MECHANICS

DOI: 10.18721/JPM.13213 УДК 539.3

DETERMINATION OF THE EFFECTIVE YOUNG'S MODULUS OF MEDIUM WITH MICROSTRUCTURE TYPICAL FOR HYDROGEN DEGRADATION

K.P. Frolova

Institute for Problems of Mechanical Engineering RAS, St. Petersburg, Russian Federation; Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation

The paper aims at calculation of the effective elastic properties of metals with a microstructure typical for hydrogen-enhanced degradation. For the purpose of this study, we use the Maxwell homogenization scheme and explicit expression for compliance contribution tensor to determine the overall Young's moduli. The model introduces oblate spheroids to describe intergranular microcracks and spheres to describe pores. Within the frame of the paper, we consider random orientations of the microcracks, certain preferential orientation accompanied by random scatter with the scattering parameter and random orientations of the spheroids' axes in the same plane. The dependences of the effective Young's moduli on the porosity and aspect ratio of the spheroid have been studied.

Keywords: effective Young's modulus, Maxwell homogenization scheme, hydrogen degradation, spheroidal inhomogeneity

Citation: Frolova K.P., Determination of the effective Young's modulus of medium with microstructure typical for hydrogen degradation, St. Petersburg Polytechnical State University Journal. Physics and Mathematics. 13 (2) (2020) 142–154. DOI: 10.18721/JPM.13213

This is an open access article under the CC BY-NC 4.0 license (https://creativecommons.org/ licenses/by-nc/4.0/)

ОПРЕДЕЛЕНИЕ ЭФФЕКТИВНОГО МОДУЛЯ ЮНГА СРЕДЫ С МИКРОСТРУКТУРОЙ, ХАРАКТЕРНОЙ ДЛЯ ВОДОРОДНОЙ ДЕГРАДАЦИИ

К.П. Фролова

Институт проблем машиноведения РАН, Санкт-Петербург, Российская Федерация; Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация

Работа посвящена определению эффективных упругих свойств металлов с микроструктурой, характерной для водородной деградации. С целью определения эффективных модулей Юнга решается задача гомогенизации по схеме Максвелла в терминах тензоров вклада. Микротрещины, возникающие по границам зерен, моделируются сплюснутыми сфероидами, поры – сферами. Рассматривается три варианта ориентации осей симметрии сфероидов в материале: произвольная, преимущественная ориентация с параметром рассеяния, произвольная ориентация в одной плоскости. Исследуются зависимости эффективных модулей Юнга от пористости материала и от соотношения длин полуосей сфероидов.

Ключевые слова: эффективный модуль Юнга, схема гомогенизации Максвелла, водою родная деградация, сфероидальная неоднородность

Ссылка при цитировании: Фролова К.П. Определение эффективного модуля Юнга среды с микроструктурой, характерной для водородной деградации // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2020. Т. 2 № .13. С. 160–174. DOI: 10.18721/JPM.13213

Это статья открытого доступа, распространяемая по лицензии CC BY-NC 4.0 (https:// creativecommons.org/licenses/by-nc/4.0/)

Introduction

Hydrogen dissolved in metals may lead to degradation of mechanical properties and premature fracture of metal workpieces. The impact of hydrogen on the properties and character of material fracture largely depends on both external factors, and the features of the internal structure and characteristics of materials. This is why the phenomenon of hydrogen degradation, comprising an entire range of negative effects induced by hydrogen, remains an important topic in materials science demanding further comprehensive studies [1, 2].

Many works considered the effects of hydrogen on the material microstructure [3-9]. Hydrogen is assumed to diffuse through the metal lattice and interact with the defects of the structure, such as dislocations, pores, vacancies, etc., thus inducing microcracks. The defects develop in workpieces during production, and are typically located along the boundaries of grains or inclusions in alloys (the defects are also found inside the grains, but to a lesser extent). Ultimately, if there are no significant internal or external stresses, hydrogen-induced microcracks form, propagating along the grain boundaries [3-5, 9] or blisters that lead to embrittlement of the surface [7, 9]. At the same time, microcracks can be observed at grain boundary triple junctions as well [4, 5, 8, 9]. Microcracks are often seen to initiate with a preferential orientation, which is parallel to the rolling direction [3, 7].

Several papers [10-12] studied hydrogen diffusion along the grain boundaries, finding the effective diffusion coefficient in a composite material, where one phase consisted of grain boundaries with a high diffusion coefficient, and the other phase included the actual grains with a low diffusion coefficient. However, hydrogeninduced changes in the microstructure were not simulated in these studies. For example, [13] used phenomenological approaches to solve a related problem of hydrogen transfer and changes in the defects structure of the material. The effect of hydrogen on the material was accounted for within the cumulative damage theory. A number of papers discussed hydrogeninduced degradation of elastic properties of material [9, 14, 15]; in particular, [9] dealt with hydrogen degradation in low carbon steels at different levels. The authors found that longterm hydrogen saturation leads to a reduction bulk elastic modulus. Microstructural in analysis revealed that the reasons for this may lie in the deformation of larger grains, cracks, and blisters caused by hydrogen penetration. As observed in [14], prolonged hydrogen charging may decrease the value of Young's modulus by up to 15% in a gamma titanium aluminide alloy. The experiments in [15] were conducted for three different grades of high-strength steel. Hydrogen charging of steels resulted in degradation of mechanical properties and changes in the microstructure in all cases.

Summarizing the above, we can remark that analytical models of hydrogen degradation generally tend to account for diffusion assumed to be the primary process leading to changes in microstructure and to degradation of mechanical properties. The degradation of elastic properties due to the actual changes in the microstructure has received much less attention.

The goal of our study consisted in determining the effective elastic moduli for a material whose microstructure is assumed to have formed as a result of hydrogen degradation.

For this purpose, we solve the problem of homogenization which allows to estimate the contribution of inhomogeneities to a given property. We consider the influence that the potential shape and orientation of microcracks in the material, as well as its porosity have on effective Young's moduli.

Microstructure of the material

This paper studies the influence of coin-like microcracks, as well as pores on the effective properties of materials, assuming that the former accounts for intergranular cracking, and the latter for the impact of the pores which did not merge into microcracks, and the voids near grain boundary triple junctions. It was found in [16] that jagged boundaries of planar cracks or deviations from circular shape are unimportant for elastic properties of the material, so these inhomogeneities can be simulated as elliptical.

Microcracks were modelled by oblate spheroids and pores by spheres in our study. We consider three cases of inhomogeneities in the material.

In the first case, we assumed that microcracks have random (isotropic) distribution in the bulk. This pattern is characteristic for metal products weakly deformed during production.

In the second case, we assumed that microcracks have preferential orientation (for instance, in case of rolling and layered structure of material). A factor that we took into account was that microcracks may deviate from the preferential orientation in this instance.

Finally, to complete the picture, we considered the case when the symmetry axes of spheroid microcracks have random orientation in a certain plane. This situation is observed, for example, when a material is compressed and there are no cracks forming in the plane of loading.

Compliance tensor of spheroid microcrack

Contribution tensors are used within the homogenization method to describe the contributions of individual inhomogeneities into the given properties [17].

Taking a homogenous elastic material (matrix) with the compliance tensor S^0 , let us consider a representative volume V, containing an isolated inhomogeneity of volume V_1 with the compliance tensor S^1 . The volume V should be, on the one hand, large enough to reflect the characteristic microstructure, and, on the other hand, small enough compared with the entire volume of the material so that the variations of the macroscopic fields are negligible.

Correct choice of representative volume is discussed, for example, in [17]. The effective elastic properties of the material are estimated by means of a tensor accounting for the contribution of inhomogeneities to compliance: it is a fourth-rank tensor **H**, which describes extra strain $\Delta \varepsilon$ generated in volume V due to inhomogeneity:

$$\Delta \boldsymbol{\varepsilon} = \frac{V_1}{V} \mathbf{H} : \boldsymbol{\sigma}_0, \qquad (1)$$

where σ_0 is the stress field depending on boundary conditions, which would be generated in the volume in the absence of inhomogeneities.

The tensor accounting for the contribution of an ellipsoidal inhomogeneity to compliance can be expressed in terms of compliance tensors of the matrix, inhomogeneities characterizing the material properties, and the second Hill's tensor \mathbf{Q} reflecting the influence of inhomogeneity shape:

$$\mathbf{H} = \left[\left(\mathbf{S}^{1} - \mathbf{S}^{0} \right)^{-1} + \mathbf{Q} \right]^{-1}.$$
 (2)

The fourth-rank tensor Q is related to the first Hill's tensor P by

$$\mathbf{Q} = \mathbf{C}^0 - \mathbf{C}^0 : \mathbf{P} : \mathbf{C}^0,$$

where C^0 is the matrix stiffness tensor.

In turn, the fourth-rank tensor P is expressed in terms of derivatives of Green's function G for displacements as

$$\mathbf{P} = \left(\nabla \int_{V_1} \mathbf{G}(\mathbf{x} - \mathbf{x}') \nabla dV'\right)_{(1,2)(3,4)}^{S}, \quad (3)$$

where () $_{(1,2)(3,4)}^{S}$ indicates symmetry with respect to permutation of subscripts in the first and the second pair.

Pores and microcracks are characterized by zero elastic moduli. Then $S^1 \rightarrow \infty$, and expression (2) is reduced to $H = Q^{-1}$. Tensors H and Q are transversely isotropic for a spheroidal microcrack in an isotropic matrix (the symmetry axis is codirectional to the inhomogeneity symmetry axis), and can be expressed as linear combinations of the tensor basis elements $T_1, T_2, ..., T_6$ [18]:

$$\mathbf{H} = \sum_{k=1}^{6} h_k \mathbf{T}_k, \ \mathbf{Q} = \sum_{k=1}^{6} q_k \mathbf{T}_k.$$
(4)

The basis elements have the following form:

$$\mathbf{T}_{1} = \boldsymbol{\theta}\boldsymbol{\theta}, \ \mathbf{T}_{2} = \frac{1}{2} \Big(\Big(\boldsymbol{\theta}\boldsymbol{\theta}\Big)_{(1,4)}^{\mathrm{T}} + \Big(\boldsymbol{\theta}\boldsymbol{\theta}\Big)_{(2,4)}^{\mathrm{T}} - \boldsymbol{\theta}\boldsymbol{\theta} \Big), \\ \mathbf{T}_{3} = , \mathbf{nn}, \ \mathbf{T}_{4} = \mathbf{nn}, , \\ \mathbf{T}_{5} = \frac{1}{4} \Big(\mathbf{n}\boldsymbol{\theta}\mathbf{n} + \Big(\mathbf{n}\boldsymbol{\theta}\mathbf{n}\Big)_{(1,2)(3,4)}^{\mathrm{T}} + (\mathbf{\theta}\mathbf{nn}\Big)_{(1,4)}^{\mathrm{T}} + (\mathbf{\theta}\mathbf{nn}\Big)_{(2,3)}^{\mathrm{T}} \Big), \\ + \Big(\boldsymbol{\theta}\mathbf{nn}\Big)_{(1,4)}^{\mathrm{T}} + \Big(\boldsymbol{\theta}\mathbf{nn}\Big)_{(2,3)}^{\mathrm{T}} \Big), \\ \mathbf{T}_{6} = \mathbf{nnnn}, \end{aligned}$$
(5)

where $\theta = \mathbf{I} - \mathbf{nn}$ (**I** is the second-rank unit tensor) is the projection to the plane normal to the unit vector **n** along the symmetry axis.

The basis introduced allows to represent the transversely isotropic tensor $\mathbf{B} = \sum b_i \mathbf{T}_i$ (summation over repeated indices from 1 to 6) and its inverse in one basis [17]:

$$\mathbf{B}^{-1} = \frac{b_6}{2\Delta} \mathbf{T}_1 + \frac{1}{b_2} \mathbf{T}_2 - \frac{b_3}{\Delta} \mathbf{T}_3 - \frac{b_4}{\Delta} \mathbf{T}_4 + \frac{4}{b_5} \mathbf{T}_5 + \frac{2b_1}{\Delta} \mathbf{T}_6,$$
(6)

where $\Delta = 2(b_1b_6 - b_3b_4)$.

Thus, determining the tensors \mathbf{Q} and \mathbf{H} for a pore or a microcrack is reduced to determining the components of tensor \mathbf{Q} , which are calculated as follows in case of a spheroidal inclusion [19]:

$$q_{1} = \mu^{0} \Big[4\kappa - 1 - 2(3\kappa - 1) f_{0} - 2\kappa f_{1} \Big],$$

$$q_{2} = 2\mu^{0} \Big[1 - (2 - \kappa) f_{0} - \kappa f_{1} \Big],$$

$$q_{3} = q_{4} = 2\mu^{0} \Big[(2\kappa - 1) f_{0} + 2\kappa f_{1} \Big], \quad (7)$$

$$q_{5} = 4^{1/4} \Big[f_{0} + 4\kappa f_{1} \Big],$$

$$q_{6} = 8\mu^{0} \kappa \Big[f_{0} - f_{1} \Big], \quad \kappa = (1 - \nu^{0}) \Big/ 2,$$

where μ^0 and ν^0 are the shear modulus and Poisson's ratio of the matrix, respectively.

Parameters f_0 and f_1 depend on the aspect ratio of spheroid semiaxes $\gamma = a_3/a$ (a_3 is the axis of rotation) as follows:

$$f_{0} = \frac{1-g}{2(1-\gamma^{-2})},$$

$$f_{1} = \frac{1}{4(1-\gamma^{-2})^{2}} \Big[(2+\gamma^{-2})g - 3\gamma^{-2} \Big],$$

where

$$g = \begin{cases} \frac{1}{\gamma\sqrt{1-\gamma^2}} \arctan\frac{\sqrt{1-\gamma^2}}{\gamma}, \ \gamma \le 1; \\ \frac{1}{2\gamma\sqrt{\gamma^2-1}} \ln\left(\frac{\gamma+\sqrt{\gamma^2-1}}{\gamma-\sqrt{\gamma^2-1}}\right), \ \gamma \ge 1. \end{cases}$$

For a spheroidal inhomogeneity, $\gamma = 1$, g = 1, $f_0 = 1/3$, $f_1 = 1/15$. The compliance tensor of a spheroidal pore \mathbf{H}_p is isotropic and takes the following form:

$$\mathbf{H}_{p} = \frac{15(1-V)}{2\mu} \times \left[\frac{1}{10(1+V)}\frac{1}{3}\mathbf{II} + \frac{1}{7-5V}\left(\mathbf{J} - \frac{1}{3}\mathbf{II}\right)\right],$$
(8)

where I is the second-rank unit tensor,

$$\mathbf{J} = \frac{1}{2} \left(\left(\mathbf{II} \right)_{(1,4)}^{T} + \left(\mathbf{II} \right)_{(2,4)}^{T} \right)$$

is the fourth-rank unit tensor.

Tensors **II** and **J** can be represented as follows in the transversely isotropic basis [17]:

$$\mathbf{II} = \mathbf{T}_1 + \mathbf{T}_3 + \mathbf{T}_4 + \mathbf{T}_6,$$

$$\mathbf{J} = \frac{1}{2}\mathbf{T}_1 + \mathbf{T}_2 + 2\mathbf{T}_5 + \mathbf{T}_6.$$
 (9)

Effective properties of metals with spheroidal microcracks and pores

Effective properties of heterogeneous materials can be determined by different methods. A historical review of these methods can be found, for example, in [20], while [17] presents analysis of the current situation. All analytical methods are approximate solutions, while the exact solution can be obtained only numerically for specific materials with a known microstructure. The bestknown analytical methods include:

non-interaction approximation,

effective media schemes,

differential scheme,

effective field methods (including both Mori-Tanaka and Kanaun-Levin methods),

Maxwell scheme.

These methods differ in their approaches to accounting for the mutual influence of multiple inhomogeneities, while their applicability is limited by material symmetry, shape and orientation of inclusions. The Maxwell scheme seems to be an optimal method to describe the contributions of inhomogeneities of different shape and orientation [21].

Let us find an effective compliance tensor using the Maxwell scheme in terms of contribution tensors:

$$\mathbf{S}^{eff} = \mathbf{S}^{0} + \left\{ \left[\frac{1}{V_{\Omega}} \sum_{i} V_{i} \mathbf{H}_{i} \right]^{-1} - \mathbf{Q}_{\Omega} \right\}^{-1}, (10)$$

where \mathbf{Q}_{Ω} is the second Hill's tensor determined for a homogenized region Ω which contains isolated inhomogeneities and possesses the required effective properties.

In the absence of \mathbf{Q}_{α} , the effective compliance tensor coincides with the value determined neglecting the interaction of inhomogeneities.

Let us determine the total contribution of isolated inhomogeneities to compliance. If the inhomogeneities have the same shape and size but different orientation, then their total contribution can be determined as the product of the averaged contribution by volume fraction of inhomogeneities [17]. The averaged value of the contribution tensor for spheroidal inclusions coincides with the contribution tensor of a separate spheroidal pore \mathbf{H}_p due to symmetry. If spheroidal microcracks and spherical pores are present in the material, their total contribution is determined as

$$\frac{1}{V}\sum_{i}V_{i}\mathbf{H}_{i}=\boldsymbol{\varphi}_{mc}\left\langle \mathbf{H}_{mc}\right\rangle +\boldsymbol{\varphi}_{p}\mathbf{H}_{p},\qquad(11)$$

where φ_{mc} and φ_{p} are the volume fractions of oblate spheroids and spheres, respectively, $\langle \mathbf{H}_{mc} \rangle$ is the value of the averaged total tensor describing the contribution of microcracks to compliance.

It is sufficient to average the elements of the tensor basis to determine $\langle \mathbf{H}_{m} \rangle$, i.e.,

$$\langle \mathbf{H}_{mc} \rangle = \sum_{k=1}^{6} h_{mc(k)} \langle \mathbf{T}_{k} \rangle.$$

If there is a preferential orientation \mathbf{m} , the symmetry axes \mathbf{n} of spheroidal microcracks tend to coincide with \mathbf{m} with a certain deviation depending on the scatter parameter λ .

Let us introduce a probability density function for the orientation distribution of spheroid axes of symmetry over a semisphere $(0 \le \theta \le \pi/2)$ in accordance with [22]:

$$\Psi_{*}(\theta) = \frac{1}{2\pi} \Big[\left(\lambda^{2} + 1 \right) e^{-\lambda \theta} + \lambda e^{-\lambda \pi/2} \Big].$$
(12)

If $\lambda = 0$, the microcracks have a random orientation in the representative volume and the material is isotropic. If $\lambda \to \infty$, the symmetry axes of the microcracks are oriented strictly along the preferential direction and the material is transversely isotropic with the symmetry axis coinciding with **m**. To average the elements of the tensor basis, let us integrate them with respect to the surface of a semisphere $\tilde{\Omega}_{1/2}$ of unit radius:

$$\langle \mathbf{T}_i \rangle = \frac{1}{2\pi} \int_{\tilde{\Omega}_{1/2}} \mathbf{T}_i d\tilde{\Omega}_{1/2}.$$
 (13)

If the spheroid axes of symmetry **n** are randomly oriented in a certain plane normal to **m**, the material is transversely isotropic and its axis of symmetry is co-directional to **m**. To average the tensor basis elements, let us integrate them with respect to a unit circle l_1 lying in a plane normal to **m**:

$$\langle \mathbf{T}_i \rangle = \frac{1}{2\pi} \int_{l_1} \mathbf{T}_i dl_1.$$
 (14)

The averaged values of the elements of transversely isotropic basis are given in the Appendix.

The choice of homogenized domain Ω used in the Maxwell scheme to account for the interactions of inhomogeneities is discussed in detail in [22].

In case of spheroidal inhomogeneities, this domain is also a spheroid with the aspect ratio of semiaxes expressed as

$$\tilde{a}_{\Omega} = \begin{cases} \sum_{i} V_{i} Q_{3333}^{(i)} / \sum_{i} V_{i} Q_{1111}^{(i)}, \\ \text{if } \sum_{i} V_{i} Q_{3333}^{(i)} / \sum_{i} V_{i} Q_{1111}^{(i)} \leq 1, \\ \sum_{i} V_{i} P_{1111}^{(i)} / \sum_{i} V_{i} P_{3333}^{(i)}, \\ \text{if } \sum_{i} V_{i} Q_{3333}^{(i)} / \sum_{i} V_{i} Q_{1111}^{(i)} > 1, \end{cases}$$
(15)

where Q_{ijkl} , P_{ijkl} are Hill's tensor components **Q** and **P**, respectively.

In general, the shape of homogenized domain depends on concentration, orientation and shapes of inhomogeneities. If the inhomogeneities have isotropic orientation distribution, the shape is spherical. Otherwise, if the material contains spherical pores of the same size and spheroidal microcracks of the same size and shape, we need to define the quantity

$$\frac{1}{V}\sum_{i}V_{i}\mathbf{Q}_{i} = \varphi_{mc} \langle \mathbf{Q}_{mc} \rangle + \varphi_{p}\mathbf{Q}_{p},$$

$$\langle \mathbf{Q}_{mc} \rangle = \sum_{k=1}^{6}q_{mc(k)} \langle \mathbf{T}_{k} \rangle.$$
(16)

After we find the components of the effective compliance tensor, S_{ijkl}^{eff} , we can determine effective Young's moduli. To be definite, let us assume that the symmetry axis of the material coincides with the direction \mathbf{e}_3 of the Cartesian basis (\mathbf{e}_1 , \mathbf{e}_2 , \mathbf{e}_3).

Then the effective Young's moduli of the transversely isotropic material $E_{11}^{\text{eff}} = E_{22}^{\text{eff}}, E_{33}^{\text{eff}}$ can be calculated as follows:

$$E_{11}^{eff} = E_{22}^{eff} = \frac{1}{S_{1111}^{eff}}, \ E_{33}^{eff} = \frac{1}{S_{3333}^{eff}}.$$
 (17)

Results and discussion

In this study, we found the effective elastic properties of steel with shear modulus $\mu^0 = 80$ GPa and Poisson's ratio $v^0 = 0.3$. Young's modulus of steel E^0 follows the expression

$$E^{0} = 2 \ \mu^{0}(1 + v^{0}).$$

If the inhomogeneities have random orientation distribution, the material is isotropic, i.e.,

$$\mathbf{S}^{eff} = K^{eff}\mathbf{II} + \mathbf{i}^{eff}\left(\mathbf{J} - \frac{1}{3}\mathbf{II}\right), \qquad (18)$$

where K^{eff} and μ^{eff} are the effective values of the coefficient of compressibility and shear modulus respectively.



Fig. 1. Dependences of moduli K^{eff}/K^0 (solid lines) and μ^{eff}/μ^0 (dashed lines) on porosity of material (*a*) and density of cracks (*b*). Pores are modeled by spheres (1, 2), microcracks by spheroids with aspect ratio of semiaxes $\gamma = 0.1$ (3, 4)

Fig. 1, a shows the dependencies of moduli K^{eff}/K^0 , μ^{eff}/μ^0 on porosity of the material φ for a spherical pore ($\gamma = 1$) and a spheroidal microcrack (at $\gamma = 0.1$). Evidently, the porosity of the material with spherical inhomogeneities may theoretically reach 100% (the material disappears). In case of microcracks of oblate spheroidal shape, the elastic moduli approach zero at porosities less than 100% (around 26% at $\gamma = 0.1$). Negative values of elastic moduli at high concentrations of inhomogeneities indicate that the problem of homogenization cannot be solved correctly for this material.

Thus, the acceptable porosity of the material is defined by a relation between the aspect ratio of the microcrack semiaxes. To take this correlation into account, we can introduce crack density into the model

a) b)

$$\mu^{eff/\mu^0}$$
 μ^{eff/μ^0} μ^{eff/μ^0} 1.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.5 0.0 0.0 0.2 0.4 0.6 0.8 1.0 0.0 0.2 0.4 0.6 0.8 1.0 0.0 0.2 0.4 0.6 0.8 1.0 0.0 0.2 0.4 0.6 0.8 1.0 0

$$\rho = (4/3)\pi a^3 N/V$$

(*N* is the number of microcracks) [17], related to porosity φ as $\varphi = \rho \gamma$.

Fig. 1, *b* shows the dependences of moduli K^{eff}/K^0 and μ^{eff}/μ^0 on crack density.

To find a possible explanation for the limited acceptable porosity, we studied the dependence of effective shear modulus μ^{eff}_{12}/μ^0 on porosity for different scatter parameters λ . We considered spheroidal microcracks with $\gamma = 0.10$ and 0.05. The results are shown in Fig. 2.

The results indicate that given the same aspect ratio of spheroid semiaxes γ , the porosity of the material may theoretically reach 100% if it contains parallel oriented microcracks ($\lambda \rightarrow \infty$), or, if the microcracks deviate from the preferential orientation, the acceptable porosity decreases, reaching the minimum with an isotropic distribution ($\lambda = 0$). As evident from comparing Figs. 2, *a* and *b*, spheroids with a high value of γ have a higher value of acceptable



porosity. Apparently, when porosity reaches a certain value depending on the degree of deviation of spheroid microcracks from the preferential orientation, as well as on their degree of oblateness, multiple narrow microcracks cannot be regarded as isolated. Since this assumption is actually adopted for self-consistent schemes (which also include the Maxwell method), more accurate methods need to be found to account for the mutual influence of inhomogeneities.

We determined the dependences of effective Young's moduli E^{eff}/E^0 on porosity of material φ for three case of orientation distribution of inhomogeneities:

isotropic distribution (I),

preferential orientation with the scatter parameter λ (II),

random distribution of symmetry axes of inhomogeneities in a certain plane (III).

We assumed that the material contained two types of inhomogeneities: oblate spheroidal microcracks with $\gamma = 0.1$ and spherical pores.

Total porosities φ of all inhomogeneities were taken in the range between 0 and 10%.

Materials with the following types of microstructure were considered:

only oblate spheroids are present ($\varphi_{mc} = \varphi$, $\varphi_p=0);$

ratio of total volume of oblate spheroids to total volume of pores is 2 : 1 ($\varphi_{mc} = 2\varphi/3$, $\varphi_p = \varphi/3;$

total volume of oblate spheroids equals total volume of pores $(\phi_{mc} = \phi/2 = \phi_p)$; only pores are present $(\phi_{mc} = 0, \phi_p = \phi)$. Fig. 3 shows the computational results tak-

ing into account the given conditions. As expected, an increase in porosity leads to a decrease in elastic moduli in all cases. Evidently,



Fig. 3. Dependence of moduli E^{eff}/E^0 on porosity of material for different orientation distributions of inhomogeneities $(\gamma = 0.1)$: I (a), II (при $\lambda = 10$) (b, c) and III (d, e) (see explanations in the text). The following types of microstructures were considered: $\varphi_{mc} = \varphi$, $\varphi_p = 0$ (*I*); $\varphi_{mc} = 2\varphi/3$, $\varphi_p = \varphi/3$ (*2*); $\varphi_{mc} = \varphi/2 = \varphi_p$ (*3*); $\varphi_{mc} = 0$, $\varphi_p = \varphi$ (*4*)



Fig. 4. Dependences of moduli E^{eff}_{ii}/E⁰ on parameter γ at different orientation distributions of inhomogeneities (crack density ρ = 0.1): I, II (a, b) and III (c) (see explanations in the text);
a, b correspond to the scatter parameters λ = 0 (dashed lines), λ = 10 (solid lines) and λ→∞ (dotted-dashed lines);
c corresponds to the moduli E^{eff}₁₁/E₀ (dashed lines) and E^{eff}₃₃/E₀ (solid lines)

pores have less effect on Young's modulus than microcracks at the same value of φ for an isotropic distribution (Fig. 3, a). For example, if $\varphi = 0.10$, then the value of modulus $E_{ii}^{eff}/E^0 \approx 0.82$ at $\varphi_{mc} = 0$, $\varphi_p = \varphi$ and $E_{ii}^{eff}/E^0 \approx 0.58$ at $\varphi_{mc} = \varphi$, $\varphi_p = 0$.



Fig. 5. Dependences of moduli E_{11}^{eff}/E_0 (dashed line) and E_{33}^{eff}/E_0 (solid line) on scatter parameter; parameter values $\gamma = 0.1$, $\varphi = 0.01$ were taken

If microcracks have a preferential orientation in the material (Fig. 3, *b*, *c*), Young's modulus along the material axis decreases more than Young's modulus in the isotropic plane. Narrow cracks make a larger contribution to E_{33}^{eff} compared to pores, and a smaller contribution to E_{11}^{eff} . Conversely, if the symmetry axes of microcracks are distributed in the isotropic plane (Fig. 3, *d*, *e*), Young's modulus along the material axis decreases less than Young's modulus in the isotropic plane. Narrow cracks make a larger contribution to E_{11}^{eff} compared to pores, and a smaller contribution to E_{33}^{eff} .

Next, we studied the dependence of effective Young's moduli $E_{ii'}^{eff}/E^0$ on the aspect ratio of spheroid semiaxes γ . An increase in the parameter γ from 0 to 1 describes the change in the shape of the spheroid from a disk to a sphere. As established above, the total porosity cannot be random in case of narrow microcracks, so the concentration of cracks was assumed to be constant and, thus, the total porosity varied due to varying γ . It was assumed that crack density $\rho = 0.1$; in this case, if $\gamma = 0.1$, the total porosity of material amounts to 1%, which provides the best agreement with the experimental data.

Fig. 4 shows the computational results for the considered cases of orientation distribution of inhomogeneities. Evidently (see Figs. 4, a, b), if $\lambda > 0$, the presence of oblate spheroids leads to a larger decrease in Young's modulus along the material axis and to a smaller decrease in the isotropic plane. For example, the values of the moduli are $E_{33}^{eff}/E_0 \approx 0.86$, $E_{11}^{eff}/E_0 \approx 0.92$ at $\lambda = 10$, $\gamma = 0.5$. If the symmetry axes of microcracks have random orientations in a certain plane (see Fig. 4,c), Young's modulus in the isotropic plane of the material is more sensitive to the decrease of the aspect ratio γ of spheroid semiaxes than Young's modulus along the material axis. For example, we obtained $E_{11}^{\text{eff}}/E_0 \approx 0.89$, $E_{33}^{\text{eff}}/E_0 \approx 0.92$ at $\gamma = 0.5$. A decrease in Young's moduli was observed with an increase in γ for all orientation distributions of inhomogeneities, because the total porosity of material depends linearly on the parameter γ .

We considered a separate case of preferential orientation of spheroids and studied the dependence of effective properties of the material on the scatter parameter λ , taking γ = 0.1, φ = 0.01. Fig. 5 shows the computational results. The material is isotropic at λ = 0, characterized by effective Young's modulus $E^{\text{eff}}_{\text{iff}} E^0 \approx 0.95$. As seen from Fig. 5, the more the symmetry axis of inhomogeneities deviate from the preferential orientation (with decreasing λ), the more significantly the effective moduli change. Different patterns are observed in the changes in Young's moduli along the material axis and in the isotropic plane: Young's modulus along the material axis decreases if inhomogeneities smooth out $(\lambda \rightarrow \infty)$, while Young's modulus in the isotropic plane conversely decreases with increasing scatter ($\lambda \rightarrow 0$).

Conclusion

We have analyzed the variation in effective Young's moduli of metals with microstructures typical for hydrogen-enhanced degradation, specifically, for the microstructures containing intergranular microcracks and pores. Microcracks were modeled by oblate spheroids, and pores were modeled by spheres. The homogenization problem was solved using the Maxwell problem in terms of contribution tensors. We have studied the dependences of effective elastic properties on porosity, degree of oblateness of spheroids and orientation distribution of inhomogeneities. We have established that effective Young's moduli heavily depend on the aspect ratio of semiaxes of spheroidal microcracks and porosity of the material. Effective Young's moduli along different directions can change to a greater or lesser degree depending on the orientation of microcracks in the material. This proves that it is essential to account for the structure of metal products (for example, layered structure of metal) and, consequently, the method by which they were produced (for example, rolling) when determining the characteristics of metals charged with hydrogen. Moreover, depending on orientation, microcracks can make smaller or greater contributions compared to pores, with the same concentration of microcracks and pores. In addition, we have found that the correlation between the porosity of material and the shape of microcracks should be taken into account in solving the homogenization problem.

Appendix

Averaged values of transversely isotropic basis elements

If inhomogeneities have isotropic orientation distribution, the averaged values of the transversely isotropic basis elements have the following form [16]:

$$\langle \mathbf{T}_{1} \rangle = \frac{1}{15} \Big[7\mathbf{T}_{1} + 2\mathbf{T}_{2} + 6(\mathbf{T}_{3} + \mathbf{T}_{4}) + 4\mathbf{T}_{5} + 8\mathbf{T}_{6} \Big],$$

$$\langle \mathbf{T}_{2} \rangle = \frac{1}{15} \Big[\mathbf{T}_{1} + 6\mathbf{T}_{2} - 2(\mathbf{T}_{3} + \mathbf{T}_{4}) + 12\mathbf{T}_{5} + 4\mathbf{T}_{6} \Big],$$

$$\langle \mathbf{T}_{3} \rangle = \langle \mathbf{T}_{4} \rangle = \frac{1}{15} \Big[3\mathbf{T}_{1} - 2\mathbf{T}_{2} + 4(\mathbf{T}_{3} + \mathbf{T}_{4}) - -4\mathbf{T}_{5} + 2\mathbf{T}_{6} \Big],$$

$$\langle \mathbf{T}_{5} \rangle = \frac{1}{30} \Big[\mathbf{T}_{1} + 6\mathbf{T}_{2} - 2(\mathbf{T}_{3} + \mathbf{T}_{4}) + 12\mathbf{T}_{5} + 4\mathbf{T}_{6} \Big],$$

$$\langle \mathbf{T}_{6} \rangle = \frac{1}{15} \Big[2(\mathbf{T}_{1} + \mathbf{T}_{2}) + \mathbf{T}_{3} + \mathbf{T}_{4} + 4\mathbf{T}_{5} + 3\mathbf{T}_{6} \Big].$$

If the symmetry axes of inhomogeneities have a preferential orientation along the axis **m** with the scatter parameter λ , the averaged values of transversely isotropic basis elements are expressed as

$$\langle \mathbf{T}_1 \rangle = (1 - 2g_1(\lambda) + g_3(\lambda))\mathbf{T}_1 + g_3(\lambda)\mathbf{T}_2 + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_3 + \mathbf{T}_4) + (1 - g_1(\lambda) - g_2(\lambda) + g_4(\lambda))(\mathbf{T}_4 + g_4(\lambda))(\mathbf{T}$$

$$\begin{aligned} +4g_{4}(\lambda)\mathbf{T}_{5}+(1-2g_{2}(\lambda)+g_{5}(\lambda))\mathbf{T}_{6},\\ \langle\mathbf{T}_{2}\rangle &= \frac{g_{3}(\lambda)}{2}\mathbf{T}_{1}+\left(1-2g_{1}(\lambda)+\frac{g_{3}(\lambda)}{2}\right)\mathbf{T}_{2}+\\ &+\frac{1}{2}(g_{1}(\lambda)+g_{2}(\lambda)+g_{4}(\lambda)-1)(\mathbf{T}_{3}+\mathbf{T}_{4})+\\ &+2(g_{4}(\lambda)-g_{1}(\lambda)-g_{2}(\lambda)+1)\mathbf{T}_{5}+\\ &+\frac{1}{2}(g_{5}(\lambda)-2g_{2}(\lambda)+1)\mathbf{T}_{6},\\ \langle\mathbf{T}_{3}\rangle &= (g_{1}(\lambda)-g_{3}(\lambda))\mathbf{T}_{1}-g_{3}(\lambda)\mathbf{T}_{2}+\\ &+(g_{2}(\lambda)-g_{4}(\lambda))\mathbf{T}_{3}+(g_{1}(\lambda)-g_{4}(\lambda))\mathbf{T}_{4}-\\ &-4g_{4}(\lambda)\mathbf{T}_{5}+(g_{2}(\lambda)-g_{5}(\lambda))\mathbf{T}_{6},\\ \langle\mathbf{T}_{4}\rangle &= (g_{1}(\lambda)-g_{3}(\lambda))\mathbf{T}_{1}-g_{3}(\lambda)\mathbf{T}_{2}+\\ &+(g_{1}(\lambda)-g_{4}(\lambda))\mathbf{T}_{3}+(g_{2}(\lambda)-g_{4}(\lambda))\mathbf{T}_{4}-\\ &-4g_{4}(\lambda)\mathbf{T}_{5}+(g_{2}(\lambda)-g_{5}(\lambda))\mathbf{T}_{6},\\ \langle\mathbf{T}_{5}\rangle &= \left(\frac{g_{1}(\lambda)}{2}-g_{3}(\lambda)\right)\mathbf{T}_{1}+\\ &+(g_{1}(\lambda)-g_{3}(\lambda))\mathbf{T}_{2}-g_{4}(\lambda)(\mathbf{T}_{3}+\mathbf{T}_{4})+\\ &+(g_{1}(\lambda)+g_{2}(\lambda)-4g_{4}(\lambda))\mathbf{T}_{5}+\\ &+(g_{2}(\lambda)-g_{5}(\lambda))\mathbf{T}_{6},\\ \langle\mathbf{T}_{6}\rangle &= g_{3}(\lambda)(\mathbf{T}_{1}+\mathbf{T}_{2})+\\ &+g_{4}(\lambda)(\mathbf{T}_{3}+\mathbf{T}_{4}+4\mathbf{T}_{5})+g_{5}(\lambda)\mathbf{T}_{6}.\end{aligned}$$

 $g_1(\lambda) = \frac{18 - \lambda e^{-\frac{\pi\lambda}{2}} (\lambda^2 + 3)}{6(\lambda^2 + 9)},$ $g_2(\lambda) = \frac{\left(3 + \lambda e^{-\frac{\pi\lambda}{2}}\right) (\lambda^2 + 3)}{3(\lambda^2 + 9)},$

$$g_{3}(\lambda) = \frac{30}{(\lambda^{2}+9)(\lambda^{2}+25)} - \frac{30}{(\lambda^{2}+9)(\lambda^{2}+25)} - \frac{3}{(\lambda^{2}+9)(\lambda^{2}+25)} - \frac{3}{(\lambda^{2}+9)(\lambda^{2}+25)} + \frac{3(5+\lambda^{2})}{(\lambda^{2}+9)(\lambda^{2}+25)} + \frac{3(5+\lambda^{2})}{(\lambda^{2}+9)(\lambda^{2}+25)} + \frac{3(5+\lambda^{2})}{15(\lambda^{2}+9)(\lambda^{2}+25)} + \frac{3(5+\lambda^{2})}{(\lambda^{2}+9)(\lambda^{2}+25)} + \frac{3(5+\lambda^{2})}{(\lambda^{2}+9)(\lambda^{2}+$$

If the symmetry axes of inhomogeneities have a random orientation along the plane normal to the axis \mathbf{m} , the averaged values of transversely isotropic basis elements are expressed as follows [16]:

$$\langle \mathbf{T}_{1} \rangle = \frac{1}{4} \Big[\mathbf{T}_{1} + \mathbf{T}_{2} + 2 \big(\mathbf{T}_{3} + \mathbf{T}_{4} \big) + 4 \mathbf{T}_{6} \Big],$$

$$\langle \mathbf{T}_{2} \rangle = \frac{1}{8} \Big[\mathbf{T}_{1} + \mathbf{T}_{2} - 2 \big(\mathbf{T}_{3} + \mathbf{T}_{4} \big) + 8 \mathbf{T}_{5} + 4 \mathbf{T}_{6} \Big],$$

$$\langle \mathbf{T}_{3} \rangle = \frac{1}{4} \Big[\mathbf{T}_{1} - \mathbf{T}_{2} + 2 \mathbf{T}_{4} \Big],$$

$$\langle \mathbf{T}_{4} \rangle = \frac{1}{4} \Big[\mathbf{T}_{1} - \mathbf{T}_{2} + 2 \mathbf{T}_{3} \Big],$$

$$\langle \mathbf{T}_{5} \rangle = \frac{1}{4} \Big[\mathbf{T}_{2} + 2 \mathbf{T}_{5} \Big],$$

$$\langle \mathbf{T}_{6} \rangle = \frac{1}{4} \Big[\mathbf{T}_{1} + \mathbf{T}_{2} \Big].$$

REFERENCES

1. Koyama M., Akiyama E., Lee Y.K., et al., Overview of hydrogen embrittlement in high-Mn steels, International Journal of Hydrogen Energy. 42(17) (2017) 12706–12723.

2. Yakovlev Yu.A., Tretyakov D.A., Frolova K.P., Hydrogen diagnostics structural elements and engineering constructions, Methods of Control and Diagnostics in Mechanical Engineering. (3) (2019) 117–120.

3. Shen C.H., Shewmon P.G., A mechanism for hydrogen-induced intergranular stress corrosion cracking in alloy 600, Metallurgical Transactions A. 21(5) (1990) 1261–1271.

4. Koyama M., Springer H., Merzlikin S.V., et al., Hydrogen embrittlement associated with strain localization in a precipitation-hardened Fe-Mn-Al-C light weight austenitic steel, International Journal of Hydrogen Energy. 39 (9) (2014) 4634-4646.

5. **Kuhr B., Farkas D., Robertson I.M.**, Atomistic studies of hydrogen effects on grain boundary structure and deformation response in FCC Ni, Computational Materials Science. 122 (September) (2016) 92–101.

6. Villalobos J.C., Serna S.A., Campillo B., Lypez-Marthnez E. Evaluation of mechanical properties of an experimental microalloyed steel subjected to tempering heat treatment and its effect on hydrogen embrittlement, International Journal of Hydrogen Energy. 42(1) (2017) 689–698.

7. Merson E.D., Myagkikh P.N., Klevtsov G.V., et al., Effect of fracture mode on acoustic emission behavior in the hydrogen embrittled low-alloy steel, Engineering Fracture Mechanics. 210 (1 April) (2019) 342–357.

8. Sun B., Krieger W., Rohwerder M., et al., Dependence of hydrogen embrittlement mechanisms on microstructure-driven hydrogen distribution in medium Mn steels, Acta Materialia. 183 (15 January) (2020) 313–328.

9. Wasim M., Djukic M.B., Hydrogen embrittlement of low carbon structural steel at macro-, micro-and nano-levels, International Journal of Hydrogen Energy. 45 (3) (2020) 2145–2156.

10. Jothi S., Croft T.N., Wright L., et al., Multi-phase modelling of intergranular hydrogen segregation/trapping for hydrogen embrittlement, International Journal of Hydrogen Energy. 40 (43) (2015) 15105–15123.

11. Hoch B.O., Metsue A., Bouhattate J.,

Received 30.03.2020, accepted 20.04.2020.

Feaugas X., Effects of grain-boundary networks on the macroscopic diffusivity of hydrogen in polycrystalline materials, Computational Materials Science. 97 (1 February) (2015) 276–284.

12. Knyazeva A.G., Grabovetskaya G.P., Mishin I.P., Sevostianov I., On the micromechanical modelling of the effective diffusion coefficient of a polycrystalline material, Philosophical Magazin. 95 (19) (2015) 2046 -2066.

13. Arkhangelskaya E.A., Lepov V.V., Larionov V.P., The connected model for delayed fracture of damaged media, Physical Mesomechanics. 4 (5) (2001) 75–80.

14. Ruales M., Martell D., Vazquez F., et al., Effect of hydrogen on the dynamic elastic modulus of gamma titanium aluminide, Journal of Alloys and Compounds. 339 (1–2) (2002) 156–161.

15. Rahman K.M., Mohtadi-Bonab M.A., Ouellet R., Szpunar J.A., Comparative study of the role of hydrogen on degradation of the mechanical properties of API X60, X60SS, and X70 pipeline steels, Steel Research International. 90 (8) (2019) 1900078.

16. **Kachanov M., Sevostianov I.,** On quantitative characterization of microstructures and effective properties, International Journal of Solids and Structures. 42 (2) (2005) 309–336.

17. **Kachanov M., Sevostianov I.,** Micromechanics of materials, with applications, Vol. 249, Springer, Berlin, Germany, 2018.

18. **Kanaun S.K., Levin V.M.,** Metod effektivnogo polya v mekhanike kompozitnykh materialov [Effective field method in the mechanics of composite materials], Petrozavodsk State University, Petrozavodsk, 1993 (in Russian).

19. Sevostianov I., Kachanov M., Compliance tensors of ellipsoidal inclusions, International Journal of Fracture. 96 (1) (1999) 3–7.

20. **Markov K.Z.**, Elementary micromechanics of heterogeneous media, In the book: Heterogeneous Media, Birkhguser, Boston, MA, 2000.

21. Sevostianov I., Kachanov M., On some controversial issues in effective field approaches to the problem of the overall elastic properties, Mechanics of Materials. 69 (1) (2014) 93–105.

22. Sevostianov I., On the shape of effective inclusion in the Maxwell homogenization scheme for anisotropic elastic composites, Mechanics of Materials. 75 (August) (2014) 45–59.

THE AUTHOR

FROLOVA Ksenia P.
Institute for Problems of Mechanical Engineering RAS, Peter the Great St. Petersburg Polytechnic University
61 Bolshoi Ave. of V. Isl., St. Petersburg, 199178, Russian Federation kspfrolova@gmail.com

СПИСОК ЛИТЕРАТУРЫ

1. Koyama M., Akiyama E., Lee Y.K., Raabe D., Tsuzaki K. Overview of hydrogen embrittlement in high-Mn steels // International Journal of Hydrogen Energy. 2017. Vol. 42. No. 17. Pp. 12706–12723.

2. Яковлев Ю.А., **Третьяков Д.А., Фролова К.П.** Водородная диагностика элементов конструкций и инженерных конструкций // Мехатроника, автоматика и робототехника. 2019. № 3. С. 117–120.

3. Shen C.H., Shewmon P.G. A mechanism for hydrogen-induced intergranular stress corrosion cracking in alloy 600 // Metallurgical Transactions. A. 1990. Vol. 21. No. 5. Pp. 1261–1271.

4. Koyama M., Springer H., Merzlikin S.V., Tsuzaki K., Akiyama E., Raabe D. Hydrogen embrittlement associated with strain localization in a precipitation-hardened Fe-Mn-Al-C light weight austenitic steel // International Journal of Hydrogen Energy. 2014. Vol. 39. No. 9. Pp. 4634-4646.

5. Kuhr B., Farkas D., Robertson I.M. Atomistic studies of hydrogen effects on grain boundary structure and deformation response in FCC Ni // Computational Materials Science. 2016. Vol. 122. September. Pp. 92–101.

6. Villalobos J.C., Serna S.A., Campillo B., Lypez-Marthnez E. Evaluation of mechanical properties of an experimental microalloyed steel subjected to tempering heat treatment and its effect on hydrogen embrittlement // International Journal of Hydrogen Energy. 2017. Vol. 42. No. 1. Pp. 689–698.

7. Merson E.D., Myagkikh P.N., Klevtsov G.V., Merson D.L., Vinogradov A. Effect of fracture mode on acoustic emission behavior in the hydrogen embrittled low-alloy steel // Engineering Fracture Mechanics. 2019. Vol. 210. 1 April. Pp. 342–357.

8. Sun B., Krieger W., Rohwerder M., Ponge D., Raabe D. Dependence of hydrogen embrittlement mechanisms on microstructure-driven hydrogen distribution in medium Mn steels // Acta Materialia. 2020. Vol. 183. 15 January. Pp. 313–328. 9. Wasim M., Djukic M.B. Hydrogen embrittlement of low carbon structural steel at macro-, micro- and nanolevels // International Journal of Hydrogen Energy. 2020. Vol. 45. No. 3. Pp. 2145–2156.

10. Jothi S., Croft T.N., Wright L., Turnbull A., Brown S.G.R. Multi-phase modelling of intergranular hydrogen segregation/trapping for hydrogen embrittlement // International Journal of Hydrogen Energy. 2015. Vol. 40. No. 43. Pp. 15105–15123.

11. Hoch B.O., Metsue A., Bouhattate J., Feaugas X. Effects of grain-boundary networks on the macroscopic diffusivity of hydrogen in polycrystalline materials // Computational Materials Science. 2015. Vol. 97. 1 February. Pp. 276–284.

12. Knyazeva A.G., Grabovetskaya G.P., Mishin I.P., Sevostianov I. On the micromechanical modelling of the effective diffusion coefficient of a polycrystalline material // Philosophical Magazin. 2015. Vol. 95. No. 19. Pp. 2046–2066.

13. Архангельская Е.А., Лепов В.В, Ларионов В.П. Связная модель замедленного разрушения повреждаемой среды // Физическая мезомеханика. 2001. Т. 4. № 5. С. 81-87.

14. Ruales M., Martell D., Vazquez F., Just F.A., Sundaram P.A. Effect of hydrogen on the dynamic elastic modulus of gamma titanium aluminide // Journal of Alloys and Compounds. 2002. Vol. 339. No. 1–2. Pp. 156–161.

15. Rahman K.M., Mohtadi-Bonab M.A., Ouellet R., Szpunar J.A. Comparative study of the role of hydrogen on degradation of the mechanical properties of API X60, X60SS, and X70 pipeline steels // Steel Research International. 2019. Vol. 90. No. 8. P. 1900078.

16. **Kachanov M., Sevostianov I.** On quantitative characterization of microstructures and effective properties // International Journal of Solids and Structures. 2005. Vol. 42. No. 2. Pp. 309–336.

17. **Kachanov M., Sevostianov I.** Micromechanics of materials, with applications. Berlin, Germany: Springer, 2018. Vol. 249. 712 p. 18. **Канаун С.К., Левин** В.М. Метод эффективного поля в механике композитных материалов. Петрозаводск: Изд-во Петрозаводского гос. ун-та, 1993. 598 с.

19. Sevostianov I., Kachanov M. Compliance tensors of ellipsoidal inclusions // International Journal of Fracture. 1999. Vol. 96. No. 1. Pp. 3–7.

20. Markov K.Z. Elementary micromechanics of heterogeneous media // Heterogeneous Media.

Birkhguser, Boston, MA, 2000. Pp. 1-62.

21. Sevostianov I., Kachanov M. On some controversial issues in effective field approaches to the problem of the overall elastic properties // Mechanics of Materials. 2014. Vol. 69. No. 1. Pp. 93–105.

22. Sevostianov I. On the shape of effective inclusion in the Maxwell homogenization scheme for anisotropic elastic composites // Mechanics of Materials. 2014. Vol. 75. August. Pp. 45–59.

Статья поступила в редакцию 30.03.2020, принята к публикации 20.04.2020.

СВЕДЕНИЯ ОБ АВТОРЕ

ФРОЛОВА Ксения Петровна — младший научный сотрудник Института проблем машиноведения РАН, Санкт-Петербург, Российская Федерация; аспирантка Высшей школы теоретической механики Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Российская Федерация.

199178, Российская Федерация, г. Санкт-Петербург, Большой проспект В.О., 61. kspfrolova@gmail.com

© Peter the Great St. Petersburg Polytechnic University, 2020