Enabling Sustainability in Glass Optics Manufacturing by Wafer Scale Molding

Christian Strobl[1,a] *, Paul-Alexander Vogel[1,b], Anh Tuan Vu[1,c],
Hendrik Mende[1,d], Tim Grunwald[1,e], Robert H. Schmitt[1,2,f], Thomas Bergs[1,2,g]

[1]Fraunhofer Institute for Production Technology IPT, Aachen, Germany

[2]Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Aachen, Germany

[a]christian.strobl@ipt.fraunhofer.de, [b]paul-alexander.vogel@ipt.fraunhofer.de, [c]anh-tuan.vu@ipt.fraunhofer.de, [d]hendrik.mende@ipt.fraunhofer.de, [e]tim.grunwald @ipt.fraunhofer.de, [f]R.Schmitt@wzl.rwth-aachen.de, [g]T.Bergs@wzl.rwth-aachen.de
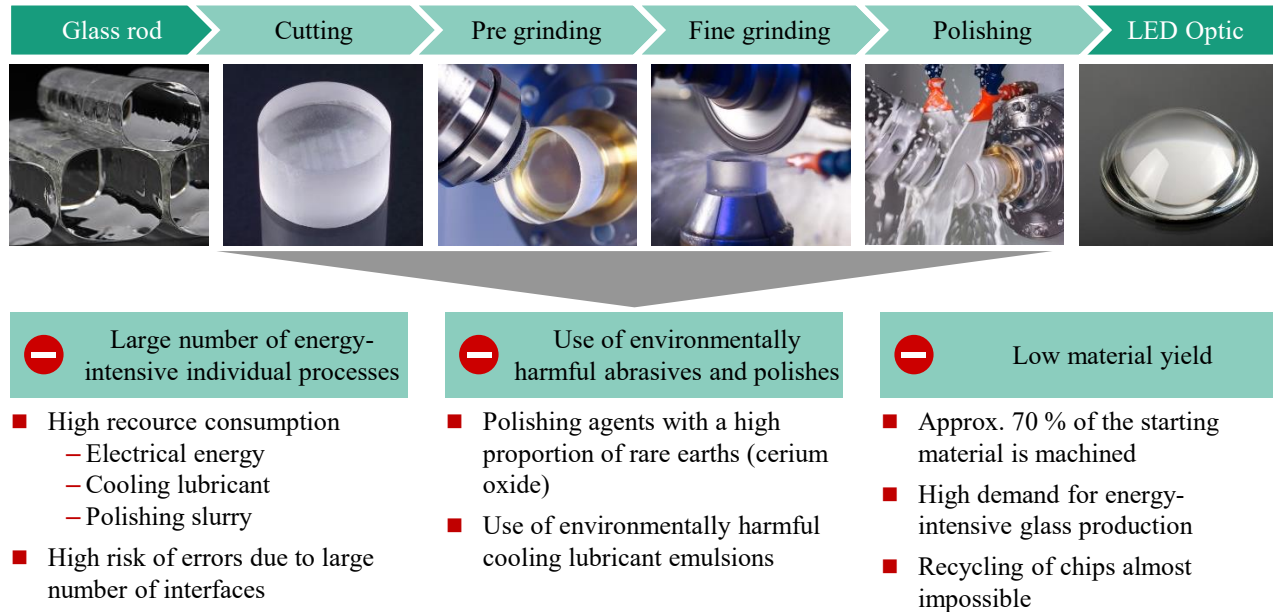
Abstract. Numerous optical applications have rising demands for ever increasing quantities from lighting and projection optics for modern vehicles to home or street lighting using LED technology. Glass is the material of choice for most of those application fields. It has several advantages over polymers, including heat and scratch resistance as well as longevity and recyclability. Nonisothermal glass molding has become a viable hot forming technology for mass production of optics. The major challenge is enabling a scalable replication process allowing the optical glass elements to be manufactured with high form accuracy and at low-cost production with low reject rates. This work introduces recent developments in glass optics manufacturing that allow the fulfilment of seemingly contradicting criteria: the economic growth and the need for less consumption of resources and energy. While single cavity nonisothermal molding is state-of-the-art, a manufacturing innovation through wafer-scale molding enables an exponentially increasing number of optics to be produced per production shift, allowing a significant reduction of unit costs. In parallel, as multiple optics are produced in one manufacturing cycle, the energy consumption and the consequent CO_2 emission can be reduced. In contrast, the technological development arises several challenges that will be discussed in this work. Besides the selection of suitable mold concepts and materials, the challenges also include the temperature control of the mold and the blank up to the optimization of flow and shrinking mechanisms of the glass during rapid forming. Another difficulty in the nonisothermal glass molding is to maintain the low form deviation required for precision optics, repeatability, and low failure rates through process optimization. Finally, detail calculations of cost, energy and CO_2 consumption, in comparison with conventional fabrication of glass components using grinding and polishing as well as single cavity molding, will be demonstrated. The nonisothermal wafer-level glass molding is a new technological solution for the sustainable manufacturing of optics at large-scaled production.

Introduction

LED-based automotive lighting and street illumination, light projection, and sensor components are just some of the diverse applications of lighting and projection optics [1]. The global LED market is projected to grow at a compound annual growth rate (CAGR) of 12.5% during the forecast period from 2021 to 2028 [2]. In the context of connected and autonomous vehicles, efficient processes for mass production of mostly optical sensor and lighting systems are more important than ever. Lenses made of glass represent important components in these systems. Consequently, the demand for precise optics, which should not only be cost-effective but also ecologically efficient, is increasing. Glass is superior to plastics required for those applications, particularly because of its UV-radiation and heat resistance, as well as its durability and mechanical strength [3]. Conventional manufacturing of optical products by means of grinding and polishing can neither serve the geometrical shape complexity nor the required production quantities for a high demand of complex geometries. In the process shown in Fig. 1, up to 70% of the raw material is machined in a time-consuming process using

polishing slurry and similar environmentally harmful substances. This method is, therefore, not suitable for the production of geometrically complex shapes in large quantities and is also ecologically questionable.

| Glass rod | Cutting | Pre grinding | Fine grinding | Polishing | LED Optic |

🚫 **Large number of energy-intensive individual processes**

- High recource consumption
  - Electrical energy
  - Cooling lubricant
  - Polishing slurry
- High risk of errors due to large number of interfaces

🚫 **Use of environmentally harmful abrasives and polishes**

- Polishing agents with a high proportion of rare earths (cerium oxide)
- Use of environmentally harmful cooling lubricant emulsions

🚫 **Low material yield**

- Approx. 70 % of the starting material is machined
- High demand for energy-intensive glass production
- Recycling of chips almost impossible

Fig. 1 Process flowchart of optics manufacturing by grinding and polishing

Precision glass molding (PGM) is an established, replicative process for the forming production of optics. In this process, the glass is heated to the forming temperature (significantly above the glass transition temperature) together with the forming tool without a significant temperature gradient and then pressed. Finally, a slow cooling process takes place to minimize stresses in the glass and to control the shrinkage. This process is very precise, but has the disadvantage of comparably long cycle times (Fig. 2) [4,5].

In contrast to PGM, nonisothermal glass molding process (NGM) involves external heating of the glass blank until it reaches the forming temperature. Forming then takes place in a preheated mold whose temperature is well below that of the glass. After molding, an external fine cooling process takes place. This significantly reduces the occupancy time of the mold. In the nonisothermal molding process, a cycle time of less than half a minute can be achieved for one lens in the single-cavity concept [6,7]. An example of this is the so-called rod pressing process, in which a glass rod is subsequently formed into individual lenses; however, the rod pressing process owns itself several disadvantages including insufficient form accuracy and glass waste. In more recent years, intensive research has been focusing on the enhancement of the process efficiency where glass preforms or gobs in well-defined volumes are used in the NGM process so that the drawbacks remaining in the rod forming can be diminished [8,9]. Nevertheless, the process was mainly developed based on the single-cavity molding; hence, the production volume cannot be enhanced [10,11]. To enable the mass production, current research aims at replicating several lenses in one press cycle using wafer-scale concepts. Thus, a large number of lenses can be produced simultaneously with similar process parameters. This allows a significant reduction of costs, time and energy input related to a single lens [1].
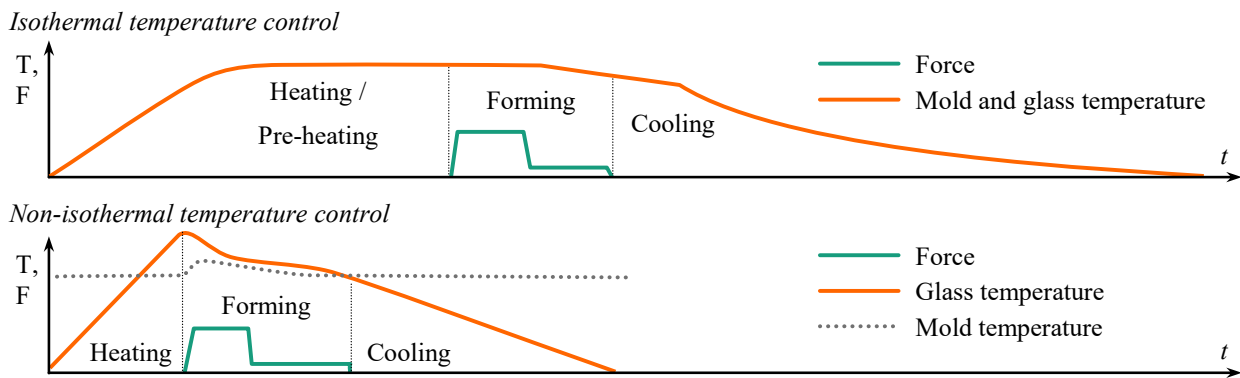
Fig. 2 Comparison of isothermal precision glass molding to nonisothermal glass molding process

Methodology

In the following, the widely used process of rod pressing is reviewed and then compared with wafer-scale forming.

The rod pressing process, shown in Fig. 3, is a partially automated process, but it requires manual labor and experience of the operator regarding handling and process control. A glass rod is used as the blank for rod pressing. The tip of the rod is heated externally in a furnace to the molding temperature. Conventionally, a gas-fired furnace is usually used for this purpose. The hot rod is then transported to the mold. Here, the glass is formed into the optical shape between the colder mold halves. The mold halves are conventionally heated by gas. Subsequently, the formed optic is separated from the rod and finally annealed. Since the glass rod usually provides a higher volume than is required for the lens, there is an overhang for each lens, which ends up as waste. This must be separated from the actual lens in a further process step by grinding and centering. Rod pressing represents one of several single-cavity processes. Other possibilities differ primarily in the use of other blanks (e.g., balls or so-called gobs) and the process sequences adapted to them. The efficiency of such a single-cavity process is significantly limited, since only one lens is formed per press cycle. This has an impact on cycle times and process costs as well as on energy consumption and CO_2 emissions. This represents the limiting factor for nonisothermal blank molding in the single-cavity range. The inputs and outputs of material and energy flows for the process are also shown in Fig. 3 [1].
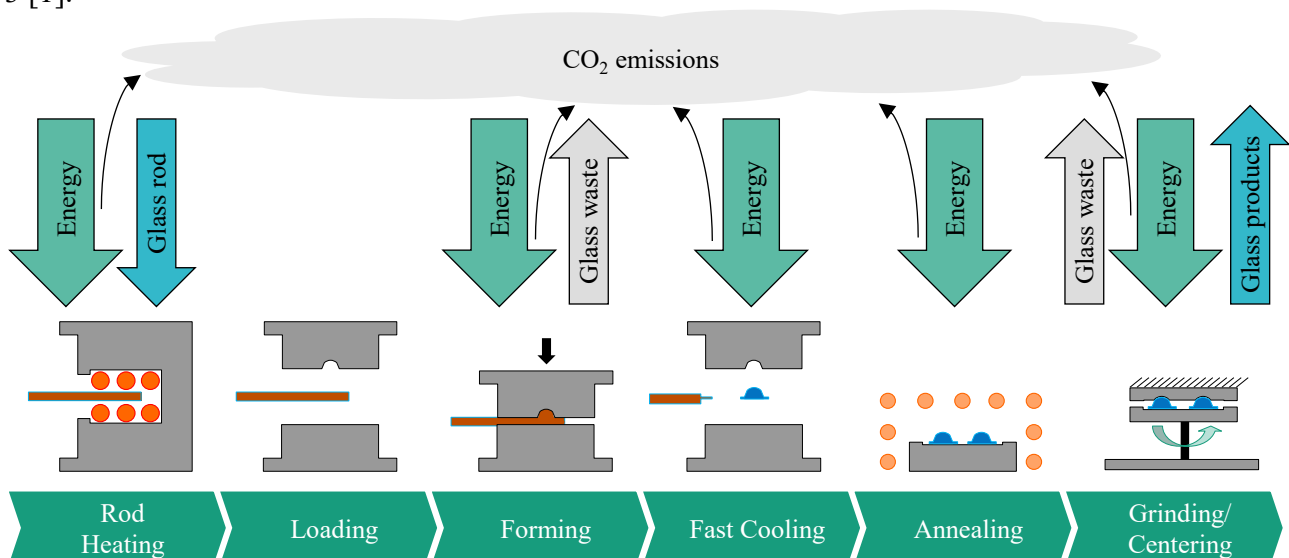

Fig. 3 Process chain of the rod pressing process

In addition, there are general requirements for glass molding, especially nonisothermal glass molding. These include the need for low form deviation to ensure the performance of the manufactured optics. Furthermore, low reject rates as well as high repeatability must be ensured.

The use of multi-cavity molds represents an economically, scientifically and ecologically interesting possibility for advancing nonisothermal glass molding. For this purpose, first developments have already been made in the field of PGM, which take into account both several individual cavities and a wafer-scale arrangement [12,13]. By using multiple cavities, a large number of optics can be produced in one press cycle. In the nonisothermal process, the use of one blank per cavity can hardly be implemented in a process-safe, economical and efficient manner due to the parallel but external heating with regard to material handling. Therefore, in the nonisothermal wafer-scale forming process, float glass blanks are used as blanks to press a large number of lenses from one blank, which subsequently only have to be separated in a cutting process. The process flow is shown in Fig. 4 together with its inputs and outputs. In contrast to the rod pressing process, the wafer is heated on the preheated lower mold. The glass heats up to the molding temperature faster than the mold tool itself. The forming, cooling, and fine cooling phases are similar to the rod pressing process. Finally, the glass is separated by cutting processes [1,12,13].
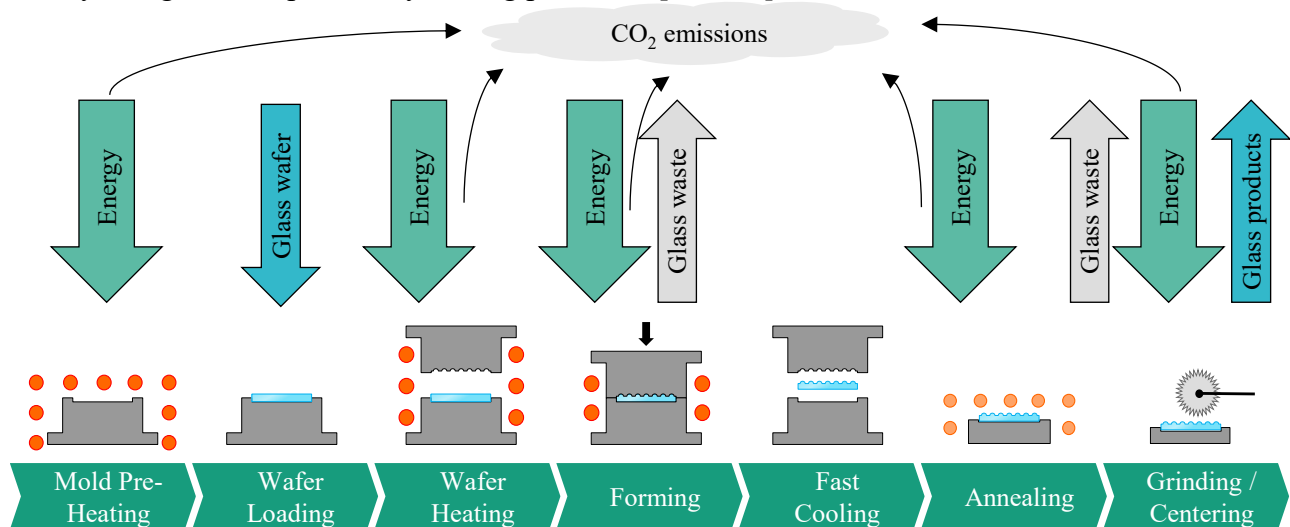

Fig. 4 Process chain of the wafer scale process

In nonisothermal glass molding, high-alloy steels or alloys with high chromium and nickel contents are used in general [14]. The suitability of these materials for the wafer-scale process has yet to be demonstrated.

However, this novel process approach faces many challenges that have to be overcome for a successful industrial employment of the process. In particular, these include the controlled influencing of the glass flow. The latter is influenced both by process parameters, e.g. temperature and molding force (e.g., Maxwell [15,16] or Burgers' models [17,18]), the heat transfers at the glass-mold interface [19–21] and by system variables such as the geometry of the blank and that of the mold, as well as the surface properties [22]. Another challenge is the control of shrinkage, which is also significantly influenced by thermal and system parameters [23]. The consequence of uncontrolled or excessive shrinkage can be glass breakage [24,25]. In addition, in the wafer-scale process exists an increased risk of adhesion when the hot glass blank first comes into contact with the mold due to the more complex multi-cavity geometry. In summary, both thermal control and correct mold geometry design can be considered as essential challenges of the nonisothermal wafer scale process. Regarding the mold geometry, both the arrangement of the cavities and their periphery have to be accounted. Linear, concentric, or even hexagonal arrangements can be taken into consideration. Furthermore, it is possible to use monolithic molds or those with mold inserts.

When analyzing the molded wafer, various quality features are essentially evaluated (Fig. 5). These include the characteristics of center thickness, form deviation and centering errors between the upper and the lower side of the lens, which are known from single-cavity molding. Additionally, in wafer-scale molding, the bending of a wafer must be considered, as well as the so-called pitch error [26]. This describes the deviation of the position of the lens on the wafer from its target position [1,22].
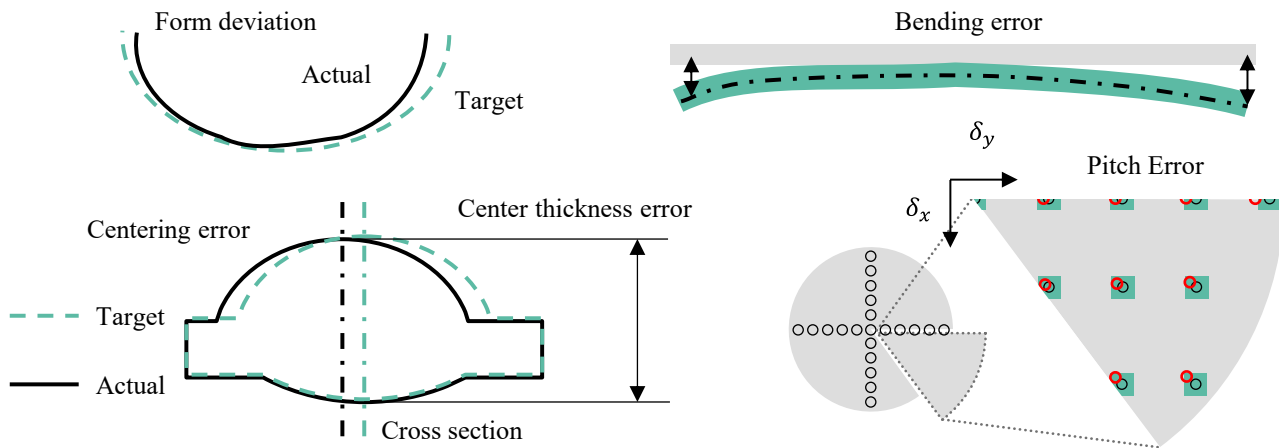
Fig. 5 Quality features in wafer scale molding

The two processes described above are compared in the following with regard to their economic efficiency and sustainability on the basis of real process data. The demonstrator lens geometry is shown in Fig. 6.
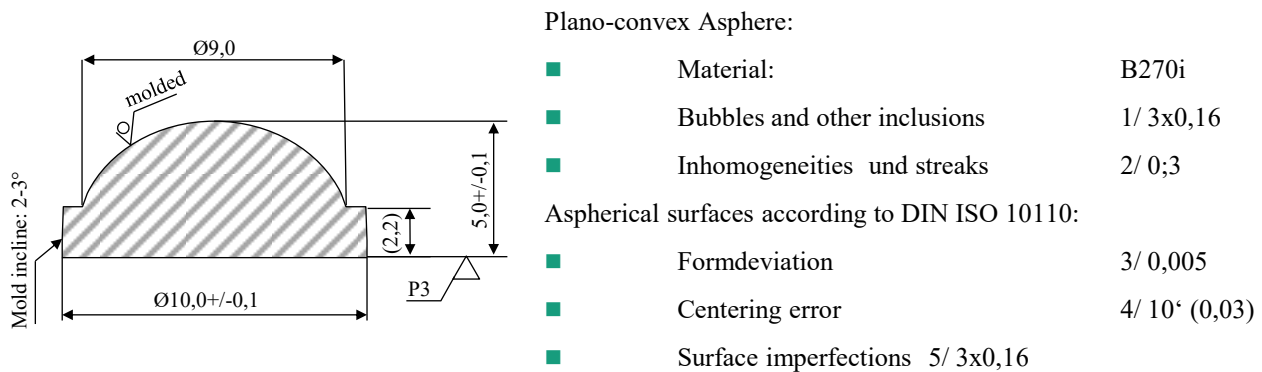

Plano-convex Asphere:

- Material: B270i
- Bubbles and other inclusions 1/ 3x0,16
- Inhomogeneities und streaks 2/ 0;3

Aspherical surfaces according to DIN ISO 10110:

- Formdeviation 3/ 0,005
- Centering error 4/ 10' (0,03)
- Surface imperfections 5/ 3x0,16

Fig. 6 Demonstrator lens geometry

For data acquisition, the existing press machine was equipped with appropriate sensors for recording forces, temperatures, and other variables. These process data were collected in a central SQL database and subsequently analyzed [27]. The comparison was made with respect to energy aspects and the CO_2 footprint within the context of a Life Cycle Analysis (LCA). This is a standardized method that covers the entire life cycle from raw material extraction to disposal of all waste [28]. The commercial software "GaBi[®]" (German: Ganzheitliche Bilanzierung; translatable to "holistic accounting") was used for this purpose. This software allows process chains to be entered together with their inputs and outputs. Using a database, the relevant parameters including energy and CO_2 for individual process steps and materials including glasses and chemicals are selected and calculated on a quantity basis. In this way, the product sustainability performance can be determined. In this study, the goal of the LCA is to compare the two process chains, i.e., rod pressing and wafer scale. Hence, the system boundaries for the LCA only contain the forming processes as shown in Fig. 7. Inputs are glass preform (rod or float glass) and energy, and outputs are the final single lens as well as CO_2 and glass waste. Assembly, usage, and end of life were not taken in the analysis since they are treated equally in these aspects. Furthermore, the mold manufacturing process was not considered. Molds for hot forming can be refurbished several times without exceptional consumption of energy or CO_2. Nevertheless, these refurbishing processes were considered in the cost calculations. This is due to cost intensive high precision machining, which is necessary for surfaces with highest qualities. Fig. 3 and Fig. 4 illustrate the corresponding material and energy flows. To determine the real data, energy consumption and the number of units produced per period of time were measured. The Global Warming Potential (GWP) was determined with the aid of the GaBi[®] databases for individual raw materials and with data sheets of the machines.
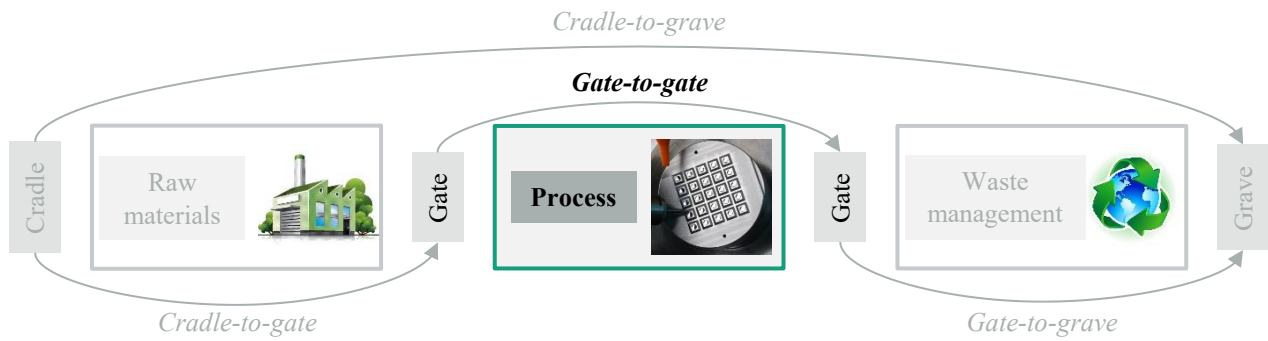
Fig. 7 System boundaries for the Life Cycle Analysis

For the wafer-scale process, a 5x5 lens array was used for forming. The cavities are arranged in a linear, equidistant pattern to make good use of the area of the wafer and to allow the lenses to be separated by common methods such as diamond cutting, waterjet cutting or laser cutting.

To calculate the unit-related product costs, a cost calculation tool was used which was developed at the Fraunhofer IPT and specifically designed for nonisothermal glass molding for the comparison. Investment costs such as machines and heating devices as well as costs for molds and raw materials were all accounted. In addition, energy and personnel costs were implemented. These costs were considered for all steps along the process chain. They included the cleaning of the mold and raw glass, the heating of the glass and mold, molding, fine cooling and, if necessary, the final separation of lenses. Added to this are intermediate handling steps. This also results in the process times or the cycle time of a product. Reject rates were also taken, as well as the quantities to be produced, the service life of molds, and the maximum capacity of a machine.

Key Findings

Analysis of real production data shows that the process times for each ready-to-use lens have been significantly reduced. Specifically, it is possible to produce about 700 lenses in one work shift (8 hours) using the rod process. With wafer-scale forming, 1500 optics can be produced in the same period. This initially illustrates the potential of the multi-cavity approach for high volume production. In the following, the processes are considered normalized to 1000 pieces per shift to ensure comparability of the data.

For both processes, the assumptions listed in Table 1 were used in the following calculations. Due to the simpler geometry for a single cavity mold, the service life of a mold for rod pressing is significantly higher, and the costs are lower due to the simplicity. Due to the requirement of more complex and modern machines, the wafer scale process has higher fixed costs.

Table 1 Assumptions regarding the process comparison

	Rod Pressing	Wafer Scale
Mold life time	High (5x)	Low
Mold cost	Low	High (2x)
Fixed cost	Low	High (3x)
Machine capacity	Low	High (2,5x)
Reject rate	9,5 %	9,5 %
Machine downtime	10 % / year	10 % / year

The normalized unit costs are broken down according to their composition in Fig. 8 on the left for the rod pressing process and on the right for the wafer scale process. The fixed costs (e.g., machine investment), tooling, energy, personnel, material and reject costs were considered. It is noted that the

energy costs for the rod process were divided into thermal and electrical costs, since the thermal energy was provided by gas.
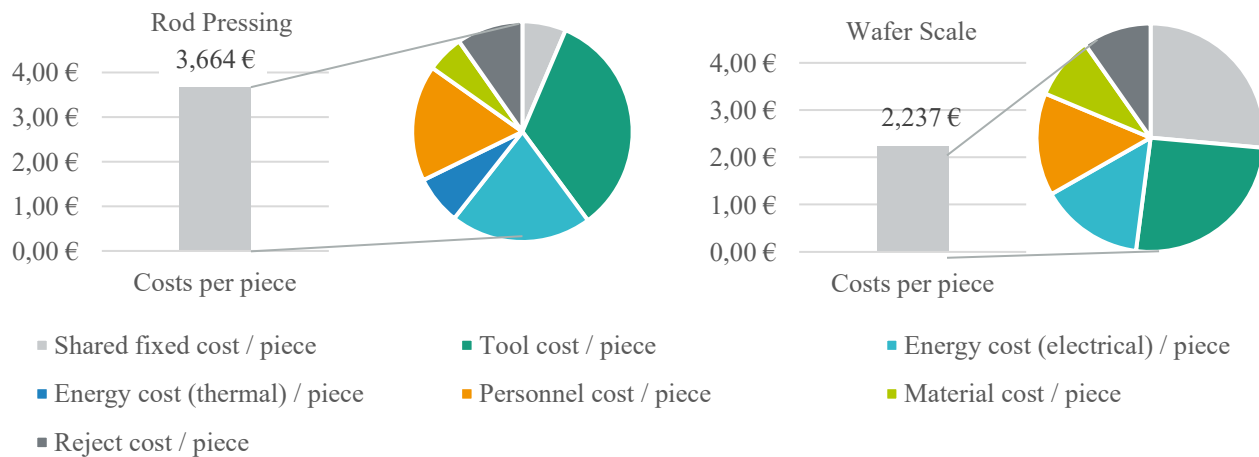

Fig. 8 Process cost per piece – left: rod pressing process, right: wafer scale process

The comparison of the individual cost shares illustrates the significant differences, which are composed of the mold, energy, personnel as well as reject costs. The total costs per unit differ by 38.9 %. In addition to the energy costs, the mold costs represent the most significant influence factor. Although these are higher in absolute terms for a wafer-scale mold than for a single-cavity mold, the mold costs are divided among 25 lenses per pressing for a 5x5 wafer. Furthermore, the significant difference in the shared fixed cost must be considered. This results from the more complex, modern and expensive equipment technology used for the wafer-scale process. This enables both higher process forces and a better distribution of these forces via centering devices.

A closer look at the energy costs shows that these are also significantly lower for the wafer-scale process, although substantially higher electricity prices than gas prices were assumed (by a factor of 3). In addition, longer heating times were assumed for the float glass blank, since it was heated on the lower mold and multiple glass rods can be heated in parallel. Thus, the energy consumption to produce a wafer with 25 lenses increases compared to a single lens in the rod pressing process. By dividing the consumption among the individual lenses of the wafer, the energy consumption related to one lens can be significantly reduced.
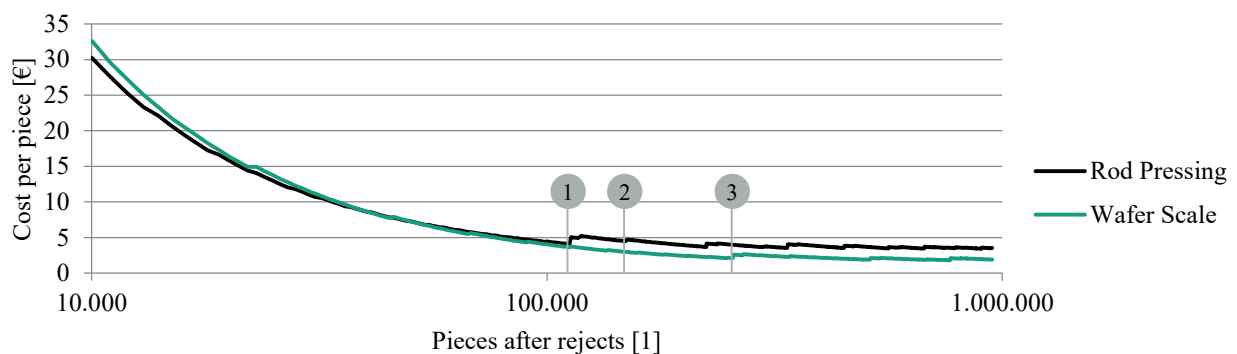

Fig. 9 Course of unit costs of both processes depending on annual production

Fig. 9 shows the curve of unit costs versus the number of units after taking rejects into account. The curve generally depends on various factors. These include the initial costs, which are primarily determined by the machine costs. They influence the unit costs, particularly for low quantities, since the comparatively high investment costs for machines are distributed over a minor production volume. Tool costs and their service life are further factors. The recognizable, smaller discontinuities in the graphs represent the need for refurbishment of the mold halves (position 2). The distance of the discontinuities (X-axis section) represents the mold lifetime, and the height of the discontinuity is

equivalent to the mold refurbishment costs. The larger discontinuities represent the need for another machine (position 1). Here, the X-axis section represents the machine capacity, and the jump height represents the machine costs. This is particularly noticeable for the rod pressing process at about 112,000 units (position 1). At this point, the maximum capacity of a molding line is reached. For the wafer-scale process, this is only the case at around 260,000 units (position 3). Due to the less expensive plant technology and simpler tools, the rod process is more favorable than the wafer-scale process for low volumes (below 50,000 units per year). Due to the better scalability of the process, wafer-scale molding is preferred for high volumes (over 112,000 units per year). Consequently, the wafer-scale process can serve the very high volumes required in the addressed markets of illumination optics. In the range between 50,000 and 112,000, unit costs are at a similar level. Hence, optimization of the rod pressing process can help to open up this plateau. One possible approach would be to press two to three lenses simultaneously, similar to a simplified wafer-scale process. Thus, the total costs can be reduced in the entire unit volume range.

Energy costs account for a significant proportion of the total process costs. This is particularly true for the rod pressing process, where the energy needed to heat the glass and the mold is provided by gas. Energy costs account for 27.9% of the total cost per finished optic for the rod process, but only 14.7% for the wafer-scale process. This does not consider energy costs for the production of the raw material for glass and also molding tools.

Fig. 10 shows a detailed breakdown of the energy consumption of the two processes. In the rod pressing process, gas heating of the glass and mold accounts for well over 50% of the total energy. In the wafer-scale process, this is completely substituted by electrical heating with high efficiency. In addition, the float glass blank is heated more efficiently than the rod, which absorbs a lot of heat that is subsequently not used.
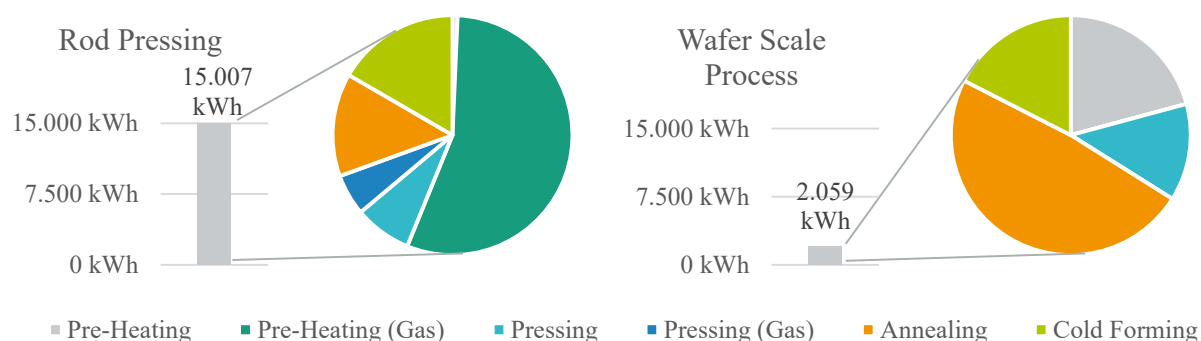

Fig. 10 Energy consumptions of the rod pressing process (left) and wafer scale process (right)

The other components, such as molding, separation (cold forming) and rejects, also require significantly less energy in relation to an optic. This results in the significant energy savings of 86.28% shown in Fig. 10, consisting of 64% savings in electrical energy and full substitution of gas-based by electrical heating.

The closely related analysis of the GWP provides analogous results to the energy analysis. Here, a reduction of 79.25 % can be determined when considering the entire process chain. Fig. 11 shows the savings per process step.
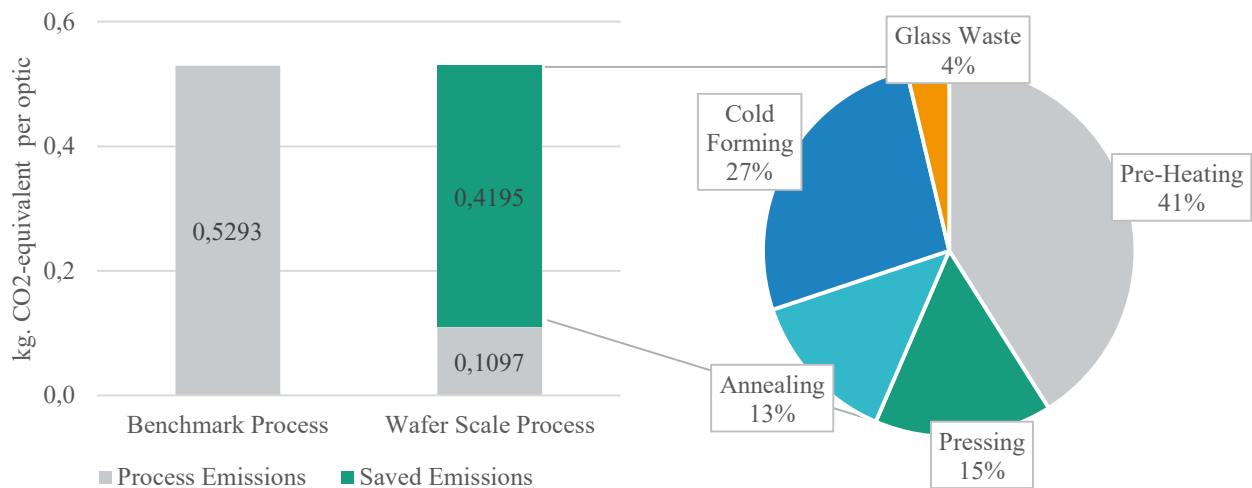
Fig. 11 Breakdown of GWP savings by process step

Once again, preheating is the driving process step, accounting for 41% of the total savings. This is due to the savings in total energy described above as well as to the substitution of gas by electrical energy. A non-negligible share is also accounted for by cold forming. This includes post-processing after forming. This involves cutting in the wafer-scale process and polishing in rod pressing. The already mentioned environmental impact of the polishing slurry has a significant effect on the savings in GWP.

Summary

Nonisothermal glass molding is a viable manufacturing process for precision optics with a wide range of applications. Nevertheless, the processes that are currently state of the art are limited in their efficiency. One solution to this problem is wafer-scale forming. In this work, it was shown that this multi-cavity approach offers high economic and environmental potential. This is particularly evident when compared with rod pressing as a single-cavity approach. Cost savings of 38.9% are possible while increasing the possible output per period by more than a factor of 2. In addition, a life cycle analysis has shown that savings of around 80% are possible in terms of energy consumption and GWP. However, many challenges remain in nonisothermal wafer-scale forming. These include the optimization of the thermal characteristics as well as the glass flow to further reduce the forming error.

References

[1] P.-A. Vogel, C. Strobl, H. Mende, Verbundvorhaben: EFFEkT - Energie- und ressourceneffiziente Prozesskette zur Fertigung komplexer Glasoptiken Teilvorhaben: Entwicklung eines Blankpressprozesses Final Report Berichtszeitraum: 01.12.2015-30.11.2019 (2020).

[2] Grand View Research, LED Lighting Market Size, Share & Trends Analysis Report By End-use (Residential, Commercial), By Product (Lamps, Luminaires), By Application (Indoor, Outdoor), By Region, And Segment Forecasts, 2021 - 2028, 2021. https://www.grandviewresearch.com/industry-analysis/led-lighting-market (accessed 6 December 2021).

[3] A.-T. Vu, H. Kreilkamp, O. Dambon, F. Klocke, Nonisothermal glass molding for the cost-efficient production of precision freeform optics, Opt. Eng 55 (2016) 71207. https://doi.org/10.1117/1.OE.55.7.071207.

[4] T. Grunwald, Modellierung des Werkzeugverschleißes bei der Quarzglasumformung, first ed., Apprimus Wissenschaftsverlag, Aachen, 2021.

[5] D. Hollstegge, Process-induced changes in optical properties of precision molded glass lenses. Dissertation, first edition, 2016.

[6] H. Kreilkamp, Analyse der Einflüsse auf die Gestaltabweichung gepresster Glasoptiken beim nicht-isothermen Blankpressen. Dissertation, first edition, 2018.

[7] J. Bliedtner, G. Gräfe, Optiktechnologie: Grundlagen - Verfahren - Anwendungen - Beispiele, second., aktualisierte Auflage, Hanser, München, 2010.

[8] A.T. Vu, H. Kreilkamp, L. Gang, O. Dambon, F. Klocke, Numerical modeling-based design of the newly developed nonisothermal glass molding process for complex glass optics, in: Glass Service (Ed.), 13th International Seminar on Furnace Design – Operation & Process Simulation, Czech Republic, 2015, pp. 376–390.

[9] A.T. Vu, H. Kreilkamp, B.J. Krishnamoorthi, O. Dambon, F. Klocke, A hybrid optimization approach in non-isothermal glass molding, AIP Conference Proceedings Vol. 1769 (2016) 40001–40006. https://doi.org/10.1063/1.4963428.

[10] H. Kreilkamp, A.T. Vu, O. Dambon, F. Klocke, Replicative manufacturing of complex lighting optics by non-isothermal glass molding, in: Polymer Optics and Molded Glass Optics: Design, Fabrication, and Materials 2016, San Diego, California, United States, SPIE, 2016, 99490B.

[11] H. Kreilkamp, A.T. Vu, O. Dambon, N.F. Klocke, Non-isothermal glass moulding of complex LED optics, in: S.K. Sundaram (Ed.), 77th Conference on Glass Problems, John Wiley & Sons, Inc, Hoboken, NJ, USA, 2017, pp. 141–149.

[12] T. Grunwald, O. Dambon, F. Klocke, Warmumformung von Präzisionsoptiken, in: Jahrbuch Optik und Feinmechanik.

[13] G. Liu, J.-H. Staasmeyer, O. Dambon, T. Grunwald, Scalability of the precision glass molding process for an efficient optics production, in: Optical Manufacturing and Testing XII, San Diego, United States, SPIE, 19.08.2018 - 23.08.2018, p. 17.

[14] H. Kreilkamp, A.T. Vu, O. Dambon, Establishment of an integrated process chain for the cost-efficient manufacturing complex glass optics. Grant Agreement No.: FP7-SME-2013-606105, CENTiMO, Final Report, 2015.

[15] G. Liu, A.-T. Vu, O. Dambon, F. Klocke, Glass Material Modeling and its Molding Behavior, MRS Advances 2 (2017) 875–885. https://doi.org/10.1557/adv.2017.64.

[16] T.D. Pallicity, A.-T. Vu, K. Ramesh, P. Mahajan, G. Liu, O. Dambon, Birefringence measurement for validation of simulation of precision glass molding process, J American Ceramic Society 100 (2017) 4680–4698. https://doi.org/10.1111/jace.15010.

[17] A.T. Vu, P.-A. Vogel, O. Dambon, F. Klocke, Vacuum-assisted precision molding of 3D thin microstructure glass optics, in: Fiber Lasers and Glass Photonics: Materials through Applications, Strasbourg, France, SPIE, 22.-26.04.2018, pp. 1–21.

[18] A.T. Vu, A.N. Vu, T. Grunwald, T. Bergs, Modeling of thermo-viscoelastic material behavior of glass over a wide temperature range in glass compression molding, J American Ceramic Society 103 (2020) 2791–2807. https://doi.org/10.1111/jace.16963.

[19] A.T. Vu, A.N. Vu, G. Liu, T. Grunwald, O. Dambon, F. Klocke, T. Bergs, Experimental investigation of contact heat transfer coefficients in nonisothermal glass molding by infrared thermography, J American Ceramic Society 102 (2019) 2116–2134. https://doi.org/10.1111/jace.16029.

[20] A.T. Vu, T. Helmig, A.N. Vu, Y. Frekers, T. Grunwald, R. Kneer, T. Bergs, Numerical and experimental determinations of contact heat transfer coefficients in nonisothermal glass molding, J American Ceramic Society 103 (2020) 1258–1269. https://doi.org/10.1111/jace.16756.

[21] A.T. Vu, S. Gulati, P.-A. Vogel, T. Grunwald, T. Bergs, Machine learning-based predictive modeling of contact heat transfer, International Journal of Heat and Mass Transfer 174 (2021) 121300. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121300.

[22] J.-H. Staasmeyer, G. Liu, M. Friedrichs, Skalierbare Abformung von Linsen für IR-Anwendungen (2017).

[23] A.T. Vu, T. Grunwald, T. Bergs, Thermo-viscoelastic Modeling of Nonequilibrium Material Behavior of Glass in Nonisothermal Glass Molding, Procedia Manufacturing 47 (2020) 1561–1568. https://doi.org/10.1016/j.promfg.2020.04.350.

[24] G. Liu, Modeling Fracture Behavior in Precision Glass Molding, first edition, Apprimus Wissenschaftsverlag, Aachen, 2018.

[25] P.-A. Vogel, A.T. Vu, H. Mende, T. Grunwald, T. Bergs, R.H. Schmitt, Approaches and methodologies for process development of thin glass forming, in: Optifab 2019, Rochester, United States, SPIE, 14.-17.10.2019, p. 68.

[26] F. Klocke, Y. Wang, D. Hollstegge, F. Wang, G. Liu, Precision glass molding of wafer lens optics, in: Proceedings of the 12th International Conference of the European Society for Precision Engineering and Nanotechnology: June 4th - 7th [8th] 2012, Stockholm, Sweden, Euspen, Bedford, 2012, pp. 181–184.

[27] H. Mende, P.-A. Vogel, M. Padrón Hinrichs, R.H. Schmitt, Industrie 4.0 in praxisnaher Anwendung*: Vom Retrofit über Datenspeicherung zum maschinellen Lernen am Beispiel der Glasumformung, wt-online 2019 (2019) 779–784.

[28] R.B. Tan, H.H. Khoo, An LCA study of a primary aluminum supply chain, Journal of Cleaner Production 13 (2005) 607–618. https://doi.org/10.1016/j.jclepro.2003.12.022.