Technological heredity and destruction processes in units and joints

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The analysis of failures of aviation engineering [1] and experimental studies [2] show that premature failures of fasteners are caused mainly by fatigue and are accompanied by cracks propagation. One of the methods to increase the strength and reliability of fasteners is the formation of thread profile by rolling [3] that results in creating favorable residual technological stresses in the surface layer.

The estimation of brittle strength of such threaded connections with account of residual technological stresses and analysis of the fracture mechanism is connected with the determination of the value of the stress intensity factor both in the area of the structural stress concentrator and outside of it. The stress intensity factor K in the valley of the thread profile with account of external load and residual technological stresses can be determined by the formulae:

$$K_1 = \begin{cases} K_{1p} + K_{1res} \ , & \left(K_{1p} + K_{1res}\right) > 0 \\ 0 \ , & \left(K_{1p} + K_{1res}\right) < 0 \end{cases} \tag{1}$$

where K_{1p} stress intensity factor caused by the load distributed on turns of the thread profile; K_{1res} stress intensity factor of residual technological stresses.

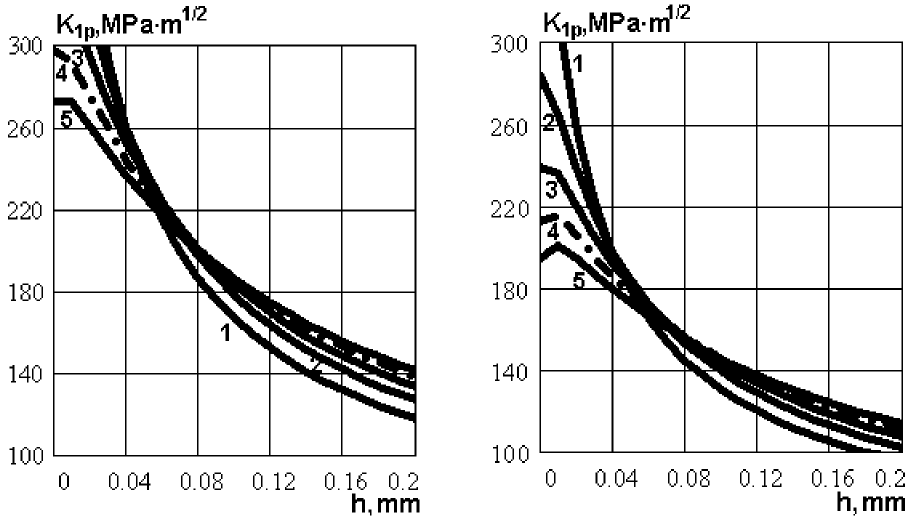
The use of equation (1) bases on the superposition method [4], which can be used if the value of stresses near the structural stress concentrator does not overcome the material yield strength. Stress intensity factor of the first order in the area of the structural stress concentrator caused by the load on turns was calculated by the formula:

$$K_{1p} = 1{,}12\sigma_n K_T \frac{\sqrt{\pi}}{2}\left[1{,}67\sqrt{h} + \beta \frac{d}{2\pi\sqrt{2}}\sqrt{\frac{(d-2h)+(h+t/2)}{(d-2h)(h+t/2)}}\right] \tag{2}$$

where
$$\beta = \frac{Q_i}{\sum Q} = \frac{\int_i^{i+p} q(z)dz}{\sum \int_i^{i+p} q(z)dz} = \frac{\int_i^{i+p} \frac{Q\cdot\beta_p}{sh\beta_p M} ch\beta_p \cdot z}{\sum \int_i^{i+p} \frac{Q\cdot\beta_p}{sh\beta_p M} ch\beta_p \cdot z} \tag{3}$$

$$K_T = \sqrt{\frac{t}{h+r_0}\left(1+\frac{r_0}{\xi h + r_0}\right) + \frac{r_0}{\xi h + r_0}} \tag{4}$$

r_0 radius in the valley of thread profile; ξ coefficient of pliancy of the thread turns; t the working height of the turn of thread; d average diameter of thread; h depth of a crack measured at the maximum distance from thread valley; σ_n nominal stress in the thread profile valley; K_T coefficient of concentration of elastic stresses.



b=0.30 b=0.42

Figure 1. Dependence of stress intensity factor on the radius in the thread valley r_0 and coefficient of load transfer b:
1 r_0=0.05mm; 2 r_0=0.1mm: 3 r_0=0.15mm; 4 r_0=0.20mm; 5 r_0=0.30mm

Figure 1 show the dependence of K_1 on the reduced depth of a crack for thread profile M10 with various radius in the thread profile valley. Formulae (2) gives good results when calculating the stress intensity factor (SIF) in the region of relative crack lengths h<1.0. For larger cracks, which is beyond the zone of structural stress concentrator, calculation of stress intensity factor were carried out by method of finite elements with the use of FEM system ANSYS 5.1 [5]. Fig. 2a,b shows finite-element models of boll joint M10-6e made from alloy BT3-1 ($E = 2.1\times10^5$MPa, n = 0.3). Isoparametric elements was used for FE-modeling of stud-nut threaded joint; and singular elements with midside nodes, placed at the crack tip, allows accurate modeling of the stress and displacement fields near the crack tip according to equation:

$$\left.\begin{aligned} K_1 &= \frac{E}{2\left(1-n^2\right)}\sqrt{\frac{p}{2L}}\Delta U_1 \\ K_2 &= \frac{E}{2\left(1-n^2\right)}\sqrt{\frac{p}{2L}}\Delta U_2 \\ K_3 &= \frac{E}{2}\sqrt{\frac{p}{2L}}\Delta U_3 \end{aligned}\right\} \qquad (5)$$

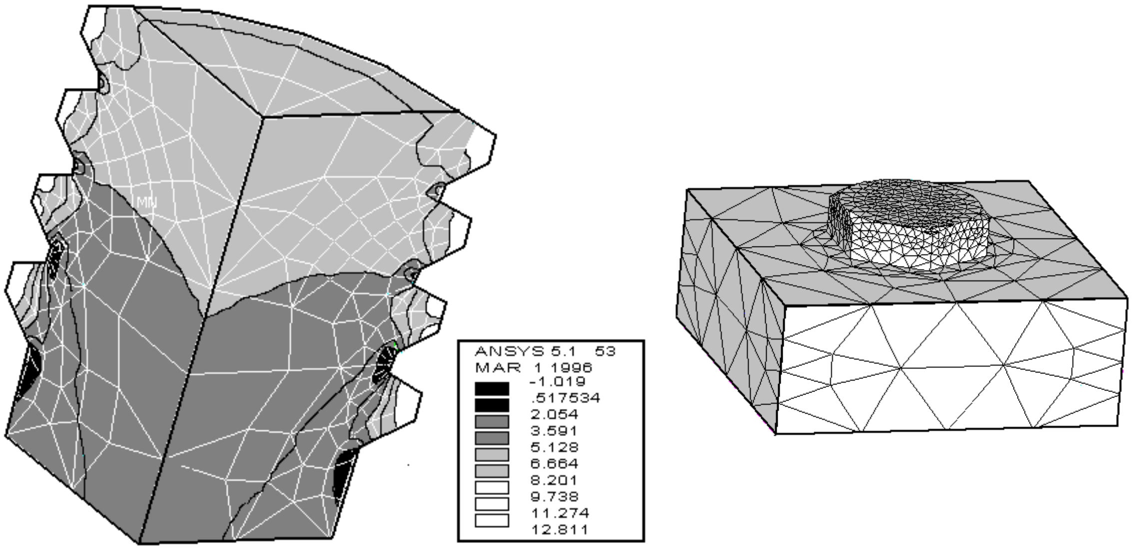
where DU_1, DU_2, DU_3 - functions of displacements vector projection to the local axes of coordinates connected with the crack.

In case when the calculations include all the 3 modes the effective stress intensity factor is determined according to equation

$$K_e = \left[\left(1-n^2\right)\left(K_I^2 + K_{II}^2\right) + \frac{K_{III}^2}{1-n}\right]^{1/2} \qquad (6)$$

In plastic deformations appears near the structural concentrator, the estimation of effective stress intensity factor was found according to formulae

$$K_e = \sqrt{JE'} \qquad (7)$$



a) b)

Figure 2.

Fig. 2a shows the stress isolines on the solid model of the bolt threaded part. The results of the standardized SIF $Y_1 = K_1/\left(\sigma\sqrt{\pi h}\right)$ calculation with account of crack inclination are shown in fig. 3. depending on nut coefficient of shapes.

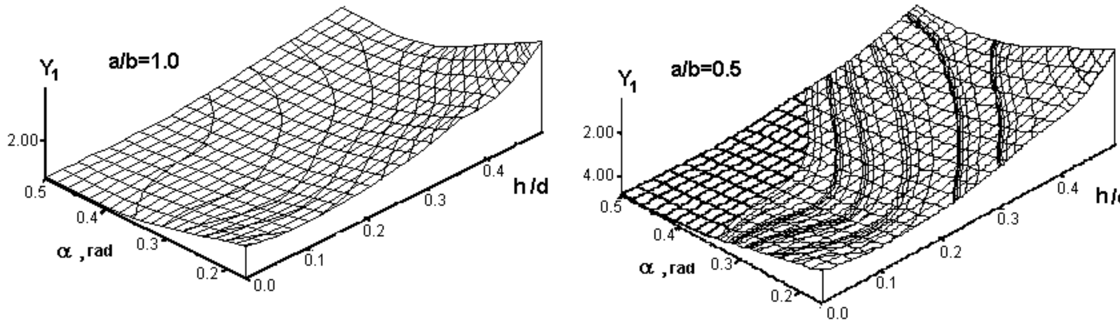


Figure 3. Dependence of the stress intensity factor on the given crack depth h.

Stress intensity factor caused by the effect of residual technological stresses in the area of stresses concentration is determined by the formula obtained for the hole with a crack with arbitrary pressure at edges [6,7]

$$K_{1res} = \sqrt{\pi h}\int_{h_0}^{h_1} f(x/h)\left(\partial\sigma_\varphi/\partial x\right)dx \quad \text{or} \quad K_{1res} = \frac{H}{K^*}\int_{h_1}^{h_2}\sigma_\varphi(x)\frac{\partial U}{\partial h}dx \qquad (8)$$

where $f(x/h) = 0.8(x/h) + 0.04(x/h)^2 + 0.352\cdot 10^{-4}\exp(11.18x/h)$,

σ_φ residual stresses; h crack depth.

The total stress intensity factor of the first order for the crack in the area of the structural stress concentrator effect ($h>r$) was calculated by the formulae

$$K_{1\Sigma} = \sqrt{\pi h}\left[\sigma_n Y_1(h/d_2) - \int_{h_1}^{h_2} f(x/h)\left(\partial\sigma_\varphi/\partial x\right)dx\right] \qquad (9)$$

where $Y_1(h/d_2)$ dimensionless coefficient depending on the geometry of the connection, crack depth and the load application peculiarities.

The results of calculations by formulae (8) and (9) are shown in Figure 4. The comparison of the curves reveals that the stress intensity factor of the first order is considerably reduced for the small cracks ($h < r_0$) owing to the presence of technological compressive stresses. This results in both the increase of the period of fatigue crack formation by 1.5...1.9 times and the shift of the center of the main fatigue crack formation that is well proved by experimental results.

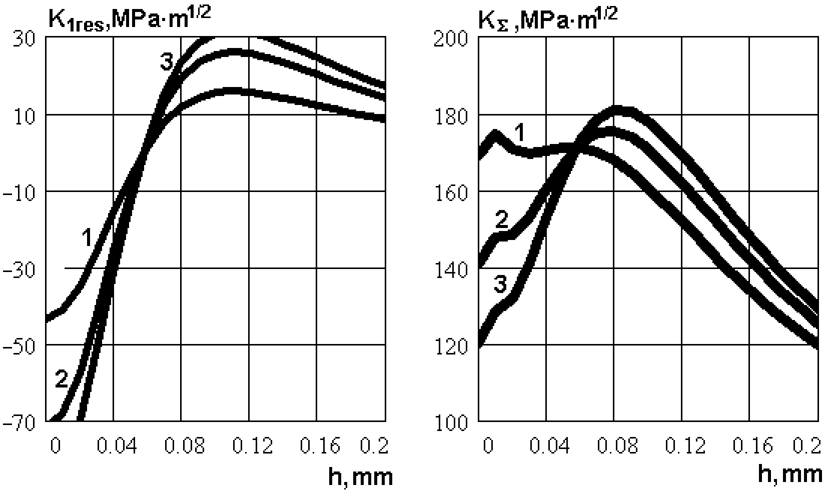


Figure 4. Dependence of the stress intensity factor on the given crack depth h.
1 λ_h=1.04, 2 λ_h=0.99, 3 λ_h=0.92

For large cracks ($h > r_0$) the influence of residual technological stresses on the value of SIF is less considerable, this influence decreases with h increase. If $h \geq (2.5\ldots3.0)r_0$ the curves of the dimensionless coefficient $Y_1(h/d_2)$ coincide for studs either with residual technological stresses or without them. The presence of the compressive technological stresses in the surface layer of the thread profile at $h \geq (1.5\ldots3.0)r_0$ alters mainly the velocity of crack propagation across the surface of the first loaded turn valley and as a result changes the shape of the fatigue crack front. The present work shows the results of the investigation of crack resistance of M6-6e thread made of titanium alloy BT3-1 dependent on the degree of plastic deformation in thread and resulted residual stresses.

Two lots of samples with different plastic deformation in thread were rolled for testing. The conditions of rolling of both lots were kept constant and were controlled by oscillography. Various degree of deformation was reached by changing of position of the limiter of roller motion.

Workpieces for rolling were prepared by turning the annealed rod 8.5mm diameter with the following mechanical characteristics: σ_j = 1030...1100MPa, δ = 15...18%, ψ = 40...45%.

The degree of the plastic deformation of the turns of the thread profile was calculated by the formulae:

$$\lambda_h = h_1 / h_{10} \tag{10}$$

where h_{10} - minimum depth of the roller intrusion into the workpiece at which the thread rolling is begun in the deformed contour; h_1 - real depth of intrusion.

The degree of plastic deformation in thread was λ_h= 0,96 for samples with the thread rolled in the non-deformed contour and λ_h=1,01 for samples with the thread rolled in the deformed contour.

The results of determination of meridional residual stresses across the thickness of the valley surface layer are given in figure 5.

It is established that maximum values of residual stresses for investigated degrees of the plastic deformation in thread differ insignificantly from each other. But for samples with the plastic deformation degree λ_h<1 the reduction of the residual stresses across the sample thickness is more sharp than for ones with λ_h>1. Such behavior of the residual stresses is in good coincidence with the conclusions made in the present work.

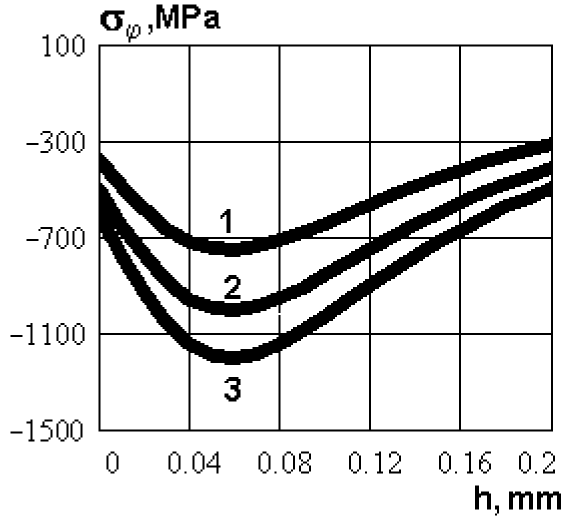


Figure 5. Residual technological stresses
1 - λ_h=1.04, 2 - λ_h=0.99, 3 - λ_h=0.92

The influence of the thread deformation degree λ_h and residual technological stresses σ_φ on crack resistance at multicycle fatigue was studied by use of electromechanical vibrobench and method of "marks". The velocity of cracks propagation dh/dN across the sample cross-section were determined by marks formed in the result of the relief change at the fracture surface at load variation. Figure 6 shows characteristic shapes of marks formed at the fracture surface of threaded samples rolled with different degree of plastic deformation in thread (a arched crack front, b straightened one).

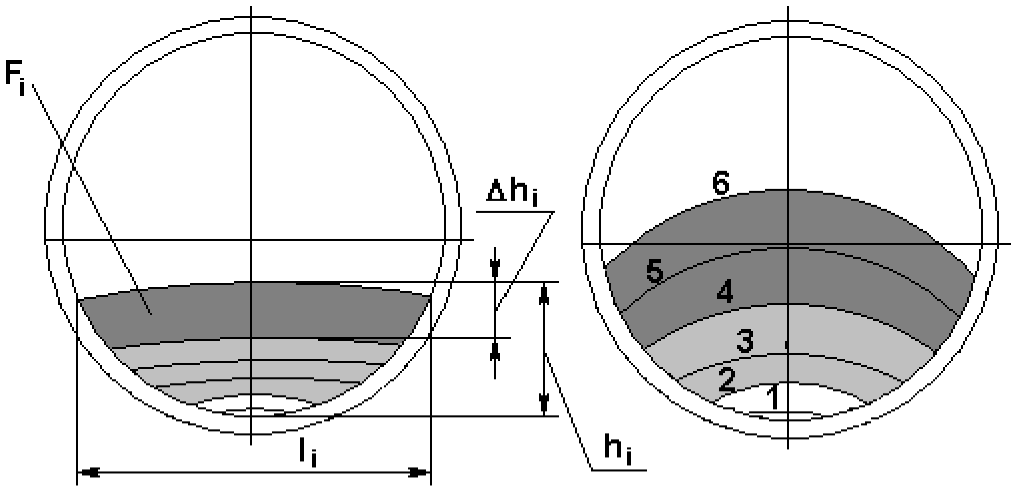


Figure 6. Shapes of the crack front in thread
1 - 5000 cycles, 2 - 10000 cycles, 3 - 15000 cycles, 4 - 20000 cycles, 5 - 25000 cycles, 6 - 30000 cycles

The results of fatigue tests of M6 studs made of BT3-1 alloy revealed that both the value and the character of residual stresses influence considerably on the service life of thread connections. The process of breakage should be divided into the durability period till the first visible mark occurrence and the time period from the first mark till breakage; the greatest difference between the samples of two lots is observed during the period of the fatigue crack formation. In fig.7 the kinetic diagrams of M6-6e studs breakage with the thread rolled with different degree of deformation are given.

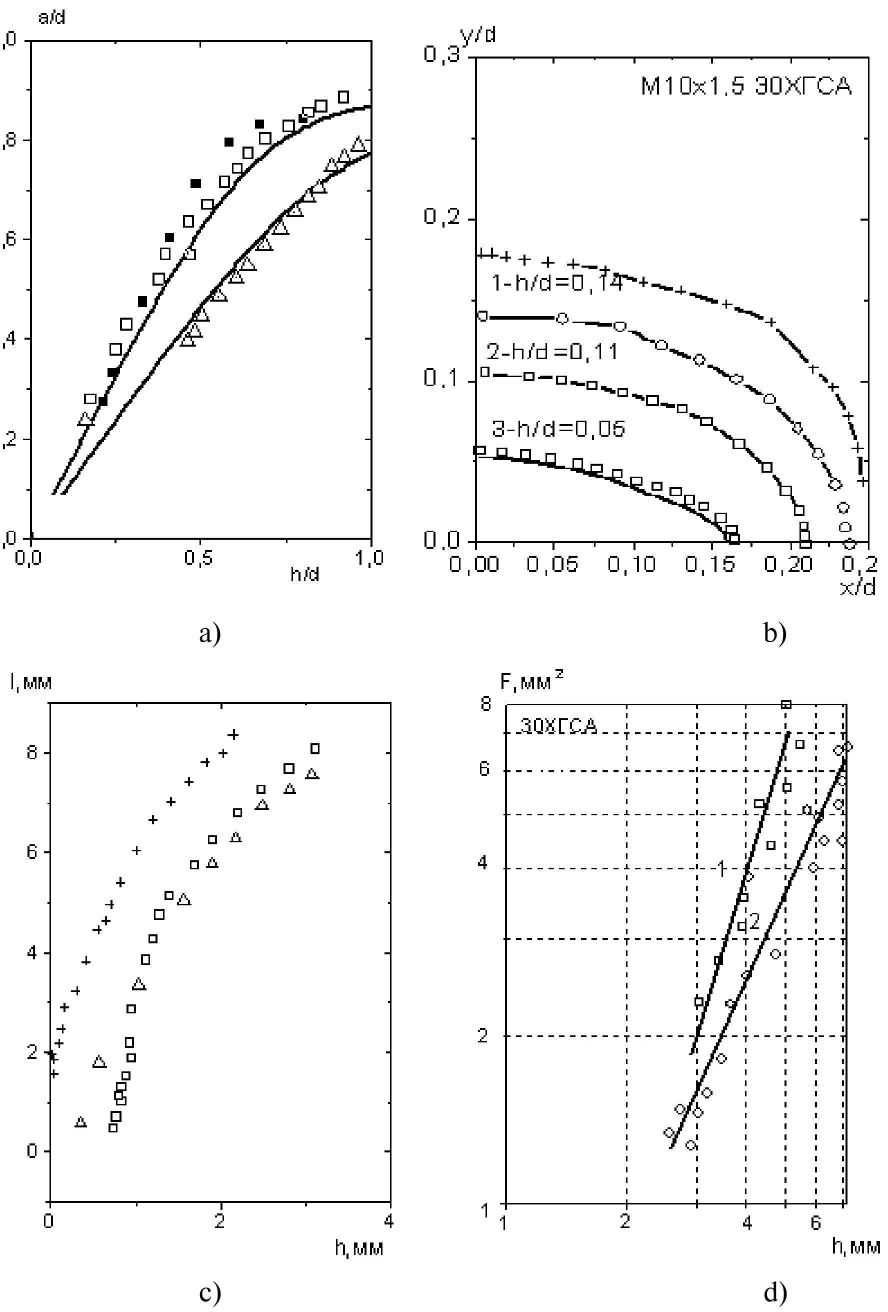


Figure 7.

It is established that despite of close values of maximum residual stresses in both lots crack propagation across the depth of a threaded part influences greatly on the breakage resistance, shape of fatigue crack front, critical crack length and velocity of the crack propagation.

The logarithm of the fatigue crack propagation velocity for stresses intensity factor lgK_e = 1,4 and 1,6 differs for samples with the degree of plastic deformation in thread l_h= 0.96 and l_h = 1,01 by 1,12 and 1,14 respectively. The cyclic crack resistance of M6-6e studs made of BT3-1 alloy rolled in the non-deformed thread will be higher than that of studs with the thread with plastic deformation coefficient l_h >1.

The estimation of duration of periods of fatigue cracks formation and propagation was carried out by fractographic analysis of breaked studs. The number of cycles required for the formation of a crack 0.1 mm deep was adopted as "the formation period". Such choice of the initial crack depth was stipulated by the resolution power of the fractographic marks method and measurement error of the microscope. The crack formation period was calculated by the formulae:

$$N_3 = N_p - [(n-1)N_0 + N_z] \qquad (11)$$

where N_3 - number of cycles till the part breakage; n - number of marks on the breakage (fig. 6) beginning from the fatigue crack depth 0.1 mm; N_0 - number of test cycles in operating conditions; h_M - distance to the first visible mark; N_z - number of cycles after the last visible mark counted by the cycle counter of testing machine.

On the bases of experimental data the next equations are obtained for period of a crack formation in the threaded joint:

$$N_3 = 0.34 N_p^{1.07} \quad \text{for} \quad \lambda_h = 0.96...0.99 \qquad (12)$$

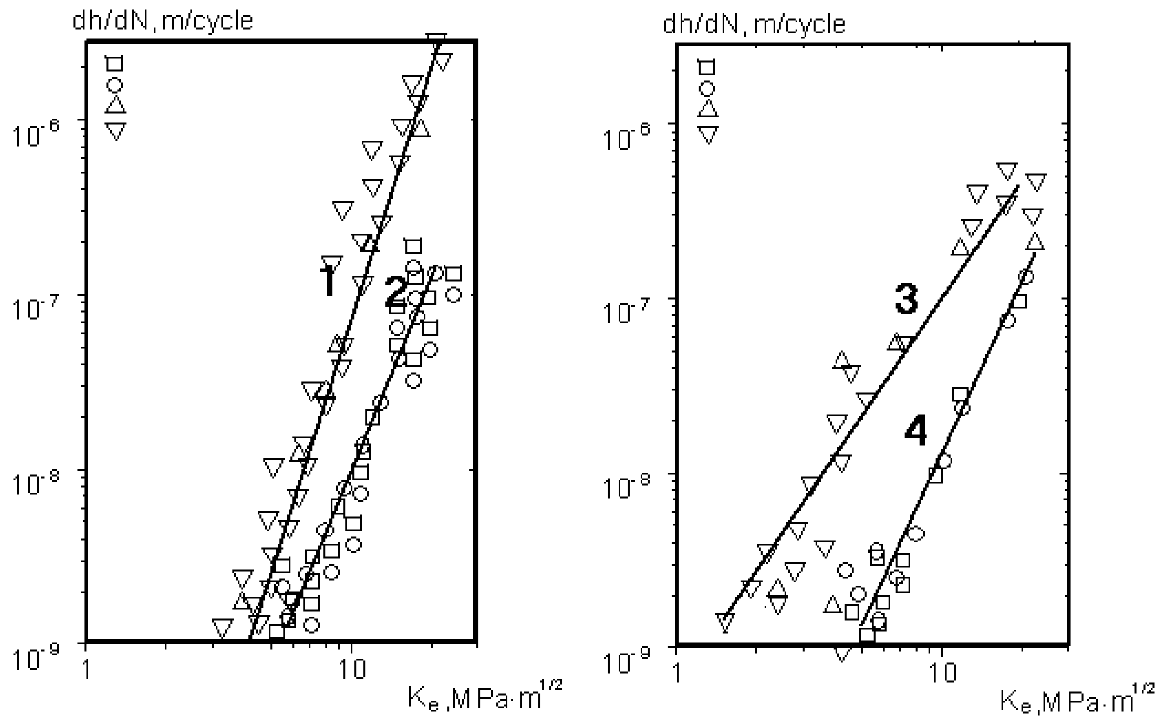
$$N_3 = 0.26 N_p^{1.04} \quad \text{for} \quad \lambda_h = 1.01...1.08 \qquad (13)$$

The calculated values of N_3 and known values of N_p were summarized in tables and then statistically processed. In table the ratios of total durability to the number of cycles till crack formation depending on the plastic deformation in thread are given for M6-6e stud at $\sigma_a/\sigma_p = 0.12$ and $\sigma_m/\sigma_p = 0.35$.

Table

Plastic deformation in thread λ_h	0,92...0,96	0,98...1,01	1,03...1,1
N_p/N_3	1,04...1,4	1,4...3,0	3,0...6,0

As it is seen from the table the number of cycles till cracks formation reduces considerably with the increase of plastic deformation in thread. It is explained by a higher damage of the thread rolled with a high level of deformation as well as by decrease of residual compressive stresses. The experimental results of study of the fatigue crack formation period in thread were approximated by the exponential equation.



BT3-1 30XGCA

Fig. 7. Cyclic crack-resistance diagram: 1,3 - λ_h=0.96...0,98, 2,4 - λ_h=1.01...1.08,

As studs of small dimensional types (M6-M10) were studied in the present work for which the cracks 1,5-3 mm were critical at stresses close to fatigue limit the problem of formation and propagation of short cracks in the thread of such connections is of a principal importance. It is clear that the period of formation and growth of a short crack can make the major part of the total durability and will determine the connection fatigue resistance. In fig.8 the diagrams of short cracks growth versus their length are shown. As it is seen the behavior of short cracks alters depending on conditions of cyclic loading. As low loading amplitude (50% from s_a) the velocity of growth of such cracks decreases firstly, the minimum velocity is observed at the crack depth approximately 0,15 - 0,30 mm, then it goes up. At relatively high alternating load $s = s_a$ the velocity of fatigue crack growth increases monotonously.

A considerable spread in experimental data can be explained by a high sensitivity of short crack growth velocity to the conditions of alternating loading, microstructure and technology of manufacture.

It should be noted that in the thread connection during the period of fatigue crack formation the process is controlled by a shift mechanism which turns into the disrupture mechanism.

Conclusions

1. In the present work the use of the "superposition" principle in the calculation of stress intensity factor with account for residual technological stresses is theoretically substantiated and experimentally tested.

2. The values of the stress intensity factor are determined both in the area of the structural concentrator of the thread connection and during the crack propagation with the range of crack depths 0,1 < h/d < 0,5.

3. The basic mechanisms of thread connection breakage depending on residual stresses and deformation level are revealed both in the area of short cracks and long ones. Diagrams of cyclic crack resistance of studs M10 and M6 made of BT3-1, BT16 and 30XGCA alloys were drawn up.

4. The period of fatigue cracks formation in thread parts is determined, the influence of loading level is revealed.

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