Thermal Forming of Glass — Experiment vs. Simulation

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Abstract

Thermal forming is a technique for forming glass foils precisely into a desired shape. It is widely used in the automotive industry. It can also be used for shaping X-ray mirror substrates for space missions, as in our case. This paper presents the initial results of methods used for automatic data processing of in-situ measurements of the thermal shaping process and a comparison of measured and simulatated values. It also briefly describes improvements of the overall experimental setup currently being made in order to obtain better and more precise results.

Keywords: X-ray mirrors, Comsol Multiphysics, simulations, thermal forming, gravity forming, in-situ measurements, data processing.

1 Thermal forming process for lightweight optics

Thermal forming is a technique for shaping lightweight precise space X-ray mirrors that has been under development for several years. Teams working on the topic include the NASA team led by Dr. Zhang [7] working on the former CON-X project, an Italian group [8], and the Czech group consisting of people from CTU, ICT, the Astronomical Institute and Rigaku company, working on the former XEUS/IXO/Athena mission [9].

The principle of the technique is rather straightforward. A precise form (a mandrel) is prepared. A glass sheet is then placed atop the mandrel (or between two mandrels) and a temperature profile is applied. Since glass behaves like a viscous liquid above certain temperatures, forming can occur and the shape remains even after the sample cools down.

The method described in this paper is very similar to the method outlined above, except that no mandrel is used. The glass sheets are held only on their edges, and shaping at high temperatures takes place only due to gravity [6]. The principle is demonstrated in Figure 1. A similar method is used for manufacturing car front windows, however with a lower precision requirement.

2 Metrology

The shape of the formed glass sheet was measured by two principally different methods and provided complementary information about the forming process.

In order to acquire information about the dynamics of the forming process, a noncontact optical method was used. A scheme of the setup is shown in Figure 1. The sample remains in its position inside the furnace while it is observed via a camera with an objective. Figure 2 shows a typical image obtained by the camera. The typical period between two consecutive images was 5–10 minutes. A set of images with timestamps was obtained, and was further processed in order to obtain valid data.

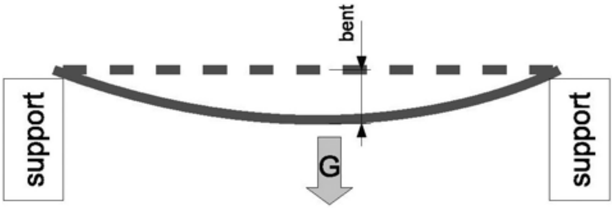

Fig. 1: Schematic view of the experiment. The glass was placed atop the support only by its edges. The temperature was increased and gravity performed the actual forming. The maximal bending as a function of time and temperature was then measured and compared with the simulations

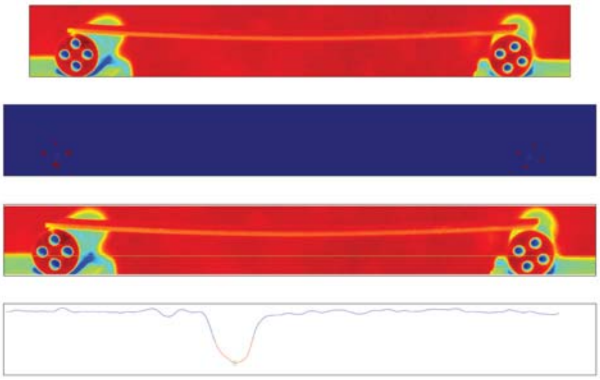

Fig. 2: Example of image processing of the in-situ optical measurement. The original image (upper, false colors) is processed in order to obtain reference points (second image), the reference line and the vertical line for glass position measurement is found (third, overlaid on the original image, false colors) and the position of the glass is finally found in this vertical line (fourth)

Several Matlab scripts were written in order to process the images automatically, if possible, or semiautomatically. The most important information for developing the forming process that can be obtained from measurements of this kind is the dynamics of the process. Thus, the total bend of the sample at each time was measured. The algorithm first located two fixed reference points within each image. This is because the images can be shifted and inclined relative to each other, as the doors needed to be opened each time in order to take the image. Then the center of the sample was found, where the maximal bend was expected. The relative position of the center with respect to the reference points — the total bend — was identified. This was done either automatically, when the lighting conditions were optimal, or semiautomatically with some help from the user. Finally, the values were calibrated in order to obtain values in mm and not in pixels. A single step of the script is shown in Figure 2.

The other semiautomatic script was also written, and was able to process the image in order to determine the sample profile. It was used to detect the shape change of the sample between the end of the forming process and the end of the cooling process.

As the method used standard commercial equipment only (camera, lenses, tripod, etc.) and the doors had to be opened each time, the precision of the method is low, typically 0.1—0.5 mm. It can therefore be used successfully only for a study of the process dynamics. The Taylor Hobson PGI PLUS contact profilometer was used to obtain more accurate data for shape fitting. This device is able to measure profiles up to 120 mm in length, sampling down to 0.25 micron and with vertical resolution at the nanometer scale.

Three lines were measured on each sample at each of the orthogonal directions, two close to the edges and one close to the center of the sample. The data from the device was initially processed by the Taylor Hobson software, and was further exported and processed in Matlab as well. The profiles were rotated in order to make them horizontal and concentric, as it is impossible to position the sample perfectly on the table. Varioius curves were then fitted onto the data, including polynomials of the order 2 and 4, a circle and a catenary curve.

3 Simulations

Computer simulation of the forming process is a complex task [1–4]. Generally, a combination of a thermal model and a mechanical model has to be applied. The thermal model should contain spatial and temporal temperature profiles, as well as the thermal interaction of the furnace and the form with the sample. This can be either measured or simulated. Mechanically, it can be modelled as a simple beam made of a viscoelastic material, where several border conditions need to be met. The gravitational force is easily applied as a volume force. The dynamic viscosity of the material as a function of the temperature at a given location has to be known. The proper sample/support interaction must be entered. Either a rigid system or a system where some movements with defined friction are allowed, etc. Surface tension can be included.

The simulation performed here used the Comsol Multiphysics software with the CFD module [5], but with several simplifications. The temperature of the sample was assumed to be homogeneous and identical to the temperature of the furnace. This seems to be unrealistic, but it is a good starting point. More work needs to be done to justify and modify this condition. Rigid borders were applied, no slip, no squeezing of the glass, and the sample lay freely on the support. Uncertainty in border definition is expected to produce differences in the bending speed of the order of 20 % [2]. Most of the forming time was spent above the transform temperature, thus a viscous Newton liquid model was used with the dynamic viscosity given by the curve in Figure 3. The output of the Comsol Multiphysics simulations was only a velocity field as a function of time. The data was thus imported to Matlab and integrated in order to obtain the actual profile.

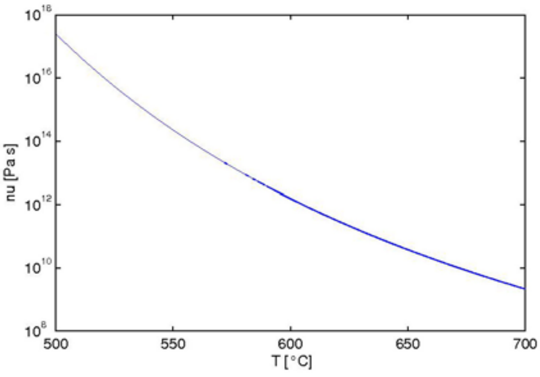

Fig. 3: Dynamic viscosity as a function of the temperature used in the simulation in the form of the Vogel-Fulcher Tammann equation [6]

4 Processing experimental data

The experiments were performed with glass samples made from Desag D263 glass. Two different sample sizes were used: $75 \times 25 \times 0.75$ mm^3 and $100 \times 100 \times 0.4$ mm^3. The forming process, temperatures, measurements and fits by different curves as well as a description of the equipment used in the experiment are described in greater detail in [6]. The average forming speed as a function of the forming temperature for one of the samples is shown in Figure 4, together with the simulated data.

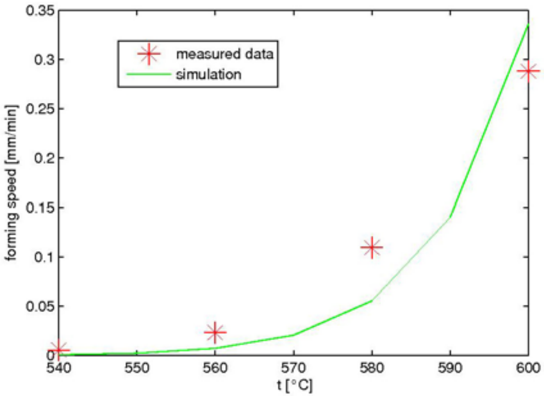

Fig. 4: Average forming speed for a sample 100 × 100 × 0.4 mm^3 in size as a function of temperature. The measured values are compared with the simulation

All the forming experiments were measured in-situ, and the results were processed by the noncontact method. The resulting data was then combined into the form of a unified plot where the change in shape (the bending) is a function of the forming time and the temperature (see Figure 5).

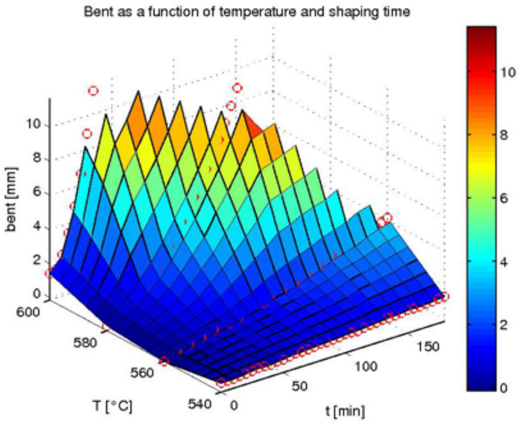

Fig. 5: Measured bending as a function of time and forming temperature for 100 × 100 × 0.4 mm^3 samples

A simulation of all the experiments was performed and the data was processed in the same way as the experimental data in order to provide a comparison (see Figure 6). The overall shape and values are consistent, although not perfectly matching yet, see Figure 4, which compares the average shaping speed as a function of temperature.

Detailed contact profilometer measurements show that, due to short openings of the doors in order to make in-situ images for noncontact measurements, there are temperature gradients that result in inhomogeneous forming. It can be seen that the shape is different at the edge closer to the doors. Further, we have no actual information about the temperatures and the temperature gradients in the glass, which is very important for the simulation. It is expected that, together with the poorly defined support, this leads to most of differences between the simulation and the experiment. Inaccurate noncontact measurement is not important for average forming speed detection, as least square fitting is used.

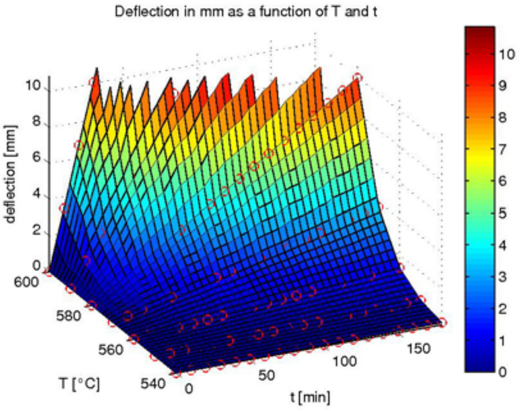

Fig. 6: Simulated data based on the experiments from Figure 5. More data points are used for interpolating the colored surface

5 Expected improvements

Several key points were identified during the experiments described above, which affect the measurements and the forming process itself, and are currently being upgraded. The shaping process is strongly affected by opening of the doors for making images, thus a sapphire window in the doors will be used. In addition, poorly defined support will be replaced by stable and perfectly defined mechanical support. Independent temperature measurements inside the furnace for greater precision will be performed. In order to be able to increase the precision of the optical measurements, a camera at a fixed point relative to the furnace will be used. It will be equipped with a telecentric lens. The lighting will be adjusted to enable automatic data processing for all images.

6 Conclusions

A general method for in-situ measurements of a thermal free fall glass forming process has been demonstrated, including automatic data processing. The data was used for improvements to a forming method suitable for space X-ray telescopes, and as an input for computer simulations of the process. The simulation and the experiments are consistent, but more work needs to be done. Key points which need to be modified and corrected in future experiments have been identified, and experimental upgrades are currently underway.

Acknowledgement

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