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THE INFLUENCE OF IMPURITIES IN METAL ALLOYS AND FREQUENCY OF THE COMPELLED FLUCTUATIONS ON THE EVOLUTION OF FATIGUE DAMAGE

The article describes theoretical studies of the influence of vibration frequency on the development of fatigue failure of metal alloys. The influence of impurities in secondary aluminum alloys on Frank Read source dislocation is shown.

It was revealed that when critical stresses are reached, irreversible displacement and an increase in the number of dislocations occur, which means the beginning of the fatigue failure process. The obtained dependence made it possible to establish that the same degree of displacement of dislocations, with an increase in the frequency of forced oscillations, is achieved at high stresses.

Pilot testing of theoretical calculations showed the same nature of frequency dependences of threshold stresses, fatigue strength at cycles and critical stresses. Aluminum alloys (D16 and AK9M2) were subjected to loading by alternating bending in a wide frequency range (0.3–18.0 kHz).

Key words: dislocation, oscillation frequency, stress, fatigue characteristics, fatigue strength.

Introduction. Aluminum-based alloys in terms of production are inferior only to materials based on iron due to the presence of a complex of mechanical and technological properties [1, 2]. Very important is the task of increasing the use of secondary aluminum, the production of which allows reducing energy consumption several times in comparison with the primary metal [3–5].

In construction materials, including aluminum alloys, a certain type of defect structure is formed in order to ensure specific operational qualities of these materials, such as strength, elasticity, wear resistance, etc. This type of defect structure includes, among other things, extended and point defects and either stabilizes positions of the dislocations in space or allows their displacement within certain limits. Accordingly, certain properties of hardness, brittleness and elasticity of materials are ensured.

Aluminum alloys created with the use of recycled materials are characterized by a significant amount of impurities, a wide range of content of the main components, contamination with nonmetallic inclusions and heterogeneity of the structure. The presence of coarse inclusions of iron-containing phases is most dangerous for the complex of mechanical characteristics. These factors significantly complicate the physical picture of development of the fatigue destruction process and lead to the necessity to take into account the interaction of dislocations with impurity atoms. Moreover, due to the fact that many details (such as pistons and radiators) manufactured with the use of recycled materials operate at elevated temperatures, the model in development requires consideration of the temperature factor as well.

Main part. We have considered certain features of behavior of the dislocation segment placed under the effect of alternating stress of low and intermediate frequencies with consideration of the influence of temperature mechanisms on the elastic interaction of substitutional impurities with dislocations within the surrounding atmospheres of point defects. We have also analyzed the contribution of the said processes to characteristic parameters of metals describing properties of materials within the conditions similar to the fatigue loading conditions.

The critical stresses of the onset of microplasticity are the result of the triggering of dislocation segments according to the Frank-Read scenario and under alternating loading represent an analogue of the yield stress under static loading. Irreversibility of microscopic deformation for any type of loading is associated with the movement of already existing dislocations, as well as with the possibility of generating new dislocation loops by a fixed source.

The known principles of the dynamics of a dislocation segment in the description of internal friction in the string model approximation are adapted in this case to the problem of consideration of not only inertial, viscous and elastic forces, but also additional forces of interaction with impurity atoms. Impurities are known to form atmospheres around extended defects, and the motion of dislocations depends on the type and size of the foreign atoms of implantation and substitution.

Under the conditions of loads alternating over time, the temperature factors, as the literature sources and the results of the experiment show, have a certain effect on the strength characteristics. As a starting approximation, we choose a string model of the dynamics of a dislocation segment with a modified right side [6]. In accordance with the expansion of the dislocation theory of the absorption of the energy of the Köhler-Grenato-Lucca elastic vibrations by J. Swartz and J. Wirtman, a dislocation in the material is affected by a force that prevents its movement and is opposed to the applied stress. This force is due to the presence of binding energy between a helical, edge or mixed dislocation with an impurity atom from the surrounding atmosphere. The magnitude and sign of the binding energy are determined by the distance of the impurity atom to the dislocation core and its position with respect to the extraplane. An essential role in this is played by the difference in the size of the impurity atoms and the atoms of the material itself. On the other hand, the quantity or concentration of impurity atoms near the dislocation and their Friedel distribution are determined by the sign of the binding energy and the relation of this energy to the characteristic energy of the thermal vibrations included in the so-called Boltzmann factor.

In developing the model, it is assumed that in the model metallic material impurity atoms are predominantly substitutional atoms with radii greater than the atoms of the base; therefore, they are attracted to the region under the extraplane and have a negative binding energy in the resulting positions. Subsequently, under an external elastic stress of a variable sign such atoms will prevent the motion of the segment. This means that in such consideration, the value of the amplitude of the external stress effectively decreases. Accordingly, the differential equation describing the small oscillations of the segment in the field of the given alternating stress shall be represented in the following form:

$$A\frac{\partial^2\varsigma}{\partial t^2}+B\frac{\partial\varsigma}{\partial t}-C\frac{\partial^2\varsigma}{\partial y^2}=$$

$$=\left(b\sigma-\frac{bG\varepsilon c_0}{4}\exp\left[\left(\frac{W}{kT}\right)\right]\right)\sin\omega t, \qquad (1)$$

here $A = \rho b^2 / \pi$ – is the effective mass of dislocation per unit length; ρ – is the material density; b – is the Burgers vector; ζ – is the value of displacement of the dislocation segment from the equilibrium position along its length y, which is minimal at the fixation points and reaches its maximum at the center; t – is the time; B – is the coefficient determining the force of dynamic viscous friction of the segment, which is a function of temperature, as it is determined by electronic and phonon components of the effect on displacement of atoms from the equilibrium position;

$C=\dfrac{2Gb^2}{\pi(1-\nu)}$ – is the coefficient determining elastic effect of the segment on itself under tension; G – is the elastic displacement modulus; ν – is the Poisson's ratio; $b\sigma$ – is the amplitude value of the alternating force of external stress source acting with a cyclic frequency ω reduced to the dislocation length ω;

$\varepsilon=\dfrac{R_i-R_0}{R_0}$ – is the relative difference between the radii of the impurity atoms R_i and atoms of the material itself R_0; c_0 – is the bulk equilibrium concentration of impurity atoms at a distance from the dislocation segment;

$W(r)=\dfrac{GbR_0^3\varepsilon(1+\nu)\sin\theta}{3\pi(1-\nu)r}$ – is the general form of the expression for the binding energy of a segment with impurity atoms in the Cottrell atmosphere, considering their position with respect to the extraplane and their size with respect to the intrinsic atoms of the metal; r – is the distance from the dislocation core to the impurity atom, θ – is the azimuth angle between the Burgers vector and the radius vector of the impurity atom r, k – is the Boltzmann's constant; T – is the absolute temperature.

In the course of further calculations, to denote the effective stress of the elastic interaction of impurities with the dislocation segment partially compensating for the action of external alternating stress, we use the following notation:

$$D=\frac{G\varepsilon c_0}{4}\exp\left[\left(\frac{W}{kT}\right)\right].$$

To solve the equation (1), we have applied the operational method implying direct and inverse integral transformation in accordance with the expression:

$$\overline{\varsigma}(y,s)=\int_0^{\infty}\varsigma(y,t)\exp(-st)\,dt; \qquad (2)$$

$$\varsigma(y,t)=\frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty}\overline{\varsigma}(s,t)\exp(st)\,ds.$$

We have performed direct and inverse transformation of the time variables $\omega t \to t' \to t$ is performed, which allows us to bring the differential equation (1) from the form characterized by the presence of partial derivatives to the usual nonhomogeneous algebraic equation of the second order with constant coefficients for integral Laplace transforms.

$$\frac{d^2\overline{\varsigma}}{dy^2}-\frac{A\omega^2 s^2+B\omega s}{C}\overline{\varsigma}=$$
$$=-\frac{A\omega^2 s+B\omega}{C}\varsigma(t=0)-\frac{A\omega^2}{C}\frac{d\varsigma(t=0)}{dt}-$$
$$-\frac{b(\sigma-D)}{C}\frac{1}{1+s^2}. \qquad (3)$$

The solution of the given algebraic equation (3) makes it possible to determine the local displacement from the equilibrium position of the segment along its length. Applying the method of variation of the arbitrary Lagrange constant, we obtain:

$$\overline{\varsigma}(y,s)=D_1\exp(\Omega y)+D_2\exp(-\Omega y)+$$
$$+\left\{\frac{A\omega^2 s+B\omega}{C}\varsigma(t=0)+\frac{A\omega^2}{C}\frac{d\varsigma(t=0)}{dt}+\right.$$
$$\left.+\frac{b(\sigma-D)}{C}\frac{1}{1+s^2}\right\}\cdot\frac{C}{A\omega^2 s^2+B\omega s}, \qquad (4)$$

here $\Omega=\left[\frac{A\omega^2 s^2+B\omega s}{C}\right]^{\frac{1}{2}}$, and D_1 and D_2 are the integration constants, which are to be determined using realistic boundary conditions. In order to determine constants D_1 and D_2 we apply the condition on the zero displacement of the segment at the fixing points both for the direct time and for the reverse time after the Laplace transform. As a result, we get:

$$\overline{\varsigma}(y,s)=\left[-\frac{\exp(\Omega y)+\exp(-\Omega y)}{\exp(\Omega y)-\exp(-\Omega y)}+1\right]\times$$
$$\times\left\{\frac{A\omega^2 s+B\omega}{C}\varsigma(t=0)+\frac{A\omega^2}{C}\frac{d\varsigma(t=0)}{dt}+\right.$$
$$\left.+\frac{b(\sigma-D)}{C}\frac{1}{1+s^2}\right\}\cdot\frac{C}{A\omega^2 s^2+B\omega s}. \qquad (5)$$

As can be seen from the expression obtained, the area occupied by the dislocation segment in the process of oscillation under the action of an alternating force determines the degree of its readiness to trigger when the central part reaches a certain critical displacement from the equilibrium position.

For convenience of analysis and consideration of the cumulative nonequilibrium state of the segment, as the next step it is expedient to determine the average length of the displacement along the length through summation of local contributions:

$$\left\langle\overline{\varsigma}(s)\right\rangle=\frac{1}{2l}\int_{-l}^{l}\overline{\varsigma}(y,s)\,dy. \qquad (6)$$

As a result of taking the integral of (5) in accordance with expression (6), the average displacement along the length turns into a parameter depending only on the variable for the integral transformation s:

$$\left\langle\overline{\varsigma}(s)\right\rangle=\left[-\frac{\exp(\Omega l)+\exp(-\Omega l)}{\exp(\Omega l)-\exp(-\Omega l)}\frac{1}{\Omega l}+1\right]\times$$
$$\times\left[\frac{1}{s}\varsigma(t=0)+\frac{A\omega^2}{A\omega^2 s^2+B\omega s}\frac{d\varsigma(t=0)}{dt}+\right.$$
$$\left.+\frac{b(\sigma-D)}{A\omega^2 s^2+B\omega s}\frac{1}{1+s^2}\right]. \qquad (7)$$

After the reverse integral transformation procedure according to Scenario (2) using the contour integration for complex variable functions and the theory of residues, the average displacement of the dislocation segment as a function of time takes the following form:

$$\left\langle\varsigma(t)\right\rangle=\frac{b(\sigma-D)l^2}{3C}\left[\frac{\exp(i\omega t)}{2i\left(1+\frac{i\omega Bl^2}{2C}\right)}-\right.$$
$$\left.-\frac{\exp(-i\omega t)}{2i\left(1-\frac{i\omega Bl^2}{2C}\right)}+\frac{\exp\left(-\frac{2C}{Bl^2}t\right)}{\left(1+\frac{4C^2}{\omega^2B^2l^4}\right)\frac{\omega Bl^2}{2C}}\right]. \qquad (8)$$

In accordance with (8), the average displacement of the dislocation segment has an oscillating component as well as a component of the relaxation type. Such a solution corresponds to the presence of a transient process and to the steady motion at the frequency of the exciting external force.

As can be seen from numerical estimates, the characteristic relaxation time $Bl^2 / 2C$ for a wide range of metals is about 10^{-1}–10^{-5} seconds. Consequently, during a very short period after activation of the external load, the transient processes within the relaxation time $Bl^2 / 2C$ are completed, and only the asymptotic values of parameters characteristic of the forced segment oscillations remain. Therefore, the asymptotic average displacement along the length as a function of time can be represented in the following form:

$$\langle \varsigma(t) \rangle = \frac{b(\sigma - D)l^2}{3C} \times$$

$$\times \frac{\exp(i\omega t)\left(1 - \frac{i\omega Bl^2}{2C}\right) - \exp(-i\omega t)\left(1 + \frac{i\omega Bl^2}{2C}\right)}{2i\left(1 + \left(\frac{\omega Bl^2}{2C}\right)^2\right)}. \quad (9)$$

Using Euler's formula, expression (9) can easily be reduced to expressions containing trigonometric functions:

$$\langle \varsigma(t) \rangle = \frac{b(\sigma - D)l^2}{3C} \left\{ \frac{\sin(\omega t) - \frac{\omega Bl^2}{2C}\cos(\omega t)}{1 + \left(\frac{\omega Bl^2}{2C}\right)^2} \right\}. \quad (10)$$

In expression (10), the average displacement along the length of the segment contains two components: the one coincident in phase with the exciting force and the one shifted in phase by $\pi / 2$. The in-phase one with the exciting force of the segment displacement component corresponds to the net dissipationless movement of the segment and the phase-shifted component of the motion determines the weight of the viscous friction forces. Formally, when the dynamic viscosity coefficient tends to a large value, the expression for the displacement amplitude can be reduced to the following form:

$$\langle \varsigma(t) \rangle = -\frac{2b(\sigma - D)}{3\omega B}\cos(\omega t). \quad (11)$$

It follows from (11) that in the presence of significant viscous forces, the displacement amplitude averaged along the length of the segment will be negligible. It is clear that with a high level of mechanical energy dissipation, it is possible to ensure sufficient bending of the segment leading to the generation of new dislocations, given the considerable amplitudes of the external elastic stresses.

Due to the presence of additional impurities, we have also considered another limit with respect to the forces of viscosity, in which the dissipative component in the motion of the segment is less significant. In this event, the expression for the displacement of the segment will contain both the in-phase component and the component that is phase-shifted by a quarter of the period. This allows us to determine the threshold value of the external stress, which leads to the onset of generation of new dislocation segments:

$$\sigma = \langle \varsigma(t) \rangle \left(1 + \left(\frac{\omega Bl^2}{2C}\right)^2\right) \times$$

$$\times \frac{6Gb}{\pi(1 - \nu)l^2} + \frac{G\varepsilon c_0}{4}\exp\left(\frac{W}{kT}\right). \quad (12)$$

The transformation of expression (9) allows us to obtain the value of the stress of external alternating forces, which essentially corresponds to the cyclic limit of elasticity, which in depends on temperature to a certain extent:

$$\sigma = \frac{Gb}{l}\left[\frac{6}{\pi(1 - \nu)}\left(1 + \left(\frac{\omega Bl^2 \pi(1 - \nu)}{4Gb^2}\right)^2\right) + \right.$$

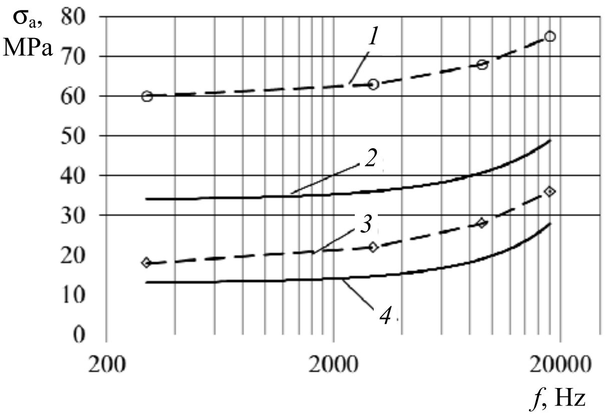
$$\left. + \frac{l\varepsilon c_0}{4b}\exp\left(\frac{W}{kT}\right)\right]. \quad (13)$$

The transformation of expression (13) in the first approximation gives us certain relationship between the level of the threshold voltage leading to the effective triggering of the dislocation segment and material parameters. It should be noted that the elastic moduli themselves are weak temperature functions and even in the static load approximation the threshold stresses of the yield strength decrease insignificantly with temperature.

For experimental check of the values of critical stresses and comparison of fatigue characteristics determined at different test frequencies, it is suggested to use the threshold values of cyclic loads corresponding to the stresses below which the irreversible fatigue damageability is absent at unlimitedly large test bases. Threshold stresses were determined by means of X-ray structural and microstructural analyses as well as analysis of microhardness and electrical resistance upon reaching the level of cyclic stresses, below which changes in the parameters of these physical and mechanical properties were not registered by instruments. A significant growth of the above characteristics was recorded with the increase in the level of threshold characteristics and the beginning of hardening [9]. Усталостные испытания реализовывались с использованием оборудования и методик, описанных в статьях [10–14].

Good correlation of experimentally determined threshold values and critical stresses of the beginning of the process of fatigue destruction of the found theoretical values shall also me noted (figure).

Comparison of the curves of frequency dependencies of threshold stresses and endurance liits of the materials determined in the examined frequency range demonstrated their equidistance, which was observed at normal and elevated temperatures for various test bases using both longitudinal and bending oscillations. Thus, the difference between the limited endurance limits and the magnitude of threshold stresses for each material in the examined frequency range is a constant value. Due to the fact that threshold stresses are determined in a very simple manner, for example, by changes in micro-hardness, it is possible to predict characteristics of low-frequency fatigue strength using the results of high-frequency tests [15]. This approach allows reducing the costs associated with the research significantly.



Threshold (1, 3) and critical (2, 4) stresses for alloys D16 (1, 2) and AK9M2

Conclusions. 1. Recording of interaction of the dislocation segment with the impurity atoms demonstrated that the threshold stress value at lower temperatures is more sensitive to distribution of impurities in the segment region, while in the region of high regions the presence of non-equilibrium configurations of impurity atoms influences dynamic properties of the segment to a lesser extent. This is due to the fact that at low temperatures the concentration of impurity atoms in the Cottrell and Snooke atmospheres increases to the point of saturation and precipitation of separate new phases; as the temperature increases, clouds of impurity atom atmospheres near dislocations dissipate up to the equilibrium concentration characteristic of the regions distant from extended defects.

2. The obtained dependence of critical stresses of the beginning of the fatigue destruction process on the frequency of alternating oscillations allows refining physical model of development of the fatigue destruction process of the studied aluminum alloys. It should be noted that the temperature influences the motion of the dislocation segment in a twofold manner: through the dynamic viscosity coefficient, which at temperatures of around the Debye temperature and higher is a linear temperature function, and through the elastic forces of interaction of the segment with impurities in long-range stress fields.

3. The experimental check (comparison of the curves of the frequency dependencies of critical stresses and threshold stresses determined experimentally) demonstrated their identical character (located almost equidistantly) both for the deformable alloy (D16) and for the cast alloy (AK9M2) obtained using recycled materials. This allows us to talk about the possibility of use of this model to predict characteristics of low-frequency fatigue of a wide range of metallic materials containing significant amounts of impurity atoms.

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