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The Influence of the Multiaxial Stress State due to a Concentrator and Residual Stresses on High-Cycle Fatigue of Steel

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Keywords: concentrator, stress components, lifetime, criterion

ABSTRACT: Experimental and computational investigations have been performed into a local multiaxial stress state in a concentrator with residual stresses which revealed the possibility of using the criterion of shear octahedral stresses to establish the equivalence with a smooth specimen. The modification of the criterion is proposed to take into account the stress ratio in a cycle due to residual stresses. Basing on this criterion, the authors have justified a method for lifetime calculation for a structural element with a concentrator and residual stresses using as an example a steel plate with a hole.

Introduction

In most cases the influence of nonuniaxiality of stresses on the ultimate state of materials has been studied and evaluated on the basis of their behaviour in macroscopic volumes. Under such conditions the realization and measurement of stress components are simple. At the same time, the major part of failures, fatigue ones in particular, initiate at the sites of local action of nonuniaxial stresses induced by design, technological, operation factors or by their combinations. One of the most typical cases occurring in machine parts is the presence of a design stress concentrator whose technological execution causes residual stresses. When such an element is cyclically loaded, a local multiaxial stress state is induced in the concentrator with a static field of residual stresses superimposed which relaxes with time. The solution of the problem on the life of such an element involves difficulties which resulted in the appearance of the works (1, 2, 3, 4) devoted to the investigation of this problem. As it follows from the data from the literature, there is no unambiguous solution of this problem. This is associated with its manifold character: relaxation of nonuniaxial residual stresses, multiaxial stress state in terms of static and cyclic components, different gradients of these components along different axes.

In the present report an attempt has been made to take all these factors into account. Main attention has been paid to studying the influence of stress concentration and residual stresses, initiated by different methods of concentrator surface deformation, upon high-cycle fatigue of steel 15GN2MFA and to the substantiation of the model which enables one to take into account the influence of local multiaxial stress state in the stress concentrator zone upon fatigue strength and life of a structural element under consideration.

Experimental and stress calculation procedures

Experiments were performed on plane specimens of rectangular cross-section 14x2.5 mm in size under conditions of symmetrical tension-compression with a loading frequency of 36 Hz. A central round hole 3 mm in diameter was made in the specimens, for which a theoretical stress concentration factor was 2.6.

Residual stresses in the concentrator were induced by different types of prestressing. The following types of the material preloading in the concentrator were realized: 1 - pressing a pin into the concentrator hole with a radial interference of 2 and 4%; 2 - the same but with pressing out the pin prior to fatigue testing; 3 - tensioning the specimen until a plastic strain of 2% is induced on the concentrator surface with subsequent unloading; 4 - compression of the specimen until a plastic strain of 2% is induced on the concentrator surface with subsequent unloading; 5 - inducing, in the process of specimen cyclic loading, biaxial static stresses in the longitudinal (coaxially with cyclic load, OY axis) and transverse (in the specimen plane at an angle of 90° to the longitudinal load, OX axis) directions. In the latter case, the ratio of longitudinal to transverse loads was such that in the stress concentrator the stress state was induced with the transverse static stress exceeding the longitudinal one.

The magnitude and the pattern of residual stress distribution were determined by calculation using the strain model whose equations were solved by the finite element method (5, 6). The initial data for the calculation are the material stress-strain diagram, geometrical characteristics of the specimen and the parameters of the specimen external loading. The calculations were made both for the cases of residual stress initiation in the concentrator and for the conditions of cyclic loading. In so doing the stress-strain diagrams were used for static and cyclic loading, respectively. In the latter case the procedure was used (7) which involved the results of fatigue testing of specimens of round cross-section 5 mm in diameter. Stress-strain diagrams were represented in a tabulated form with the use of a computation program. The experiments were performed with a low-alloy steel 10GN2MFA. Main characteristics of its mechanical properties are $\sigma_b = 620$ MPa, $\sigma_{0.2} = 540$ MPa .

Results of residual stress calculation and fatigue testing

Figure 1 shows the results of the calculation of residual stress distribution through the depth of the material in the stress concentrator. The analysis of these data reveals that residual stresses have been generated in the vertex of the concentrator with different ratios of the components along the OX and OY axes and different signs of stresses. In this case, loading according to schemes 1 and 2 induces the stresses of the same order of magnitude along both axes, whereas schemes 3 and 4 yield appreciable excess of the σ_{OY} component over σ_{OX}. Note also that the computation of residual stresses for scheme 1 with a reduction of the theoretical stress concentration coefficient down to $\alpha = 0.2$ (instead of 2.6) results in an appreciable change of the σ_{OX} and σ_{OY} ratio (curves 6 in Fig. 1).

Loading scheme 5 is used to induce static stress components in the surface layer of the concentrator in the direction of the OX axis, with them being actually absent along the OY axis, which could not be attained by the schemes of prestressing for the chosen value $\alpha = 2.6$. A device designed for this purpose is used.

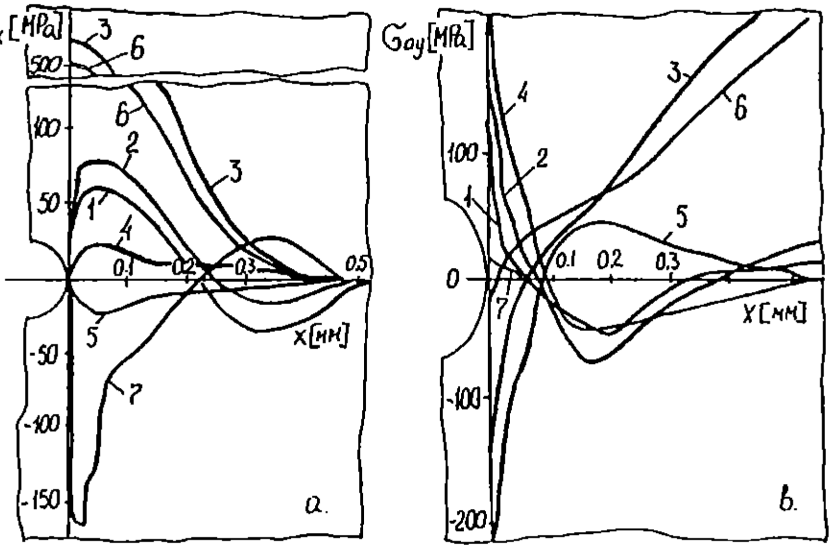


Fig. 1. Distribution of residual stress cjvgjytync through the thickness of the material in the concentrator: 1 - pulling a pin througth the hole with an interference of 2%; 2 - pulling a pin through the hole with an interference of 4%; 3 - prssing in a pin with an interference of 2% (α=2.6); 4 - prestressing by compression; 5 - prestressing by tension; 6 - pressing in a pin (α=2); 7 - biaxial compression

The residual stresses given in Fig. 1 are taken as the initial ones, i.e. they were initiated prior to fatigue testing. In the course of cyclic loading these stresses are relaxing that leads to a change of their magnitudes and ratios along the axes, and also to the redistribution through the material depth. To take those changes into account subsequently when considering multiaxial stress state in the concentrator, the analysis has been made of the data on the residual stress kinetics in steels of similar grade. It has been found (8) that the level of stabilized values of residual stresses for high-cycle fatigue can be described by the relationship of closed form. In so doing account must be taken of the level of stress concentration and plasticity under static and cyclic loading. With a knowledge of the distribution of initial residual stress components through the depth and the distribution of cyclic stress components one can calculate stabilized residual stress values for any depth from the surface of the concentrator.

From the analysis of the experimental data on residual stress relaxation it also follows (8) that in low-cycle fatigue the stage of residual stress stabilization occupies not more than 10% of the total life to crack initiation. For this reason, in the subsequent assessment of cyclic life for specimens with a concentrator and residual stresses the material damaging at the stage of their relaxation is not taken into account.

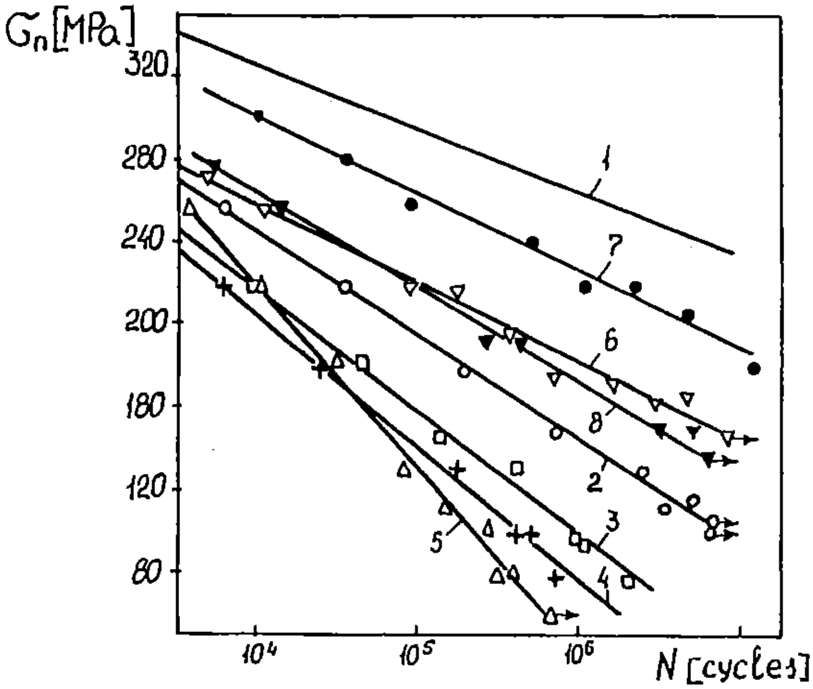


Fig. 2. Fatigue curves for the investigated specimens: 1 - smooth specimens; 2 - specimens with a concentrator without residual stresses; 3,4 - after pressing in a pin with an interference of 2 and 4%, respectively; 5 - after prestressing in compression; 6 - after prestressing by tension; 7 - with a pin; 8 - in biaxial static compression.

In order to develop and verify the computation procedure for the assessment of cyclic life of the components in question considering the material local multiaxial stress state, induced by the concentrator and residual stresses, fatigue curves were obtained for specimens prepared in accordance with the schemes described above. The results of fatigue tests are shown in Fig. 2. They exhibit essential correspondence to conventional notions about the influence of residual and static stresses on the fatigue behaviour of steels. The presence of tensile static (or residual) stresses reduces fatigue strength of steel 10GN2MFA (curves 3, 4, 5 in Fig. 2), whereas the presence of compressive stresses increases it (curve 6). Enhancement of fatigue characteristics of the specimens with a pin in the stress concentrator (curve 7) is related to both static stresses introduced by the pin, and a change in the procedure of deformation of the filled hole. The presence of static compressive stress along the axis perpendicular to the axis of cyclic load application also results in an increase of the material fatigue strength (curve 8) though somewhat less intensive than that caused by the same stress but coaxial with the cyclic load.

Analysis of the stress state in the concentrator

To establish the relationship between the stress state in the stress concentrator and the life as well as the correspondence with cyclic strength of smooth specimens, several levels of lifetime and the corresponding nominal stresses were chosen from the data in Fig. 2 and the stress components from cyclic load were calculated for them. The results of the calculations are presented in Fig. 3 as the distributions of the stress amplitude intensity (σ_{ai}) through the material depth in the concentrator. The points which correspond to the stress intensity at the same lives in smooth specimens under cyclic tension- compression are also marked on the stress intensity distribution curves. The results presented reveal that the distribution pattern of the stress amplitude intensity in the concentrator σ_{ai} is onmonotonic. In this case the stress intensity on the surface of the concentrator and down to a certain depth exceeds the stress intensity in the smooth specimen at equal cyclic lives to crack initiation. We designate this depth by X_{eq} and note that on the surface of the concentrator ($X = 0$) and at the material depth, where the stress distribution curve σ_{ai} reaches its maximum($X = X_{\max}$), the σ_{ai} values which characterize the stress state in the concentrator are appreciably higher than those at the depth $X = X_{eq}$ wherein the equivalence of σ_{ai} is observed for smooth and notched specimens with similar lives. The difference in stresses between points $X = 0$ and $X = X_{eq}$ is growing with the nominal stress applied to a notched specimen.

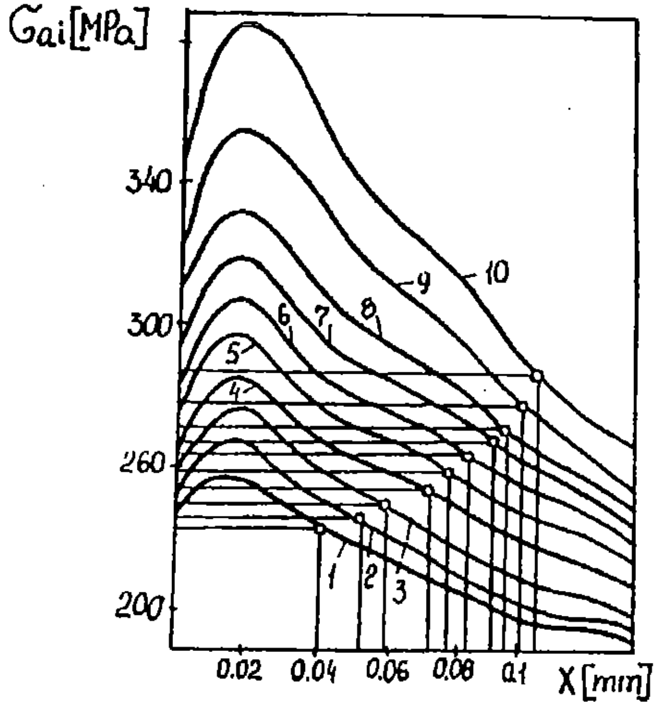


Fig. 3. Distribution of stres intensity amplitudes through the depth of the material in the concentrator: σ_n=106 (1), 114 (2), 121 (3), 130 (4), 137 (5), 146 (6), 153 (7), 166 (8), 177 (9), 180 (10) MPa.

Considering the aforesaid, one can suggest that when a notched specimen is cyclically loaded to the number of cycles which corresponds to the life of a smooth specimen under the stress equal to the stress intensity value at the depth X_{eq}, some ruptures and microdiscontinuities have already been formed in the concentrator down to the depth X_{eq} and there is a nucleated crack equivalent to that in a smooth specimen. It should be noted that unlike the assumption of the constancy of the critical depth of the material surface layer, wherein the equivalence of stresses in smooth and notched specimens is observed (9, 10), the results presented exhibit an increase in the X_{eq} value with nominal stresses applied to the specimen with a concentrator. The analysis of the results for the steels tested and for some other materials reveals that at high-cycle fatigue lives X_{eq} varies within 40...100 Om for steel 10GN2MFA, 40...240 Om for aluminium alloy AMg6, 60...200 Om for steel 45, 45... 140 Om for steel 1Kh2M.

Similar analysis performed for other materials allows one to conclude that at low characteristics of cyclic plasticity the X_{eq} value is close to a constant value which is in agreement with refs (9, 10), whereas with an essential cyclic plasticity in a high-cycle fatigue region this assumption results in appreciable errors in life calculations.

Consideration of a multiaxial stress state in the concentrator under cyclic asymmetric loading

With the use of the established relationship (8), stabilized residual stresses were estimated for the tested specimens with a concentrator and residual stresses for the concentrator material depths $X = 0$, $X = X_{\max}$ and $X = X_{eq}$. In what follows the obtained values are taken into account as static stresses and the calculations are made for the life $N = 2 \cdot 10^5$ cycles, since for other lives of the high-cycle fatigue region the conclusions made and the relationships obtained are similar.

Since the residual stresses are nonuniaxial and their maximum values for the cases realized fall on different axes, one-dimensional schemes for taking cycle stress ratio into account are unacceptable. Taking by convention the intensity of residual compressive stresses as a negative value, we constructed the diagrams of limiting amplitudes in terms of stress intensities (Fig. 4) for the stresses at different distances from the concentrator surface: $X = 0$, $X = X_{\max}$ and $X = X_{eq}$. From those results it follows that:

- the best description of the results is observed for the depth $X = X_{eq}$ which indicates the necessity of introducing it into calculations;
- the scatter of the results with respect to the approximating line is high which does not allow taking it as a criterion;

- the results where residual stresses along different axes have different signs do not fit in with the coordinates chosen.

Taking these conclusions into account, the authors considered the possibilities of using equivalent stresses in the determination of which the influence of normal or hydrostatic stresses on the limit values of the maximum shear or octahedral shear stresses is allowed for (4). The best agreement with the experiment was exhibited by the criterion of octahedral stresses in the form (9):

$$\tau_{oct} + AP_{\max} = B \qquad 1)$$

where A and B are constants; $P_{\max}$ is the maximum hydrostatic stress in a cycle, τ_{oct} is the octahedral stress determined by the following relationships:

$$P_{\max} = \frac{1}{3}(\sigma_{OX} + \sigma_{OY} + \sigma_{OZ} + \sigma_{aX} + \sigma_{aY} + \sigma_{aZ}); \qquad (2)$$

$$\tau_{oct} = \frac{1}{3}\sqrt{\left(\sigma_{aX} - \sigma_{aY}{}^{2}\right) + \left(\sigma_{aY} - \sigma_{aZ}\right)^{2} + \left(\sigma_{aZ} + \sigma_{aX}\right)^{2}}. \qquad (3)$$

Figure 5a presents experimental points calculated according to Eqns (1), (2) and (3) for the life equal to $2 \cdot 10^5$ cycles and a depth of $X = X_{eq}$. The criterion lines for $N = 2 \cdot 10^5$ cycles (line I) and $N = 2 \cdot 10^6$ (line II) have been constructed using the test results for smooth specimens in tension-compression and in torsion. For those cases, respectively

$$\tau_{oct} = \frac{\sqrt{2}}{3}\sigma_a; \quad P_{\max} = \frac{\sigma_a}{3}; \qquad (4)$$

$$\tau_{oct} = \sqrt{\frac{2}{3}}\tau_a; \quad P_{\max} = o. \qquad (5)$$

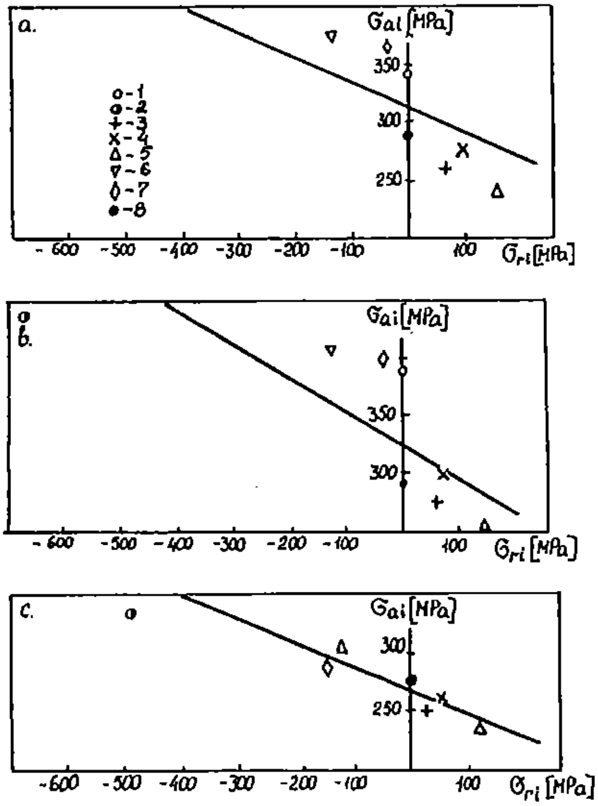


Fig. 4. Conventional diagrams of limiting amplitudes in terms of stress intensities: 1 - without residual stresses; 2 - pressing in a pin; 3,4 - pulling a pin through with an interference of 2 and 4%; 5,6 - prestressing by compression and by tension; 7 - biaxial compression; 8 - smooth specimen.

The deviation of the experimental points from lines I and II for specimens with a concentrator is a regular phenomenon which testifies to the neglect of the cycle asymmetry influence upon the stress amplitude values in relationships (2) and (3) since residual stresses of different signs deviate the experimental points to opposite sides from line I.

To take into account this factor, it is assumed that each of the stress amplitude components in relationships (2) and (3) should be determined considering the stress ratio in a cycle Ψ:

$$\sigma_{ajr} = \sigma_{aj} - \Psi\sigma_{oj} \qquad (6)$$

where $j = x, y, z$.

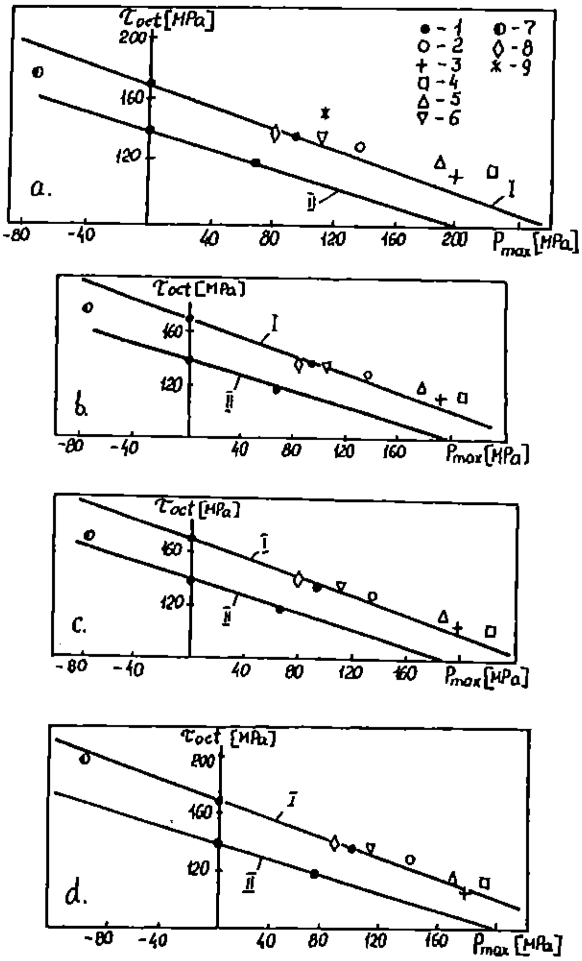


Fig. 5. The influence of the allowance for the cycle asymmetry on the correspondence to the criterion of shear octahedral stresses: a, b, c, d correspond to Eqns (1), (9), (10), (11); I, II - criterion lines

Then Eqns (2) and (3) will be written as:

$$\tau_{oct(r)} = \left(\frac{1}{3}\right)\sqrt{\left(\sigma_{axr} - \sigma_{ayr}\right)^2 + \left(\sigma_{ayr} - \sigma_{azr}\right)^2 + \left(\sigma_{azr} - \sigma_{axr}\right)^2}; \qquad (7)$$

$$P_{oct(r)} = \left(\frac{1}{3}\right)\left[\sigma_{OX} + \sigma_{OY} + \sigma_{OZ} + (1 - \Psi)\left(\sigma_{ax} + \sigma_{ay} + \sigma_{az}\right)\right]; \qquad (8)$$

Three variations of relationship (1) were examined for validity: when the cycle stress ratio is taken into account in the calculation of τ_{oct} alone, of P_{max} alone and of both the former and the latter. These relationships are, respectively:

$$\tau_{oct(r)} + A\ P_{max} = B \quad (9)$$

$$\tau_{oct} + A\ P_{max(r)} = B \quad (10)$$

$$\tau_{oct(r)} + A\ P_{max(r)} = B \quad (11)$$

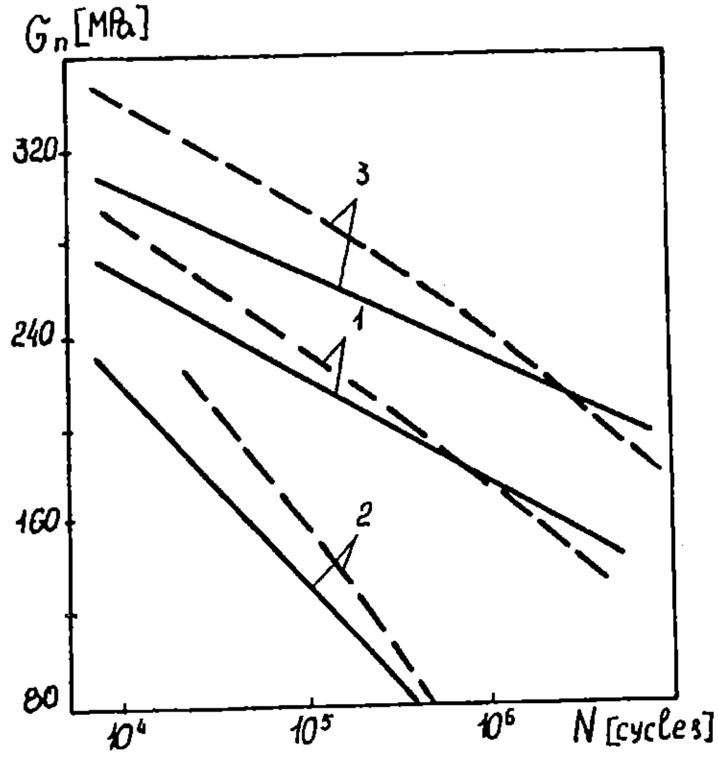
Figures 5b,c,d, give the test data presented in the form of those equations from which it follows that their fit with the line constructed for smooth specimens is observed when Eqn (11) is used, i.e. when in the calculations of τ_{oct} and P_{max} the change in the stress amplitude components is taken into account in accordance with Eqn (6). Thus, the criterion proposed in the form of (11) is the extension of criterion (1).

Cyclic Life Prediction for the Elements with Concentrators and Residual Stresses

A series of investigations performed makes it possible to determine the algorithm for calculating cyclic life of a structural element with a concentrator under symmetrical loading with the account taken of relationship (11). For the calculation it is necessary to have the data on smooth specimens: fatigue curves in tension-compression and in torsion, stress-strain diagrams for cyclic and static loadings. The criterion relationships τ_{oct} vs P_{max} for several lives are constructed from the fatigue curves for smooth specimens, whereas the distribution curves for the components of residual and cyclic stresses (for different levels of nominal stresses applied) and octahedral cyclic stresses τ_{oct} are constructed from the concentrator geometry and stress-strain diagrams. Using the τ_{oct} vs X curves and the criterion curves, the X_{eq} value is determined for the given values of σ_{a1}, N_1 by the method of successive approximations. Stabilized values of residual stresses are found for this depth (X_{eq}) and their consideration as a cycle asymmetry is made according to dependences (7) and (8). By introducing the refinements according to formula (11) the N_1 value is found using the criterion curves τ_{oct} vs P_{max}, which corresponds to the life of the specimen with a stress concentrator and residual stresses under the action of nominal stress

σ_{1n}. By specifying several values of σ_a, N_1 and repeating the described procedure, we get the fatigue curve for an element with a stress concentrator.

The described algorithm for assessing cyclic life was realized for several variations of tested specimens with concentrators and residual stresses. The results are given in Fig. 6 as calculated and experimental fatigue curves. As follows from the data obtained, the prediction is satisfactory, though an increase in the prediction error is observed with a decrease in cyclic life. We relate this fact to a larger error of the determination of stabilized residual stresses for those lives



.Fig. 6. Comparison of the calculated and experimental fatigue curves: dashed lines - calculation, solid lines - experiment: 1- biaxial compression; 2 - prestressing by compression; 3 - pressing in a pin.

Conclusions

On the basis of the calculations and experiments performed, the applicability of the criterion of octahedral stresses has been determined taking into account a hydrostatic stress.

However, it has been shown that this criterion should be modified to take into account the components of the cycle asymmetry along different axes. The results have been demonstrated on plane specimens with a central hole and residual stresses induced therein whose stabilized values are taken for static components of the loading.

On the basis of the modified criterion of the material ultimate state, the algorithm has been proposed for the calculation of high-cycle fatigue life for a typical structural element with a concentrator and residual stresses in it, and the agreement between the calculated and experimental results has been shown.

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