INITIATION AND PROPAGATION MECHANICS OF LOW CYCLE FATIGUE CRACKS IN BOLTS

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ABSTRACT

Force and stress distribution, conditions of initiation and propagation of cracks in threads of model bolt (stud) joints at low cycle loading have been studied. The experiments were made on threaded joints having diameters from 8 to 52 mm with number of cycles 1-5.10^4. During the experiments, forces, general strain, crack length and the number of cycles were measured. It is shown that with the increase of loads and number of cycles, local plastic strains arise in threads and lead to static and cyclic creep. Cracks appear in the first thread. Their rate is described by equations of Paris-Forman type. The final fracture is described by equations of linear fracture mechanics. Formulae for life calculation are given.

KEY WORDS

Bolt (stud); low-cycle fatigue; crack; crack growth rate; fatigue life calculation; local plastic strains; force relaxation.

PREFACE

Threaded joints are important elements of many machines and installations, defining in many cases the strength and life of the whole structure. Because of the high demands to structure reliability, during calculation and designing of threaded joints there usually arise the tasks of achieving static strength and durability under variable external loads on the stage of crack initiation. The supporting power of threaded joints under static ($N = 1$) and multi-cyclic ($N \geqslant 10^5$) loadings has been sufficiently studied up to the present moment (Serensen, Kogaiev, Shneiderovich, 1975; Heywood, 1969, etc.) The increase of working parameters of modern highly loaded devices leads to an essential increase of structural elements strain; therefore specified life (the general number of their loadings) may be equal to 10^2-10^4 cycles (low-cycle loading range).

However, up to the present time the particularities of the processes of strain and fracture of threaded joints under low-cycle loading have not been sufficiently studied because of the complexity of both theoretical and experimental research of processes taking part in coupled elements (stud-nut) (Snow, Langer, 1967; Norms, 1973; Kagan, Liaonavichius, Kazmitskas, 1976; Zatsarinny, Ioselevich, Kagan, 1979).

Due to increased nominal stresses, non-uniformity of force distribution and stress concentration under repeated low-cycle loading, plastic strains arise on the thread root.

Alongside with local plastic strains, to the features of initiation and growth of low-cycle fatigue cracks in threaded joints belong reduced life on the stage of crack formation and brittle ultimate fracture due to the high strength and reduced plasticity of the metal of bolts (studs).

EXPERIMENTAL PART

The experimental research program envisaged the studying of the supporting power of threaded joint models (stud-nut, stud-body) under static and cyclic axial loading, taking into consideration their structural forms, scale factor, production process and the kinetics of cyclic fracture in zones of high stress concentration and strains (of thread roots). For life calculation estimate of threaded joints on the stage of crack initiation, analysis data of local elasto-plastic strains and low-cycle fracture curves have been used.

The tests were made at room temperature on stud joints with diam. from 8 to 52 mm; the number of cycles to fracturing was from $N = 1$ till $N = 5.10^4$. The maximum stresses of the cycle varied in the range from 0,4 till 1,4 from the yield limit $\sigma_{0,2}$; the coefficient of loading cycle asymmetry R varied from 0 to 0,6; loading frequency was not larger than 10 cycles/min. For studs were used low-alloy steels with mean mechanic properties given in Table 1. In all cases nuts of compression were used; the dimensions of the nut (its height and external diameter) widely varried. According to the standard recommendations for steel threaded joints the nut height is usually equal to (0,8-1,0)d; the screwing length in the joints stud-body is (1,2-1,6)d, where d is the thread diameter.

TABLE 1 Mechanical properties of studied steels

Steel	σ_Y	σ_u	ψ	δ_5	Used for producing			Stud size
	MPa		%					
25X1MФ Normalization 1030-1050°C tempering 630-650°C	935	1035	58	16	+	+	+	M20
25X1MФ hardening 900°C tempering 650°C	750	1055	50	18,5	+	+	+	M24x1
12X2MФA normalization	455	525	75				+	

For estimating the loading of threads, strain measurement of force values under conditions of static and repeated loading was made. The parameters of material strain and fracture have been defined on standard cylindrical specimens.

Studs, nuts and bodies have been made by means of turning. The thread root of the nuts (bodies) was made plane cut, and the thread root of the studs - both curved along the radius and plane cut. The radius of curvature of the thread root was $\tau = (0,108-0,144)\cdot S$,where S is the pitch of thread in mm. The control of the parameteres of stud thread was performed on a universal stage microscope; the control of the parameters of nut thread was made by means of a set of gauges.

The studying of the process of fracture in a model threaded joint (Fig. 1a) was made by means of the luminescentmagnetic method and optical microscope. The stud (1) was loaded by an axial force P , transferred to the nut (2) and flange (3) through a system of intermediate elements (4). The displacements between the ends of the nut and the flange were measured by a tensometer (5). The forces P in the time τ varied in a pulsating (R = 0) and asymmetric (R=0,3 and R=0,6) cycle (Fig. 1b).

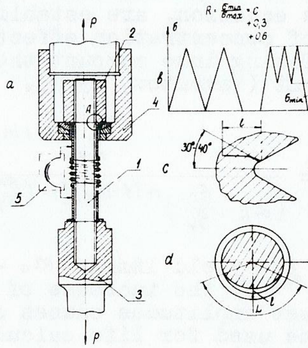

Fig. 1. Scheme of the structure unit and loading scheme.

The analysis of force distribution in threads and of the stressed state in the thread shows that in the stud-nut joint approximately 1/3 of the applied to the joint load falls on the first (from the nut bearing surface) thread. Exploitation practice and the results of experimental research show that cyclic fracture mainly takes place in this location.

The most loaded place in coupled thread is the point (in the thread root of the stud), near to the beginning of the transition from the arch of the curvature radius to the rectilinear part of the thread profile (for the thread with a curved profile of the root when $\tau = 0,144\ S$). For threads with a smaller value of $\tau < 0,1\cdot S$ the most loaded place is in the middle of the arch; for plane cut threads - in the point of intersection of the rectilinear part with the cut-off line. The crack is initiated just in this place (Fig. 1c).

The direction of the initial crack development according to Fig. 1c corresponds to the direction of the greatest tangential stress with successive transition to the direction perpendicular to the stud axis. The inflection point is on the depth 0,2-1,5 mm and its place depends on the level of applied maximum stresses, material properties, joint dimensions and precision of their production. Schematization of the kinds of low-cycle fracture of threaded joints is shown in Fig. 2.

The calculation of the threaded joints cyclic strength on the stage of crack formation is made with use of degree equations of Manson-Langer type and strain concentration coefficients K_e which are larger than theoretic concentration coefficients α_σ

$$\varepsilon_a = \frac{1}{4N^m + \frac{1+r_e}{1-r_e}} \ln \frac{100}{100-\psi} + \frac{\sigma_{-1}/E}{1+\frac{\sigma_{-1}}{\sigma_B}\;\frac{1+r_e}{1-r_e}}$$

where $\varepsilon_a = \frac{\sigma_{na}}{E} K_e$ is the amplitude of local cyclic strains, defining the crack initiation; σ_{na} - the amplitude of nominal stresses; E - elastic modulus; ψ - necking; σ_{-1} - fatigue limit; $m \simeq 0{,}5$; $r_e = \varepsilon_{min}/\varepsilon_{max}$ - coefficient of strain asymmetry.

The conditions of crack formation in the thread root, defined on the basis of this equation, are established with taking into account the increase of concentration effects due to the appearance of plastic strains. Taking into account these strains, the strain concentration coefficient (Makhutov, 1971).

$$K_e = \frac{\alpha_\sigma^{2/(1+m_o)}}{\left(\alpha_\sigma \cdot \frac{\sigma_n}{\sigma_Y}\right)^{n(1-m_o)[1-(\frac{\sigma_n}{\sigma_Y} - \frac{1}{\alpha_\sigma})]/(1+m_o)}}$$

where: σ_Y is the yield limit; m_o - the strengthening index ($\sigma = \sigma_Y (e/e_Y)^{m_o}$). The increase of the coefficients of stress asymmetry at pre-set amplitudes causes stud life decrease. The above equation can be used for life calculation of large diameter (more than 100 mm) studs.

On the stage of crack initiation and propagation, at a low number of loading cycles, loading combines with creep and relaxation of the bolt stress beginning with the levels of nominal stresses approximately $0{,}6 \cdot \sigma_{0,2}$ (static and cyclic creep) (Zatsarinny, Iosilevich, Kagan, 1979). At initial stud tightening ($N = 1$) the creep increases with the increase of stress and dwell time (τ); at cyclic loading, creep and relaxation processes slow down substantially (Table II)

TABLE II Accumulated creeps in the stud at static and cyclic loading on the stress level $\sigma_{max} \simeq \sigma_{0,2}$

Dwell time τ, min	Creep, %		
	Static loading	Cyclic loading	
	N = 1 cycle	N = 100 cycles	N = 100 cycles
1	0,043	0,0044	0,0022
10	0,06	0,0071	0,0036
100	0,09	-	-

The analysis of isocyclic and isochronic static and cyclic strain curves for different cycle numbers N and dwell times τ permits to calculate the processes of creep and relaxation for establishing the tightness and working capacity of threaded joints.

The abovementioned strains lead to the decrease by 4-7% of tightening forces at nominal stresses $\sigma_n \leqslant \sigma_{0,2}$.

The kinetics of crack development is characterized by the initiation of crack along the first loaded thread, by fast crack growth along the circumference of the first thread and by decrease of crack rate into the depth of the cross section. At stresses which are near to the yield limit $\sigma_{0,2}$, the outline of the crack front is near to circumference, displaced from the cross section centre of gravity (Fig. 2a). Which the decrease of the cycle maximum stresses the outline becomes ellipsoidal (Fig. 2b). When the value $\sigma_{max} = 0{,}5 \cdot \sigma_{0,2}$ is reached, the ellipse is displaced and touches the root (Fig. 2c).

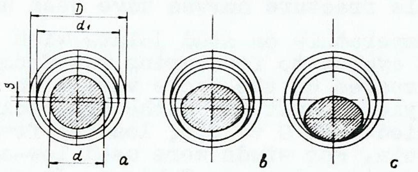

Fig. 2. Schematization of the kinds of low-cycle stud fracture.

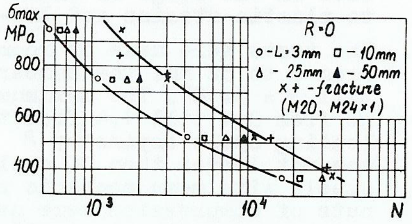

Fig. 3. Resistance to low-cycle fracture of joints stud-nut M20 and M24x1 from steel 25X1MФ.

The fatigue fractures of the studs can be divided into 3 zones: the crack initiation zone, the development zone and the zone of accelerated development in the last cycles before ultimate fracture.

The interaction of adjacent threads of the nut and the stud influences the crack propagation and its expansion angle. Therefore the transition from the zone of crack accelerated development to the ultimate fracture takes place under conditions which make difficult the process of brittle failure. The transition from accelerated fatigue failure combines with tough failure, decreasing the zone of brittle ultimate fracture.

When the radius of curving at the stud thread root decreases ($r \leqslant 0{,}108 \cdot S$) or when the root is plane cut the crack propagation character changes. The crack propagation in the thread root along the circumference b takes place during a small number of cycles and tenacity of such threaded joint mainly depends on the crack propagation into the depth of the cross section ℓ. The characteristic view of the fractures during tests on low-cycle fatigue of threaded joints from M8 to M52 does not practically change.

Figure 3 shows the data on the resistance to low-cycle fatigue of the threaded joint M20 stud-nut at R = 0 on different stages of fracture, and threaded joint M24x1 at ultimate fracture (experimental points and envelopes). Depending on the level of cycle maximum stresses the ratio of total life on the stage of crack formation decreases at the decrease of loading level (the increase of the number of cycles to fracture) and changes from 3,5 to 2 at the change of maximum stress from $\sigma_{max} = 1{,}1 \cdot \sigma_{0,2}$ to $\sigma_{max} = 0{,}4 \cdot \sigma_{0,2}$. The investigation of the influence of design and technology of production showed that the life of joints, made by means of turning and grinding, is approximately equal both relative to the crack initiation and ultimate fracture. The life of the joints stud-body (body of 12X2MΦA) is longer relative to crack formation approximately by 10% and relative to ultimate fracture - by 10-20%. The joints stud-nut with a plane-cut profile of the stud thread are less durable relative to ultimate fracture than the joints with studs having a curved thread profile ($\tau = (0{,}108 - 0{,}144) \cdot S$).

The research of the scale influence on the resistance to low-cycle fracture showed that the scale effect is the strongest in the diameter range from M8 to M16, and at the further increase of thread diameter its influence decreases. The increase of the absolute dimensions of bolt section causes the decrease of fracturing stress amplitudes according to the exponential law, with the increase of the diameter, and leads both to an earlier crack initiation and final fracture (Fig. 4).

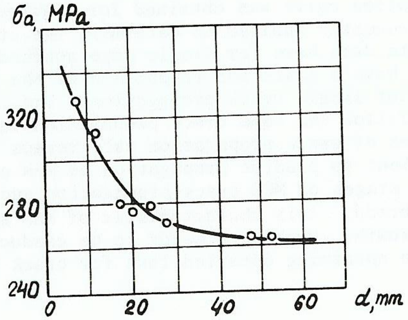

Fig. 4. Influence of stud-nut joint dimensions on the resistance to low-cycle fracture (steel 25X1MΦ, normalization N = 10^4 cycles).

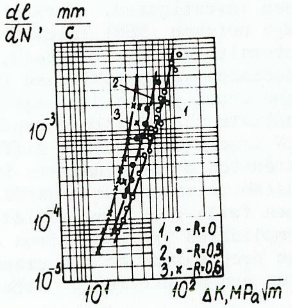

Fig. 5. Crack growth rate in joints from steel 25X1MΦ(normalization): comparison of experimental results (o, ○, x) with theoretical rezults (1, 2, 3).

Crack rate in threaded joints, depending on its depth (length), is well described by an exponention function of Paris type (Fig. 5).

$$\frac{d\ell}{dN} = C(\Delta K)^n$$

ℓ - crack depth (length) (see Fig. 1b); C , n - parameters, obtained from the experimental results.

For the tested joints M20 the critical crack depth varied from 3 to 7 mm. The growth of the loading cycle asymmetry coefficient from 0 to 0,6 increases the critical depth to a very small extent. Fig. 6 represents the data on the crack rate for 3 values of the asymmetry coefficient R at $\sigma_{max} = 760$ MPa.

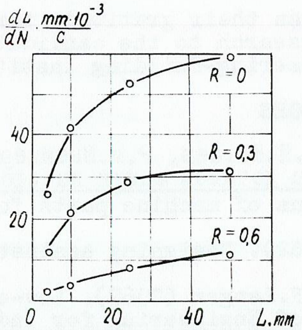

Fig. 6. Fatigue crack growth rate depending on its length in the joint stud-nut M20 (steel 25X1MΦ , normalization σ_{max} = = 760 MPa).

For the description of crak rate in threaded joints, depending on the range of stress intensity factor ΔK , equations of Forman type have valid:

$$\frac{d\ell}{dN} = \frac{C(\Delta K)^n}{(1-R)K_C - \Delta K}$$

The final fracture is defined by the critical value of the stress intensity factor K_C . The crack path depends on the presence of tensile and bending stresses at the thread root.

The calculation results and experimental data on this dependence give a satisfactory correlation.

The stress intensity factor ΔK and K_C for the above schematization of fracture forms (Fig. 2) were estimated according to formulae (Panasiuk, Andreikiv, Kovchik, 1977)

$$\Delta K = \frac{\Delta P}{D\sqrt{d}} \cdot Y \qquad K_C = \frac{P_C}{D\sqrt{d}} \cdot Y$$

where

$$Y = 0{,}7978 \frac{\sqrt{d/D[1-(1-S/d)(d/D)]}\ [1+\sqrt{1+3(S/D)}\,(D/d-1)]^2}{\sqrt{1+(2\,S/D - 0{,}8012)\cdot d/D}}$$

For joints from steel 25X1MΦ the value K_c is in the range 120÷130 MPa $m^{1/2}$.

CONCLUSIONS

The obtained above experimental data are used for defining calculation dependences while estimating life and safety factors. They allow to estimate life for different stages of stud (bolt) damage defined in the limits from the moment of crack initiation ($\ell = 0{,}5$ mm) to its critical value $\ell = \ell_{crit}$.

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