OPTIMUM SHOT PEEN PROCESS ON THE SUCKER ROD FATIGUE LIFE

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ABSTRACT

In the reciprocating rod lift system, the sucker rods are subjected to cyclic stresses during service which accumulate leading to fatigue failures. It is well known that the shot peen process increases the fatigue life on metal parts; with respect to sucker rods several manufacturers claim to have implemented shot peening in their manufacturing process for years. To achieve optimal parameters which yield a dramatic increase in fatigue life requires extensive studies on both input parameters and comparative fatigue testing. This paper will discuss the steps and challenges involved in achieving the optimized shot peen process and benefits on the sucker rod fatigue life. Process inputs such as shot size, shot metallurgy, shot velocity, the volume of shot and peening time was studied and evaluated by an axial fatigue test which replicated downhole loading condition. The laboratory test results were also validated with field data to show increased runtime on sucker rods. The laboratory axial fatigue test showed that the optimized shot peen process increased the fatigue life of the sucker rod approximately 37 times as compared to non-shot peened rod. Sucker rod failures relating to fatigue were tracked after the implementation of optimum shot peen parameters into the manufacturing process and the field data showed a decreasing trend in sucker rod failure rates which supports the laboratory results. This paper presents an insight into how an optimized shot peen process can help to improve the sucker rod quality from a fatigue perspective.

INTRODUCTION

Most common fatigue failures are originated at the surface with the presence of tensile stress which initiates crack. Various studies show crack initiation and propagation are minimized in a compressive stress zone. Sucker rods are operated at alternating tensile stress and typically fail due to fatigue (See Fig.1). Shot peening the sucker rod surface will mitigate any residual tensile stress from the manufacturing process and create a compressive stress layer to help reduce or delay the crack initiation when subjected to externally applied tensile loads.

Shot peening is a mechanical cold working process in which the abrasive particles are directed to the surface in a controlled manner in order to create a compressive layer (see Fig. 2). Effective shot peening is achieved by controlling the process variables such as shot properties, shot velocity, shot flow-rate and exposure time. Parameters like shot physical properties, impingement angle and velocity will determine the thickness of the compressive stress layer created on the rod surface. Desired peening coverage on rod surface is achieved by regulating the shot flow-rate and the exposure time.

Optimum shot peen process is achieved by altering each input variable and validating by the laboratory fatigue test. This iteration process is continued until the desired fatigue life is achieved from the fatigue test. The implemented optimum shot peen process shows a noticeable decrease in rod string fatigue failure rates.

This article provides insight into an optimized shot peen process and the resulting improvement on sucker rod fatigue life.

INPUT SHOT PEEN PROCESS PARAMETERS

Shot Properties

Shot physical and mechanical properties play a significant role in the quality of the compressive stress layer created on the rod surface. The impact energy available to form the compressive stress is defined by the equation $1/2mv^2$, where the shot mass (m) is defined by shot size and density. Shot mechanical properties such as hardness, shape, chemistry, texture will determine the shot durability while maintaining the intensity of compressive stress layer. The type of shot for the sucker rod is selected based on the SAE specification AMS2431.

Shot Velocity

The impact energy required to create compressive stress is largely dependent on the shot velocity which is determined by the type of machine and distance to the part. Once the shot properties are defined, changing the shot velocity will yield different shot intensity values for a given exposure time. The required shot velocity is derived by comparing the actual measured almen strip intensity with the target intensity.

Impingement Angle

Shot impact angle is based on the machine configuration and a perpendicular angle to rod surface is recommended. Steeper impingement angle will cause a lower compressive stress layer and interference between incoming and exiting shot particles.

Shot Flow Rate

Shot flow rate is selected in a way to achieve the optimum number of impacts per square surface area. It is also important to note that excessive shot flow rate will lead to surging which produces inconsistent shot velocity.

Exposure Time

Minimum exposure time is derived by plotting a saturation curve as per SAE J443. This curve serves as a statistical tool to determine the minimum exposure time in order to achieve the optimum target intensity. Final exposure time is established by increasing the peening time until desirable coverage is obtained.

SHOT PEEN PROCESS CONTROL

Intensity

Intensity is a measurement of impact energy induced on the rod surface by the shot media. It is directly proportional to the compressive stress layer created on the rod surface. Shot properties, shot velocity and impingement angle need to be controlled to achieve consistent intensity for an effective shot peen process.

Intensity is measured using almen strip which is a flat rectangular test strip made to specification SAE J442. A custom test fixture is designed for the sucker rod application as per the specification SAE J442 (see. Fig 3). When the almen strip is exposed to the shot stream, the residual compressive stress created by the shot impact will plastically deform the strip creating a curvature once it is removed from the fixture. The measured height of this curvature is called arc height which is an indication of peening intensity (see. Fig 4.) A saturation curve is created using arc height with respect to the exposure time as per SAE J443, J2597. The saturation intensity is obtained when the arc height does not increase more than 10% when doubling the exposure time (see. Fig 5). Saturation time is the minimum exposure time to achieve target intensity, which derived from the saturation curve solver program specified in SAE J2597. Intensity is verified and controlled by measuring the arc height at a regular interval as per the SAE J443 guidelines.

Shot physical properties are controlled by sending the processed shot media through abrasive classifier before the next cycle. Abrasive classifier consists of certain size sieves to remove broken and uneven shot media as specified in SAE J444. Uniform shot media will help to achieve consistent intensity throughout the rod surface and a proper shot maintenance program will maintain optimum shot-peening results.

Any change in almen strip reading will likely indicate that the input parameters such as shot properties, shot velocity need to be adjusted.

Coverage

Peening coverage is defined as the surface area of part which is exposed to shot media. Shot flow-rate and exposure time are the two most important variables to achieve desired coverage. The uniform and complete coverage will result in fatigue life improvement since the compressive stress layer will be evenly distributed on the rod surface. By increasing the exposure time from the derived saturation time, coverage on the rod surface will be increased. In order to successfully determine when optimum coverage has been achieved, a series of laboratory fatigue tests are necessary to compare the data and evaluate best-case scenario.

ITERATIVE METHOD

Optimum shot peen parameters are derived by iterating each input variable until the target intensity and a pre-defined fatigue life by the laboratory fatigue test are achieved (see Fig. 6). An almen strip study is conducted (see Fig. 7) to determine the intensity for different shot property and shot velocity.
Each shot size is studied separately, and the intensity is calculated at different velocities based on exposure time and arc height.

Iterations which meet the target intensity is moved to the next step on shot peening the samples for fatigue test. Pony rods are shot peened at the respective iterative parameters with a minimum exposure time derived from the saturation curve. Shot peened samples are tested in an in-house axial fatigue test machine until the pre-defined fatigue life is satisfied.

For the shot peen samples that failed prior to meeting the pre-defined fatigue life, new samples were processed with an increased exposure time for better coverage. This step is continued until the pre-defined fatigue life is satisfied.

AXIAL FATIGUE TEST

Test Setup

Hydraulic powered axial fatigue test machine is used to test the shot peen rods. Pony rods are connected to a custom-made test fixture on both ends and the threads are preloaded as per the API 11BR specification. Fixture ends are gripped in the fatigue machine at the calculated grip supply pressure based on the actual loading value (See Fig. 8).

Test Parameters

API 11BR (Recommended Practice for Care and Handling of Sucker Rods) provides guideline on rod loading based on “Modified Goodman Diagram” (See. Fig. 9). According to API 11BR, “sucker rods operating in a non-corrosive environment and in the proper stress range as shown in Fig.9 will theoretically exceed 10 million load reversals”. Testing will be longer, and all samples may reach 10 million cycles if the test loading condition is selected from the modified good diagram. Elevated loading conditions are selected in order to obtain comparable results in an accelerated manner.

Sucker rods will not go in compression in an ideal pumping condition. It is decided to maintain a minimum stress on the test samples as 1000 psi which keeps the rod in tension all the time. Based on the API Modified Goodman diagram, for the API grade D rod with a minimum tensile strength of 115000 psi the maximum allowable stress is calculated as 29312.5 psi (see. Fig 10). In the laboratory fatigue testing, the rod is loaded to a maximum of 60% of ATS (actual tensile strength) (See. Fig 11) and loaded to minimum stress of 1000 psi. Alternating stress on the fatigue test samples are approximately 58% higher than the API recommended stress range. The samples are cycled (periodic alternating stress) at a rate of .067 seconds.

LABORATORY TEST RESULTS

Preliminary Test Data

For a good comparative baseline, non-shot peened rods and shot blasted rods are fatigue tested until failure. Non-shot peened rods are the samples in a heat-treated condition and not processed through shot blasting or shot peening. Shot blasted rods are the samples processed through a surface cleaning process to remove any contaminants from the heat treatment. Shot blasted rods are cleaned by directing accelerated uncontrolled abrasive particles to the surface of sucker rod. The abrasive particles will create negligible amount of compressive stress which showed 18% increase in fatigue life on the WFT KD grade shot blasted rods as compared to WFT KD grade non-shot peened rods (See Fig. 12).

Iterative Test Data

WFT KD grade rods are used for the iterative study. Rods shot peened with two different shot size at various iterations are fatigue tested until failure. From Fig. 12, it is shown that shot size 2 at iteration 4 produces an optimum intensity and coverage which resulted in the fatigue life improvement in the order of 42 as compared to the non-shot peened rods. It is also noted that the fatigue life between iteration 3 and 4 for shot size 2 reached an equilibrium due to the uniform coverage. At this point, it is safe to say the optimum shot peen process is established by using shot size 2 at iteration 3.

Validation Test Data

The optimum shot peen process is achieved using WFT KD grade rods. The shot peen process is validated on a S87 grade rod to study the improvement on fatigue life. As shown in Fig. 13, the optimum shot peen process on the WFT S87 rods increased the fatigue life by 11 times as compared to a non-shot peened S87 rods.

Comparative Test Data

WFT shot peen rods are compared with the rods produced by different manufacturers. WFT KD grade equivalent from manufacturer A and B are tested at 60% of ATS. The test results show (See. Fig. 14) WFT KD grade performed 2.5 times better than the next closest manufacturer. WFT HD grade equivalent from manufacturer A, B are tested at 60% ATS and the WFT HD grade outperformed the next closest manufacturer by 3.25 times (See Fig. 14).

Summary of Laboratory Test Data

The laboratory test data on the WFT rods reveal that the shot peen process has improved the fatigue life significantly. The developed shot peen process is verified by actual fatigue testing at different level before implementing the process in manufacturing.

FIELD DATA

In order to validate the laboratory results presented in this paper, proper fatigue-life evaluation of the shot-peened rod in the actual oil field under cyclic conditions was necessary. There are many variables which affect the life of the rods in their actual reciprocating mechanism such as loading conditions, taper lengths, speed and length of stroke, etc. making this task extremely difficult to compare.

The field data compared in this study was from the actual failure laboratory, over the years a consistent number of failures were gathered and sent in for metallurgical analysis by various operators. In this study, all the fatigue-related rod failures were used to obtain an average failure frequency by year. Any corrosion-fatigue failure was also accounted for as fatigue related.

The optimum shot-peening implementation occurred in 2016, anything prior to this date was considered to have been shot-blasted.

Based on the data gathered, in 2015 and 2016 there were approximately 300 fatigue related failure reports generated by the laboratory per year. After the shot-peening implementation date the number of fatigue-related failure reports decreased to 100 per year in 2018 and 2019 as seen in Figure 15.

From the failure reports generated over the past years, there is a definitive decrease of approximately 66% in fatigue-related failures observed coming in for analysis. This information aids in the conclusion that after the 2016 shot-peening implementation, the newly optimized sucker rods are lasting longer in the field.

CONCLUSION

The implementation of shot-peening to the sucker rod manufacture has been observed as the single-most important process in dramatically increasing the life of the sucker rod over the past decade. The difference between shot-blasting and shot-peening according to this study was observed at a 30 times fatigue life increase.

From the information presented in this paper, in order to achieve optimum results, it is crucial to understand all the variables tied to shot-peening process. The careful optimization of each of these variables successfully achieved a sucker rod life increase of at least 2.5 times that of the next competitor.

The field data gathered from the failure laboratory supported the laboratory tests by presenting a definitive decrease in fatigue-related failures after the 2016 shot-peening implementation.

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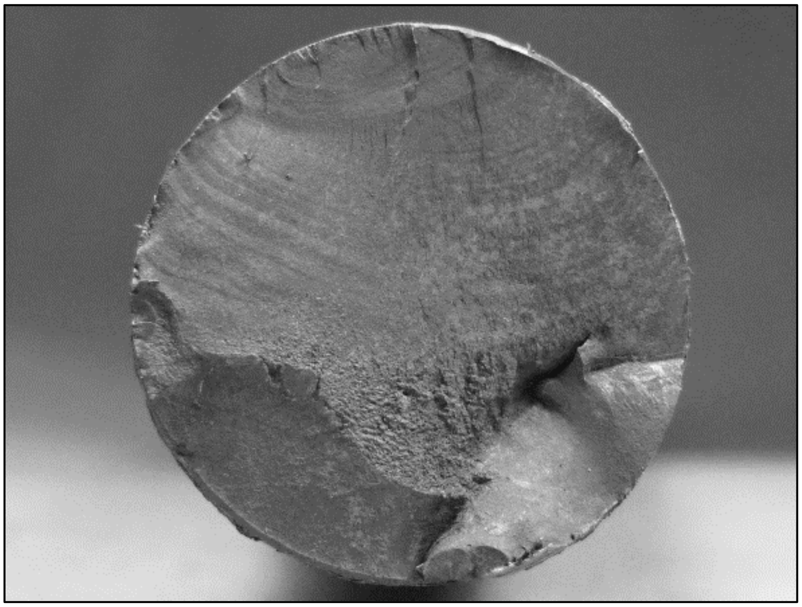


Figure 1 – Sucker rod field failure under fatigue mode

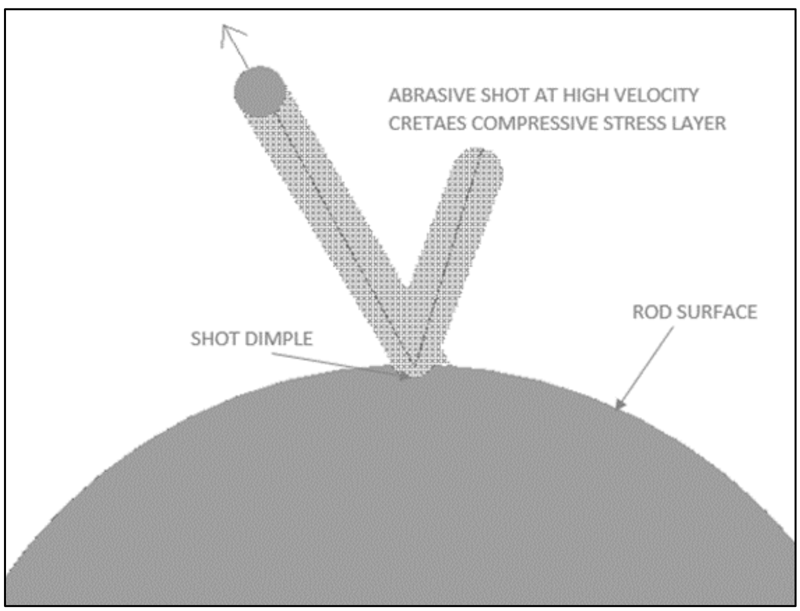


Figure 2 – Sucker rod surface is treated with abrasive media
to create compressive stress layer

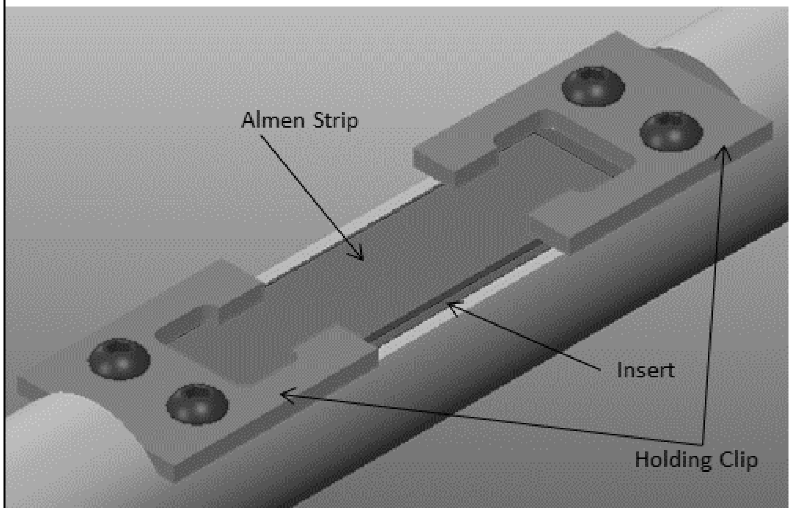
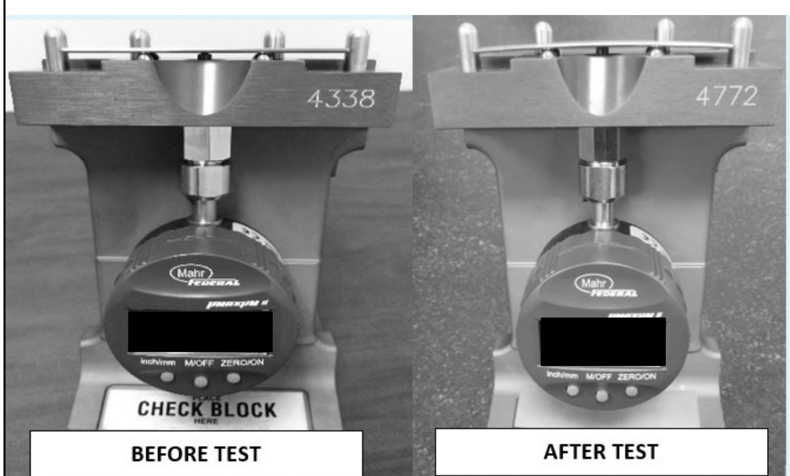


Figure 3 – Custom made almen strip holder designed for sucker rod application as per SAE J442



(a) (b)

Figure 4 – (a) Almen strip is measured for any pre-bow using almen gage before exposing to shot stream. (b) Curved Almen strip is measured for arc height after shot peening

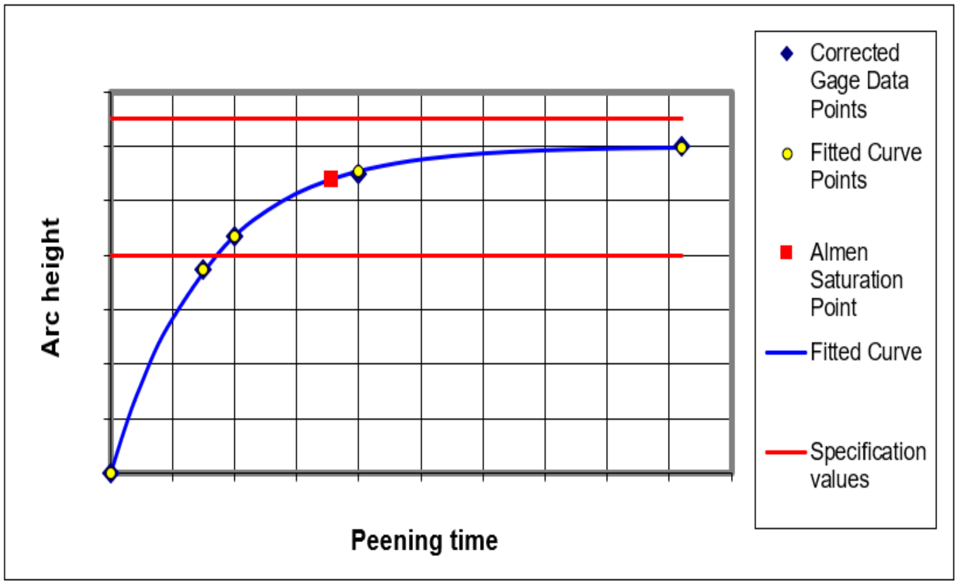


Figure 5 – Plotted Saturation curve using Dr. Kirk's solver program

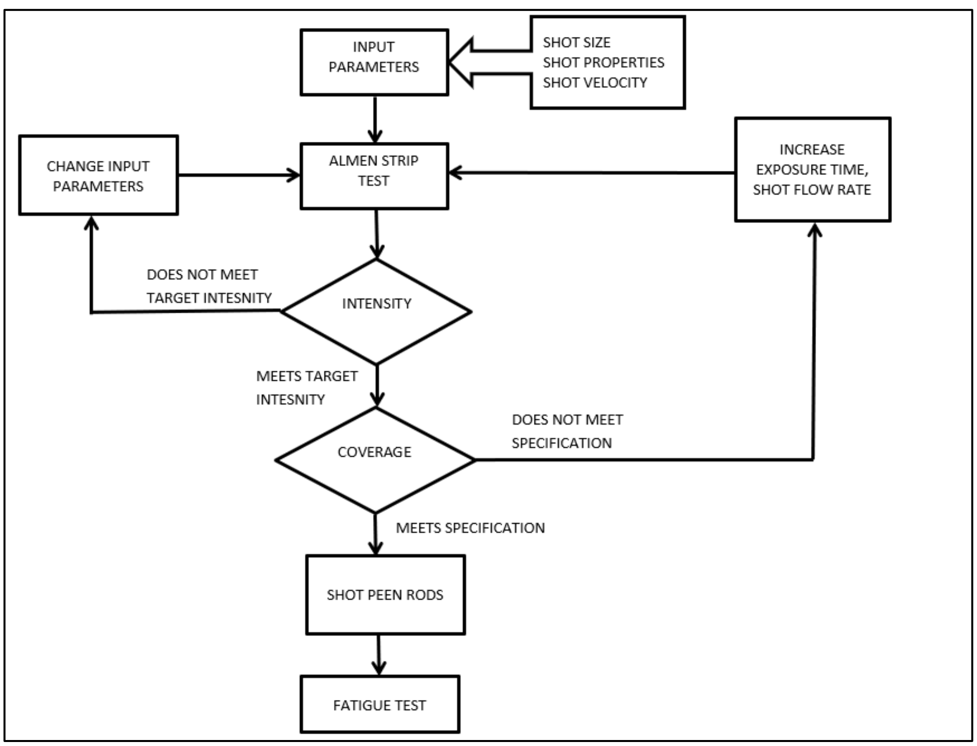


Figure 6 – Flow chart for achieving optimum shot peen process

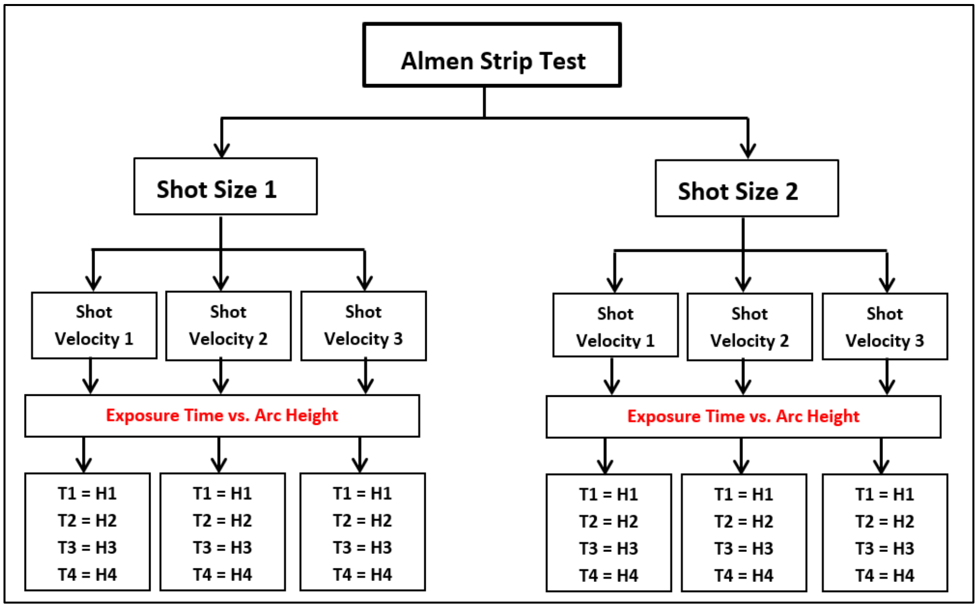


Figure 7 – Flow chart for iterative almen strip study

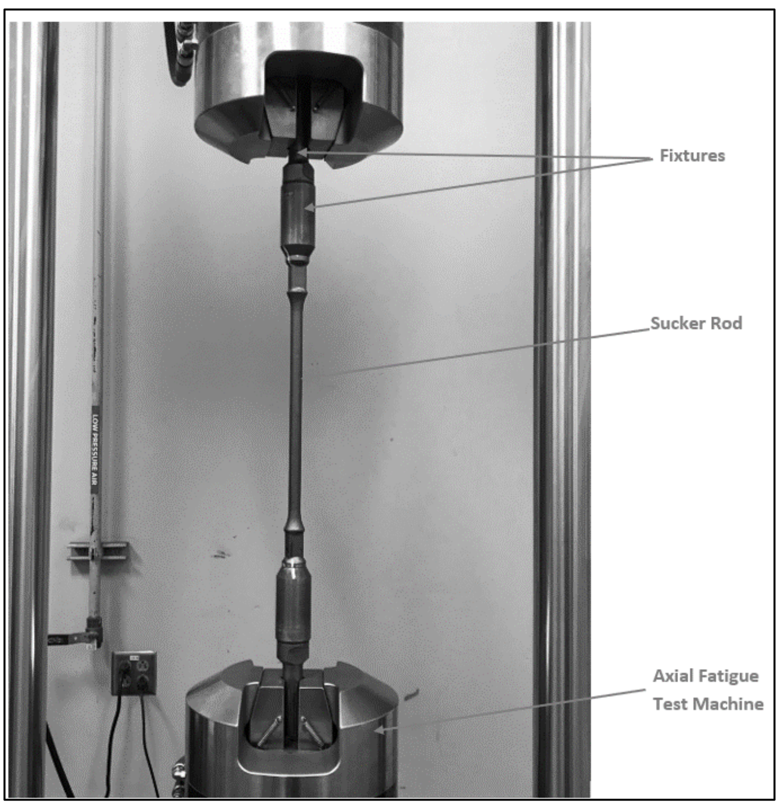


Figure 8 – Test setup of the axial fatigue machine

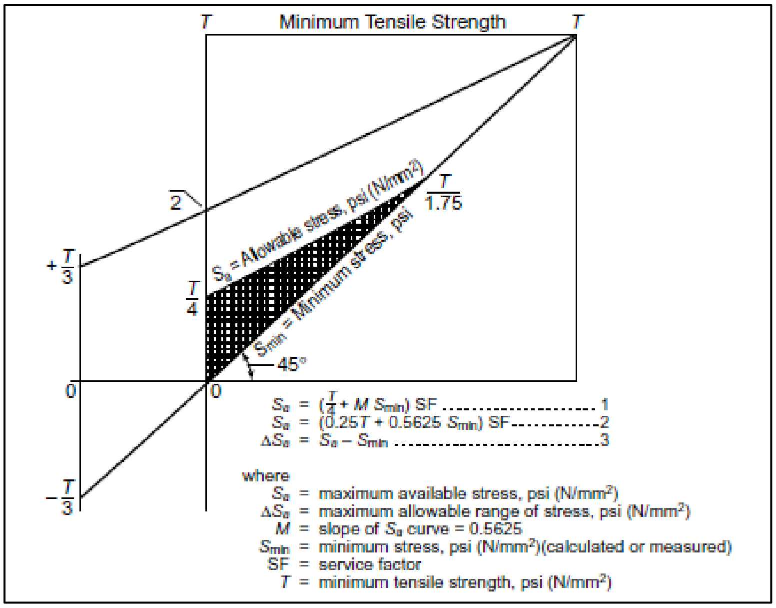


Figure 9 – API Modified Goodman diagram from API 11BR

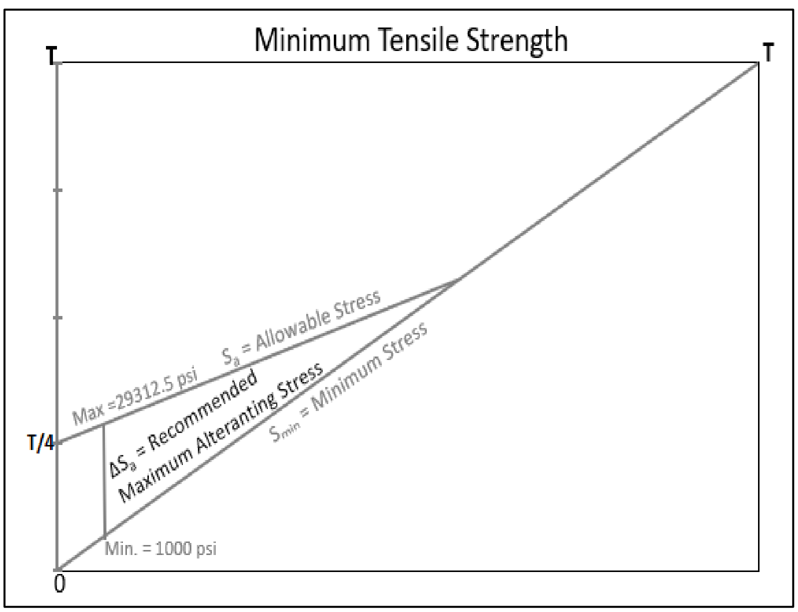


Figure 10 – Load conditions based on API Goodman Diagram

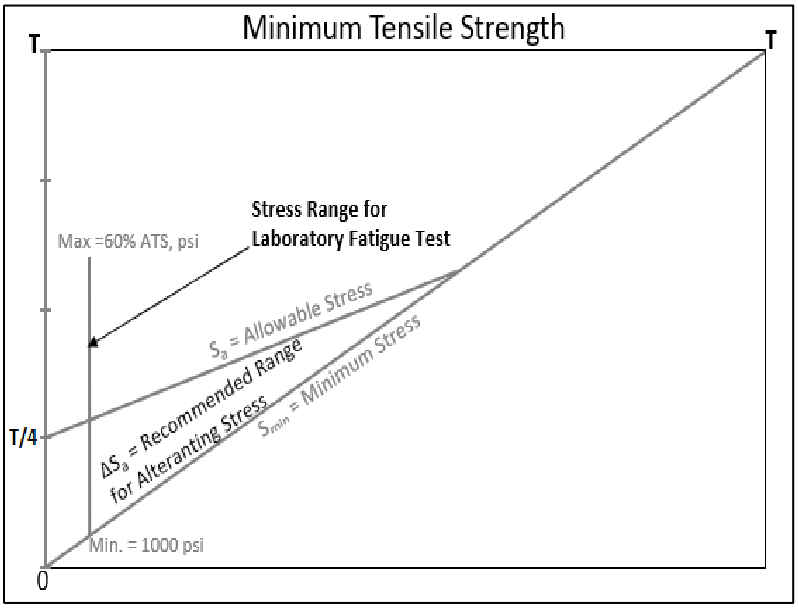


Figure 11 – Laboratory load conditions as compared to API Goodman Diagram

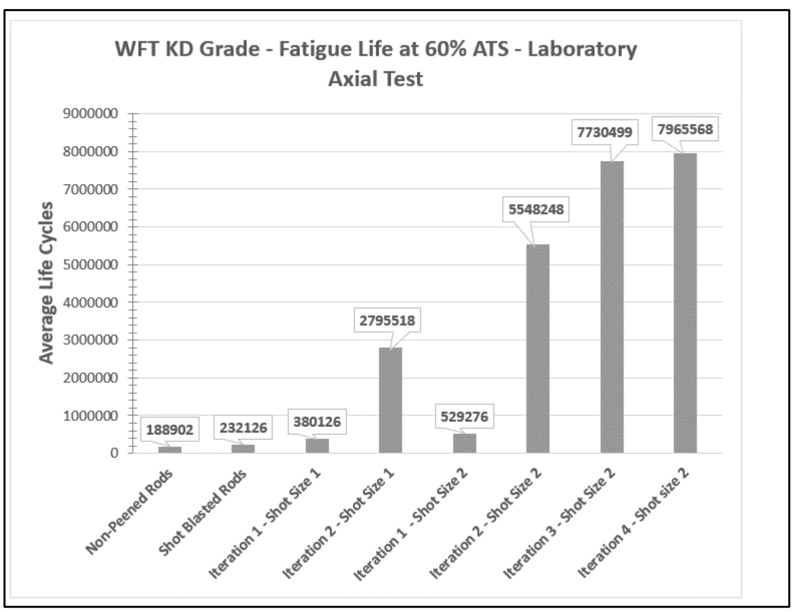


Figure 12 – Laboratory test data of WFT KD grade rod at different shot peen iterations

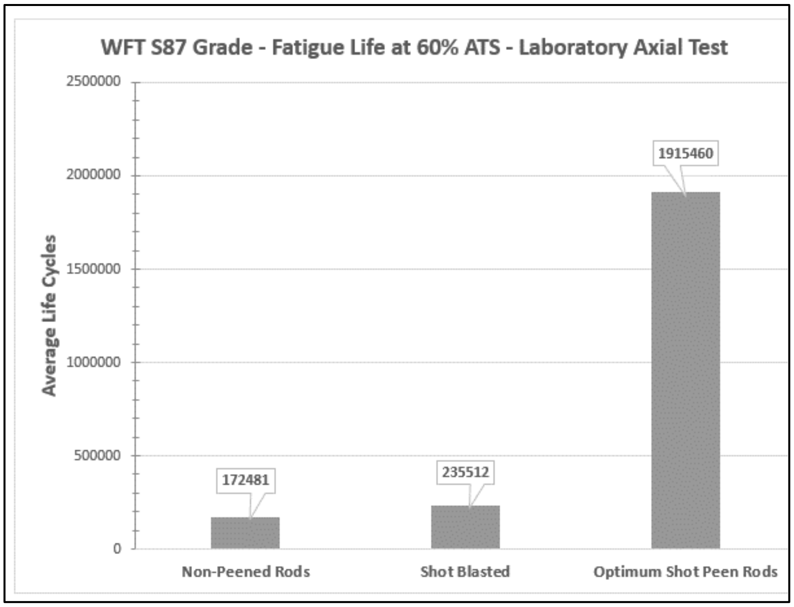


Figure 13 – Laboratory test data of WFT S87 grade rod at different surface conditions

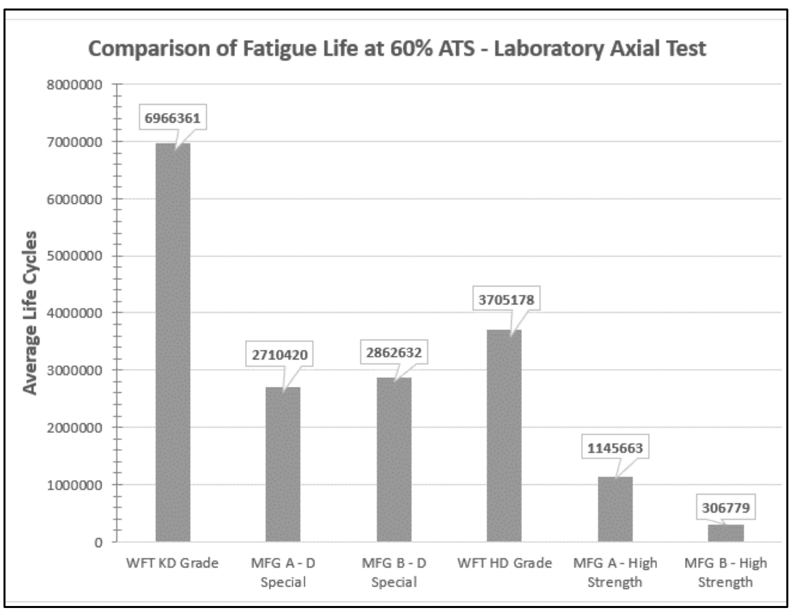


Figure 14 – Laboratory comparative test data of WFT vs. competitors rods

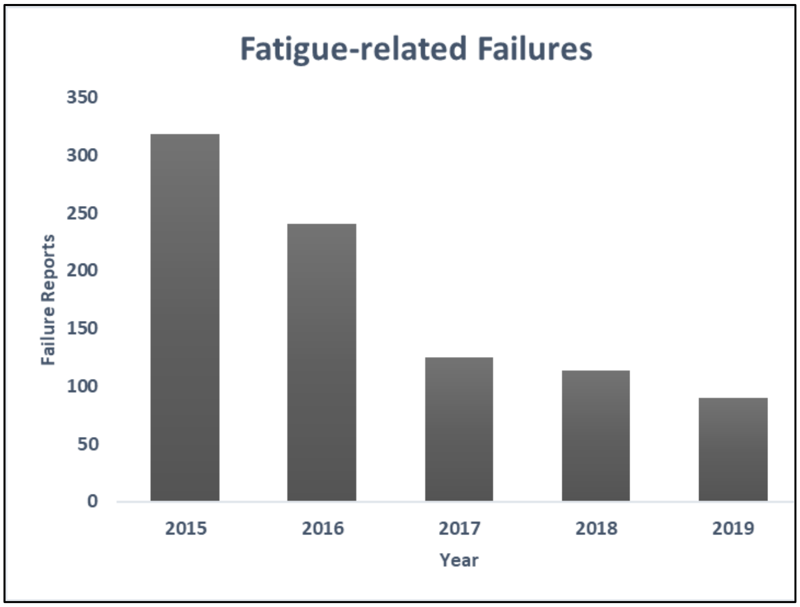


Figure 15 – Graph showing the number of fatigue-failures received per year.