Analysis on Viscous Flow of VAD Silica Glass During Heat Forming

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Silica glass is well-known as being substantially higher in purity and more transparent than fused-quartz glass. Therefore, it is widely used not only for optical fibers but also for electronics industry applications like optical lenses for semiconductor exposure apparatus and photomask substrates for optical lithography. The authors have developed and improved the technique for manufacturing high-quality VAD silica glass that has excellent mass productivity. In the process of forming silica glass into optical components such as optical fibers and fiber couplers, thermal processing based on the conventional uniaxial deformation model is mainly used. However, in order to stabilize the quality of 3D-shaped glass like optical lenses, the method of conventional uniaxial analysis may be insufficient. In this paper, as part of the study of analytical procedure of silica glass viscous flow, the authors conducted both the uniaxial deformation analysis by classic model and the viscous flow analysis by 3D thermal fluid program. The authors confirmed that it was possible to predict deformations that are concerned with only the load direction by analysis based on the conventional classic model. The authors also confirmed that analysis software "FLOW-3D" was useful for grasping in details the viscous flow phenomenon exhibited by glass.

1. Introduction

Silica glass is well-known as being substantially higher in purity and more transparent than fused-quartz glass. Therefore, it is widely used not only for optical fibers but also for electronics industry applications like optical lenses for semiconductor exposure apparatus and photomask substrates for optical lithography. The authors have developed and improved a technique for manufacturing high-quality VAD silica glass that has excellent mass productivity. In the process of forming silica glass into optical components such as optical fibers and fiber couplers, thermal processing based on the classical uniaxial deformation model is mainly used. However, in order to ensure quality stability of 3D-shaped glass optical components like optical lenses, the method of conventional uniaxial analysis may be insufficient.

In this paper, as part of the study of analytical procedure of silica glass viscous flow, the authors conducted both a uniaxial deformation analysis with the classical model and a viscous flow analysis with 3D thermal fluid analysis software, and studied a process to thermally form optical fiber-grade VAD silica glass in a heating furnace and the resulting expansion of glass diameter to 300 mm (12 in.) or more.

2. Analysis of heat forming using classic model

It is known that uniaxial viscous deformation can be described as follows [1]:

$$f = 3h(T)\cdot S\cdot \frac{dv}{dz} \quad \cdots\cdots (*)$$

Here, f is load or tension, T is absolute temperature, $\eta(T)$ is glass viscosity, S is sectional area, v is longitudinal deformation velocity and Z is longitudinal axis.

Using the formula (*) described above, deformation volume can be calculated for a glass column shown in **Fig. 1** that has an arbitrary sectional area S and a thickness z and is subjected to an arbitrary heating temperature T and a load F. The viscosity $\eta(T)$ of this silica glass was measured using the penetration method[2] in a temperature range between 1100 and 1500 deg. C.

In order to verify the result of the numeric calculation mentioned above, a silica glass sample was actually heat-formed and its volume of deformation was measured. **Figure 2** is the schematic diagram of an experimental setup for studying heat-forming behavior. The setup has a potentiometer at the top of the heating furnace for monitoring the displacement of glass sample. A load was applied to the glass sample using weights.

Table 1 shows the parameters of the silica glass sample. The sample was placed in a mold form in the heating furnace as shown in **Fig. 2**, and its diameter was expanded from 150 mm to 305 mm under a load. The concentration of OH-group that affects glass viscosity is 5 ppm.

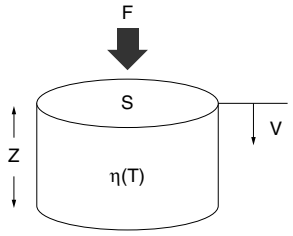

Fig. 1. Analytical model of heat forming

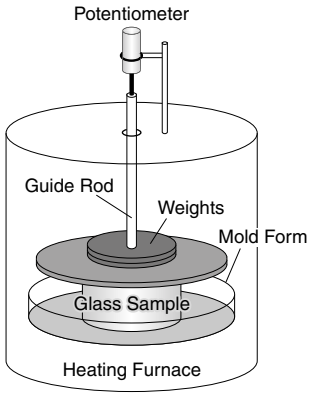

Fig. 2. Experimental set-up for studying heat forming behavior

Table 1. Silica glass sample parameters

Item	Before heat forming	After heat forming
Diameter	150mm	305mm
Height	150mm	36mm
OH-group content	5ppm	

Table 2. Heat forming conditions

Item	Condition
Heat temperature	Max. 1800℃
Load	6.5 kg (constant)

The conditions for heat forming are shown in **Table 2**. The sample was heat formed at a constant peak temperature of 1800deg. C for one hour under a static load of 6.5 kg applied by weights.

Figure 3 shows a comparison of sample deformation volume between calculated (broken line) and actual measured values (plotted points). It is observed that the deformation (diameter expansion) started at around 1550 deg. C and ended at 1800 deg. C, and that the two curves correspond well to each other. As far as deformation volume is concerned, it was confirmed by this experiment that good prediction is possible by analysis using the classical model.

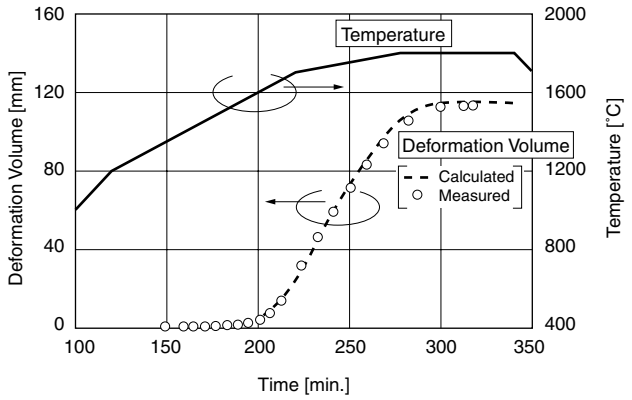

Fig. 3. Comparison of glass sample deformation volume between calculated and measured values

3. Viscous flow analysis using "FLOW-3D"

It has been prospected that the volume of deformation induced by heat forming can be predicted using the classic model as mentioned previously. However, in order to grasp the details of viscous flow phenomenon in glass and to ensure stability of quality characteristics such as optical properties, it is necessary to closely examine deformation behavior using a three-dimensional analysis approach.

In simulating viscous flow during heating deformation of silica glass, it is important to precisely calculate the deformation behavior and heat transfer of glass interface.

There are two kinds of method for establishing glass boundary models: One is "direct modeling" represented by the Lagrangian method or the Euler method, and the other is "indirect modeling" represented by the VOF (volume of fluid) method[3]. Direct modeling has an advantage that model elements that match boundary shapes can be created, but it also has a drawback that calculation accuracy falls with increasing element aspect ratio in large deformation analyses. On the contrary, indirect modeling is effective for use in large deformation analyses, but because modeling is done using grids, there are concerns that accuracies of flows near boundaries or heat transfer are inadequate. Therefore, in order to solve the drawbacks in the direct and indirect modeling approaches, the authors considered the use of "FLOW-3D" fluid analysis simulation software of Flow Science Inc. This simulation software uses the VOF method combined with the Fractional Area-Volume Obstacle Representation ("FAV OR") method[4] in which calculation cells within an orthogonal grid are cut to provide a smooth boundary contour, thus it is possible to analyze flow and heat transfer near a wall with high accuracy while maintaining the advantage of indirect modeling.

This three-dimensional thermo-fluid dynamics simulation software can simulate a wide range of flow dynamics, such as boundary shape (free surface), phase change, compressibility, and dynamic coupling with fluid/solid motion, and many reports[5] were made concerning the validity of simulation results. However, to the authors' knowledge, no report has been made so far on analysis of large-size, high-viscosity materials like silica glass. The following reports on the analysis the authors made on silica glass using FLOW-3D.

3-1 Preparation for analysis

(1) Analysis conditions

The analysis was made using an axisymmetric FLOW-3D model. The viscosity of the silica glass sample the authors entered was temperature dependent. Different temperature conditions were provided from the outside to change the sample's viscosity and bring about deformation. Because a massive amount of computational effort

will be required if analysis reflects actual deformation time, in order to decrease analytical time, deformation was simulated on a time scale of 100 times the actual deformation time, which makes the viscosity of the glass sample 1/100. The validity of this time scale is described in detail in the following section.

(2) Verification of time scale

In order to find out the permissibility of different time scales, by using the sample parameters in **Table 1**, displacement magnitude was compared on a model in-which deformation is caused only by a static load of 6.5 kg due to low viscosity setting. **Figure 4** shows the relation between time scale and deformation volume. When the volume of deformation from the initial height of 150 mm is 51 mm on a 1:1 time scale, the numerical results show that deformation volume is 53 mm (2 mm displacement difference) on a 100:1 time scale and 55 mm (4 mm displacement difference) on a 1000:1 time scale. It was observed from these results that there is no big displacement difference on time scales up to 100:1, and it was decided that analysis is done on a 100:1 time scale with both computational load and computational accuracy taken into consideration.

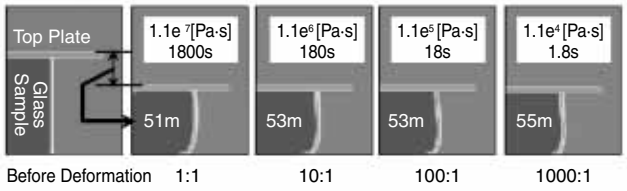

Fig. 4. Relation between time scale and deformation volume

3-2 Analytical results of viscous flow mechanism

In order to study the viscous flow mechanism of the glass sample during heat forming, a plurality of lines were marked in advance on the sample as shown in **Fig. 5**, and visible changes in these lines accompanying deformation were observed. The study results for the cases where temperature distribution is uniform and where temperature variation exists in the glass sample are as follows.

(1) Case of uniform sample temperature distribution

The parameters of the glass sample used for calculation are the same as those in **Table 1**. The load applied

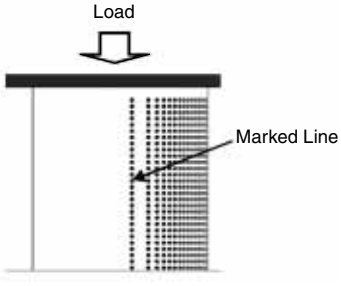

Fig. 5. Lines marked for viscous flow study

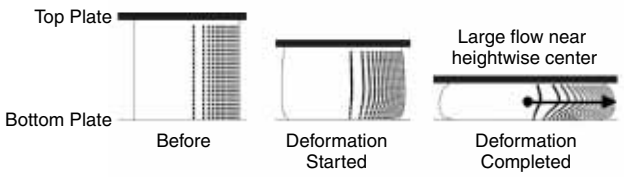

Fig. 6. Visual appearance of viscous flow due to heat forming

was 6.5 kg and the temperature distribution in the sample was uniform. The calculation results are shown in **Fig. 6**.

At around the heightwise center of the sample, the amount of outward flow (flow to the horizontal direction) is relatively large as can be seen in **Fig. 6**, and the area that was initially around the outer circumference of the sample had flown down into the bottom area. This behavior can be explained as follows. A frictional force is generated between the lower surface of a top plate and the upper surface of the sample, and between the upper surface of a bottom plate and the lower surface of the sample. The frictional force between the sample lower surface and the bottom plate upper surface is larger because the sample's own weight (5.4 kg) is also applied. Because frictional force acts in the opposite direction of viscous flow, viscous flow is less likely to occur in the areas that were initially around the sample's upper and lower surfaces than in the area around the center of the sample height. This is especially prominent at the sample lower surface where an especially large frictional force is generated, and this is assumed to be the cause of the downward flow of glass from the outer circumference of the sample.

(2) Case of temperature variation in sample height direction

Next, study is made on heat forming of a taller silica glass sample that has a large aspect ratio. It is assumed that a certain level of temperature variation is generated between the upper/lower surfaces and the heightwise center of the sample because the glass sample is subjected to radiant heat from a heating furnace heater and also to heat transfer from the top and bottom plates during heat forming. Such temperature variation might become a destabilizing factor in the process and quality of heat forming that inhibits forming in the perpendicular direction and disrupts the initial axisymmetry.

In analysis, temperature variation was implemented between the upper/lower surfaces and the heightwise center of the sample by increasing the amount of heat transfer to the sample upper/lower surfaces. Intermediate state during deformation was compared between the cases of small and large temperature variations. **Table 3** shows the parameters of the sample used for calculation. The load applied in this analysis was 11.0 kg.

Table 3. Glass sample parameters and load condition

Item	Size/condition
Outside diameter	170mm
Height	320mm
Load	11.0kg

Figure 7 shows the deformation and temperature distribution of the glass sample immediately after the start of deformation. The figure shows a comparison between the results for the cases where the time elapsed since the start of deformation is the same but temperature variation is different (within 10 deg. C and more than 50 deg. C). In both cases, viscosity is higher around the heightwise center and lower around the upper and lower surfaces, which means that deformation starts from the upper and lower surfaces of the sample.

Furthermore, in **Fig. 8**, visual changes in marked lines were shown as in **Fig. 6**, and a comparison between the cases of large and small temperature variations was presented. The comparison result shows that viscous flow behavior depends on the magnitude of temperature variation.

When temperature variation is small (10 deg. C), only small parts of the lines marked on the sample are parallel to the loading direction, indicating that the amount of flow around the heightwise center of the sample is large. On the other hand, when temperature variation is large (50 deg. C), most parts of the lines on the sample remain parallel to the loading direction, which shows that the amount of flow around the heightwise center of the sample is small. It is assumed that this is caused by temperature being higher around the sample upper/lower surfaces than around the sample heightwise center as previously mentioned, Low viscosity around the sample upper and lower surfaces overcomes the frictional force between the sample and the top and bottom plates, allowing a large amount of viscous flow to the outer circumference of the sample. This result suggests that viscous flow can be controlled by proactively creating temperature distribution within a heating furnace, which leads to assurance of quality characteristics such as optical properties.

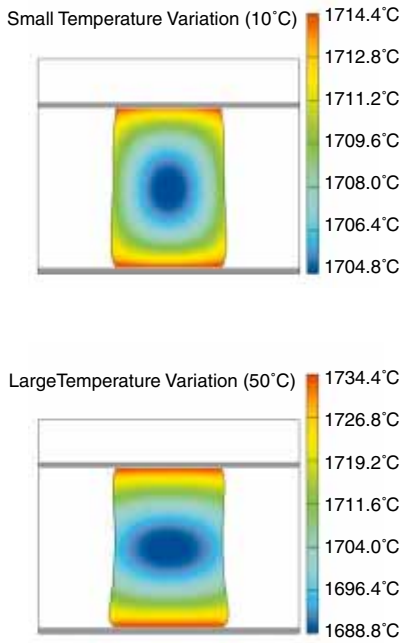

Fig. 7. Deformation and temperature distribution immediately after samples with small or large temperature variation started to deform

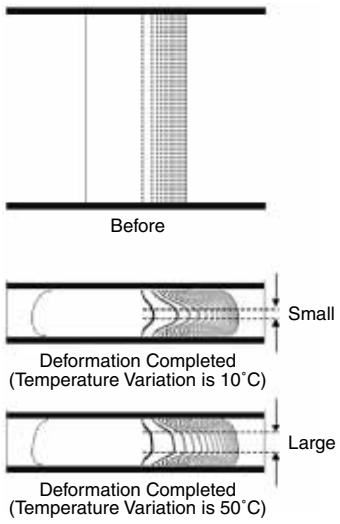

Fig. 8. Visual observation of viscous flow by heat forming when temperature distribution is in sample height direction

4. Conclusion

An analysis was conducted on the viscous flow behavior of VAD silica glass during heat forming. When taking into account only the volume of deformation in the direction of uniaxial loading, sufficient analysis can be made by a conventional method using the classical model. In the latter half of this paper, viscous flow analysis of silica glass using "FLOW-3D" simulation software was also reported. It was confirmed that this software is useful for observing viscous flow phenomenon in glass and contributes to enhancing glass quality stability.

*FLOW-3D is a registered trademark of Flow Science Inc. in the USA and other countries.

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Besides, many publish in following Flow Science company HP http://www.flow3d.com/resources/tech_paper/res_tp_main.html.

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