Definition of the strain-stress distribution of porous glass in the retarded cooling temperature range

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Abstract. The estimation of the strain-stress distribution (SSD) of porous glass (foamed slag glass, FSG) is assessed by annealing temperature curves according to the given values of the thermomechanical and thermophysical properties of porous glass, which are in correlation with the properties data of the host glass and its structure. When calculating cooling processes (cooling rate) of porous glass products, the A.N. Daivalter’s formula, which takes into account only the stresses arising from the safe product cooling, but does not take into account those that remained there to the cooling start point, is usually used. The cooling rate in the interval of the annealing zone itself should be sufficiently low so that residual stresses, arising after they pass it, have small values. Since methods, that make it possible to determine the residual stresses that appear in the porous glass after passing through the initial annealing zone, are currently poorly developed, numerical simulation methods should be used to determine the porous glass SSD under the influence of thermal loads. Numerical study of the strain-stress distribution of porous glass allowing for thermal loads in the annealing temperature range was carried out in the Ansys Workbench software package.

1 Introduction

In industrial and civil engineering thermal insulation materials based on glass and designed to perform effectively the functions of heat protection and the heat accumulation and cold in buildings are of great importance [1]. In conjunction with properties and thermophysical characteristics, porous glass (foam glass) is considered to be promising in use [2]. The powder method of production is the most prevalent in industrial production. It includes four main stages: heating of the foaming mixture (charge), foaming, quenching, annealing. The annealing of the material is aimed to stabilize the structure and to reduce the appearing stresses to acceptable values. It is necessary to note two factors that occur when a temperature changes in a porous glass during its production. When the ambient temperature that surrounds the sample of the porous glass changes, the heat is gradually transferred along the layers of material due to the limited thermal conductivity of the material, so that there will be the temperature difference between the outer and inner layers in the sample. This heat transfer process requires a certain time. The glass matrix of the porous glass changes its linear dimensions when the temperature changes (it expands upon heating and shrinks upon cooling), and, consequently, the layers of material tend to accept the temperature-determined boundaries, which leads to the appearance of which depends on the presence of the crystallization process in the glass. The resulting crystalline phase has a thermal expansion coefficient different from glass (TCLE). Due to this, there will be a difference between the compression values of the crystal and the glass matrix, which will lead to stresses at the contact boundary. Also, when it comes to improper cooling of the glass, there may occur residual stresses, which reduce the strength of the finished product and subsequently lead to destruction, even after a long time.

Both the structure relaxation process and the stress relaxation process in the glass are well studied and provide the basis for the development of stress analysis methods [3, 4]. The calculation of stress relaxation is based on the traditional approach to the solution of viscoelastic problems – using the Boltzmann superposition principle, the validity of the application is confirmed by experimental data [5, 6]. The finite element method is defined as the most promising for mathematical modeling of heat exchange processes and stress analysis for the desired material at the technological stage of annealing [7].

2 Object description

The object (Figure 1) is a sample of a porous glass with dimensions 30 × 30 × 30 mm, a perforation coefficient of 0.2589, an average pore diameter of 3 mm, placed on a 100 × 100 × 3 mm support, 12X18H9T support material [8]. The gas in the pores is CO2.
The stationary heat equation for an isotropic medium has the form:
\[ \text{div}(\lambda \cdot \text{grad}T) = 0, \]
where \( T \) – desired temperature distribution function; \( \lambda \) – coefficient of thermal conductivity.

In accordance with the peculiarities of the technological mode of the annealing stage, the decrease in the ambient temperature is carried out linearly with a low speed (2-3 °C / min).

In light of this, the stresses are found from the system of equations of the following form [12]:
\[
\sigma_{ik} = 2G \left[ \varepsilon_{ik} + \mu \frac{S}{1 + \mu} \delta_{ik} - \alpha T \delta_{ik} \right],
\]
\[
\varepsilon_{ik} = \varepsilon_{ik} = \frac{1}{2} \left( \frac{\partial U_k}{\partial x} + \frac{\partial U_i}{\partial x_i} \right), \quad i, k = 1, 2, 3,
\]
\[
\sum \frac{\partial \sigma_{ik}}{\partial x_i} = 0,
\]
where \( \sigma_{ik} \) – stress, \( (\sigma_{ik} (i \neq k)) \) – tangential stresses; \( \sigma_{ik} \) – strains; \( U_i \) – displacement; \( S = \sum \sigma_{ik} \) – sum of the normal stresses, \( T \) – ambient temperature, \( G \) – shear modulus, \( 2G = \frac{E}{(1 + \mu)} \), \( E \) – the Young’s modulus; \( \mu \) – the Poisson’s ratio; \( \alpha \) – thermal-expansion coefficient; \( \delta_{ik} = \begin{cases} 1, & i = k, \\ 0, & i \neq k \end{cases} \) – Kronecker symbol.

The main stages in solving this problem are – building a model, setting the initial data, solving and processing the results. It should be noted that the results of calculating the thermal state are the basis for solving the strength problem.

To create geometric models, CAD systems can be used. In this paper we implemented a comprehensive approach to creating a solid model – import of the geometry of a porous glass sample from the PC “GMSH” [13] with subsequent refinement in PC ANSYS (fig. 1).

The process of creating a model of a porous glass sample is automated – the geometry of the sample is formed depending on its size and porosity. The location of the pores is structured – it can have a hexagonal or ordinary arrangement of pores (depends on the thickness of the matrix walls that defines the skeleton of the porous glass); the pore size can be constant with the volume of the sample, or to have random nature. In the presented calculation, pore material is described by a certain number of spherical cavities of small diameter (in the region of 3 mm) and a constant composition possessing gas properties.

Work with materials is carried out by the Engineering Data module used to organize and store material data, describe material properties and input parameters of mathematical models using the additional
interface of the Workbench. When calculating the
temperature fields in the Transient Thermal module, the
physical properties of materials such as thermal
cconductivity, heat capacity, etc. are available in the
Toolbox window. It is necessary for thermal analysis to
set the thermal conductivity in the material properties.
The material can be anisotropic or isotropic (orthotropic). For an anisotropic material, the value of the
thermal conductivity coefficient does not depend on
the direction, i.e. is constant along the X, Y, and Z axes,
and for the orthotropic material three thermal
conductivity coefficients are specified in the X, Y, and Z
directions.

When performing static strength calculations in the
Static Structural module in the Toolbox window the
mechanical properties of materials and models are
available to describe the behavior of materials under the
action of loads (plasticity, creep models, etc.).

To verify the efficiency of the proposed approach to
the evaluation of heat transfer in a porous glass,
numerical studies of thermal processes in the target
material were carried out, the main task of which was to
reveal the distribution of the temperature field with the
volume of the sample with a change (decrease) in the
temperature at the outer boundary of the calculating
region (the thermal chamber wall) according to the
annealing process. The calculations used real
thermophysical and radiative properties of carbon
dioxide, a matrix of porous glass and a steel support [14,
15, 16, 17]. The values of the thermal conductivity of
carbon dioxide at the upper and lower boundary curves,
at the critical point and on isobars from 30 to
200 kg / cm² to a temperature of 1000 °C are presented
as temperature dependence. The thermal conductivity
and the specific heat of the porous glass matrix were
determined by the laser flash method [18] in the
temperature range 25-700 °C in the TC-9000H thermal
conductivity measuring device at the collective use
center "Technologies and Materials of the Belgorod
State University", Belgorod. The remaining physical
characteristics of the porous glass matrix were chosen in
accordance with its chemical composition [8].

The results of the temperature and the strain-stress
distribution analyses are made at the calculated points
(fig. 2).

The change in temperature over the cross section of
the sample (along the lines, fig. 2) for the time point
12000 (the termination of annealing) is shown in fig. 3.
The time point corresponds to the temperature at the
boundary of the calculated region (furnace wall) of
25 °C. The results of stress analyses are shown in fig. 4.

3 Conclusion
The nature of the change in the temperature field in a
sample of porous glass corresponds to the assumptions
presented in the literature [19, 20, 21]. The created
mathematical model adequately describes the thermal
processes and stresses arising in the porous glass at the
annealing stage and can be used to create optimal (for
energy-consuming) technological processes for the
production of porous glass.
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