BREAKAGE MECHANISMS OF COMPLEX PARTS OF AVIATION STRUCTURES WITH ACCOUNT FOR TECHNOLOGICAL HERITAGE

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ABSTRACT: In the present paper the approaches of linear mechanics of breakage were used in the estimation of durability of fasteners. The values of the stress intensity coefficient of the first order were determined with account for residual technological stresses both in the portion of the radius transition and outside of it. Breakage diagrams were drawn up and basic mechanisms of fatigue crack formation in threaded parts were determined with account for technological heritage.

KEY WORDS: Crack resistance, linear mechanics of breakage, stress intensity coefficient, degree of plastic deformation, fatigue formation period, shape of crack spot.

ANALYSIS

The analysis of breakdowns during aviation engineering operation (Senik V.J., 1971) and experimental studies (Chiznik A.A., Gorynin V.I., 1981) showed 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 (Petrikov V.G., Vlasov A.P., 1991) that results in creating favourable residual technological stresses in the surface layer.

The estimation of brittle strength of such threaded connections with account for residual technological stresses from the point of view of breakage mechanism is connected with the determination of the value of the intensity coefficient of stresses both in the area of the structural stress concentrator and outside of it. The stress intensity coefficient K_1 in the valley of the thread profile with account for load on turns and residual technological stresses was determined by formula:

$$K_1 = \begin{cases} K_{1p} + K_{1res} & \text{in case} \quad (K_{1P} + K_{1res}) > 0 \\ 0 & \text{in case} \quad (K_{1P} + K_{1res}) < 0 \end{cases} \qquad (1)$$

where K_{1p} - stress intensity coefficient depending on the load distributed on turns of the thread profile

K_{1res} - stress intensity coefficient with account for residual technological stresses.

The use of equation (1) implies that the field of stresses formed by the load on turns of the thread profile is elastic and does not change the stressed-deformed state in the area of residual technological stresses effect. It is reasonable as the amount of stresses in the area of the structural stress concentrator does not overcome the material yield strength in the multicycle area of tests.

Stress intensity coefficient of the first order in the portion of the structural stress concentrator resulted from the load on turns was calculated by the formula derived by the superposition method Budilov I.N. (1986):

$$K_{1P} = 1{,}12\ \sigma_n K_T \frac{\sqrt{\pi}}{2}\left[1{,}67\sqrt{h} + 0{,}15\frac{W}{\pi\sqrt{2}}\sqrt{\frac{(W-2h)+(h+t/2)}{(W-2h)(h+t/2)}}\right] \qquad (2)$$

where t – the working height of the turn of thread;

$W = d_2$ – 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 in the portion of the first loaded turn.

In fig.1 the plot of K_1 versus the reduced depth of a crack for thread profile M10 with various radius in the thread profile valley is shown.

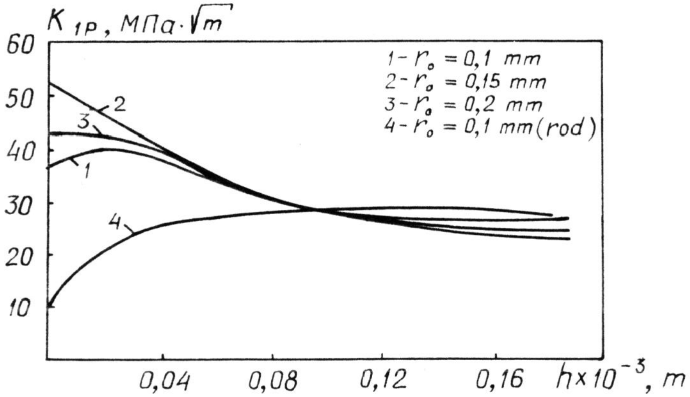


Fig. 1.

Stress intensity coefficient caused by the effect of residual technological stresses in the area of stresses concentration is determined by the formula derived for the hole with a crack and an arbitrary pressure at edges:

$$K_{1res} = \sqrt{\pi h}\int_{h_0}^{h_1} f(x/h)(\partial\sigma_\varphi/\partial x)dx, \qquad (3)$$

where $f(x/h) = 0{,}8(x/h) + 0{,}04(x/h)^2 + 0{,}352\ 10^{-4}\ \exp 11{,}18(x/h)$.

σ_φ – the curve of residual stresses shown in fig.4;

h – crack depth.

The total stress intensity coefficient of the first order for the crack in the area of the structural stress concentrator effect (h>R) was calculated by the formula:

$$K_1 = \sqrt{\pi h}\left[\sigma_n Y(h/d_2) - \int_{h_1}^{h_2} f(x/h)(\partial\sigma_\varphi/\partial x)dx\right], \qquad (4)$$

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

The results of calculations by formulae (3) and (4) are shown in fig.2 in the plot of the dimensionless coefficient $Y(h/d_2)$ (fig.2a) versus crack depth, as well as in the plot of the total stress intensity coefficient of the first order with account for residual technological stresses (fig.2b).

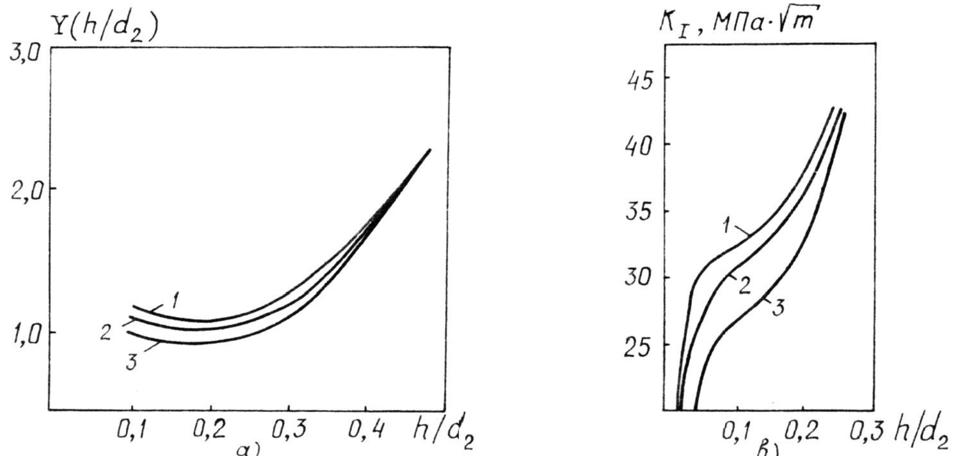


Fig. 2.

The comparison of the curves (fig.2b) reveals that the stress intensity coefficient of the first order is considerably reduced in the area of small cracks ($h \leqslant R$) 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 and the shift of the center of the main fatigue crack formation that is well proved by experimental results.

In the event of large cracks ($h > R$) the residual technological stresses do not influence considerably on the value of the stress intensity coefficient and such influence even decreases with h increase.

In the area where $h \geqslant (2{,}5 - 3)R$ the curves of the dimensionless coefficient $Y(h/d_2)$ 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 $h \geqslant (1{,}5 - 3)R$ 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.

In fig.3 the influence of the residual technological stresses on the shape of the fatigue crack front and the square of the fatigue crack spot F are shown.

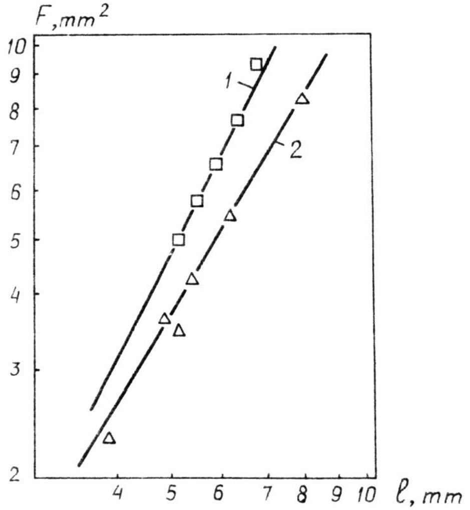


Fig. 3. 1) with ressidual stresses marked;
2) without residual stresses.

In the present work the results of the investigation of crack resistance of M6-6e thread made of titanium alloy BT3-1 in dependence of the degree of the plastic deformation in thread and the behavior of the resulted residual stresses are presented.

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

Workpieces for rolling were prepared by turning the annealed rod 8,5 mm in diameter with the following mechanical characteristics: σ_B=1030...1100 MPa, δ =15...18%, ψ = 40...45%.

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

$$\lambda_h = h_1/h_{10} , \tag{5}$$

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 fig.4.

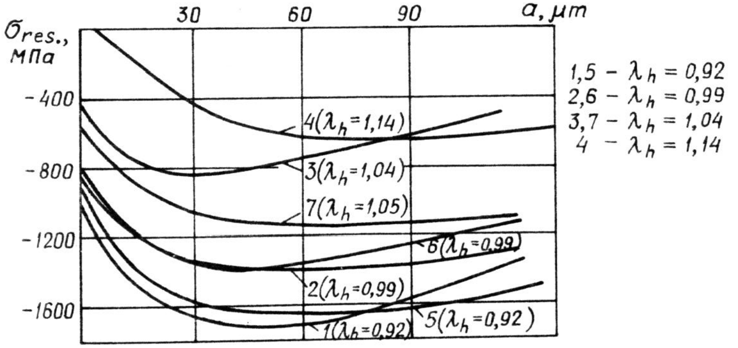


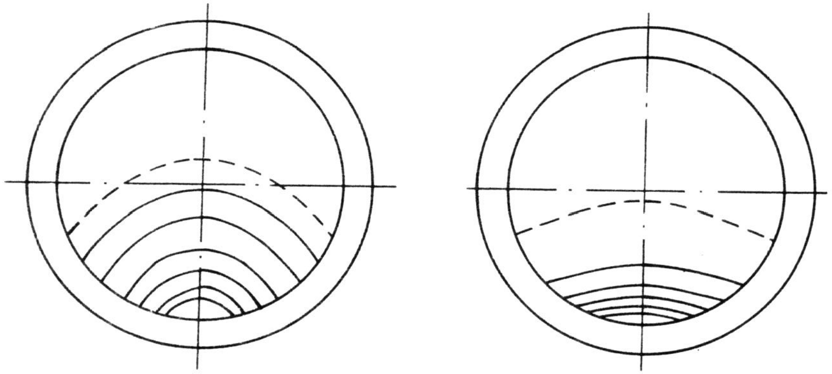
Fig. 4. Residual technological stresses

It is established that maximum values of residual stresses for investigated degrees of the plastic deformation in thread differ insignificantly from each other. But in case of the deformed contour the reduction of the residual stresses across the sample thickness is more sharp than in case of the deformed contour. Such behavior of the residual stresses compares well with the conclusions made in the present work.

The influence of the thread deformation degre λ_h and residual technological stresses σ_φ on crack resistance at multicycle fatigue loading was studied at the electromechanical vibrobench by the method of "marks". The values of 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 surface of the breakage at load variation.

In fig.5 characteristic shapes of marks formed at the surface of breakages of threaded samples rolled with different degree of plastic deformation in thread (a – arched crack front, b – straightened front) are shown.

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. Moreover should the process of breakage be divided into the durability period till the first visible mark occurence 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.6 the kinetic diagrams of M6-6e studs breakage with the thread rolled with different degree of deformation are given.



a) $\lambda < 1$ b) $\lambda > 1$

Fig. 5. Shapes of the crack front in thread

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

The logarithm of the fatigue crack propagation velocity for stresses intensity coefficient $\lg K_1 = 1{,}4$ and 1,6 differs for samples with the degree of plastic deformation in thread $\lambda_h = 0.96$ and $\lambda_h = 1{,}01$ 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 plastic deformation coefficient >1.

The estimation of duration of periods of fatigue cracks formation and propagation was carried out by fractographic analysis of studs breakages. The number of cycles required for the propagation of a crack 0,1 mm deep was relatively taken for the formation period. Such choice of the initial crack depth was stipulated by the resolution power of the fractographic marks method as well as by measurement error of the microscope. The crack formation period was calculated by the formula:

$$N_з = N_p - (n_M - 1)N_o + N_z + \int_{0,1}^{h_M} dh/V(h), \qquad (6)$$

where N_p – number of cycles till the part breakage;

n_M – number of marks on the breakage (fig. 5) beginning from the fatigue crack depth 0,1 mm;

N_o – 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 by the meter of cycles.

The calculated values of $N_з$ 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.

Table

Dimensional types	$N_p / N_з$			σ_a/σ_p	σ_m/σ_p
	Plastic deformation in thread λ_h				
	0,92-0,96	0,98-1,01	1,03-1,1		
M6-6	1,04-1,4	1,4 - 3,0	3,0 -6,0	0,12	0,35

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.

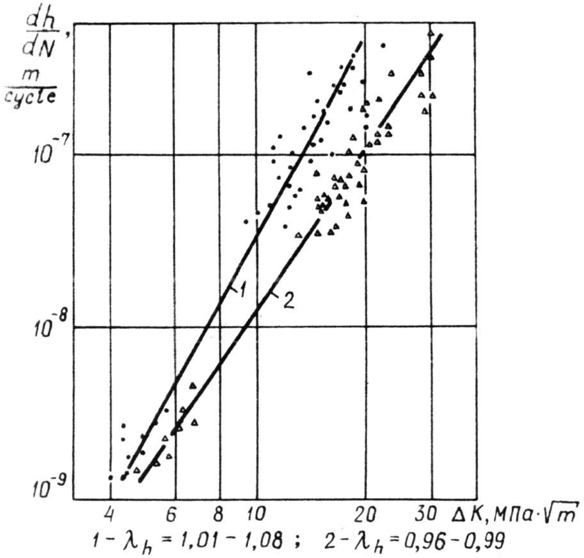


Fig. 6. Cyclic crack-resistance diagram

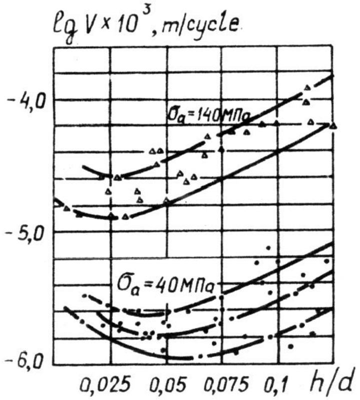


Fig. 7.

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.7 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 σ_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 $\sigma = \sigma_a$ 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 coefficient with account for residual technological stresses is theoretically substantiated and experimentally tested.

2. The values of the stress intensity coefficient 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 $0,1 \leqslant h/d \leqslant 0,5$.

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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