23. G. S. Pisarenko and A. A. Lebedev, Deformation and Strength of Metals in a Complex Stressed State [in Russian], Naukova Dumka, Kiev (1976).
24. E. Shiratori, K. Ikegami, and F. Yoshida, "The subsequent yield surfaces after proportional preloading of the Tresce-type Materials," Bull. J. Soc. Mech. Eng., 19, No. 136, 1122-1128 (1976).
25. N. Nadai, T. Kakuma, and Y. Miyamoto, "Mechanical behavior of Zircalloy-2 and SUS-316 cladding tubes under biaxial stresses," Kobe Steel Eng. Rep., 33, No. 1, 66-69 (1983).
26. K. Ikegami, "Experimental plasticity on the anisotropy of metals," Colloq. Int. CNRS, No. 295, 201-242 (1982).
27. A. A. Lebedev, V. V. Kosarchuk, and B. I. Koval'chuk, "Investigation of scalar and vector properties of anisotropic materials in a complex stressed state. Report 1. On the yield condition of anisotropic materials," Probl. Prochn., No. 3, 25-31 (1982).
28. W. Prager, "The theory of plasticity: A survey of recent achievements," Proc. Inst. Mech. Eng., 169, No. 1, 41-57 (1955).
29. H. Zeigler, "A modification of Prager's hardening rule," Quart. Appl. Math., 17, No. 1, 55-60 (1959).
30. R. T. Shield and H. Ziegler, "On Prager's hardening rule," Z. Angew. Math. Phys. A., 9, No. 3, 260-276 (1958).
31. B. I. Koval'chuk, V. V. Kosarchuk, and A. A. Lebedev, "Investigation of the scalar and vector properties of anisotropic materials in a complex stressed state. Report 2. Plastic deformations of anisotropic materials under simple loading," Probl. Prochn., No. 8, 114-121 (1982).
32. D. W. A. Rees, "Hardening model for anisotropic materials," Exp. Mech., 21, No. 7, 245-254 (1981).
33. V. T. Koiter, "Relationships between stresses and deformations, variational theorem, and the theorem of singularity for elastoplastic materials with a singular yield surface," Mekh., 60, No. 2, 117-121 (1960).
34. A. S. Vavakin, S. A. Zlatomrezhev, V. N. Kasatikov, and L. P. Stepanov, Experimental Investigation of the Elastoplastic Properties of Aluminum Alloys AMg6 and D16 during Proportional Deformation [in Russian], Inst. Probl. Prochn., Akad. Nauk SSSR (1984), p. 42.

EVALUATION OF THE INFLUENCE OF RESIDUAL INTERNAL MICROSTRESSES ON THE STRENGTH OF 18Kh2N4VA STEEL WITH THE USE OF THE CRITERION OF TENSILE STRESSES

V. M. Mishin and V. I. Sarrak

UDC 539.319:620.163.32

The appearance of a crack, according to the criterion of tensile stresses [1], occurs upon reaching a stress equal to the critical σ_F in a local area. In the absence of residual internal microstresses, the critical local tensile stress is reached as the result of a load applied from the outside. Therefore, σ_F may be evaluated from the level of the local tensile stress at the moment of crack origin.

In the case when there are residual internal microstresses in the metal the failure load may decrease. This is related to the fact that to reach the critical local tensile stress in the presence of residual internal microstresses the level of local stress provided by the load applied from outside must be less by an amount equal to the residual internal microstress at the point of crack origin. In accordance with this as a first approximation the local failure stress at the point of crack origin may be represented in the form of two independent components, the concentrated stress occurring under the action of the externally applied load and the residual internal microstress coinciding with it in direction:

$$\sigma_{loc} = \sigma_{con} + \sigma_{in}. \quad (1)$$

At failure normally $\sigma_{loc} > \sigma_y$ and Eq. (1) may be considered as a first approximation for evaluation of the effective local stresses in a body with a notch.

Central Scientific-Research Institute for Ferrous Metallurgy, Moscow. Translated from Problemy Prochnosti, No. 4, pp. 57-62, April, 1986. Original article submitted February 23, 1984.

 0039-2316/86/1804-0482$12.50

In hardened steel the residual internal microstresses are distributed nonuniformly in the structure. The second-order residual internal microstresses occurring within the limits of a martensite crystal and observed from broadening of the x-ray lines and also the residual internal "peak" microstresses localized at the points of junctions of the martensite crystals with the austenitic grain boundaries and not observable by x-ray methods differ [2]. In comparison with second-order residual internal microstresses, the latter reach higher values and are more dangerous in the development of brittle fracture [2].

Therefore, a grain boundary, possessing, as a rule, on the one hand, the lowest local strength while, on the other, being the point of action of the maximum residual microstresses, is energywise the most favorable point of crack origin.

Since the residual internal peak microstress was evaluated as a first approximation as the difference in the critical tensile stress and the concentrated stress for conditions of the material differing in the absence and presence of residual internal microstresses, the value of the residual internal microstress determined characterizes not the absolute "peak" of the stress but the contribution of the residual internal peak microstresses to crack origin, being, therefore, the "effective." Then the effective residual interval microstress is understood as the residual **internal** microstress.

The purpose of this work was an evaluation of the influence of residual internal microstresses at the point of crack origin on the concentrated failure stress created by application of a load.

Material and Method. 18Kh2N4VA steel (0.19 C, 1.5 Cr, 4.1 Ni, 0.2 Si, 0.37 Mn, 0.82 W, 0.003 S) melted in an open-induction furnace was investigated. The above specimen was heated to 1000°C, held for 10 min, and water hardened. To protect the surface from decarburization before heat treatment, the specimens were sealed in ampuls previously evacuated of air. After heat treatment the four lots of specimens were held for different times (15, 2700, 4600, and 8700 min) at room temperature.

There exist structural conditions differing only in the level of residual internal microstresses. For example, for martensite, holding leads to a decrease in the level of residual internal microstresses without a change in structure. Therefore, by changing the time of hold it is possible to change the level of residual internal microstresses [2].

After the corresponding hold, a portion of the specimens of each lot was heated (100°C, 2 h) for relaxation of the residual internal microstresses related to the formation of the martensitic structure to a level equivalent to an infinite hold time. With an increase in tempering temperature there is a transition from brittle to ductile fracture since the residual internal microstresses lose the determining role in brittle crack origin.

Specimens with dimensions of 55 × 10 × 10 mm and a sharp notch with a depth of 2 mm, an angle of opening of 45°, and a radius of curvature of 0.34 mm were used. The three-point bend tests were made with a loading rate of 0.5 cm/min to failure. The load was recorded at the moment of brittle fracture of the specimen. The nominal failure stress (without taking into consideration the influence of the notch) was determined using the equation

$$\sigma_N = \frac{3PL}{2B(H-a)^2}, \qquad (2)$$

where P is the applied load, L is the distance between the supports, B is specimen thickness, H is specimen height, and a is notch depth.

Determination of the Stresses in Front of the Notch. At present there are various methods of determination of the failure stress in front of the notch [1]. The use as the test object of notched specimens makes it possible to determine the maximum value of the tensile stress in front of the notch, the concentrated stress σ_{con}. Before the appearance of the plastic zone, this stress is determined as the product of the elastic stress concentration factor and the nominal stress:

$$\sigma_{con} = \sigma_N K_y \qquad (3)$$

After appearance of the plastic zone under plane strain conditions, the stress at the boundary of the plastic and elastic areas, where the maximum tensile stress is reached, is determined as the product of the overstress Q and the yield strength of the unnotched specimen:

$$\sigma_{con} = Q_y \qquad (4)$$

The overstress Q depends upon the geometry of the specimen and notch and the degree of deformation, quantitatively characterizing the hydrostatic component of the stress in front of the notch [3].

The relationship of the overstress to the nominal stress is found in the form of the function [3]

$$Q(\sigma_N) = 1 + (Q_{g.y} - 1)\frac{\sigma_N K_y - \sigma_y}{\sigma_{N\,g.y} K_y - \sigma_y}, \tag{5}$$

where σ_y is the yield strength of the unnotched specimen and σ_y = 1600 MPa, σ_N is the nominal stress, K_y is the elastic stress concentration factor, and $Q_{g.y}$ and $\sigma_{N(g.y)}$ are the overstress and the nominal stress corresponding to the start of general yield.

For a notch with an angle of opening of 45°, a depth of 2 mm, and a radius of curvature of 0.34 mm, K_y = 2.98 [4]. To the start of general yield determined for three-point bending of a standard impact specimen with an angle of opening of 45° and a notch depth of 2 mm correspond the coordinates $[\sigma_{N(g.y)}/\sigma_y]$ = 1.95 [3] and $Q_{g.y}$ = 1.94 [1].

After substitution of the data in Eqs. (4) and (5) and transformations, the expression was obtained for determination of the stress caused by application of the load at the boundary of the plastic and elastic areas for specimens of the given geometry in three point bending:

$$\sigma_{con} = 0{,}799\sigma_y + 0.584\sigma_N. \tag{6}$$

The Relationship of the Failure Stress to the Residual Internal Microstresses. As has been noted, in this work it is assumed that the local tensile stress acting at the point of crack origin is determined by addition of the values of the concentrated stress caused by application of the load externally and by the action of the stress raiser and of the residual internal microstress.

Figure 1 presents the plan of distribution of tensile stresses in front of the notch at the moment of crack origin for two conditions, without residual internal microstresses (curve 1) and in the presence of them (curve 2). To each point of the curve 2 covering the peak microstresses correspond its own peak. This is related to the fact that the specimen has a sufficient thickness so that to each point of the coordinate X corresponded a grain boundary with a peak microstress localized on it. As a first approximation, the tensile stress in the presence of residual internal microstresses may be represented by superposition of the stress caused by application of the load (curve 3) and the residual internal microstress (curve 4). The positions of the tips of the peaks correspond to the grain boundaries.

The relationship of the concentrated failure stress to hold time is shown in Fig. 2. As may be seen, with an increase in hold time, the failure stress increases. The failure stress determined on specimens tempered at 100°C for 2 h corresponds in hold time, that is, a greater contribution from the direction of external load, the failure stress increases as the result of relaxation of residual internal microstresses.

According to the criterion of tensile stresses [1], failure occurs upon the local tensile stress reaching the critical local tensile stress σ_F, which characterizes the resistance to normal rupture in the local area and is determined by the micromechanical properties of the structure [1]. Curve 5 of Fig. 1 corresponds to the level of σ_F, which changes in movement from the body to the boundary of the grain. As shown in Fig. 1, the minimum values of σ_F correspond to the grain boundaries. At the same time, the maximum values of residual internal microstresses correspond to the latter.

During the hold of hardened steel, relaxation of the residual internal microstresses occurs without a change in the value of σ_F. Therefore, the condition of crack origin in a local area taking into consideration the residual internal microstresses on the basis of the criterion of tensile stresses has the form

$$\sigma_{loc} = \sigma_F, \tag{7}$$

or taking into consideration Eq. (1)

$$\sigma_{con}(T_{hold}) + \sigma_{in}(T_{hold}) = \sigma_F, \tag{8}$$

where σ_{con} is the concentrated failure stress created by the applied load at the point of crack origin (curves 3 of Fig. 1), σ_{in} is the residual internal microstress (curve 4), σ_F is

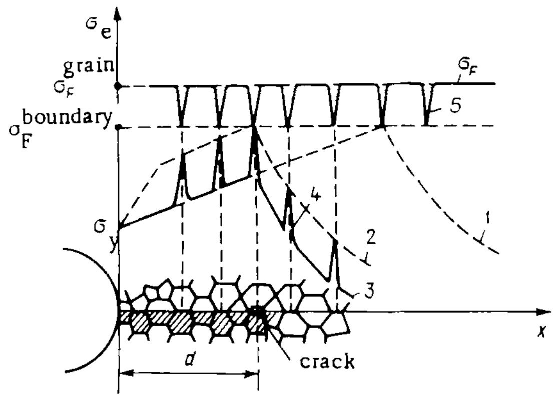


Fig. 1

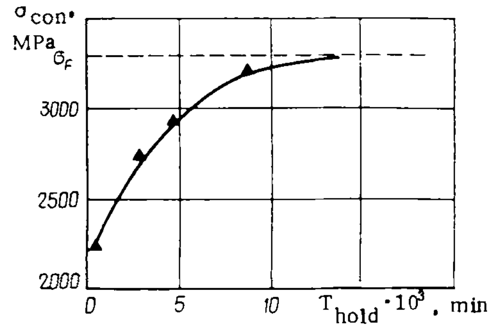


Fig. 2

Fig. 1. Plan of distribution of the tensile stresses in front of a notch at the moment of crack origin taking into consideration the residual internal microstresses.

Fig. 2. Relationship of the concentrated stress to hold time.

the critical local tensile stress (curve 5), T_{hold} is the hold time, and σ_{loc} is the local tensile stress at the point of crack origin.

Consequently, the value of σ_{con} necessary for crack origin depends upon the level of residual internal microstresses. The residual internal microstresses were determined as the difference between the critical local tensile stress and the stress caused by the external action of the load according to the equation

$$\sigma_{in}(T_{hold}) = \sigma_F - \sigma_{con}(T_{hold}). \tag{9}$$

Figure 3 presents the relationship of residual internal microstress to hold time.

Localization of the residual internal microstresses at the grain boundaries determines the point of crack origin and the intergranular character of its growth.

Influence of Residual Internal Microstresses on the Extent of the Plastic Zone. In loading of a specimen with a notch, the occurrence of stresses exceeding the yield strength of the material and causing the formation of the plastic zone is possible at the base of the notch. Growth of the plastic zone in active loading of the specimen leads to an increase in the overstress controlling the degree of exceeding of the yield strength by the stress σ_{con} [1]. According to the slip line theory, the maximum tensile stress in front of the notch (concentrated stress) before the start of general yield depends upon the extent of the plastic zone in the following manner [1]:

$$\sigma_{con} = \sigma_y\left[1 + \ln\left(1 + \frac{d}{\rho}\right)\right], \tag{10}$$

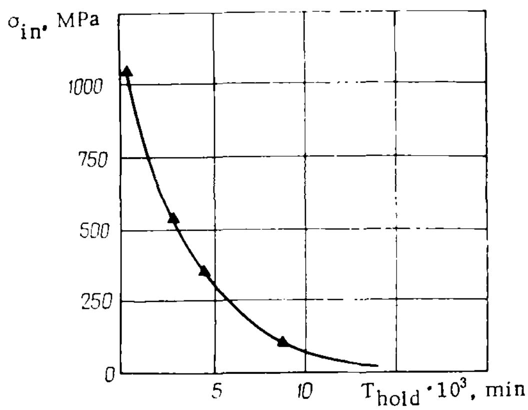
where d is the extent of the plastic zone and ρ is the radius of curvature of the notch.

On the other hand, knowing the value of σ_{con} it is possible to determine the extent of the plastic zone, which is related to the stress σ_{con} by the exponential rule [1]:

$$d = \rho\left[\exp\left(\frac{\sigma_{con}}{\sigma_y} - 1\right) - 1\right]. \tag{11}$$

To find d the values of the concentrated stress obtained by conversion using Eq. (6) of the experimentally established values of the nominal failure stress were used.

Figure 4 shows the relationships of the extent of the plastic zone to the concentrated stress under conditions of active loading until failure in the absence of residual internal microstresses and with them. In these cases the plastic zone appears with $\sigma_{con} = \sigma_y$. In the absence of residual internal microstresses failure occurs with $\sigma_{con} = \sigma_F$ and in the presence of them with $\sigma_{con} + \sigma_{in} = \sigma_F$ and the failure concentrated stress is less by the value of σ_{in} than in the absence of these stresses (Fig. 4). A lower overstress and, consequently, a smaller extent of the plastic zone requires a lower concentrated stress.



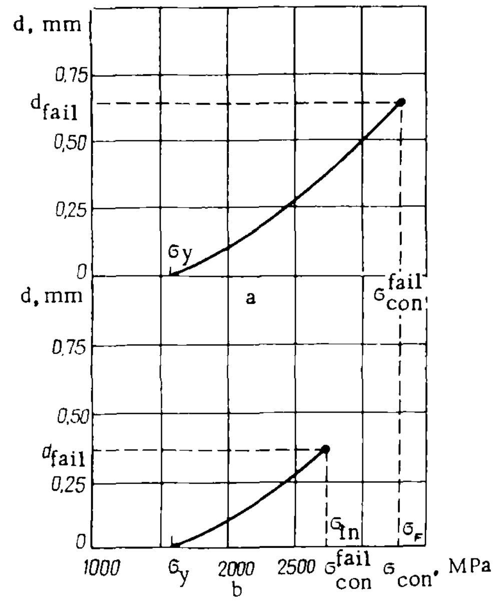


Fig. 3

Fig. 4

Fig. 3. Relationship of the residual internal microstress to hold time.

Fig. 4. Increase in the extent of the plastic zone in front of the notch until the moment of failure with an increase in the concentrated stress with σ_{in} = 0 (a) and σ_{in} = 550 MPa (b).

The extent of the plastic zone is determined by the amount of the stress σ_{con} since the residual internal microstresses at the grain boundaries are localized in such volumes that their contribution to the growth of the extent of the plastic zone is negligibly small. This is confirmed by a comparison of the residual deflections of the specimens after failure and the increase in residual deflection, the amount of which is proportional to the extent of the plastic zone [1], corresponds to the reduction in the level of σ_{in}.

The sequence of events occurring in origin of a cleavage crack in front of the notch in a material with residual internal microstresses and without them may be represented with the use of curves (Fig. 5) in relation to the amount of the local stress. Figure 5 presents the results of theoretical calculation of the extent of the plastic zone from the values of the local tensile stress at different levels of residual internal microstresses according to Eq. (12).

In the case when residual internal microstresses are absent in the material, the local tensile stress is equal to the concentrated stress. The appearance of the plastic zone occurs upon the local tensile stress (equal to the concentrated) reaching the yield strength (curve 1 of Fig. 5). The growth of the plastic zone until failure, which occurs upon the local tensile stress, equal to the concentrated, reaching the level of critical local tensile stress, is described by Eq. (11). The extent of the plastic zone at the moment of failure was calculated from the experimentally determined value of the nominal failure stress with the use of Eqs. (6) and (11).

In the case when residual internal microstresses exist in the material the increase in the extent of the plastic zone is determined by Eq. (12), which may be obtained by substitution of the values of σ_{con} from Eq. (1) in Eq. (11):

$$d = \rho\left[\exp\left(\frac{\sigma_{loc} - \sigma_{in}}{\sigma_y} - 1\right) - 1\right]. \qquad (12)$$

In this case the plastic zone appears upon the concentrated stress reaching the yield strength, but at the same time the local tensile stress exceeds the concentrated and is equal to the sum of the yield strength and the residual internal microstress (curves 2-5 of Fig. 5). At the points of intersection of all of the curves of the X-axis on Fig. 5 the stresses $\sigma_{con} = \sigma_y$ and they differ in the value of the local stress σ_{loc} as the result of the different level of σ_{in}. A further increase in the stress σ_{loc} with an increase in external load occurs as the

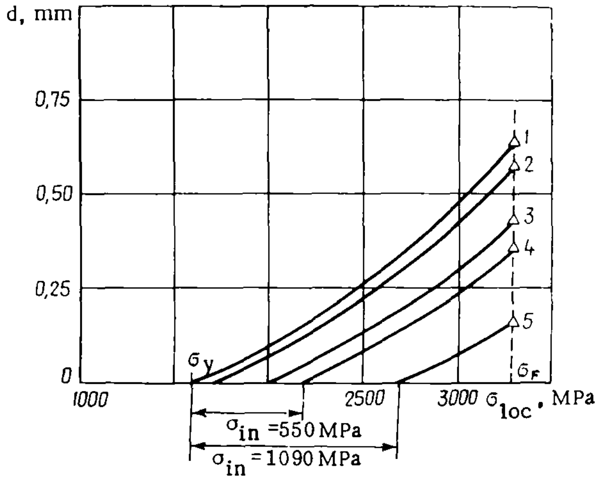


Fig. 5

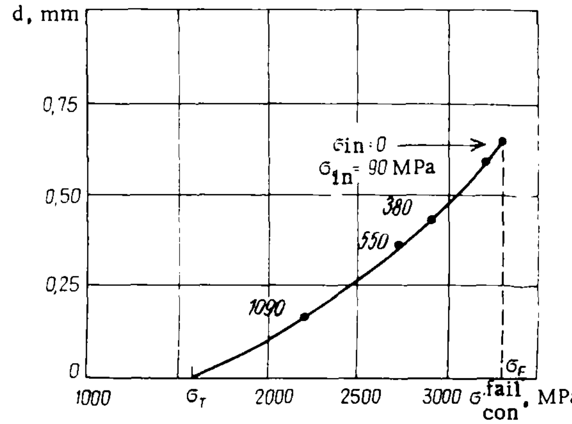


Fig. 6

Fig. 5. Relationships of the growth in the extent of the plastic zone in front of a notch to the local tensile stress at different levels of residual internal microstress: 1) σ_{in} = 0; 2) 90 MPa; 3) 380 MPa; 4) 550 MPa; 5) 1090 MPa.

Fig. 6. Relationship of the extent of the plastic zone at the moment of failure to the concentrated stress at different levels of residual internal microstress.

result of the increase in σ_{con} with a constant σ_{in} and the increase in σ_{con} causes an increase in the plastic zone d.

Crack origin occurs upon the local tensile stress, equal to the sum of the concentrated and residual internal microstresses, reaching the value of σ_F. From Fig. 5 it may be seen that in the presence of residual internal microstresses σ_{in} a crack originates with a lower value of the concentrated stress than in the absence of them. Correspondingly the size of the plastic zone necessary for an increase in the concentrated stress by overstressing is less.

Therefore, the decrease in the residual internal microstress during a hold leads to an increase in the extent of the plastic zone at the moment of crack origin. Figure 6 shows the relationship of the extent of the plastic zone to the concentrated failure stress drawn from the experimentally determined values of the nominal failure stress with the use of Eqs. (6) and (11). To each experimental point of the d = $f(\sigma_{con}^{fail})$ relationship corresponds its own level of the residual internal microstresses.

From Fig. 6 it may be seen that an increase in the concentrated failure stress leads to an increase in the extent of the plastic zone at the moment of failure. As was shown above, this occurs because of a decrease in the residual internal microstresses as the result of stress relaxation processes. It may be assumed that the role of residual internal microstresses includes weakening of the forces of the interatomic bonds at the point of action of these microstresses as the result of displacement of the atoms from a position of equilibrium.

LITERATURE CITED

1. J. F. Knott, Fundamentals of Fracture Mechanics [Russian translation], Metallurgiya, Moscow (1978).
2. V. I. Sarrak and G. A. Filippov, "The brittleness of martensite," Metalloved. Term. Obrab. Met., No. 4, 21-26 (1978).
3. D. Randall and K. Early, "The relationship between the applied failure load, the critical failure stress, the yield strength, and the stress concentration factor for high strength steels," in: New Methods of Evaluation of the Resistance of Metals to Brittle Fracture [Russian translation], Mir, Moscow (1972), pp. 198-212.
4. M. M. Leven and M. M. Frocht, "Stress-concentration factors for a single notch in a flat bar in pure and central bending," J. Appl. Mech., No. 12, 560-561 (1972).