Comparison of methods of evaluating materials' tendency to brittle fracture

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Abstract. This article concerns different methods of evaluating material's tendency to brittle fracture. It includes results of impact bending tests of cold-resistant metastable austenitic steel 12Cr18Ni10Ti (AISI 321) and ferritic steel 0Ni9A in a broad temperature range. The article shows that evaluation of the effectiveness of the material should be carried out in consideration of numerous factors, especially the specific exploitation conditions of the materials.

1. Introduction

Equipment operating at low temperatures can be subject to severe damage or destruction when the additional load is applied. Whether the fracture would be brittle or ductile depends on two fundamentally different reasons. The first reason is related to purely physical factors, second - to mechanical. In certain cases, brittle or ductile fracture can occur in a state of the constant stress condition as the result of the change in material's properties. In other cases, fracture occurs due to change in the character of the stress condition while the material's properties remain unaltered. Understanding the nature of materials' embrittlement allows us to rationally choose methods of evaluating materials in terms of brittle fracture [1-9].

Even in the first studies concerning evaluation of fracture toughness of different metals, we already considered possibility of correlation between this parameter and other traditional mechanical tests. Attempts were made in the following areas: 1) replacement of $K_{IC}$ evaluation by measurement of more simple parameters of mechanical properties; 2) the possibility of interpretation of fracture toughness' essence by certain physical models of cracks propagation.

Studies [1, 10-13] proved the correlation between the size of the original austenitic grain in pearlitic steel and the frost fracture and fracture toughness. Authors [9] tried to find the correlation between the microstructure of the fracture and $K_{IC}$ of high-tensile steel 45Cr2Ni2Mo. The analysis of 223 combinations of $K_{IC}$ and $\sigma_0.2$ for steels, aluminium and titan alloys, conducted by N.V. Oleynik [13] indicates the impossibility of composing a universal correlation between different alloys.

Studies [1, 10] also included attempts of composing universal correlations between $K_{IC}$ and $\sigma_b$, which were unsuccesfull.

Correlation with toughness [11] has a limited, partial character. Impact strength results may be useful in predicting fracture toughness. Several authors [1, 11-14] analyzed the correlation between the dynamic fracture toughness and $K_{IC}$. The correlation between $G_{ld}$ and $KC_{p}$ also occurs in the case of low-ductility high-carbon steels.
Studies conducted with ARMCO-iron (0.04% C) and 17ГС steel show that critical brittle temperature heavily depends on methods of evaluating steel's tendency to brittle fracture [1,11,12]. This is a well-known fact, as well as the fact that the critical brittle temperature even in the same tests depends on the sample and the notch geometry.

For materials used in low-temperature conditions, various stress concentrators should be considered, leading to difficult stress conditions, in addition to the possible dynamic load.

2. Materials and research methods

This study focuses on cold-resistant austenitic and ferrite steel of grades 12Cr18Ni10Ti (AISI 321) and 0Ni9A. See their chemical composition in table 1.

| No. | Steel grade        | Chemical composition, % |
|-----|--------------------|-------------------------|
| 1   | 12Cr18Ni10Ti       | C: 0.11, Mn: 1.3, Si: 0.65, P: 0.035, S: 0.020, Cr: 18.9, Ni: 10.2, Cu: 0.21, Ti: 0.30, N: 0.30, B: - |
| 2   | 0Ni9A              | C: 0.07, Mn: 0.67, Si: 0.42, P: 0.015, S: 0.021, Cr: -9.3, Ni: -, Cu: -, Ti: -, N: -, B: - |

Steels were smelted in the induction furnace with a main slag of a magnesite capacity of 150 kg. Then the steel is poured into 50-kg cast iron moulds and steep wafer-type rods. After grinding and stripping, ingots were forged into square billets with a cross section of 25x25 mm. Then, the preforms were subjected to heat treatment in order to obtain an austenitic structure in 12Cr18Ni10Ti steel and ferritic structure in 0H9A steel. Impact bending tests were carried out in accordance with GOST 9454-78 using regular samples with stress concentrators of types U (type 10), V (type 11) and T (type 15), irregular samples with lateral notches made to achieve complicated stress condition (type 25 – with a V-shaped notch, type 26 – with a T-shaped notch).

3. Results and their consideration

When evaluating the effectiveness of the materials in the most severe conditions, a natural overvaluation of the low boundary of the material is used. Analyzing the data from [1-6], the permissible temperature range, in which the material can be used, can be divided into several subareas.

![Figure 1](image.png)

**Figure 1.** Threshold values of cold shortness (brittleness), determined by various methods: 1 - static bending tests according to Irwin; 2 - dynamic tests of standard samples with a notch Menaget; 3 - by measuring changes in the resistance to crack propagation under conditions of plane deformation under the action of impact forces.
In the area I, metals without stress concentrators and with large crack initiation can work under load. The same metals can be used in zone II with stress concentrators, but without impact forces.

The same materials can work in zone III even in the presence of impact forces if there are no critically sharp cracks. In area IV, the material can work even in presence of sharp cracks with the lowest probability of brittle fracture.

Typically, steels and alloys, used in low-temperature environment, do not have a distinct cold-shortness threshold. However, the presence of sharp stress concentrators (notches) causes local stresses to increase at the top of the notch and moves the serial position curve to the area of higher temperatures.

The research considered the effect of notch's top radius and test temperature on the impact strength of the studied steel grades. The impact test results of samples of types 1 and 11 (according to GOST 9454-78) are shown in table 2.

| No. | Steel grade       | Impact strength, J/cm² |
|-----|-------------------|------------------------|
|     |                   | 20°C  | -50°C | -100°C | -196°C |
| 1   | 12Cr18Ni10Ti (AISI 321) | 290    | 240   | 280    | 230    | 260    | 220    | 220    | 180    |
| 2   | 0Ni9A             | 290    | 180   | 200    | 180    | 180    | 140    | 160    | 100    |

As can be seen, the impact strength's value declines both for austenitic steel 12Cr18Ni10Ti and for ferritic 0Ni9A in the entire temperature range. Evaluation of notch's sharpness effect shows that the impact strength of the samples with sharp V-shaped notch is lower. This means that the temperature of brittle-plastic transition will move to the area of higher temperatures.

Decline in impact strength in correlation with decrease of the radius of the notch's top can be explained by the process that occurs during deformation and cooling of these steels [14-16]. The amount of martensite formed in the deformed part of the sample near the notch depends on the work absorbed during deformation before the crack initiation and the stress conditions' scheme in the notch area. The work of absorption during deformation before a crack emergence increases along with the notch's top radius, and the stress condition strengthens inversely to the notch's top radius increase.

Additional research was conducted to determine which factor exerts a greater impact on the reduction. We used non-standard samples with lateral notches, which lead to a more complicated stress condition in the notch area. The cross section of the specimens with side recesses was equal to the cross section of ordinary Charpy-type specimens.

The test results of standard and non-standard samples at a temperature of -196 °C are shown in table 3.

| No. | Steel grade       | Impact strength KC, J/cm², for samples of types: |
|-----|-------------------|-----------------------------------------------|
|     |                   | 11    | 25    | 15    | 26    |
| 1   | 12Cr18Ni10Ti (AISI 321) | 180    | 170   | 150   | 140   |
| 2   | 0Ni9A             | 100    | 57    | 75    | 40    |

An analysis of the results show that stressful conditions affect the martensitisation process occurring in the metastable austenitic steel 12Cr18Ni10Ti (AISI 321) under the influence of deformation and low temperatures much more than the volume of deformation. Thus, in the area of sharper stress, the concentrator amount of martensite is bigger ceteris paribus than it is in the soft notch area, which provides for the lower values of impact strength for both regular and irregular samples.
The decrease of the impact strength of samples made of metastable austenitic steels can be considered as a total decrease in the work, consisting of decrease in crack initiation work as a result of decrease in deformation volume, and the decrease in crack propagation work as a result of martensitisation. This can be explained by the fact that in martensite the crack propagates more slowly than it does in the austenitic matrix.

For ferritic steels, which after heat treatment have residual austenite in the structure, the decrease of test temperature and creation of the additional stress condition in the additional cracks' area results in the finishing of structural transformation $\gamma \rightarrow \alpha$. As a result, a decrease in impact strength occurs. For 09HA steel, a temperature of -100°C is obvious from the point of view of ductility. Therefore, we can predict a sharp decline in impact strength for the samples with both soft and harder notches at lower temperatures.

4. Conclusion
The analysis shows that evaluation of the tendency of a material to brittle fracture should be conducted differentially, considering the material's exploitation conditions.

Thus, the most stringent evaluation of materials should be applied in the case of material operating with impact forces and sharp stress concentrators (cracks). The method of impact strength assessment should be used to evaluate materials if in the future they will be used to produce components without sharp stress concentrators (without cracks) occurring during possible impact forces.

The static tension method with an extremely sharp notch should be used when working with the components working under stationary or cyclic loads, where cracks can occur.

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