Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 100 (2015) 314 – 320

Procedia Engineering

www.elsevier.com/locate/procedia

25th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2014

Investigations on Laser Forming of Flat Glasses

Bliedtner J.*, Barz A., Hecht K., Schwager A.-M

University of Applied Sciences Jena, Germany

Abstract

A modified high-power laser system with an output power of 2.0 kW and an effective focus diameter of 1 mm allows a flexible forming of flat glass products. Due to the high absorption of most glasses in the mid infrared wave length range the CO_2-laser can be used very efficiently. The investigations show the potential of laser radiation for the partial forming of flat glass and the formability of glass materials depending on material thickness and the thermal expansion coefficient. Smaller and smaller glass components with more complex geometries can be processed because of the high focusability of the laser beam. With this intensity, it was possible to achieve forming depths of up to 6 mm. Another part of the studies is the creation of mechanical stress and its minimisation for which photoelastic methods as well as the differential interference contrast microscopy are used. The new technology can be applied especially in the fields of display glasses, sensor and medical technology.

Peer-review under responsibility of DAAAM International Vienna

Keywords: glass; laser; forming; heating; warm-bent glass; glass melt

1. Introduction

The number of applications for curved glasses with complex contours and various functions is increasing. Warm-bent glasses can be manufactured in different qualities e.g. float glass, semi-tempered glass or tempered safety glass. [1]

The application of laser technology for glass processing has a number of advantages such as a local heat input, and the reaching of melting temperatures within very short process times. It has, however, disadvantages too e.g.

* Corresponding author. Tel.: +49-3641-205444; fax: +49-3641-205351.
E-mail address: jens.bliedtner@fh-jena.de

Peer-review under responsibility of DAAAM International Vienna
doi:10.1016/j.proeng.2015.01.373

undesired states of stress after the treatment. A reason for this result can be seen in the high temperature gradients which are due to the fast local melting and solidifying of the glass material in the interaction zone. Besides the experimental optimisation of the process parameters, also simulation calculations can be made in order to analyse states of stress. [2]

When glasses are formed with laser radiation, the base material is partially heated beyond the softening point. In this process the materials are only brought to a viscoplastic state, whereat the heated volume is neither completely molten nor sublimated. An essential process advantage of the laser treatment compared to conventional glass treatment procedures is the locally highly limited and controllable heat input into the component.

The change in shape is very often carried out without additional tools or moulds, as it is typical for conventional glass forming procedures (pressing or blowing). Centrifugal forces, created through rotational movements or capillary forces which partially break the surface tension of the glass are also utilised.
Typical applications of forming with laser radiation are:

- glass forming for the creation of special geometries
- glass melt-offs
- glass-metal fusings
- manufacture of glass closures with integrated temperature-sensitive elements. [3]

2. Basics

Knowing the expansion coefficient α is crucial for the thermal treatment of glass, as it defines the possibility of a treatment of glasses with minimised stress. It is also very important to know and consider the expansion coefficient of the glasses for the thermal treatment with a laser.

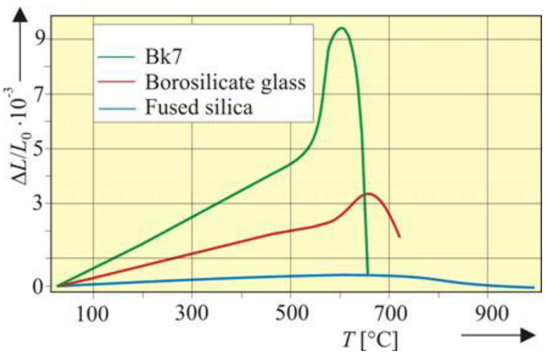

Fig. 1. Thermal expansion of selected glasses [3].

The thermal expansion coefficient α for the selected glasses in fig. 1 ranges from $0.5 \cdot 10^{-6}\,K^{-1}$ to ca. $10 \cdot 10^{-6}\,K^{-1}$. The treatment of quartz glass is very similar to the treatment of metallic materials within the linear part of the curve, although avoiding stress and cracks is essential also with this material for the applicability of the laser beam.

Temperature differences develop in the material due to the heating of locally limited volume areas by means of the laser radiation which results in the creation of temperature gradients in axial and radial direction of the component. The low heat transmission is the reason for the thermal stress σ_T in the glass volume. The following relation can be assumed for a homogeneous and one-dimensional temperature field:

$$\sigma_T = \alpha \cdot E_M \cdot \Delta T$$

α lin. expansion coefficient, E_M modulus of elasticity (1)

For the description of 3-dimensional states of stress and temperature gradients in the examined directions, the analytic solutions are much more complicated. Cracks appear when the thermal stress reaches the break strength σ_{Br}:

$$\sigma_T > \sigma_{Br} = \frac{K_{IC}}{\sqrt{l_R \cdot f_f}}$$ K_{IC} critical stress intensity factor l_R crack length, f_{ff} Form factor (2)

The resulting type of crack, whether tangential or radial crack, depends on the direction in which the tensile stress reaches the breaking point. This point is different in the heating process compared to the cooling process. During the heating process the expansion of the glass is restrained in radial direction. Thus compression stress occurs in radial direction and perpendicularly to it tensile stress in tangential direction. After being exposed to radiation for a certain time, this tensile stress can exceed the break strength of the glass and cracks occur. If the stress gets too high, the component can break. In the cooling process the conditions reverse due to the volume reduction of the glass. [4]

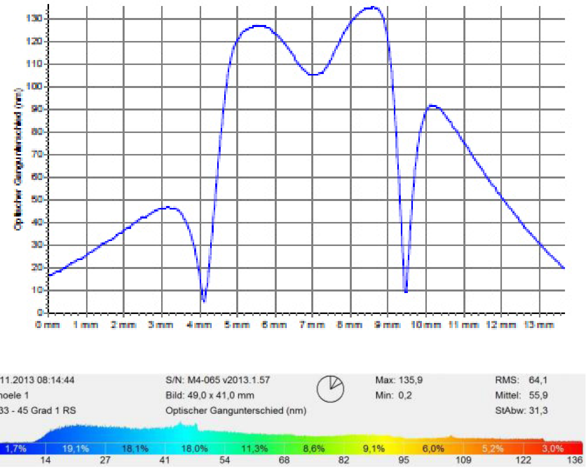

Fig. 2. State of stress on a formed edge without optimization.

Figure 2 illustrates these facts instancing a laser-formed edge for borosilicate glass. The stress double refraction method is used for illustrating states of stress. The thermal interaction on the formed edge leads in this example to distinct tensile and compressive stress zones. Normally, the stress caused by the laser treatment has to be eliminated through subsequent stress-relieving cooling. [5]

3. Experimental setup

Fig. 3 illustrates the experimental setup for the laser forming with a scanning laser beam utilising a CO_2-laser. With the used laser wavelength of 10.6 µm the glass material shows a very high absorption capacity. Beam power of up to a maximum of 2000 W could be used in the experiments.

Relatively low intensities (typically $I \sim 10^3$ W·cm^{-2}) are applied in order to keep the material removal through vaporisation as low as possible. That is why a galvanometrically driven mirror is used which enable scanning speeds of up to 8 m·s^{-1}. Furthermore, multiple scans along the geometries to be formed allow a quasi-simultaneous heating of the interaction zone. The integration of a fast-moving telescope mirror enables a dynamic focussing in order to form different areas of the glass component. Temperature is an essential process parameter for the forming process. Temperature ranges can be analysed during the treatment through the integration of temperature measuring systems (thermographic camera or pyrometer) in the test setup. For geometries where a homogeneous heating is not possible, a control circuit can be made from the received temperature signal and the laser power can be adjusted according to the effective temperature value. The high process speed requires fast PID-control algorithms.

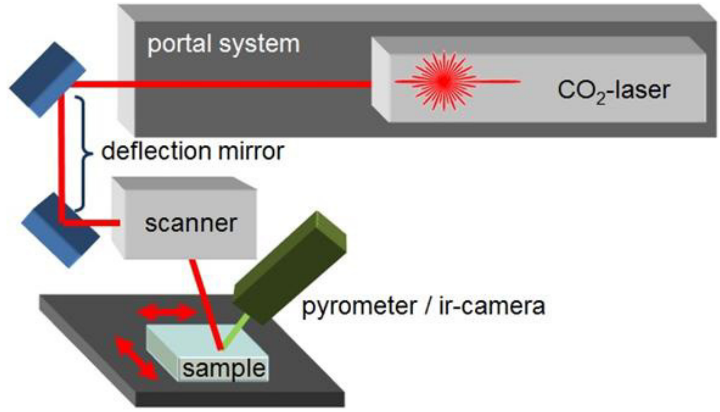

Fig. 3. Experimental setup for the laser beam forming of flat glasses.

4. Results

Flat glasses, which are preferably used in the display technology, were treated in the examinations. The substrate thickness ranged between 0.5 mm and 1 mm. Borosilicate float glasses "Boro33" of the company Schott were examined with a linear expansion coefficient of $3.3 \cdot 10^{-6}$ K^{-1}. Table 1 summarises selected glass characteristics which are relevant for the forming.

Table 1. Selected glass characteristics for the glass "Boro33".

characteristics	parameter	borosilicate glass BF33
optical	transmission (< 80%) [nm]	310 - 2700
thermal	heat conductivity λ_F [$W \cdot m^{-1} K^{-1}$]	1.13
	expansion coefficient α [K^{-1}]	$3.3 \cdot 10^{-6}$
	temperature shock resistance T_{WB} [K]	280
mechanical	bending strength σ_B [$N \cdot mm^{-2}$]	25

Crucial for the forming process is the setting of the process parameters for the necessary viscosity range of the base material. This range strongly depends on the temperature and it is different for the various glasses. This connection is shown in fig. 4 for the glass "Boro33". If the specified forming range is not kept, these are the results:

a) If the viscosity is too high, there will not be a sufficient forming or bending radius or areas to be formed differ from the required dimensions.
b) If the viscosity is too low, too much melt can occur which can even lead to material separation.

The setting of the optimal viscosity-temperature range depends primarily on the process parameters laser power, scanning speed and exposure time.

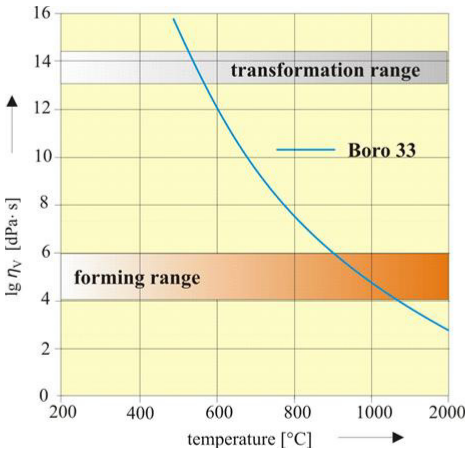

Fig. 4. Viscosity η_V depending on the temperature for the forming of "Boro33".

Figure 5 shows typical examples for formed edges. The area to be formed can randomly be positioned on the flat glass. A minimal edge distance of 5 mm could be determined in the tests, so that the desired edge angle can be achieved without additional means but only by gravity. The experimentally defined forming angles can be set as desired between 5° and 90°. The good focussability of the laser radiation to very small focus diameters of ca. 300 µm allows very small bending radiuses compared to classical forming procedures. Example c illustrates the possibility of forming different areas of the component. The fast scanner movements basically allow a simultaneous forming of several edges or structures. The necessary process time for the forming of an edge length of 150 mm is 3 seconds. Table 2 shows significant laser and process parameters.

a) **b)** **c)**

Fig. 5. Selected forming results on borosilicate glasses (material thickness: 0.5 mm). a) equal-sided 45° forming, b) edge forming 125°; c) double edge forming 125°.

Table 2. Selected laser and process parameters for the forming of borosilicate glass.

	parameter	**value**
laser	used laser power	100 – 650 W
	continuous operation	-
	wavelength	10.6 µm
scanner	focal length	f = 360 mm
	max. field	250 mm x 250 mm
process	edge geometry	5°- 90° (settable)
	edge length	150 mm
	forming time	3 s (for 150 mm edge length)

There is a state of stress in the glasses (as shown in fig. 2) after the forming process and the fast cooling of the components in air.

A subsequent cooling process is necessary for a reliable application of laser-formed flat glasses. Thus residual states of stress are achieved which meet the optical requirements of DIN ISO 10110.

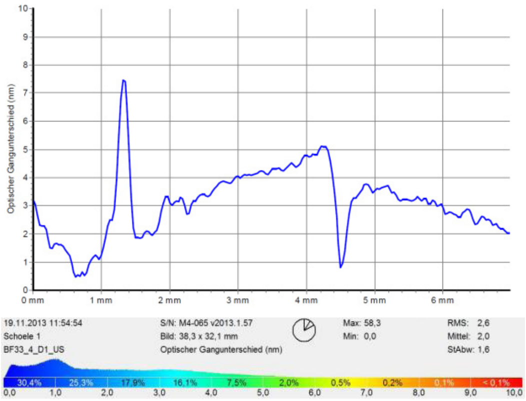

Fig. 6. State of stress on a cooled, low-tension component.

Figure 6 shows the photoelastic image of a cooled display glass. During the treatment it is intended to heat the area to be formed homogeneously. A respective temperature distribution can be detected by means of a pyrometer or IR-thermographic camera. The available pyrometer measures temperatures between 500 and 2500 °C at a wavelength of 5.14 µm (especially for glass surfaces), with a detection time of 100 ms. Temperature distributions over a certain area can be defined by means of specially adjusted thermal imaging systems /*6*/.

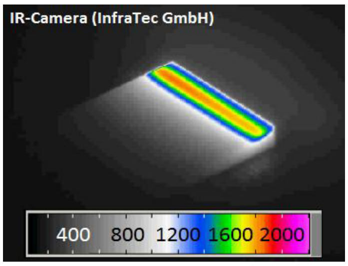

Fig. 7. Measured temperature courses by means of the thermographic analysis on a glass surface during a scanning process [*6*].

Figure 7 shows a relatively constant temperature value across the component width, illustrated by the example of a fast scanning movement of the laser beam during a polishing process. This temperature measuring setup can easily be adapted to the laser forming.

Conclusion

Laser beam forming is advantageous for thin flat glasses, as they are used e.g. for displays. Very fast forming processes can be repeatably realised with scanner-based laser applications. The fast heating and cooling processes of the laser treatment require a subsequent cooling of the processed components.

References

[1] Glaser, S.: Flexibles-Flachglas-Biegeverfahren: Abschlussbericht BMBF-Projekt. Karlsruhe. 2012.
[2] Hildebrand, J.; Hecht, K.; Bliedtner, J.; Müller, H.: Advanced analysis of laser beam polishing of quartz glass surfaces. LANE2012. Physics Procedia 00(2011). Erlangen. 2012.
[3] Bliedtner, J.; Müller, H.; Barz, Andrea: Lasermaterialbearbeitung- Grundlagen-Verfahren-Anwendungen-Beispiele. Carl-Hanser-Verlag. ISBN 978-3-446-42168-4. 2013.
[4] Buerhop, C.: Glasbearbeitung mit Hochleistungslasern. Dissertation. Universität Erlangen-Nürnberg. 1994.
[5] Bliedtner, J., Gräfe, G., Hector, R.: Optical Technology. McGraw-Hill Companies, Inc., New York, 2011.
[6] Hecht, K.: Entwicklung eines Laserstrahlpolierverfahrens für Quarzglasoberflächen. Dissertation. Technische Universität Ilmenau. 2012.