https://doi.org/10.7494/miag.2023.3.555.37

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A study of the resistance of sucker rods to fatigue failure

The article presents the results of laboratory tests on the fatigue of samples made from full-scale sucker rods of 15H2GMF steel in various corrosive environments. For comparison, similar tests were carried out on corrosion fatigue of samples made from full-scale sucker rods of steels 20N2M, 15H2NMF and 15N3MA. The limited endurance limit of the tested rods of 15H2GMF steel in formation water is 22% lower than that of 20N2M steel and 13% lower than that of 15H2NMF steel, and in an environment simulating the action of H_2S it is 34% lower than that of 20N2M steel and 32% lower than that of steel 15H2NMF. The results were obtained using a complex surface method of strengthening sucker rods, which was developed in the laboratory of the Department of Oil and Gas Machines and Equipment of the Ivano-Frankivsk National Technical University of Oil and Gas and tested at the NGVU "Dolynanaftogaz".

Key words: *fatigue damage, corrosion fatigue, pump rod, drilling*

1. INTRODUCTION

Studying the behavior of pump rods made of different materials operating in brine waters from different oil fields is crucial in facilitating the selection of the right manufacturer. Due to the fact that rods operate in environments with variable degrees of corrosivity, the fatigue resistance of a given rod model may be different for each well location [1–9].

A reliable analysis of this issue requires a two-track approach involving both laboratory and field tests. Under laboratory conditions, due to limitations in reproducing the full range of factors occurring in commercial practice, it is only possible to establish qualitative relationships between different types of steel in one of the most aggressive environments or in the case of rods made of the same material in different corrosive environments. On the other hand, field tests, with an appropriate number of wells and different parameters of media and materials used to make the rods, enable the identification of not only qualitative but also quantitative indicators related to the durability of the rod s under different operating conditions.

The influence of corrosive environments on material fatigue should be considered by taking into account the time of their impact in comparison with the rate of development of fatigue damage. On this basis, two main mechanisms of media impacting the mechanical properties of metal can be distinguished: the first group includes mechanisms acting very quickly (the adsorption mechanism), and the second includes those that require much longer time intervals to have a significant effect [6, 10–11]. The second type of impact is most often processes related to corrosion, and electrochemical corrosion in. The first group includes the adsorption mechanism, while the second group includes processes related to corrosion, in particular electrochemical corrosion.

This article determines the strength limit for pump rods made of three steel grades (20N2M, 15H2NMF and 15N3MA) operating under zero-average cyclic loading in two types of environments – in brine and in a hydrogen sulphide H_2S environment. It has been shown that in most cases the presence of a liquid medium accelerates the formation and development of corrosion-fatigue cracks, leading to the degradation of the rod.

2. METHODOLOGY AND RESEARCH RESULTS

To conduct laboratory tests of samples made from 15H2GMF steel sucker rods for fatigue, a base of $2 \cdot 10^7$ cycles was selected. The selected base allows us to evaluate the response of the first and second mechanisms of exposure to a corrosive environment. To determine the limited endurance limit of new sucker rods in order to establish the influence of various corrosive environments, we examined samples from new sucker rods without surface treatment made of 15H2GMF steel with a diameter of 19 mm. The design of the samples is shown in Figure 1. Basic data on the chemical composition of steel are given in Table 1.

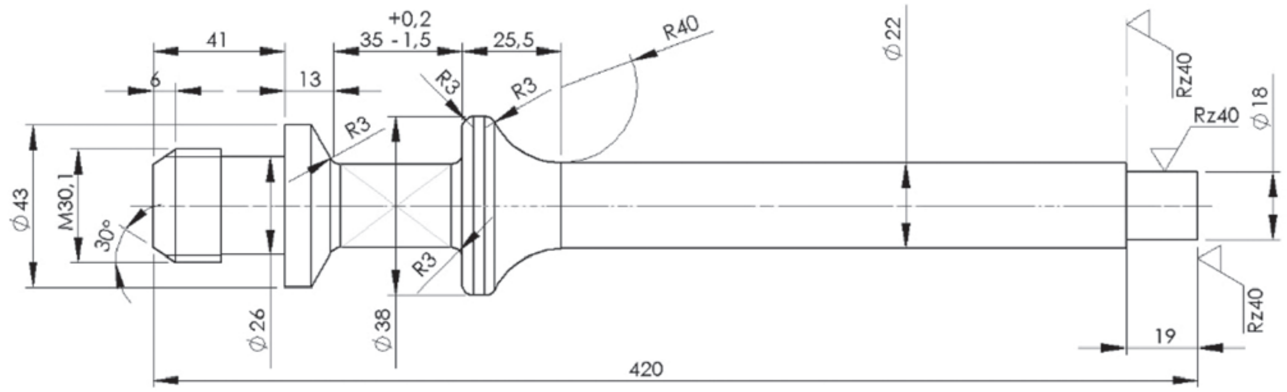

Fig. 1. Design of samples made of steel 15H2GMF with a diameter of 22 mm

Table 1

Chemical composition of steel 15H2GMF

Element	C	Si	Mn	Kr	Ni	S	P	Mo	V	Cu
Participation [%]	0.16	0.27	0.65	2.06	0.99	0.015	0.013	0.24	0.11	0.15

The studies were carried out at a loading frequency of 15.8 Hz in:

- distilled water,
- 3% NaCl solution,
- formation water from the wells of NGVU Dolynanaftogaz,
- an environment simulating the action of H_2S.

Figure 2 shows the corrosion fatigue curves of samples from full-scale sucker rods when tested in the above-mentioned environments.

The shape of the fatigue curves, as studies have shown, depends on the environment in which the experiments were carried out. Analysis of the curves shows that in corrosive environments the service life of new sucker rods is sharply reduced when loaded with alternating bending [2]. The greatest reduction in durability is observed in an environment simulating the action of H_2S. An environment that imitates the action of H_2S strongly dissociates and causes hydrogenation of steel, which is the main reason for the decrease in durability during high-cycle fatigue. Based on tests of $N = 2 \cdot 10^7$ cycles, the limited endurance limit is: σ_{1k}

- 72 MPa in distilled water,
- 49 MPa in a 3% aqueous solution of NaCl,
- 49 MPa in formation water,
- 30 MPa in an environment simulating the action of H_2S.

The test results are shown in Table 2.

For comparison, similar tests were carried out on the corrosion fatigue of samples made from full-scale sucker rods of steels 20N2M, 15H2NMF and 15N3MA. The studies were carried out at a loading frequency of 15.8 Hz in formation water from the wells of NGVU Dolyinanaftogaz and in an environment simulating the action of H_2S. The test results are presented in Table 3.

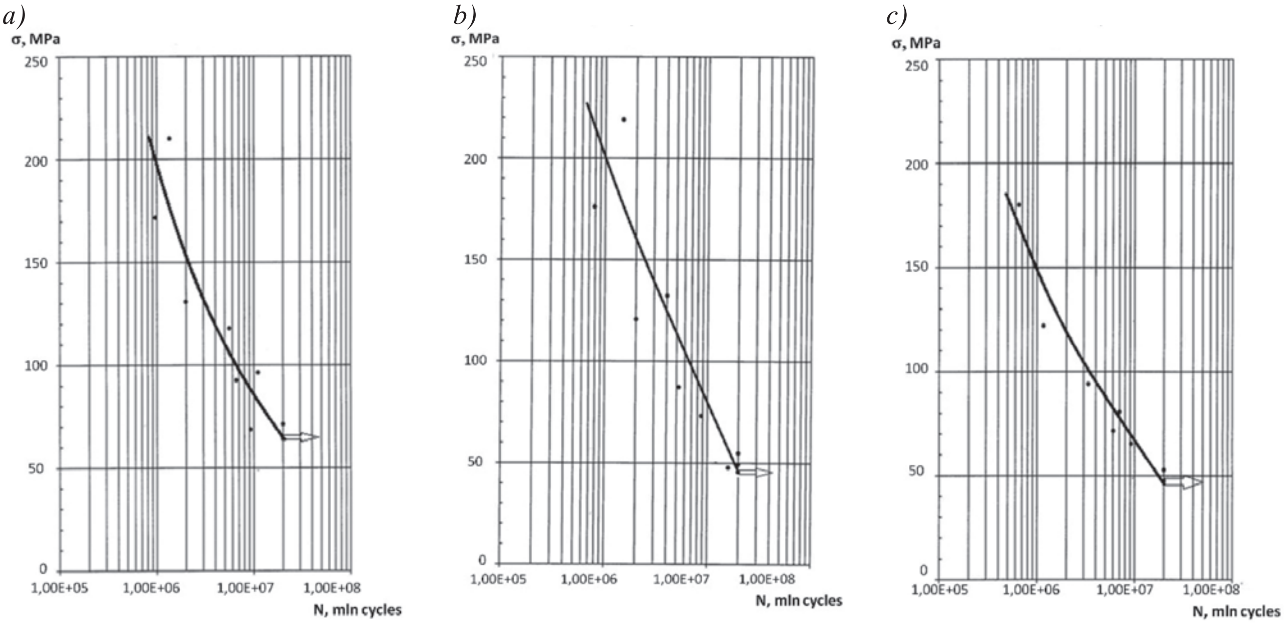

Fig. 2. Corrosion fatigue curve of sucker rod samples with a diameter of 19 mm from steel: a) 15H2GMF when tested in distilled water; b) 15H2GMF when tested in 3% aqueous NaCl solution; c) 15H2GMF when tested in formation water

Table 2

The influence of the environment on the durability of sucker rods with a diameter of 19 mm made of steel 15H2NMF

Limit of endurance σ_{1k} [MPa]	Test medium	Durability *N* [mln cycles]
72	distilled water	20
49	3% aqueous solution of NaCl	20
49	formation water	20
30	environment simulating the action of H_2S	20

Table 3

The results of testing samples from sucker rods with a diameter of 19 mm for fatigue in corrosive environments

Sucker rods	Steel grade	Test medium	Limited endurance limit $\sigma_{1\kappa}$, MPa
New	15H2NMF	formation water	60
New	20N2M	formation water	68
Used	15H2NMF	formation water	57
New	15N3MA	formation water	220
New	20N2M	simulation H_2S	47
New	20N2M	simulation H_2S	40
Used	15H2NMF	simulation H_2S	44
New	15H2NMF	simulation H_2S	46
Used	15H2NMF	simulation H_2S	38

Based on the analysis of data from Tables 2 and 3, it was established that the highest limited endurance limit for 15N3MA steel when tested in formation water is 220 MPa. It decreases in steels with reduced nickel content and is: for steel 20N2M – 68 MPa; for steel 15H2NMF – 62 MPa; for steel 15H2GMF – 51 MPa.

The results of full-scale corrosion fatigue tests of samples made from sucker rods of steel 15H2GMF (Tabs. 2 and 3, Fig. 3) show: the limited endurance limit of the tested rods in formation water is 22% lower than that of 20N2M steel and 13% lower than that of 15H2NMF steel; the limited endurance limit of the tested rods in an environment simulating the action of H_2S is 34% lower than that of 20N2M steel and 32% lower than that of 15H2NMF steel; the tested rods made of steel 15H2GMF are not recommended without hardening (surface plastic deformation) and appropriate protection (coating with anti-corrosion varnishes, enamels, the use of corrosion inhibitors) for corrosive operating conditions containing hydrogen sulfide.

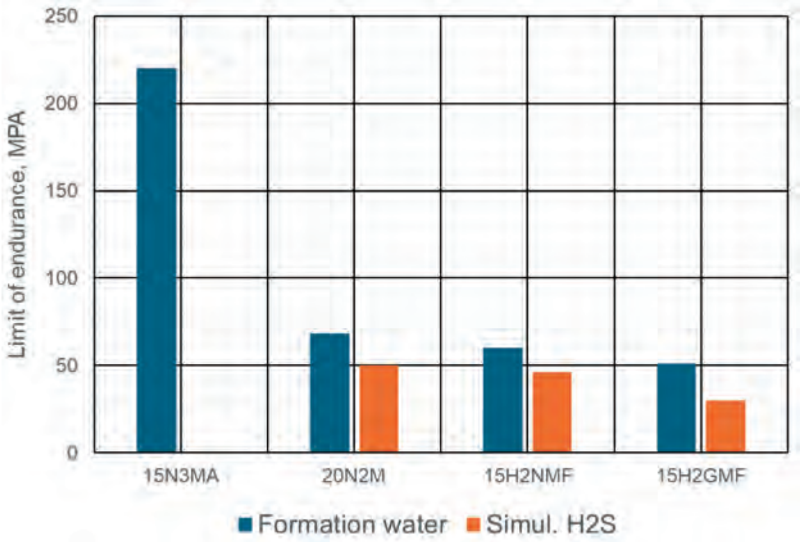

Fig. 3. Comparison of fatigue strength under alternating bending rotating samples from sucker rods with a diameter of 19 mm at loading frequency 15.8 Hz in corrosive environments

We consider it useful in the article to present the results obtained using a complex surface method of strengthening sucker rods which was developed in the laboratory of the Department of Oil and Gas Machinery and Equipment of the Ivano-Frankivsk National Technical University of Oil and Gas and tested at the NGDU “Dolinanaftogaz”. The mechanism of surface hardening is intended to create a stronger and chemically resistant surface layer and residual compressive stresses in this layer. The method of the surface hardening of sucker rods consists of blasting the body with shot, applying an anodic metallization and subsequent protective anti-corrosion coating.

The purpose of shot blasting is to neutralize the effect of stress concentrators, strengthen the surface of the rod body and prepare it for the subsequent application of a zinc (aluminum) coating. The most suitable for shot blasting the surface of rods is cast iron crushed shot of medium fractions with a size of 1.5–2.5 mm (40–50%) and round (60–50%). The efficiency of shot blasting is ensured by choosing the optimal parameters that determine the mode as a whole. As a result of shot processing, residual compressive stresses are created which increase the fatigue strength of the rods. The most important parameters are the composition and size of the shot, the duration of processing, the air pressure in the system, the diameter and shape of the nozzle, the distance of the nozzle to the surface of the rod being processed. All of them were selected on the basis of accumulated field experience, numerous laboratory studies and analysis of field tests of a batch of sucker rods made of steel 20N2M and 15H2NMF. Over the course of 4 years, the laboratory of the Department of Oil and Gas Equipment carried out observations of the condition of a hardened batch of sucker rods. During this period, not a single rod breakage occurred. In addition, with each lifting of the rod string, a visual assessment of the condition of the metal-polymer coating on the reinforced rods was carried out. During the first three years of work in the wells, the metal-polymer coating on the surface of the rods remained in a satisfactory condition. However, after three years of operation of the hardened sucker rods, partial peeling of the metal-polymer coating began to occur. To more fully assess the condition of the hardened sucker rods after three years of operation in wells, corrosion-fatigue strength tests were carried out. The tests were carried out in laboratory conditions on the IKSh-25 installation using produced water from the NGVU Dolyinanaftogaz well. The tests were carried out on full-scale samples of sucker rods with a diameter of 19 mm made of 20N2M steel which had worked in the well for 3 years, and samples of new hardened sucker rods.

The tests show that after three years of work in the well, a decrease in corrosion-fatigue strength occurs. As is it known, corrosion-fatigue strength largely depends on residual compressive stresses [2]; therefore, to explain the decrease in corrosion-fatigue strength, studies were carried out to determine the residual compressive stresses in the material of a sucker rod sample that had worked in a well for 3 years. As the research results show (Figs. 4 and 5), after three years of operation in the well, relaxation of residual compressive stresses occurs, it is especially noticeable in the upper layers of the metal, and therefore there is a noticeable decrease in corrosion-fatigue strength.

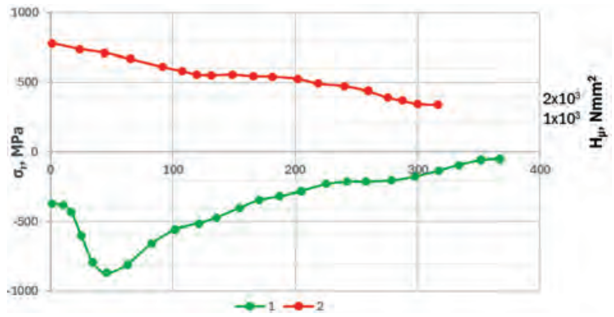

Fig. 4. Distribution of residual compressive stresses σ_r (I) and microhardness Hμ (2) in 19-millimeter samples of new pump rods made of 20N2M steel after hardening

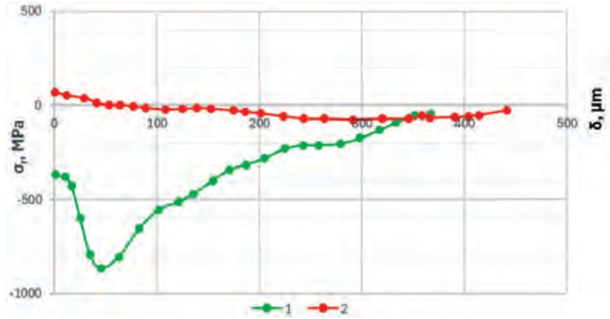

Fig. 5. Distribution of residual stresses in the surface layers of pump rods after the complex strengthening method (1) and their 3-year operation (2)

In addition, measurements were taken of the microhardness of the material of new hardened sucker rods that had worked in wells for 3 years. Microhardness measurements were carried out every 60 μm from the surface to the center. The results of the measurements show that after three years of operation in the well, the microhardness in the sucker rod material decreases and levels out along the depth of the rod. A decrease in the microhardness of the sucker rod material subsequently gives rise to the initiation of microcracks, which also affects the decrease in corrosion-fatigue strength [5]. Thus, the residual compressive stresses that formed during the process of complex surface hardening decrease over time of operation under the combined action of a corrosive environment and prolonged cyclic loads. This leads to a decrease in resistance to corrosion-fatigue failure. However, for 3 years, 100% protection of the rod body from environmental influences is provided. Recently, new composite materials [12–17] have started to be used for the production of sucker rods, such as carbon fiber and hybrids (a carbon fiber core and a fiberglass shell), which have very high resistance to the action of corrosion.

3. SUMMARY

The limited endurance limit of the tested rods of 15H2GMF steel in formation water is 22% lower than that of 20N2M steel and 13% lower than that of 15H2NMF steel, and in an environment simulating the action of H_2S it is 34% lower than that of 20N2M steel and 32% lower than that of steel 15H2NMF. The residual compressive stresses that have been formed during the process of complex surface hardening decrease over time under the combined action of a corrosive environment and prolonged cyclic loads.

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