Simulation of Temperature Field within Flat Tempered Glass Cooling Process

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Abstract. The purpose of this paper is to explore the temperature field change rule within flat tempered glass cooling process. Temperature field mathematical model was established with flat tempered glass cooling process, and the finite element software Msc. Marc was used for temperature field simulation. Temperature change law of the glass key point in the cooling process was studied. The simulation results show that the trend of temperature difference between the internal center point and vertex is the first increase and then decrease. When cooling time is 107s, the largest glass temperature difference is 375.2°C. When the cooling time is 588.5s, the glass center point temperature is 79.5 °C, and the vertex temperature is 30°C. The cooling rate of glass is the trend of the first and then slow. The glass vertex cooling rate is the fastest, and the glass center cooling rate is the slowest.

Introduction

The cooling process is very important for the performance of physical toughened glass. On the one hand, the cooling rate is different, resulting in residual heat stress within the material, and sometimes may lead to toughened glass burst. On the other hand, the glass material undergoes shrinkage deformation, which in turn affects the cooling conditions. Therefore, many scholars have applied the computer simulation technology to the research of the glass[1-4]. The computer software is used to simulate the temperature field of the glass tempering cooling process, which is beneficial to modify the process parameters, optimize the process, and improve the quality of tempered glass by numerical test method.

In this paper, a mathematical model of the temperature field in the cooling process is established by considering the heat transfer of the glass surface and the environment. MSC.MARC finite element method is used to simulate the temperature field of the tempered glass, and The temperature change law of the glass key points is analyzed. The theoretical basis is provided for the process optimization of the glass physical tempering cooling process. This study may provide some theoretical basis for the process optimization of glass physical tempering cooling process.

Mathematical Model Establishment

Tempered glass cooling is a complicated dynamic process, and its temperature field change is instantaneous. In the glass, the heat conduction conforms to the Fourier law, and the convection heat transfer between the glass and the liquid or gas conforms to the Newton cooling formula. According to the Fourier law and the conservation of energy, the differential equation of heat conduction in cylindrical coordinate system can be obtained as follows:

\[
c_\rho \frac{\partial T}{\partial t} = \lambda \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right) + Q(r, z, t)
\]  

(1)
In the formula, \( T \) - for the temperature (K); \( t \) - for time (s); \( C \) - for the material specific heat capacity \( J/(Kg.K) \); \( \rho \) - material density \( (Kg/m^3) \); \( r, z \) - point in cylindrical coordinate position (m); \( \lambda \) - a heat conduction coefficient \( (w/m.k) \).

The inner heat source \( Q(r, z, t) \) is zero in the glass cooling process, and heat diffusion coefficient \( \alpha = \frac{\lambda}{c\rho} \). Therefore, the heat conduction differential equation can be simplified as:

\[
\frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}
\]  

(2)

**Initial Condition**

When the temperature is 630°C, the glass is semi melted. Therefore, it is assumed that the initial temperature is 630°C. That is

\[
T = T_0 = 630^\circ C
\]  

(3)

**Boundary Condition**

In this paper, considering the convection heat transfer between glass and the environment, the formula can be expressed as follows:

\[
\lambda \frac{\partial T}{\partial Z} = h(T_e - T_s)
\]  

(4)

In the formula; \( h \) - convection heat transfer coefficient; \( T_e \) - ambient temperature (K); \( T_s \) - glass surface temperature (K).

**Geometric Modeling and Mesh Generation**

In order to facilitate the observation of changes in the internal temperature field of the glass, the tempered glass is cut along the thickness direction, and the surface length is 100mm, the thickness is 20mm plane mesh model, the length is subdivided into 100 grids, and the thickness direction is subdivided into 20 grids.

**Initial Conditions and Boundary Conditions**

The glass temperature is assumed to be 630°C. The ambient temperature is assumed to be 25°C. The convective heat transfer coefficient is 180w/ (m².K)\(^6\).

**Thermal Properties of Toughened Glass Materials**

The specific heat capacity \( C \) and the heat transfer coefficient of toughened glass are changed with the temperature \( T \) as shown in Table 1.

<table>
<thead>
<tr>
<th>( T/^\circ C )</th>
<th>20</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda/(w.m^-1.K^-1) )</td>
<td>1.38</td>
<td>1.47</td>
<td>1.55</td>
<td>1.67</td>
<td>1.84</td>
<td>2.04</td>
<td>2.46</td>
</tr>
<tr>
<td>( c/(J.kg^-1.\circ C^-1) )</td>
<td>720</td>
<td>838</td>
<td>946</td>
<td>1036</td>
<td>1084</td>
<td>1108</td>
<td>1146</td>
</tr>
</tbody>
</table>

**Results and Discussion**

When the cooling time is 107s, the temperature of the glass internal center point is 492.2°C, and the vertex temperature is 117°C. At this time the temperature difference between the internal center point and the vertex is the biggest, which is 375.2°C, as shown in Figure 1. When the cooling time is 588.5s, the temperature of the glass internal center point is 79.5°C, and the vertex temperature is 30°C. Their difference in temperature is 49.5 °C, as shown in Figure 2. In the plane glass cooling
process, the trend of the temperature difference between the internal center point and the vertex is the first increase and then decrease. Due to the cooling time from 0s to 107s, the heat transfer rate between the surface and the environment is greater than that of the internal and surface. Therefore, the temperature difference between the internal center point and the vertex is increasing. However, the cooling time from 107s to 588.5s, the external environment temperature increases, and the heat transfer rate between the glass surface and ambient environment become slow. The heat transfer rate between the glass surface and the environment is less than that of the internal and surface. So the temperature difference between the internal center point and the vertex is decreasing.

Figure 1. Temperature field distribution at 107s.

Figure 2. The curve of temperature change with time in glass cooling process.

The temperature change during the glass cooling process is shown in Figure 2. The trend of cooling rate is the first fast after the slow at glass vertex, internal center point, surface center point, thickness direction surface center point. As the beginning of the glass cooling, the glass temperature is relatively high, while the environmental temperature is relatively low. So the cooling rate of the glass at each point is relatively fast. When the glass is cooled for a certain period of time, the glass temperature is lowered and the glass ambient temperature is increased. The difference between the glass temperature and the ambient temperature of the glass decreases. Therefore, the cooling rate of each point becomes slower.

As shown in Figure 2, the cooling rate of glass vertex is the fastest, while the cooling rate of internal center point is the slowest. Since the vertex has the largest contact area with the surrounding environment, and the convective heat transfer rate is the fastest, so the glass vertex cooling rate is the fastest.

Conclusion

In this paper, the temperature field of the flat glass tempering cooling process is simulated, and the following conclusions are drawn:

(I) Compared to other temperature difference, the temperature difference between the Vertex and internal center point is the largest. The maximum temperature difference is 375.2 °C with the cooling time at 107s. There is the maximum residual stress. So the connection between the two points is most likely to be the main direction of the plane glass cracking.
(II) Cooling rate is the first slow trend at glass vertex, internal center point, surface center point, thickness direction surface center point. The cooling rate of glass internal center point is the slowest. The cooling rate of the glass vertex is the fastest, leading to the largest residual stress. Therefore, the vertex may be a flat glass burst source.

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