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Sucker Rod Materials – Metallurgical Quality Evaluation and Its Influence on General Corrosion Resistance

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ABSTRACT

Sucker rod pumps are widely used in artificial lift technology of Oil & Gas production. Corrosion, fatigue and corrosion-fatigue are common failure modes that limit life of the sucker rods that drive these pumps. Of these, corrosion fatigue is probably the most common. The initiation site for corrosion fatigue is typically a corrosion pit. The factors that contribute to the formation of corrosion pits were investigated. Four different sucker rod materials were evaluated with respect to (1) chemistry, (2) non-metallic inclusion content and (3) microstructural investigation including banding severity. It was concluded that microstructural banding has a negative influence on the general corrosion rates. The higher values of quantitatively measured banding lead to increased general corrosion rates. The electrochemical potential differences between the light and dark bands is proposed as the cause of locally accelerated corrosion resulting in pits. The dark bands in the less corrosion resistant samples were lower bainite and these were presented as being more anodic.

Key words: corrosion, low alloy steels, sucker rods, inclusions, microstructure, banding, stereology, light optical microscopy

INTRODUCTION

Sucker rods pumps are downhole artificial lift equipment that are widely used in the Oil and Gas industry as the part of onshore wells production. This artificial lift technology maintains or increases well production. With sucker rods pumps, the risk is related to aggressive production environmental conditions that may contain carbon dioxide (CO₂) and hydrogen sulfide (H₂S) with other factors such as temperature, chlorides, and water cuts that cause materials corrosion and degradation. The cyclic up-and-down rod stroke movement lead to tension-tension and tension-compression stress conditions that provoke fatigue. The corrosion and fatigue synergy make corrosion-fatigue mode a predominant failure mechanism of sucker rods.¹

There are several known manufacturing approaches that have the potential to increase rods operational life by their influence on fatigue or corrosion resistance properties individually and synergistically. These approaches include (1) material selection, (2) surface treatments, (3) coatings, and (4) design.

Focusing on the material selection approach, we can consider variables such as (1) strength level, (2) chemical composition, (3) heat treat and microstructure condition, (4) cleanliness etc. These mentioned material characterization aspects could be summarized into a measure of the metallurgical quality. The strength, heat treat route and microstructure are interrelated. The heat treatments used for sucker rods are primarily quench and temper (Q&T) and normalize and temper (N&T). It was presented that Q&T materials have better sulfide stress cracking resistance, whereas N&T rods potential for better performance in CO₂ environment.²⁻⁴ Taking into account mechanical properties toughness & elongation Q&T steels are generally better than N&T steels. However, recent studies on bainitic type microstructures pointed to potential of N&T steels to have increased performance.⁵⁻⁷ Also, N&T process could be considered as air mild quench for certain products cross-sections. Looking at rods material cleanliness, this is a function of the raw material inclusion content, usually oxides and sulfides, with shape and distribution controlled by melting practice and hot rolling process. It should be mentioned that inclusions have a negative influence on fatigue and corrosion-fatigue properties of rods playing a role of initiation sites for corrosion and weak surface/subsurface spots that reduces the incubation time for crack initiation.

With corrosion-fatigue as the predominant rod failure mechanism, the presence of general or localized corrosion has a huge effect on the incidence of the failure mechanism. It could be noted that variations in sucker rod material properties, can also be observed in field operational reliability. These differences should be related to actual metallurgical quality of rods material and its connection to corrosion resistance.⁸ The metallurgical quality can be estimated by investigating the primary sources of quality reduction such as inclusions, microstructural banding and internal and surface defects. It is worth noting that banding is found in both Q&T and N&T conditions. Dendritic liquation during solidification followed by solid-state segregations during hot forming & heat treatment makes microstructural inhomogeneity a relatively complex topic with multifactor production parameters influence on final structure condition.

One of the drivers for this investigation was the ability to use quantitative stereology to define and characterize steel microstructural banding.⁹⁻¹¹ Stereological evaluation of sucker rods banding rate and comparison with corrosion resistance are highlighted in this paper.

Though highly alloyed corrosion resistant sucker rod materials have been shown to exhibit reliable and improved corrosion-fatigue properties, especially in CO₂ environment, this paper focuses only on low-alloyed steels rod materials.^{12,13}

EXPERIMENTAL PROCEDURE

The experiments and analyses were based on the comparison of general corrosion rate test results and metallurgical quality investigation of actual 3/4" rods in different microstructural conditions.

General corrosion rates were obtained by weight loss tests during 7 days of immersion.¹⁴ The test solution was as follows: stagnant, deaerated, 124 g/L NaCl; 4g/L NaCH₃COOH; pH 4.5; temperature 25°C, saturated by CO₂. Three samples were used for each rod and represented by solid 0.8 cm thick disks. Transverse cross-sections were masked, and only longitudinal outside diameter surfaces were exposed during tests.

Metallurgical quality evaluation was based on rods chemical analysis via optical emission spectroscopy, non-metallic inclusion (NI) evaluation by ASTM⁽¹⁾ E1245 and microstructural investigation including application of ASTM E1268 standard that had been updated recently with additions to practice of quantitative measurement and characterization of microstructural anisotropy.¹⁵ This practice is based on stereological principles and grayscale image analysis approach where measurement & evaluation of second phase fraction (usually dark) on directed secants along and across the hot rolling direction allows to calculate banding rate (BR).¹⁶⁻¹⁸ The higher BR values is corresponded to more severe banded microstructure condition.

All metallography specimens were sectioned in the longitudinal direction and investigated after standard preparation procedures ending by 0.5 microns diamond suspension final polishing. Microstructures were revealed by 4% Nital etching. In order to validate the revealed microstructural conditions hardness test were performed by Vickers method with 1 kg load indentation.

RESULTS

Metallurgical quality evaluation results are presented and discussed sequentially with the obtained general corrosion data from the parallel comparison to further emphasize contribution factors and correlations. Based on three samples weight loss tests for each rod general corrosion rates in mm per year (mm/y) are presented in Table 1.

Table 1: Corrosion rates measurements results

Rod material	Corrosion rate, mm/y
#1	0.14 ± 0.03
#2	0.15 ± 0.05
#3	0.49 ± 0.10
#4	0.54 ± 0.18

According to Table 1 it could be recognizably seen that rod materials #1 and #2 had much lower corrosion rate in comparison with #3 and #4. Obtained values (Table 1) were used as a response function of measured metallurgical quality parameters.

Compositions

Chemical composition analysis results are presented in Table 2.

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Table 2: Chemical compositions and corrosion rates of studied rods

Rod	Composition*, wt. %												Corrosion rate, mm/y
	C	P	S	Si	Mn	Cr	Ni	Mo	Al	Nb	V	Ca	
#1	0.39	0.017	0.026	0.23	0.93	1.00	0.12	0.18	<0.001	0.005	0.043	0.0021	0.14 ± 0.03
#2	0.20	0.014	0.027	0.21	1.00	0.87	1.18	0.26	<0.001	0.007	0.034	0.0023	0.15 ± 0.05
#3	0.37	0.011	0.002	0.23	1.32	0.61	0.04	0.30	0.016	0.037	0.059	0.0018	0.49 ± 0.10
#4	0.32	0.009	0.024	0.18	0.85	0.80	1.74	0.22	<0.001	0.007	0.077	0.0020	0.54 ± 0.18

According to chemical composition data (Table 2) several observations were made and discussed. It is clearly seen that rod material #2 had much lower carbon content 0.20 wt. % in comparison with others 0.32 – 0.39 wt. %. The nickel contents of rods #2 and #4 are much higher than in #1 and #3: 1.18 and 1.74 wt. % vs 0.12 and 0.04 wt. %. The studied rods chromium content varies in range of 0.61 – 1.00 wt. % and molybdenum in range of 0.18 – 0.30 wt. %. General comparison of corrosion and composition data did not provide clear correlations that could be interpreted.

It clearly could be seen that rod material #3 had much lower sulfur content which is probably related to positive influence on calcium modification in presence of aluminum considerable remaining concentration. Additionally, rod #3 had significant increased niobium and manganese contents that tend to segregate into interdendritic liquid and cause chemical and structural inhomogeneity.¹⁹

By comparing general corrosion rates data with chemical analysis results it could be noticed that there is not a clear chemistry variation positive influence (C, Cr, Mo) in studied range of compositions. Also, there is no positive influence of extremely reduced sulfur content from general corrosion state point of view.

Non-metallic inclusions

NI measurements represent cleanness of rods materials from melting and casting point of view. NI morphologies observed examples are presented in Figure 1.