CORROSION FATIGUE RESISTANT SUCKER RODS

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ABSTRACT

Corrosion fatigue (CF) is an important concern for structures that are exposed to cyclic loads in corrosive environments, especially in the case of oil and gas operations like drilling, offshore risers or sucker rods in artificial lift. The combination of complex wells completions and the increase of water cuts, CO_2, H_2S and Bacteria represent a higher risk for CF failures in sucker rods. This combined effect force operators to choose a steel for either corrosive environments or high loads and increase the chemical inhibition programs.

In response to the new downhole challenges, Tenaris created a research and development program (R&D) to analyze the key factors that affect sucker rods performance under CF. As a result, a new corrosion fatigue resistance sucker rod has been developed. The present paper summarizes the development process, the new sucker rod characteristics and its performance.

CORROSION FATIGUE IN SUCKER RODS

Corrosion fatigue is defined as the sequential stages of metal damage that evolves with accumulated load cycling, in an aggressive environment, and resulting from the interaction of irreversible cyclic plastic deformation with localized chemical or electrochemical reactions. Environment-enhanced fatigue is a modern term; however, corrosion fatigue is traditionally used when emphasizing electrochemical environments. The environment-enhanced fatigue resistance is notably lower when compare with performance in air, and here lays the importance of its study and evaluation in sucker rods behavior under well conditions (figure 1). [ii]

Three steps are identified in the process of corrosion fatigue failures: a. crack initiation, b. fatigue crack propagation and c. onset of fracture (figure 2).

a. Crack Initiation:

Different mechanisms have been suggested to explain faster crack initiation when steel is exposed to a corrosive environment. These mechanisms include:

- Corrosion pits leading to stress concentrations
- Preferential electrochemical attack at locations on the surface of fatigued metal where plastic deformation is localized
- Dissolution of metal after mechanical damage of passive films by persistent slip bands (PSB)
- Reduction in the surface energy of the alloy due to the adsorption of environmental species.

Each of the corrosion fatigue crack initiation mechanisms presented above have good basis to explain effects observed in corrosion fatigue; however, in previous studies it has been observed that none of them can fully explain all the cases. Initiation of CF is a very complex phenomenon, like Hertzberg said "no precise definition for crack initiation has been or perhaps can be identified". [iii]

b. Crack Propagation and c. Onset of Fracture

Gangloff [i] presented the following mechanisms:

i. Hydrogen environment embrittlement is an important mechanism for CF crack propagation in ferritic and martensitic steels. Different mechanism such as hydrogen-affected lattice bond decohesion, grain or dislocation cell boundary decohesion, and enhanced localized plasticity are proposed for those materials.

ii. A second mechanism for CF is based on the passive film rupture due to localized deformation and crack advance by transient anodic dissolution of metal at the damaged zone of the passive layer. A decreasing rate takes place while the surface re-passivates pending repetition of this sequence.
iii. Several CF mechanisms were proposed based on interactions between dislocations and environment-based processes at initiation sites or crack tip surfaces. These mechanisms have not been developed and tested quantitatively.

Summarizing, corrosion fatigue crack propagation is influenced by various mechanical, chemical and microstructural parameters that interact locally at the tip of the crack. The damage mechanisms are controversial and lifetime predictions are still empirical. In the case of sucker rods, it is important to highlight that there is almost none or limited bibliography related to CF applicable to field cases, so the objective of this work was not only to develop a new family of steels but a new CF behavior assessment in order to increase the understanding of the industry about sucker rods behavior in corrosive environments.

DEVELOPMENT PREMISES

Based on the failure analysis historical data collected by Tenaris and the current material selection criteria implemented in North America, there is a clear impact of the present operating conditions and the industry standard steel offer in the run life of sucker rods. Between the increased number of shale oil wells and the need to keep secondary and enhanced recovery cost effective, rod-pumping systems has been pushed to the limits: deeper wells, deviated geometries, corrosive environments and higher production rates. The combination of these conditions challenged the material selection and the string designs with the limited resources given by the industry knowledge about corrosion fatigue.

As the pump setting depth increases, higher strength metallurgy steel sucker rods are often used. These rods are not suitable for corrosive environment due to its low toughness (low notch resistance) and high corrosion tendency, leaving the corrosion control to chemical inhibition with mixed results. Consequently, under the combined effect of all those conditions, sucker rod usually fail due to a synergistic interaction of localized corrosion, corrosion fatigue (CF) and, in some cases, H_2S embrittlement.

A Research and Development (R&D) program was implemented in Tenaris, focused on the analysis of those key factors that affect the CF performance of sucker rods exposed to CO_2 and/or H_2S environments.

The R&D program was divided in task groups:

a. Steel design and research assessment
b. Corrosion fatigue resistance evaluation of different materials in CO_2 y H_2S environments, at lab scale.
c. Based on the results obtained in a) and b), optimization of steel design and industrial deployment. After this task, sucker rods and couplings were produced and evaluated in many field trials.

IMPACT OF MICROSTRUCTURE IN SUCKER RODS PERFORMANCE

Corrosion resistant alloys (CRAs) commonly used in tubing and casing applications form a passive layer of different deposits depending on the surrounding environment, these deposits act like a coating and prevent the contact of the fluid with the substrate. In the case of corrosion fatigue resistant steels, the microstructure is formulated to target the behavior of the steel under cycling loading in a corrosive environment, not forming passive layers. The steel design of a CF resistant steel aims the final run life by extending the fatigue resistance of the resultant microstructure.

Previous Tenaris' studies showed that the steel microstructure and the resulted toughness are key factors to improve sucker rods CF performance. The metallurgical steel design criteria followed the guidelines of sour service product developments that ensures an optimal combination of mechanical resistance and toughness, allowing an improved CF performance in CO2 and/or H2S environments.

A carefully controlled chemical composition and conditions during manufacturing process are required in order to increase the mechanical properties and keeping an adequate toughness. Such balance of mechanical properties and toughness is achieved by a quenched and tempered martensite and imperative to avoid the presence of bainite that is deleterious for toughness. In addition, the control of the previous austenitic grain size is also a key tool to get an optimum combination.

In order to achieve the optimal microstructure, the following parameters were designed, evaluated and carefully controlled:

A. Steel Cleanness

Raw materials and steelmaking process conditions have to be tightly controlled to reduce residual elements such us Sulphur (S), Phosphorus (P) and Oxygen (O). The cleanness of the steel is a key factor because inclusions could act as nucleation areas of cracks. Consequently, S and O contents must be limited to minimize the quantity of inclusions and specifically oversize oxides. Additionally, the P concentration has to be controlled because its segregation on the grain boundaries reduces the microstructure resistance to CF and Sulphide Stress Cracking (SSC).

B. Chemical Composition And Heat Treatment Conditions

A balanced combination of C, Mn, Cr, Ni, Mo, Nb, Ti, B, and V is required to ensures a fine-as rolled microstructure through the hot rolling process and control the effect of Niobium nitride and carbonitride precipitates in the CF performance. The target is to obtain an as quenched microstructure with more than 95% of martensite as well as an adequate hardenability in accordance with the used quenching conditions and material geometry.

The main goal is to obtain a final microstructure mostly constituted by tempered martensite + fine ferrite grains + very fine carbides. Not only the chemical composition but also the heat treatment design (austenization, quenching and tempering) are key to get this optimum microstructure.

C. Microstructure and grain size

The important role of microstructure on SSC and CF resistance has been studied and recognized for many years. Quenched and Tempered microstructures with a low dislocation density in addition to a homogenous and fine distribution of spherical carbides have shown the best performance.

Among the lab tests performed, the NACE Standard Double Cantilever Beam Test (DCB) was used to compare the effect of the factors mentioned previously (figure 3). The critical stress intensity factor, KISSC, was determined for samples with different microstructures and yield strengths. Results plotted in Figure 4 show the negative effect of increasing the mechanical properties on H_2S cracking resistance. Additionally, the remarkable effect of the microstructure is also evident where a microstructure constituted by tempered martensite + fine ferrite grains + very fine carbides shows a notable better performance when compared with a tempered martensite but with less quantity of fine carbides.

The effects of grain size on the fatigue life and crack initiation mechanism for sucker rod steels were part of the steel design. The results indicated that the specimens with the new steel had fine (~4μm) own the longest corrosion fatigue lives than those with intermediate size like MMS (4138M) grade (~15μm). The threshold for fatigue cracks were often higher for specimens with intermediate grain size, while it was not easy to be initiated on the fine grain specimens.

The stress intensity factor threshold for the new steel show a 25% compared to the highest toughness steel tested (DS 4330M).

<u>LAB TEST VALIDATION: CORROSION FATIGUE TESTS AND MECHANICAL PROPERTIES</u>

Ad-hoc test machine and time-to-failure tests were performed to determine fatigue “in air” endurance limit and corrosion fatigue limits of different materials. Longitudinal tensile specimens were machined from the center of rods and grinded. For corrosion fatigue, tests were carried out in CO2 and H2S simulated production environments. Maximum and minimum stresses were established in order to reproduce an operation condition that caused premature field failures (less than 500,000 cycles).

In order of stablish reference parameters, other conventional sucker rod materials were included in the testing program (KD 4320M, D 4142M, DS 4330M, UHS 4330M, and MMS 4138M).

1. Fatigue Testing in Air: Determining the Endurance Limit

As part of the analysis and to define a baseline for a proper string design evaluation, a fatigue endurance limit evaluation was completed. A dog bone and full-scale axial fatigue testing was implemented to determine the endurance limit in air and to compare its performance in air to industry standard steels.

The results position the new steel among the High Strength steels available in the market (See chart in Fig. 7).

2. Toughness

In materials science and metallurgy, toughness is the ability of a material to absorb energy and plastically deform without fracturing. One definition of material toughness is the amount of energy per unit volume that a material can absorb before rupturing. It is also defined as a material's resistance to fracture when stressed. Toughness requires a balance of strength and ductility. [iv]

The new developed steel presents twice as higher toughness than the tougher available materials for sucker rods (See chart in Fig. 9).

3. Corrosion Fatigue Test Conditions In CO2 Environments

Tests were performed in a Hastelloy autoclave adapted to perform CF tests (Fig 5). High temperatures and pressures and harsh environments, like those found in oil and gas production and transportation, can be achieved. The time to failure (number of cycles) was determined. Failed specimens were analyzed using scanning electron microscopy (SEM).

<u>Testing conditions</u>:

- Test solution (simulated formation water) 124g/l NaCl and 1.315g/l NaHCO3 (pH~5.5).
- Temperature: 140F.
- Gas composition: CO2+ pure Nitrogen
- CO2 partial pressure: 145 psi
- Total pressure: 450 psi
- Loading cycle: maximum strength 47 Ksi; minimum strength 12 Ksi. This loading cycle represents a Goodman load of 82% of High Strength Sucker Rods and 149% for D Grade Sucker Rods SF:1)
- Frequency: 20 cycles/min. This frequency is higher than the field frequency to reduce test duration but restricted taken into account that corrosion fatigue is a time-dependent process.

Results: twice higher in corrosion fatigue in CO_2 compared to all the standard grades (See chart in Fig. 10).

4. Corrosion Fatigue Test Conditions In H_2S Environments

Considering the detrimental effect of H2S on CF resistance, tests were carried out to assess the performance of the new material when exposed to sour environment. In order to compare the results with those observed in CO2 tests, load conditions and frequency of cycling for H2S were as described for CO2 tests.

<u>Testing conditions</u>:

- Test solution: 50g/l NaCl + 4 g/l sodium acetate (NaCH3COO) in distilled or deionized water, pH is adjusted to the selected value (4.5) by addition of HCl or NaOH.
- Temperature: 77 F

- Gas composition: pure H2S
- Total pressure: 14 psi
- Loading cycle: maximum strength 47 Ksi; minimum strength 12 Ksi
- Frequency: 20 cycles /min

Results: four times higher corrosion fatigue resistance in H_2S compared to all the standard grades (See chart in Fig. 11).

5. Sulfide Stress Cracking Test

The chemical composition plus the quenching conditions have to ensure an adequate hardenability to avoid non desirable microstructures after quenching. The target is more than 95 % of as quenched martensite. Increasing tempering temperature as much as possible by adjusting the chemical composition (Cr-Mo and microalloying V-Nb) is recommended to get the optimum final microstructure.

Results: SSC curves (Method A from NACE TM0177) are shown in Fig. 6. The new developed steel had a substantial SSC resistance increase compared to all the standard grades.

MODIFIED GOODMAN DIAGRAM: STRING DESIGN

The definition of the proper admissible tension diagram equation was necessary. The equation and the chart of figure 8 denote the proper placement and application range for this new steel, taking as reference not only the current standard grades but also real data from axial loading testing over dog bone samples for validation.

FIELD VALIDATION

For the last two years, field tests had been carried out in wells where a previous high rate failure due to environmental attack has been reported. Most of the selected wells belong to fields where injection of water has been used for many years and the ratio water/oil (water-cut) is 95% or higher. Another mutual characteristic these trials share was the high sucker rod failure ratio (2 to 4 failure/year).

The target to trial success was set as increasing the previous run time by two. Currently almost all the trials were completed with a high rate of success. These results confirmed the developing premises and the lab results to conclude with the R&D process.

CONCLUSIONS

Based on a carefully controlled chemical composition and conditions during manufacturing process the new developed steel increased the mechanical properties keeping high toughness. Such balance of mechanical properties and toughness is achieved by an especially design heat treatment that maximize tempered martensite content, fine grains and very fine carbides.

The unique set of corrosion fatigue testing performed proved that the new developed steel has a substantial increase of fatigue resistance in air and different corrosive conditions compared to all the standard grades, and achieving a load capacity of high strength grades.

For the first time a comparative assessment of sucker rod corrosion fatigue behavior was successfully addressed, complemented by lab and field tests that now gives the industry a better understanding of the sucker rod performance under corrosive environments.

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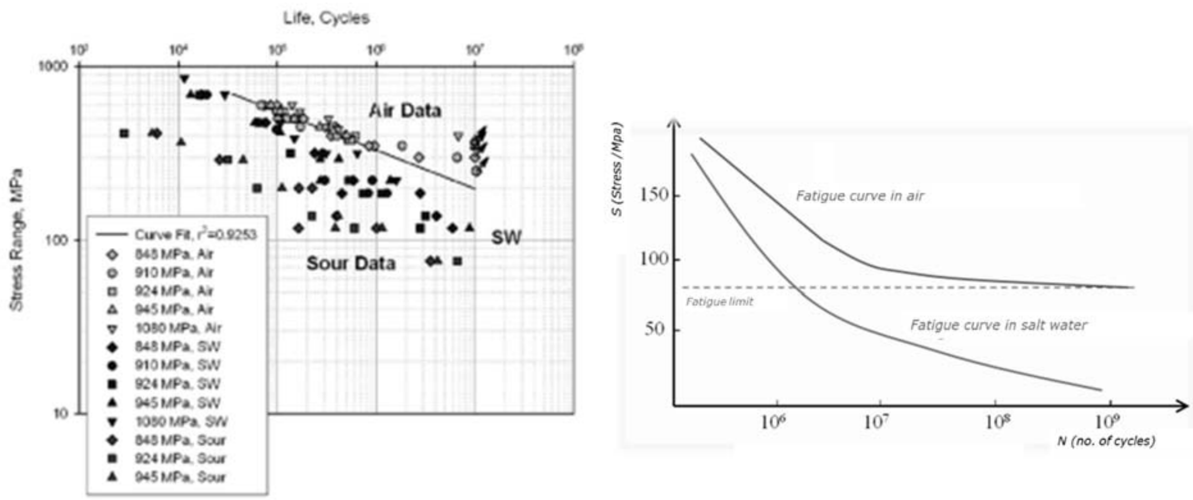
iii. R. Eadie, K. Szklarz Fatigue Initiation and Crack Closure of Low Alloy Steels in Sour Environments NACE Corrosion 99 Paper 610

iv. “Toughness", NDT Education Resource Center, Brian Larson, Editor, 2001-2011, The Collaboration for NDT Education, Iowa State University



a) **b)**

Figure 1 - a) Comparison of stress vs. cycles to failure performance in air, seawater with cathodic protection and sour brine environments; b) S-N curves schematic: fatigue behavior in air vs. corrosive environment.

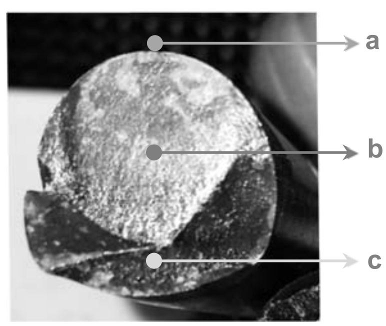


Figure 2- Stages of a Fatigue Failure: a. crack initiation, b. fatigue crack propagation and c. onset of fracture

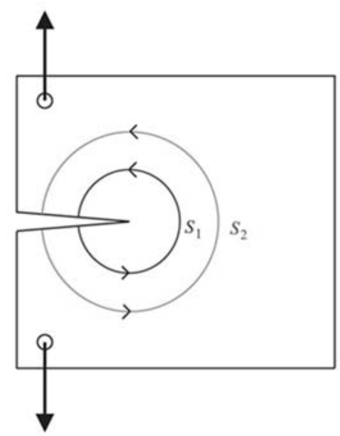
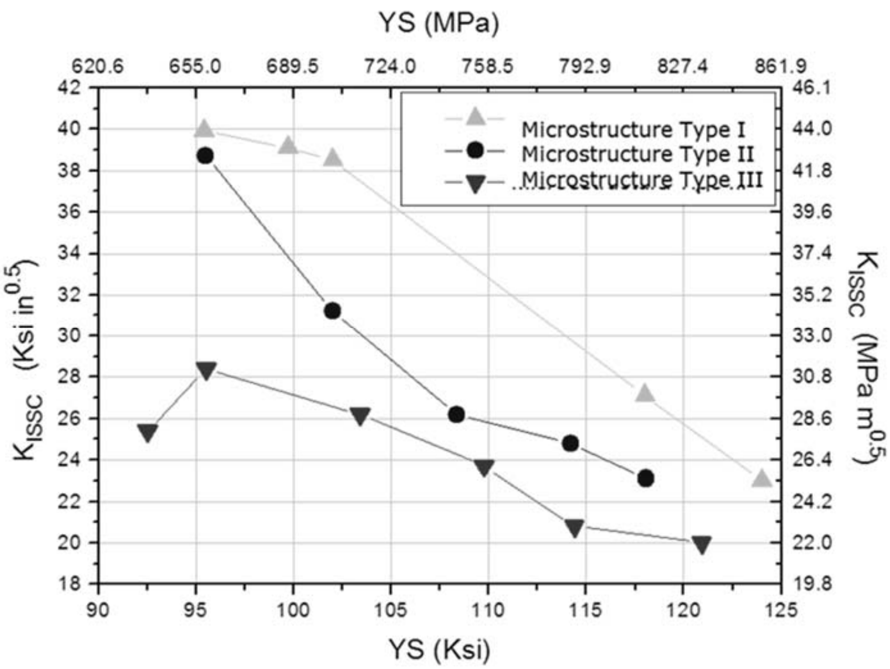


Figure 3 - Double Cantilever Beam Test A NACE TM0177-2016



Type I: Tempered martensite+ fine ferrite grains + very fine carbides
Type II: Tempered martensite with less quantity of fine carbides
Type III: Tempered martensite + upper bainite

Figure 4 - Effect of mechanical properties and microstructure on cracking resistance of LAS (expressed in terms of a critical stress intensity factor) Test solution A NACE TM0177-2016

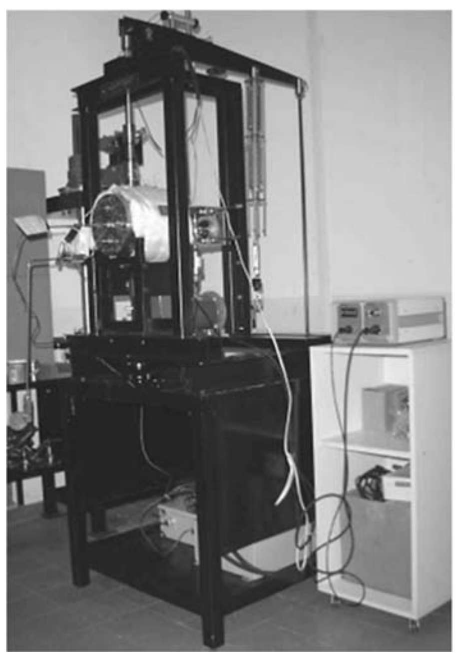


Figure 5 - Developed corrosion fatigue testing machine

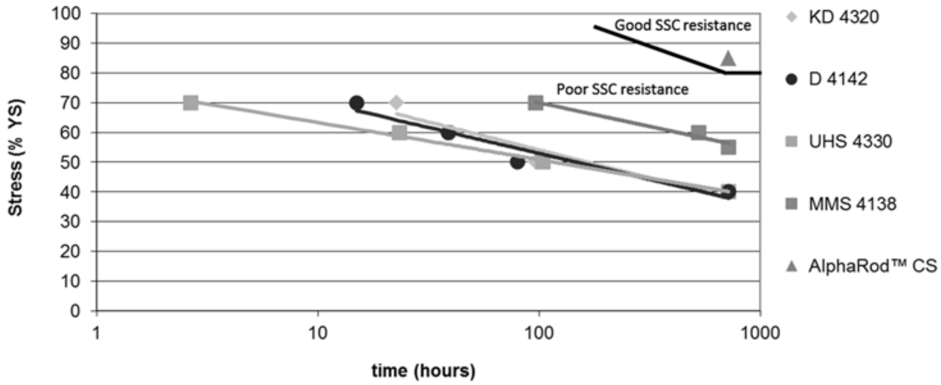


Figure 6 - SSC curves (Method A from NACE TM0177)

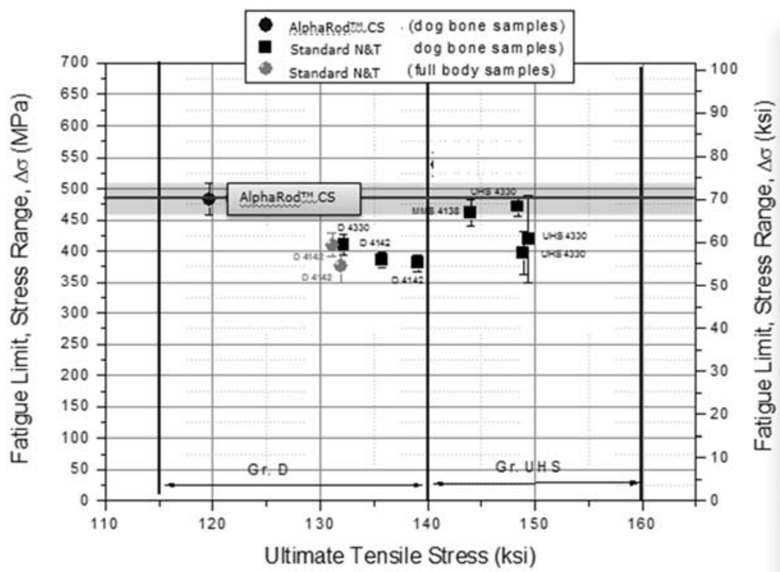


Figure 7- Fatigue Endurance in Air (Axial Full scale and dog bone)

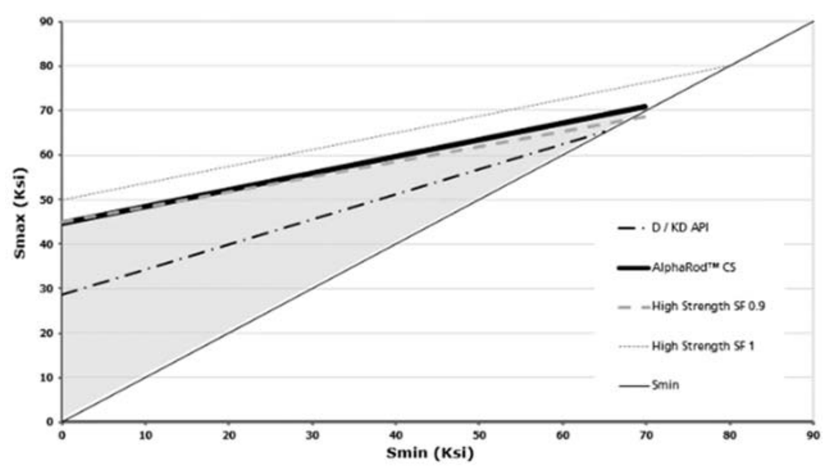


Figure 8 - Modified Goodman Diagram

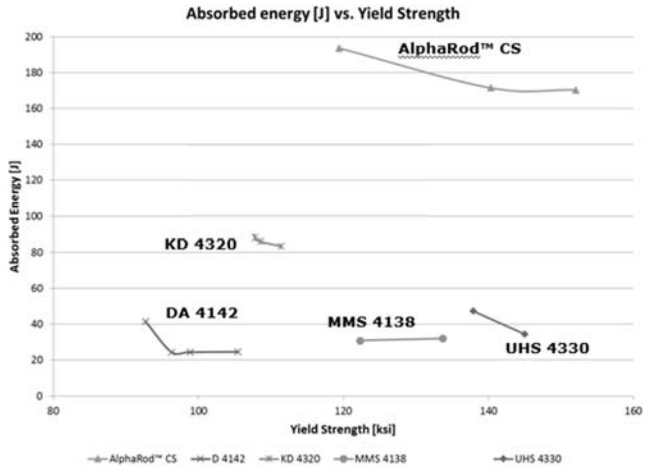


Figure 9- Impact Toughness comparison among industry standard grades and the new development

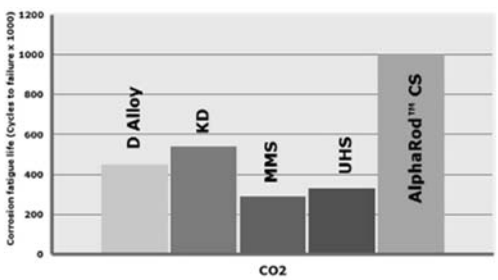


Figure 10- Corrosion Fatigue lab test results: CO_2

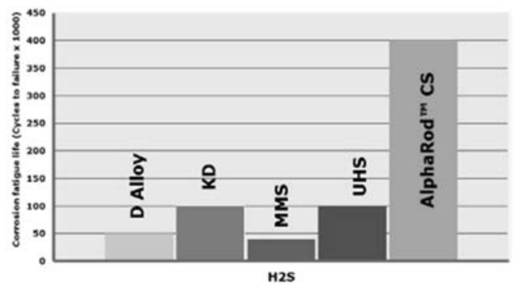


Figure 11- Corrosion Fatigue lab test results: H_2S

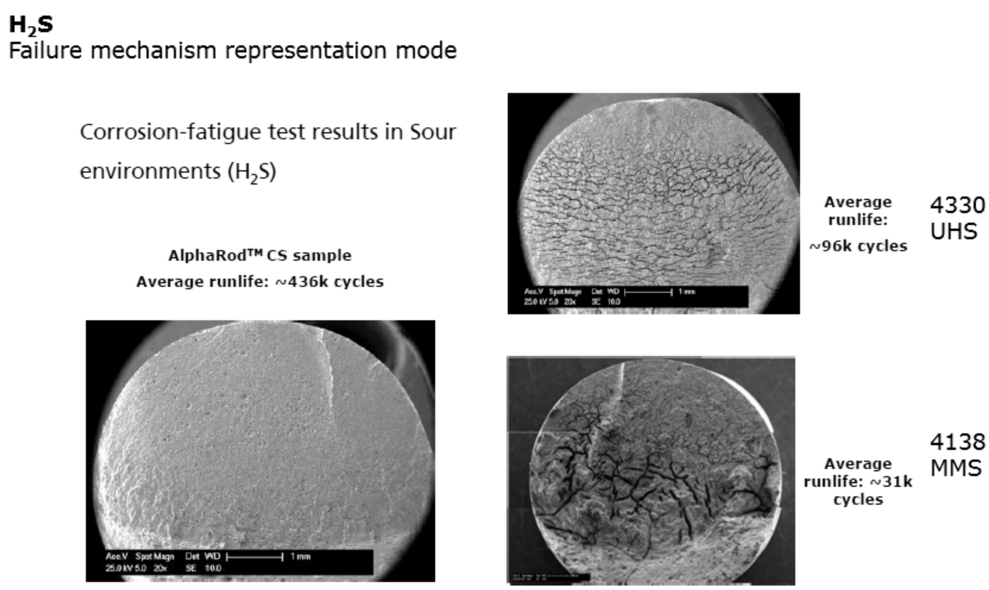


Figure 11- H2S Failure Mechanism for AlphaRod™ CS, UHS and MMS