Analyzing Causes of Damage to the Plunger Stem and Cylinder of a Sucker Rod Pump

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Abstract. This paper presents the results of analyzing the reasons for damage to the plunger stem and cylinder of sucker rod pumps, which were operated in an environment with hydrogen sulfide. The chemical composition, mechanical properties, and hardness of the products were studied in order to assess how the material of the parts conforms to the technical documentation. Likewise, the reasons for damage were analyzed using an optical electron microscope. It was established that damage to the plunger stem happened along the first thread of the threaded connection of the rod inside the body of the adapter, while destruction to the cylinder was observed in the area of the threaded connection to the body of the pump’s suction valve. Results showed that the main reason for damage was the combination of a corrosive H2S environment and mechanical stress, which led to sulfide corroded cracking under stress. Suggestions were put forward about extending the service period of the SRP parts and reducing the likelihood of their destruction.

1. Introduction
A significant number of oil wells in the trade are equipped with well sucker rod pumps (WSRP), whose number in oil drilling increases yearly. Besides the great advantages, these systems have drawbacks as well which are related to accidents of the deep pump equipment.

When operating the wells with sucker rod pump equipment, some of the main problems of damage are broken rods and mechanical friction of the parts, particularly the rods on the pump compressor tubing and the plunger on the cylinder during a long period of work in the wells. The wear and tear of the deep pump equipment also depends on the presence of formation mineralized water in the well products, which causes corrosion of the tubes, rods and parts and weakens their durability. Due to the causes mentioned above, broken and bent rods lead to accidents, while the leaks that increase in proportion to the increase in gaps between the SRP plunger and cylinder reduce the productivity of the pump after several months of work until the supply has completely stopped. Likewise, the occurrence of emergency situations can be related to the material of the parts not conforming to the requirements of technical documentation (TD), and to the improper selection of materials during operation, human factor, and so on.

The reliability of the sucker pump equipment, its functional possibilities and maintainability are determining factors for the efficient work of the sucker rod pumps.

Dealing with accidents at the place of extraction is a relevant and important problem and requires significant costs relating to stoppages, repairs, and eliminating consequences of the accidents. Reducing these costs is possible with accident prevention through timely repairs or replacing damaged parts. Therefore, papers aimed at increasing the operation efficiency of sucker rod pumps (SRP) are relevant.
Analyzing the damaged parts of SRP and identifying the reasons for the damage is necessary in order to recommend actions and protective measures focused on preventing and stopping accidents at the places of operation.

The goal of this paper was to identify the reasons for damage to the plunger stem and cylinder from two different SRP after being damaged during operation. In order to do this, mechanical tensile tests were studied, the material chemical composition of the parts and the measurements of hardness were analyzed. Breakages and damage to the parts were analyzed using an optical electron microscope.

2. Methodological Part

The object of research was Russian produced parts from two different sucker rod pumps after being damaged during operation: the plunger stem with the adapter from the pump and the cylinder with the valve from the pump. According to TD, it is known that the SRP products were operated in an environment containing H₂S and CO₂.

In order to confirm the conformity of the materials of the damaged parts with the TD, an analysis of the chemical composition and mechanical properties and hardness measurements was conducted.

The chemical composition of the SRP parts was analyzed using the method of atomic emission spectroscopy with the emission spectrometer “Iskroline-100” in accordance with GOST 54153-2010. Testing of the mechanical properties and preparation of the samples were carried out according to GOST 1497-84, GOST 10006-80 and GOST 11701-84. The universal testing machine INSTRON 8801 (100 kN) was used with the software Instron Bluehill 2.6 for tensile testing.

Macro-hardness of the studied parts was measured based on the Rockwell method for measuring hardness on the hardness tester ТР5006 № 85 according to GOST 9013-59.

Additional study of the micro-hardness was carried out using the microscope attachment MICRO-DUROMAT 4000E in accordance with GOST 9450-76. The micro-hardness was assessed according to the recovered-print method on the optical microscope Reichert-Jung (×500) at ×500 magnification. Hardness was measured using Vickers hardness test with a load of 180g (HV0.18). The hardness was converted from the HV scale to the HRA scale according to the standard ASTM E 140 [15].

In order to do metallographic studies, the samples cut from damaged parts were pressed and their surfaces were sanded using abrasive paper with a grain of 120-1200 grid and polished with polishing cloths on the grinder-polisher BUEHLER ECOMET 4. In order to identify the microstructure of the metal, the samples were etched with a 3% nitric acid solution (HNO₃) in alcohol. The structure was studied using methods of optical metallography on the microscope Reichert-Jung with ×500 magnification.

The chemical composition of the inclusions was studied out using the scanning electron microscope SUPRA 55VP WDS with an X-ray spectral analysis attachment.

3. Results and Analysis

3.1. Researching Conformity of the Parts to Technical Documentation

SRP plunger stem

Figure 1 shows an SRP plunger stem with the adapter. As can be seen from the figure, the damage occurred along the first thread of the threaded connection of the stem inside the body of the adapter.
**Figure 1.** SRP plunger stem with its adapter: (a) SRP plunger stem (the place of breakage is outlined in red); (b) stem adapter (side view, the place of breakage is marked in red); (c) stem adapter (view from above, the place of breakage is outlined in red).

The plunger stem part was studied according to the requirements of the technical documentation. Table 1 shows the requirements for the material of the plunger stem according to the TD and the results of mechanical tests of the sample material.

Table 1. Pivot table of results from mechanical testing of the plunger stem.

| Parameter               | Flow stress $\sigma_{0.2}$, MPa | Ultimate tensile strength $\sigma_B$, MPa | Hardness of material, HV |
|-------------------------|---------------------------------|----------------------------------------|-------------------------|
| Test results            | 680                             | 790                                    | 340                     |
| According to TD         | > 586                           | > 793                                  | -                       |

According to the results from studying the mechanical properties of the stem metal, the value of the flow stress equaled 680 MPa, and the ultimate tensile strength equaled 790 MPa.

The hardness of the sample was 340 HV (34 HRC according to ASTM E140 [15]). According to the requirements of NACE MR0175 Part 2 for low-alloy steels used in hydrogen sulfide environments, the hardness of the material should equal less than 22 HRC; in rare exceptions up to 26-33 HRC [17].

Test results for the chemical composition of the stem material are given in Table 2. According to TD, the material of the plunger stem must meet the steel strength class “D” according to API Spec 11B [16], which includes the steel grades 40CrMnMoA, 30CrMoA and 38CrMnTi.

Table 2. Pivot table of results from testing the chemical composition of the plunger stem.

| Parameter               | Steel grade                  | C       | Si     | Mn     | Cr    | Mo    | Cu    | S     | P     |
|-------------------------|------------------------------|---------|--------|--------|-------|-------|-------|-------|-------|
| Results of chemical     | 0.425                        | 0.27    | 0.90   | 0.95   | 0.22  | 0.094 | 0.00  | 0.01  | 0.019 |
| analysis                |                              |         |        |        |       |       |       |       |       |
| Steel of hardness class | 40CrMnMoA                    | 0.37-0.42| 0.17-0.40| 0.6-0.9| 0.9-1.2| 0.15-0.25| up to 0.3| 0.03 | 0.03 |
| “D” according to API     |                              |         |        |        |       |       |       |       |       |
| Spec 11B [16]           | 30CrMoA                      | 0.26-0.33| 0.17-0.37| 0.4-0.7| 0.8-1.1| 0.15-0.25| up to 0.3| 0.02 | 0.02 |
|                          | 38CrMnTi                     | 0.37-0.43| 0.17-0.37| 0.5-0.8| 0.4-0.6| 0.15-0.25| up to 0.3| 0.03 | 0.03 |

According to the chemical composition obtained, it was established that among steels of the hardness class “D”, the material of the SRP stem corresponds to steel type 40CrMnMoA, meeting the requirements of the TD.
The material of the plunger stem meets the requirements of the technical documentation in terms of mechanical properties and chemical composition.

**SRP Cylinder**
The SRP cylinder with the body of the valve is presented in Figure 2.

![Figure 2](image)

**Figure 2.** SRP cylinder and valve body: a) SRP cylinder, breakage area from the exterior; b) SRP cylinder, breakage area from the interior; c) SRP valve body (the area of attachment to the cylinder is outlined in red).

Study of the SRP cylinder part was carried out according to the requirements of the TD. Table 3 shows the requirements for the cylinder material according to the TD along with the results of mechanical tests of the sample material.

| Parameter          | Flow stress $\sigma_{0.2}$, MPa | Ultimate tensile strength $\sigma_{B}$, MPa | Presence of a nitrided coating                                      | Material hardness |
|--------------------|----------------------------------|------------------------------------------|----------------------------------------------------------------------|-------------------|
| Test results       | 480                              | 820                                      | Hardness of coating: 1100 HV, at a depth of 0.127 mm – 800 HV        | 61.5 HRA [15]     |
| According to TD    | $> 480$                          | -                                        | Hardness of coating: 870 HV, at a depth of 0.127 mm – 446 HV         | 55-62 HRA         |

According to the results of studying the mechanical properties of the cylinder metal, the flow stress value equaled 480 MPa, while the ultimate tensile strength equaled 820 MPa. The hardness of the sample was 61.5 HRA in accordance with ASTM E140 [15].

In order to monitor the quality of the material for the hardness parameter, it was of interest to check for the presence of a nitrided layer on the surface of the cylinder part. A section of the cylinder was studied...
for hardness from the outer wall in order to identify the nitrided layer. For this, a lateral metallographic cut was made of the cylinder section. The results of the research are presented in Figure 3.

![Figure 3](image-url)

**Figure 3.** Hardness values of the cylinder section from the outer wall: a) graph of dependency of hardness on distance; b) structure of the material surface laterally.

According to the results obtained, the thickness of the nitrided layer equaled around 200 μm, while the hardness of the main metal was between 240 and 260 HV0.18.

The results from studying the chemical composition of the cylinder material are presented in Table 4. According to the TD, the material of the cylinder should meet the steel grade 38Cr2MoAl in accordance with API Spec 11B [16].

| Parameter                                      | C  | Si   | Mn  | Cr  | Mo  | Al  | Cu  | S    | P    |
|------------------------------------------------|----|------|-----|-----|-----|-----|-----|------|------|
| Results of chemical analysis                   | 0.37 | 0.024 | 0.44 | 1.69 | 0.17 | 0.92 | 0.14 | 0.003 | 0.016 |
| Chemical composition of the steel grade 38Cr2MoAlA according to API Spec 11B [16] | 0.35-0.42 | 0.20-0.45 | 0.3-0.6 | 1.35-1.65 | 0.15-0.25 | 0.7-1.1 | Up to 0.3 | 0.04 | 0.04 |

According to the results of studying the chemical composition of the cylinder material, it was established that the composition of the material meets the requirements of the TD and are of steel type 38Cr2MoAlA.

The cylinder material of the SRP valve meets the requirements of the technical documentation in terms of mechanical properties and chemical composition.

### 3.2. Analyzing the Reasons for Damage

**SRP plunger stem**

As it was previously established (from Figure 1), damage to the SRP plunger stem occurred along the first thread of the threaded connection of the stem within the body of the adapter. Impact marks of the counterparts appear on the stem guide and stem adapter during operation. During visual examination of the fracture, at a magnification up to 30 times, it was established that the damage was brittle in nature. In Figure 4, the red line marks the area the crack originated, the starting point of the first thread. The yellow line indicates the place of complete break.
The structure of the sample material was studied on a lateral metallographic cut (Figure 5, a). It was determined that the structure of the material of the plunger stem was upper bainite.

The surface of the fracture and a chemical analysis of the corrosion products (Figure 4, highlighted in red) were studied using an electron microscope. The chemical composition of the corrosion products on the surface (Figure 5, b) is presented in Table 5.

From the table it can be seen that sulfides and chlorides were discovered on the surface of the fracture in the area where the crack originated. This corresponds to the conditions of operation for the plunger stem part in an environment with hydrogen sulfide.

Judging by the corrosion products and the type of fracture (brittle), the reason for the damage to the stem could have been sulfide corrosion stress cracking (SCSC). An increased likelihood of damage is related to impact to the counterparts and a possible overload during operation.
SRP cylinder
As seen in Figure 2, the SRP cylinder has two cracks in the area of the threaded connection with the body of the pump’s suction valve. Upon visual inspection of the fracture, at a magnification of up to 30 times, it was noticed that the damage to the lengthwise fracture was brittle in nature. In Figure 6, the broken fifth thread of the cylinder is marked with a red line.

![Macro images of lengthwise fracture of cylinder: a) lateral view; b) view from inside the tube, from the threaded side.](image)

Figure 6. Macro images of lengthwise fracture of cylinder: a) lateral view; b) view from inside the tube, from the threaded side.

The structure of the sample material was studied on a lateral metallographic cut (Figure 7, a). When doing metallographic research, it was established that the material of the cylinder had a ferrite-pearlite structure, with a grain score of 8.5. Figure 7, b presents the eighth thread in order to study the breakage area of the cylinder thread. In order to do this, a metallographic cut lengthwise to the cylinder thread was prepared. The depth of the cracks was established to be 100μm.

![Structure of the SRP cylinder material magnified to x500 (a) and cracks in the area between the 8th and 9th thread magnified to x100 (b).](image)

Figure 7. Structure of the SRP cylinder material magnified to x500 (a) and cracks in the area between the 8th and 9th thread magnified to x100 (b).

A fracture spreading across the radius of the cylinder is presented in Figure 8.
According to the nature of the crack presented in Figure 8, it can be proposed that this radial crack is secondary, the origin and spread of which is a result of increased tensile loads (mechanical factor) on this section of threads after lengthwise damage to the cylinder. The surface of the fracture and a chemical analysis of the corrosion products (Figure 6, highlighted in red) were studied using an electron microscope. The chemical composition of the corrosion products on the studied parts of the surface (Figure 9) is presented in Table 6.

Sulfides and chlorides were discovered on the surface of the fracture in the area where the crack originated. It is also known that the operational environment of the SRP cylinder was an environment containing H₂S. Thus, the overall high stress concentration in transition zones, i.e., mechanical impact, and the corrosive environment help to conclude that the main reason for damage to the material of the cylinder could be sulfide corrosion stress cracking (SCSC).

4. Discussion
Initially, the task was set to exclude the version that damage to the equipment was caused by not meeting the requirements of the technical documentation. All of the tests conducted showed that the materials of the SRP plunger stem and the SRP cylinder have the claimed indicators in accordance with the TD. It is important to note that the TD for the material does not contain any requirements for the hardness of products. According to the research results, it was learned that at 33 HRC, the hardness of the parts exceeds the maximum acceptable values according to NACE MR0175 [17]. The hardness of the material.
is an important indicator capable of influencing the quality of the material, and a deviation of the hardness from recommended standard values can lead to damage to the material in aggressive environments and, as a result, to damage to the part. When used in H2S environments, it is necessary for the materials to be qualified according to the standard NACE MR0175, which contains a requirement for the maximum acceptable values of hardness. In the examined case, a deviation of the hardness values could have influenced the brittleness of the material and acted as one of the reasons for damage to the part.

Since the parts were used in an environment containing H2S and CO2, it was assumed that the main cause of damage was sulfide corrosion stress cracking. Study of the damaged surfaces and an analysis of the corrosion products showed that sulfides and chlorides were present in the fractured area. The joint effect of mechanical loads and a corrosive environment during operation likely led to damage to the SCSC mechanism. Similar incidents are described in the following works [1].

In summary, it can be noted that steels of grades 40CrMnMoA and 38Cr2MoAlA are susceptible to sulfide corrosion damage in working environments containing H2S. Therefore, equipment from low-alloy steels is not recommended to use in hydrogen sulfide environments.

In order for material used in aggressive conditions such as H2S and CO2 to function, it is necessary to finalize the TD in terms of hardness, as well as to monitor that the specific material meets the given requirements. Lab tests can be conducted in order to be certain of the durability of the material. For other protective measures of preventing such damage, it is recommended to lighten the load on the SRP, to use inhibitors to reduce the aggressiveness of the environment, to monitor the properties of the materials used or to use more corrosion resistant materials to manufacture SRP parts [3].

5. Conclusion

Foreign standards regulate the requirements for the hardness of materials used in hydrogen sulfide environments. However, such requirements are missing from technical documentation on the tested parts. Increased hardness leads to an increased tendency to sulfide corrosion cracking, and therefore it is recommended to take this parameter into account in documentation. Extending the service life of SRP parts and reducing the likelihood of damage is possible with a more detailed analysis of the anticipated conditions of operation and monitoring of the materials used.

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