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Numerical simulation of the hot dip spin coating process for the fabrication of glass optical waveguides

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Abstract

Hot dip spin coating has been successfully applied to the fabrication of optical waveguides in fluoroaluminate glasses for applications in integrated optics. Fluid dynamics modelling offers an efficient means to study the importance of the main physical effects and gain a deeper understanding of the process fundamentals. This knowledge enables the selection of the best material properties and processing conditions for a given quality requirement. The POLYFLOW CFD package has been used to better understand the hot dip spin coating process and optimise waveguides for uniformity and thickness. This is particularly important when determining whether spin coating should be applied to new materials, in order to avoid time consuming experimental trials. This paper describes the extension of previous successful two-dimensional modelling of the process to capture three dimensional film non-uniformities. Computer modelling is used in order to understand the origins of non-uniformities in spin coated films and to determine which types of glasses might also be suitable for fabrication into films using the hot dip spin coating technique.

Introduction

Rare-earth doped fluoroaluminate glass thin films have important applications as the basis for efficient waveguide optical amplifiers. For high quality devices, film thickness must be of the order of a few microns and uniformity and flatness should be as good as possible.
As sketched at fig 1, the hot dip spin coating process consists of three stages. During the first stage, the "dip" stage, a glass substrate at the temperature of 430°C is dipped in molten glass (1000°C). Then, the substrate is withdrawn from the molten glass and a meniscus forms. Finally, the substrate is spun and the glass film is thinned out.

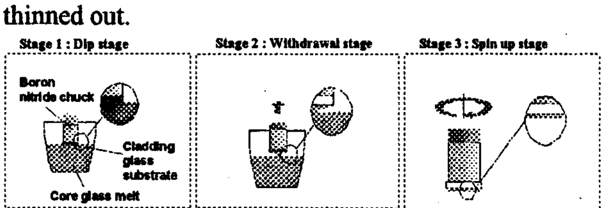

Fig 1- Three stages of the hot dip spin coating process

Experimental observations revealed trends in the film thickness and uniformity. Qualitatively, as the spin speed was increased, the film thickness was reduced but at the expense of a degradation in film uniformity. However, experimental study is expensive and has to deal with the difficulty of physically observing such phenomena at high temperature. Simulation is an alternative cost-effective route to the understanding of the process.
The hot dip spin coating process was already the subject of 2D axisymmetric simulations (1), performed with the POLYFLOW software. This previous study determined the mechanism of hot dip spin coating and identified those parameters that affect the film thickness and the uniformity of the waveguide, i.e. the spin speed and the initial thickness of the film.
However, such a study was not sufficient to highlight some 3D effects, like the *spiral arms*, that appear as helical patterns in the surface of the substrates. Experimentally, it has been observed that the optimum conditions occur for a spin speed around 2000 rpm. This work addresses the 3D simulation of hot dip spin coating to show the presence of 'spiral arms'-like effects.

Stage 1 : the dip stage

The glass substrate is suspended from a boron nitride vacuum chuck that is preheated to a temperature of 430°C while the bulk waveguide material is melted at 1000°C. When the substrate is dipped in the molten glass, a heat exchange becomes established and the temperature and hence the viscosity distributions can be calculated.
This was easily set up in POLYFLOW as a heat conduction problem between two entities: the substrate, at 430°C, which maintains this temperature at the back surface due to the large thermal mass of the boron nitride chuck, and the film of molten glass which is initially at 1000°C. Each entity is characterized by the same material data, cf. Table 1.

Stage 2: the withdrawal stage

Calculating the position of the molten meniscus, when the substrate is pulled out from the melt, is difficult due to the large deformations of the computational mesh, and due to the discontinuity in the solution of the fluid equations.

Furthermore, the knowledge of the meniscus is not necessary for the third stage. As has been demonstrated by Emslie (2), the final thickness can be shown to be independent of the initial film thickness h_o [m] provided that the following inequality is satisfied:

$$h_o >> \sqrt{\frac{3\eta}{4\rho\omega^2 t}}$$

where ω [s^{-1}] is the angular velocity and t [s] the spin time. A simple calculation based on 'worst-case' values reveals that the initial film should be a few hundred microns thick or greater (1). As a consequence, we chose a constant thickness of 500 microns.

Stage 3: the spin stage

The spin coated film geometry consists of three regions, cf. fig 2: the 'crown', the spin-off zone, characterized by an important deformation of the substrate edges, and the central 'uniform' spin-coated region. Only, this last one was considered for the simulation. Furthermore, edge effects and surface tension are ignored.

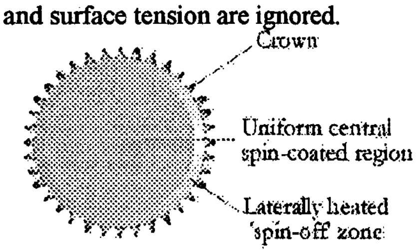

fig 2 – The three regions of the substrate

It can be shown that the temperature reached by the interface between the molten glass and the substrate is sufficient for the substrate to soften. As a consequence, the substrate and the film are both parts of the computational domain. The lower surface of the film is a free surface that deforms under the rotation of the boron nitride chuck.

Results

Whatever the spin speed, spiral arms appear at the surface of the film, cf. fig 3. However, their presence is more obvious and their magnitude more important from a spin speed, of 4000 rpm, as has been observed experimentally.

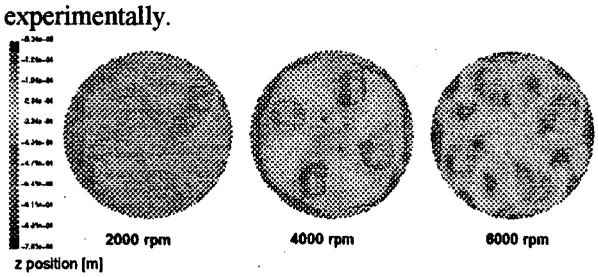

Fig 3 – z position of the surface of the film at different spin speeds.

The spiral arms seem to be a 3D characteristic effect of the hot dip spin coating. Figure 5, which plots the variation in flatness along a cross section (defined in fig 4), shows the influence of the spin speed on the film uniformity. As has been observed experimentally and with the previous 2D axisymmetric simulations, the film uniformity improves for slower spin speeds.

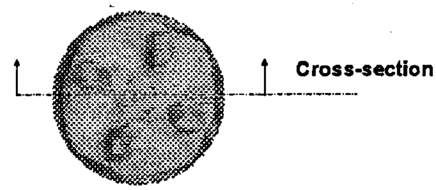

Fig 4 – position of the cross-section for film uniformity comparison

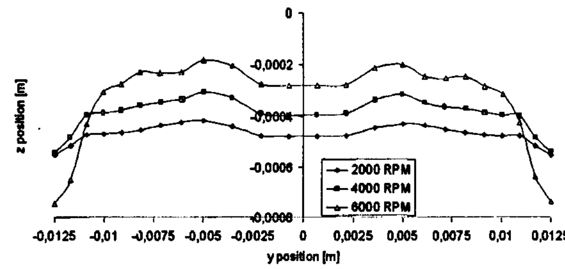

Fig 5 – z position of the film surface along the cross-section

Conclusion

The 3D simulations of the hot dip spin coating process reproduce experimental observations and are consistent with the results of 2D simulations for the relationship between spin speed and film uniformity. In particular, they successfully reproduce the non axisymmetric 'spiral arms' effect: the most significant degradation of surface flatness. These first results are extremely encouraging – further work will highlight the effect of time on the film thickness distribution, and allow the best spin coating conditions to be selected.

References

[1] D.W.J. Harwood, Towards a 1.3 micron planar neodymium doped fluoride glass waveguide amplifier, PhD. Thesis, University of Southampton, 2000.

[2] A. G. Emslie, F. T. Bonner, and L. G. Peck, Journal of Applied Physics, 29, 858-862 (1958).

Material Property		Unit	Value
Density	ρ	Kg/m^3	3600
Thermal conductivity	κ	W/m.K	3.7
Specific heat capacity	Cp	J/kg.K	1013
Viscosity	η	Pa.s	$\log\eta = 7.294 - \frac{1.74510^{-4}}{T} + \frac{8.35410^{6}}{T^2}$

Table 1. Thermophysical material data