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Review

Effect of glass thickness on temperature gradient and stress distribution during glass tempering

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ABSTRACT

The thickness of tempered glass is usually more than 3 mm. To achieve thinner tempered glass, it is necessary to clarify the stress change during its quenching process. Glass toughening involves high temperatures, which made the real-time measurement of the temperature distribution, stress distribution, and phase changes occurring difficult. However, these parameters directly affect the strength of the tempered glass. In this paper, for the purpose of evaluating and optimizing the tempering process, nonlinear finite element analysis method has been used to simulate the distribution of the temperature gradient, and the final residual stress of the glass samples with different thickness. The geometry and mathematical model to be used were established, and the boundary conditions for the simulations were set on the basis of the actual toughening conditions. It is found that the thickness has a great influence on the quenching period, temperature gradient and stress fields distribution.

Contents

1. Introduction

Tempered glass exhibits numerous advantages over ordinary glass, such as high resistance to wind and impact toughness [1], owing to which the former is employed widely in buildings worldwide. Building-integrated photovoltaic are important devices with respect to solar energy utilization [2]. These photovoltaic modules are composed primarily of solar cells and tempered glass. By decreasing the glass thickness, the efficiency of the photovoltaic modules can be increased and their weight can be decreased [3]. Moreover, thin tempered glass has been used in electronic flat-panel display devices and other such devices [4]. The thickness of tempered glass is usually more than 3 mm [5]. Although chemically tempered glass can be formed with a thickness lower than 1 mm, it has a shorter lifespan [6]. In contrast, the lifetime of physically tempered glass can exceed 30 years [7].

Tempered glass is a glass that has been subjected to a pre-stressing force. After the toughening process, a uniform compressive stress is

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Table 1
The thermoviscoelastic characteristics are given in this table [14,22].

Young's modulus (Pa)	Poisson's ratio	Glass material factor (K)	Solid-state expansion (K^{-1})	Liquid expansion (K^{-1})
E_0	ν	D	α_g	α_l
7.1×10^{10}	0.22	5.5×10^5	1.12×10^{-5}	3.0×10^{-5}

generated on the glass surface, while a tensile stress forms internally; this improves the bending and impact strength of the glass. The residual stress determines the strength of the glass. According to the American standard ASTMC1048, the stress in a tempered glass surface should be greater than 6.9×10^7 Pa [8]. For half-tempered glass, it can be $2.4–5.2 \times 10^7$ Pa [9]. For a given set of tempering conditions, the internal stress distribution varies with the glass thickness. Glass toughening involves high temperatures. Therefore, the real-time measurement of the temperature distribution, stress distribution, and phase changes occurring within the glass being tempered is difficult. However, these parameters directly affect the strength of the tempered glass.

Usually, the tempering process parameters are optimized through trial and error, resulting in a long product development cycle, high costs, and difficulties in ensuring high product quality [10]. In addition, ascertaining the temperature-change history for the cooling process on the basis of experience-based judgment and experimental results is very difficult. However, computer simulations of the glass tempering process, the distribution of the temperature gradient, and the final residual stress can make the process of evaluating and optimizing the tempering process more effective in terms of both time and cost. Unfortunately, there have been few theoretical simulation studies in this area. In 1969, based on results reported by Lee et al., Narayanaswamy and Gardon proposed the viscoelastic consolidation theory, which predicted the existence of transient stress tempered glass and could be used to determine the final stress in such glass [11–13]. In 2010, Nielsen et al. used the finite element analysis software ANSYS to simulate the cooling of tempered glass around a hole in a 10-mm-thick glass sample [14].

In this study, we used the nonlinear finite element analysis software ABAQUS [15] to simulate the toughening process for glass samples with different thicknesses. The ABAQUS is widely used mainly because it has advantages of computational efficiency for large deformation and highly non-linear problems [16,17]. During glass tempering process, not only the dependence of temperature and stress on time is nonlinear, but also material properties change significantly as strain rate and temperature increase. The geometry and mathematical model [18] to be used were established, and the boundary conditions for the simulations were set on the basis of the actual toughening conditions.

2. Simulation analysis

Glass tempering primarily involves blowing air on both sides of a glass sample heated to the initial glass temperature T_0 (usually approximately 650 °C), in order to quench the glass sample to a certain temperature (approximately 200 °C). Thus, mathematical models for the material and thermal boundary load are required to investigate the glass tempering process. Calculations based on the material model parameters and the thermal boundary conditions can provide information on the history of the temperature and the stress changes occurring during the glass toughening process, as well as on the magnitude and distribution of the final residual stress.

2.1. Finite element temperature model

For a three-dimensional glass sheet, the temperature distribution over a given area is assumed to be a function of the position and time coordinates, that is, $\theta = f(x,y,z,t)$, where θ is the temperature; x, y, and z are the position coordinates; and t is the time. The differential equation for heat conduction during the tempering process is as follows:

$$\rho c \frac{d\boldsymbol{\theta}}{d\boldsymbol{t}} = k\left(\frac{\partial^2 \boldsymbol{\theta}}{\partial^2 x} + \frac{\partial^2 \boldsymbol{\theta}}{\partial^2 y} + \frac{\partial^2 \boldsymbol{\theta}}{\partial^2 z}\right) \tag{1}$$

where ρ is the density of the material; c is the specific heat capacity of the material (glass); t is the time; and k is the thermal conductivity of the material in the x, y, and z directions W / (m K). Further, the following equation is then satisfied:

$$\frac{d\theta}{dt} = \frac{\partial \theta}{\partial t} + k\left(\frac{\partial \theta}{\partial x} + \frac{\partial \theta}{\partial y} + \frac{\partial \theta}{\partial z}\right) \tag{2}$$

Using Eqs. (1) and (2), the entire glass temperature field can be expressed as an integral form equivalent to a finite number of units:

$$\begin{aligned} &\int_{vol}\left[\boldsymbol{\rho c}\cdot\boldsymbol{\delta\theta}\left[\frac{\partial\theta}{\partial t} + \{v\}^T\cdot\{L\}^T\right] + \{L\}^T\cdot\delta T([D]\cdot\{L\}^T)\right]d(vol) \\ &= \int_{S_2}\delta\theta q^* d(S_2) + \int_{S_3}\delta\theta\lambda(\theta_B - \theta)d(S_3) \end{aligned} \tag{3}$$

where the subscript "*vol*" indicates the unit volume; θ_B is the air temperature; $\boldsymbol{\delta}\theta$ is the temperature of dummy variables; S_2 is the heat flux applied area; S_3 is the applied convection area; [D] are the heat conduction properties of the matrix material; and {v} is the conductivity of air.

If the temperature change within the unit cell can be assumed to be represented by a polynomial, then the integral child domain decomposition division unit can be expressed as follows:

$$T = \{N\}^T\{\theta_e\} \tag{4}$$

where $\{N\}^T$ is the unit shape function and $\{\theta_e\}$ is the unit node temperature vector. By considering the temperature in the integral equation (Eq. (4)), obtain the following:

$$\begin{aligned} &\int_{vol}\boldsymbol{\rho c}\{N\}^T\{N\}d(vol)\{\theta\} + \int_{vol}\boldsymbol{\rho c}\{N\}^T\{v\}^T(B)d(vol)\{\theta\} \\ &+ \int_{yol}\{B\}^T(D)(B)d(vol)\{\theta\} = \int_{S_2}\{N\}\boldsymbol{q}^* d(S_2) + \int_{S_3}\{N\}\boldsymbol{\lambda}\theta_B d(S_3) \\ &- \int_{S_3}\{N\}^T\{N\}\boldsymbol{\lambda} d(S_3) \end{aligned} \tag{5}$$

where $[B] = \{L\}^T\cdot[N]$. By taking into account the material properties,

Table 2
The thermal conductivity and the specific heat are characteristics varying with temperature as shown in this table [14].

Temperature (°C)	150	200	250	300	350	400	450	500	550	600	650
Specific heat C_p(J(kg K)$^{-1}$)	1427	1428	1429	1430	1431	1432	1433	1434	1435	1436	1437
Thermal conductivity λ(W(m K)$^{-1}$)	1.14	1.19	1.24	1.29	1.34	1.39	1.44	1.49	1.54	1.59	1.64