Recovery of strength properties of pump rods by means of functional gradient materials generating

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Abstract. The article considers the issues of increasing the environmental safety of oil producing areas at the expense of application pump rods put out of operation. It is demonstrated that it is reasonable to consider the recovered pump rod as a functional gradient material with specified strength properties. Factors, influencing fatigue strength of material under conditions of interaction with corrosive medium, are analyzed. Corrosive fatigue strength criterion is formulated considering residual axial stresses. It is demonstrated that the most suitable process to create the required gradient material is tensioning with further plastic rod torsion.

1. Introduction

All developed countries utilize resources after its usage that makes beneficial environmental impact. Thus, the disposal consideration problem vanishes, as well as buying the equipment for waste recycling. The methods for recovery used equipment are in the use actively that increases the efficiency of its usage.

Currently, the issue of finding the technologies to recover underground equipment, especially pump rods, is very actual for oil-producing enterprises. Worked out rods are sent to melting or disposed. A great number of used rods are collected next to the fields that represent an additional source of environmental hazard in oil-producing areas. Recovery process not only elongates the pump rod service term but also leads to a significant decrease in risks connected to ecology violations in oil-producing areas. Therefore, development of used rods operability recovery methods is an important and actual problem of modern oil-producing industry.

It is known that rod columns operate in severe conditions of alternating cyclic loading and corrosive atmosphere conditions. Joint action of variable stresses and electro-chemical corrosion to metal leads to a significant decrease in its fatigue strength and, accordingly, to rod fracture and breakage. The observed data show that the pump rods breakage is more than 60% of the total number of accidents.

Generally speaking, working capacity of the rods line is considered, first, by the material quality, manufacturing product quality, adequate according to the rod string extraction conditions, following the procedure of rods usage and non-increasing the working stress, taking into account the corrosion medium properties.
Requirements for pump rods specify conditions for non-exceedance of allowable reduced stresses in the rod body within the loading cycle and allowable stresses are established depending on the rod material and the size, its treatment during production, as well as medium corrosion activity.

Therefore, one can conclude that the main reason of pump rods breakage is their corrosion fatigue caused by cyclic loading and impact of aggressive medium. That is why after recovery, strength properties of a pump rod shall be not less than those for a new one. Meantime, it shall be stressed that, when assessing corrosion fatigue of recovered rod, processes of its operation and recovery shall be considered.

2. Analysis of factors impacting to strength properties of materials at pump rods recovery
It is known that different thermoplastic impact processes [1], leading, among others, to changes in material strength properties, are widely used at pump rods recovery. As mentioned in work [2], common impact of thermoplastic straining onto fatigue strength is defined by summary impact of three factors:

- material strain hardening (cold work hardening);
- material damage accumulation;
- occurrence of residual stresses.

It is recognized [3] that the first factor, generally, positively impacts fatigue strength of material operated in a corrosive medium. On the opposite, the second factor usually leads to a decrease in fatigue strength of material. Third factor of the impacts on fatigue strength of material significantly depends on axial residual stresses distribution over rod radius. As shown in works [4], surface compressive residual stresses increase not only fatigue limit, but also durability of loaded material.

Special interest is attracted to the studies of the residual stresses impact onto fatigue strength in a corrosive medium, which shows that corrosive fatigue fractures are mainly developed in the areas of maximal tensile stresses [3]. This speaks for the favorable impact of compressive residual stresses on corrosive fatigue of material.

Therefore, it can be said with great measure of confidence that guidance of the favorable field of residual stresses within pump rods recovery process affects positively their fatigue strength and, accordingly, provides necessary operability at further operation.

3. Consideration of recovered pump rod as functional gradient material
As indicated above, the main factor impacting to strength properties of pump rod is corrosive fatigue of material within operation. However, in aggressive medium conditions, only small external pump rod layer “works”, while the rest rod material is in more favorable conditions. Therefore, there is a necessity to create functional gradient material with different properties over the rod radius. In this case, it is necessary to reach the following effects at the expense of the surface layer of rod material: increase of wear resistance and corrosion resistance in corrosive medium, as well as prevention of development of material’s micro-fractures accumulated within previous operation. As multiple experimental studies show, e.g. those represented in work [5], this can be achieved by generating compressive residual axial stresses in the surface layer of rod material. In this case, axial stresses distribution over the rod’s body in radial direction shall be self-balanced [5] that leads to the occurrence of tensile residual axial stresses in internal layers of pump rods. Being added to tensile stresses arising because of operational forces, they can lead to micro-fractures development and, accordingly, to material breakage in internal layers of the pump rod. Therefore, the task arises to define such figures of compressive and tensile residual axial stresses, which would provide specified strength properties of the recovered pump rod, as some functional gradient material.

Fig. 1a represents preferable epure of axial residual stresses $\sigma_z$ over the pump rod cross section, where $a$, $b$ and $h$ are parameters of such epure depending on the rod recovery process; $h^*$ is the
thickness of the material external layer, whereon corrosive external environment impacts (in Fig. 1a, the value $h^*$ coincides with $h$); $R$ is the rod radius.

![Diagram](image)

**Figure 1.** Distribution of axial residual stresses: a – preferable epure; b – after surface treatment; c – after tension with torsioning

As can be seen from Figure 1, compressive residual stresses exist in the external layer that increases rod's corrosive resistance and strength. Conversely, tensile stresses increase in the internal layer, but from the rod strength viewpoint, this is not so dangerous, as far as in this place there is no contact with a corrosive medium. According to pump rods requirements, their operability is defined by the following cyclic strength criterion [3]:

$$\sqrt[3]{\sigma_{\text{max}}} \cdot \sigma_a \leq [\sigma], \quad \sigma_a = (\sigma_{\text{max}} - \sigma_{\text{min}})/2.$$  \hspace{1cm} (1)

Here $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ is max. and min. number of axial stresses per a rod loading cycle; $[\sigma]$ is allowable stress for material staying in corrosive medium.

Considering residual stresses, this equation can be re-written as follows:

$$\sqrt[3]{(\sigma_{\text{max}} - \bar{b}) \cdot \sigma_a} \leq [\sigma]_h, \quad r \in [R - h, R], \quad \sqrt[3]{(\sigma_{\text{max}} + a) \cdot \sigma_a} \leq [\sigma]_2, \quad r \in [0, R - h].$$  \hspace{1cm} (2)

Here $\bar{b}$ is a compressive stresses resultant module, $[\sigma]_h$ is allowable stress for material staying in a corrosive medium, $[\sigma]_2$ is the same for the sample polished in the air.

It is not hard to re-write the last two restrictions against $a$ and $b$ values. As is evident from Fig. 1a, $b$ value shall be close to value $\bar{b}$. Considering this assumption, one will get:

$$a(z) \leq \left[ \frac{[\sigma]_h}{\sigma_a} \right] - \sigma_{\text{min}}, \quad b(z) \geq \left[ \frac{\sigma_{\text{max}} - [\sigma]_h}{\sigma_a} \right], \quad \forall z \in [0, L].$$  \hspace{1cm} (3)

where $z$ is a longitudinal coordinate and $L$ is a rod length.

Rod resistance to external corrosive effects is also defined by thickness $h$ of the compressive strength layer; therefore, the following restriction for this thickness shall be introduced
Now, the question arises on how to create required functional gradient material from worn rod, in such a way that it can meet conditions (1)-(4). Enough big quantity of rod treatment processes are known, which enable to strengthen material significantly. Such technologies can include heat-strengthening, tool rolling and shot peening of rod surface or plastic torsion.

It worth noting that it is reasonable to recover pump rod in oil-producing areas. Therefore, energy consuming heat-strengthening process is not suitable in this case. Beside this, in the course of heat strengthening the rod can lose its straightness that is not permissible for further operation.

Surface treatment processes, which include tool rolling and shot blasting, enable rod strengthening at the expense of surface cold working and creating compressive axial residual stresses. However, as experimental and design results demonstrate [6], surface strengthened layer of acquired gradient material is usually of small thickness (Fig. 1b) that does not enable meeting the requirement (4).

From our viewpoint, the moist suitable technology to create required functional gradient material is tension process followed by plastic rod torsion [7]. Recovery process in this case consists of 2 stages: longitudinal plastic strain of the pump rod by stressing till definite value and plastic stressing rod buckling in some torsion angle. The recovery process parameters are usually selected experimentally taking into account the material and rod scale as well as type of heat-treat when manufacturing it. Selecting the reduction process mode must be carried out with account of the potential heterogeneous distribution of mechanical properties along the rod, occurred by the process of manufacturing and service conditions.

As is shown by experimental and theoretic studies [7, 8], this process enables formation of the favorable field of residual axial stresses over the worn rod cross section (Fig. 1c), whereat required strength conditions (1)–(4) are met. It worth noting that in this case compressive stresses resultant module \( b \) can be considered as equal to \( 2b/3 \) with enough accuracy; then, the second equation in the formula (3) will be \( b(z) \geq \frac{3}{2} \left[ \sigma_{\max} - \frac{\sigma_f}{\sigma_u} \right] \). Besides this, this process enables achieving the value \( h(z) \) much bigger than \( h^* \), that approximates \( b \) to the values \( b(z) \).

It is to be noted that the process of recovery by tension followed by the plastic rod torsion can be realized at enough small expenses in the oil-producing area that makes this method justified not only from the strength viewpoint, but also from the economic one.

4. Conclusion
Performed studies demonstrate that the main reason of pump rods breakage is their corrosive fatigue. Accordingly, the task to recover strength properties of pump rods arises. This can be achieved, if the pull rod is considered as a functional gradient material with specified strength properties.

It is shown that for the successful recovery process realization, compressive residual axial stresses of the required value shall be created on the rod surface, and these will provide required rod strength parameters at further operation.

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