Impact of technological and operational deviations of the thread flank angle on the fatigue life of the tool joint

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Abstract. The total effect of technological and operational factors can lead to various types of deviations of the flank angle of the tool joint thread profile, which are uneven along the axis. It is shown that uneven deviations of the flank angle appear when tapered threading with a lathe tool with a non-zero rake angle. To analyse the effect of these deviations on the fatigue strength of the joint, a parametric axisymmetric finite element model of the ZN-80 tool joint was developed in Abaqus/CAE. In the fe-safe program, dependences of the fatigue life in the thread roots on the deviations of the flank angle of the pin thread were obtained. The box thread has not been changed. To increase the fatigue strength of the pin, in most of the cases considered, negative deviations of the flank angle of the short flank of the pin thread should be avoided, and preference should be given to positive ones. Negative relative deviations of both flanks usually worsen the fatigue strength of the pin due to the "wedge" effect. Types of deviations have been found that significantly increase fatigue strength and have an "anti-wedge" effect or equalize the load in the thread. They need detailed studies and can be the basis for optimizing the values of flank angle deviations on each turn.

1. Introduction and Literature Review

Threaded tool joints are designed to connect the elements of the drill string. They are subject to the requirements of high static and fatigue strength, wear resistance, leak-tightness and resistance to self-loosening. To ensure the reliability of threaded connections and elements of the drill string, a lot of research has been carried out in the field of:

– design. In particular, prevention of self-loosening [1, 2, 3], static and fatigue strength [4, 5, 6, 7], leak-tightness [8];

– manufacture. In particular, the study of machining errors [9, 10], cutting conditions [11] and technological inheritability [12, 13];

– operation. In particular, the study of leak-tightness, fem [14], corrosion fatigue [15, 16, 17], make-up [4-7, 18].

Analytical [1, 5, 17, 19-21], numerical [3, 22-27] and experimental [4-6, 18, 28] methods are used to calculate contact pressures, stresses and strains in threaded connections.

The tool joint is subjected to various cyclic loads – axial, bending and torsional [18]. The stresses in this type of connection are unevenly distributed along the thread with a maximum at the first turns (Fig.

1) [5]. Many stress distributions in tool joint threads have been studied by modeling [25, 26, 29, 30] and experimentally [4, 6, 18].

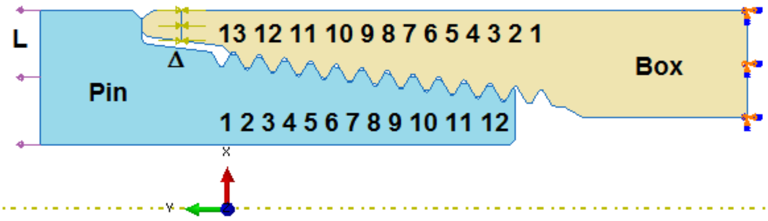


Fig. 1 Model of the ZN80 tool joint with numbered thread roots of the pin and box

Typical tool joint failures are pin or box breakage, chipping of the turns, thread stripping, self-loosening, thread wear, seizing and washout by drilling mud [4, 18]. Most often, the fracture of the pin and box occurs in the area of their first (Fig. 1) turns due to material fatigue [7]. Chipping, most often in the area of the first and last turns, also occurs due to fatigue [4]. Thread stripping is caused by wear, washout, or chipping of turns.

About 80% of all tool joint thread rejections are related to their wear [4]. Thread wear is usually not uniform. On the pin, the first turns are sharpened at the top, while the other turns are rounded [4]. The longer flank of the thread wears out during the make-up operation [18]. Its flank angle φ increases from the first to the last turn [4]. Also, the longer flank is washed out more intensively [4]. The short flank wears out during tightening and operation of the tool joint under conditions of significant variable loads. Its shape, mainly on the first turns, becomes concave with a reduced φ at the crest [4].

An increase in fatigue strength can be achieved by changing the thread profile: increasing the root radius, reducing diametrical clearances [5, 10], using a special profile [27], increasing or decreasing the flank angle [8], cutting at an angle of the first turns of the box, variable pitch [5, 31]. With the help of FEA, the equalization of loads in the thread and an increase in the fatigue strength of the joint after modifying the profile of the loaded side of the turn was found [27]. Negative deviations of the flank angle φ of the loaded flank of the pin thread increase the contact pressure, increase the stress and reduce the fatigue safety factor in the first turns of the pin thread [29, 32]. In these works, fatigue safety factor was calculated using the not very accurate Sines dependence and other variants of angle deviations were not investigated.

Thus, profile deviations caused by technological and operational factors can be different. The impact of various flank angle deviations on the fatigue strength of the tool joint has not been studied in depth.

2. Research Methodology

2.1. Methodology of theoretical research

Tapered tool joint threads are made using metal cutting tools on lathes. Most often, this is done with the use of a full-profile carbide insert with contour, that coincides with the axial profile of the thread (Fig. 2).

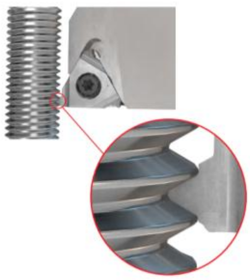


Fig. 2 Threading

At the same time, it should be noted that a typical tool joint thread is conical, in relation to the surface on which it is formed, and unlike other types of threads, its profile is not completely symmetrical. This means that the length of the straight sections of the profile of the cut is different: short – the segment *BC* and long – the segment *EF* (Fig. 3), and the semi-profile angles φ_2 and φ_1 are the same and according to the API 7 standard are: 30°±45'.

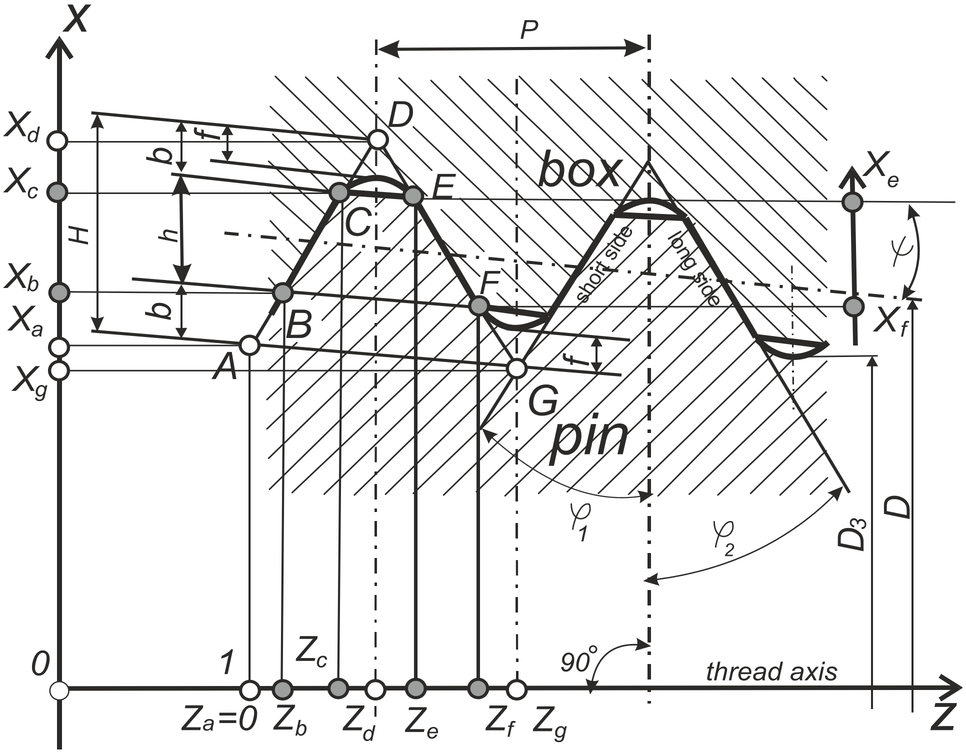


Fig. 3 The profile of the tool joint connection of the box (internal thread) + pin (external thread) according to the ARI 7 standard. *P* – Pitch, *f* – root truncation, *b* – crest truncation, *h* – basic depth of thread, *H* – depth of fundamental triangle, φ_2 and φ_1 – half-angle of symmetrical thread (flank angle), D_3 – minor diameter for pin, major diameter for box, *D* – pitch diameter.

To improve the operating conditions of cutters, it is recommended to ensure the same values of the relief angles α_L and α_R (Fig.4) [33]. Therefore, it is better to set the cutter at an angle β, which is equal to the helix angle Φ, which can be determined by the follow:

$$\Phi = arctg\left(\frac{P}{\pi D}\right). \quad (1)$$

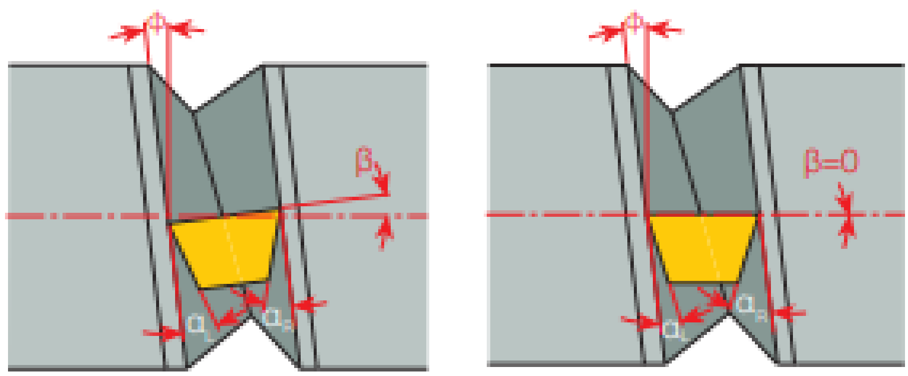


Fig. 4 Recommendations for installing a cutter for turning threads

However, in this case, the straight sections of the cut profile will have a slightly different appearance, and in the *ZX* coordinate system in Fig. 3, it is possible to determine the *Z* coordinates of points *B*, *C*, *E*, *F* by the *X* coordinate [34]:

$$Z(x) = tg(\varepsilon)x\frac{\sin\tau}{\sin\eta} - \frac{P}{2\pi}\tau, \quad (2)$$

where:

$$tg(\varepsilon) = \frac{P\cos\beta\cos\eta}{2H} = \frac{P\cos\beta}{2H}\cos\left[arctg\frac{P\sin\beta}{2H}\right], \quad (3)$$

$$\tau = \eta - \arcsin\left(\frac{r\cdot\sin\eta}{x}\right), \quad (4)$$

where:

$$\eta = arctg\left[\frac{P\sin\beta}{2H}\right],$$

$$r = \frac{D_3}{2} \pm f. \quad (5)$$

According to the algorithm (2-5), the values of the semi-profile angles (Fig. 3) will change, the values of which are determined by the formulas:

$$\varphi_1 = arctg\left(\frac{|Z_c - Z_b|}{|X_c - X_b|}\right), \quad (6)$$

$$\varphi_2 = arctg\left(\frac{|Z_f - Z_e|}{|X_e - X_f|}\right). \quad (7)$$

2.2. *Finite element analysis*

The parametric finite element model of the tool joint [35] was used. The model was developed by authors in Abaqus/CAE. We considered the drilling tool joint ZN-80 GOST 5286 with Z-66 GOST 28487 thread (2 3/8 REG API Spec. 7 equivalent). The material of the parts is SAE-4140 steel with a Young's modulus E = 201 GPa, a Poisson's ratio v = 0.33, a yield strength σ_y = 965 MPa, a ultimate tensile strength σ_t = 1076 MPa, an endurance limit σ_{-1} = 572 MPa. Material plasticity with isotropic hardening and friction with penalty friction formulation are simulated. Make-up was simulated by axial elongation of the box shoulder by the value Δ = 0.25 mm (Fig. 1). Fatigue life *N* was calculated using Brown-Miller strain-life dependence [36] and fe-safe 6.5 software. In an axisymmetric model, only axial loads can be taken into account. Such a tensile load was modeled by pressure *L* (Fig. 1). Slightly increased fatigue loads with cycle (L_{min} = 0 MPa, L_{max} = 350 MPa) were considered.

We considered different pairs of deviations ($\Delta\varphi_1$, $\Delta\varphi_2$) of the thread flank angles (Fig. 3) of the pin from the nominal value, where $\Delta\varphi_i = \varphi_i$-30 (in degrees), index 1 means the short (loaded) flank, 2 – the long (unloaded) flank. The box thread has not been changed. From the point of view of the variability of $\Delta\varphi_1$ and $\Delta\varphi_2$ values along the thread axis, the following cases were considered.

Case I – identical pairs ($\Delta\varphi_1$, $\Delta\varphi_2$) on each turn: (+0.5, +0.5), (-0.5, -0.5), (+0.5, -0.5), (-0.5, +0.5), (+0.5, 0), (0, +0.5), (-0.5, 0), (0, -0.5).

Case II – deviations $\Delta\varphi_1$ and $\Delta\varphi_2$ increase linearly from 1th to 12th turn: $\Delta\varphi_1 = x_1(i\text{-}1)$ and $\Delta\varphi_2 = x_2(i\text{-}1)$, where *i* is the number of the turn (Fig. 1); x_1, x_2 are deviation increments on each turn (in degrees). For example, for a pair (x_1 = +0.1, x_2 = +0.1) on turn 1 there will be deviations $\Delta\varphi_1$ = 0.1(1-1) = 0°, $\Delta\varphi_2$ = 0.1(1-1) = 0°, and on turn 12 – $\Delta\varphi_1$ = 0.1(12-1) = +1.1°, $\Delta\varphi_2$ = 0.1(12-1) = +1.1°.

Case III – deviations increase linearly from 12th to 1st turn: $\Delta\varphi_1 = x_1(12\text{-}i)$ and $\Delta\varphi_2 = x_2(12\text{-}i)$. For example, for a pair (x_1 = +0.1, x_2 = +0.1) on turn 1 there will be deviations $\Delta\varphi_1$ = 0.1(12-1) = +1.1°, $\Delta\varphi_2$ = 0.1(12-1) = +1.1°, and on turn 12 – $\Delta\varphi_1$ = 0.1(12-12) = 0°, $\Delta\varphi_2$ = 0.1(12-12) = 0°.

Case IV – deviations $\Delta\varphi_1$ increase linearly from 12th to 1st turn: $\Delta\varphi_1 = x_1(12\text{-}i)$, and deviations $\Delta\varphi_2$ increase linearly from 1st to 12th turn: $\Delta\varphi_2 = x_2(i\text{-}1)$.

Case V – deviations $\Delta\varphi_1$ increase linearly from 1st to 12th turn: $\Delta\varphi_1 = x_1(i\text{-}1)$, and deviations $\Delta\varphi_2$ increase linearly from 12th to 1st turn: $\Delta\varphi_2 = x_2(12\text{-}i)$. For cases II-V, the following pairs of values (x_1, x_2) were considered: (+0.1, +0.1), (-0.1, -0.1), (+0.1, -0.1), (-0.1, +0.1), (+0.1, 0), (0, +0.1), (-0.1, 0), (0, -0.1). Connection without deviations ($\Delta\varphi_1$ = 0°, $\Delta\varphi_2$ = 0°) were also considered.

Given the small values of $\Delta\varphi$, the considered models can also be interpreted as having relative deviations $\Delta\varphi = \varphi_p - \varphi_b$, where φ_p is the pin flank angle, φ_b is the box flank angle. For example, the deviation $\Delta\varphi = +0.1$ can be obtained for different pairs (φ_p, φ_b): (30.1, 30), (30, 29.9), (29.9, 29.8), etc. During operation, positive deviations $\Delta\varphi$ can be caused by wear of the pin thread flanks near the crests or wear of the box thread flanks near the roots, and negative relative deviations – by wear of the pin thread flanks near the roots or the box thread flanks near the crests.

The analysis should take into account not only the values of lg*N* on the surface, but also the area *A* and the direction (Fig. 5) of the zone with the lowest values of lg*N* (a crack can grow in different directions). It should also be taken into account that the unequal flank angles of the box and the pin can cause an increase in contact pressures on the flanks and gaps that worsen the leak-tightness of the connection.

3. Results

3.1. Results of theoretical research

The profile data of the tool joint tapered thread 2 3/8 Reg with the following parameters were used for the research: P=5.08 mm, H=4.376 mm, h=2.626 mm, f=0.508 mm, b=0.875 mm.

The calculation was made for the diameter D_3 for the major base of the taper cone D_3= 66.68 mm and the minor base of the taper D_3= 47.68 mm. Table data *ZE*, and *ZF* are shown reduced by half a step for ease of comparison (Table 1).

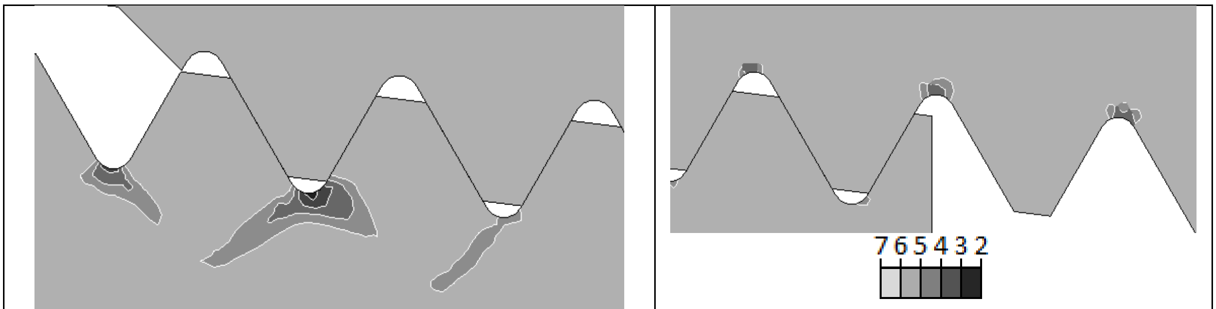
Table 1 Theoretical results

Xc, mm	X_B, mm	Zc, mm	Z_B, mm	φ_1, °	X_E, mm	X_F, mm	Z_E, mm	Z_F, mm	φ_2, °
Diameter of Minor cone base D_3= 47.68 mm									
23.845	21.220	2.020	0.508	**29.94**	23.815	20.855	0.507	2.21	**29.91**
Diameter of Major cone base D_3= 68.68 mm									
28.725	31.355	2.020	0.504	**29.96**	31.695	28.725	0.505	2.215	**29.93**

Therefore, the semi-profile angles are variable from a maximum of 29.96° per turn with the major diameter to 29.91° per turn with the minor diameter.

3.2. Results of FEA

The biggest problem is a sharp decrease in lg*N* values in the roots 1, 2 of the pin (Fig. 5a). The minimum values on the surface of the roots for a connection without deviations (0, 0) in zone 1 are 3.68, and in zone 2 are 2.2.



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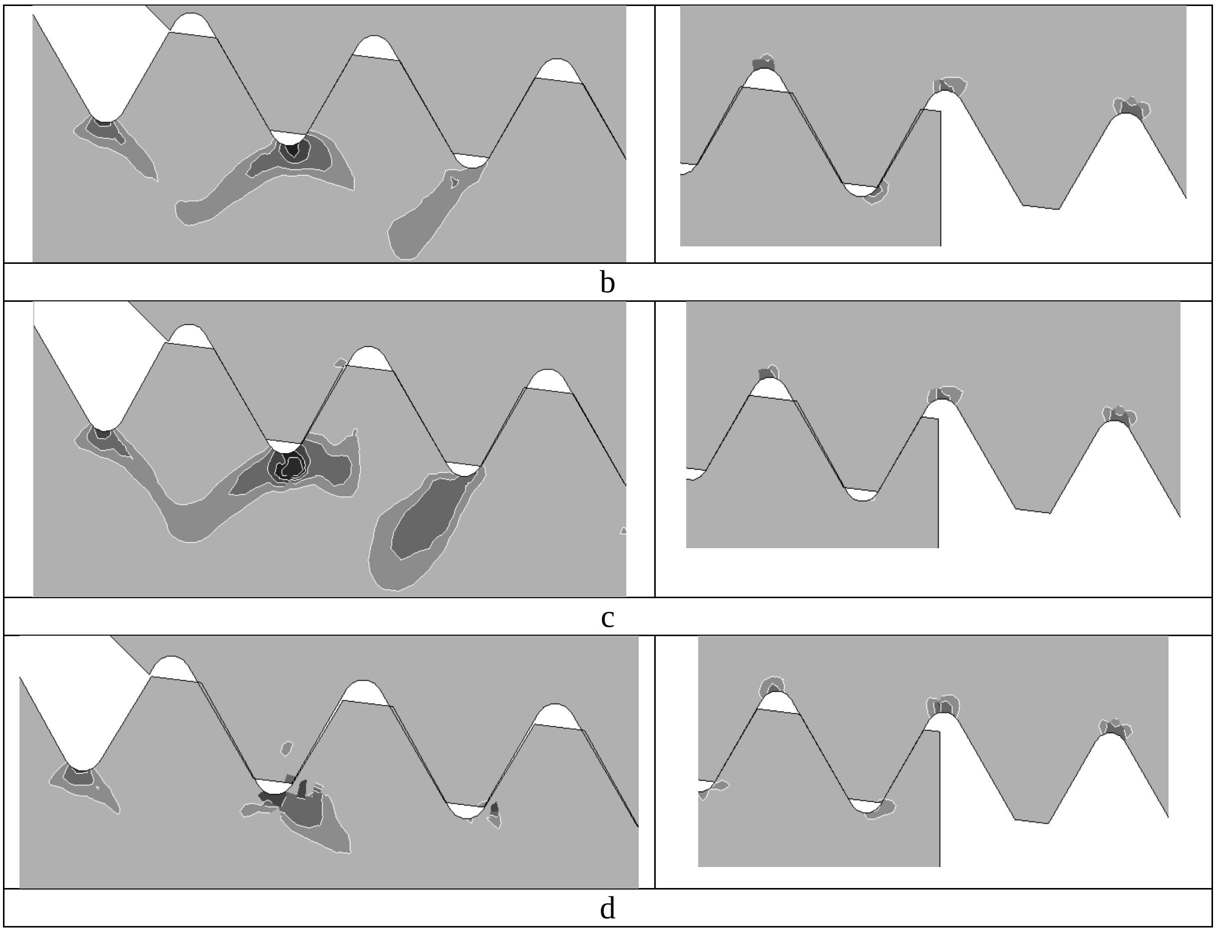


Fig. 5 Distribution of lg$N$ in the zone of roots 1 (left) and 12 (right) of the pin for the cases: a – (0, 0), b – II (-0.1, -0.1), c – IV (-0.1, -0.1), d – III (+0.1, -0.1)

The values in the zone of the free root 1 of the pin are almost independent of the deviations of the flank angle. For all cases considered, the values in this zone vary from 3.28 to 3.75 with an arithmetic mean of 3.57 (Table 2, Fig. 6a). This is also typical for the free root 1 of the box thread – values from 4.21 to 4.6 with an arithmetic mean of 4.37 (Table 3, Fig. 6b). Therefore, the values in free roots should be reduced in other ways: increase the radius at the root, treat the area with surface plastic deformation, etc. All analysis results can be found in the document "Fatigue life on flank angle deviations.pdf" on the project website [35].

The smallest values are observed in the pin root 2 and spread much more widely, from 1.94 to 3.58 with an arithmetic mean of 2.82 (Table 2, Fig. 6a). In the box root 2 – from 3.99 to 4.64 with an arithmetic mean of 4.23 (Table 3, Fig. 6b). Therefore, the fatigue life in the most dangerous zones 2 depends significantly on the deviations of the flank angles.

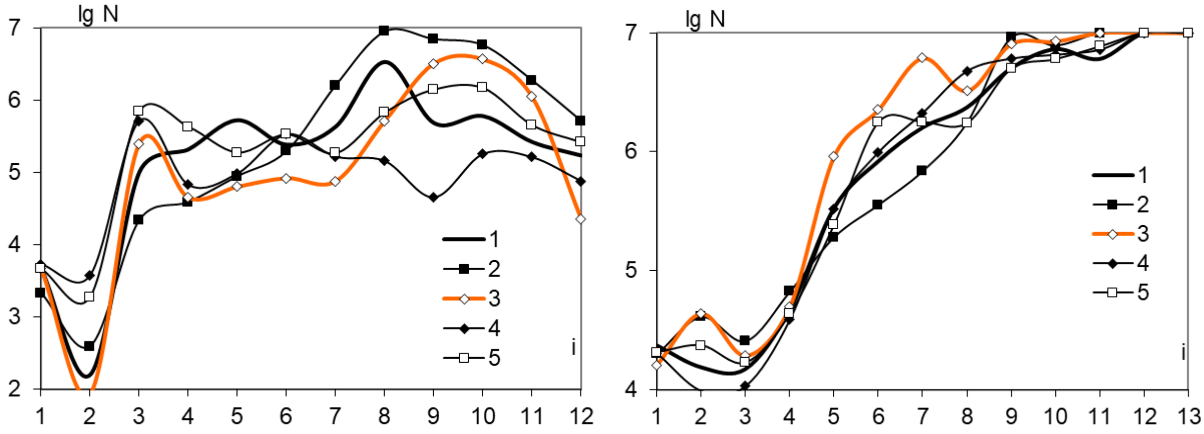
Table 2 Values of lg$N$ in the root 2 of the pin thread for different cases

Case	Pairs $\Delta\varphi_1$, $\Delta\varphi_2$ (for case I, z=0.5°) and x_1, x_2 (for cases II-V, z=0.1°)								
	+z, +z	-z, -z	+z, -z	-z, +z	+z, 0	0, +z	-z, 0	0, -z	0, 0
I	3.35^a	2.55^b	3.29^a	2.97^b	3.29^a	3.17	3.14^b	2.51	2.2
II	2.39	1.94	2.56	2.15	2.28	2.22	2.29	3.28	
III	3.54^a	3.17^b	3.58^a	2.74^b	3.55^a	2.04	2.72^b	2.49	
IV	3.54^a	2.59^b	3.49^a	2.64^b					
V	2.87	2.14	2.64	3.28					

Note: index a – compared with (0, 0), the area A is smaller, b – is larger

Table 3 Values of lg$N$ in the root 2 of the box thread for different cases

Case	Pairs $\Delta\varphi_1$, $\Delta\varphi_2$ (for case I, z=0.5°) and x_1, x_2 (for cases II-V, z=0.1°)								
	+z, +z	-z, -z	+z, -z	-z, +z	+z, 0	0, +z	-z, 0	0, -z	0, 0
I	4.06	4.37	4.05	4.38	4.06	4.19	4.33	4.15	4.19
II	4.15	4.64	4.11	4.36	4.14	4.19	4.27	4.37	
III	3.99	4.39	3.99	4.38	3.99	4.19	4.38	4.20	
IV	3.99	4.62	4.04	4.45					
V	4.14	4.28	4.14	4.27					



a b

Fig. 6 Values of lg$N$ in roots i of pin (a) and box (b) threads: 1 – (0, 0), 2 – IV (-0.1, -0.1), 3 – II (-0.1, -0.1), 4 – III (+0.1, -0.1), 5 – II (0, -0.1)

In case I, the smallest lg$N$ values in the root 2 of the pin thread are observed for the following pairs ($\Delta\varphi_1$, $\Delta\varphi_2$): (-0.5, -0.5), (0, -0.5) (Table 1). An increased area A is also observed for (-0.5, +0.5), (-0.5, 0). The largest lg$N$ values with reduced area A are for (+0.5, +0.5), (+0.5, -0.5), (+0.5, 0). A common type of wear, forming deviations with (0, +0.5) [18] slightly improves fatigue strength. Consequently, negative deviations of the flank angles (primarily $\Delta\varphi_1$) degrade the fatigue strength. There is a “wedge” effect that tries to “break” the thread root 2. For positive deviations, this effect is absent and the fatigue strength improves.

For case II, almost all variants (x_1, x_2), due to the absence of deviations in zone 2 of the pin, in terms of lg$N$ values (Table 2) and area A (Fig. 5b) do not differ significantly from the nominal variant (0, 0). The worst variants: (-0.1, -0.1), (-0.1, +0.1), (-0.1, 0). For (-0.1, -0.1) the same negative "wedge" effect occurs, which reduces durability the worst. The most common wear type II (0, +0.1) [4] almost does not change the fatigue strength. Best variants: (0, -0.1), (+0.1, +0.1), (+0.1, -0.1), (+0.1, 0). For (0, -0.1) there is a significant increase in the value of lg$N$ (3.28), which can be explained by the effect of equalizing the loads in thread (Fig. 6a) and it is important that the short (loaded) flank remains unchanged. In case II, negative deviations x_1 should be avoided, positive ones should be preferred, and negative deviations x_2 should be preferred.

For case III, due to the “wedge” effect, the area A is increased in the variants (-0.1, 0), (-0.1, +0.1), (-0.1, -0.1). The best variants are (+0.1, -0.1), (+0.1, 0), (+0.1, +0.1). Their area A is small (Fig. 5d), and the lg$N$ curve is gently sloping (Fig. 6a), which indicates a significant equalization of loads. Therefore, negative values of x_1 should be avoided and positive values should be preferred. At the same time, negative deviations x_2 should be provided.

For case IV, the worst variants (x_1, x_2) with a significantly increased area A are (-0.1, -0.1) (Fig. 5c) and (-0.1, +0.1). The latter is a very common type of pin thread wear according to [4]. The lg$N$ curve is steeper (Fig. 6a), which indicates a less equal distribution of loads. Due to the effect of load equalization, the best variants are (+0.1, +0.1) and (+0.1, -0.1).

For case V, due to the "wedge" effect, the worst variant is (-0.1, -0.1). Due to the effect of load equalization, (-0.1, +0.1) is the best variant. Here, the negative value of x_1 does not lead to a decrease in lg$N$ due to the absence of deviations on the first turns.

4. Conclusions

1. To increase the fatigue strength of the pin, in most of the cases considered, negative deviations of the flank angle of the short flank of the pin thread should be avoided, and preference should be given to positive ones. In particular, it is undesirable to make up a new box with a pin with $\Delta\varphi_1 < 0$, as well as a new pin with a box with $\Delta\varphi_1 > 0$. Negative relative deviations $\Delta\varphi$ of both flanks usually worsen the fatigue strength of the pin due to the "wedge" effect.

2. Variants that significantly increase fatigue strength have an "anti-wedge" effect (I (+0.5, +0.5), I (+0.5, -0.5), I (+0.5, 0)) or equalize the load in the thread (III (+0.1, -0.1), III (+0.1, 0), III (+0.1, +0.1), IV (+0.1, +0.1), IV (+0.1, -0.1), II (0, -0.1), V (-0.1, +0.1)). They need detailed studies and can be the basis for optimizing the values of flank angle deviations on each turn according to the method described in [31]. Often, a decrease in lg$N$ values in the pin roots is associated with their increase in the box roots and vice versa (Fig. 6, Tables 2, 3). Since the minimum values in the box are approximately 2 times greater than the minimum values in the pin, then when optimizing the design, one should try to increase the value in the pin until they are equal to the values in the box. Thus, we obtain equal strength pin and box.

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