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Compensation of structure distortion in nonisothermal hot forming of laser structured thin glass

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Abstract

Modern automotive industry employs a variety of complex shaped glass components, from touchscreen displays, dashboard screens, weather resistant windshields to tinted sunroofs. Currently around 50% of these components are functionalised by adding microstructures in a process based on etching or replication processes with structured forming tools, which are neither environmentally nor economically friendly. We present a new approach to functionalise such surfaces by direct laser structuring of glass substrates, thereby reducing costs and energy consumption by up to 60% and avoiding harmful chemicals compared to conventional processes. Current developments in high-power laser-beam sources and laser system technology enable low cycle time direct structuring of glass substrates. Laser-based direct structuring can generate a large portfolio of functional structures of different sizes which we showcase in haptic, hydrophobic and anti-glare structures. The downstream forming of structured glass interferes with high demands of the automotive industry due to shape distortions and positional distortions of the structure. Therefore, we developed a FEM-based predistortion method to adjust the laser trajectory, compensating for the influence of 2D glass moulded into a 3D shaped product. The compensation method was validated by conducting hot forming experiments with different laser-induced geometries on one-dimensional curved forming tools. We were able to reduce the distortion error by more than 90%.

Hot forming, thin glass, laser structuring, green production

1. Introduction

Glass is an indispensable material for numerous components in electronics, the semiconductor industry and sensor technology. The potential of the material lies in its properties: It is light, scratch-resistant, temperature-resistant and very stable. With a thickness of only a few millimitres, such thin glass is the preferred material for high-quality automotive interiors, such as centre consoles, rear-view mirrors, door elements and speedometer units. In more than 50 percent of all thin-glass components, the glass surfaces are functionalised by introducing micro- and nanostructures. These modifications are various: from improved haptics to anti-fogging surfaces to anti-glare and anti-reflection properties [1,2].

Industrially established methods for functionalising such thin glass are either chemical etching or replicative moulding. These methods are inefficient in terms of their carbon footprint, raw material consumption, energy consumption and manufacturing costs. In the context of green transformation of industry it is necessary to develop new approaches for the production of functionalised glass [3,4].

We propose a new process chain that can process functionalised thin glass ecologically and economically. This is achieved by combining laser material processing of the semi-finished glass and the subsequent nonisothermal hot forming. Current industrial ultra-short pulsed laser beam sources provide sufficient energy to process semi-finished glass economically for mass production [5]. In addition, nonisothermal glass forming offers a number of advantages over competing moulding processes thanks to its long tool life and low cycle times [6].

To implement the proposed process chain, several challenges need to be addressed. Firstly, laser structures must be developed and the high-speed laser processing of glass investigated [7]. Furthermore, the forming of a planar semi-finished product into a 3D part results in geometric distortions of the induced laser texture.

These shape and positional distortions of the structure interfere with high demands of the automotive industry. Therefore, we developed a finite element method (FEM)-based predistortion procedure to adjust the laser trajectory and compensate for the influence of 2D glass moulded into a 3D shaped product.

2. Methodology

In order to implement the proposed process chain, laser trajectories for the respective functionalisations must be generated on the basis of the final 3D glass geometries and then adapted for processing on 2D glass.

To allow this adaption, the forming process needs to be predicted using FEM simulations. On this basis, a deformation field linking positions on the 2D to the 3D glass can be generated. Using the 3D position information of the laser structure and the deformation field, the generated laser trajectories can be compensated for the processing of the 2D glass. In order to validate the proposed method, equidistant circular ring segments are simulated on a 2.5D (bending around one axis) deformed glass, and corresponding compensated laser

trajectories are textured into the 2D glass before hot forming (see Fig. 1). The distances between the ring segments on the 2D glass should therefore no longer be equidistant.
Following the hot forming process the distances between each circular ring are measured and validated against simulations.

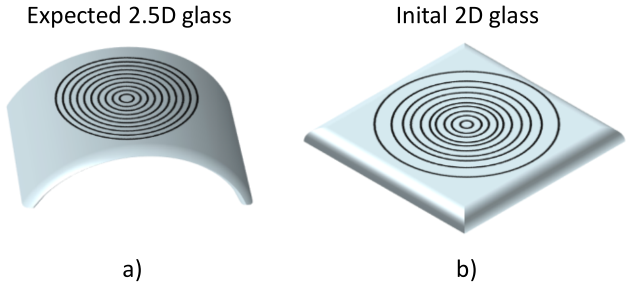

Figure 1. a) Expected 2.5D formed glass with equidistant circular rings. Based on this model the proposed distortion method generates 2D laser trajectories based on FEM simulations with b) deformed ring geometries on the initial 2D glass, which is then hot-formed.

2.1 FEM Simulation of nonisothermal hot forming process

Fraunhofer IPT uses FEM simulations to describe the behaviour of the glass during forming in order to optimise the forming process. This is achieved with material models developed in-house that describe the highly non-linear, visco-elastic behaviour of glass. The model is composed of a mechanical and a thermal model [8]. In particular, the models take glass flow and the thermally induced shrinkage into consideration. Based on this data, an optimised tool design can be derived, thus improving the final shape accuracy. In addition, FEM simulations can be used to predict the macro- and micro-scale distortions caused by the forming process due to compression and tension of the laser structures applied to the glass [9]. These distortions are described by distortion vectors used for the suggested predistortion method. Therefore, a nonisothermal gravity slumping process with a 2.5D deformation (bending around one axis) was simulated using the generalised Maxwell model with 156 meshed elements for the glass and 96 elements for the mould. The forming tool with a bending radius of 100 mm had an initial temperature of 450 °C and the glass (B270i, soda-lime glass) was heated up to 700 °C (see Fig. 2). By simulating viscosity induced deformations over time the resulting shape accuracy of the formed glass and the shape deviation can be predicted [10]. Subsequently, a 30 minutes cooling phase was simulated in order to cool the glass to room temperature (25°C). The result (see Fig. 2) indicates a spring-back phenomenon at the glass edges. Eventually this effect leads to glass shrinkage. This process-specific challenge is known in nonisothermal hot forming and can be reduced by adjusting the process parameters, especially in the cooling phase [11]. The influence of shrinkage is not considered for the described feasibility study.

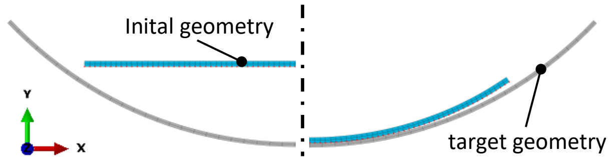

Figure 2. Initial undeformed glass of the simulation at time t=0 (left) and fully deformed glass after forming process at time t=end (right). The deformed glass shows shrinkage in the edge area which leads to deviations from the target geometry.

The overall accuracy of the simulation depends on many factors. For example, to obtain sufficiently accurate information about the macro- and microscopic distortion of the structures, temperature-dependent and glass-specific properties such as stress and structural relaxation values are required. In addition, material heat transfer coefficients are crucial for the accuracy of the simulations. [8] Those values were determined at Fraunhofer IPT for B270i soda-lime glass.

2.2. Predistortion method

The results of the FEM simulation can be used not only for predicting the shape of glass after hot forming but also for generating geometries of pre-deformed structures that later could be hot formed into the designed shape. Intrinsically, FEM simulation results have no temporal nature. Therefore, if structures, geometries and their respective positions are known for the 3D part, inverting the simulation can be a tool to derive positions and distortions for a 2D surface. The idea of applying inverse transformation relies on mapping points on the initial un-deformed (2D) and deformed (3D) surface. Basically, the position of each point marked on the flat glass can be paired with a spatial position of this marker on the deformed glass, since modelling of the deformed geometries in FEM-based simulations is performed in a discrete piecewise manner. Figure 3 illustrates the case of forming a quarter hemisphere. Orange points on the 2D surface (before forming) are connected with blue points after forming. The points are distributed mostly evenly in a rectangular grid. The positional data was acquired from FEM simulation results. The set of points represent a displacement field that is used to derive a deformation field.
The arrangement of structures on the glass is designed with 3D curves on top of CAD surfaces of the formed glass. To map 3D curves onto the displacement field, deformation vectors at arbitrary 3D curve-points need to be interpolated. This is achieved by barycentric coefficients within grid points found in the vicinity of 3D curvature points. Based on the analysis of the deformation field, it is possible to derive a local deformation (elongation, stretching, shear). This information is used to adjust pre-planned 3D laser trajectories onto a 2D surface.

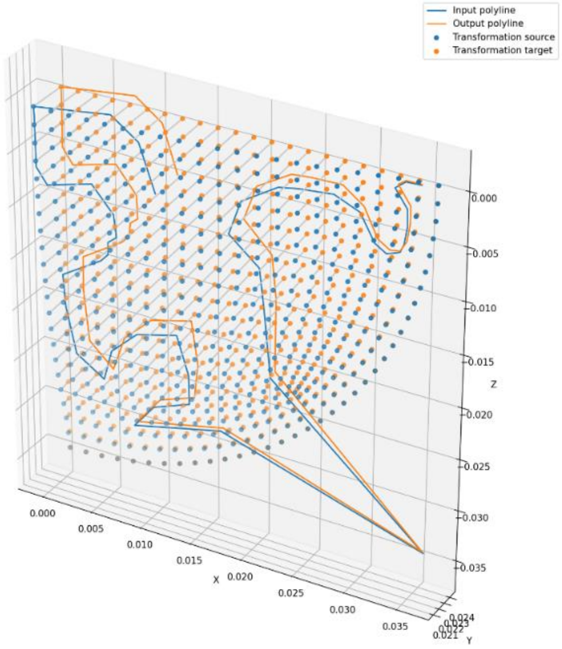

Figure 3. Deformation field between a 2D surface and a 3D quarter hemisphere. The position of a polyline before and after deformation is shown

3. Glass processing

Due to availability Panda-MN228 float glass was used for laser ablation and subsequent hot forming instead of B270i soda-lime glass. Equidistant ring geometries with a spacing of 2 mm (see Fig. 1) were compensated using the described approach in

Chapter 2. The resulting deviation for each circular ring radius used for the compensation of laser trajectories is shown in Figure 4. Using the compensated laser trajectories, the 2D glass was textured with ring segments. The laser-treated 2D glass was then nonisothermally hot formed into a 2.5D shape with a bending radius of 100 mm.

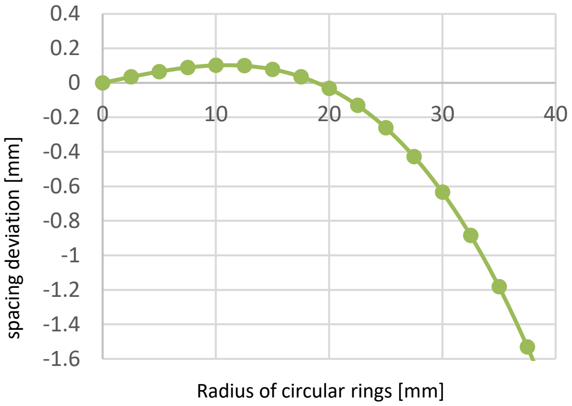

Figure 4. Simulated deviation of the 3D equidistant circular spacing on 2D glass per mm.

3.1 Laser ablation

An ultrashort pulsed Trumpf (model Tru Micro 2230) laser source provides collimated pulsed laser radiation (350 fs) with a maximum power of 10 W and pulse energies up to 25 µJ at a central emission wavelength of 532 nm with a Gaussian intensity distribution. The raw beam (3.8 mm) passes through a liquid crystal polariser into an optical z-axis (varioScan20i_de) with a beam expansion factor of 2.5. Using the optical z-axis, the laser beam can be focused in 3D from the working plane by +-6 mm in the z-direction. A galvanometer scanner (excelliScan14) was used for lateral beam deflection with high precision repeatability (< 1 µm) followed by a telecentric f-theta lens with f = 100 mm focussing the laser onto the glass with a spotdiameter of d_s = 8.5 µm.

A clamping system designed and manufactured at Fraunhofer IPT was used to prevent laser reflections into the glass by clamping the glass only at the edges and thus transmitting the laser beam into air after passing through the glass (see Fig.5).

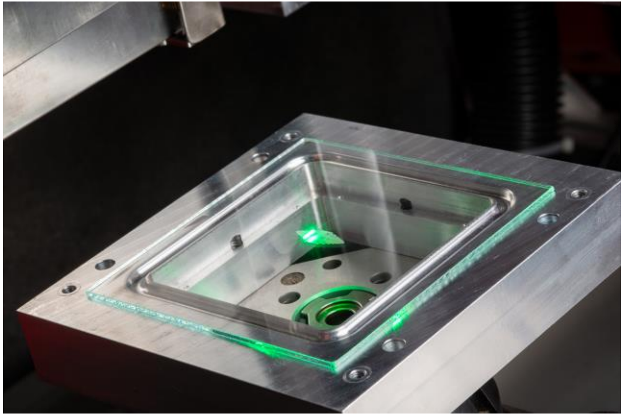

Figure 5. Laser ablation of 100x100 mm floatglass. Using the clamping system for processing laser radiation is transmitted through glass to prevent back-reflections into the glass.

For this system, suitable process parameters were determined to introduce required textures or markings into the glass. Thus, the following process parameters were varied in a full factorial experimental study: (i) laser power, (ii) laser frequency (iii) pulse overlap, (iv) laser bursts and (v) hatching. Results indicate parameter sets for high throughput laser ablation with ablation rates up to 0.06 mm²/min and corresponding roughness of S_a =0.15 µm.

Using the predistortion method (see Fig 3), laser trajectories were generated with varying spacing (see Fig 1b) and subsequently textured onto the 2D glass for downstream hot forming.

3.2 Hot forming

A nonisothermal thin glass forming machine (NI-TG Forming Machine) (see Fig 6) from the manufacturer Vitrum Technologies was used for the hot forming experiments.

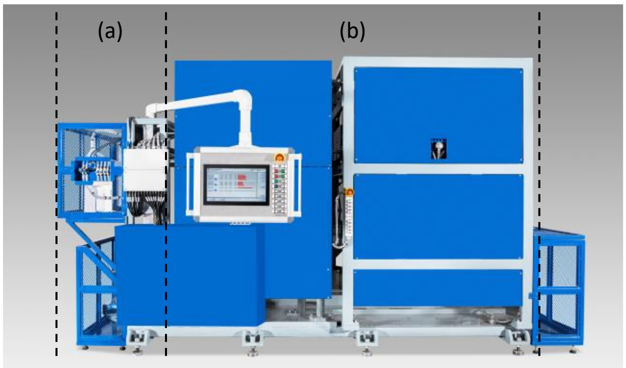

Figure 6. Vitrum Technologies´ non-isothermal thin glass forming machine (NI-TG Forming Machine) with a loading station (a) and several oven chambers (b).

The machine is equipped with several oven chambers offering a temperature range limit of up to 1300 °C and several high-precision movement axis with a position repeatability of < 1 µm. All actuators (axis, valves, heating systems) can be controlled via an intuitive human machine interface (HMI). As a result, the machine is well suited for the development of new glass hot forming processes. All sensor data, actuator positions, movements and energy consumption of the machine are provided with marker signals and time stamps. All data is written into a database every 15 ms using an internal clock signal. This provides the prerequisites for a digital twin model and alignment with the FEM simulations of Fraunhofer IPT.

The machine features four types of thin glass forming processes (i) gravity slumping, (ii) vacuum-assisted slumping, (iii) press bending and (iv) deep drawing.

This publication focuses on gravity slumping with no additional forces applied during the forming process. Without external forces applied, any kind of temperature phenomenon has a major impact on the hot forming result. For this reason the furnace system was calibrated to achieve highest temperature accuracy of < 1 K.

The laser structured glass is loaded onto the mould system by a robot handling system and then transported into the furnace unit. The temperature of the glass and the mould are both monitored during the process. The machine operator is able to observe the process through a view port.

Once the glass has completely fallen into the mould cavity, the mould and glass are transported automatically to the loading area to be unloaded.

During the process development, parameters were optimised systematically based on three fundamental methods: (a) based on experience, the operator chooses sensitive parameter and ranges, (b) temperature and process time prediction based on FEM simulations, (c) using trained machine learning tools to solve non-linear optimisation problems in glass hot forming. A combined approach of the methods (a) and (b) was sufficient to determine the process parameters of these experiments.

4. Results

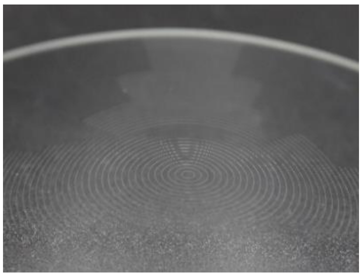

Figure 7 Photograph of the formed glass with compensated ring structures on the surface

The ring segments of four formed glass components were measured up to a radius of r = 48 mm using confocal micros-copy. The respective radius of each circular ring was determined. The measurements were conducted in the bending direction (x - direction) and along the y-direction.

Each measured radius was compared with the expected target radius and plotted (see Fig. 8). No distortions in the y-direction were identified due to a 2.5D bending radius in the x-direction. However, deviations from the expected position were measured for compensated ring segments in the direction of curvature (x-direction). The deviation within the radius interval from 1 mm to 14 mm is smaller than 10 µm. The data then shows a significant deviation of up to 140 µm in the radius interval of 14 mm to 22 mm. The deviation then decreases again for a radius of 22 mm before linearly increasing for larger radii.

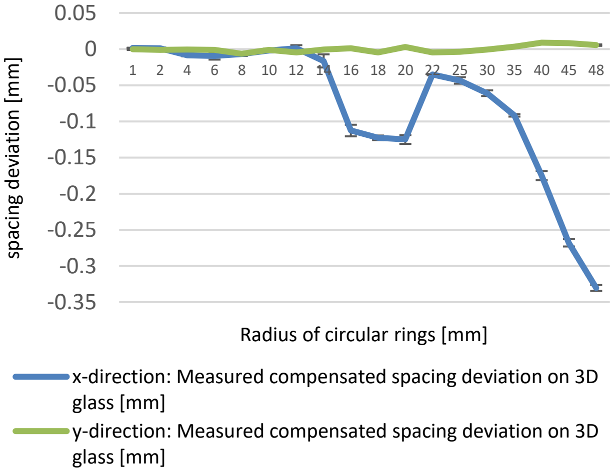

Figure 8. Deviation of compensated circular ring segments with regard to the targeted ring position

The significant increase in positional deviation of ring segments can be explained by comparing the simulated glass bending radius with the actual glass bending radius. Based on the confocal 3D data, the bending radius of the glass was determined to be 93 mm. This deviates by 7 mm from the simulated bending radius (100 mm). This could indicate a possible deformation of the sheet mould during the forming process. Therefore, compensated laser trajectories are based on a differing simulated bending radius.

According to the simulation (see Fig. 4), a zero crossing of the deviation is expected at 21 mm. This means that laser trajectories for this ring radius were not compensated.

For the measured actual bending radius of 93 mm, the zero crossing shifts to a radius of 18 millimetres. This results in a faulty deviation compensation for radii of 16 to 22 mm leading to a subsequent deviation compensation error for larger radii.

Nevertheless, compared to an uncompensated ring geometry on a formed glass, the accuracy for the areas outside the specified error range (16 mm to 22 mm) could be increased by 75% to 99% (see Fig.9).

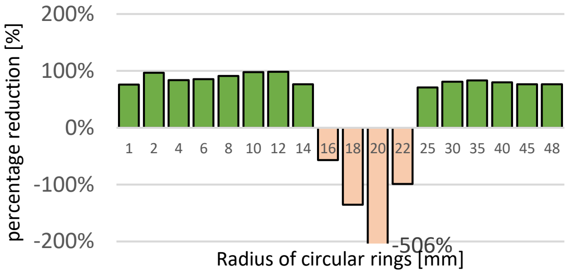

Figure 9. Percentage reduction of formed uncompensated circular rings compared to compensated rings

5. Conclusion and outlook

When 2D glass is formed into a 3D shape, there are positional deviations and shape distortions of a texture introduced beforehand. We validated a new approach to reduce these distortions by up to 90%. The method and results indicate a significant advancement towards an economical series production of functionalized glass, addressing e.g. automotive industry. To even reduce current distortions further we will introduce forming tools made of high-alloy, temperature-resistant stainless steel in the future leading to constant bending radii in the glass.

Acknowledgements

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