CONTROL OF STRESSES DURING PRODUCTION OF SHEET GLASS

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An attempt to analyze the annealing of sheet glass leads to some unexpected conclusions. Namely, the limitation of the stresses distributed over the thickness of the glass, which most researchers in our country and abroad consider to be one of the main purposes of annealing, in actual fact has little influence on the effectiveness of the process. In order to substantiate this assertion, let us formulate the main goals of annealing: To preserve the integrity of the glass ribbon before cutting into sheets and that of the glass sheets after the cutting and to ensure a satisfactory strength and other properties of the finished products during use.

Even with careful annealing, however, when the residual thickness stresses (face stresses in the conventional terminology) are below the established standards (6 mm/cm per mm thickness of glass), the finished sheets may be warped and the edges of the ribbon may bulge, longitudinal cracks may appear, and difficulties may be encountered in cutting and severing the edges. Therefore, slow annealing, which induces the need to increase the size of the annealing furnace, adversely affects the economic index, and at the same time there is no guarantee of the efficiency of the overall process.

When speeding up production, therefore, one should strive to optimize the stress distribution rather than to reduce the level of stresses. This, however, requires more complete information about all the component stresses that arise in the glass and about how they are interrelated with the various stages of the technological process.

For this purpose we undertook a study of the processes in which stresses are formed and redistributed in a glass ribbon and in sheets of glass [1, 2]. We carried out a mathematical simulation of the respective processes on the basis of a numerical solution of boundary-value problems of the mechanics of a deformable solid and heat conduction, using the method of finite elements [3] and also conducted experimental studies on sample and directly under production conditions.

For convenience in analyzing the results it is desirable to isolate the following stages in the formation of technological stresses in the glass: the annealing proper, postannealing cooling, forced cooling before cutting, cutting of the ribbon into sheets, and severing the edges.

The true three-dimensional stressed state in this case is conveniently considered as the sum of two forms of stress (Fig. 1): thickness stresses, due to uneven cooling over the thickness of the glass ribbon, and planar stresses, which are caused by the nonuniform distribution of temperature and residual strains in the plane of the ribbon. The interrelation between the total, thickness, and plane stresses is described by the expressions

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\sigma_P^t = \frac{1}{h} \int_{-h/2}^{h/2} \sigma_x dz;
$$

$$
\sigma_P^p = \frac{1}{h} \int_{-h/2}^{h/2} \sigma_y dz;
$$

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\sigma_x^t = \sigma_x (x, y, z) - \sigma_P^p (x, y);
$$

$$
\sigma_y^t = \sigma_y (x, y, z) - \sigma_P^p (x, y),
$$

where $h$ is the thickness of the ribbon; $x$, $y$, and $z$, respectively, are the coordinates along, across, and over the thickness of the ribbon; $\sigma_x^P$ and $\sigma_y^P$ are the plane longitudinal and transverse stresses; and $\sigma_x^t$ and $\sigma_y^t$ are the thickness longitudinal and transverse stresses.
The experimental studies were carried out most often with the aid of polarimeters on small glass samples (e.g., 30 × 100 mm). Only the thickness stresses were recorded in this case since plane stresses are eliminated completely when small samples are cut from sheets of ordinary size. A characteristic feature of plane stresses is that they change when the glass ribbon is subjected to technological processes and when the ribbon is cut into sheets; the magnitude and distribution of these stresses depend essentially on the size of the sheets [1, 2]. This greatly hinders experimental investigations and evidently this is why their role in the technological process has been underestimated.

The mechanism by which thickness residual stresses are formed has been well studied at the stage of the principal annealing and the value of these stresses can be regulated effectively with the cooling rate [4, 5]. The corresponding calculations, however, were carried out on the assumption that the cooling curve is linear or consists of linear segments. In a recent simulation of real heat exchange in modern annealing furnaces,* we found that such regimes virtually cannot be realized and the distribution of thickness residual stresses depends more on the distinctive features of the cooling curve than on the average cooling rate in the annealing interval.

The plane residual stresses are determined in the principal annealing stage mainly by three factors, viz., a nonuniform temperature distribution over the width of the glass ribbon after the forming unit, unidentical ribbon-cooling conditions over the width of the furnace because of anomalies in the radiative heat exchange, as well as edge effects which cause a more intensive heat exchange in the region of the edge than in the plane of the ribbon.

We determined that in real annealing regimes the plane residual stresses act along the ribbon, i.e., tangential and transverse components are virtually absent, but they do appear as the ribbon is cut into sheets and can have a considerable effect on the strength of the ribbon and sheets [1, 2].

A typical shape of the curves of plane stresses measured at the exit from the annealing furnace is shown in Fig. 2. The local peaks are due to the enhanced heat intake while the ribbon is in contact with the rollers. The disequilibrium of the curves of the plane stresses is attributed to tensile forces acting along the ribbon; these forces are due to the difference between the speed of the ribbon and that of the conveyor rollers. The curve of the thickness stress is parabolic. The maximum values of the thickness stresses, as a rule, are a fraction of those of the plane stresses.

During post-annealing cooling of a glass ribbon with a complicated field of residual strains additional thermal strains are caused by the nonuniform temperature distribution at this stage.

The true stresses in the ribbon thus are the sum of the residual and thermoelastic stresses as well as the stresses due to the tensile action of the rollers.

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* A. Ya. Starozhinskii and I. S. Melamed participated in the development of methods for calculating the heat exchange in annealing furnaces and the package of programs for automating pre-design analysis of variants of the design of modern annealing furnaces for sheet glass.