A NOVEL TECHNIQUE TO MAXIMIZE CORROSION FATIGUE RESISTANCE OF SUCKER RODS

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PROBLEM STATEMENT

The proprietary quench and tempered rod product line developed to overcome more demanding requirements and offer a solution to corrosion-fatigue failures has been deployed to the world since 2015 after a multiyear technology development (Buhler M. et al). Around one million of the rods have been installed in wells from Argentina to Canada and all the way to Europe and Middle East. Outstanding performance especially in Corrosion Fatigue (CF) scenarios has already been described in the paper “Performance of a Special Sucker Rod…” (Oliva et. al) following 5 years of installs and results.

The strategy following the development of the Critical Service (CS) grade was to engineer an ultra-high strength rod grade (HS) targeting those applications that challenged all the system components and even pushed the limits of the application range of reciprocating rod lift into deeper well depths and higher production ranges (Figure 1). These applications include early life unconventional wells, shallow high-volume wells, and highly deviated wells with so much deviation induced friction that they were thought to be unpumpable by reciprocating rod lift.

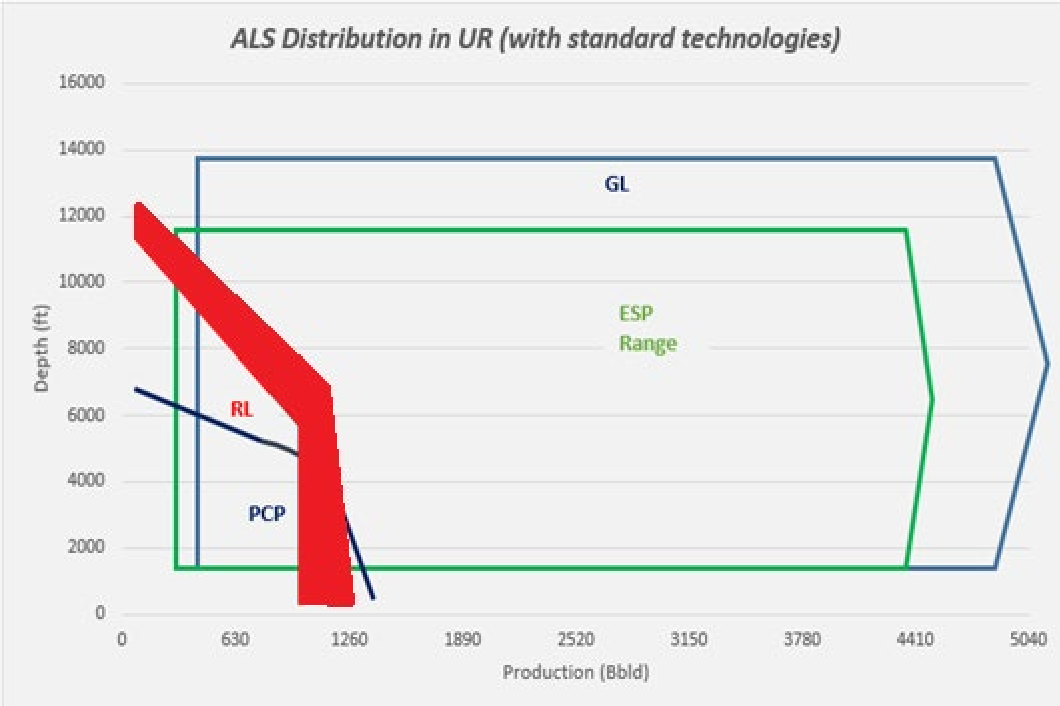

Figure 1 Artificial lift application range – The shaded red area depicts the potential production increase to RL with the incorporation of new technologies

The HS grade was to have higher mechanical properties and Modified Goodman characteristics than all other existing grades in the industry. This grade began being deployed to wells mid-2016 and arrived in North America by early 2019.

In development of the HS grade, knowledge of Oil Country Tubular Goods for sour service, offshore and high fatigue resistance applications was leveraged, as well as the capability to develop and manufacture proprietary steel grades. The main characteristics of the steel grade were ultra clean steel making practice, low carbon/low alloy steel, low inclusion level, and finer grain size. These basic features are key for the ability to heat treat (Q&T) and obtain a high level of martensitic microstructure obtain a superior CF targeted rod grade. The resulting properties made it stand above all other existing options in the industry: higher Ultimate Tensile Strength (UTS), superior toughness, and superior fatigue resistance. In a large majority of over 250 installs, the HS grade performance exceeded expectations, but in a few cases, short run times (<1 year) were occurring (Figure 2).

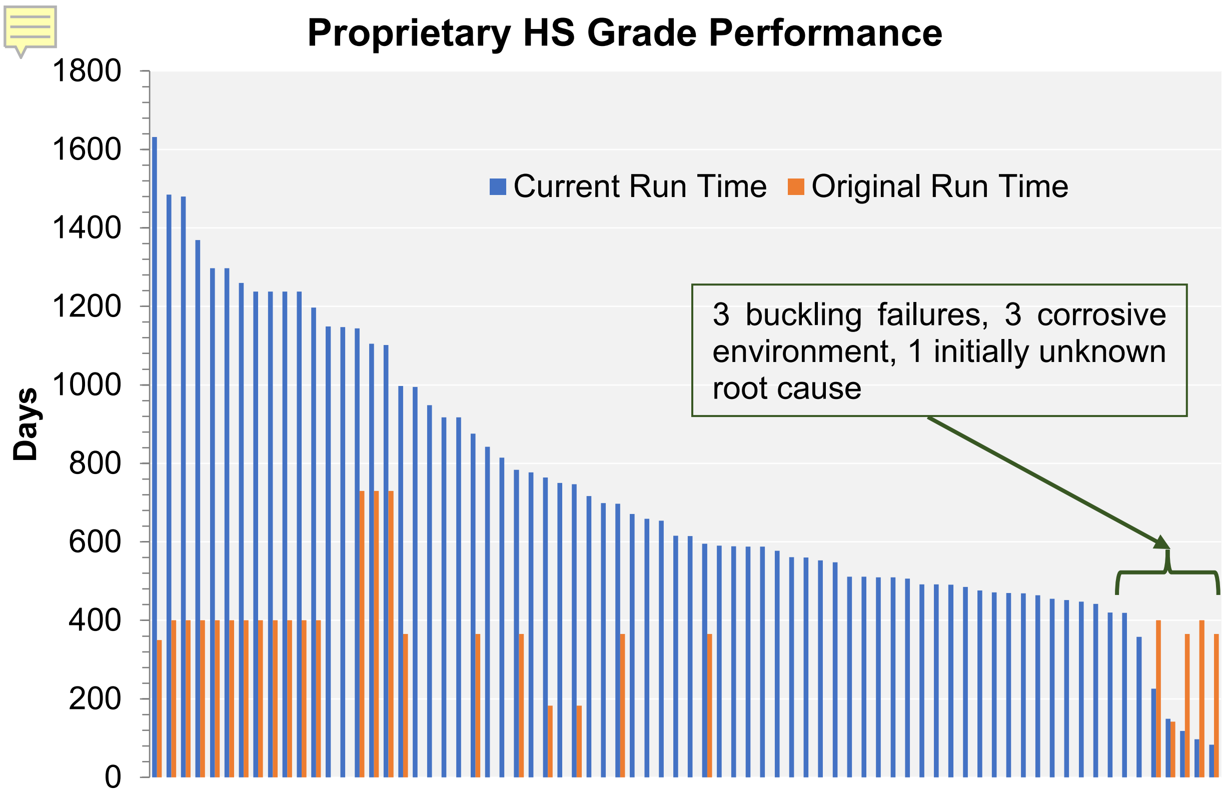

Figure 2 HS Grade install run times

The failure events analyzed were primarily from wells in the Bakken and mostly showed mechanisms related to corrosive environments being beyond the optimal application of the HS grade and buckling. There was one short run time failure in specific that did not show any clear “smoking guns” (Although the failure mechanism was Corrosion Fatigue). This was a Chord Energy well that accumulated consecutive short run time failures and on the same well pad, there was another well operating with the HS grade without problems. The geographical area of this well had several problem wells with various rod grades and manufacturers. These were extremely harsh operating conditions in this area and rigorous Root Cause Analysis (RCA) was necessary to not only find the root cause but pose some corrective actions.

One of the key findings during the Root Cause Analysis was the lack of correlation between the string loading coming from both industry standard rod design softwares and what the analyzed samples revealed as the stresses experienced during operation. Finite Element Analysis (FEA) was used during the investigation to understand the loads experienced by a rod on a much smaller scale than traditional modeling software can predict. It was found that the combination of the axial and lateral loads inflicted to the sucker rod in the well could create stresses exceeding the predicted loads by more than 30%. Essentially, the deviation of the well generated effective stress concentrations near upset because the stiff connection concentrated the bending stress on the more flexible upset transition area (Figure 3). This would explain the root cause of the events but was not showing an obvious way to a solution.

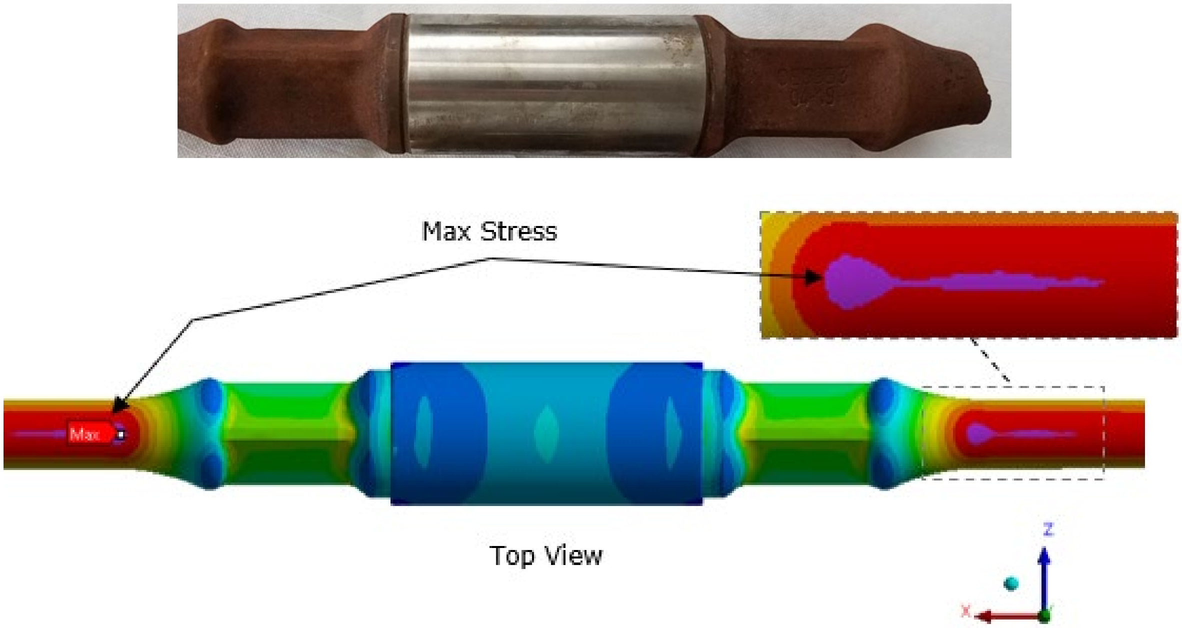

Figure 3 Failed sample and FEA output

The prevention of reoccurrence for these events came through the integrated approach that follows:

1. Design practices to identify well and operating conditions that could create high effective stress concentrations with elevated risk of accelerated fatigue failure

2. Implementation of rod sizing and guiding to distribute the loads on the rod and reduce the localized effective stresses in the more susceptible regions of the string

3. Initiate Research and Development to provide the HS rod grade with higher fatigue resistance for the extreme high load applications in the US Unconventional wells

The remainder of this report will focus on the third bullet of the list above.

CONTINUOUS IMPROVEMENT PROCESS

This HS rod grade as it was originally engineered and developed had already shown outstanding lab and field performance through the above-mentioned characteristics. For example, Figure 4 below shows the toughness compared to other High Strength grades commonly available. Continuous improvement of the CF resistance was still the goal.

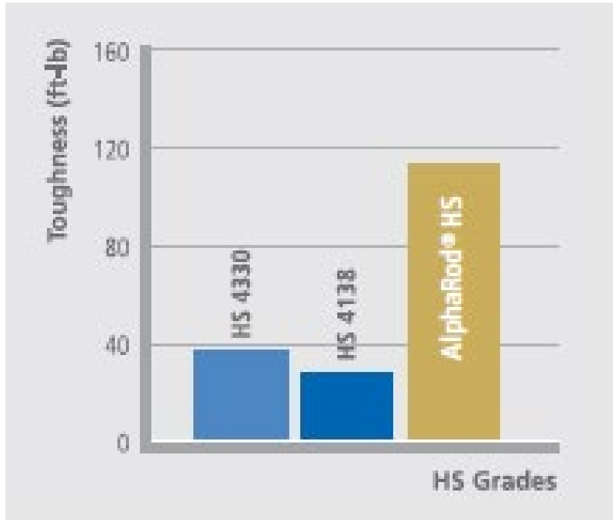

Figure 4 Toughness comparison of HS grades

Corrosion fatigue resistance has been extensively explained and developed, but there are still improvements to be explored. The challenge for Artificial Lift applications is created by the considerable number of variables that affect a mechanical load-bearing component such as the sucker rod. Detailed explanation of the fatigue mechanism initiation on a sucker rod is in Martin Buhler's SPE paper 184899. Essentially, many variables of the rod grade had already been optimized for corrosion fatigue resistance, but continuous improvements must always be a goal, and after deliberation, Surface Texture and Finishing (ST&F) was selected as the variable to optimize.

Surface Texture & Finish is important for fatigue resistance enhancement as it can delay and prevent the initiation of micro cracks via two ways:

1. Controlling morphological irregularities
2. Introducing compressive residual stress on the surface of the steel

The product line already had a proven surface finish (shot peening), but the goal was to develop a new process that would enhance CF resistance significantly, instead of small increments. Advanced lab testing in an in-house R&D center in Argentina (REDE-AR) as well as deep knowledge and expertise of steels in R&D centers across the globe were already a powerful resource to learn if this goal would be achievable. Additionally, extensive research and lab testing on ST&F technology was performed to benchmark techniques:

Scanning Electron Microscopy
With this technique, the surface is bombarded with electrons and their interaction is used to generate images. Due to its high resolution down to the sub-nm range, the SEM is the standard tool for investigating precipitates, inclusions, layer systems, grain sizes or topographic features (pores, sub-μm structures...). In the area of damage analysis, fracture surfaces, crack propagation or defects can be analyzed and evaluated (Figures 5 & 6).

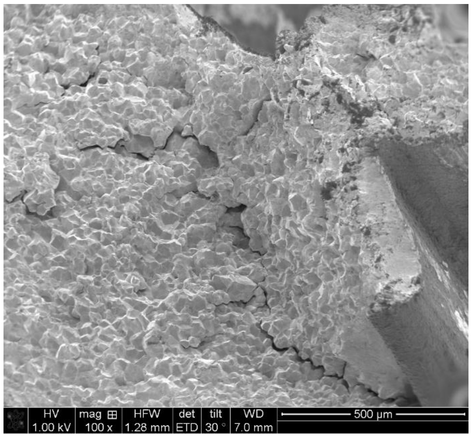

Figure 5 Imagery obtained via SEM

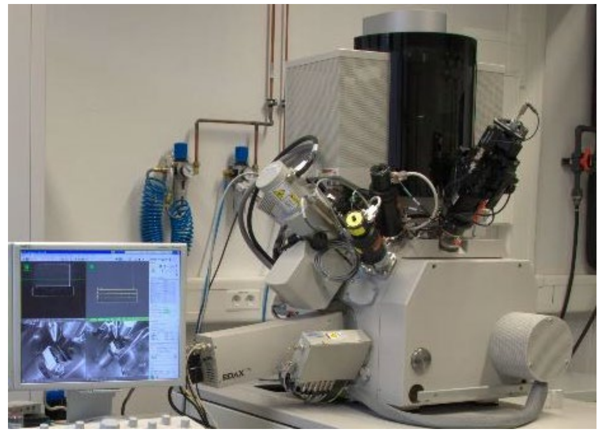

Figure 6 SEM Equipment

X-Ray Diffraction (XRD) Stress Analysis

This analysis provides information on the crystalline structure (structure, lattice constant, mesh plane spacing). It also provides integral information on phase composition, residual stress and texture state, grain size of nanocrystalline materials and deformation state as well as thickness and quality of thin films.

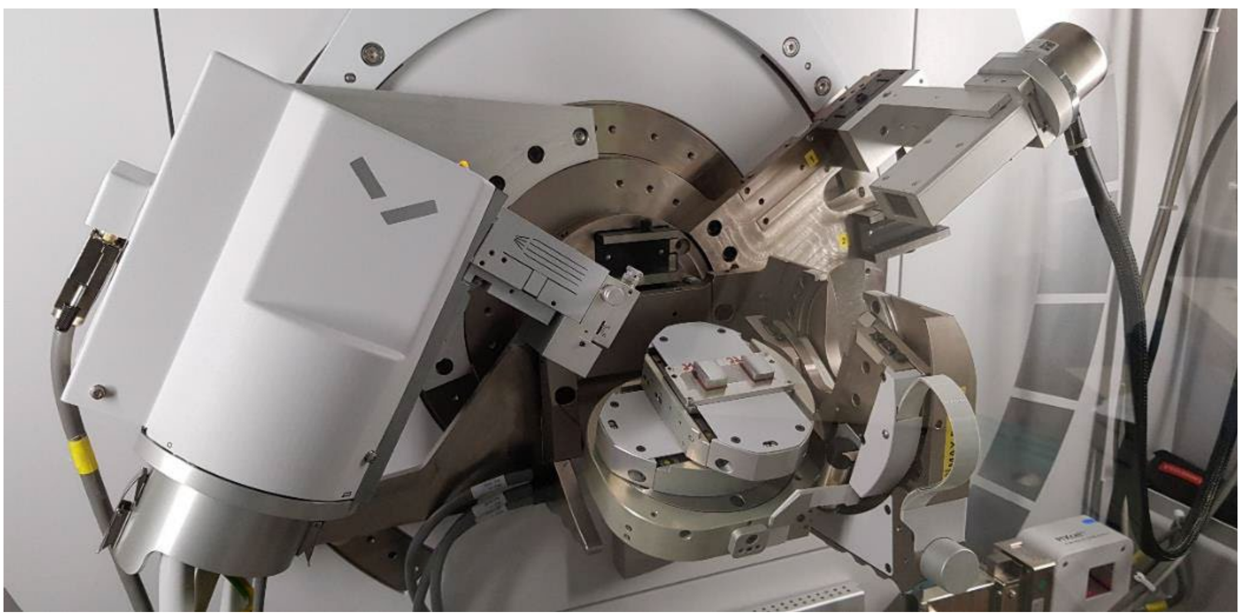

Figure 7 X-Ray Diffraction Equipment

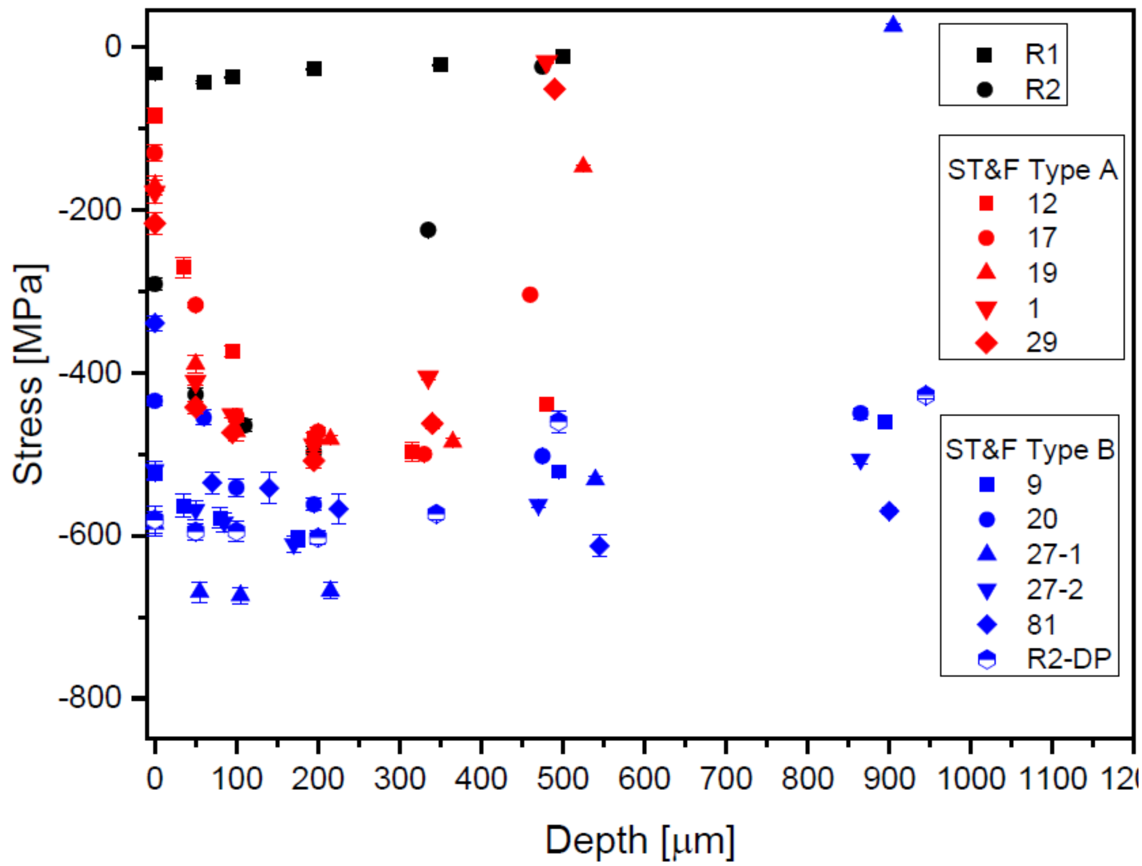

Figure 8 XRD results - each color/symbol correspond to a different ST&F process

Micro Hardness

Important complementary information to assess heat treatments, textures and finishings or hardening depths.

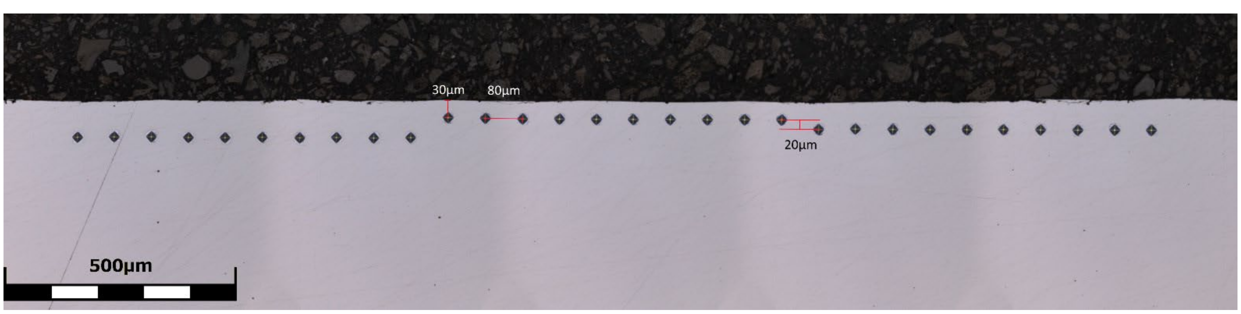

Figure 9 Micro Hardness inspection

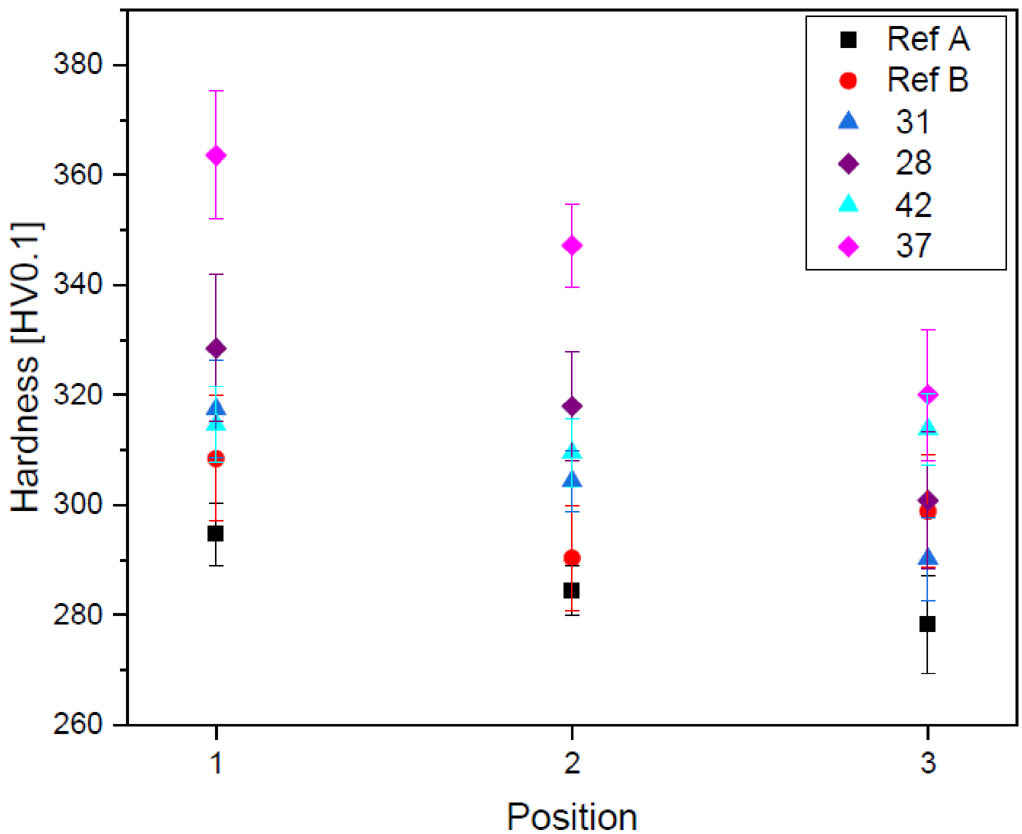

Figure 10 Micro Hardness – each color/symbol correspond to a different ST&F process

3D Laser Scanning Microscopy
Thanks to laser scanning microscopy, 3D surface parameters such as roughness or texture can be determined with a Z-direction resolution of up to 10 nm

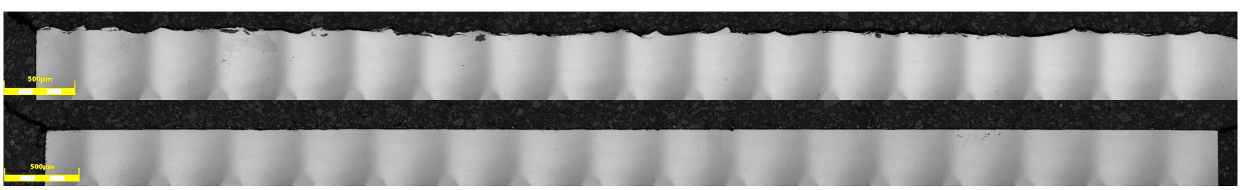
Figure 11 Comparison of two ST&F processes via 3D Laser Scanning Microscopy

Backscatter Electron Imaging
A backscattered electron image is an image formed by backscattered (reflected) electrons which are emitted by elastic scattering of the incident (primary) electrons. A backscattered electron image reveals the compositional difference in a specimen (difference in the average atomic number). Back scatter electron imaging clearly contrasts different grains.

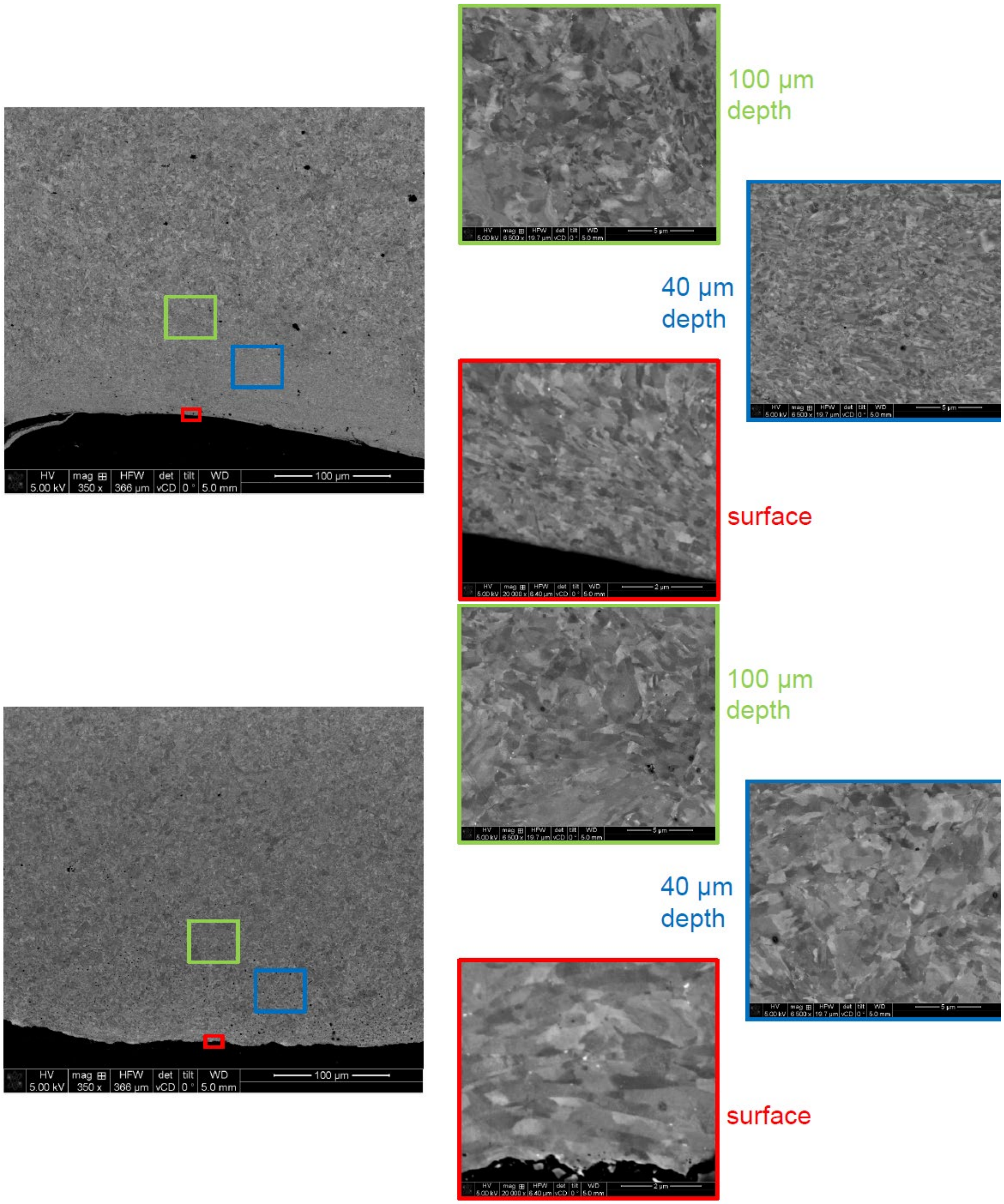

Figure 12 Comparison of two ST&F processes via Backscatter Electron Imaging

Electron Backscatter Diffraction
Crystallographic investigations can be performed using EBSD system

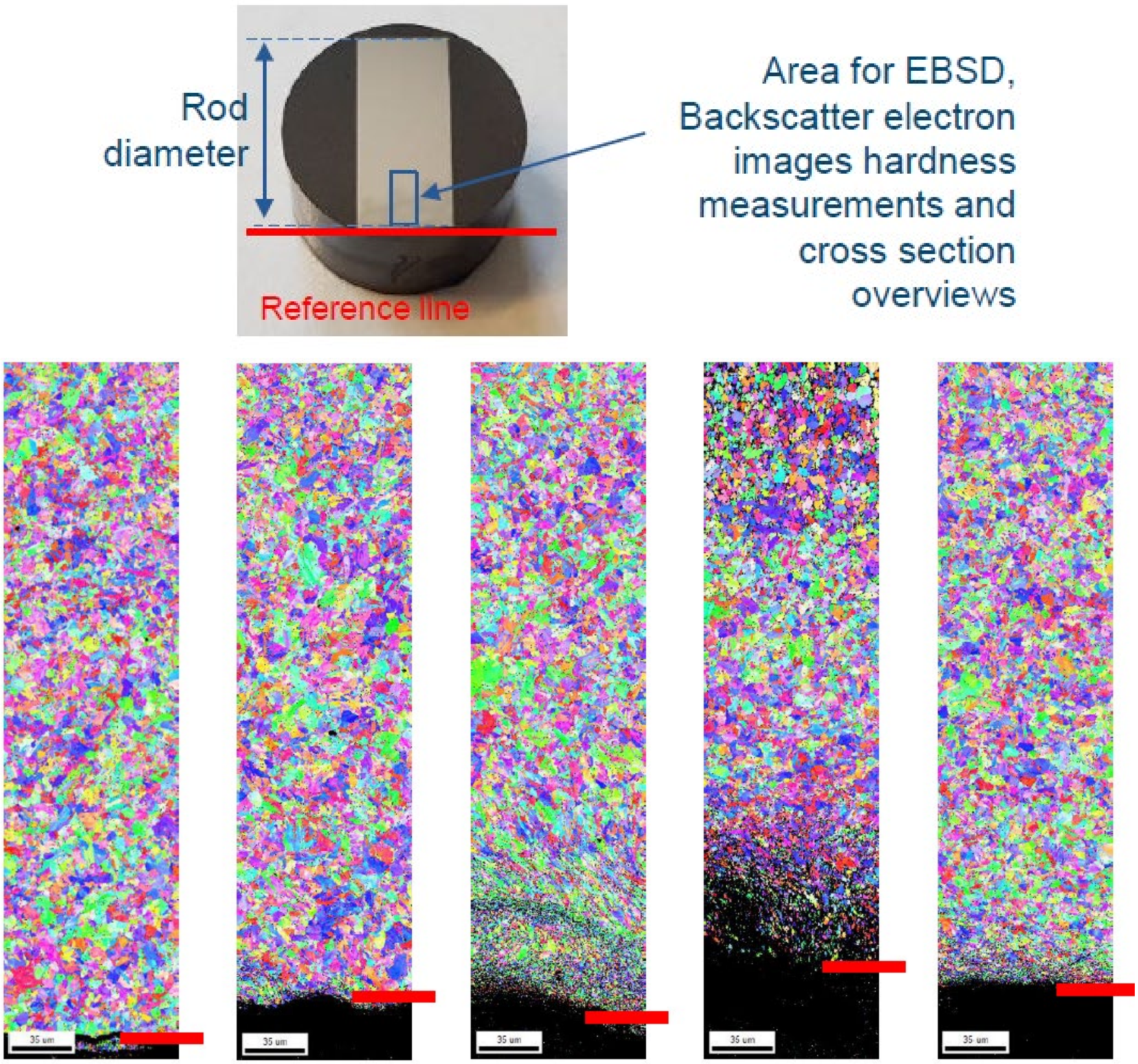

Figure 13 Comparison of several ST&F processes via EBSD

Once a set of ST&F were selected using the above testing, 40+ HS grade pony rod samples were processed with various ST&F and tested using in-house tensile-tensile axial corrosion fatigue testing machines (Figure 14).

Figure 14 Corrosion fatigue testing machine and test chambers

As shown in the above figure, there is a test chamber that can contain a corrosive fluid, in this case 5% NaCl in distilled water at room temperature. The test loads used were 153% of the Modified Goodman of the HS grade and at 1Hz frequency to get test results in a timely manner. The results of that testing are shown below in Figure 15.

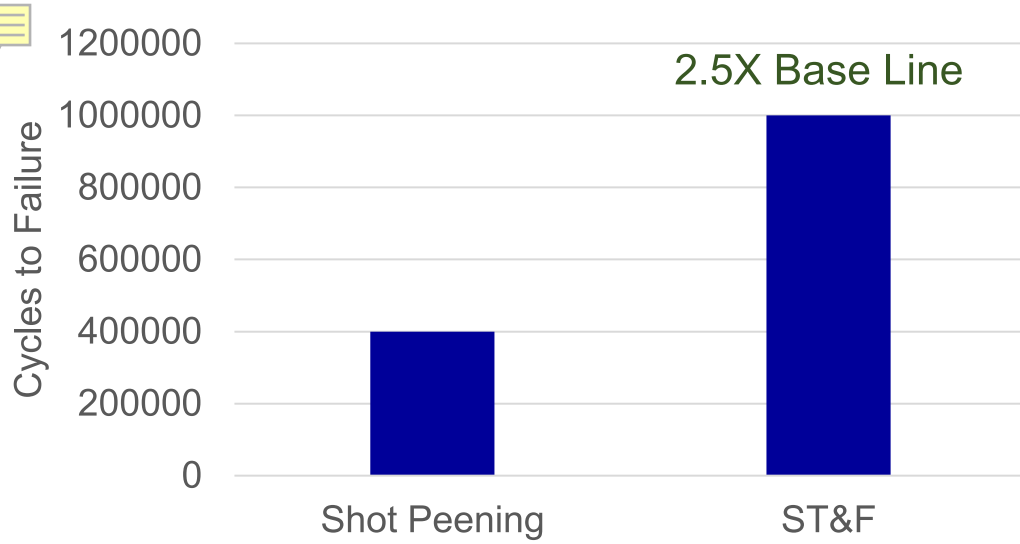

Figure 15 Corrosion fatigue testing results

At a 2.5x increase in cycles to failure, the corrosion fatigue testing results were very promising, and helped identify which ST&F to choose for further validation.

FIELD TRIALS

The next steps in confirming the performance of the optimized ST&F product were field trials, and for this, over 4000 rods were prepared. Trial wells were carefully selected that fit the criteria of a corrosion fatigue mechanism failure with less than 1 year run time in any quenched and tempered rod grade. Additionally, it was preferred to make minimum changes to the design and operation of the well as possible and replace with full strings or full tapers. The rods were installed in 6 ideal trial wells and the run time comparison in those wells is shown below in Figure 16. After the first 6 trial wells, the remaining rods were installed in a variety of 10 other more "typical" wells, including high run time wells, to have a higher sample size. 5 out of 6 of the trial wells had little to no changes from the previously installed rod designs (Table 1).

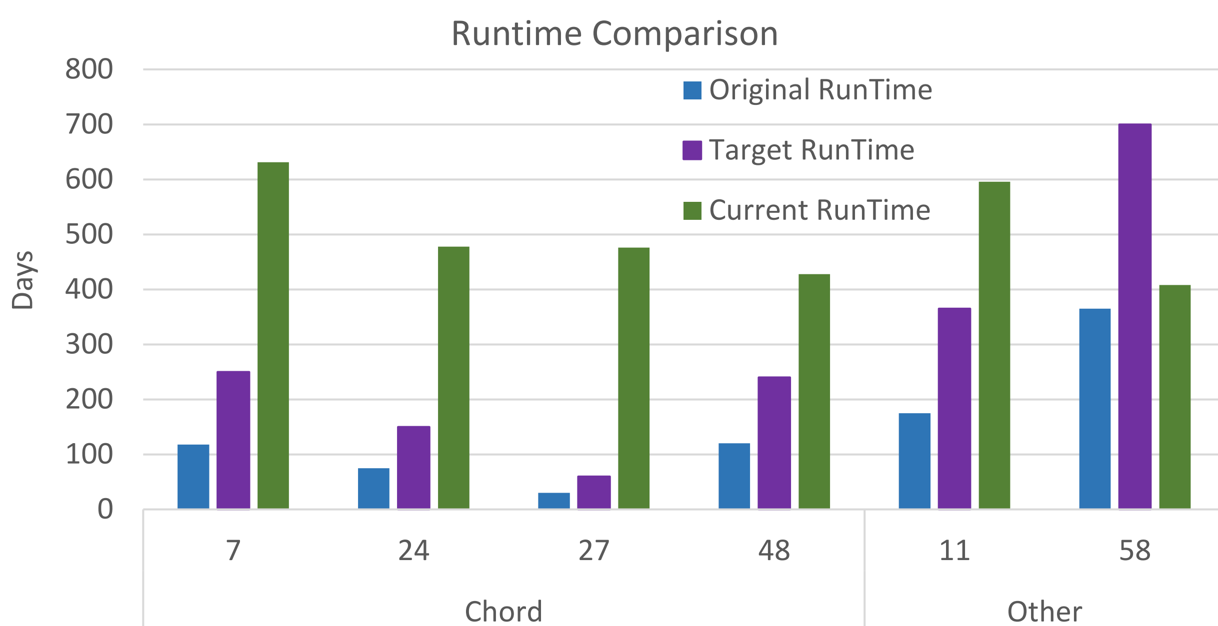

Figure 16 Run time comparison of previously installed rod grade and ST&F

Table 1 Failure type and design changes

Well ID	Failure Type	Changes
7	CF HS Failure	Reduced pump size (2" to 1.75"), reduced stroke length, added guided rods, 10-15% less loading
24	CF Competitor HS Failure	Slight taper and guiding adjustments, replaced sinker bar with 1x3/4 Sinker Rod
27	CF Competitor HS Failure	No Changes
48	CF Competitor HS Failure	Slight increase to sinker taper, and other slight taper/guiding adjustments
11	CF HS Failure	No Changes
58	CF HS Failure	No Changes

The current run time shows the average run time before rod failure of the previously installed rod grade(s) and the target run time was double original run time. All installs are currently exceeding original run time and only one has not yet reached target run time. There are no failures in any of 16 wells as of March 2023 and current run times of the original 6 trial wells have increased at a rate of almost 3 1/2 times, from an average run time of ~147 days to an average of 500 days and counting. Average run times of all installs is also approximately 500 days.

CONCLUSIONS

- Root Cause Analysis is a powerful tool to improve artificial lift performance
- Unconventional wells benefit from a highly corrosion fatigue resistant ultra-high load rod grade to push the application envelope of reciprocating rod lift
- Optimized Surface Texture & Finishing is an excellent choice to enhance corrosion fatigue resistance of a steel by delaying the initiation of a fatigue crack
- Field trials of the improved ST&F product show great results and align with lab corrosion fatigue testing at over 3x increase in average run time as of March 2023
- The results were so clear that the new proprietary process will be applied to both proprietary quenched and tempered rod grades starting in Q3 2023 after a considerable investment in a sucker rod manufacturing facility

REFERENCES

Buhler M. et al, (2017) Development of a Fatigue Corrosion Resistant Steel for Sucker Rods, SPE-184899-MS, Society of Petroleum Engineers
Oliva et al, Performance of Special Sucker Rod (AlphaRod® CS) After 5 Years of Field Experiences Worldwide https://www.tenaris.com/en/products-and-services/artificial-lift/alpharod-series/

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