Fracture toughness experimental investigations of metal structures from low-alloyed steel

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Abstract. Presented are the results of experimental fracture toughness investigations of metal structures from low-alloyed steel (<0.12% C, 0.6-0.9% Cr, 0.8-1.1% Si, 0.5-0.8% Ni, 0.4-0.6% Cu and others), the influence of structural, technological and operational factors taken into account. The results of the investigations can be used to form a fracture toughness data bank of metal structures for mechanical engineering, to conduct of metal structure defectation, to assess of the brittle fracture risk due to the presence of crack defects, to improve the quality control system at the production stage and to solve other problems of ensuring the safety of machinery and equipment.

1. Introduction

Low-alloyed structural steel (<0.12% C, 0.6-0.9% Cr, 0.8-1.1% Si, 0.5-0.8% Ni, 0.4-0.6% Cu and others) is widely used in mechanical engineering for manufacturing welded metal structures and various parts, the requirements of high strength and operating temperature from -70 to 450 °C being taken into account. It is necessary to emphasize the favorable combination of mechanical characteristics (strength, ductility and impact strength) in this steel, good technological properties, which determines its wide application for manufacturing critical welded structures of technological equipment for rocket and space complexes, lifting equipment, bridges, ship hulls, etc. [1-3]. Under modern economic conditions a number of technical devices, machines and equipment are characterized by their intended use outside the standard / warranty periods of operation. In this regard, the issues of ensuring the reliability and safety of long-term operation of critical welded structures under conditions of material characteristics changing, the development of damage and defects, as well as the flow of other destruction processes become relevant. The greatest danger is the development of fatigue cracks, which can cause sudden destruction of structures, sometimes with disastrous consequences.

The aim of the research was to form a fracture toughness data bank of metal structures from low-alloyed steel (<0.12% C, 0.6-0.9% Cr, 0.8-1.1% Si, 0.5-0.8% Ni, 0.4-0.6% Cu and others) [4], to determine the characteristics of fracture toughness and fracture mechanism of welded steel, the influence of constructive, technological and operational factors being considered.
2. Materials and equipment
Many methods and criteria have been developed for assessing the structures fracture toughness [5]. Determination of fracture toughness characteristics under the static loading was carried out in accordance with the requirements of the State standard GOST 25.506-85 [6] based on the assessment of the stress intensity factor.

Fracture toughness was estimated incase of the maximum tensile stresses being perpendicular to the plane of the initial crack, i.e. for a crack of normal separation according to the I model of linear fracture mechanics.

Rectangular compact samples of type 3 with an edge crack were made from welded steel billets for off-center tension testing in accordance with the requirements of the State standard GOST [6]. The initial welded joints with symbols C8, C15, C17 are shown in table 1.

| Welded joint symbol | Cross-sectional shape of prepared edges | Cross-sectional shape of the weld |
|---------------------|----------------------------------------|----------------------------------|
| C8                  |                                        |                                  |
| C15                 |                                        |                                  |
| C17                 |                                        |                                  |

The samples were prepared to identify the dependence of fracture toughness on the thickness of the metal samples. Initiating cracks on the samples were applied to the base metal (BM), the weld (W), and the heat-affected zone (HAZ) of the welded joint.

Test samples were made from metal structures of lifting structures that fulfilled the standard service life to assess the destruction of low-alloyed steel elements under the influence of long-term operation [1-3].

The conditions were provided to ensure minimal hardening, residual stresses, as well as changes in the structure and phase composition in the area of application of the initiating incision when cutting and manufacturing the samples.

Experimental investigations planning and statistical processing of the results were carried out while taking into account the requirements of Standardization guidance document RD 50-705-91 [7].

A fatigue pulsator machine of the CDM PU-10t type were used to apply initial fatigue cracks on test samples, a TIRAtest 2300 test machine were used to load the samples to failure.

After the test, additional metallophysical investigations were carried out. There were fractographic analysis by the Tescan VEGA II LMU scanning electron microscope with INCA energy-dispersive and wave-dispersive microanalysis systems and metallographic analysis by the AxioVert.A1 microscope to determine the presence of non-metallic inclusions in accordance with the requirements of the State standard GOST 1778-70 [8].

3. Results and discussion
The tests have shown that the fracture toughness of the base metal and the zones of structures welded joints made of low-alloyed steel varies from 79 to 107 MPa·m$^{1/2}$ [3].

Evaluation of the influence of the structural factor (thickness) on the fracture toughness have shown that the fracture toughness of metal structures increases slightly in the thickness range from 4 to 20 mm (figure 1) [3].
Figure 1. The average values and confidence interval of base metal fracture toughness depending on the thickness of the steel samples.

When analyzing the mechanics of welded structures destruction, features of the welded joints structure and defects should be taken into account [9].

The assessment of the influence of zones and types of welded joints on fracture toughness is shown in figure 2 [3].

Figure 2. The average values and confidence interval of fracture toughness depending on the zone and type of welded joints.
The change in the structures fracture toughness after long-term operation is insignificant (about 3-6%) (figure 3) [1, 3].

![Figure 3](image3.png)

**Figure 3.** The average values of base metal fracture toughness taking into account the influence of long-term operation.

During the tests, the characteristic feature of the individual samples destruction was revealed. There was lamination, which contributes to a decrease in the base metal fracture toughness (figure 4). This feature was identified both for the structures before the start of operation (fracture toughness reduced by up to 10%) and for the long-term operation structures (fracture toughness reduced by up to 14%) [3].

![Figure 4](image4.png)

**Figure 4.** The average values of base metal fracture toughness taking into account the lamination.

The complex of metallophysical investigations was carried out in order to clarify the reasons for the lamination of samples. The results of fractographic analysis and chemical composition analysis allows us to understand the factors that contribute to the lamination of the samples during the tests:

- quantitative composition of chemical elements in the sample of low-alloyed steel (figure 5) meets the requirements of the State standard GOST [4], however, the sample is characterized by a high content of silicon and sulfur in the fracture zone near the lamination;
the welded joint of a sample of low-alloyed steel (figure 6) has non-metallic inclusions and non-melting areas with a high content of manganese, silicon and sulfur in its structure.

Figure 5. Fracture surface of base metal sample with lamination: (a) – x12; (b) – x600.

Figure 6. Fracture surface of base metal sample in the heat affected zone: (a) – x19; (b) – x600, non-metallic inclusion.

Metallographic analysis has shown that samples with lamination and reduced fracture toughness are characterized by an increased content of a number of non-metallic inclusions: non-deformable silicates (CH, figure 7), brittle silicates (CX, figure 7), and sulfides [3].
The results of metallophysical investigations of the destroyed samples show that, most likely, separate inconsistencies in the production technology (rolling) led to lamination. Inconsistencies in the technology are expressed in the increased content of non-metallic inclusions. A lamination of rolled steel is not allowed. Rolled products are checked for the absence of lamination by inspection of the edges and ends without the use of magnifying devices. In addition, the lamination of rolled products can be controlled using the ultrasonic method of non-destructive testing. However, ultrasonic testing showed that no fixed or unacceptable defects of the samples were detected (an ultrasonic flaw detector A1212 MASTER was used) [3].

It should be noted that the methods of rolled steel control do not include a mandatory quantitative and qualitative assessment of non-metallic inclusions, which probably contributed to the lamination of the metal. In this regard, it is advisable to conduct additional investigations in order to establish requirements for contamination of rolled products made of low-alloyed structural steel with non-metallic inclusions.

4. Conclusions
The complex of experimental investigations of metal structures from low-alloyed steel(<0.12% C, 0.6-0.9% Cr, 0.8-1.1% Si, 0.5-0.8% Ni, 0.4-0.6% Cu and others) was carried out. This involves determination of fracture toughness characteristics under the static loading and metallophysical investigations of destroyed samples.

The features of fracture toughness and the mechanism of welded metal structures destruction have been identified, the influence of structural, technological and operational factors taken into account.

The results of the investigations can be used to form a fracture toughness data bank of metal structures for mechanical engineering, to conduct of metal structure defectation, to assess of the brittle fracture risk due to the presence of crack defects, to improve the quality control system at the production stage and to solve other problems of ensuring the safety of machinery and equipment.

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