Destruction features of the cylindrical samples with the annular notching at cyclic loading

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Abstract. This article is devoted to the issues of metals fatigue destruction under the cyclic loading. There is the experimental procedure description given, as well as an analysis of the parameters characterizing the reliability of the obtained results held.

1. Introduction
There is a question of the current interest, arising at the enterprises of the oil and gas industry, and it is a reliability assessment of welded constructions in relation to brittle and fatigue failure [1]. There are various types and combinations of mechanical, thermal and corrosion loads, which can occur during the equipment operation in the technological processes of extraction, transportation and processing of oil and gas. Taking into the account the deterioration level of the units and designs of the equipment, the assessment of the residual resource is still one of the main problems in this industry. There are reseaches, determining the fracture characteristics of metals, given both in domestic and foreign literature, however, there is no consensus on the study of welded joints for steel constructions using various methods and evaluation criterias [2, 3].

2. Materials and methods
The sections of welded pipe joints were objects of our research. The pipes were made of the structural low carbon and low alloy steel, the specimens were cut from a long time operated pipeline. An assessment was made on the material properties degradation the over time, and it included both an assessment of the strength and deformation characteristics, as well as an assessment of the cyclic crack resistance in the various zones of the annular welded joint.

Mechanical tests were carried out on an Instron 8801 servo-hydraulic testing machine (figure 1). This machine is equipped with three control channels. The controller of the test machine allows testing with pole position manage of the test machine, developing a load and an axial deformation. In the performed study the tests control was carried out by maintaining a constant amplitude of the load acting on a sample. The samples were subjected to a cyclic action in the sample axial direction with a constant stress range and a cycle asymmetry coefficient of 0.1. WaveMatrix certified software by Instron provided the test control managing. The constant test frequency of 10 Hz was maintained during the test. The criterion for the test end was the loss of the load bearing capacity of the sample and, as a consequence, sample’s complete destruction.
To ensure macroscopic fractographic study for determining the nature of the fracture surface a Carl Zeiss Stereo Discovery V20 stereo microscope with AxioVision software was used. A photograph of the microscope is shown on figure 2. Also, by means of this microscope, the geometric parameters of the fatigue crack contour were determined.
3. Experiment details
All samples for the mechanical testing were machined according to the requirements of GOST 25.502-79 [4], which establishes the mechanical testing methods of metal and alloy samples for fatigue. However, this document does not examine and does not analyse the reliability of the test results for cylindrical samples with an annular notch. The assessment of the provided tests correctness is given in the standard GOST 25.506-85 [5].

As it was mentioned above, samples for the cyclic testing of welded joints were cut from the pipes had have been in an operation for a long time. The samples were made of a cylindrical shape, round cross-section, with a V-shaped annular notch according to GOST 25.502-79, type V [4] and were grooved up to a residual diameter of 5 mm, a scheme of applying an annular notch is shown on figure 3. A series of five samples with a notch in the zone of the fusion line and five samples with a notch in the weld metal zone was prepared for testing from each pipe section. The loading mode for each series of the samples was selected basing on the static tensile testing results of the the first sample with an annular notch from the each serie. During the cyclic exposure the samples with a ring concentrator (the notch) were loaded under a soft loading mode by the way of a variable axial tensile force with a cycle asymmetry coefficient R = 0.1, the loading scheme of the samples is shown in figure 4.

![Figure 3](image_url)  
**Figure 3.** Scheme for applying an annular notch on a sample.

![Figure 4](image_url)  
**Figure 4.** Sample loading scheme.

An important parameter for the testing was the choice of loading mode [6]. For each circular welded joint of a pipe, a serie of tests was carried out with four different modes of cyclic loading for samples with an annular groove (notch) in the zone of the fusion line and with four modes of samples with an annular groove in the zone of the welded metal (weld metal). In order to determine the correct place for machining the concentrator, the cylindrical preforms were preliminarily etched in a 5% alcohol solution of nitric acid.

After the method of cyclic axial impact on the sample testing the macro-fractographic studies and measurements of the distances between the center of the cross section of a cylindrical sample with a notch and the center of the fatigue crack contour, determined in two mutually perpendicular directions in accordance with GOST 25.506-85 [5], were carried out. Also, in accordance with GOST 25.506-85 [5], the data of these measurements allows us to determine the parameter s, which characterizes the correctness of the performed tests and represents the distance between the mentioned above centers.

4. Results and discussion
During the tests, the samples series with the annular notch in the fusion line zone and the weld metal zone were loaded with the different maximum cycle load.

After the samples being fractured as a result of cyclic loading, the macro fractographic studies of the fracture surfaces were carried out, which made it possible to research a development nature of the fatigue
fracture (fatigue crack growth) and residual (final) fracture (rapid fracture) [7], as well as to determine the necessary parameters. The magnification of the stereo microscope in the studies was x20.

Figure 5 reveals the fatigue fracture photographs of the notched sample series in the fusion line zone, destroyed at four different cycles with the maximum load. Figure 6 reveals fatigue fracture photographs of the notched sample series in the weld metal zone, which have been also obtained for different levels of the cycle maximum load. There are the measured values of the parameter \( s \) and the maximum load of the cycle at the bottom of the each photograph. The minimum load of each cycle was 10% from the cycle maximum load.

\[
s = 0.09 \text{ mm}; F_{\text{max}} = 12.0 \text{ kN} \\

s = 0.22 \text{ mm}; F_{\text{max}} = 10.9 \text{ kN} \\

s = 0.36 \text{ mm}; F_{\text{max}} = 9.7 \text{ kN} \\

s = 0.65 \text{ mm}; F_{\text{max}} = 8.5 \text{ kN}
\]

**Figure 5.** The surfaces photographs of the fatigue fracture samples in the fusion line zone.

As a result of the failure fractographic analysis it was possible to observe a center displacement of the fatigue crack from the center of the sample itself, as well as a change in shape from rounded to elliptical as the cycle maximum load decreases. A similar tendency to the uneven development of the fatigue crack and the change in the shape of the rapid fracture area was observed in the most tests. The only samples series were rejected from the research, in which the fracture occurred not in the annular notch plane or the sample did not fail in a given number of cycles.

The structure of the fatigue cracks has characteristic areas of its development: the crack incipience area is located at the opening boundary of the annular notch, then there is a fatigue crack growth (slow fracture), the name of which can be also found in the literature as “beach marks” [8] and then we have a rapid fracture area (final failure). The direction of crack growth is determined by the position and geometry of the notch, the crack growth is observed from the edges to the center.
\[ s = 0.04 \text{ mm}; F_{\text{max}} = 12.6 \text{ kN} \]

\[ s = 0.15 \text{ mm}; F_{\text{max}} = 11.4 \text{ kN} \]

\[ s = 0.43 \text{ mm}; F_{\text{max}} = 10.2 \text{ kN} \]

\[ s = 0.63 \text{ mm}; F_{\text{max}} = 8.9 \text{ kN} \]

**Figure 6.** The surfaces photographs of the fatigue fracture samples in the weld metal zone.

The obtained by the fractographic data the geometric dimensions of the various fatigue crack areas made it possible to determine the parameter \( s \) [6]. The values of the distance \( s \) averaged for each cycle load level depending on the averaged over cycle maximum load are presented in the graphs in figure 7.

The presented dependence of the influence of the cycle maximum load on the displacement of the fatigue crack center tested on cylindrical specimen with a notch is a power-law and is approximated with a sufficiently high coefficient of determination. The question of the test results correctness for the cylindrical samples with an annular notch in the fusion line are and in the weld metal area suggests identifying the reasons of the parameter \( s \), increasing with a decrease in the cycle maximum load. The structural heterogeneities associated with the structure degradation of the heat-affected zone and the welded joint zone during the pipe operation [9], and, as a result, the uneven resistance of the material to fatigue failure can occur.
Figure 7. The dependence graphs "Distance (s) between the centers of the cross section and the fatigue crack of a cylindrical sample with an annular notch, mm - Maximum load in the cycle (F_{max}), kN:

a) for a notch in the fusion line zone;
b) for a notch in the weld metal zone.

5. Conclusion
The development nature of the fatigue crack under the influence of the cyclic loads on the samples with an annular notch was analyzed, the dependence between the displacement s and the cycle maximum load was revealed as the result of the studies. In most cases, an increase in the displacement of the fatigue crack centers from the sample cross section centers with a decrease in the cycle maximum load was observed, but the identified characteristic dependence takes place both for the concentrator (notch) in the fusion line zone and for the concentrator in the weld metal zone.
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