THE THERMOMECHANICAL PROCESSES IN METAL-GLASS COATINGS OF VESSEL CONSTRUCTIONS AND FLOATING FACILITIES FOR RADIOACTIVE CARGO

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Abstract: The article describes the thermomechanical processes that occur under the influence of thermal effects in the structure of new metal-glass coatings of constructions of biological protection of vessels and floating facilities, which are intended for transportation and storage of radioactive cargo with a capacity of residual energy 2 ... 20 kW. Two new mathematical models, which describe thermomechanical processes in new types of irradiated coatings at the micro- and nanoscale has been developed. Those are thermo-mechanical model of behavior of protective metal-glass coating under the influence of thermal effects up to 500℃ and the model of surface hardening of the composite layer by the diffusion flux of ionizing radiation. Mathematical models are tested on metal-glass materials and coatings with steel and aluminum matrix filled with hollow glass microspheres, powders of sodium silicate and leaded glass. The developed models take into account the structural characteristics of the materials and coatings, allow to evaluate and predict their strength properties.
Keywords: metal-glass materials and coatings, microspheres, ionizing radiation, thermo-mechanical processes, thermal stresses, thermal effects, surface hardening.

Introduction

In the process of transportation and storage of radioactive substances, most of them continue being sources of ionizing radiation and cause changes in the structure and properties of the construction materials. Constructions of biological protection are the peculiarity of vessels and floating structures; they restrict the cargo area from the harmful influence of radiation and temperature changes (Baryshnikov, 2010; Luna, 2004; Vieru, 2012). Composite coatings with enhanced absorbing and attenuating ability, which are applied to the irradiated surface, are used for additional protection of the structures (Was, 2007). The diffusive radiation fluxes have not only the energy effect on the composite layer, but they also provide multiple temperature loads, which can lead to a loss of mechanical properties. The effectiveness of the protection is determined by their composition, structure and properties. Composites filled with carbon, glass and metalized microspheres are used in modern technologies (An, 2012; Was, 2007; Zhang, 2005). Application of polymer matrix, which is based on epoxy, phenol-formaldehyde, polymer resins, synthetic rubber, vulcanized rubber, does not increase the structural mass. However, the impact of the thermal effects can lead to the polymer destruction and to destruction of the material on the metal-glass surface (Ostrik, 2003). The articles, which are devoted to the thermomechanical processes in polymeric composite materials, consider their use for the production of aircrafts, where they are exposed to intense fluxes of cosmic X-ray radiation (Chittineni, 2010; Ostrik, 2003). In such cases the absorption of energy is accompanied by the formation of a shock wave in the protective layer of the material. Due to the high absorbency, polymeric composite materials like spheroplastic transform absorbed radiation energy into pressure, and they are not destroyed under repeated exposure. The effective Gruneisen coefficient is a thermodynamic parameter, which is the ratio of the thermal pressure in the unit cell to the thermal energy density; it is taken as the criteria in works (Efremov, 2010; Ostrik, 2003). However, taking into account other operating conditions of constructions of biological protection of vessels and floating facilities for transportation and storage of radioactive cargo, considered in articles (Efremov, 2010; Ostrik, 2003) models cannot be used for the prediction of strength properties.

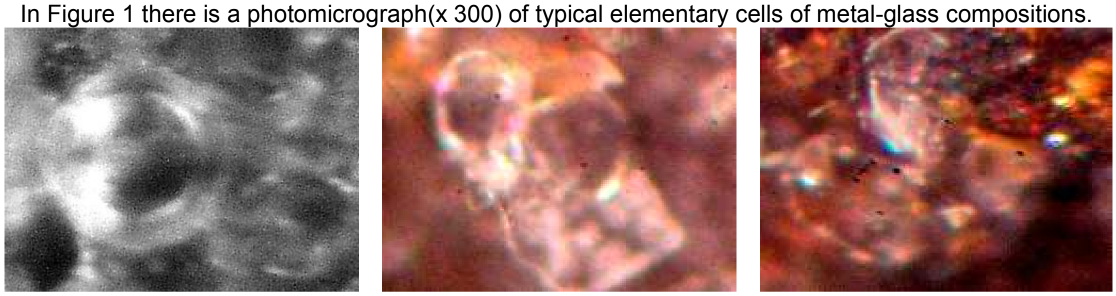
The alternative is composite materials and coatings with metal matrix; hollow glass microspheres, sodium silicated powders and the leaded glass powders are used as fillers (Kazymyrenko, 2013).The coatings can be formed using the electric-arc spraying method or can be manufactured in the form of tiles by the hot pressing method. The regularities and mechanisms of interaction of ionizing radiation are considered in the article by the author (Kazymyrenko, 2013, 2014).The radiation resistance of electric-arc metal-glass coatings based on of Sv-08G2C and Sv-AMg5 has been investigated in work (Kazymyrenko, 2015). Thermomechanical processes of influence of cargo ionizing radiation on materials and coatings has not been investigated yet. Their description requires the creation of new mathematical models, which describe the physical processes during the absorption of radiation. The aim of this work is to develop new models, which will describe the behavior of the protective metal-glass layer of constructions of biological protection of vessels and floating facilities under the irradiation.

Results

Thermomechanical processes are considered on the example of metal-glass electric-arc coatings based on of Sv-08G2C and Sv-AMg5 filled with hollow glass microspheres, sodium silicated and leaded glass powders. Models, proposed in the work, can also be used for prediction of strength properties of other composite materials and coatings with metal matrix and glass inclusions; method of their production is set out in the article (Kazymyrenko, 2013). The development of mathematical models is based on the results of microstructural investigation of metal-glass materials and coatings made by using the method of electronic and optical microscopy; on the results of X-ray structural analysis, which was carried out at the DRON-3 unit; on the measurement results of the microhardness *H*μ of the irradiated coatings, which were defined using PMT-3 microhardness tester at the load of 20g for metallic matrix and 200g for glass inclusions. The method of the unit cell (Ostrik, 2003) has been chosen for description of the mechanisms of deformation of structural elements; it allows to determine the effective mechanical characteristics of structurally heterogeneous material.

The thermomechanical behavior model of the metal-glass protective layer (coating) under the thermal effects

In Figure 1 there is a photomicrograph(x 300) of typical elementary cells of metal-glass compositions.



a b c

Fig. 1. Unit cells of the coatings: a - a hollow glass microsphere surrounded by metal; b - the area of sintered microspheres; c - a frame made of sintered microspheres with metal inside

For the cell *a* temperature stresses occur on the boundary of the metal - glass phase, in cells *b* and *c*–on the surface of the metal – glass phase and between the microspheres; their compound is possible either during the sintering process or as a result of uneven distribution during the spraying. According to the article (Krzhechkovskij, 1976) temperature stresses $\sigma_t$on the surface of metal – glass phase are expressed in formula (1), and on the surface of the unit cell $\sigma_t^{(0)}$–in formula (2)

$$\frac{\sigma_t}{K_m} = \frac{3(\alpha_s \cdot \Delta T - \Delta_m)\cdot(1+2\vartheta_s)}{2\left(\frac{K_m}{K_S}\cdot\vartheta_m + \rho + \vartheta_s\right)} \quad (1)$$

$$\frac{\sigma_t^{(0)}}{K_m} = \frac{9(\alpha_s \Delta T - \Delta_m)\cdot\vartheta_s}{2(\frac{K_m}{K_s}\cdot\vartheta_m + \rho + \vartheta_s)} \quad (2)$$

where α_s –the thermal linear expansion coefficient of the glass of microspheres, , K^{-1}; α_m - the thermal linear expansion coefficient of the matrix material; ϑ_s – the relative volume content of microspheres in the composition of the metal-glass layer; ρ – the density of metal-glass layer; K_m –

the apparent modulus of elasticity of volume compression of the metal matrix; K_s –the apparent modulus of volume compression of hollow microsphere; ΔT – the temperature difference; $\Delta m = \alpha_m \cdot \Delta T$ –linear deformation of the metal matrix.

To simplify the problem, the author puts the following assumptions: the unit cell volume is constant in case of thermal effects; there is no structural phase transformation in the protective layer throughout the process of operation; the value of the relative radial deformations of glass inclusions and the metal matrix material are equal due to the small thickness of the interface.

In formulas (1) and (2) the mechanical specifications represent the strength properties of nonporous materials. In view of the developments in the field of modeling of processes of hydrostatic compression on the closed-porous unit cell (Oshurkova, 2000), author takes into account the value of the porosity of the compositions, which have been defined experimentally using hydrostatic method of weighing.

Consequently, formulas (3) and (4) have been proposed for the determination of the values of the conventional volume compression of the metal matrix K_m and values of the conventional modulus of volumetric compression of a hollow sphere K_s according to porosity and volume content of microspheres.

$$K'_m = \frac{E_m}{\left(\frac{\rho_m(0{,}0026\rho_m+\rho)}{\rho^2} + 0{,}0016\frac{\eta_o\pi(\rho_m-\rho)(1+\nu_m)(2\nu_m^2+\nu_m+5)}{\rho_m\left(\sqrt[3]{\frac{\rho_m}{\rho_m-\rho}}-1\right)^3}\left(1+10\sqrt[3]{\frac{\rho_m}{\rho_m-\rho}}-1\right)^2\right)^2} \tag{3}$$

where E_m - the elastic modulus of the metal matrix material; ρ_m - the metal matrix density; ρ - the density of metal-glass material or coating; η_o - the metal matrix porosity; ν_m - Poisson's ratio of the metal matrix.

$$K_c = \frac{E_{cm}}{\left(\frac{\rho_c(0{,}0026\rho_c+\rho)}{\rho^2} + 0{,}0016\frac{\eta_з\pi(\rho_c-\rho)(1+\nu_c)(2\nu_c^2+\nu_c+5)}{\rho_c\left(\sqrt[3]{\frac{\rho_c}{\rho_c-\rho}}-1\right)^3}\left(1+10\left(\sqrt[3]{\frac{\rho_c}{\rho_c-\rho}}-1\right)^2\right)\right)^2} \quad (4),$$

where E_{cm} - the elastic modulus of glass; ρ_c - the glass density; ρ - the metal-glass protective layer density; $\eta_з$ - closed porosity, enclosed inside of the hollow glass microspheres, which can be equated with the volume content of microspheres in the composite; ν_c - the Poisson's ratio of glass.

The source and the resulting data are presented in Table 1. As an example, Figure 2 shows graphs of temperature stress for coatings with 40% volume content of microspheres. Lines 1 and 3 on the graphs show the theoretical values of thermal stress for nonporous structures; lines 2 and 4 - σ_t considering the porosity of the metal matrix (10 ... 20%) and the porosity enclosed in hollow glass microspheres.

Determination of thermal stress between sintered microspheres (Figure 1 b, c) is reduced to the solution of the problem about the action of forces on the border of the body (in conditions of the stationary heat flow) (Timoshenko, 1975). In case of wall thickness neglecting (≈ 1 mm), thermal stresses can be defined as the tangential using formula (5), which are caused by pressure, which interferes the free expansion of small spherical elements.

$$\sigma_t = \frac{1}{3}\frac{\alpha_* T E a^3}{(1-\nu)r^3} \tag{5}$$

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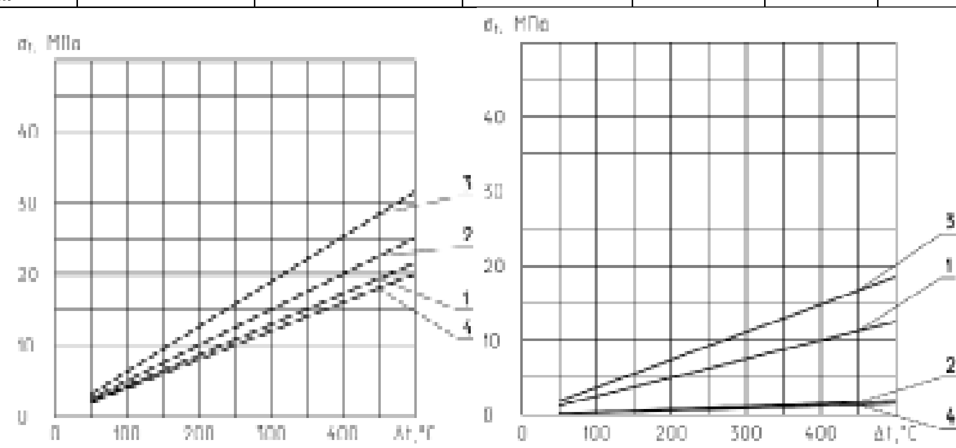
where α_* - the effective thermal coefficient of linear expansion; T - the temperature; E - the modulus of elasticity of glass; ν - the Poisson's ratio of glass; a - the inner radius of the sphere; r - the distance from the center of the sphere.

Table 1

Physical properties and effective mechanical characteristics of metal-glass materials and coatings

The material or coating	The initial data			Effective mechanical characteristics		
	Glass volumetric content, %	Density, kg / m^3	Porosity, %	K_s, GPa	K_m, GPa	α* x 10^6, K^{-1}
Sv-08G2C - glass	40±7	6000…6400	10…20	37,0	173,5	4,0
Cv-AMg5-glass	40±7	1300…1700	10…20	41,72	44,12	5,6
Glass-aluminum composite material	50	1200	20	34	41,25	7,05



a B

Fig. 2. Dependence of the thermal stress on the temperature for electric-arc metal-glass coatings filled with hollow glass microspheres: a - on the basis of Sv-AMg5, b – on the basis of Sv-08G2C

In Figure 3 there is a graph of dependence of the tangential stresses on the temperature, which arises on the boundary between microspheres with an average diameter of 20, 40 and 100 microns. This dependence is typical for composite materials, which have been obtained by sintering method, including aluminum-matrix materials, which have been obtained by hot pressing method with the following isothermal exposure.

The necessary step is to calculate the allowable stresses using formula (6) (Timoshenko, 1975):

$$\sigma_{экв} = \frac{\alpha E T}{1-\nu} \quad (6)$$

where α_* of metal-glass composite materials should be used instead of α in calculations; instead of the elastic modulus should be used E – $K_m^{'}$; ν -the Poisson's ratio of the metal matrix; T - the operational temperature.

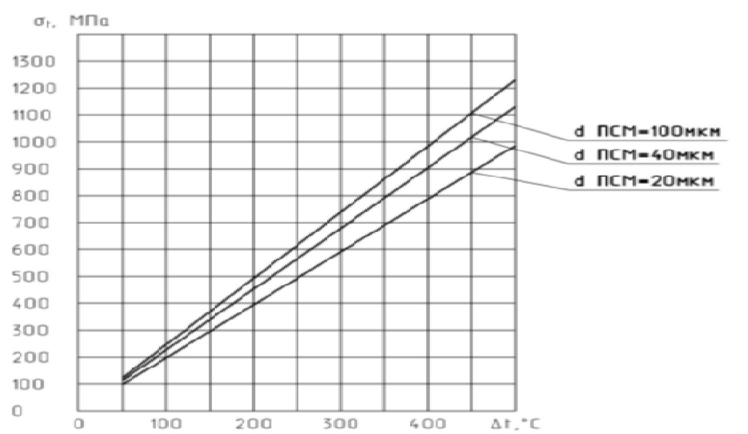


Fig. 3. The dependence of tangential stresses on the temperature on the boundary between sintered microspheres

The fields of allowable stresses, which are generated on the surface of the metal – glass phase in conditions of thermal effects and temperature changes up to 500° C, are represented in logarithmic coordinates in Figure 4.

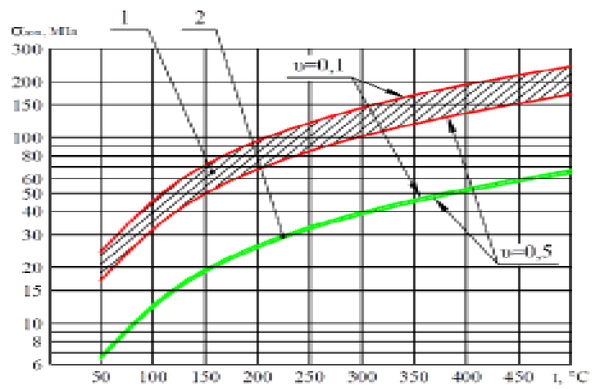


Fig. 4. Fields of allowable stresses on the surface of the metal – glass phase:
1 – aluminum-glass compositions; 2 - steel - glass composite coatings

The results has shown that when the temperature increases at the borders of the allocated microvolumes, thermal stresses increase too, but they do not exceed the allowable values. Theoretical values, which have been obtained for nonporous structures, are almost 2 times higher than the thermal stresses of porous materials and coatings; the effect of the composition of glass inclusions is insignificant. The maximum thermal stresses are generated in the aluminum-glass compositions on the surface of the metal - glass phase. The areas of sintered microspheres create a dangerous state of stress because thermal stresses are 3-4 times higher than the allowable; when the diameter of microspheres increases, thermal stresses increase too. However, microstructural researches have shown that the existence of areas of sintered microspheres has a local character and is not regular.

The model of surface hardening of the composite layer by the diffusion flux of ionizing radiation

As a result of researches (Kazymyrenko, 2015) the author has established the effect of surface hardening of metal-glass electric-arc coatings under the influence of the diffusion flux γ-rays from Co^{60}. However, the mechanisms and laws of hardening are still unexplored. The basis of the modeling is the hypothesis about the formation of nanostructured elements in metals under the influence of thermal effects. The microhardness of the phase components has been selected as the criterion of hardening; the results of microhardness measurements $N\mu_{20}$ of metal matrix section depth are shown in Figure 5.

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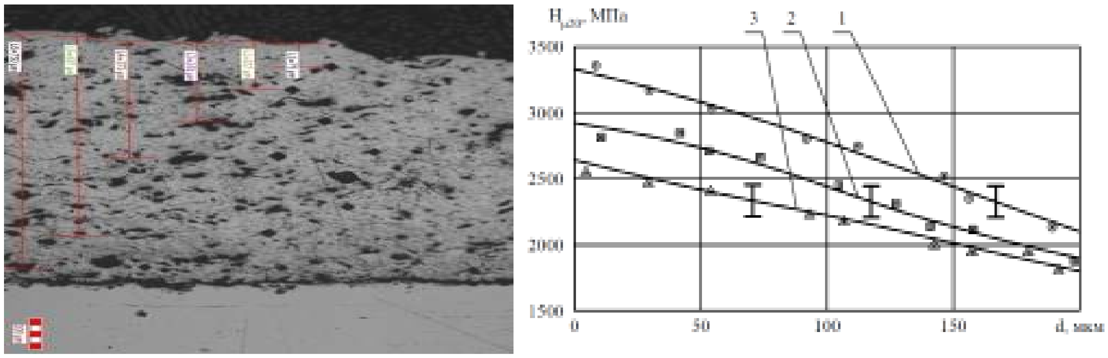

a b

Fig. 5. Distribution of the microhardness of phase components of the coating over the section depth based on Sv-08G2C: a - the microphotograph of measurements; b - filled with: 1 - hollow glass microspheres; 2 - sodium silicated glass powder; 3 - leaded glass powder

Physical formulation of the problem is the formation of temperature fields under the influence of thermal effects; during the absorption of the quantity of heat by the coating thickness in the areas of maximum thermal stress, substructural elements are generated - details of the structure of the material with sufficiently small linear dimensions compared to the resolution of the microscope.

We apply the criterion equation (7), after we conventionally divided 2 mm coating thickness on monolayers with a thickness of one glass particle (Was, 2007).

$$q = \frac{\lambda}{\delta}(T_0 - T) \tag{7}$$

where q - specific quantity of heat, expressed as the ratio of the power of residual energy release to the mass of metal-glass protective layer $\frac{Q}{m}$; λ - coefficient of thermal conduction of the metal-glass coating.

The values of the power of residual energy release of radioactive cargo: 2 kW, 8 kW and 20 kW were used in calculations as energy parameters. The coefficients of thermal conduction of coatings on the basis of Sv-08G2C constitute 18 ... 25 W / (m · K); the coefficients of coatings on the basis of Sv-AMg5and aluminum-matrix materials - 65 ... 80 W / (m·K). Surface hardening effect is the most evident for coatings filled with hollow glass microspheres; this fact can be explained by low thermal conduction of those coatings compared to solid glass particles. In case of equal quantity of absorbed radiation dose, the basic quantity of heat is absorbed by metal matrix because of low thermal conduction of hollow glass microspheres. The calculations have shown that on average one square meter of monolayer of Sv-08G2C coating with microspheres absorbs 3.2 kJ of heat; from the composition of Sv-AMg5 with microspheres - 5.5 kJ.

Discussion

The hypothesis of the formation of substructural elements, which has formed the basis of the modeling, is indirectly confirmed by the results of numerical processing of radiographs of coatings, which were taken from the samples before and after irradiation. Sizes of areas of coherent scattering of X-ray radiation have been taken as a structural criterion. It has been established that the effect of surface hardening of metal-glass coatings under the influence of thermal effects, which were caused by the diffusion fluxes of ionizing radiation, is accompanied by the formation of substructural elements with an average size of areas of coherent scattering 80 ... 110 nm. This effect is comparable to the mechanism of hardness increase under the influence of recrystallization heat treatment at a temperature of 490..500C and can be observed during irradiation of the protective layer of the composite constructions of vessels and floating facilities for transportation and storage of radioactive cargo - sources of γ-radiation: pieces of equipment, uniforms and so on.

New mathematical models, that can be used for evaluation and prediction of the mechanical properties of composite constructions of vessels and floating facilities, which are intended for transportation and storage of radioactive cargo with the residual heat generation capacity in the range of 2 ... 20 kW, have been developed. The developed models describe thermo-mechanical processes in the structure of the metal-glass materials and coatings under the influence of thermal effects in the temperature range up to 500^{o} C at the micro and nano levels.

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