Simulation of thermal stresses during annealing uncoordinated soldered joints from glass and metals

N. E. Putyrin O. N. Lyubimova
nikitahome@yandex.ru

Abstract

Welding glass with metals is widely used in various fields of engineering and construction. Mathematical modeling of the kinetics and temporary thermal stresses has allowed to execute more qualitatively heat treatment and to control residual stresses. The processes, which take place in glass and metal during welding, complicate the mathematical modeling. They are: changes in the state of aggregation of glass from solid to viscous and back: diffusion in the weld zone and relaxation during annealing. O.V. Mazurin, in his paper [1], suggested the method of calculation of stresses for soldered joints from glass and metals. In most cases, this method is used for a quarter century chemists and technologists to determine the residual stresses not only for soldered joints from glass and metals, but in amorphous coatings on metallic substrates [2, 3]. The simplicity of this method, due to a number rather crude approximations, which in some cases gives the corresponding calculation with experiment, while others include estimates for residual stresses in the coating or group of existing the soldered joints, however in practice they does not exist or contrary [3]. When forming the laminated composite in which the layers may be of the same order, for example, in glass-and-metal-composite [4], there is a need to monitor the stress-strain state, not only glass but also metal. Furthermore, the welding glass and metal diffusion zone may be present, which, as shown in [5], also affects the stress-strain state in the composite. The object of this work is to develop a more rigorous model allows to analyze the technological stresses in junction glass with metal, taking into account the relaxation processes in the glass at certain stages of the process. To achieve this goal considered the problem of strain of a cylinder composed of two different materials are viscoelastic (for glass) and elastic (for metal) under the action of an unsteady temperature field. The problem was solved in a cylindrical coordinate system with the acceptance of the hypothesis of plane strain and axial symmetry. Equations of state for glass written in integral form as the ratio of the Boltzmann-Volterra, in same time in metal bond stress with strains adopted into law Duhamel-Neumann. Analytical formulas for the stresses, strains and displacements in a two-layer composite with consideration of relaxation processes in materials, using the obtained dependence can be investigated thermo-stressed state in layered composites.

Welding glass with metals is widely used in various fields of engineering and construction. Among the many ways to connect glassy materials with metals occupies a special place diffusion welding, because it allows to receive strong connections and solve a number of technical challenges, for example, to skip some intermediate operations such as heating the paste, heat treatment, application of solder required in case of a connection method soldering. Technology for producing a glass weld metal by diffusion welding includes three basic temperature modes: heating, extract and cooling which are a consequence of technological stresses which may lead to reduced performance qualities of the product and their degradation during manufacture. Mathematical modeling of the kinetics and temporary thermal stresses has allowed to execute more qualitatively heat treatment and to control residual stresses. However, modeling processes, that occur in the glass and metal in time of welding, is difficult, when glass layer changes from solid to viscous and back. Annealing - heat treatment of the welded joint according to any regime undertaken in order to obtain in predetermined temperature range stresses which are within a predetermined magnitude. From the high-temperature range is limited to the higher annealing temperature. Isothermal control of glass at this temperature allows to eliminate up to 95% of internal stresses without deformation of the product. Isothermal control at lower temperature removes only 5% of the internal stresses. Accumulated tensions in this range constitute a significant portion of residual stresses. Everything said about the annealing of glass in most cases remains valid for the agreed junctions glass to metal, however, in the case of mismatched junctions is a big difference between the coefficients of linear thermal expansion makes override all parameters annealing mode: relaxation time, cooling rate and annealing temperature. O.V. Mazurin, in his paper [1], suggested the method of calculation of stresses for soldered joints from glass and metals. In most cases, this method is used for a quarter century chemists and technologists to determine the residual stresses not only for soldered joints from glass and metals, but in amorphous coatings on metallic substrates [2, 3]. The simplicity of this method, due to a number rather crude approximations, which in some cases gives the corresponding calculation with experiment, while others include estimates for residual stresses in the coating or group of existing the soldered joints, however in practice they does not exist or contrary [3]. Since the model was developed for design and control of stress in the compound, the main objective was to assess the level of technological stresses in the glass is depending on the temperature model and difference of coefficient of linear thermal expansion of the glass and metal, to prevent breakage during manufacture. Method Mazurina is used for assessing technology stresses in amorphous coatings, it is warranted due to the small thickness of the coating and the possible presence in the resulting coating dangerous for brittle materials tensile stresses. When forming the laminated composite in which the layers may be of the same order, for example, in glass-and-metal-composite [4], there is a need to monitor the stress-strain state not only glass, but also metal. Furthermore, the welding glass and metal diffusion zone may be present, which, as shown in [5], also affects the stress-strain state in the composite. The object of this work is to develop a more rigorous model allows to analyze the technological stresses in junction glass with metal, taking into account the relaxation processes in the glass at certain stages of the process.

The problem of deformation of a long cylinder composed of two different materials under the influence of unsteady temperature field in plane strain and axial symmetry Fig.1. For determining the thickness of the cylinder by welding, carried out in an induction furnace is not difficult to show that the temperature is the same across the thickness of the cylinder and substantially reflects the thermal conditions inside the furnace. Then all the unknowns functions of deformation, strain and stress depends on two variables, r - radius and t -time and as a result of the assumptions made of them remain u_r, e_{rr}, $e_{\phi\phi}$, σ_{rr}, $\sigma_{\phi\phi}$, σ_{zz}.

For the inner cylinder 0<r $\leq r_1$ defining relations written in the framework of linear viscoelasticity theory, considering the absence of volume relaxation in the glass, then

$$S_{\mathrm{ij}}(r,t) = 2\mu_{\mathrm{g}}\Big(\epsilon_{\mathrm{ij}}(r,t) - \int\limits_0^t R(\eta(t,\tau))\epsilon_{\mathrm{ij}}(r,t)d\tau\Big) \tag{1}$$

here S_{ij}=σ_{ij}-$\sigma\delta_{ij}$ - stress deviator, ϵ_{ij}=e_{ij}-$\frac{1}{3}$eδ_{ij} - strain deviator, σ=$\frac{1}{3}\sigma_{kk}$ - average stress,

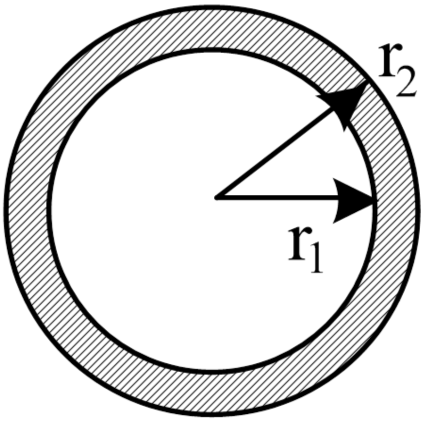

Figure 1: Geometry of the composite: 1-glass (0<r $\leq r_1$); 2-metal (r_1<r $\leq r_2$)

e=e_{kk} - relative volume change, μ_g - instantaneous shear modulus of glass, K_g - instantaneous modulus of volume deformation, R($\eta(t,\tau)$) - core relaxation characterizes the rheological properties of glass, $\theta(r,t)$=$e_{kk}(r,t)$-3$\alpha_g\Delta T(t)$, α_g - coefficient of linear thermal expansion of the glass.

For the outer cylinder r_1<r $\leq r_2$constitutive equations written in the framework of the Duhamel-Neumann with appropriate mechanical characteristics for metal μ_m,K_m,α_m.

$$\sigma_{ij}(r,t) = 2\mu_m e_{ij}(r,t) + (3\lambda_m e(r,t) - 3K_m\alpha_m\Delta T(t))\delta_{ij} \tag{2}$$

here λ_m - lame parameters for metal.

Cauchy relations e_{rr}=$\frac{\partial u_r}{\partial r}$ and e_{rr}=$\frac{u_r}{r}$ in (1) и (2), rewrite the equation of equilibrium

$$\frac{\partial\sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\phi}{r} = 0$$

in movements the first and second layer separately

$$(K_g+\frac{4}{3})\mu_g)(\frac{\partial^2 u_r}{\partial r^2}+\frac{1}{r}\frac{\partial u_r}{\partial r}-\frac{1}{r^2}u_r)-\frac{4}{3}\mu_g\int\limits_0^t R(\eta(t,\tau))(\frac{\partial^2 u_r}{\partial r^2}+\frac{1}{r}\frac{\partial u_r}{\partial r}-\frac{1}{r^2}u_r)d\tau = 0, 0 < r \leq r_1$$

$$\frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} - \frac{1}{r^2}u_r) = 0, r_1 < r \leq r_2$$

Given the limitations movement in $x \to 0$ solutions take the form:

$$u_r(r,t) = C_1(t)r, 0 < r \leq r_1$$

$$u_r(r,t) = C_2(t)r + C_3(t)\frac{1}{r}, r_1 < r \leq r_2$$

Conditions on junction of layers consider by type ideal contact and conditions for the absence of external pressure are set on outer surface of metal layer:

$$\sigma_{rr}(r_1 - 0,t) = \sigma_{rr}(r_1 + 0,t)$$

$$u_r(r_1 - 0,t) = u_r(r_1 + 0,t)$$

$$\sigma_{rr}(r_2,t) = 0$$

obtain a system with respect to unknown of integration $C_1(t)$, $C_2(t)$ and $C_3(t)$ allowing that have:

$$C_2(t) = \frac{1}{r_1^2\mu_m + r_2^2(\mu_m+\lambda_m)}\left(r_1^2\mu_m C_1(t) + \frac{3}{2}r_2^2 K_m\alpha_m\Delta T\right)$$

$$C_3(t) = \frac{1}{r_1^2\mu_m + r_2^2(\mu_m+\lambda_m)}\left(r_1^2 r_2^2(\mu_m+\lambda_m)C_1(t) - \frac{3}{2}r_1^2 r_2^2 K_m\alpha_m\Delta T\right)$$

The unknown constant of integration $C_1(t)$ have Volterra integral equation of the second kind, which can be solved, for example, the method of successive approximations [7]:

$$D_1C_1(t) + D_2\int_0^t R(\eta(t,\tau))C_1(\tau)d\tau + D_3 = 0$$

here

$$D_1 = \frac{2}{3}\mu_g + 2K_g + \frac{2\mu_m(r_2^2 - r_1^2)(\mu_m+\lambda_m)}{r_1^2\mu_m + r_2^2(\mu_m+\lambda_m)}$$

$$D_2 = -\frac{2}{3}\mu_g$$

$$D_3 = 3(K_g\alpha_g - K_m\alpha_m)\Delta T - \frac{3r_2^2(2\mu_m+\lambda_m)K_m\alpha_m\Delta T}{r_1^2\mu_m + r_2^2(\mu_m+\lambda_m)}$$

Processes for mechanical and structural relaxation in glasses can be described by using the function [6]:

$$R(t) = e^{-\left(\frac{\xi(t)}{t_g}\right)^\beta}$$

here t_g - relaxation time, β - empirical constant for nonisothermal process when the temperature depends strongly on the time, the reduced time is introduced $\xi(t) = \int_\tau^t \frac{\eta_0}{\eta(T)}dt'$, η_0 - viscosity coefficient comparison, η - the dynamic viscosity coefficient, which according to equation Tamman -Fulcher can be written in the form:

$$\ln\eta = A + \frac{B}{T - T_0}$$

here A, B and T_0 - constant for a given composition of glasses, T- temperature. Then the core relaxation takes the form:

$$R(t,\tau) = e^{-\left(\frac{1}{\tau_g}\int_\tau^t \frac{\eta_0}{A+Bt'}dt'\right)^\beta} = e^{-\frac{1}{\tau_g^\beta}\left(\frac{\eta_0}{B}\ln\left|\frac{A+Bt}{A+B\tau}\right|\right)^\beta}$$

According to laboratory physical and chemical properties of glass for window glass $\tau_g = 0,65 \pm 0,05$. Value β for most industrial glass varies in the same range (maximum value β while that for industrial multicomponent glass is 0,8). In Fig.2 shows a graph of change the temperature and viscosity of the time, on the whole temperature range of welding. The calculation results are the average values of stress in Fig.3 are presented for glass-to-metal junctions with two different ratios of the coefficients linear thermal expansion. The graphs of Fig.3 show the obtained analytical dependence of the stresses on the mechanical parameters of materials under the action of non-stationary temperature fields allow you to control the technological stress not only during annealing, but also for heating, welding and cooling to the annealing temperature.

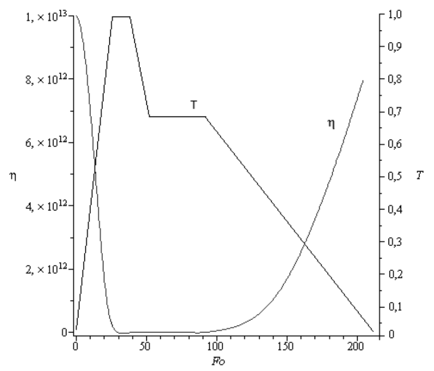

Figure 2: Graph of changes in temperature and viscosity of the time

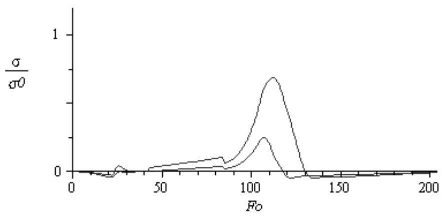

Figure 3: Results of calculations average voltage

References

[1] Mazurin O.V. Annealing of soldered joints from glass and metals – L.: Energy, 1980. – 140 pages.

[2] Gonchukova N.O. Calculation of stresses in the plazmenno sprayed coatings of metal amorphous//Glass Physics and Chemistry .–2003. – T 29, №3.- P. 435-441.

[3] Mazurin O.V. , Lebedeva R.B., Startcev Y. K. Method of calculation of stresses in soldered joints from glass and metals //Glass Physics and Chemistry .–1980. – T 6, №2.- P. 190-194.

[4] Lyubimova O.N.,Pestov, Kayak G.L., Gridasova E.A. Method of making glass-and-metal-composite. Patent №2428388 RU.-10.09.2011.-Bul №25

[5] Gridasova E.A. Increase structural behaviour of glass as a result of metallization by a method of diffusion welding. 2013. FEFU, 2013. – 134 pages.

[6] Bartenev G. M., Sanditov D. S. Relaxation processes in the glass-forming systems. – Novosibirsk: Science, 1986. – 239 pages.

[7] Krasnov M.L., Kiselev A.I., Makarenko G.I. Integral equations - M.: Editorial URSS, 2003. - 192 pages.