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The influence of microdamage on the elastic characteristics of metastable austenitic steels under fatigue

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The relationship between the elastic moduli and the change in the phase composition and microdamage of metastable austenitic steel under fatigue was studied. An algorithm for calculating microdamage is developed taking into account the influence of a complex of factors on the elastic characteristics — the formation of strain-induced martensite, which has a contrast of elastic moduli with the material matrix, and changes in the crystallographic texture. A high correlation between the normalized value of microdamage relative to its critical value, corresponding to the appearance of a macrocrack and the damage calculated using the Palmgren-Miner linear summation of damage, which is widely used to assess the service life characteristics of steels.

Keywords: austenitic stainless steel, metastable austenite, damage, ultrasonic method, elastic moduli, eddy current method.

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Introduction

The destruction of metal alloys is characterized by a complex set of structural changes that determine their resource and strength characteristics. The crystallographic texture changes, microdefects accumulate at various structural levels and other processes associated with metal degradation occur during destruction. Generally, the destruction of metal alloys significantly increases the density of defects such as vacancies and dislocations, the formation of mesodefects, grain fragmentation [1], the formation of micropores and microcracks [2]. In some cases, active phase changes are observed. In particular, this is typical for metastable austenitic steels. Processes of accumulation of microdamages, changes in phase composition and crystallographic texture have a commensurate effect on the elastic and acoustic characteristics of the metal as was shown by previous studies [3–5].

Theoretical studies of the effect of the dislocation structure on the elastic modulus and velocity of elastic waves are presented in [6]. The change of the modules in case of a significant dislocation density is a fraction of a percent. Microdefects that interrupt the continuity of the material such as micropores, microcracks result in an order of magnitude greater change in modules of about a percent, and in some cases greater [7–9].

The dependence of the elastic modulus and the Poisson's ratio on the magnitude of micro-damage ψ associated with the formation of microcracks is determined by the expressions [8]:

$$K = K_0(1 + k_{K\psi}\psi),\ E = E_0(1 + k_{E\psi}\psi),\ \nu = \nu_0(1 + k_{\nu\psi}\psi), \tag{1}$$

where K_0, μ_0, E_0, ν_0 — the bulk modulus shear, Young and Poisson's ratio of undamaged material; K, μ, E, ν — after the formation of microcracks, $\psi = n\bar{a}^3 = \frac{\Delta\rho_\psi}{\rho_0}$, where n and $\bar{a}$ — concentration and average size microcracks , respectively; $\Delta\rho_\psi = (\rho - \rho_0)$ — change of density due to microcracking, ρ_0 — density of undamaged material, ρ — current value of density, $k_{K\psi}$, $k_{E\psi}$, $k_{\nu\psi}$ — coefficients.

The coefficients $k_{K\psi}$, $k_{E\psi}$, $k_{\nu\psi}$ are written as follows [8]:

$$k_{K\psi} = -\frac{16}{9}\frac{(1-\nu_0^2)}{(1-2\nu_0)},$$

$$k_{E\nu} = -\frac{16}{45}(10-3\nu_0)\frac{(1-\nu_0^2)}{(2-\nu_0)}, \tag{2}$$

$$k_{\nu\psi} = -\frac{16}{15}(3-\nu_0)\frac{(1-\nu_0^2)}{(2-\nu_0)}.$$

We obtain the coefficient $k_{\mu\psi}$ from equations (1), (2) and the dependence $\mu = 0.5E/(1+\nu)$ for the shear modulus, the relationship of which with the value ψ is expressed as $\mu = \mu_0(1 + k_{\mu\psi}\psi)$:

$$k_{\mu\psi} = -\frac{32}{45}\frac{(1-\nu_0)(5-\nu_0)}{(2-\nu_0)}. \tag{3}$$

The destruction of metastable austenitic steels is accompanied by the phase transformation from paramagnetic

γ austenite (face-centered cubic lattice) to ferromagnetic α'-martensite (body-centered cubic lattice), which has an elastic contrast with the matrix of the material. Martensitic transformations can occur as follows: $\gamma \to \varepsilon \to \alpha'$ or $\gamma \to \alpha'$, where ε-martensite has a hexagonal close-packed lattice [10]. α'-martensite has higher strength and thermodynamic stability in contrast to ε-martensite because of the differences in the structure of and its formation is more preferable. Phase transformations result in a noticeable change of the elastic, acoustic and strength properties of alloys and strongly change magnetic characteristics.

The structural changes described above should be taken into account for evaluation of the condition at the early stages of destruction of austenitic stainless steels, which are widely used in nuclear power, hydropower and other industries.

The following expression is used for calculation of the modules of a two-phase material in the Voigt approximation [11]:

$$M_c = M_1\vartheta_1 + M_2\vartheta_2 = M_1(1 - \vartheta_2) + M_2\vartheta_2, \tag{4}$$

where M_c — the modulus of elasticity of the entire material; M_1 and M_2 — the modulus of elasticity of the phase 1 and phases 2, respectively; ϑ_1 and ϑ_2 — the content of the first and second phases, $\vartheta_1 + \vartheta_2 = 1$. In our case, phase 1 — γ-austenite, phase 2 — α'-martensite.

The formation of strain-induced martensite affects the origin and development of microcracks. [2] shows that micro-cracks density has high correlation with volume fraction of the strain-induced martensite. A model of crack formation near a martensite crystal is provided in [12].

The crystallographic texture is a notable factor affecting the elastic and acoustic characteristics of polycrystalline alloys. The relationship of the crystallographic texture with the velocities of bulk elastic waves is investigated in [13–15].

There is a combination of elastic wave velocities that does not depend on the crystallographic texture and its changes, which occur, for example, during cyclic deformation of polycrystalline metals. [15] shows that the terms of the bulk modulus and shear modulus with a certain weight coefficient can be determined for polycrystalline materials containing cubic crystals and possessing rhombic symmetry, for example, rolled metal alloys using the sum of the squares of the velocities of shear and longitudinal waves

$$\rho(V_{zz}^2 + V_{zx}^2 + V_{zy}^2) = K + \frac{10\mu}{3}, \tag{5}$$

where V_{zx} and V_{zy} — the velocities of shear waves polarized along and across the axis of symmetry of an orthotropic material (for example, the direction of rolled sheet) and propagating perpendicular to the surface of the sheet; V_{zz} — the velocity of longitudinal waves propagating in the same direction.

The sum of the squares of the velocities does not depend on the crystallographic texture and, accordingly, the right part of the expression (5) is not related to the coefficients of the orientation distribution function (ODF).

The combination of elastic modulus included in equation (5) is denoted by the parameter P, which depends on the value of ψ and the volume content of α' martensite Φ:

$$P(\psi, \Phi) = \rho(\Phi, \psi)\Sigma_{x,y,z}V_{z(x,y,z)}^2 = K(\psi, \Phi) + \frac{10\mu(\psi, \Phi)}{3}. \tag{6}$$

The dependence of density ρ on ψ and Φ for metastable austenitic steel is expressed as follows [3]:

$$\rho(\Phi, \psi) = \rho_0(1 - \psi - k_\Phi\Phi), \tag{7}$$

where k_Φ is the coefficient that equals to 0.037 according to [3] for metastable austenitic steel AISI 321.

The purpose of this work is to study the effect of fatigue of metastable steel AISI 321 on the velocity of bulk elastic waves and the intensity of formation of the α'-martensite for development of an algorithm for evaluation of micro-damage using acoustic and eddy current measurements.

1. Fatigue destruction stages, micro-damage evaluation algorithm

The change of elastic modulus the density of the material and, accordingly, the parameter P is associated with the formation of strain-induced martensite and with the micro-damage accumulation. It was previously found that a staged character of destruction is observed during cyclic deformation of metastable austenitic steels which affects the dynamics of changes of elastic characteristics [4].

The first stage corresponds to the initial stage of loading, at which practically no α'-martensite is formed (the incubation stage according to the terminology of the authors of [16]), micropores and microcracks are not formed.

The second stage is characterized by the active formation of strain-induced martensite and a slight change of the value of $\psi \approx 0$. The relationship of the parameter P with Φ is determined by the following expression at the second stage taking into account the equation (4):

$$\begin{aligned} P^{II} =& \rho(\Phi, \psi = 0)\Sigma_{x,y,z}V_{z(x,y,z)}^2 = K_{A0}(1 - \Phi) + K_{M0}\Phi + \\ &+ \frac{10}{3}(\mu_{A0}(1 - \Phi) + \mu_{M0}\Phi) = P_{A0} - \Phi(P_{A0} - P_{M0}), \end{aligned} \tag{8}$$

where $P_{A0} = K_{A0} + 10/3\mu_{A0}$, $P_{M0} = K_{M0} + 10/3\mu_{M0}$, K_{A0}, μ_{A0} and K_{M0}, μ_{M0} — the bulk modulus and shear modulus of austenite and martensite, respectively, at $\psi \cong 0$.

The values P_{A0} and P_{M0} can be determined using the relationships $P^{II}(\Phi)$ at this stage:

$$P_{A0} = \frac{P_2^{II} - P_1^{II}(\Phi_2/\Phi_1)}{1 - (\Phi_2/\Phi_1)}, \quad P_{M0} = P_{A0} - \frac{P_2^{II} - P_1^{II}}{\Phi_1 - \Phi_2}, \tag{9}$$

where P_1^{II}, P_2^{II} and Φ_1, Φ_2 — the values of the parameter P and the volume fraction of strain-induced martensite at the characteristic points of relationship $P^{II}(\Phi)$, for example, at the beginning of the second stage (point 1) and at its end (point 2).

Micropores and microcracks are actively formed at the third stage, the volume fraction of strain-induced martensite continues to increase, the intensity of formation of which at this stage, as a rule, decreases. Using expressions (1)−(4), and taking into account that α'-martensite has significantly higher strength properties [2,10] as a result, the failure occurs mainly in austenite or at the interface of two phases, the following is written for the third stage

$$P^{III} = \rho(\Phi,\psi)\Sigma_{x,y,z}V^2_{z(x,y,z)} = K_{A0}(1-\Phi)(1-k^A_{K\psi}\psi) + K_M\Phi + \frac{10}{3}(\mu_{A0}(1-\Phi)(1-k^A_{\mu\psi}\psi) + \mu_M\Phi), \quad (10)$$

where $k^A_{K\psi}$, $k^A_{\mu\psi}$ — the values of the coefficients for austenite, determined using expressions (2) and (3).

The following is obtained from expressions (7) and (10) at the third stage

$$\psi = -\frac{P_\Phi - P_{A0} + \Phi(P_{A0} - P_{M0})}{(K_{A0}k^A_{K\psi} + 10/3\mu_{A0}k^A_{\mu\psi})(1-\Phi) - P_0}, \quad (11)$$

where $P_\Phi = \rho_0(1-k_\Phi\Phi)\Sigma_{x,y,z}V^2_{z(x,y,z)}$; $P_0 = \rho_0\Sigma_{x,y,z}V^2_{z(x,y,z)0}$; ρ_0 and $V_{z(x,y,z)0}$ — density and velocities of undamaged material at $\Phi = 0$, respectively.

The change of parameter P during cyclic deformation does not affect the value of ψ because this parameter does not depend on the crystallographic texture.

So, the measurement of the velocities of bulk elastic waves included in expression (6) and taking into account the change of material density depending on the volume fraction of α'-martensite (expression (7)) make it possible to determine the kinetics of the development of the value ψ of metastable steel during its cyclic deformation at the stage of active formation microcracks before the development of a macrocrack.

2. Experimental technique

The impact of the cyclic deformation on the elastic characteristics of AISI 321 steel was studied by the ultrasonic echo testing. The volume fraction of the α'-martensite was measured using the eddy current testing.

Chemical composition of the examined steel (mass.%]: C 0.02, Si 0.43, Mn 0.74, Cr 17.76, Ni 9.16, Ti 0.32, S 0.002, P 0.033, Cu 0.23.

Universal BISS Nano testing machine was used for cyclic deformation of the specimens. The strain amplitude $\Delta\varepsilon$ was: 0.25, 0.3, 0.35, 0.4, 0.5, 0.6 and 0.7% with a loading frequency of ~ 2 Hz.

The shape of the specimens and the ultrasonic and eddy current transducer setup diagram are shown in Fig. 1. Plane-parallel pads with a width of 3 mm and a length of 18 mm were cut on each specimen for eddy current and ultrasonic

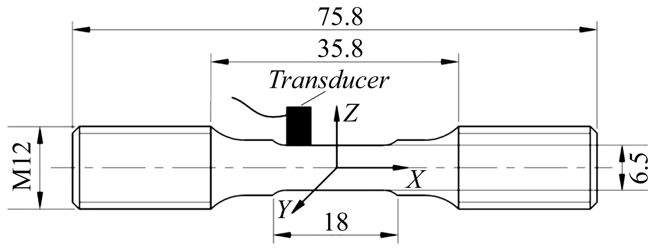

Figure 1. The shape of the fatigue test specimen and the transducer setup diagram

measurements. The thickness of the specimens h before testing in the working area was 6 mm.

Cyclic deformation (zero deformation cycle, cycle asymmetry coefficient $R = 0$) was carried out in stages, ultrasonic, eddy current studies and thickness measurements were carried out at the initial state and after each loading stage up to the formation of 1 mm long macro crack.

Elastic waves propagation time was measured using ultrasound echo-method. Piezoelectric transducers V157 and V1057 manufactured by Olympus with a working plate diameter of 3 mm and a carrier frequency of 5 MHz were used to excite shear and longitudinal waves, respectively. Longitudinal and shear waves propagate perpendicular to the loading axis at an angle of 0° relative to the transducer installation. The polarization of shear waves was directed both along the loading axis and across the loading axis.

The ultrasonic flaw detector A1212 MASTER was used as an electrical pulse generator. The LA-n1USB digital oscilloscope with ADCLab software was used to record the amplitude-time diagram of echo pulses from a piezoelectric transducer to a personal computer. The sampling rate is 1 GHz, the time resolution is 1 ns. The length of the echo pulses was 0.6−0.8 μs.

The time of propagation of elastic waves t_{zx}, t_{zy} and t_{zz} after each loading stage was obtained as a result of data processing. The average value of time of propagation was used, measured in three zones of the working part of the specimen. The error of measurement of the propagation time was 2−3 ns.

The velocity of elastic waves was found as $V_{z(x,y,z)} = 2h/t_{z(x,y,z)}$. The error of determination of the velocity ~ 5 m/s.

The density of the undamaged material ρ_0 was determined by hydrostatic weighing [3]. The measurement error ρ was no more than 0.08% for the studied steel $\rho_0 = 7919$ kg/m^3.

μ_{A0}, K_{A0} and ν_{A0} were calculated using the following expressions using the values of the velocities and densities of the material in the initial state ($\Phi \approx 0$):

$$\mu_{A0} \approx \rho_0\left(\frac{V_{zx} + V_{zy}}{2}\right)^2,$$

$$K_{A0} \approx \rho_0\left(V^2_{zz} - \frac{4}{3}\left(\frac{V_{zx} + V_{zy}}{2}\right)^2\right), \quad (12)$$

$$\nu_{A0} \approx \frac{3K_{A0} - 2\mu_{A0}}{6K_{A0} + 2\mu_{A0}}.$$

The value of the modulus was $K_{A0} = 161.2\,\text{GPa}$, $\mu_{A0} = 79.2\,\text{GPa}$, Poisson's ratio $\nu_{A0} = 0.291$. The coefficients calculated using the expressions (2),(3) were $k^A_{K\psi,} = -3.87$; $k^A_{\mu\psi} = -1.39$.

The error of determination of the modulus K_{A0} and μ_{A0} practically does not affect the calculated value ψ because of the small impact of the crystallographic texture on the wave velocity.

The volume fraction of the strain martensite Φ was measured using multifunctional eddy current device „MVP-2M" with 1 kHz transducer. The device was pre-calibrated using samples with a known ferritic phase content. The application of this device is based on the fact that the magnetic properties of ferrite and ferromagnetic α'-martensite differ only slightly [17]. The relative measurement error did not exceed 5%.

3. Results and discussion

A change of the parameter $P_\Phi(\Delta P_\Phi = P_\Phi - P_0)$ was obtained depending on the loading cycles N according to the test results (Fig. 2). The cycles of loading with the range of strain amplitudes from 0.35 to 0.7% corresponds to the area of low-cycle fatigue, while the number of cycles of loading with strain amplitudes ranging from 0.25 to 0.3% corresponds to the transition from the area from low-cycle to the area of high-cycle fatigue.

The results of experimental studies showed that the stage of destruction is best illustrated by the dependence of $\Delta P_\Phi(\Phi)$ under loading in the range of strain amplitudes from 0.25 to 0.35% (Fig. 3). Stage 1 (incubation) and stage 2 practically merge at $\Delta\varepsilon > 0.35\%$. A sharp change of the parameter P_Φ at stage 1 ($\Phi \approx 0$) is apparently associated with the relaxation of residual microstresses during the first loading cycles, which is indirectly confirmed by the activity of acoustic emission signals at this stage for similar steel [18]. The curve $\Delta P_\Phi(\Phi)$, shown in Fig. 3, reflects the change of the combination of elastic modulus K and μ equation (6) at stage 2 due to the formation of the strain-induced martensite at stage 3 — both due to the formation of α'-martensite and the accumulation of micro-damage. The control of the parameter $\Delta P_\Phi(\Phi)$ allows determining the stage of metal destruction before the formation of a macrofracture.

Figure 4 shows the dependence $\psi(\Phi)$ for the third stage of destruction, obtained using the expression (11).

Let's determine the relative value of micro-damage, which is calculated as the ratio of the current value ψ to the critical value ψ^* (ψ^* — corresponds to the number of loading cycles N^* when a macro crack is formed). Fig. 5,*a* shows that the dependences of ψ/ψ^* on the content of the α'-martensite Φ split into two regions. The upper region corresponds to the strain amplitudes in the range from 0.25 to 0.5%, the lower

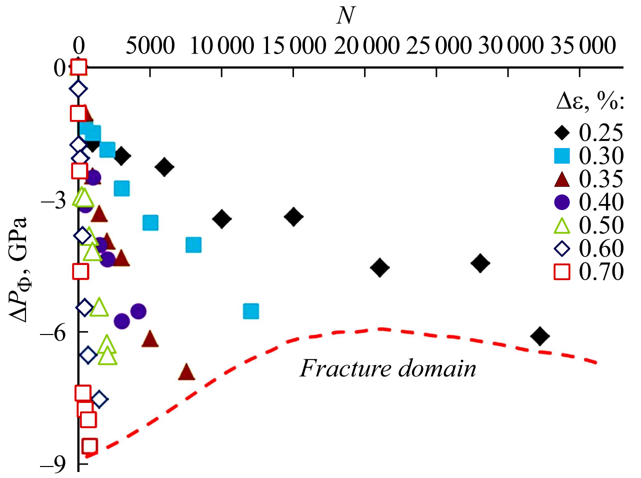

Figure 2. Dependence of the parameter change P_Φ on the number of loading cycles.

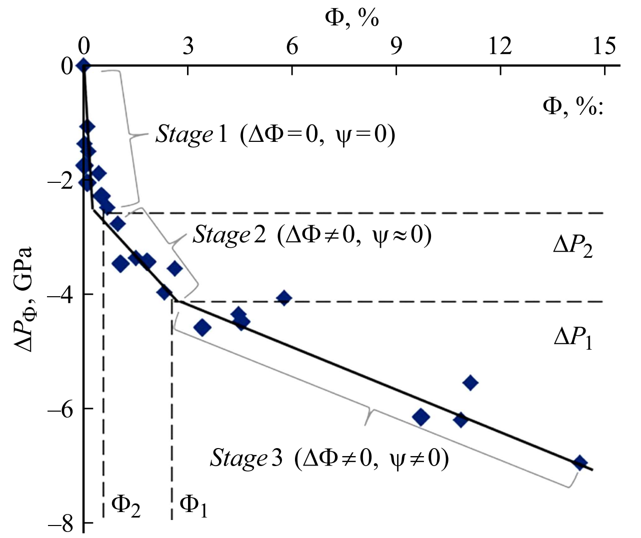

Figure 3. Staging of destruction depending on $\Delta P\Phi(\Phi)$ at strain amplitudes 0.25–0.35%.

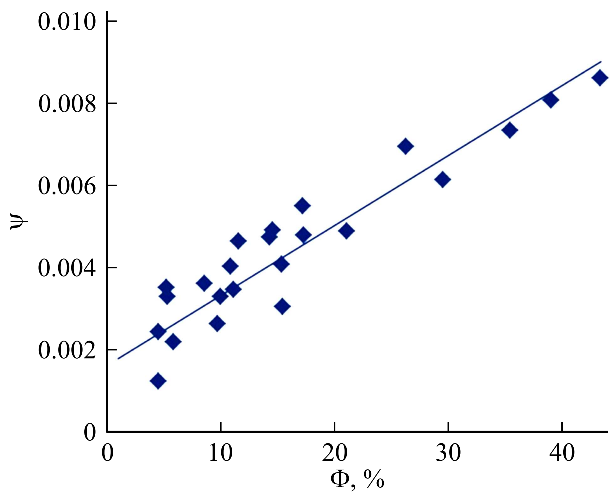

Figure 4. The dependence of micro-damage ψ on the volume fraction of α'-martensite Φ.

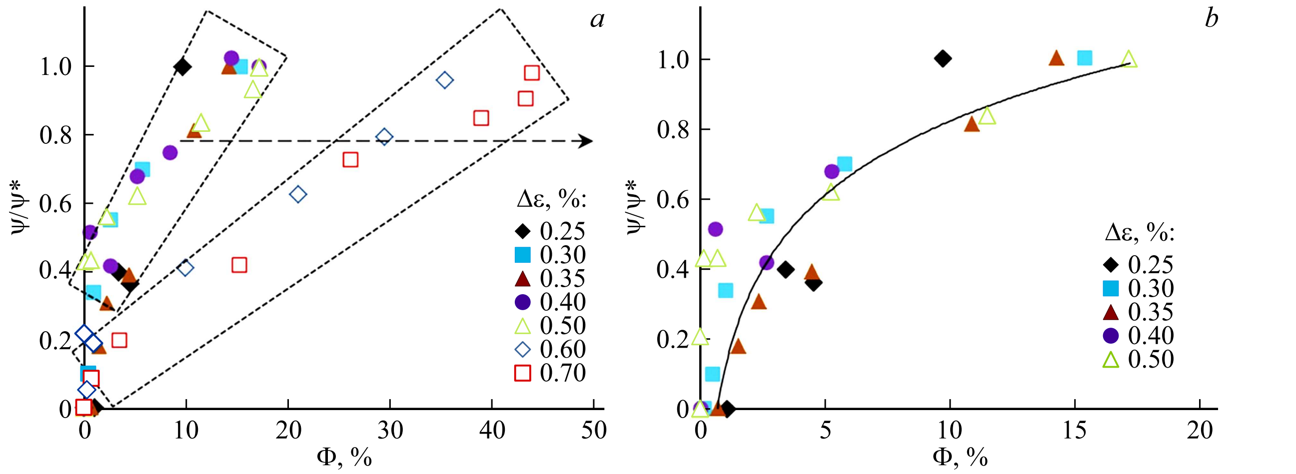

Figure 5. Dependence ψ/ψ^* on the change of the volume fraction of martensite Φ (a), for strain amplitudes from 0.25 to 0.5% (b).

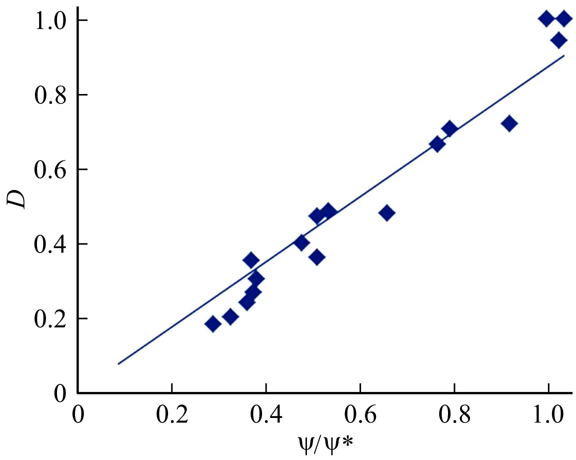

Figure 6. The relationship of the damage D with the value ψ/ψ^*.

region corresponds to the amplitudes of 0.6 and 0.7%, close amplitudes corresponding to repeated static loading.

The curves $\psi/\psi^*(\Phi)$ for the upper region (Fig. 5, b) are well described by the logarithmic relationship

$$\psi/\psi^*(\Phi) = 0.333\ln(\Phi) + 0.0858. \qquad (13)$$

The value $\psi/\psi^* = 1$ corresponds to the depletion of the material resource. ψ/ψ^* prediction error is about 10%, the correlation coefficient is ~ 0.9.

A regression dependence can be used to predict the value of ψ/ψ^* in the range of strain amplitudes of 0.25–0.7%

$$\psi/\psi^*(\Phi, \Delta P_\Phi) = k_{0\psi} + k_{1\psi}\Delta P_\Phi + k_{2\psi}\Phi + k_{3\psi}\frac{\Delta P_\Phi}{\Phi}, \qquad (14)$$

where $k_{0\psi} = 0.082$; $k_{1\psi} = -0.178\,\text{GPa}^{-1}$; $k_{2\psi} = -1.34$; $k_{3\psi} = 0.00197\,\text{GPa}^{-1}$.

The expression (14) allows for calculation of the ratio ψ/ψ^* using a combination of elastic wave velocities and the volume content of strain-induced martensite.

The relationship between ψ/ψ^* and damage $D = N/N^*$ $(0 \le D \le 1)$, calculated using the Palmgren–Miner linear summation hypothesis is described by a linear dependence with a correlation coefficient of 0.98 (Fig. 6):

$$D = 0.88\psi/\psi^*. \qquad (15)$$

Therefore, the algorithm presented in this paper for calculation of micro-damage together with the ultrasonic and eddy current measurement technique can be used as a method for determining the residual life of structural materials: $\text{Re} = 1 - D$, where the value D is determined from the expression (15).

Conclusion

It was found that the change of the elastic properties of austenitic metastable steel reflects the metal destruction stages: the incubation stage, characterized by small phase changes, the stage of intensive formation of strain-induced martensite and the micro-damage development stage.

A method is proposed for calculation of the micro-damage associated with the formation of micropores, micro-cracks in metastable steel subjected to fatigue. The method is based on the measurement of the propagation velocities of elastic longitudinal and shear waves and the volume fraction of strain-induced martensite. The advantage of the algorithm is that the calculation results are not affected by changes in the crystallographic texture of the material during cyclic deformation.

A high correlation of the obtained values of micro-damage of metastable steel exposed to fatigue was obtained with the values calculated in accordance with the damage linear summation rule — the Palmgren-Miner hypothesis.

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Conflict of interest

The authors declare that they have no conflict of interest.

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