ANISOTROPY OF FRACTURE TOUGHNESS CHARACTERISTICS OF PRESTRAINED ORTHOTROPIC MATERIAL UNDER UNIAXIAL CYCLIC LOADING

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ABSTRACT

Anisotropy of fracture toughness characteristics of an orthotropic plastically prestrained material under uniaxial cyclic loading is studied experimentally. The study was carried out using flat specimens with a lateral notch. The specimens are cut out from the rolled strip of titanium alloy at different angles to an anisotropy axis. As the fracture toughness characteristics, a number of cycles to failure, critical crack size, critical value of a stress intensity factor, and crack growth rate on the interval of crack stable propagation are used. It is shown that the more strong crack strength is observed, if the crack propagates perpendicularly to the direction of rolling. Such regularity is attributed to the fact that in the case under consideration the crack necessitates to cross the additional number of grain boundaries compared with the case, when it propagates along the rolling direction.

Prestraining the sheet strip in the range of small plastic strains under uniaxial tension in the rolling direction leads to deterioration of the anisotropy of the fracture toughness characteristics. If the specimen axis is oriented at an angle to the anisotropy axis, the crack propagates not along the normal to the load applied, but at the angle to it. The value of such deviation depends on the load orientation relative to anisotropy axes. In this case fracture occurs by combination of opening and transverse-shear modes.

Keywords: anisotropy, fracture toughness, prestrained orthotropic material, cyclic loading

1. INTRODUCTION

In the course of production of semifinished items, in particular, by plastic form, metallic materials acquire anisotropy of mechanical properties and become, as a rule, orthotropic. The anisotropy of mechanical properties of such materials have been studied adequately and outlined in [1-4]. Works [5-7] address the influence of plastic prestraining on fatigue strength of isotropic or quasi-isotropic materials, works [8-10] consider such influence on fracture-toughness characteristics. The present paper studies the effect, which the prestraining exerts on the fracture toughness characteristics of an orthotropic material under cyclic uniaxial loading in tension.

2. EXPERIMENTAL PROCEDURE

As the object for studying, titanium-based alloy VT-6, which is the analoque of MILT 9047G alloy (USA, ASTM) and 2TA.28 alloy (UK) [11], was used. The VT-6 alloy was studied in the form of sheet rolled products. As it was shown in [1, 2], this alloy is orthotropic with regard to the yield and ultimate strengths. Note that titanium-based alloys have such peculiarities as a hexagonal lattice and limited number of slip planes. Mechanical properties of the material (yield strength σ_{ys},ultimate strength σ_{us}, uniform component of plastic elongation ε^{p}, Young's modulus E, and Poisson's ratio μ) are presented in Table 1.

Table 1. Mechanical properties of the material in the initial state.

Orientation of specimens	σ_{ys}, MPa	σ_{us}, MPa	ε^{p},%	$E \cdot 10^{-5}$, MPa	μ
along the rolling	800	1020	3,1	1,12	0,31
across the rolling	730	980	2,4	1,10	0,32

The study was carried out with flat specimens having a V- shaped lateral notch. The specimens were cut out from plates at different angles to the rolling direction. The widt *b* of the specimens, their thickness *t*, and depth *h* of the notch are 27, 2, and 4 mm, respectively. The specimens were loaded in uniaxial cyclic tension with constant amplitude of nominal stresses $\sigma_n = \frac{P}{(b-h)t}$ (here *P* is the maximum value of the load), using the ZDMU-30t modernized testing machine, at the frequency *f* = 50 cycle/min and stress ratio *R*= 0.1.
As the crack-toughness characteristics, we took the number of cycles *N* to fracture, the value of the fracture stress σ_c, the critical crack length l_c the critical value of the stress intensity factor K_{1C}, and velocity of the crack propagation at the stage of stable growth. To evaluate the influence of strain hardening, we tested the plates prestrained in the rolling direction up to the certain prescribed level of the plastic strain ε^{1p}. During testing we determined, using a cathetometer, the crack length. Based on these data, kinetic curves of crack growth were plotted. The critical value of the crack length was found by measuring a spot of the fatigue fracture. The value of the fracture stress σ_c we determined by the formula

$$\sigma_c = \frac{P}{(b-l_c)t}(1+\frac{3l_c}{b-l_c}) . \qquad (1)$$

The kinetic curves are plotted in *l* versus *N* and lg *dl/dN* versus lg K_1 coordinates, where K_1 is the stress intensity factor, which was calculated by the formula

$$K_1 = \frac{Pl^{3/2}}{bt}Y . \qquad (2)$$

Here $Y = f(1/b)$ is the function of the relative crack length determined by

$$Y = 1{,}99 - 0{,}41\left(\frac{l}{b}\right) + 18{,}7\left(\frac{l}{b}\right)^2 - 38{,}48\left(\frac{l}{b}\right)^3 + 53{,}85\left(\frac{l}{b}\right)^4 . \qquad (3)$$

The kinetic curves at the stage of stable growth were approximated by the empirical Paris equation [12]

$$\frac{dl}{dN} = C(\Delta K_1)^m, \tag{4}$$

where C and m are the material chacacteristics. This equation for the broad circle of materials is in a good agreement with experimental data. Here $\Delta K_1 = (1-r)K_{1\max}$, $r = K_{1\min}/K_{1\max}$. As the disadvantage of this equation, the fact can be mentioned that it does not describe kinetic curves at the initial and final sections of the fatigue fracture diagram.

Characteristics C and m were determined using the least-square method by formulas

$$C = \frac{\sum_{i=1}^{n}\left(\lg\frac{dl}{dN}\right)_i \sum_{i=1}^{n}(\lg K_{1i})^2 - \sum_{i=1}^{n}(\lg K_{1i})\sum_{i=1}^{n}\left(\lg\frac{dl}{dN}\right)_i \lg K_{1i}}{n\sum_{i=1}^{n}(\lg K_{1i})^2 - \left(\sum_{i=1}^{n}\lg K_{1i}\right)^2};$$

$$m = \frac{n\sum_{i=1}^{n}\left(\lg\frac{dl}{dN}\right)_i \lg K_{1i} - \sum_{i=1}^{n}\lg K_{1i}\left(\lg\frac{dl}{dN}\right)_i}{n\sum_{i=1}^{n}(\lg K_{1i})^2 - \left(\sum_{i=1}^{n}\lg K_{1i}\right)^2}, \tag{5}$$

where n is the number of experimental points.

3. RESULTS AND DISCUSSION

The plots σ_n verses N given in the semilogarithmic coordinates are presented in Fig.1. Here σ_n is the maximum value of the cycle amplitude, N is the number of cycles to the specimen fracture. Here the following designations are adopted: 1 and 2 – stand for the crack oriented in the direction of rolling, 3 and 4 – for the crack oriented perpendicularly to the rolling direction; 1 and 3 – stand for ε^{1p} =0, 2 and 4 – for ε^{1p} =3%.

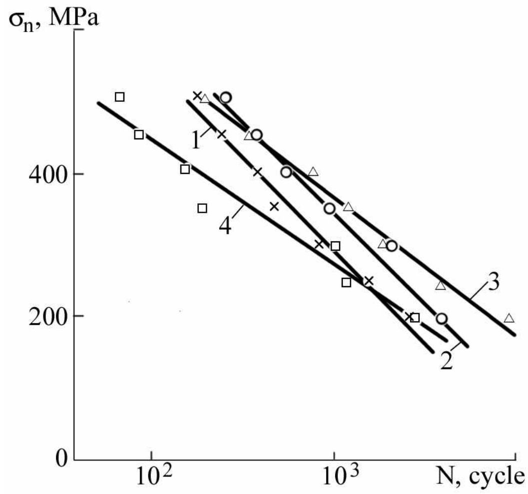

Figure 1. Dependences of the stress σ_n on the number of cycles N to fracture.

Figs.2 and 3 show kinetic curves of the crack growth in the material in initial $(\varepsilon^{1p} = 0)$ and deformed $(\varepsilon^{1p} = 3\%)$ states for σ_n = 400 MPa: in Fig.2 as the crack length l versus the number of cycles of loading N, in Fig.3 as the crack velocity dl/dN versus the stress intensity factor K_1. The designations are identical to those in Fig.1. As is seen from the plots presented, the material in the initial state (curves 1 and 3) is anisotropic relatively to fracture strength, i.e. it displays different crack toughness characteristics in the direction of rolling and in the perpendicular direction. In this case the most strong fracture strength is held when the crack is oriented perpendicularly to the rolling direction. Such character of anisotropy is caused by presence of an aligned structure stipulated by the rolling. For this reason the crack, in moving at the right angle to the rolling direction, is forced to cross the most number of barriers in the form of grain boundaries.

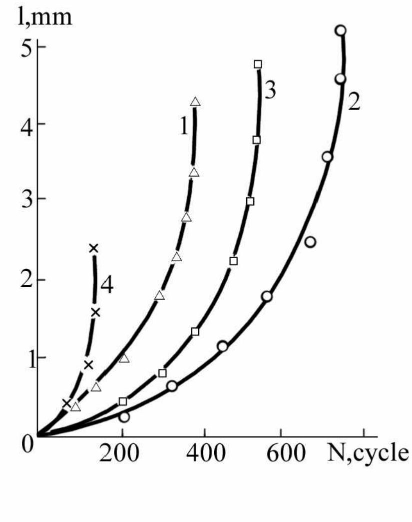

Figure 2. Kinetic curves of crack propagation.

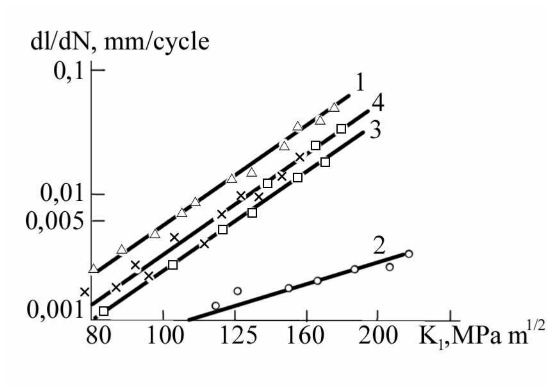

Figure 3. Dependences of the crack growth velocity on the value of the stress intensity factor.

Plastic deformation of the material in uniaxial tension in the rolling direction has caused decrease of fracture strength in the case, when the crack is oriented perpendicularly to the rolling direction. If the crack is aligned with the rolling direction, the fracture strength increases. Thus, the plastic deformation under rolling and the following uniaxial tension effect essentially on the kinetics of a fracture process, resulting in decrease of the crack growth velocity in the one case and in its increase in another case. In the case being considered we observe sharpening of the anisotropy of the crack growth velocity. The kinetic curves in coordinates *dl/dN* versus K_1 are satisfactorily approximated by expression (4).

Numerical values of the durability *N*, critical crack length l_c (with allowance for the notch depth), and critical value of the stress intensity factor K_{1C} for different levels of the maximum stress σ_n of the cycle are presented in Table 2. Here the values corresponding to the crack aligned with the rolling direction are given in the numerator and those corresponding to the transverse orientation of the crack are given in the denominator.

Along with the investigation of the anisotropy of the fracture strength of VT-6 alloy we studied the trajectory of the crack propagation depending on the orientation of a specimen relative to the axes of anisotropy in the as-received state $(\varepsilon^{1p} = 0)$ and after preliminary plastic deformation. The investigation showed that, if the specimen is oriented in the rolling direction or perpendicularly to it (φ =0 and $\varphi = 90^{\circ}$, respectively), the crack at the stage of stable growth propagates in the direction of the notch axis. In this case fracture is of the opening-mode type.

If the specimen is oriented at the angle φ (0<φ <90) to the rolling direction, the crack keeps the form of a straight line and propagates at the angle α to the notch axis that is indicative of two-faced character of fracture, combining in such a way opening and transverse-shear modes. In this case at the finishing stage the crack turns in the direction of the normal to the load applied.

Table 2. Values of fracture-toughness characteristics under cyclic loading.

σ_n, MPà	*N*, cycle		l_c, mm		K_{1C}, MPa $\cdot$ м$^{1/2}$	
	$\varepsilon^{1p} = 0$	$\varepsilon^{1p} = 3\%$	$\varepsilon^{1p} = 0$	$\varepsilon^{1p} = 3\%$	$\varepsilon^{1p} = 0$	$\varepsilon^{1p} = 3\%$
200	$\frac{2588}{8898}$	$\frac{3800}{2595}$	$\frac{17,3}{15,5}$	$\frac{13,9}{12,8}$	$\frac{312}{374}$	$\frac{294}{244}$
300	$\frac{822}{1878}$	$\frac{2070}{1070}$	$\frac{11,2}{12,5}$	$\frac{12,6}{9,9}$	$\frac{291}{352}$	$\frac{360}{242}$
350	$\frac{467}{1202}$	$\frac{948}{176}$	$\frac{10,7}{12,0}$	$\frac{12,0}{8,0}$	$\frac{315}{385}$	$\frac{377}{214}$
400	$\frac{389}{773}$	$\frac{556}{151}$	$\frac{10,7}{10,5}$	$\frac{11,2}{7,9}$	$\frac{357}{351}$	$\frac{386}{239}$
450	$\frac{252}{343}$	$\frac{361}{84}$	$\frac{9,9}{8,4}$	$\frac{10,1}{7,8}$	$\frac{359}{528}$	$\frac{370}{266}$

Fig.4 shows the dependence of the angle α, which defines the orientation of the crack trajectory, on the angle φ characterizing direction of the specimen cutoff respectively to the rolling direction. Here the following designations are used: 1- ε^{1p}=0; 2 - ε^{1p}=1%; 3 - ε^{1p}=3%.

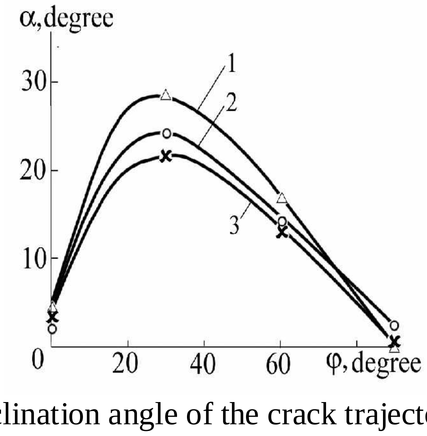

Figure 4. Dependence of the inclination angle of the crack trajectory on specimen orientation.
As is seen, the character of the dependences presented for the mentioned states qualitatively is identical. The maximum deviation of the crack trajectory from the notch axis is held for

$\varphi \approx 30^{\circ}$ and reaches 28° for the material in the initial state. In the case of the prestrained material to ε^{1p} =1% and ε^{1p} =3% it decreases to 23° and 21°, respectively.

4. CONCLUSIONS

Based on the investigation carried out, it should be noted the following.
The orthotropic VT-6 alloy studied under conditions of uniaxial cyclic tension in the initial state reveals different fracture toughness in the rolling direction and in the perpendicular direction. Moreover, the value of the fracture toughness is higher in the second case compared with the case, when the crack propagates along the rolling direction. This fact can be attributed to presence of a crystallographic oriented structure. Plastic deformation under uniaxial tension in the rolling direction causes decrease in the fracture strength for specimens oriented perpendicularly to the rolling direction and increase in the fracture strength of specimens with the crack oriented along the rolling direction.
If the load is applied at the angle to the anisotropy axes, the crack propagates not along the normal to the applied load but at the angle to it. Value of this deviation depends on the load orientation with respect to anisotropy axes. In this case fracture occurs as combination of opening and transversal-shear modes, i.e. is characterized by two stress intensity factors – K_1 and K_{11}. The plastic deformation that has been realized under single uniaxial tension leads to perturbation of the crystallographic structure formed during rolling, whereby the new structure due to smallness of the strain has yet to be formed. This fact is the reason why the above regularities concerning the existence of the anisotropy of fracture-toughness characteristics are held.

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