Changes in the Structure and Properties of Welded Joints of Low-Alloy Steels, Subjected to Cyclic Loads

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Abstract. Time-varying loads negatively affect the properties and structure of materials. Structural failures typically occur at loads below the yield point. In this work, fatigue tests of welded joints of low-alloy steels were carried out in an asymmetric cycle at loads of 60 and 80% of the yield strength. The stress ratio was 0.8-0.9. On the basis of the results of the tests, equations linking the number of cycles to failure with test parameters were obtained. Such equations can be used for estimating the residual life of elements both under construction and in operation. It has been found that the failure is not instantaneous. Specimens of steels continue to resist variable loads for 4000 - 26000 cycles to failure, depending on steel grade and the parameters of the test. Under operating conditions, it gives an opportunity to discover the onset of failure and dispose of the defective part or to replace the entire structure. A standard technique was used to measure the microhardness on the fractured specimens. The distance between the nearest indentations was 0.2 mm. The results of the measurements were plotted in graphs of hardness change characteristic for all steels under study. A microhardness “step” has been discovered in areas with high dislocation density, as evidenced by x-ray diffraction and transmission electron microscopy. An intermediate stage of the investigation is the development of recommendations for determining the moment of failure of welded constructions with a probability of 95%.

Introduction
In the operation of equipment and engineering products, it has been found that failure of a large number of objects occurs at stresses below the yield point. Repeated exposure of the material to cyclic stresses causes a change in its structure. Microscopic discontinuities appear which subsequently increase in size and become the site of crack initiation and propagation. This is facilitated by repeated alternation of areas with variable stresses. Cyclic loads affect the majority of operating objects: bridge constructions, road and rail transport, metalworking machinery and tools, presses, aircrafts, lifting mechanisms, pipelines, etc. Welded engineering constructions have designed-in structural differences between deposited metal, base metal and heat affected zones. Furthermore, residual stresses form in welded joints and there is a danger of appearance of hardened areas that may lead to cracking. Therefore, investigation of the fatigue of welded structures and their components assumes particular importance [1].

By now, a great number of works have been published on the fatigue of welded joints. Much has been written about the influence of the welding process, types of the connection, residual stresses, and grades of the deposited and base materials, operating conditions, shapes and sizes of structures. However, studies investigating the effect of structural features on the fatigue characteristics of welded joints are not numerous. One such work was the work of the authors [2], which studied the peculiarities of fatigue failure of pipe steels. This paper is a continuation of this study.
1 Materials and technique of research

Table 1 and 2 shows the chemical composition and mechanical properties of the materials studied.

Table 2: Chemical composition of the steels

| Grade of steel | C   | Si  | Mn  | Ni  | Cu  | Cr  | S   | P   |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| 09G2S          | 0.087 | 0.75 | 1.71 | 0.07 | 0.1  | 0.06 | 0.025 | 0.03 |
| 17G1S-U        | 0.18  | 0.5  | 1.0  | 0.15 | 0.05 | 0.03 | 0.022 | 0.023 |
| 16G2AF         | 0.162  | 0.41 | 1.43 | 0.01 | 0.07 | 0.06 | 0.019 | 0.018 |

Table 2: Mechanical properties of the investigated steels.

| Strength class of steel | Ultimate strength σう, MPa | Yield strength σ0,2, MPa | Specific elongation δ, % |
|-------------------------|-----------------------------|--------------------------|--------------------------|
| 09G2S                   | 490                         | 415                      | 29.8                     |
| 17G1S-U                 | 590                         | 491                      | 20.6                     |
| 16G2AF                  | 600                         | 450                      | 20.9                     |

Fatigue tests were performed at a ZD-20 test machine. Type IV specimens were fabricated according to GOST 25.502. A variable tensile load from the maximum stress σmax to the minimum stress σmin acted along the axis of the specimen (perpendicular to the weld seam) The frequency of loading cycles was 10 Hz. 7 specimens were used in each series.

Microhardness was measured at a PMT-3 microhardness-testing machine, using standard techniques (load weight 0.981 H). The X-ray diffraction analysis was performed at a DRON-7 diffractometer using cobalt radiation. Electron microscopic studies of the structure were carried out at a TESLA-100 transmission electron microscope using the method of thin foils.

To monitor the quality of the weld, the methods of visual measurement and radiographic inspection were used. To determine the onset of crack initiation as well as its position and depth, the metal magnetic memory method (IKN-8 unit), the ferroprobe («Polus») and electropotential (EPD-8 crack detector) methods were used.

2 Results and discussion

On the basis of the results of fatigue tests [3-5], using the program STATISTICA 6.1 ( multiple correlation coefficient 0.95, level of significance 0.01 ) we calculated regression equations between the number of cycles to failure of specimen N and test parameters : the maximum tensile stress σmax and the stress range Δσ.

For welded specimens of 09G2S steel

\[ N = 1.5768 \cdot 106 + 743.344 \cdot \sigma_{max} - 82834.5135 \cdot A\sigma - 3.0898 \cdot \sigma_{max} + 58.6958 + + A\sigma \cdot \sigma_{max} + 1031.6689 \cdot A\sigma^2; \]

For welded specimens 17G1S-U steel

\[ N = 5.1787 \cdot 105 + 251.4986 \cdot \sigma_{max} + 151.026 \cdot A\sigma - 0.6914 \cdot \sigma_{max} - 2.1285 \cdot A\sigma \cdot \sigma_{max} - 164.4628 \cdot A\sigma^2; \]

For welded specimens 16G2AF steel

\[ N = 1.5428 \cdot 106 - 3370.1296 \cdot \sigma_{max} - 21406.875 \cdot A\sigma + 7.1868 \cdot \sigma_{max} - 77.2361 \cdot A\sigma \cdot \sigma_{max} + 526.6146 \cdot A\sigma^2. \]
Figure 1 shows an example of a geometric interpretation of resulting equations, which indicates a complex correlation of the test parameters. The equations allow us to estimate the residual life of a welded construction on the basis of specified operating parameters, knowing the number of loading cycles at the specified moment of operation [6].

![Graphical interpretation of the equation of correlation between the number of cycles to failure of welded 16G2AF steel specimens N, maximum tensile stress σmax and stress range Aσ.](image)

It has been found that structural failure does not occur immediately after the detection of the crack with the help of the above-mentioned devices. Specimens of 09G2S steel continue to resist variable loads for 6000 - 10000 cycles to failure, whereas 17G1S-U steel can resist for only 4000 - 6000 cycles depending on the parameters of the test. For 16G2AF steel, the number of cycles from the appearance of a crack to the failure of the specimen increases to 18000 - 26000. Under service conditions, it gives an opportunity to detect the onset of failure and dispose of the defective part or to replace the entire structure [7].

After carrying out the fatigue tests, microhardness was measured on the side surface of the fractured specimens (Fig. 2) from the center of the weld to the grips; the distance between the nearest indentations was 0.2 mm.
The results of the measurements have shown that the character of variation in the microhardness of all investigated steels is similar. The hardness gradually increases from the center of the deposited metal to the fusion zone and then, in the overheated zone [8]. Farther away, the microhardness increases again, reaching a maximum in the normalization area, and then, goes down to form an intermediate "step" before stabilizing.

**Figure 2.** Microhardness of different zones of welded joints
1 - 09G2S steel; 2 – 17G1S-U steel; 3 – 16G2AF steel

**Figure 3.** Changes in the density of dislocations (x40000)
a - in the area where the "step" has formed; b - in the base metal near the grips
As evidenced by X-ray analysis, the microhardness "step" is caused by an increase of dislocation density in the zone of its formation. Direct observations of the structure of steels with a transmission electron microscope confirm that the main cause of the increased microhardness is accumulation of dislocations (Figure 3).

Conclusion
1. On the basis of the experimental data on cyclic fatigue life of welded joints of low-alloy 09G2S, 17G1S-U and 16G2AF steels under constant sign loading with cycle asymmetry 0.8 - 0.9, quadratic equations have been obtained, which describe the correlation between the number of cycles to failure of welds in the investigated steels, the maximum tensile stress and the stress range. These equations allow estimating the residual life of a welded construction with regard to designated test parameters (or operating conditions).
2. An increase in microhardness to 2070 - 2350 MPa near the heat-affected zone and the presence of a "step", corresponding to the region of fatigue damage accumulation have been found. Transmission electron microscopy has shown that the increase in hardness is caused by an increase in dislocation density.
3. The results of the work, allow creating a technique for determining the residual service life of welded structures under variable loads. This will broaden the base of the fatigue characteristics of materials and allow estimating the feasibility of using this or that steel under specified operating conditions.

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