Research Article

Experimental and Theoretical Study of Mechanical Properties of Matrix Composite Materials

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Article History Received: 10 January 2021; Revised: 12 February 2021; Accepted: 27 March 2021; Published online: 28 April 2021

Abstract : In this work, an experimental and theoretical study of the mechanical characteristics of the matrix composite of the Al-Mg-Cu system is carried out. A prediction is given for the elastic moduli and ultimate strength of the composite at a temperature of 20–350 C, taking into account the different volumes of reinforcing fibers, threshold defects, and fiber orientation. The results obtained made it possible to more reliably predict the properties of composites based on aluminum alloys, reinforced with aluminum oxide fibers.

Keywords: Matrix composite materials, strength, deformation, stress.

1. Introduction

In composites, an important element is the matrix, which ensures the solidity of the composite, fixes the shape of the product and the relative position of the reinforcing fibers, distributes the acting stresses over the volume of the material, providing a uniform load on the fibers and its redistribution when part of the fibers breaks. The matrix material determines the method of manufacturing products from composites, the possibility of performing structures of specified dimensions and shape, as well as the parameters of technological processes, etc. [1-5].

Thus, the requirements for matrixes can be divided into operational and technological. The first include requirements related to the mechanical and physicochemical properties of the matrix material, which ensure the performance of the composite under the action of various operational factors [6-11]. The mechanical properties of the matrix should ensure the joint operation of the reinforcing fibers under various types of loads [12-27]. The strength characteristics of the matrix material are decisive under shear loads, loading of the composite in directions other than the orientation of the fibers, and also under cyclic loading. The nature of the matrix determines the level of working temperatures of the composite, the nature of the change in properties when exposed to atmospheric, mechanic and other factors [28-39]. With an increase in temperature, the strength and elastic characteristics of matrix materials, as well as the strength of their connections with many types of fibers, decrease, the matrix material also characterizes the resistance of the composite to the external environment, chemical resistance, partially thermophysical, electrical and other properties [40-48].

2. Experimental studies of the mechanical characteristics of matrix composites

The composite is made on the basis of matrixes of the Al-Mg-Cu system (containing Mg 1,2 – 1,8, Cu 3,8 – 4,9).

The blanks for obtaining experimental samples are 3 mm thick plates made of layers reinforced with unidirectional fibers of Nextel 610 aluminum oxide. Diameter of aluminum oxide fibers: 11-14 microns. Volume content of reinforcing inclusions: long fibers 55-60% vol.

When fabricated, interfacial layers are formed in the matrix around the fibers, consisting of spinels $MgAl_2O_4$ and/or $CuAl_2O_4$, depending on the composition of the matrix. As a first approximation, we will assume that the properties of the interfacial layer are determined by the properties of the $MgAl_2O_4$ spinel (the properties of the $CuAl_2O_4$ spinel are practically unknown in the literature).

The properties of matrixes and continuous fibers of aluminum oxide, and interfacial layers from spinel are presented in Table 1. The approximation of the stress-strain diagram for the Al-Mg-Cu alloy is shown in Fig. 1 and 2.

Table 1. Properties of aluminum matrices and reinforcing fibers.

Properties\Material			Al-Mg-Cu	Al_2O_3	$MgAl_2O_4$ (spinel)
Properties	Designation, unit of measurement	T °C			

Elastic modulus	E, GPa	20	72	380	440 (250)
		350	48	380	440
Density	ρ, g/cm^3	20	2,77	3,9	3,61
Poisson's ratio	ν	20	0,33	0,22	0,3 (0,26)
		350	0,33	0,22	0,3
CTE	α, 1/K*10^{-6}	20	22,9	8	5,9 (8,4)
		350	26,5	8	5,9
Yield point / tensile strength	$\sigma_в$, MPa	20	400/470	2550	130
		350	10	2250	-
Yield point / compressive strength	$\sigma_{вcж}$, MPa	20	630/650	3100	590
		350	15	3000	
Limiting deformations, %		20	15	<1	<1
		350		<1	<1

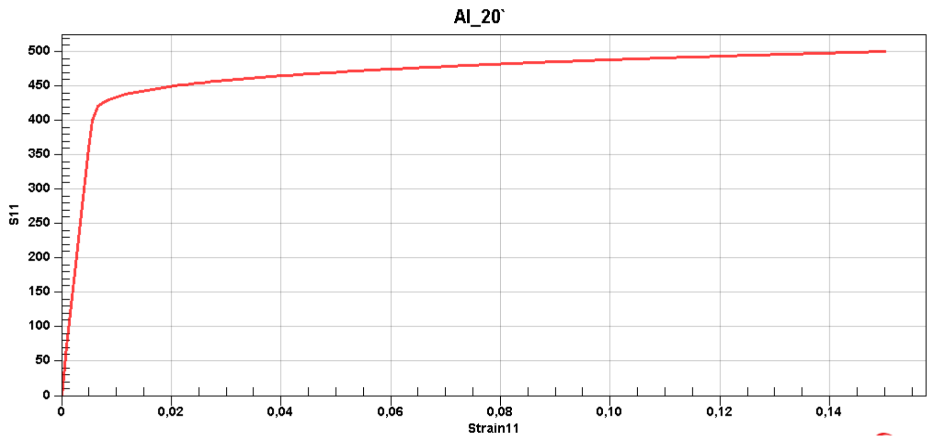

Fig. 1. Deformation-stress diagram of the Al-Mg-Cu alloy at T = 20 C, used for calculations.

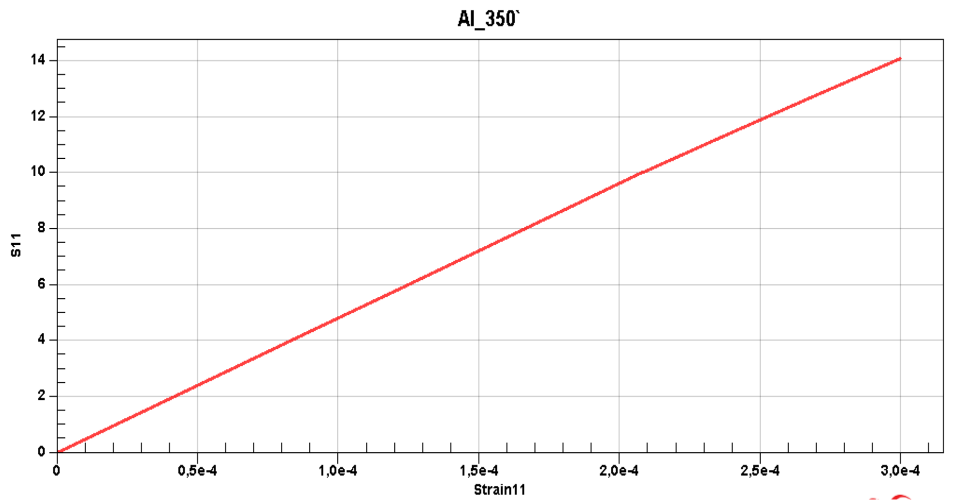

Fig. 2. Deformation-stress diagram of the Al-Mg-Cu alloy at T = 350 C, used for calculations.

The sequence of technological operations when obtaining samples of composite materials is as follows. A preform is prepared from unidirectional fiber bundles of aluminum oxide. Vacuum-compression impregnation is carried out at a temperature of 720-750 C, the total impregnation time is approximately 1-3 minutes, at a pressure of 30-40 atm. In this case, an interfacial layer of spinel forms around the fibers of aluminum oxide. A sample is removed from the melt at a temperature of 650 C.

3. Description of calculation models

All quantities are determined using homogenization by average values based on the Eshelby semi-analytical method and analytical description of the composite material as a function of its microstructural morphology, i.e. forms of inclusions, orientation, volume/mass content and behavior of each phase at the micro level. Homogenization is carried out by the Mori-Tanaka or Double inclusion method.

From the point of view of mechanics of a continuous medium, the problem of homogenization can be represented: at the macroscale, at each point of the material, if the macrostrains are known, it is necessary to calculate the macrostresses and vice versa. From the point of view of linear elasticity, the problem can be presented in a simple form: determination of macro-rigidity $\langle\sigma\rangle = \bar{C} : \langle\varepsilon\rangle$.

In linear elasticity, there is a fundamental problem with homogenization: find an equivalent homogeneous material that has the same effective macro-rigidity as a real heterogeneous material, under the same boundary conditions. There are several methods for solving this problem: asymptotic or mathematical theory of homogenization, the method of cells, subcells, direct finite element method and homogenization by mean values. In this case, the last method is applied.

The purpose of homogenization by the mean value is to calculate the approximate, but sufficiently accurate values of the volume-averaged values of the stress and strain fields (at the macrolevel and for each phase). It is important to note that averaging does not solve the problems of a representative volume in detail and, for this reason, it is not possible to calculate the microstress and strain fields for each phase.

A representative sample is considered, consisting of a matrix with stiffness C_o, reinforced with various inclusions with stiffness C_1, which in turn consist of different materials, have various shapes and orientations. In contrast to the case with one inclusion, the multi-inclusion problem has no analytical solution. Therefore, homogenization models are based on different assumptions.

In this case, a model based on the approximation of the Eshelby solution is used. It was noted that the strain concentration tensor refers to the volume averaging of strains over all inclusions, hence the strain matrix takes the form:

$$B^{\varepsilon} = H^{\varepsilon}\left(I, C_0, C_1\right),$$

which is exactly the same as the tensor for one inclusion. Later, the following simple iteration of the model was proposed, when each inclusion in a representative volume is represented as if it were isolated in the matrix.

The Mori-Tanaka model is very successful in predicting the effective properties of two-phase composites. In theory, it is limited by the limiting volumetric content of inclusions (no more than 25%), but in practice it gives good results far beyond the specified range.

Composite materials with multilayer inclusions should be especially noted. The multi-level homogenization process has also been developed for composites with coated inclusions, but in this case there is a specific choice of homogenization levels. Indeed, in this case, at a deeper level, the inclusions are homogenized with their coatings, and “equivalent” inclusions are obtained. They are homogenized with the real matrix at the top level.

We will consider a two-phase composite made of a matrix (index 0) and inclusions (index 1). Each homogeneous phase of the material obeys the following constitutive relations:

$$\sigma_o(x) = C_o\left(\varepsilon_o(x) - \alpha_o \Delta T\right), \qquad \sigma_1(x) = C_1\left(\varepsilon_1(x) - \alpha_1 \Delta T\right),$$
$$= C_o \varepsilon_o(x) + \beta_o \Delta T. \qquad = C_1 \varepsilon_1(x) + \beta_1 \Delta T.$$

Elastic stiffness and coefficients of thermal expansion (CTE), respectively, are denoted by C and α_{ij}, while $\beta = -C : \alpha$.

A representative volume of material undergoes linear displacements at the boundaries corresponding to macroscopic deformations and uniform temperature changes.

Objective: Find the appropriate elastic stiffness and thermal expansion tensors in such a way that:

$$\langle\sigma\rangle = \bar{C} : \left(E - \bar{\alpha}\Delta T\right),$$

$$= \bar{C} : \mathrm{E} + \bar{\beta}\Delta T.$$

In the isothermal case, the average parameter homogenization models for conventional two-phase composites (e.g. Mori-Tanaka or double inclusion) are determined using the strain concentration tensor B^{ε} (or A^{ε}). From the point of view of thermoelasticity, the average deformation over all inclusions refers to macroscopic deformation as:

$$\langle\varepsilon\rangle_{\omega 1} = A^{\varepsilon} : E - \alpha^{\varepsilon}\Delta T$$

with A^{ε} an identical linear elastic case and with the same homogenization scheme

$$a^{\varepsilon} \equiv \left(A^{\varepsilon} - I\right) : \left(C_1 - C_0\right)^{-1} : \left(\beta_1 - \beta_0\right),$$

$$E = \nu_0 \langle\varepsilon\rangle_{\omega 0} + \nu_1 \langle\varepsilon\rangle_{\omega 1}$$

Macro characteristics of the composite can be determined:

$$\langle\sigma\rangle = \bar{C} : E + \bar{\beta}\Delta T$$

with elastic stiffness tensor identical to the isothermal case,

$$\bar{C} = \left[\nu_1 C_1 : B^{\varepsilon} + \left(1-\nu_1\right) C_0\right] : \left[\nu_1 B^{\varepsilon} + \left(1-\nu_1\right) I\right]^{-1}$$

and

$$\bar{\beta} = \nu_0\beta_0 + \nu_1\beta_1 + \nu_1\left(C_1 - C_0\right) : a^{\varepsilon}, \qquad \bar{a} = -\bar{C}^{-1} : \bar{\beta}$$

It should be noted that the macro coefficient of thermal expansion is not an independent property, it depends on the hardness of each phase, as well as on the macro hardness.

Material loading to determine its characteristics occurs in several stages. At the beginning there is a cooling from 950 ºC to room temperature, then heating to the operating temperature, followed by holding, during which a mechanical load is applied.

In the process of homogenization, it is imperative to calculate the Eshelby tensor, which is necessary to determine the tensor of deformation concentrations B^{ε}. It was found that good numerical predictions can be obtained when the Eshelby tensor for nonlinear behavior is calculated not from the tensor of the anisotropic modulus, but from the modulus of the isotropic part of the tangent matrix. The method for extracting the isotropic part from the anisotropic tensor is not unique. Eshelby tensor is required for calculating the strain concentration tensor B^{ε} in the process of homogenization.

$$B^{\varepsilon} = \left\{I + \varsigma : C_0^{-1} : \left[C_1 - C_0\right]\right\}^{-1},$$

$$= \left\{I + P : \left[C_1 - C_0\right]\right\}^{-1}$$

where I denotes the fourth rank unit tensor, ζ - Eshelby tensor, P - Hill tensor or polarization, C_0 and C_1 - stiffness matrices for matrix and phase of inclusions, respectively.

Eshelby tensor depends on the shape and orientation of the inclusion, the stiffness matrix. In the case of an elliptical inclusion and an isotropic form of the stiffness matrix, the Eshelby tensor depends only on the ratio of the dimensions of the inclusion, their orientation, and the matrix for Poisson's ratio. For an elastically (visco) plastic matrix, Poisson's ratio is calculated from the shear modulus and shear modulus, K_t and G_t.

$$\nu_t = \frac{3K_t - 2G_t}{2\left(3K_t + G_t\right)}$$

If the matrix is elastically (visco) plastic, it can be verified that its tangent modulus tensor is anisotropic, even if the matrix model of the material is isotropic. The isotropic part of the matrix of the tangent operator based on the calculation of the tangent shear modulus and shear modulus is determined as follows:

$$C^{iso} = 3K_t I^{vol} + 2G_t I^{dev}$$

where C^{iso} is the isotropic part of the modulus of the anisotropic tensor, I^{vol} and I^{dev} is the isotropic part of the modulus of the anisotropic tensor.

4. Conclusions

A comparison is made and a good agreement between the calculated data and the results of foreign experimental studies with respect to the mechanical properties of composites is shown. The substantiation of the lowered values of strength of domestic samples of the composite is proposed, which is associated with the possible occurrence of increased residual stresses. Computational methods are selected within the framework of fiber composite models in the Digimat system for predicting the effective characteristics of the material. A prediction is given for the elastic moduli and ultimate strength of the composite at temperatures of 20-350 C, taking into account the different volumetric content of reinforcing fibers, pore defects, fiber orientation.

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