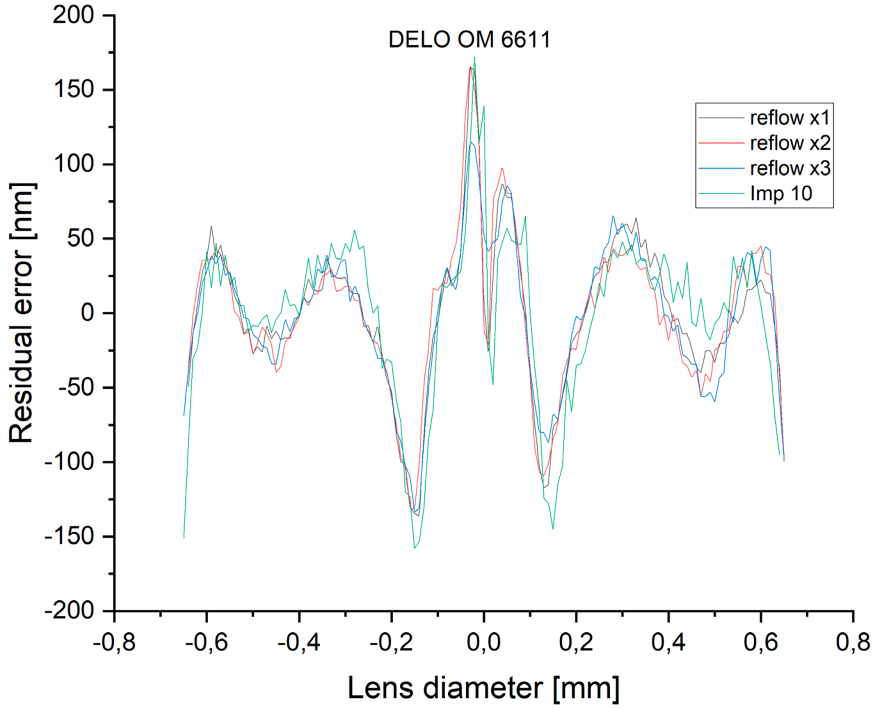


Figure 13: Residual Error Plot of Reflow Lenses in Comparison with the Imprints

To summarize, it can be said that the lenses are not influenced in their shape by the reflow process in any significant manner.

5. Process Results Conclusion

The detailed analysis of the imprinted lenses molded with DELO KATIOBOND OM6611 show consistently high-quality lens shapes with consistently low surface roughness throughout process chain. Multiple lenses from each process step were investigated to show stable pattern fidelity and repeatability of the molded shapes on a single wafer, as well as between subsequently manufactured wafers. The imprinted lenses show no measurable change in shape, transmission, or mechanical behavior when being exposed to an additional reflow process, which makes them suitable even for demanding packaging applications in optoelectronics.

The advanced molding process enabled by EVG®7300 WLO, combined with the EVGNIL UV/AF7 working stamp and DELO KATIOBOND OM6611 UV-curable optical material, yields excellent performance for wafer-level micro-optics fabrication, suitable for the mass production of high-quality polymer lenses.

Summary

EV Group, together with DELO Industrial Adhesives' tailored optical materials, provides a proven industrial solution for UV wafer level lens molding (WLO).

The results show that EVGs lens molding (NIL) process enables high-quality lenses with fully automated replication as well as automated detachment. As shown in this study, quality from the master to the final imprints can be preserved. Therefore, the processes and equipment, as well as dedicated DELO optical materials, are ready to serve the demands of next generation optical devices up to high volumes.

These developments are supported by the company's NILPhotonics® Competence Center. The infrastructure at EVG's headquarters includes state-of-the-art cleanrooms and equipment, supporting key NIL manufacturing steps such as step-and-repeat mastering, lens molding and EVG's SmartNIL® technology.