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托兰斯，加利福尼亚州90503
美国

Contact us:
Tel.: +1.42.42.71.41.11 E-mail: mail@advancedscience.org www.advancedscience.org

THE EFFECTIVE MECHANICAL PROPERTIES OF METAL-GLASS MATERIALS AND COATINGS

Yuliya Kazymyrenko
Admiral Makarov National University of Shipbuilding, Mykolaiv, Ukraine
u.a.kazimirenko@gmail.com

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Abstract: The article is devoted to the problems of strength of new metal-glass materials and coatings, which were produced by hot-pressing method and electric-arc spraying method. Composite materials and coatings with steel and aluminum matrix filled with hollow glass microspheres, powders of sodium silicate and leaded glass are perspective for the production of protective constructions of vessels and floating facilities, aircrafts, underwater vehicle. The technique has been developed, which is in contrast to existing techniques, takes into account structural features of compositions, allows identifying and predicting the mechanical properties of structurally inhomogeneous composite materials without expensive experimental studies: conventional modulus of volumetric compression of the metal matrix, conventional compression modulus of glass inclusions, the effective temperature coefficient of linear expansion, the effective shear modulus. The analytical description, which establishes the influence of porosity, shape and volume content of glass inclusions on the effective mechanical characteristics, has been obtained. The results can be used for prediction of thermomechanical characteristics and stress-strain state of composite constructions, which operate under temperature changes, full hydrostatic compression, heat and ionizing radiation. Prospects for introduction are associated with shipbuilding, energy and engineering industries.
Keywords: metal-glass materials, coatings, hollow glass microspheres, glass inclusions, effective mechanical properties.

Introduction

Modern technologies of creation of aircrafts, specialized vessels and underwater technical facilities envisage the use of new types of composite materials and coatings such as "syntactic": polymeric compositions filled with hollow glass microspheres (Chittineni, 2010). New technologies of their manufacturing are associated with increasing of the ability to absorb heat and ionizing radiation (Wawryk, 1988; Ostrik, 2003). To increase the reflectivity, microspheres are exposed to metallization (Zhang, 2005); that creates the effect of reflection of rays in the polymer matrix. However, having a low thermal conductivity, polymer syntactics are being destroyed at high temperatures under the influence of accumulated quantity of heat or destruction processes. The new kind of materials and coatings, which provides comprehensive protection for constructions of technical facilities from the influence of heat and ionizing radiation, are metal-glass compositions with steel and aluminum matrix (Kazymyrenko, 2013, 2014). These are composite materials produced by hot-pressing method, followed by isothermal exposure of aluminum powder mixture with hollow glass microspheres, and electric-arc coatings based on welding wires Sv-08G2S and Sv-AMG-5 filled with hollow glass microspheres, powders of sodium silicate and leaded glass (Kazymyrenko, 2015). Metal-glass composite materials and coatings are structurally inhomogeneous; the porosity of the metal matrix, depending on the technology, can reach 25%. The matrix and the filler have a significant difference in the values of temperature coefficient of linear expansion; that can lead to destruction in conditions of uneven heating and temperature changes. Determination of strength properties (elastic modulus, shear modulus, Poisson's ratio, and linear thermal expansion coefficient) of porous compositions, using experimental techniques, is difficult. It is advisable to use computational and experimental techniques, where effective mechanical characteristics are introduced as the criteria. The definition of effective constants of elasticity is solved in works (Landau, 2007) on simple models for the first time. In classic works (Vanin, 1985; Librescu, 2006, Tashkinov, 2010) the analytical description of the mechanical properties is considered using the theory of effective elastic modules, methods of regulation and harmonization, successive approximations to stochastic boundary value problem. The structural features such as volume content, size and shape of inclusions, the surface of the phase boundary, structure of the matrix, influence on the processes of deformation and destruction of the composite materials and coatings directly. The closest analogues are works of Vanin (1985), Korolev

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(1971), Krzhechkovskyi (1976), which were developed for the prediction of strength indicators of polymer syntactics. However, the existing methods and models cannot be used to determine the mechanical properties of new compositions due to their structural features. The analytical dependence, which was given in classical works in the field of micromechanics and radiation material science (Landau, 2007; Librescu, 2006; Was, 2007), does not allow us to describe the mechanical properties of highly porous materials under elevated temperature conditions and ionizing radiation.

The prediction of the strength characteristics of new compositions, in accordance with their structural features, represents the scientific interest and requires the development and approbation of new calculation techniques.

Results

The development of new technique is based on a model of metal-glass composite materials and coatings (Fig. 1), which has been drawn up on the basis of the researches of features of their structure (Kazymyrenko, 2014).

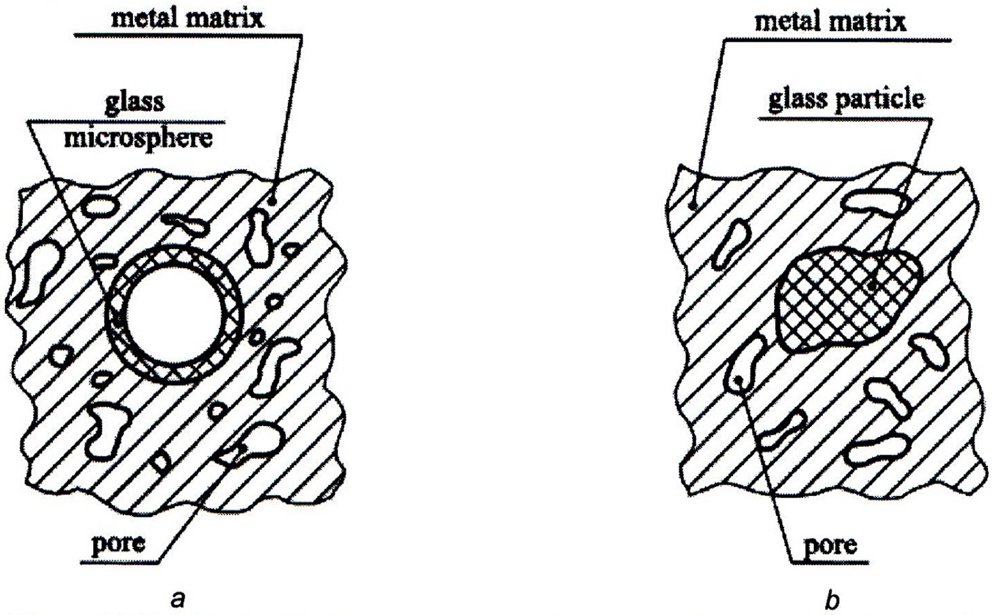

Fig. 1. The model of the cell of metal-glass materials and coatings: a - filled with hollow glass microspheres; b – filled with solid glass particles

The density of the samples with different volumetric content of glass 10 ... 50% has been determined experimentally as a result of hydrostatic weighing. Open porosity has been calculated by volume filled with distilled water. The following assumptions have been introduced in work: the strength properties do not depend on the size of the glass inclusions; the calculations do not take into account the size of the transition zone; volume content of hollow glass microspheres is equal to the volume of porosity, which is enclosed in microspheres; temperature coefficient of linear expansion of the materials and coatings does not depend on the temperature; the Poisson's ratio of the metal-glass composition is equal to the Poisson's ratio of metal matrix. The following notations have been introduced in this work:

ρ- the density of metal-glass material and coating;

α^*- the effective temperature coefficient of linear expansion of the composite material or coating;

ρ_m, ρ_c – the density of the metal of the matrix and the glass density;

ρ_s – the density of microspheres;

E_m, E_{cm} – the elastic modules of the metal matrix material and glass;

ν_m, ν_c – the Poisson's ratio of the metal matrix and glass;

α_m, α_s –the temperature coefficients of linear expansion of the matrix materials and glass;

ϑ_m, ϑ_s – the volume content of the metal and glass;

η_o – the porosity of the metal matrix;

$\eta_з$ – the closed porosity inside of hollow glass microspheres;

K'_m, K_c - the volumetric modules of elasticity of metal matrix and glass inclusions;

K_m, K_s -the conventional modulus of volumetric compression of the metal matrix and glass sphere;

G^* – the conventional shear modulus of composite materials and coatings

The results are presented as the effective mechanical characteristics, which are expressed for idealized nonporous structures and compositions with the porosity of 10 ... 20%.

The conventional modulus of volumetric compression of the metal matrix for nonporous materials and coatings can be expressed as

$$K_m = \frac{K'_m \cdot \vartheta_m}{1+\rho(1-\vartheta_m)} \tag{1}$$

where

$$K'_m = \frac{E_m}{3(1-2\nu_m)} \tag{2}$$

Taking into account the porosity, the expression for finding the conventional modulus of volumetric compression of the metal matrix takes the form:

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

Figure 2 graphically illustrates the influence of the porosity and volume content of microspheres on the conventional modulus of volumetric compression of the metal matrix.

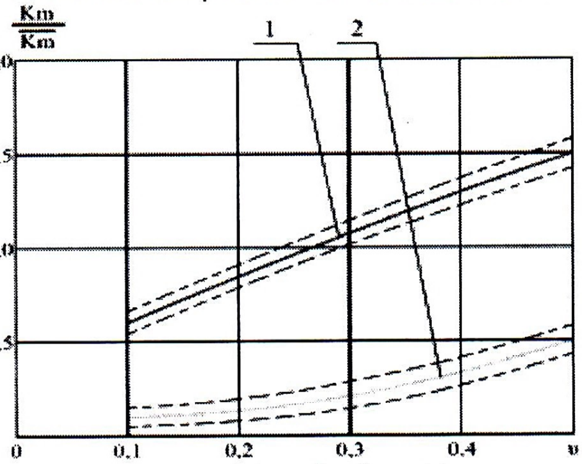

Fig. 2. The calculated values of the relative modulus of volumetric compression of the metal matrix $K_m/\overline{K}_m$: 1 - for compositions with steel matrix; 2 - for compositions with aluminum matrix

The volumetric modulus of elasticity of volume compression of a hollow sphere, taking into account the density of compositions with different volume content of the microspheres, is expressed as:

$$K_s = \frac{K_{cm} \cdot \psi}{1+\rho(1-\psi)} \tag{4}$$

$$\psi = \frac{\rho_s}{\rho_c} \tag{5}$$

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It is taken into account that with the increasing of the volume content of the hollow glass microspheres in compositions, the density of materials and coatings is reduced.

The volumetric modulus of elasticity of hollow glass microspheres in the content of compositions, with enclosed in them porosity, can be calculated as:

$$K_c = \frac{E_{cm}}{\left(\frac{\rho_c(0{,}0026\rho_c + \rho)}{\rho^2} + 0{,}0016\frac{\eta_з\pi(\rho_c - \rho)(1+\nu_c)(2\nu_c^2+\nu_c+5)}{\rho_c\left(\sqrt[3]{\frac{\rho_c}{\rho_c-\rho}}-1\right)^3}\left(1+10\left(\sqrt[3]{\frac{\rho_c}{\rho_c-\rho}}-1\right)^2\right)^2 \right)} \qquad (6)$$

Let us express the assumption about the approximation of the form of solid glass inclusions to a spherical form. Then, for metal-glass coatings filled with solid glass particles, in formula (5), we accept $\rho_s = \rho_c$, then $\psi = 1$.

Taking into account the mechanical properties of the matrix and glass, the effective temperature coefficient of linear expansion α^* is expressed as:

$$\alpha^* = \frac{(\alpha_s - \alpha_m)\cdot \vartheta_s(1+\rho)}{\frac{K_m}{K_s}(1-\vartheta_s)+\rho+\vartheta_s} + \alpha_m \qquad (7)$$

The effective shear modulus G * is possible to determine on the basis of Hashin-Shtrikman assessment; for two-phase compositions it is expressed as (Librescu, 2006)

$$G^* = \frac{3}{4}\frac{K_m}{\rho} \qquad (8)$$

Table 1

The effective mechanical characteristics

Metal-glass compositions	K_s, GPa	K_m, GPa	$\alpha^* \times 10^6$, K^{-1}	G*, MPa
Metal-glass materials (aluminum dust+microspheres 10…50 % volum.)	30,0…34,0	37,45…41,25	1,4…7,05	15,25…15,74
Metal-glass materials (aluminum powder+microspheres 10…50 % volum.)	31,45…34,5	38,15…41,5	1,43…6,4	16,1…16,5
Sv-AMg5 – hollow glass microspheres (10…40 % volum.)	31,66…37,3	39,65…44,12	1,45…8,78	17,05…19,00
Sv-08G2S – hollow glass microspheres (10…40 % volum.)	32,0…37,0	130,0…173,5	0,7…4,0	15,5…21,75
Sv-AMg5 – sodium-silicated glass (10…40 % volum.)	41,72	40,0…41,15	1,4…5,6	17,5…18,0
Sv-AMg5 – leaded glass (10…40 % volum.)	41,72.	40,25…45,65	1,1…4,43	17,65…18,5
Sv-08G2S – sodium-silicated glass (10…40 % volum.)	41,72	120,0…155,0	0,55…2,7	12,8…16,7
Sv-08G2S – leaded glass (10…40 % volum.)	41,72	120…172	0,45…2,4	12,82…21,30

The values of apparent density have been taken into account in calculations: for steel - microspheres coatings 6400 ... 5990 kg / m3, for aluminum - microspheres coatings 1000 ... 1700 kg / m3, for steel - glass coatings 6000 ... 7255 kg / m3, for aluminum-glass coatings 1700 ... 1900 kg /

m3. The porosity values have been taken in the range of 10 ... 25%. The calculation results are summarized in Table 1.

The influence of the structural characteristics has been detected: the influence of porosity and volume content of the glass filler on the effective mechanical properties of metal-glass materials and coatings:

- effective mechanical characteristics increase when the volume content of the glass components in the range of 10 ... 50% in metal-glass compositions increases;
- the presence of the porosity in 1.5 ... 2 times reduces the apparent modulus of the metal matrix K_m;
- conventional modulus of volumetric compression K_m of electric-arc coatings based on Sv-08G2S is 3 times higher than K_m of coatings based on Sv-AMg5 and K_m of hot-pressed aluminum-matrix compositions; herewith the values of the effective temperature coefficient of linear expansion α^* of steel compositions are 2 times lower;
- the kind of glass fillers insignificantly influences on the effective mechanical characteristics of metal-glass materials and coatings.

Discussion

The results can be used to predict the thermomechanical properties and the stress-strain state of the constructions.

The analytical description of the thermomechanical properties for new metal-glass materials and coatings has been done; the description is based on a model approach to the structure, which was formed by hot-pressing method and by method of electric-arc spraying; that allows to identify and predict the stress-strain state in conditions of short-term temperature loads of up to 500^o C.

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