EVALUATING THE USE OF MARTENSITIC STEELS FOR SUCKER RODS

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INTRODUCTION

Martensitic steels are extensively used in every major industry, especially in the oil and gas industry. In the sucker rod industry, however, their use is more limited due to concerns about embrittlement and corrosion issues. These concerns are equally applicable to martensitic steels and to the more widely-used ferritic-pearlitic steels. When martensitic steels are properly produced, they provide a great balance of strength, toughness, and corrosion resistance. This paper examines the Q&T process, the properties of martensitic steels, possible failure mechanisms of sucker rods, and practical guidelines for purchasing and quality control of martensitic steels.

OVERVIEW OF Q&T VS N&T

Martensitic steels are produced by the quench and temper (Q&T) process; the steel is rapidly cooled (quenched) to form martensite, and then heated at an intermediate temperature (tempering) to soften the martensite and improve the fracture toughness. When correctly performed, Q&T offers an outstanding combination of high strength and good resistance to fracture. In comparison, normalized and tempered (N&T) steels consist of a mix of ferrite and pearlite, both of which are significantly less strong than martensite.

The goal of every operator is to make money – this means getting the best balance of up-front costs and long-term performance. In many applications, Q&T steels provide this optimum balance – which is why they are so widely used in every major industry. In a previous paper from 2018[1], it was implied that the quenching process would routinely results in warping and distortion

Let’s face it; we can’t stop rig operators from doing things that would make an engineer worry: they will happen - but our goal in engineering and design should be making optimal selections that allow for the longest safe operating conditions. In this paper, we discuss the properties of martensitic steels, possible failure modes, appropriate tests, and guidance for purchasing.

TOUGHNESS AND STRENGTH

Let’s start with some definitions: Toughness refers to a material’s ability to absorb energy when a sudden load is applied to it, or alternatively as the amount of force per unit area required for fracture to occur. High impact toughness indicates a strong capability to resist crack propagation. Strength refers to the ability to carry a load without deforming or breaking, and the ultimate tensile strength is the maximum load per unit area before a fracture occurs in a tensile test. Typically, toughness and strength are inversely related: there is a trade-off in toughness as the strength increases. However, with quenched and tempered steels, it’s possible to have high strength and good toughness. This is important because cracking, especially in high-strength grades, often results from very small defects or pits that allow a crack to form and grow.

With high toughness, a crack that forms must grow to a much larger size before the sucker rod will fail. And when cracks do occur, materials with high toughness will blunt the crack and prevent it from continuing to go. Therefore, martensitic rods with good toughness are likely to be more resilient to damage and better able to withstand damage.

TESTING PERFORMED

A variety of sucker rods were obtained from different manufacturers that had been pulled from the field in a blind study, including both normalized and quenched rods. The impact toughness of the N&T rods varied extensively in our testing, with some above our defined performance standard of 40 foot-pounds and others well below. Those with toughness in the 10-30 foot-pound range are far more susceptible to environmental corrosion and fatigue. Of the Q&T rods, all were above 60 foot-pounds, and some were well above 60.

TEST METHODS

A wide variety of test methods exist that can be used for evaluating sucker rods. The benefits and drawbacks of the methods are discussed here. The important point to note is that testing should be realistic and relatable to how a failure would occur during typical use. For sucker rods, most failures occur under fairly slow cyclic loading conditions. Tensile and Charpy impact tests are widely used tests performed by many laboratories. Accelerated tests which can determine the threshold for different failure modes are ideal for preventing sucker rod failures in an economical and timely fashion. Several alternatives for accelerated testing of corrosion fatigue, stress corrosion cracking, and sour stress corrosion are described.

Hardness Testing

Hardness testing is a simple and timeless test that is widely used. A variety of hardness tests exist, each with their own advantages and disadvantages as described below. The data from all of these tests can be converted to equivalent tensile strength for many common metal alloys. Hardness testing is very easy and quick compared to the other tests and should be implemented as part of a good quality control system. The main drawback of all hardness tests is that they do not provide any information about the toughness of a material, and so they should usually be used in combination with other tests like tensile, Charpy, or fracture toughness testing.

- The Rockwell hardness test is commonly used and is generally accurate. For Rockwell C range, it uses a medium-size pyramidal indenter that puts a substantial, sharp indent into the part However, the indent left afterwards can act as a stress riser where a failure could occur. Care should be taken to do the test only in locations where an indent will not be problematic.
- The Brinell hardness test is widely used and uses a large round indenter. The advantage of this test is it leaves a permanent and easily measurable mark where the test was taken, but the round indenter does not leave a large stress concentrator. It can be performed using handheld equipment or with lab equipment.
- Microhardness indenters, including the Knoop and Vickers types, uses very small indenters that produce a small (usually 0.05 to 0.25 mm) indent at the surface of a part. This test is excellent for evaluating surface hardening, change in hardness, welds, and other fine features, but is sensitive to the surface preparation, location of test, anomalies present (like scratches, inclusions, etc.). and should be performed in replicates to have high confidence in the data.
- Ultrasonic hardness testing uses a very small pyramidal indenter and vibrates the part to measure the toughness. These provide similar resolution and accuracy as bench-top models but can be run faster than traditional machines and are portable for use in any location.

Tensile Strength

Tensile testing is widely used for measuring the ultimate tensile strength and yield strength of materials. The elongation and reduction of area data are not as widely used, but they provide a great method for confirming the toughness of a rod. Both elongation and reduction of area correlate directly with toughness; as they increase, so does the toughness. Because tensile tests occur at a relatively slow speed, they are more representative of the way that cracks normally form and grow in sucker rods.

Charpy Impact Toughness

The Charpy V-notch impact toughness test is also widely used; part of this is due to the simplicity of the test, both in terms of fabricating specimens and performing the analysis. In this test, a rectangular block that is 10 x 10 mm and 55 mm long is made with a V-shaped notch in the center. The test sample is held in place on both sides with the notch facing out, and a hammer is swung through to strike the back side and push the notch open. The change in height to which the hammer swings after striking the sample is directly proportional to the energy absorbed, which is then converted into the impact toughness value in foot-pounds or Joules. The formation and growth of the crack occurs in a tiny fraction of a second, which is typical of car crashes and other high-energy circumstances, but not typical of the cracking normally observed in sucker rod applications.

The advantages of impact toughness testing are that it is inexpensive, widely available, and easy to perform. The main drawbacks are that the measured values do not actually correspond to the way a fracture occurs in real-world use, and the values cannot be readily used in engineering or design calculations.

True Fracture Toughness

In comparison, "true fracture toughness" tests are performed using a much slower rate of loading and crack growth that is consistent with how cracks normally grow in sucker rod applications. The tests are typically performed by tensile machines or bending frames. Two of the more commonly used tests are ASTM E1820 and ASTM F1624. The specimen size requirements of E1820 make testing of sucker rods difficult or impossible, and so F1624 is more appropriate.

The F1624 samples are the same size as Charpy impact specimens, but with a thin slit notch cut by EDM instead of a V-shaped notch. Prior to testing, the samples are fatigue pre-cracked to start a crack. Each sample is then slowly loaded in incrementally rising steps, typically of 5% of the fracture load from a tensile test. A load cell is placed in line during the testing, so that when crack growth occurs a drop in the load is measured. At this point, the test is stopped and the amount of crack growth is measured. Examples of the bend test specimens for F1624 are shown in Figure 2, including a bolt from which multiple samples were removed. For a sucker rod, a set of 5 specimens can easily be made from 12" of rod. The samples can then be tested in a variety of environments

The measured change can then be used to calculate the fracture toughness value, such as K_{1C} and K_{1EAC}. These values are truly quantitative. They can be used in engineering and design calculations, including in widely used software for sucker rod applications. With this kind of data in mind, much better decisions can be made about the loads, forces, and appropriate materials for sucker rods in different environments.

Rising Step Loading aka Incremental Step Loading

The rising step load (RSL) method is an accelerated mechanical testing practice that can be applied to a variety of tests[2] to dramatically reduce the time required to evaluate cracking and fracture toughness thresholds. Taken together, this data can be used by operators and engineers to better plan for and prevent failures.

The basis of the RSL method is applying an incrementally increasing load in steps, typically of 2 or 5% of the maximum load. The first part of the process is to perform a standard tensile test to determine the ultimate tensile strength and maximum load of the sample. Then subsequent samples are RSL tested based on that data. A load cell is placed in line during the testing, so that when crack growth occurs a drop in the load is measured. The RSL method has been extensively used for evaluating hydrogen embrittlement for decades, and is included in the ASTM F519, F1624, and F1940 standards. An example of the loading profile is shown in Figure 3.

Previous studies on the impact of heat treatment on hydrogen embrittlement[3] (HE) have shown that quenched and tempered steels have the greatest resistance to HE. This is due to the decrease in toughness typically associated with normalizing and tempering.

Fatigue Testing

Fatigue is an extremely common cause or contributor to the failure of sucker rods; however, it is often not the actual root cause, because fatigue usually requires an initiating point for the crack to start. Depending on the material strength and toughness, the size of the initiation point can be fairly large (like a pit that is 10% or more of the width of the rod) or small (sometimes a small scratch or tiny pit is sufficient).

Traditional fatigue test can take months or years to complete a thorough study with enough information to thoroughly understand and prevent fatigue failures. Unfortunately, this means that often failures are not sufficiently or appropriately investigated, and that preventive measures that could be useful are not undertaken due to the time frame and cost.

However, when combined with the RSL method, the time can be reduced 90% or more in most cases, allowing for the completion of detailed quantitative threshold testing of many different forms of environmental cracking, including stress corrosion, fatigue, corrosion fatigue, sour stress corrosion cracking, and hydrogen embrittlement[4]. Instead of requiring many samples, the threshold can be assessed accurately with only one or two samples required.

Electrochemical Analysis

Traditionally, various forms of immersion corrosion testing have been used to evaluate the impact of corrosion by immersing a material in various liquid environments for a specified amount of time. These tests can take weeks or months to perform, and in the end provide an average corrosion rate over the time. In comparison, new electrochemical analyses can help with comparing initial corrosion rates, evaluating pitting corrosion susceptibility, and testing chemical inhibitors or microbial corrosion prevention methods.

The uses for electrochemical corrosion testing are widespread and still increasing. The tests can be used in project development, inhibitor evaluation, biocide analysis, and as an accountability tool for evaluating chemical providers and their solutions. Additionally, the use of electrochemical corrosion test can provide a capability to evaluate corrosion instantaneously with or without chemicals, and over time.

FAILURE MECHANISMS

There are many reasons and variables that can contribute to sucker rod failure: handling, chemical protection program, nicks and dings, downhole chemistry, fabrication issues, corrosive environment, and more. By knowing the possible failure modes, engineers, designers, and operators can better plan for and prevent failures. In this section, an overview of the most common failure modes is provided, along with possible tests that can be applied to test for each mode.

Stress Corrosion Cracking – SCC

Stress corrosion cracking occurs when the combination of high stress, a susceptible material, and corrosive environment are present. A common feature of SCC is branching cracks that occur in many places, but especially at areas where stress can be concentrated like threads, shoulders, and connections. The most common evaluation method for SCC susceptibility is through the use of C-ring or 4-point bend specimens with alternate immersion in a saltwater or other solution such as in ASTM G44 and G47. Depending on the alloy and stress levels involved, the tests can take anywhere from hours to years to complete.

The accelerated step loading method for stress corrosion cracking is being prepared for inclusion in the ASTM G44 and G47 methods as a faster, quantitative alternative. Static loading means many samples are required to determine a threshold, and even more to have statistical accuracy. In comparison, the step loading method requires a minimal number of samples of a common size. The chamber is filled with saltwater for 10 minutes, then drained and empty for 50 minutes the same as in ASTM G44, such as the one shown in Figure 4.

Sour Stress Corrosion Cracking - SSCC

Sour SCC occurs in environments where high levels of hydrogen sulfide are present, which is known as a sour environment. The failure mechanism is in many ways similar to stress corrosion but is further accelerated by the action of hydrogen sulfide and the hydrogen atoms given off during sulfide corrosion. Common tests include NACE TM0177 and TM0284. Each of these tests involves static loading of samples; for the TM0177 a proof ring is use, and for TM0284 a variety of forms are using such as double cantilever beam and C-ring samples. Each test has it's drawbacks:

- NACE TM0177 measures sulfide stress cracking (SSC), stress corrosion cracking (SCC), and hydrogen stress cracking (HSC). The practice takes from 14 to 30 days (depending on the type of sample tested) just for the exposure. Once the machining, transportation, setup times, and recording are factored in, these tests usually take many weeks in total to complete.

- NACE TM0284 is faster, taking just 4 days of exposure time. However, the end result is based on total crack length measurement and doesn't account for the effect of loads on the structure. Moreover, it is very difficult to use the data from TM0284 to effectively make judgements regarding cracks found in service based on the data obtained.

New methods based on step loading offer the ability to much better understand and prevent stress corrosion failures. Alternatives to both TM0177 and TM0284 are being developed and will provide a significant improvement in the speed of sour corrosion analysis.

Fatigue and Corrosion Fatigue

Due to the cyclic loading nature of sucker rods, they are subject to fatigue and corrosion fatigue as common failure modes. The main difference between those is extent to which corrosive elements play a role in the failure. In fatigue failures, the load required to nucleate and grow a crack is far less than the load required by a static load. When corrosive environments are present.

Galvanic, Pitting, CO_2 , and Microbial Corrosion

Other common forms of corrosion that can lead to failure are pitting, galvanic, CO2, and microbial corrosion. These can be prevented by a combination of design, corrosion inhibitors, and biocides. Consult a qualified metallurgist and chemical company if you need assistance with these failure modes.

PURCHASING AND QC REQUIREMENTS

One key to the longevity of any sucker rod, whether martensitic (Q&T) or ferritic (N&T) is implementing the right purchasing and quality control requirements to ensure you are using an appropriate product for the application. In this section, we discuss a number of lessons we have learned over time that can be applied in your purchasing and quality control (QC) practices.

Microstructure

As every metallurgist will tell you, the microstructure ultimately is the key to understanding materials properties and performance. For martensitic steels, this means there should be a fully martensitic structure with minimal amounts of ferrite and retained austenite, along with a small grain size. To evaluate the grain size of martensitic steels, the prior austenite grain boundaries should be evaluated, which requires a specific but readily available set of chemicals. The ASTM method for grain size evaluation can be used once the prior austenite grain boundaries have been revealed.

Third-party Investigations and Testing

Use of a 3rd party lab that's independent from the manufacturer and operator is often the best way to investigate failures and evaluate performance. The manufacturer naturally has a bias to not find fault with their products; and often they do not. In many cases, though, an investigation by an independent third party will reach a different conclusion. Therefore, if there is a question about why the failure occurred, the operator should either (1) consider using a third-party to perform an independent investigation, (2) insist that a metallurgist of their choosing is present when the manufacturer performs the analysis, or (3) have an experienced metallurgist evaluate the failure analysis report. When a sucker rod failure occurs, there are two pieces of the fracture surface. If the damage during retrieval is not too extensive, it is also reasonable to send one side to the manufacturer and the other to a third-party laboratory. Compared to the costs associated with a failure, the failure analysis process is a minor expense and is the key to understanding and preventing future failures.

When a Failure Occurs

Failure analysis is a critical and detailed process that is important to preventing a failure from recurring. In the failure analysis process, some simple guidelines should always be applied to maximize the likelihood of a successful evaluation:

1. Document the failure as thoroughly as possible, including all the details and photographs possible.
2. The surface where fracture occurred is the key to unravelling and understanding the cause of failure. Never put the mating fracture pieces back together to see how they fit; this can cause surface damage that prevents an accurate failure analysis from being possible.
3. Similarly, the elements and chemical compounds often also play a key role in failures. Ask the failure analyst or company before cleaning the part(s) to determine how to appropriately clean the component and what residue or chemicals from the surface should be preserved (and if so, how to preserve them).
4. Ensure the packaging used for transportation (whether across town or around the world) is sufficient to secure the item and prevent damage. A good practice is to act as if you are shipping fragile glassware and you want to make sure it survives the trip.
5. Perform the least and gentlest cleaning possible. Often the corrosive elements get completely removed during the cleaning process, and damage from cleaning can make microscopic and fracture surface analysis difficult or impossible. If you are not sure, contact a metallurgical failure analyst for guidance on how to clean prior to shipping.
6. Failure analysis reports should always include discussion of the details and recommendations of how to proceed. Work with the analyst to help understand why a failure occurred and how to prevent them in the future.

Evaluating the Fracture Initiation Point

When a failure occurs, the key area to investigate is at the initiation point of the fracture; not at the ductile lip where final tearing occurred. The reason for this is that most failures are actually from a combination of mechanisms. For example, a pit forms on the surface and provides the starting place for crack growth. Then the crack propagates by fatigue across the rod until finally the strength is reduced enough that the part fails by ductile tearing. In this example, three different mechanisms occur, but the initial pit is the root cause of the ultimate failure. By understanding the critical pit size and inspecting to remove pits above or close to this size, sucker rod life can be substantially extended.

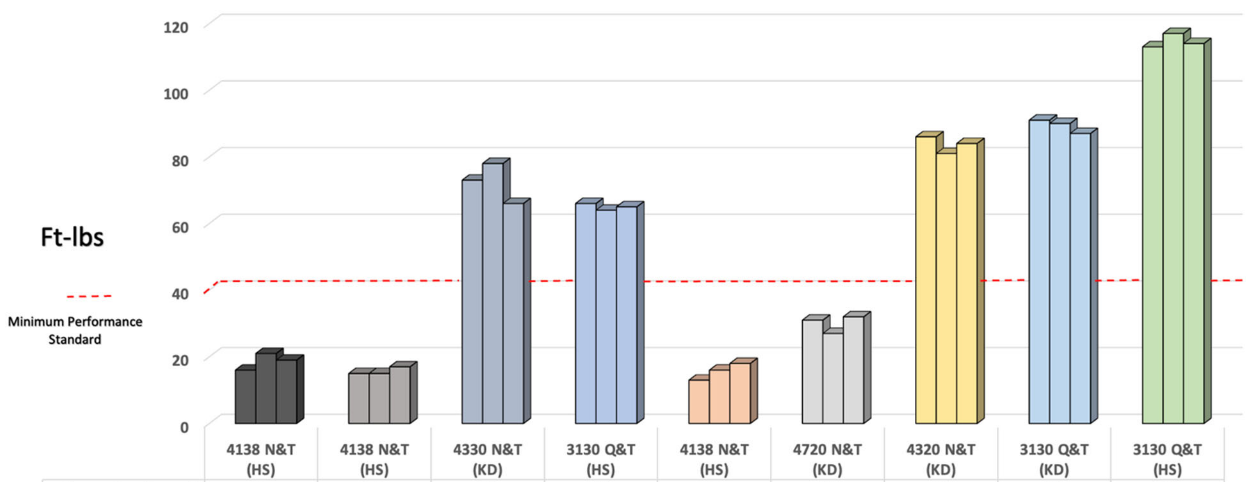
MATERIALS SELECTION AND COMPARISON

There are numerous manufacturers of sucker rods, both N&T and Q&T. Each manufacturer reports typical properties; but for different fields and geographic locations, the environment can dramatically vary, with corresponding large differences in corrosivity. NACE MR0176 defines the conditions for use of sucker rods in corrosive conditions. In general as the corrosivity increases, lower-strength rods should be used as they have more immunity from environmental corrosion issues.

The notch sensitivity shows how sensitive a rod material is to notches such as pits or mechanical damages; it increases at higher strength, meaning that high-strength rods require more detailed, precision inspection ensure they are not used once too much damage had occurred. All steels being used in corrosive environments will corrode; but understanding how well they can withstand pits and damage can help us much more effectively prevent corrosion-related failures. Figure 6 shows an example of several small notches, pits, or damage marks that results in failures of sucker rods.

The use of properly made quenched and tempered steels provides an advantage in terms of resistance to hydrogen embrittlement and stress corrosion. When accompanied by appropriate testing and quality control processes, they can perform very well for sucker rods just like they do in many other applications.

Figures:



	4138 N&T (HS)	4138 N&T (HS)	4330 N&T (KD)	3130 Q&T (HS)	4138 N&T (HS)	4720 N&T (KD)	4320 N&T (KD)	3130 Q&T (KD)	3130 Q&T (HS)
Charpy Specimen #1	16	15	73	66	13	31	86	91	113
Charpy Specimen #2	21	15	78	64	16	27	81	90	117
Charpy Specimen #3	19	17	66	65	18	32	84	87	114

Figure 1. Charpy impact testing results on a variety of N&T and Q&T sucker rods.

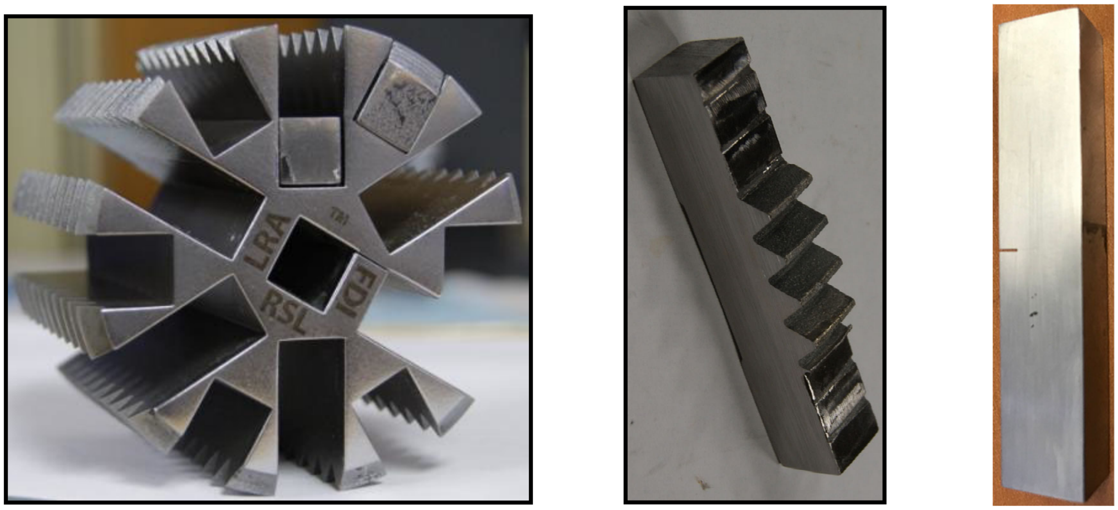


Figure 2: Specimens cut from a bolt for use in the rising step load test.

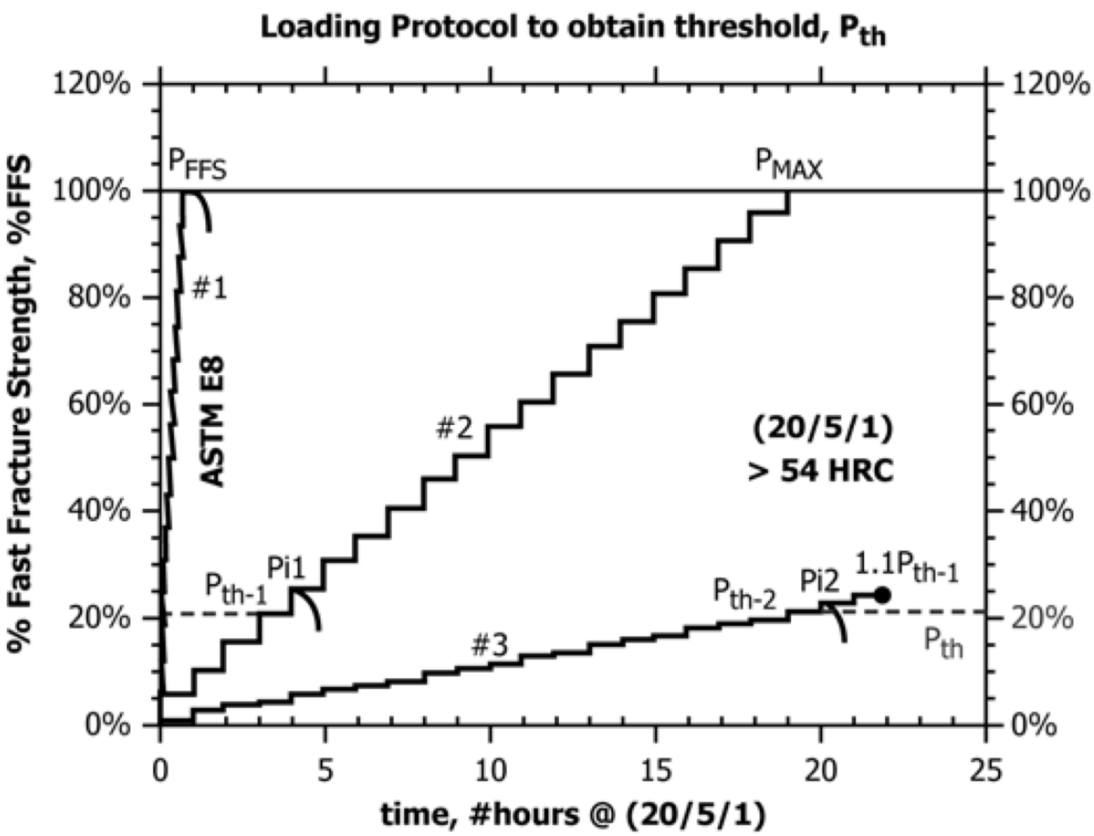


Figure 3. Typical pattern for rising step load testing per ASTM F1624.

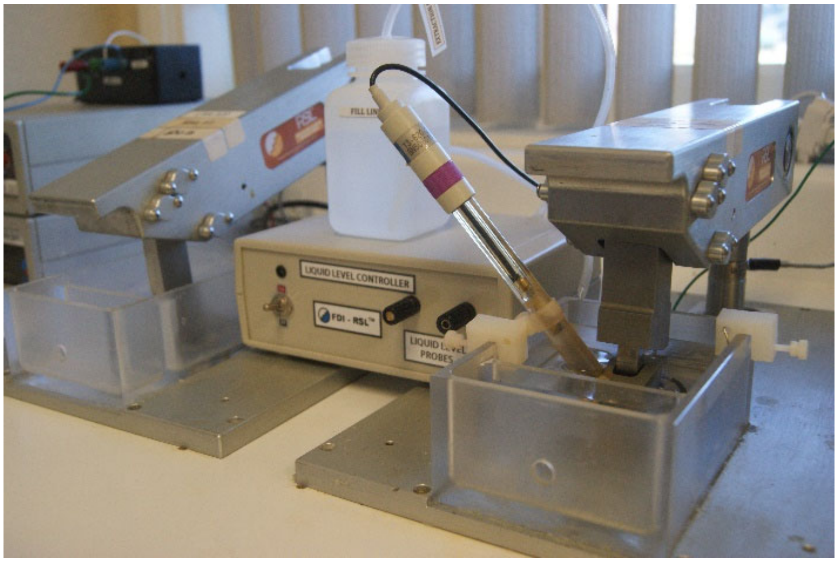


Figure 4 – Alternate immersion step loading chamber for accelerated stress corrosion evaluation.

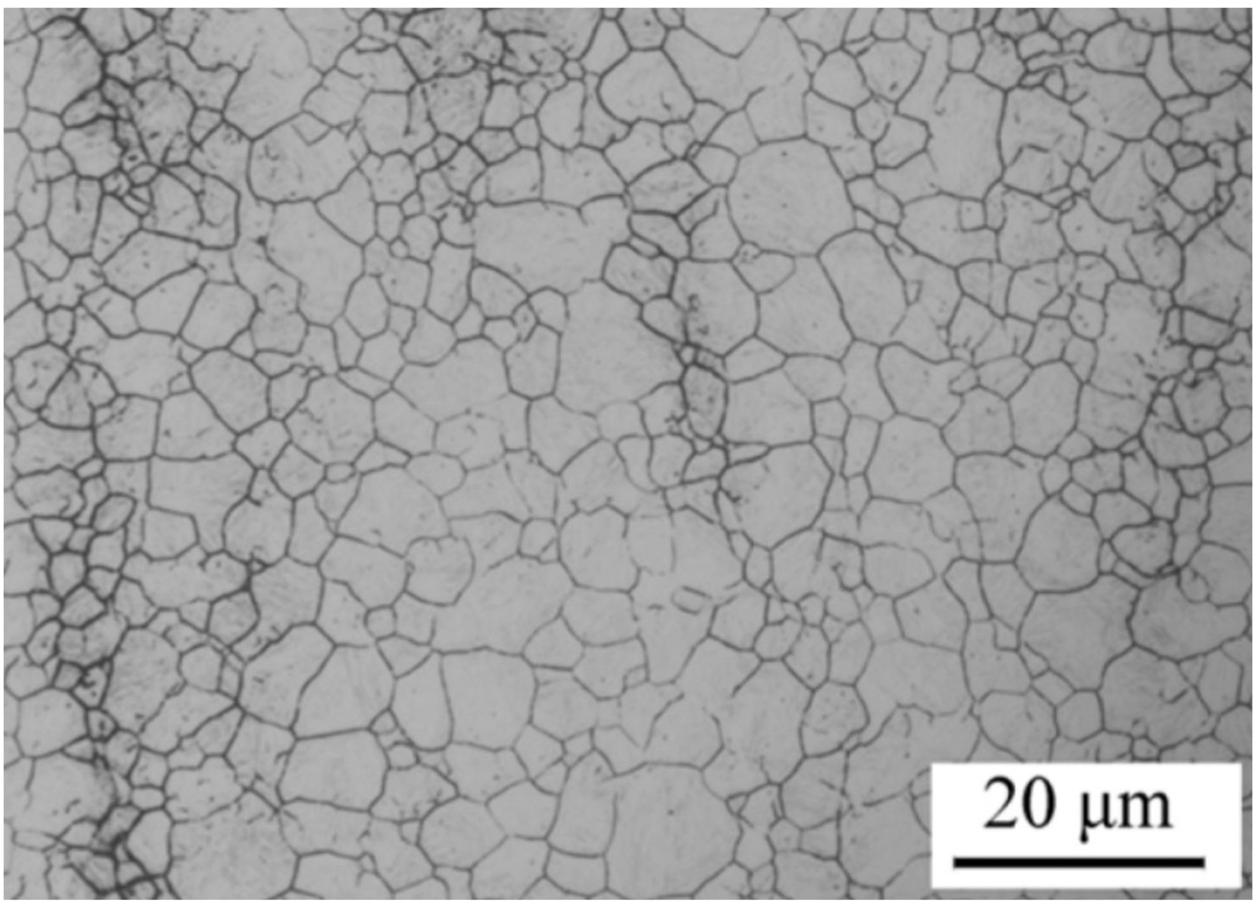


Figure 5. Prior austenite grain size of a martensitic steel.

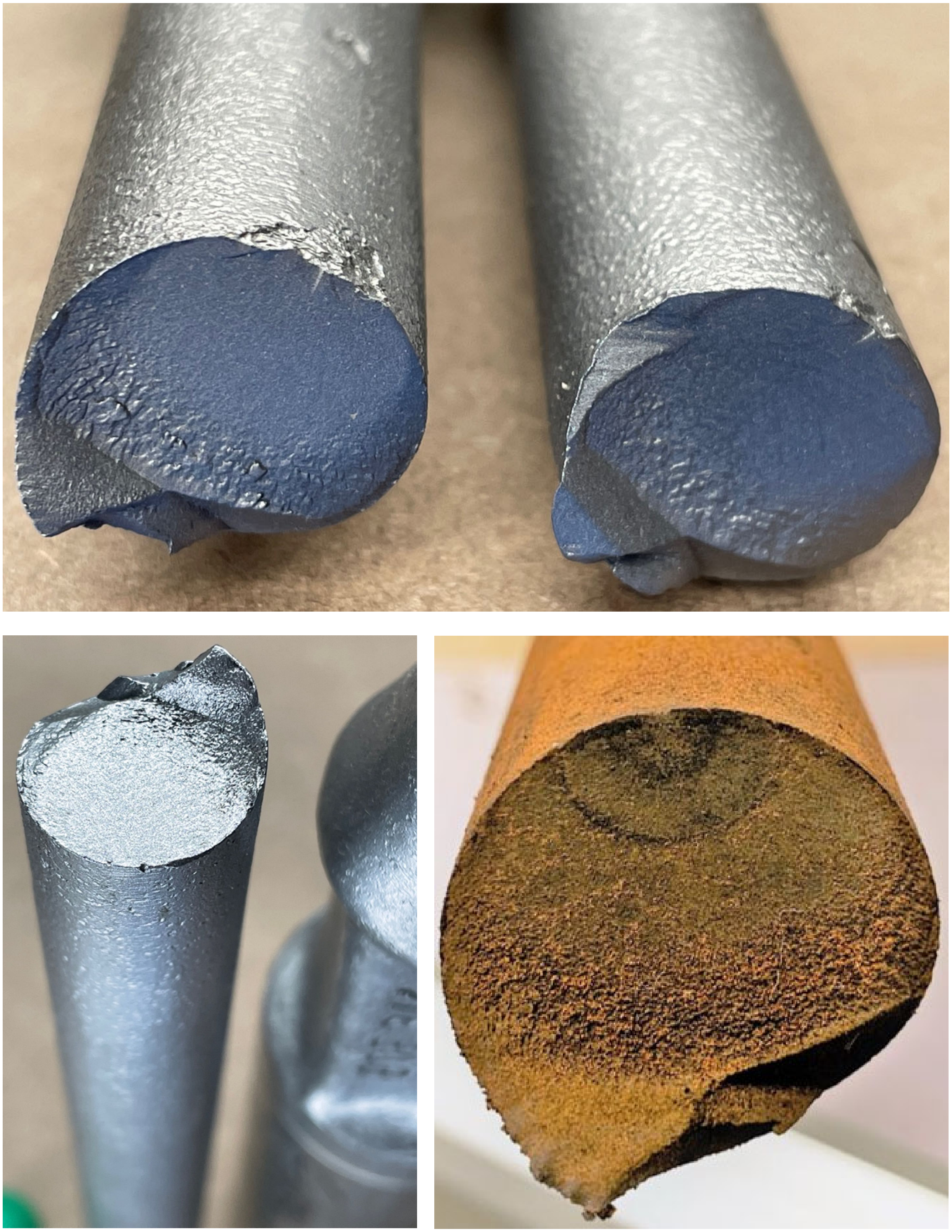


Figure 6 – Examples of sucker rod failures that initiated at very small pits or surface damage areas.

References:

[1] Eghtesad, R., Barajas, P.E, and Norris, W.S. “Influence of unconventional metallurgical variables on mechanical properties of API sucker rods”, SWPC (2018).

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[3] Ananta Nagu, G., Amarnath, and Namboodhiri, T.K.G., “Effect of heat treatments on the hydrogen embrittlement susceptibility of API X-65 grade line-pipe steel” Bull. Mater. Sci., Vol. 26, No. 4, pp. 435–439, (2003).