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Image based control system for improving fiber injection molding process

Patrick Moll[a]*, Junjie Xu[a], Sven Coutandin[a], Jürgen Fleischer[a]

[a]*Karlsruhe Institute of Technology, wbk Institute of Production Science, Kaiserstraße 12, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +49 1523 9502600; *E-mail address:* patrick.moll@kit.edu

Abstract

Fiber injection molding is an innovative process for the resource-efficient production of near net-shape long fiber preforms. The filling of the mold is crucial for the repeatability and uniformity of the produced preforms. For improving the fiber injection process a control system based on image processing has been developed. With a camera the current mold filling is recorded and processed by artificial neural networks. This information on the filling state is used for an adaptive control of the injection nozzle. The control system is validated experimentally with results showing improved reproducibility of the fiber injection molding process.

Keywords: Fiber injection molding, preforming, process control, image processing

1. Introduction

In manufacturing of fiber reinforced plastics preforming is one of the most crucial and costly process steps [1] due to its importance for the quality of the manufactured part and the high rate of cut-offs [2]. A cost-efficient alternative to preforming processes based on semi-finished products are direct fiber preforming (DFP) processes depositing cut long fibers directly in a three-dimensional shape [3,4].

A relatively new process for the manufacturing of long fiber preforms is fiber injection molding (FIM) [5]. In this process cut fibers and a binder are blown with the aid of an air stream into a mold comprising a top and bottom mold. The inner surfaces of the mold where the fibers are deposited define the geometry of the fiber blank. After the injection of the fibers, the upper mold can be changed and the fiber plank be pressed to the final geometry of the part. By blowing hot air through the fiber blank in transversal direction the binder is activated and bonds the fibers together to a molded part. This process allows the manufacturing of parts with different thicknesses and densities. As all fibers are injected in a closed mold no waste is generated.

The use of the FIM process for manufacturing of long glass fiber preforms was investigated in previous investigations. Small preform samples have been manufactured in a small laboratory mold and infiltrated in a resin transfer molding and wet compression process by [6]. The analysis of the infiltrated samples show voids indicating a non-uniform infiltration and uninfiltrated areas where the preform has a high local fiber content [6]. In [7] preforms were manufactured on an industrial scale FIM plant. Within the lot of 14 preforms the weight fluctuates between 450 g and 700 g with a relative standard deviation of 12.6%. The non-uniform fiber distribution and the weight fluctuations can be attributed to an uneven filling of the injection mold.

In order to rectify the detriments of the process found in these previous investigations this papers aims at the improvement of the mold filling in fiber injection molding. Therefor a monitoring system for the injection mold has been developed and an adaptive control of the injection nozzle has been implemented. Finally the process control has been evaluated experimentally.

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2. Process monitoring for fiber injection molding

For the control of the mold filling in fiber injection molding, the current filling within the mold has to be monitored with sensors. In other injection or infiltration processes with a closed mold different sensor classes are state of the art for process monitoring like pressure and temperature sensors in injection molding [8,9] or resistance sensors [10] and eddy current arrays [11] in the resin transfer molding process. However due to the low pressure within the injection mold in fiber injection molding and the properties of the processed glass fibers neither pressure sensors nor sensors using electrical properties are suitable for the monitoring task. Hence other sensors have to be investigated. A prototype of a monitoring system based on a camera integrated in the mold has been positively investigated in [12] and will be improved within the scope of this work to be implemented in the process control system.

2.1. Camera integration

For the integration of the camera an injection mold with a dimension of 400 x 400 mm preform area and a linear alternating nozzle movement along one edge is modified as shown in Figure 1 (a). The top and bottom of the mold are replaced by Plexiglas allowing the camera a view from the bottom in the cavity and illumination by additional LED lighting from the top to enhance contrast of the fibers. The side walls are perforated sheet metals as usually used in molds for FIM allowing the air transporting the fibers to exit the mold.

For the monitoring the camera type *UI-3290SE* of the company *IDS* (Obersulm, Germany) has been selected for its high frame rate and low-signal-noise-ratio which is required for reliable detection of the fibers. Based on the geometry of the mold and the object size an adequate matching lens of type *Tamron M111FM08* has been selected.

2.2. Computation of fiber front

Analogue to the melt front in injection molding the transition from the already filled parts of the mold to the non-filled parts is called fiber front. Based on the images of the camera from within the mold the current filling has to be computed with an image processing pipeline. The image processing consists of the steps preprocessing, segmentation and edge detection. The image processing is implemented in *MATLAB* using the *Image Processing* and *Computer Vision* toolboxes and runs on an edge device of the fiber injection molding plant with a *NVIDIA RTX2060* GPU.

In the preprocessing the images are cropped to the relevant region of interest and resized to an image size of 256 x 256 pixels to reduce computing time for the further processing steps. Additionally a histogram equalization is performed to reduce deviations in the backlighting intensity.

The segmentation distinguishes areas of the mold already containing fibers from areas which are not filled yet. For this purpose a convolutional neural network (CNN) with SegNet architecture [13] is used. CNNs have to be found more capable

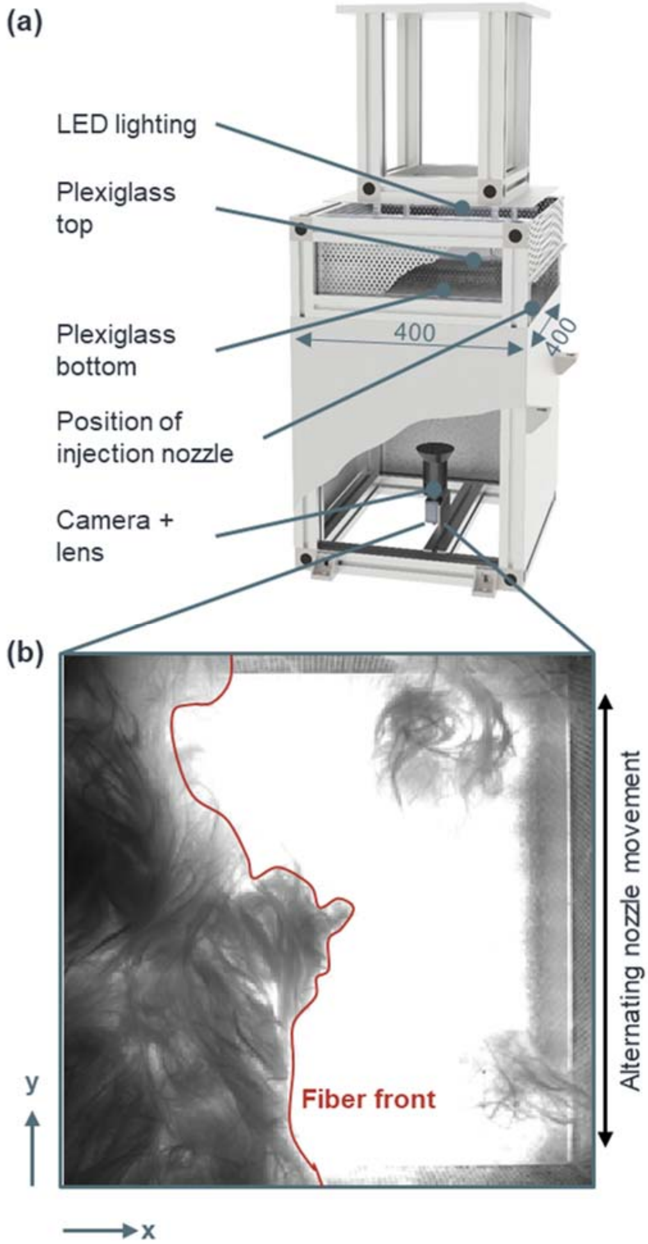

Figure 1. (a) Modified injection mold with integrated camera; (b) camera image from within the mold with fibers and detected fiberfront

for the segmentation as thresholding methods, like i.e. Otsu thresholding, as they cope better with the difficult lighting situations near the edges of the mold. For the training of the CNN 390 images of multiple recorded injection processes have been hand-labeled.

In the last image processing step the fiber front is extracted from the binarized image with an edge detection algorithm. The fiber front is then given as a vector $\boldsymbol{x_F}(y)$ with $y \in \mathbb{N}[0 \dots 255]$ corresponding to the number of pixels along the y-axis (see Figure 1 (b)).

3. Process control

3.1. Process control structure

The goal of the control system is to get a more uniform filling of the mold in order to achieve better preform uniformity and a higher reproducibility of the preforms weight. The straightness of the fiber front is a measure for the uniformity of the mold filling. In an ideal injection process with a constant flow of fibers and constant alternating movement of the injection nozzle the mold fills evenly with a fiber front running straight along the y-axis. However the formation of fiber bunions in the fiber feed system [7] and turbulences within the mold are leading to an uneven filling. As the position of the injection nozzle defines the location of fiber deposition within the mold the control of the nozzle's movement bears high potential of achieving a more uniform filling of the mold.

Based on the goal of the control system the structure of the control system as shown in Figure 2 has been developed. The dynamic system which is controlled is the filling of the injection mold. It is disturbed by the inconstant flow of fibers due to bunions and turbulences of the incoming fibers. The monitoring system described in section 2 is used as sensor in the feedback loop to feed the measured position of the fiber front $\boldsymbol{x_{F,m}}(y,t)$ to the controller which calculates the control variable for the injection nozzle based on the reference $\boldsymbol{w}(y,t)$. The injection nozzle with its position $y_{\boldsymbol{N}}(t)$ takes effect on the mold filling.

In most cases a model-based approach for the design of the controller is used. However the effects within the injection mold (i.e. flow of fibers within vicious media, formation of bunions, compression of deposited fibers) are very complex such as they cannot be described in the necessary detail by a model. Therefor an experience-based approach is used for the design of the controller to derive a control strategy for the nozzle based on the current mold filling. For the control of the nozzle a velocity and a position control strategy have been developed.

3.2. Velocity control strategy

The velocity control strategy is based on an adjustment of the velocity of the nozzle alternatingly moving along the front edge of the mold. If the nozzle passes a location within the mold which is filled less than other locations it decelerates to inject more fibers at this location and compensate the lack of fibers. Correspondingly it accelerates at locations where the fiber front is more propagated. With $y(x_{F,min})$ being the location of the smallest mold filling and a proportionality factor α the nozzle velocity $v_N(t)$ is calculated by equation (1).

$$v_N(t) = \alpha * |y_N(t) - y(x_{F,min})| + v_{N,min} \tag{1}$$

The adjustment of the velocity of a moving axis in the programmable logic controller (PLC) of the fiber injection molding plant is only possible by changing the override value $O(t)$ of the *MC_Power* motion function block.

$$O(t) = \frac{v_N(t)}{v_{N,max}} * 100 \tag{2}$$

Because of the possible movement of the nozzle limited by the geometry of the mold the term $|y_N(t) - y(x_{F,min})|$ has a maximum value it can take of 328 and the proportionality factor α can be calculated. By defining that the minimum velocity is a tenth of the set maximum velocity of the nozzle, the calculated factor α and equation (2) the control law for the override value follows.

$$O(t) = 90 * \frac{|y_N(t) - y(x_{F,min})|}{328} + 10 \tag{3}$$

3.3. Position control strategy

The position control strategy is based on the idea that the nozzle is moved directly to the location of the smallest mold filling $y(x_{F,min})$. This movement can be implemented in the PLC using the motion function block *MC_MoveAbsolute* which takes an absolute position set point and moves to this. As no new position set point is accepted during the movement of the nozzle the control variable being the position set point $y_{N,s}(t)$ can only be defined in a time discrete manner after each positioning has finished. Therefor the control law for the control variable is defined as follows with t_n being the end time of a previous positioning.

$$y_{N,s}(t) = y\left(x_{F,min}(t_n)\right) \tag{4}$$

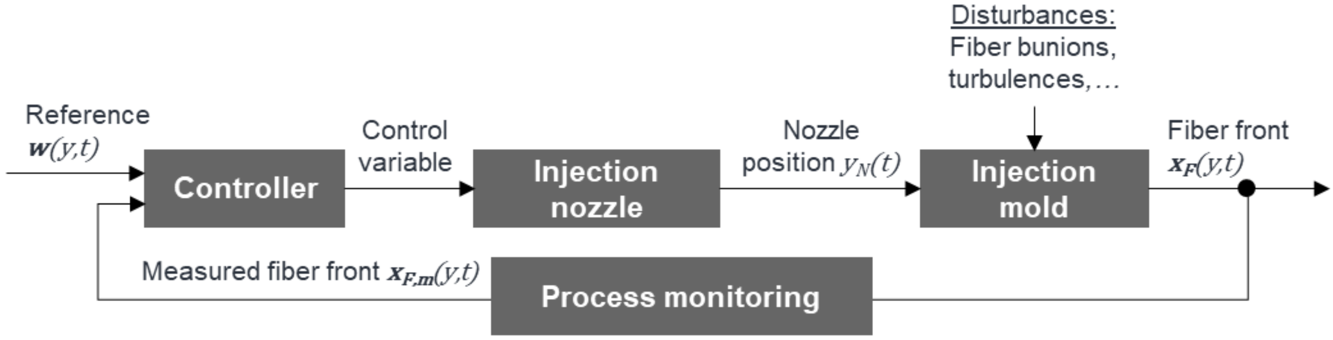

Figure 2. Structure of process control for the injection nozzle

Exemplary movement profiles of the nozzle for the two control strategies and the uncontrolled alternating movement is shown in Figure 3.

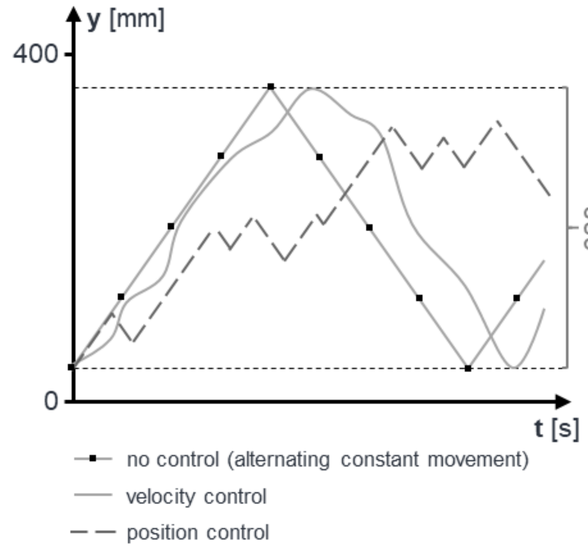

Figure 3. Schematic movement profile of injection nozzle for control strategies and reference (acceleration/deceleration of nozzle neglected)

3.4. Implementation of controller

The process monitoring and control are implemented in a fiber injection molding test plant with the architecture pictured in Figure 4. The control system requires the input of the *MATLAB* implemented process monitoring system. In order to reduce latency between the fiber front acquisition and the controller it is also implemented in *MATLAB* on the same edge device. The controller communicates with the PLC in real time via the Beckhoff ADS protocol. The controller receives the current nozzle position and sends back the override value $O(t)$ in case of the velocity control or the position set point $y_{N,s}(t)$ in case of the position control. In the PLC the motion controller receives these values and calculates the motor movement which control values are send to the motor via EtherCAT. The motor moves the nozzle in a linear movement along the front edge of the injection mold.

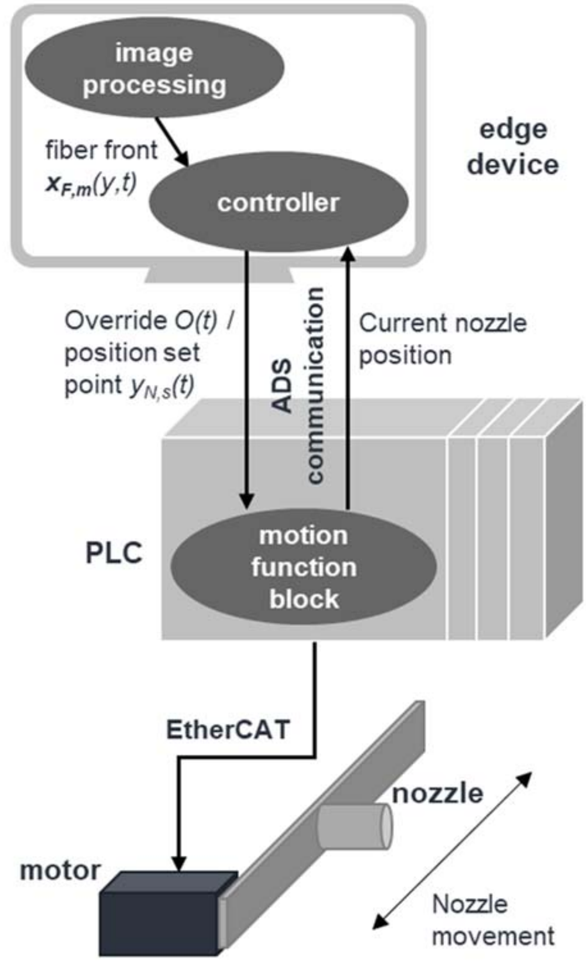

Figure 4. Implementation of process monitoring and control within the control architecture of the fiber injection molding test plant

4. Experimental validation

4.1. Experimental approach

For the comparison of the two developed control strategies and the validation of the process control system in general an experimental series has been conducted. In this experimental series two sets of five preforms each were manufactured and evaluated with a position controlled and a velocity controlled mold filling. Additionally, a set of five reference preforms without control (which corresponds to a constant alternating movement of the injection nozzle) are produced. For the experiments a glass fiber roving type *ADVANTEX R25 HX14* of *R&G Faserverbundwerkstoffe GmbH* (Waldenbuch, Germany) with a titer of 2400 tex has been processed. The other constant parameters for the injection process are given in Table 1.

Table 1. Processing parameters for experimental validation

Parameter	Value
Injection gap	100 mm
Fiber feed	500 mm/s
Fiber length	50 mm
Fan speed	2910 rpm
Nozzle velocity	150 mm/s

To validate the ability of the process control system to generate a more uniform mold filling the straightness of the fiber front is evaluated by the straightness index S which is defined by equation (5). This index is derived from the method of least squares and decreases the straighter the fiber front is.

$$S = \sqrt{\frac{1}{N}\sum_{i=0}^{N}\left(x_{F,i} - x_{F,mean}\right)^2} \text{ with } N\text{=255} \quad (5)$$

Additionally, the influence of the process control system on the properties preform weight m and uniformity is evaluated. The weight of the preforms is measured with a scale of 0.1 g precision. The uniformity is evaluated based on transmitted light images of the preforms which are taken from inside the mold at the end of the injection process as proposed by [14]. For the calculation the images are divided in small quadrants of which the mean gray value q is calculated. The uniformity index UI is then determined by equation (6). The smaller this uniformity index is the better the uniformity of the preform.

$$UI = \frac{\sqrt{Var(q)}}{\bar{q}} \quad (6)$$

4.2. Validation results

For the validation of the performance of the process control system the straightness of the fiber front during the mold filling of the 15 manufactured test preforms is evaluated based on the recorded images of the process monitoring system. For each image the straightness index S is calculated using equation (5). Then the overall straightness S_o is calculated as the mean of all straightness indexes for one mold filling. A smaller overall straightness signifies a more linear fiber front throughout the filling of the mold.

Figure 5 shows the mean overall straightness of the preforms manufactured without control, velocity control and position control with the error bars showing the standard deviation. The fillings of the mold without control show a mean overall straightness of 22.2 compared to 14.5 for the velocity controlled filling and 16.6 for the position controlled filling. These results show that the main goal of a more uniform filling of the mold is achieved by the process control system. Additionally, it can be stated that the velocity control preforms slightly better than the position control. This can be explained by the fact that the movement of the nozzle for the velocity control is more uniform than it is the case for the position control. The discontinuous calculation of a new control variable leads to a delay in the movement of the nozzle which means it is trailing the current situation in the mold.

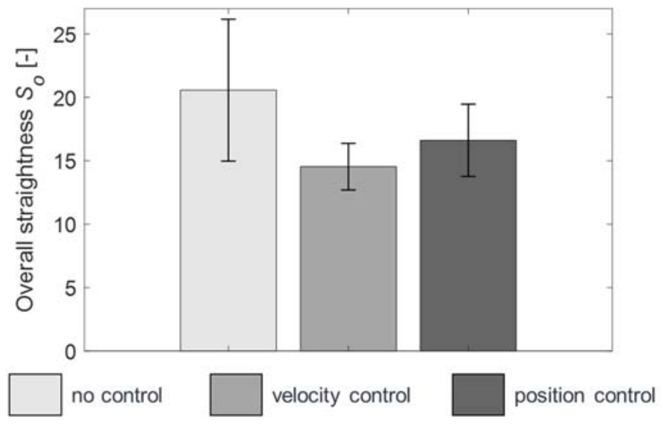

Figure 5. Calculated overall straightness of the manufactured preforms with a lower overall straightness meaning a more linear fiber front throughout the injection process

Besides the function of the process control system in regard of the goal of a more uniform mold filling its effect on the properties of the preforms is also investigated.

Figure 6 (a) shows the mean uniformity of the preforms manufactured without control, velocity control and position control. With an uncontrolled mold filling the mean uniformity index of the preforms is 0.31 whereas with a controlled mold filling a mean uniformity index of 0.37 respectively 0.4 is achieved. As the smaller the uniformity index the better the uniformity of the preform is, it can be concluded that the control system does not lead to a better uniformity independent of whether a velocity or position based approach is used. This can be explained by the fact that the control system leads to a better distribution of the fibers within the mold but the formation of fiber bunions with a more compact fiber arrangement in the fiber feed system still causes a negative effect on the uniformity.

Additionally, the mean preform weight is shown in Figure 6 (b). Looking at the values it is noticeable that the preforms produced with controlled mold filling are significantly heavier than the reference without control. If this is compared to the overall straightness it can be concluded that a more uniform mold filling leads to a higher preform weight. This can be explained by the fact that at a more linear fiber front the fibers are aligned in a more compact manner.

Further, the data shows a significantly lower standard deviation within the preform sets manufactured with controlled mold filling. Such a lower standard deviation signifies a better reproducibility of the preforms. The relative standard deviation for the reference preforms is 13.4 % which is in the same magnitude as the preforms manufactured in [7] with a standard deviation of 12.6 %. The relative standard deviation of the other two sets is 4.5 % for the velocity controlled and 7.4 % for the position controlled mold filling. This corresponds to an improvement of the reproducibility of the mold filling of almost factor 3.

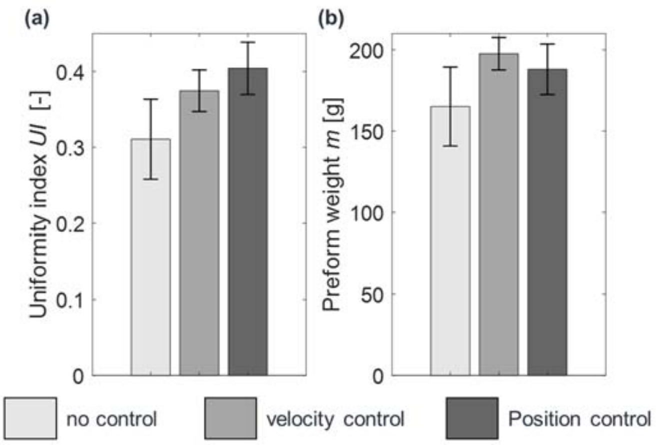

Figure 6. (a) Uniformity index and (b) weight of the manufactured preforms

5. Summary

In this paper an image based control system for the fiber injection molding has been presented. The goal of the control system is to achieve a more uniform mold filling to improve reproducibility of the preform production.

For the real time monitoring of the mold filling a camera has been integrated in the injection mold. With an image processing pipeline consisting of preprocessing, segmentation and edge detection the fiber front can be detected. Based on the acquisition of the fiber front a control system is set up to control the movement of the injection nozzle. Two approaches to control the nozzle have been implemented in a fiber injection molding test plant: a velocity and a position based control.

In an experimental series preforms have been manufactured with the two control approaches and compared to reference preforms manufactured with an alternating nozzle movement without control to validate the function of the control and its effect on the reproducibility and uniformity of the preforms. The results show that the mold filling is significantly more uniform with the process control. An improvement of the uniformity of the preforms could not be proved. Analysis of the preform weight however shows that with the process control the standard deviation is reduced significantly meaning a higher reproducibility of the process. Comparing the velocity and position control the results show a better performance of the velocity control which is due to better reaction time and a steadier movement.

It can be concluded that the implemented control system is working effectively and it has a positive effect on the reproducibility of the fiber injection molding process. This higher reproducibility allows a narrower definition of quality limits which is required from the client. Additionally, this leads to a better usage of the injected fiber material and less waste in the production of preforms.

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