Strength of structural elements with cracks

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Abstract. In almost every detail, despite careful control at all stages of production, there may be cracks. The reasons for their occurrence can be very different, including the shape and size of the part, the conditions and nature of loading, the nature of the environment, defects of a crystal lattice, the possible presence of non-metallic inclusions adverse forms, structure and grain size, depending on the technology upstream processing, fatigue, etc. The reliability of the equipment is determined by the correct choice of material and taking into account the operating conditions, including the level and nature of loading. The paper provides a comparative review of the main approaches for selecting strength criteria for structural elements with cracks. The energy and power strength criteria are considered. The energy criterion of A. A. Griffiths considered a perfectly brittle material without taking into account the plasticity reserve of real metal materials. The force criterion allows us to estimate the value of the stress taking into account the critical moment of loading, at which unstable destruction begins due to the reserve of elastic energy. It is shown that the transition of steel from a plastic state to a brittle one is influenced by the test temperature, the type and speed of deformation, and changes in the chemical composition and mode of heat treatment. Thus, when choosing a certain strength criterion, you should take into account the operating conditions and the degree of responsibility of the structure.

1. Introduction

The influence of cracks on the strength of structural elements is an urgent issue, as currently recorded a large number of cases of sudden destruction of parts, and the destruction took place at stresses below the yield strength of the material. It is impossible to guarantee the complete absence of cracks in the structures, despite the control at all stages of manufacture [1-3].

The reasons for the appearance of cracks can be very diverse: defects in the crystal lattice, technological origin, fatigue, etc. Since there is a high probability of the presence of cracks in the products, the reliability of the product can be solved in two ways: either by choosing a material that will "hold" the cracks - such that the cracks will not spread under operating loads, or by determining the level and nature of the loading. A special danger is the spread of cracks in those cases when it is committed as if spontaneously, without additional external load. This pattern of crack spread is called unstable [4, 5]. During the research, the strength criteria of structural elements with stress concentrators were considered. In developing the strength criteria, the greatest attention was paid to brittle fractures, which are the most dangerous.

One of the first attempts to obtain such a criterion belongs to A. A. Griffiths [6], who considered the question of the strength of a plate of unlimited dimensions and brittle material containing an elliptical crack.
Considering the balances of energy consumption and arrival at the appearance of a crack in a stretched and fixed plate allowed Griffiths to obtain an expression for the critical stress $\sigma_{cr}$, above which the unstable crack spread begins.

In Griffiths' solution, the material was considered to be perfectly brittle, so the crack propagation work equated to surface energy. In real metal materials, plastic deformation occurs during the propagation of cracks, which greatly increases the work of crack propagation, or, as they say, the fracture toughness.

In this regard, E. Orovan [7] proposed to unify the expression for $\sigma_{cr}$. According to Orovan, the critical stress formula has the form:

$$\sigma_{cr} = \sqrt{\frac{2EG_c}{\pi l}},$$

where $l$ is the crack length. The formula (1) can be used to determine the critical length of the $l_{cr}$ crack at which its unstable propagation occurs:

$$l_{cr} = \frac{2EG_c}{\sigma_{cr}^2 \pi}.$$

The idea of creating a force criterion is to determine the stress at the critical moment of loading, when unstable destruction begins due to the reserve of elastic energy [3-5]. Expressions for stresses in the vicinity of the dead-end of the crack were obtained on the basis of works when considering a plate of an elastic material of infinite width with a through crack subjected to uniform stretching. In the case of a plane deformation at a triaxial stress state the stress on the crack extension will be equal to:

$$\sigma_r = K_f \sqrt{2\pi r},$$

where: $K_f$ - stress intensity factor,

$r$ – the distance from the top of the crack to the point in question on the continuation of the crack.

The stress $\sigma_r$ determined at the critical moment of loading (i.e. at failure) could play the role of a force criterion. However, research have shown that when changing the size of the crack, the constant is not $\sigma_r$, but the stress intensity coefficient, experimentally determined at the critical moment of loading and is therefore a characteristic of the strength of the material, in the case when the structural element has cracks. This coefficient is denoted by $K_{lc}$.

Expression (3) was obtained from the fracture condition at the separation displacement of the crack banks. Apart from the aforementioned case of shifting can be implemented well as transverse shear, in which the surface of the crack slide over one another in a direction perpendicular to the front edge cracks and longitudinal shear, where the crack surface slide over each other parallel to the front edge of the crack. For transverse and longitudinal shear, the stress intensity coefficient is denoted by respectively $K_{IIc}$ and $K_{IIIc}$.

For a linear-elastic material, a fairly strict theory describing the stress state at the crack apex and is a good foundation for the analysis of brittle fractures is currently applied. Unfortunately, there is no such theory for describing the stress and strain state at the top of a crack with a developed plastic zone, since the solution of this problem for a material with hardening encounters insurmountable obstacles. Meanwhile, the vast majority of practically important and dangerous fractures are accompanied by the constant presence of a plastically deformed region at the top of the crack. This plastic deformation affects the shape of the tip of the crack, leads to smoothing of the stress peak, and the properties of the material being destroyed. When a sample with a crack is deformed, a plastic zone is first formed at the end of the crack, the length of which grows to some relatively small size $d$, after which a local rupture occurs at the beginning of this region coinciding with the end of the crack. The crack begins to move, and the plastic region moves with the moving end of the crack without changing its size and shape. At a distance $l > d$ from the end of the crack, the deformations will only be elastic.
Evaluation of the effective surface energy in the destruction of metals and its comparison with the true surface energy shows that the first can exceed the second by several orders of magnitude, thus determining the exceptional importance of taking into account the role of local plastic deformation at the crack tip.

The fact that the destruction of the sample in determining the intensity coefficients in most cases is plastic is the reason for the sensitivity of these coefficients to a number of factors that contribute to the transition of steel from a plastic state to a brittle one. Such factors include the test temperature, the type of deformation, changes in the chemical composition and mode of heat treatment, the rate of deformation.

Increasing the rate of application of the load affects the value of $K_{ID}$ differently in different materials ($K_{ID}$ - the value $K_{IC}$, obtained by the dynamic application of forces). In some cold-breaking steels, the $K_{ID}$ is lower than $K_{IC}$, i.e., the dynamic coefficient is lower than the static one. In other steels, especially non-cold-breaking steels, the stress intensity coefficient $K_{ID}$ increases with increasing loading speed. In the first case lowering $K_{ID}$ – the result of brittleness, in the second case, the increase in the $K_{ID}$ is the result of increasing the resistance of plastic deformation of a plastic area. In this case, the dependence $\sigma = f(\dot{\varepsilon})$ is reflected in the $K_{ID}$ value, since:

$$K_{ID} = \sigma \sqrt{\pi e} = f(\dot{\varepsilon}) \sqrt{\pi e}.$$

Based on the research, it was concluded that the choice of a certain strength criterion depends on the operating conditions and the degree of responsibility of the structure.

2. Materials and methods

Metastable austenitic steels of grades 10Cr14Mn14Ni4Ti and 10Cr14NMn20 used for the manufacture of equipment operated including at low temperatures were chosen as the object of the study [8]. The chemical composition of the studied steels is given in table 1.

Table 1. Chemical composition of low-temperature steels

| №  | Grade of steel    | Content of elements, % |
|----|------------------|------------------------|
|    |                  | C          | Mn         | Si         | P          | S          | Cr         | Ni         | Cu         | Ti         | N         | B         |
| 1  | 10Cr14Mn14Ni4Ti  | 0.10       | 14.9       | 0.70       | 0.020      | 0.019      | 14.6       | 4.6        | 0.23       | -          | -         |          |
| 2  | 10Cr14NMn20      | 0.10       | 20.3       | 0.50       | 0.012      | 0.011      | 14.8       | -          | -          | 0.30       | 0.1       |

To influence stress concentrators on mechanical properties, static tensile tests were performed in a wide temperature range on samples with an annular incision. A deep annular incision don't complicates the development of plastic deformation, beginning at its apex, as the proportion of tangential stresses decreases sharply from the incision to the center of the sample. In addition, it is known that the effect of acute deep incision is manifested for all steels, regardless of their strength level, lattice type, viscosity and plasticity [8-11].

3. Results and discussion

In research practice, when testing for static tension, the coefficients are used as structural strength criteria:

$$\alpha = \frac{\sigma^n}{\sigma_v}; \quad \alpha' = \frac{\sigma^n}{\sigma_{0.2}}; \quad \beta = \frac{\psi^n}{\psi},$$

where $\sigma_0$ – tensile strength, $\sigma_v^n$ – tensile strength of the sample with an incision, $\sigma_{0.2}$ – conditional yield strength, $\psi$ – relative contraction, $\psi^n$ – relative contraction of the sample with an incision.

In table 2 the values of the coefficients $\alpha, \alpha'$ and $\beta$ for the studied steels are given.
Table 2. Variation of the sensitivity coefficient to the stress concentration \( \alpha, \alpha' \) and \( \beta \) depending on the test temperature

| №  | Grade of steel | The diameter of the samples | \( \alpha = \sigma_0^n / \sigma_0 \) | \( \alpha' = \sigma_0^n / \sigma_{0.2} \) | \( \beta = \psi^n / \psi \) |
|----|----------------|-------------------------------|-----------------|------------------|-----------------|
| 1  | 10Cr14Mn14Ni4Ti | 6                            | 1.24            | 1.40             | 2.98            | 3.25            | 0.54            | 0.43            |
|    |                | 10                           | 1.24            | 1.11             | 3.53            | 3.01            | 0.32            | 0.29            |
| 2  | 10Cr14NMn20     | 6                            | 1.31            | 1.51             | 2.45            | 2.05            | 0.38            | 0.41            |
|    |                | 10                           | 1.49            | 1.21             | 2.43            | 1.93            | 0.27            | 0.35            |

The obtained results allow us to conclude that these coefficients are not sufficiently informative from the point of view of the performance of steels, especially at low temperatures. For example, the coefficient \( \alpha \) allows, on the one hand, to compare the studied materials on the resistance of plastic deformation in the incision. The more the strength characteristics increase (especially at low temperatures), the less plastic the material is. But, on the other hand, the coefficient of sensitivity to stress concentrators \( \alpha = \sigma_0^n / \sigma_0 \) characterizes only the change in the average stress of destruction in the presence of stress concentration, regardless of at what stage of deformation this destruction begins.

The coefficient \( \alpha' \) gives more objective information about the performance of the metal in the presence of stress concentration, because it answers two questions: 1) does the stress concentration lead to destruction at a voltage below the calculated one, and if it does not, then 2) what is the permissible margin of safety in case of excess of the calculated stresses due to possible operational loads.

Before proceeding to the analysis of the obtained values \( \alpha' \), it should be noted that in the presence of a stress concentrator (sharp incision or crack), the yield strength of the incised sample in plastic steel, regardless of the test temperature, should be close to the yield strength for smooth samples. In this case, the stress corresponding to the elastic deformation does not change its value regardless of whether the crack first appears in the material during deformation, or whether it already existed in the material before the deformation began. The transition of the material from the viscous to the brittle fracture region will be accompanied by a drop in the time resistance, and the ratio \( \sigma_0^n / \sigma_{0.2} \) will decrease. Therefore, the drop in strength should predetermine the beginning of brittle fracture. The disadvantages of the criterion \( \alpha' \) include the fact that during the destruction we do not get any information about the nature of the destruction, i.e. it is not known whether there was a noticeable plastic deformation or destruction occurred in the elastic region.

The coefficient \( \beta \) characterizes the degree of influence of the incision on the reduction of steel ductility at both normal and low temperatures. However, without analyzing the numerical values of \( \psi^n \), it is impossible to judge the reliability of steel only by the values of \( \beta \). For example, the same value of the coefficient \( \beta = 0.25 \) for steel 10Cr14NMn20 on samples of the same type at the same test temperature, means only the degree of reduction of plasticity. While the true values of \( \psi^n \) at -196°C for steel 10Cr14NMn20 are respectively 12 and 4%.

For a more complete assessment of the performance of steels at the operating temperature, the following coefficients can be additionally used:

1) \( K_1^t = \sigma_0^t / \sigma_0^{20} \), the ratio of the tensile strength of the sample with the incision, to the tensile strength of a smooth specimen determined at room temperature.

2) \( K_2^t = \sigma_0^t / \sigma_{0.2}^{20} \), the ratio of the tensile strength of the sample with the incision, at operating temperature, to the yield point a smooth sample determined at room temperature.
3) \( K_3^t = \frac{\sigma_{0,2}^{nt}}{\sigma_{0,2}^{20^\circ C}} \), the ratio of the yield strength of samples with incision or crack determined at operating temperature, to the yield strength of a smooth sample determined at room temperature.

The values of the coefficients \( K_1^t, K_2^t \) and \( K_3^t \) for the studied steels are given in table 3.

| № | Grade of steel     | Diameter, mm | \( K_1^t = \frac{\sigma_{nt}}{\sigma_{20,2}^{20^\circ C}} \) | \( K_2^t = \frac{\sigma_{nt}}{\sigma_{0,2}^{20^\circ C}} \) | \( K_3^t = \frac{\sigma_{0,2}^{nt}}{\sigma_{0,2}^{20^\circ C}} \) |
|---|--------------------|--------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 1 | 10Cr14Mn14Ni4Ti    | 6            | 1.25 1.77 2.08 2.43 4.00 5.77 6.81 7.95 4.08 2.46 | 50°C 77% 96% 196°C | 1.73 2.16 2.46 3.16 |
|   |                    | 10           | 1.20 1.58 1.76 1.81 2.73 3.56 3.96 4.33 3.34 2.60 |
| 2 | 10Cr14NMn20        | 6            | 1.32 1.80 2.07 2.34 2.40 3.26 3.77 4.08 3.80 3.11 | 50°C 77% 96% 196°C | 1.91 2.48 3.11 4.26 |
|   |                    | 10           | 1.52 1.84 2.07 2.33 2.45 3.02 3.20 3.80 3.67 2.44 |

As follows from the obtained data, the total average fracture stress at the operating temperature in comparison with the fracture stress at room temperature for all studied steels increases, as evidenced by \( K_1^t \).

The coefficient \( K_2^t \) characterizes the safety margin at the operating temperature if \( K_2^t > 1 \) or the absence of safety margin if \( K_2^t < 1 \), and thus gives information about the permissible level of operational loads. For all studied steels in the entire operating temperature range \( K_2^t > 1 \). The coefficient \( K_3^t \) allows us to judge the possible application of the calculated permissible voltages at the operating temperature equal to room temperature. As follows from the data (see table 3), for steel 10Cr14NMn20 coefficient value \( K_3^t \) at all test temperatures is higher than that for steel 10Cr14Mn14Ni4Ti.

The characteristics of the strength indicators obtained on cylindrical smooth samples with a diameter of 10 and 6 mm are approximately at the same level. Testing of non-standard samples with a diameter of 10 mm with an annular incision did not result in a more complex stress state compared to non-standard samples with a diameter of 6 mm with an annular incision. It follows that the use of samples of increased cross-section does not give advantages in determining the mechanical properties under static tension.

4. Conclusion

An important practical task for assessing the reliability of the performance of the material is to determine the influence of stress concentration on their mechanical properties. It is shown that the presence of stress concentration at low temperatures leads to a decrease in strength during the transition of the material to the brittle state. There is a continuous increasing ratio of yield point to ultimate strength with decreasing temperature, that is, the ability of hardening under elastic-plastic deformation decreases the transition temperature of the material in fragile condition disappears completely.
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