TEMPERATURE DEPENDENCE OF CRACKING RESISTANCE OF 15KhSND STEEL AND SPECIAL FEATURES OF ITS FRACTURE. REPORT 2

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In the previous article [1], we presented the results of investigations into the temperature dependence of the cracking resistance of 15KhSND steel in the temperature range −80° to +20°C obtained using the methods [2] which make it possible to produce specimens of small thicknesses.

Tests were conducted on batches of geometrically similar specimens/beams with a single-edge notch and a crack. The specimens were subjected to static three-point bending. The thickness of the specimens was 5-26 mm. In the standard temperature dependences of dimensionless work of fracture $\bar{A}$ (Fig. 1), the curve for a thickness of 14 mm is longer than the curves for other thicknesses and is displaced to high values of $\bar{A}$; the center of the transition range on this curve is displaced to subzero temperatures. In comparison with the mean level of other curves in the region of plastic failure, the value of $\bar{A}$ is ∿30% higher.

We shall now examine the special features of failure of this material which make it possible to propose a model of the process explaining the observed effects. It should be mentioned that although quantitative evaluation was carried out using the experimental data for 15KhSND steel, the model may also be used in analysis of identical effects in other widely used low-alloy steels.

We shall analyze the morphology of fracture of the specimens used to determine cracking resistance in [1]. Figure 2 shows two typical features of the structure of the fracture surfaces. In addition to the zonal nature of the fracture surface [1] reflected in the alternation of the zones of ductile and brittle fracture, there are also crack-like splits in the fracture surface oriented along the edges of the specimens.* These morphological features were detected mainly in the transition range of the test temperatures and their extent in the specimens of different thickness varied (Fig. 3). The upper range of the brittle—ductile transition temperature range in 15KhSND steel is characterized by splitting of the fracture surface.

Splitting leads to the separation of the volume of the specimen adjacent to the fracture surface into a number of weakly bonded bands; this may influence the cracking resistance of the specimen as a whole. This important result requires detailed examination because the splitting effects are also detected in various extensively used steel grades, such as 17G1S, 09G2FB, etc. The effect of splitting on the cracking resistance of the steel is evaluated quantitatively in the subsequent section.

Initially, we shall define two types of detected splitting cracks differing in their dimensions.

1. Comparatively large cracks (1-3 mm long). In most cases, these cracks have the form of main formations resulting from the coalescence of a crack chain or crack chains dis-

*Main fracture took place in all cases across the sheet, with the edges of the specimens parallel to the surface of the sheet.

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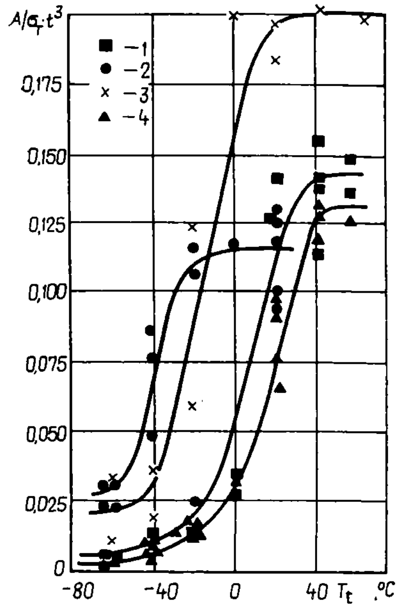

Fig. 1. Temperature dependences of dimensionless parameter $A/(\sigma_T \cdot t^3)$ for 15KhSND steel determined from the results of static bend tests on geometrically similar specimens with an edge crack: 1) 20 × 40 × 200 mm; 2) 10 × 20 × 100 mm; 3) 14 × 28 × 140 mm; 4) 26 × 52 × 260 mm.

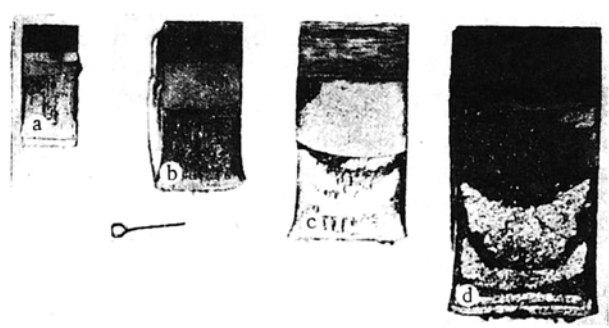

Fig. 2. Fracture surfaces of specimens with a thickness of 10 mm (a), 14 mm (b), 20 mm (c), and 26 mm (d) after tests at room temperature.

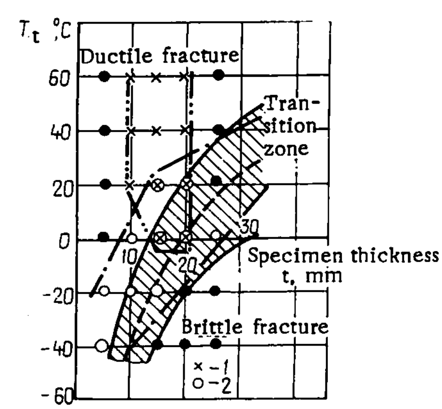

Fig. 3. Special features of the structure of the fracture surfaces: 1) splitting cracks on the fracture surface; 2) zonal nature of the fracture surface.

Fig. 4. Zone of failure of the tip of a splitting crack.

tributed in echelon form* which section a large part of the fracture surface, separating the surface into a number of parallel bands oriented along the edges of the specimen.

2. Finer cracks (∿0.1 mm) found in large quantities both in the areas of fatigue fracture and on the ductile areas of the fracture surface. Some of the cracks of this type open during subsequent loading and change to the splitting cracks of the first type. The splitting cracks of the first type propagate in specimens with a thickness of 10-20 mm and the maximum intensity of splitting is detected (for the given material) at a specimen thickness of 13.0 mm. With the test temperature increasing from 0 to +60°C, the intensity of splitting and the rate of formation of crack chains increase and the dimensions of the individual splitting cracks decrease.

Examination of the cross section of one of the 14-mm-thick specimens, tested at a temperature of +20°C, showed that the material contains a large number of elongated manganese sulfides up to 120 μm long and up to 1 μm thick. The extent of formation of the banded structure corresponded to scale number 2 (GOST 5640—68). The distribution of ferrite—pearlite bands in the thickness of the material is nonuniform.

It should be mentioned that the splitting cracks of the first and second type are confined to the areas with the most marked banded structure, although the distances between the cracks do not coincide with any of the dimensions characterizing the ferrite—pearlite bands. The micrograph of a splitting crack of the first type (Fig. 4) indicates that splitting took place by the brittle mechanism although failure through the main notch occurred by the path of mechanism. This is indicated by the transcrystalline nature of fracture along the path of crack propagation, i.e., splitting, smooth closure of the crack in its mouth, the absence of residual strains in the grains.† The trajectory of splitting coincides with the direction of the banded structure even in the vicinity of the distorted fracture front which is distinctive in the automation of the zones of ductile and brittle fracture.

Thus, the area in the vicinity of the crack consists of a zone of brittle fracture and elastic deformation adjacent to the crack and a zone of plastically deformed metal in the center. Because of the identical morphology of macrofracture on the surfaces of ductile

*It should be remembered that the straight line passing through the centers of these cracks forms an angle with the plane which differs from the right angle. These crack systems are encountered in fracture of rock [3].

†Small 'shear lips' form in the mouth of the splitting crack. The presence of these features typical of the edge of the specimen indicates that the formation of splitting cracks precedes the passage of the main ductile-fracture crack.

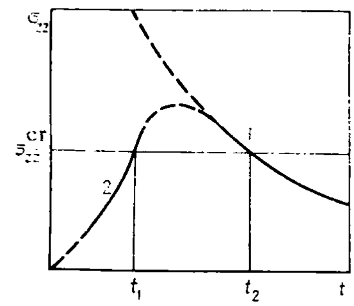

Fig. 5. Dependence of transverse stresses σ_{zz} (in relation to the rolling direction) in the net section of the specimen on its thickness t.

failure in the specimens separated and not separated by the splitting cracks into bands, the reason for the difference in the fracture parameters should be explained on the basis of the phenomena associated with the difference in the stress—strain state in the specimens with and without splitting.

Transferring to the qualitative model of the process, we shall examine consecutively the reason for appearance of splitting cracks in a limited range of the thickness of the specimens, evaluate the effective cracking resistance of the material in relation to the development of splitting cracks, and examine the mechanism of the effect of advancing splitting on the cracking resistance of the material as a whole in relation to main fracture.

On the basis of the relationships of the linear fracture mechanics (the influence of plastic effects will be taken into account later), we can propose the following qualitative explanation of the formation of splitting cracks in a limited range of specimen thickness.

Taking into account dimensional considerations and the equation for determining the stress concentration factor at the crack tip K_I in three-point bending of a prismatic specimen of finite dimensions, it may be concluded that for the variation of the thickness of the specimen in a specific intermediate range (in the transition from the plane stress to plane strain state) and geometrically similar changes in the remaining dimensions of the specimen, including the dimensions of the cracks, we can write the following equations

$$K_I \sim P \cdot t^{3/2}; \quad (1)$$

$$\bar{A} \sim K_I \cdot t^{5/2}; \quad (2)$$

$$\bar{A} \sim K_I/\sigma_{0.2} \sqrt{t}. \quad (3)$$

Equation (1) indicates, in particular (assuming that K_I at the instant of start of fracture is constant, i.e., K_I = const K_{Ic}), that the following equation may be written for the stresses σ_{yy} perpendicular to the fracture plane and the stresses σ_{zz} perpendicular to the plane of the sheet

$$\sigma_{yy},\ \sigma_{zz} \sim \frac{P}{t^{5/2}} \sim \frac{K_I}{\sqrt{t}}. \quad (4)$$

The approximate form of the $\sigma_{zz} = f(t)$ dependence is shown in Fig. 5. The value of σ_{zz} increases (curve 1) with decreasing thickness t.

We shall examine the nature of variation of the $\sigma_{zz}(t)$ dependence at low values of t. Because of the geometrically similar changes in the dimensions of the specimens with decreasing thickness t, at first sight the material does not approach the plane stress state and it is therefore not justified to assert (as in the case of transition to the plane stress state) that $\sigma_{zz} \to 0$ as $t \to 0$. However, it should be taken into account that the material has characteristic dimensions in its thicknesses: d_1, d_2 are the distances between the pearlite bands and groups of bands, and also the dimensions characterizing the distribution of sulfide inclusions. Since all the specimens were cut out from the same sheet, their d_1 and d_2 values are similar. With the reduction in the dimensions of the specimen, the $t/d_{1,2}$ ratio decreases (without influencing the ratio of thickness t to other dimensions of the specimen).

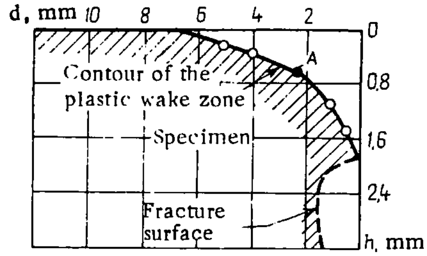

Fig. 6. An example of the profile of the plastic wake zone at the side surface of the specimen (the thickness of the specimen 26 mm, tested at +40°C).

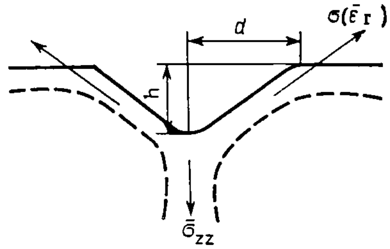

Fig. 7. Calculation diagram for evaluating the stresses σ_{zz}.

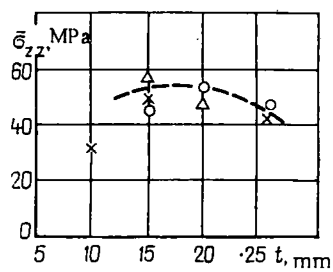

Fig. 8. Relationship between the stresses σ_{zz} and specimen thickness t.

Therefore, the extent to which the material approaches the plane stress state increases with the reduction of t. Consequently, stress σ_{zz} (t) can be reduced in a specific thickness range in which Eqs. (1)-(3) lose their validity and the following part of the $\sigma_{zz} = f(t)$ dependence is described by different asymptotics (curve 2 in Fig. 5).

It should be mentioned that the increase of the critical value of K_I with decreasing thickness as a result of formation of the plastic strains in the crack tip zone ($K_c > K_{Ic}$) [9] has no effect on the form of the curve because of Eq. (4).

We shall assume that there is a critical stress σ_{zz}^{cr} which depends, generally speaking, on temperature; when this stress is reached, normal separation cracks form in the abovementioned directions parallel to the rolling direction. If the $\sigma_{zz} = \sigma_{zz}^{cr}$ curve intersects the $\sigma_{zz}(t)$ dependence in two points t_1 and t_2 (Fig. 5), then splitting cracks should form in the planes parallel to the boundaries of the layers (pearlite bands) in the thickness range t_1-t_2. For the tested standard dimensions of the specimens, the thicknesses of 10-20 mm fall within this range at a test temperature of +20°C and $\sigma_{zz} = \sigma^{cr}$. Since the splitting effect is stronger at a specimen thickness of t = 14.0 mm, it may be expected that the maximum is found in the vicinity of this value t.

Discussing the splitting effect, it should be remembered that an increase of test temperature is accompanied by a simultaneous reduction of the stress σ_{zz}^{cr} and by an increase of the cracking resistance of the material along the boundaries of the layers. It is well known that in the case of steels with low and medium strength, the variation of cracking resistance with temperature is considerably more marked than the variation of the limiting deformation characteristics. Therefore, the dimensions of the splitting cracks should decrease with increasing temperature; this is also confirmed by the experimental results. It is evident that the existence of the above-mentioned opposite tendencies causes the elimination of the splitting effect at temperatures higher than a specific critical temperature (microcracks which may form under the effect of stress σ_{zz} as a result of high cracking resistance, do not develop along the boundaries of the layers).

To evaluate the stresses causing splitting, we shall examine the plastic wake of the side edges of the specimen in ductile failure. The plastic wake profile after final fracture of the specimen consists of two main parts. One of these parts, with a large transverse dimension, corresponds to the effect of neutral regions with respect to the crack front, whereas the other part, forming the 'avalanche' of the material on the bottom of the crater, corresponds to the effect of the peripheral area of the crack. In this case, two regions appear at the contour of the plastic wake zone. The outlines of these regions are characterized by greatly differing angles of inclination in relation to the side surface. Figure 6 shows the profile of the plastic wake zone constructed for the central area of the fracture surface of the specimen (t = 26 mm at T = +40°C). The identical structure of the profile of the plastic wake zone was described in [4].

An approximate method separates the main plastic wake zone from symmetric shear lips* for measuring the mean residual displacements of the surface layers of the plastic wake zone. The profile of the plastic wake zone shows the point of intersection of the mean level of the fracture surface with the tangent to the profile in the area of small curvature of the latter. In the case of symmetric shear lips this point is positioned on the contour of the profile (point A in Fig. 6). The remaining parameters of the plastic wake zone (its width and depth) are measured in relation to point A.

The mean residual strain in the surface layers of the specimen is associated with the parameters of the plastic wake zone by the following relationship

$$\bar{\varepsilon}_r \approx \left(\frac{\sqrt{d^2+h^2}}{d}\right)-1, \tag{5}$$

or for small values of h/d

$$\bar{\varepsilon}_r \approx \frac{h^2}{2d^2}. \tag{6}$$

This value changes nonmonotonically, increases from ∿0.4 to ∿1.4% with the thickness of the specimen increasing from 10 to 20 mm, and then decreases.

In accordance with the results of a numerical solution of the problem of the theory of elasticity for a rectangular plate with edge notches presented in, for example, [6], the stresses σ_{zz} in the direction across the thickness of the plate (in the area of stress concentration) are the highest in the central part of the plate and change only slightly. Therefore, plastic deformation in the vicinity of the crack with a straight front starts in the central part of the specimen in the area of homogeneous stresses. Consequently, the evaluation of the stresses σ_{zz} using the parameters of the plastic wake zone can be carried out using the diagram shown in Fig. 7.

The stresses σ_{zz} causing deflection and formation of the plastic wake zone in the surface layers are counterbalanced by the stresses oriented along these layers. Therefore, the magnitude of the stresses σ_{zz} can be estimated in order of magnitude by taking into account the conditions of equilibrium of the forces leading to deflection of the surface layers:

$$\sigma_{zz} \approx \sigma(\bar{\varepsilon}_r)\frac{h}{d}f, \tag{7}$$

where $\sigma(\bar{\varepsilon}_r)$ is the mean level of the stresses in the surface layers corresponding to ε_r; f is a coefficient reflecting the ratio of the effective areas of the appropriate cross sections.

The $\sigma(\bar{\varepsilon}_r)$ dependence can be determined using the diagram of static tensile loading obtained for specimens of 15KhSND steel (GOST 1497–73). For the values $\bar{\varepsilon}_r$ ∿ 0.5-1.5, the value of $\sigma(\bar{\varepsilon}_r)$ differs only slightly from $\sigma_{0.2}$.

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*The literature reports note the unsatisfactory comparability and a large scatter of the parameters of the shear lips and also the dominant role of local surface conditions in their formation [5].

TABLE 1. Values of Upper Estimates of K^*_{Ic} in Splitting for Specimens of 15KhSND Steel

Specimen No.	T_t, °C	σ_{zz}, MPa	l, mm	K^*_{Ic}, MPa$\sqrt{m}$	Type of fracture
1	+60	55,1	1,7...2,1	3,15	Ductile
8	+60	51,9	2,1...3,0	3,18	»
3	+40	41,3	1,6...2,2	2,39	»
10	+40	52,8	1,0...1,6	2,64	»
22	+40	48,6	2 0*	2,94	»
23	+20	31,2	†	—	»
17	+20	46,9	1,8...2,2	2,55	»
14	+20	52,1	1,5...1,0	2,67	Zonal
25	+20	45	—		»

*One splitting crack.
†No cracks.

The values of σ_{zz} (Fig. 8) determined using the relationship (7) indicate, in particular, that the absolute values of σ_{zz} are equal to $\sim 0.2\sigma_{0.2}$,* and the maximum stresses correspond to specimen thicknesses of 14-20 mm which are characterized by the highest rate of development of splitting. This confirms the above considerations on the existence of the range of thickness of the material with the maximum value σ_{zz}.

We shall now evaluate the cracking resistance of the material in relation to splitting cracks. Taking into account the above considerations, we shall assume that splitting cracks propagate in the conditions with stresses σ_{zz} which are homogeneous in the thickness of the specimen, and that the detected dimensions of the cracks correspond to the limiting-equilibrium state at the instant of arrest.

The parameters of the individual splitting cracks and cracking resistance K^*_{Ic}, calculated from the equation

$$K^*_{Ic} = 1.12\sigma_{zz}\sqrt{l}, \qquad (8)$$

where l is the depth of the splitting crack for an edge crack in the plate [8] (this gives the upper estimate of K^*_{Ic}), are given in Table 1 for several characteristic specimens.

The low level of the cracking resistance of the examined 15KhSND steel in relation to the splitting cracks indicates the existence of weakened zones and contacts in the direction normal to that of the surface of the sheet. It is evident that the presence of these zones is associated with the banded structure of the metal and occurrence of sulfide inclusions. This also explains the brittle nature of fracture at the tip of the splitting crack with the typically ductile fracture caused by the main crack.

In the examined temperature range, the cracking resistance parameter K^*_{Ic} depends only slightly on test temperature.

Thus, the formation of splitting cracks is accompanied by the formation of a system of weakly bonded thin plates ahead of the main fracture front. The special features of development of fracture in this fine structure depend on the conditions of failure of the individual plates.

In this connection, it should be mentioned that the variation of the thickness of the specimens results in two main types of the dependence of cracking resistance K_c on thickness. The reduction of thickness without any changes in the other dimensions increases the value of K_c [9, 10]. In geometrically similar specimens, the smaller dimension (thickness) is associated with lower values of K_c [11]. For thinner specimens, the temperature of ductile to brittle transition is lower. In the first case, the dependence of K_c on the thickness of the specimen is usually linked with the variation of strain constraint with varying thickness and at constant strain rate, whereas in the second case it is evident that the change of the strain rate becomes important.

*Estimate of the value of σ_{zz} on the basis of the distribution of elastic stresses gives for the central part of the specimen $\sigma_{zz} - 0.5\sigma_{yy}$ [5, 7] or for the boundaries of the zone in which plastic strains can develop $\sigma_{zz} - 0.5\sigma_{0.2}$.

Consequently, the effect of splitting of the specimen on its cracking resistance parameters in relation to main fracture may be described schematically in the following manner.

In the specimens of smaller thickness, regarding the geometrically similar increase of the external dimensions resulting from an increase of the number of splitting cracks, the thickness of the individual strips into which the specimen separates during fracture varies differently in comparison with the external dimensions (this thickness may even decrease). For this reason, both the reduction of strain rate resulting from an increase of the external dimension and the reduction of the degree of constraint in the single strip increase the cracking resistance K_c and energy capacity of fracture.

In thick specimens in which delamination gradually ceases to take place, an increase of the external dimensions of the specimen is also accompanied by an increase of the effective thickness of the single strip. In this case, the rate of increase of thickness is higher than that of the other dimensions of the specimen. The reduction of strain rate and the variation of the degree of strain constraint in the specimen act in the opposite directions. In cases in which this combination of the acting factors operates, it may be expected that the dependence of the fracture parameters on the external geometry of the specimen will be nonmonotonic. Specifically, in the examined material this combination was reflected in the appearance of the maximum energy capacity of fracture in the area with the highest degree of splitting of the specimen (at a thickness of $t = 14$ mm). From this point of view, the 15KhSND steel specimens 14 mm thick were optimum in respect of the energy capacity of fracture.

However, the combination of the effects in splitting cannot always lead to the nonmonotonic dependence of cracking resistance on the thickness of the specimen. If for the increase of the thickness of the specimens in the thickness range $t \leqslant 1$ mm (with other dimensions of the specimens being constant) K_c decreases [12], then splitting into thin strips does not lead to the appearance of the maximum of cracking resistance K_c.

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