# INFLUENCE OF UNCONVENTIONAL METALLURGICAL VARIABLES ON MECHANICAL PROPERTIES OF API GRADE D SUCKER RODS

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Abstract

A majority of the artificially lifted wells in the US are using sucker rod pumping systems. It has been ameliorated during past years, as the performance of the sucker rod pumping system directly impacts production volume and consequently revenue of E&P companies. The sucker rod is one of the most vulnerable components of this type of artificial lift system. The correlation between metallurgical variables and mechanical properties is of great importance to ensure proper functionality and to identify rod string optimization opportunities from the manufacturing perspective. The API 11B has classified different grades of sucker rod material to aid in the rod string selection by operators, as well as the standards for manufacturers. Corrosiveness of the wellbore fluid, well depth (Peak Polished Rod Loads), material susceptibility to $H_2S$- or $CO_2$-related cracking and mechanical properties are crucial parameters to the sucker rod's successful performance in a well. Although there is literature about sucker rods covering some of the - variables mentioned above , a set of secondary or unconventional metallurgical factors which have specific effects on mechanical properties that can aid in the sucker rod performance are the subject of this review. Some of the metallurgical variables discussed include sucker rod heat treatment, decarburization effects, thermal residual stresses, and the effect of carbon and other micro-alloying content on fatigue life. These unconventional metallurgical concepts and trends can aid in the process of continuous improvement of sucker rod manufacturing and new product offerings for a longer run life of the sucker rod.

## Introduction

The sucker rod pumping system is responsible for more than 75% of the production of total crude oil [1]. As a result, significant investments have been made by operators to optimize production. The sucker rod plays a vital role in the performance of the rod pumping system. Statistical correlations between metallurgical variables, mechanical properties and fatigue performance of sucker rods would be ideal but it becomes impractical due to the changes in downhole conditions from well to well. However, benchmark testing can aid in assessing the effect of unconventional metallurgical variables on susceptibility to failures. The difference in manufacturing processes and micro-alloying variations between sucker rod brands can determine the field performance of API grade D rods. Basic performance trends that correlate metallurgical attributes grade D sucker rods are presented in this paper.

## API Grade D Sucker Rod Classification

The API Specification 11B, 27$^{th}$ edition, has classified different grades of sucker rods to aid the sucker rod utilization by operators as well as the standards for manufacturers. In addition to dimensional requirements, API 11B has defined a specific requirement for chemical composition and mechanical properties for sucker rods made of steel alloys. Based on this classification, steel sucker rods are categorized into three main grades: K, C and D. Major parameters such as well depths (loads), wellbore fluids and its corrosiveness, production volume, operation time, etc. were influential on the API classification. Each grade has a specific category of AISI series steel. Grade D has the highest mechanical requirement in comparison to two other grades. Grade D special specifies a chemical composition that contains a combination of nickel, chromium, and molybdenum that total a minimum of 1.15% alloying content [2]. These three steel chemistry components are the subject of the fatigue tests for this paper. Table 1 displays the chemistry requirement by API 11B for grade D sucker rods.

Heat Treatment

Heat treatment is the process of heating a metallic part to a particular temperature, keeping it at that temperature for a certain amount of time, followed by cooling at a specific rate. The objective of heat treatment is to achieve desirable metallurgical and mechanical properties in a component that will be under stress in a corrosive environment. Figure 1 illustrates a basic schematic of the heat treatment process.

Steel alloy possesses different microstructural phases at various temperatures, pressures, and chemical compositions. The information concerning various steel phases is presented by phase diagram, also known as equilibrium diagram. The phase diagram displays specific microstructure of steel based on temperature and composition in equilibrium conditions. Figure 2 shows the phase diagram of steel with carbon as the main alloying element. Some of the heat treatment processes applicable to sucker rods that impact metallurgical and mechanical properties are briefly discussed in the following paragraphs.

Annealing is the process of heating the steel to temperatures in the austenite region, followed by slow cooling inside the furnace or by using any heat-insulating materials. The purpose of annealing is to soften the steel, reduce brittleness, refine the grains and reduce residual stress from steel forming processes. Annealing, however, is not typically part of sucker rod heat treatment, because it is a very slow process that could have commercial impact, due to the interruption of the continuous sucker rod production.

Normalizing is the process of heating steel to the austenite temperature, creating a uniform and fine microstructure. Normalizing is typically applied to hot forge steel alloy applications such as the case of sucker rod connections. As a result of the high temperature forging process, austenite grains usually coarsen and become non-uniform during the cooling stage from the forging temperatures. Reheating the steel during the normalizing process allows the microstructure to rearrange into a fine austenite grains. Since normalizing occurs at a much lower temperature than forging, grain growth inhibitors, e.g., vanadium typically do not dissolve at the normalizing temperature. Thus, during the cooling process, the resulting microstructure retains finer and more uniform grains from the austenite phase.

Hardening, also known as quenching, is the heat treatment process with cooling rate fast enough that the carbon, generally, does not have time to diffuse out of solution, instead, it stays trapped within developing a crystalline structure called martensite, which is a strong and hard microstructural phase. Quenching media are usually water, oil, and molten salt. Although the quenching process leads to a very strong phase, the hardened steel may have excessive brittleness and lack ductility. Consequently, another heat treatment process, called tempering, is done after hardening to increase ductility and also relieve residual stresses remaining in the steel due to the fast cooling process from the austenizing temperature. Tempering occurs by heating the steel below the lower critical line in the phase diagram, followed by air cooling, without austenite transformation during the tempering process. In addition to tempering, there is another heat treatment process done below the austenite temperature known as stress-relief annealing and is performed to remove residual stresses in the steel generated during cold working processes such as machining. Stress-relief annealing is carried out by heating parts to a temperature around 1000 $^0$F to 1200 $^0$F (below lower critical line in the phase diagram) following by slow cooling. Figure 3 represents some of these heat treatment processes.

The benefit of quenching and tempering is to achieve harder materials with microstructural phases such as martensite or bainite, depending on the cooling rate. However, fast cooling can cause distortion or cracking in sucker rods, primarily due to large aspect ratios (i.e., heat treating a 25-foot rod of ¾” diameter), the likelihood of distortion, bending or cracking for sucker rods is very high. Furthermore, with steel chemistry improvements for API grade D applications, normalizing and tempering can be engineered to obtain the toughness and fatigue performance to meet the well needs, while reducing the chances of microstructural distortion that could occur in the quenching process.

Heat treatment is a crucial step in the sucker rod manufacturing process, because it helps to achieve desirable microstructure and mechanical properties. Nevertheless, some side effects of heat treatment are discussed in some of the following sections of this paper and should be taken into consideration from the manufacturing perspective.

Thermal Residual Stresses

Some stresses remain in steel after the thermal manufacturing processes of grade D sucker rods. These stresses are known as thermal residual stresses which are caused by non-uniform plastic deformation created by thermal expansion and contraction, and/or by microstructural phase change. Heat treatment and hot forging are essential parts of sucker rod manufacturing process, but residual stresses are built up in the steel after these thermal processes. Thermal residual stresses can result in distortion or cracking and could eventually lead to premature failure, therefore, it needs to be monitored and managed carefully. Two types of changes occur during cooling of steel from high temperatures, one change is thermal volume contraction that happens during cooling of the steel without phase transformation, and the second change is cooling of the steel involving a phase transformation, such in the case of the transformation from austenite to ferrite/pearlite/martensite. Figure 4 illustrates the changes occurring during cooling with time and temperature in a rod specimen without the effects of the phase transformation. Initially there is no stress in the specimen (point A), but as it cools down, surface cools faster than the core and consequently, temperature difference develops between surface layers and core of the specimen. The surface contracts faster than the center, but the center acts as a restriction, putting the outer layers in tension as it seeks to shrink (point B). As the cooling time continuous, the core, which has been in compression from the contraction of the outer layers, cools down and contracts rapidly, releasing the applied compressive stresses from the outer layers (point C). The surface puts in compression on final cooling which is typically at room temperature (point D).

Cooling from high temperatures may also include a phase transformation, which is typically a change from austenite phase to other microstructural phases. This is the second source of residual stresses, nonetheless, the evolution of internal stresses is different. Figure 5 illustrates the residual stress formation due to cooling from austenite (it is assumed in this example that austenite transforms to martensite, but it can also transform to other phases such as bainite or ferrite/pearlite). Austenite is a closed-packed atom structure with face-centered cubic lattice. During cooling, it transforms to more open body-centered structure such as ferrite or martensite, therefore it evolves with volume expansion. As the surface cools down at a faster rate than the core of the rod, a new phase (e.g. martensite) forms and develops inwards in the radial direction. Because of the restraint of untransformed microstructure in the center of the rod, compressive stresses build up at surface layers (Figure 5b). Once the center of the rod also transforms to a new phase due to further cooling, the expansion of the center microstructure applies tension to the surface layers. The severity of these residual stresses depend upon the type of microstructural phase transformation.

Tensile residual stresses are detrimental to the steel components. It can cause cracking, distortion and premature failure of sucker rods. Any changes in processing that reduce differences in rates of cooling between surface and interior of part minimize the development of internal residual stresses. Furthermore, there are some heat treatment processes that are used for multiple purposes including the reduction of tensile residual stresses. For instance, for a hardened steel that have been fast quenched by forming phases such as martensite, tempering is the heat treatment used to decrease brittleness and tensile residual stresses of the as-quenched martensite microstructure.

Not all residual stresses are detrimental for sucker rod applications. Unlike tensile residual stresses, compressive residual stresses can be beneficial in improving steel surface attributes such as wear resistance or fatigue resistance. Fatigue cracks mostly initiate at the surface and compressive residual stresses on the surface can delay crack initiation and propagation during tension cycle loading, therefore improving fatigue life. Compressive residual stresses are applied to the sucker rod surface by processes such as carburizing or shot peening.

The sucker rods assessed for this study used a proprietary shot peening process called NorPeening®. This process is carefully controlled and monitored in regards to the shot peening media, intensity and coverage, to ensure a surface enhancement treatment that reduces sensitivity to fatigue and corrosion-related failures. Figure 6 illustrates the typical process of shot peening. Figure 7 quantifies the compressive residual stresses from the NorPeening® process measured through X-ray diffraction.

<u>Decarburization</u>

Decarburization occurs at elevated temperatures that allow carbon atoms to migrate from the surface of the rod, leaving a softer surface layer than the core of the steel. This condition reduces surface hardness, wear resistance, fatigue life and corrosion pitting resistance. Milling, rolling and additional processes such as hot forging, heat treatment all are done at high temperatures. Carbon atoms are much smaller compared to iron atoms, and they are placed interstitially among iron atoms. At room temperature, the iron atoms are stable in their position; however, by raising temperature, vibration of the iron atoms increases and facilitates a path for carbon atoms to migrate to the surface. The higher the temperature, the more amplitude of iron atoms' vibration, and the easier it is for carbon atoms to break through iron atoms. Figure 8 illustrates the atomic vibration of iron atoms and escape-path of carbon atoms. Carbon on the surface will react with scale on the steel surface which forms due to hot working operations such as hot forging or hot rolling, and escapes from the surface to the surrounding high temperature environment. The reaction below represents the carbon interaction with scales formed on the steel surface.

$$2Fe_2O_3 + 3C = 3CO_2 + 4Fe$$

In addition, in most high temperature steel operations exposed to the atmosphere air, oxygen molecules collide with steel's surface and react with carbon atoms. Typical interactions of carbon with oxygen molecules are represented by the following reaction.

$$C+O_2 = CO_2 \quad - \quad 2C + O_2 = 2CO$$

As decarburization occurs, the steel surface layer depletes its carbon. The carbon gradient starts from the surface to a depth in the where the carbon depletion ceases. The distance from the surface to the location where carbon is in its normal content is known as depth of decarburization.

Decarburization is measured by different techniques such as scanning electron microscope (SEM), micro-hardness and a localized chemical analysis. The SEM method is typically done by evaluation of a microscopical picture from the surface of the steel to a certain depth similar to figure 9, in which the condition of decarburization near surface contrasts with the subsurface. The micro-hardness method is also commonly used by measuring the hardness of surface area and subsequent subsurface layers. The reduced carbon on the surface would lead to lower hardness, and as additional micro-hardness measurements are taken towards the subsurface layers, the hardness increases up to the transition where decarburization has ceased. The localized chemical analysis technique is sometimes utilized to quantitatively measure amount of carbon on the surface and at different depths of the subsurface.

Due to high temperature exposure during sucker rod manufacturing processes, decarburization is almost unavoidable, but it can be controlled and minimized. A survey was taken on the decarburization condition of Norris grade D sucker rods and compared to decarburization of a sucker rod manufactured overseas. Two samples of the same grade of material were assessed; one in the as-rolled condition from the steel mill, and one in the forged and heat treated condition (normalized and tempered). The scanning electron microscope (SEM) method was used for the decarburization evaluation. The overseas sucker rod sample showed decarburization to depths up to 0.0047" as observed in figure 9. Figure 10 presents the decarburization condition of a Norris grade D sucker, indicating that no significant decarburization was observed in the samples representative of the as-rolled condition and after the forging and heat treating processes.

In order to maintain the decarburization effect at a minimum, the thermal manufacturing operations at Norris are continuously upgraded for tight temperature and environment controls. The furnaces have been engineered to minimize exposure to the atmospheric air. The heating system at the forging stage process has been carefully designed to avoid overheating that can lead to decarburization. In addition, the chemistry of Norris' API grade D sucker rods have been selected in the appropriate content to contain carbide forming elements that bond with carbon and minimize its diffusion out to the surface, and for other metallurgical purposes. Furthermore, any potential decarburization of the Norris API grade D sucker rods is offset by the NorPeening® process applied to the surface, which increases the strength of the steel in the surface up to a depth of 0.012-0.014".

## Effect of Steel Chemistry on Fatigue Life

Fatigue is the progressive, localized, permanent structural change that occurs to materials subject to cyclic and repeated loads, which gradually leads to failure. A fatigue failure occurs in three main stages: 1) initial fatigue damage leading to crack nucleation and crack initiation, 2) progressive cyclic growth of a crack (crack propagation) until the remaining un-cracked cross section of a part becomes too weak to sustain the loads imposed, 3) sudden fracture of the remaining cross section due to over load [3]. A large number of metallurgical and mechanical variables have been assessed for their effect in the steel's fatigue behavior; these factors include chemistry, strength level, ductility, residual stresses, grain size, and manufacturing processes affecting surface conditions. However, some of the context of the experimental data published does not pertain to the sucker rod pump industry and care should be taken when directly correlating these data to selection of sucker rod steels.

The effect of chemistry on fatigue life for rods in the as-rolled condition from the steel mill that could be used for API grade D sucker rod manufacturing was assessed on this paper. The heat treatment and manufacturing processes were skipped to study the effect of the steel chemistry only. Repeatability of the fatigue test results using multiple samples of the same as-rolled chemistry was within 5-10%. Carbon and a set of premium micro-alloying elements were selected for the study, and these represent a sample of each of the API D classifications, with varying carbon percentages, from low to medium carbon content. API 11B has classified a sub category of D special, which needs to have a minimum of 1.15% of combination of nickel, chromium and molybdenum. Nickel dissolves in microstructure and leads to solid solution strengthening that enhances strength and toughness, eventually increasing the fatigue resistance. Chromium and molybdenum are carbide forming elements and both increase the strength of sucker rod, higher strength generally increases the fatigue endurance limit. Figure 11 presents the sucker rod grades in the as-rolled condition, showing that the best performing chemistry was the low-carbon and high Nickel-Chromium-Molybdenum rod, followed by samples with higher carbon and lower micro-allowing content. The lowest fatigue life was found for the high carbon and low Nickel-Chromium-Molybdenum chemistry rod. These studies help the sucker rod manufacturers to evaluate the best steel chemistries for API grade D and other sucker rod premium applications.

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Table 1 – Chemical Composition of Grade D Steel Sucker Rods [2]

| **Grade** | **Chemical Composition** |
|---|---|
| D Carbon | AISI 10XX series steel |
| | AISI 15XX series steel |
| D Allloy | AISI 41XX series steel |
| D Special | Special alloy shal be any chemical composition that contains a combination of nickel, chromium, and molyndenum that total a minimum of 1.15% alloying content. |

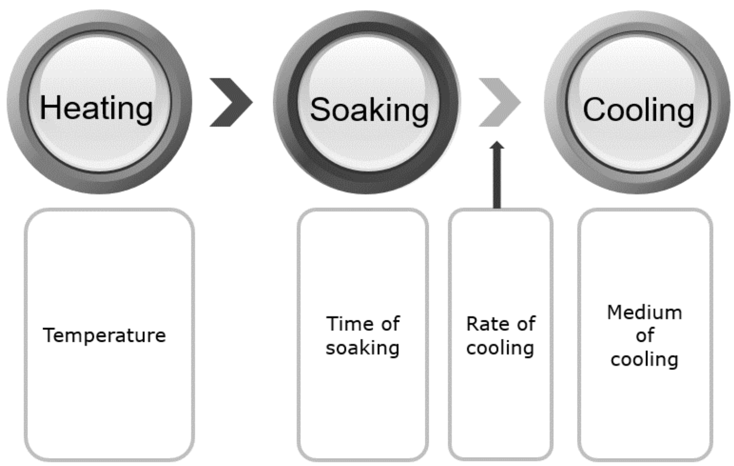



Figure 1 –Typical Heat Treatment Stages

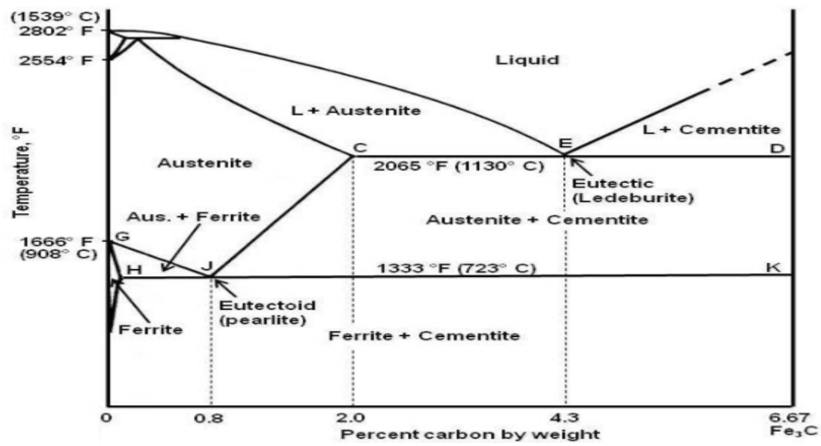



Figure 2 – Iron-Carbon Phase Diagram [4]

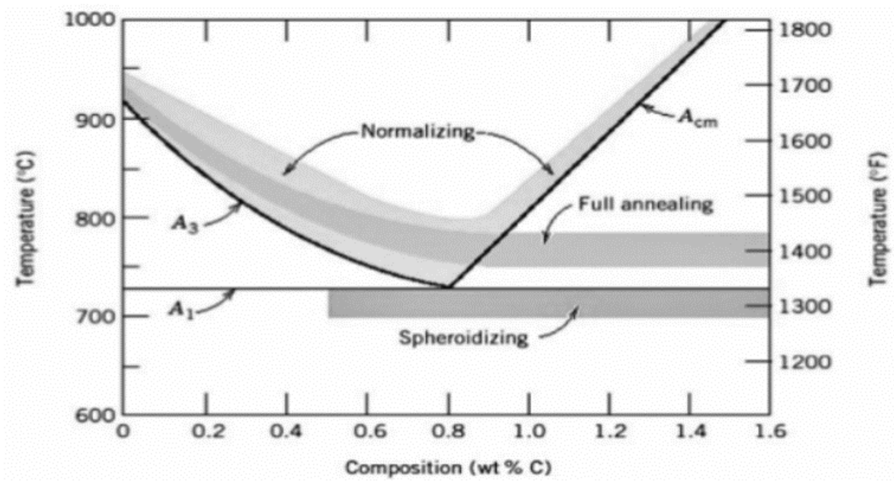



Figure 3 – Phase Diagram with Temperature Ranges for Different Heat Treatment Processes [5]

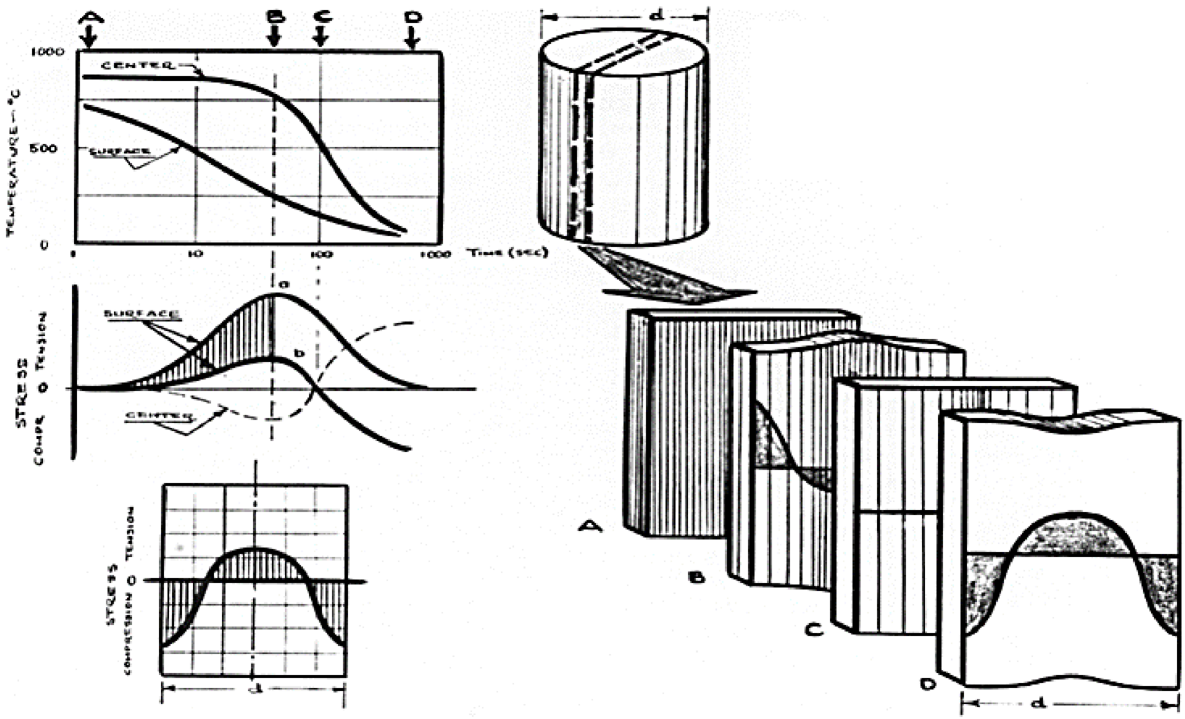



Figure 4 – Formation of Thermal Residual Stresses during Cooling without Phase (Austenite) Transformation [6]

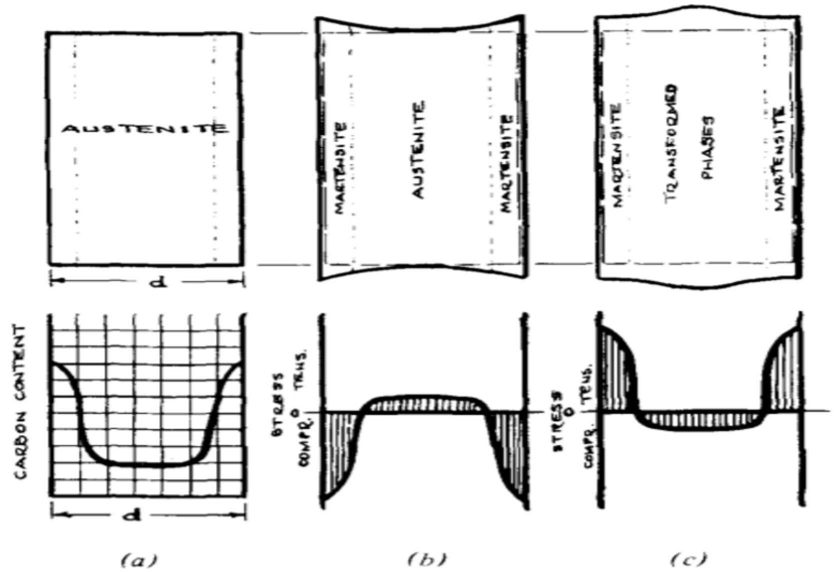



Figure 5 – Formation of Residual Stresses during Cooling with Phase (Austenite) Transformation [6]

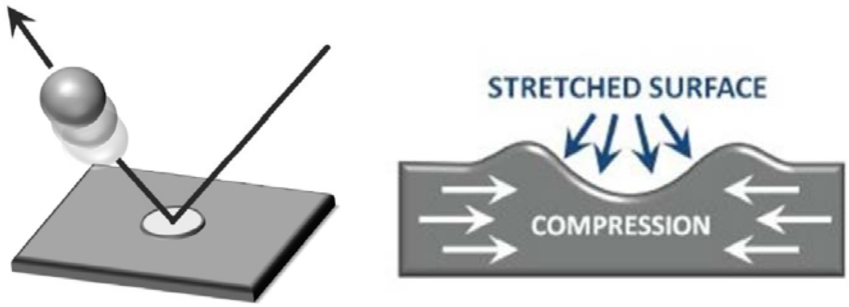



Figure 6a – Shot Peening Surface Application

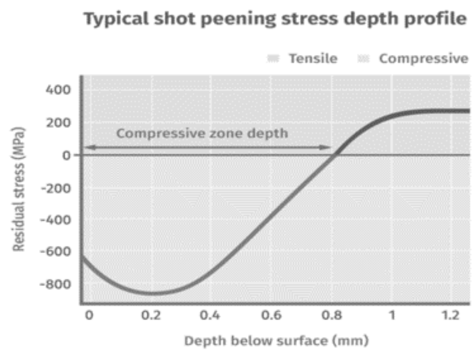



Figure 6b – Typical Effect of Shot Peening on Surface Residual Stresses [7]

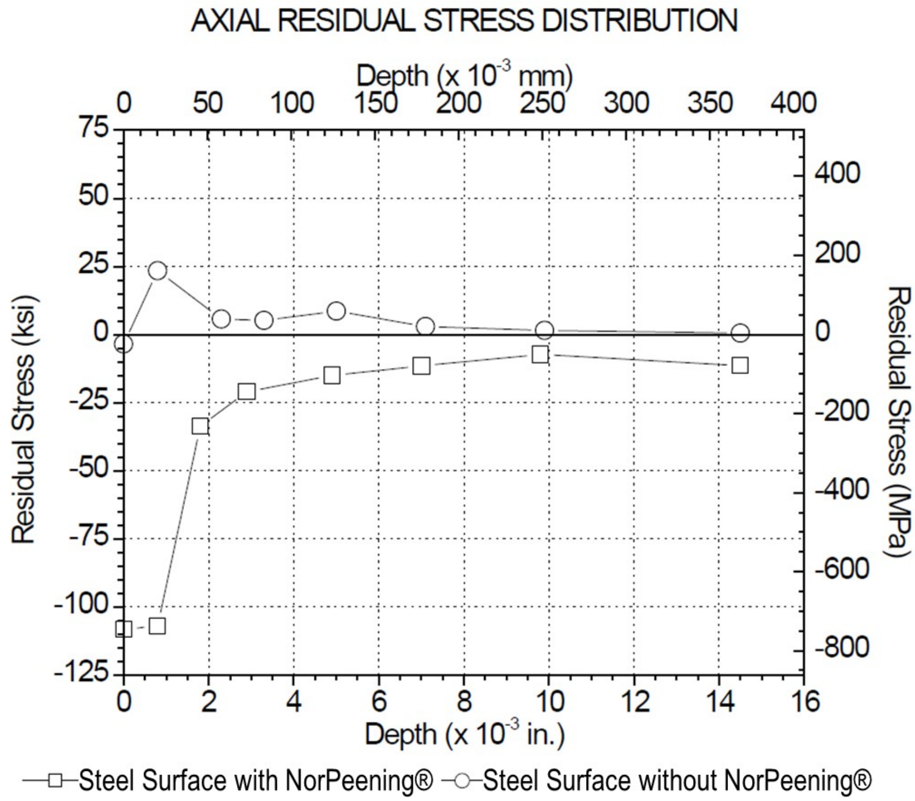
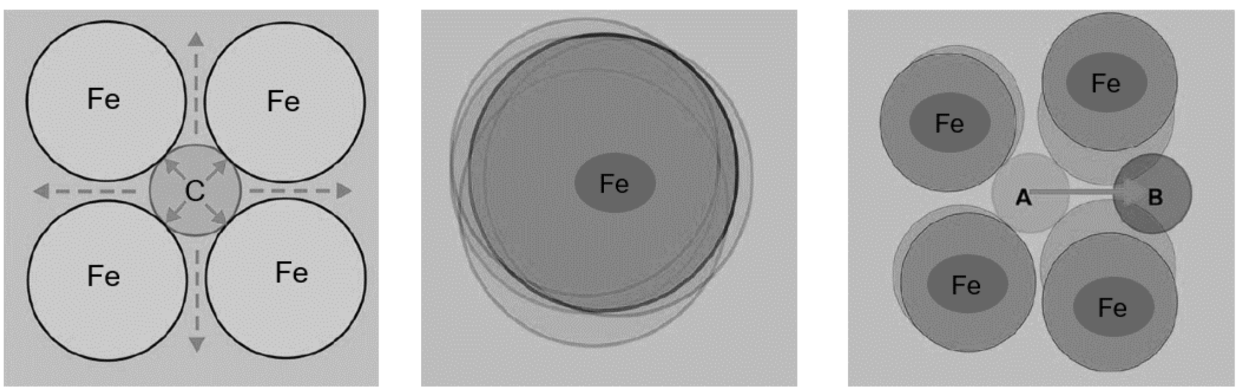



Figure 7 – Effect of the NorPeening® Process on Steel Surface Residual Stresses




(8a) (8b) (8c)

Figure 8 – a) Carbon Atom Trapped between Iron Atoms, b) Atomic Vibration due to High Temperature, c) Diffusion Path for Carbon Atom Previously Trapped Inside among Iron Atoms [8]

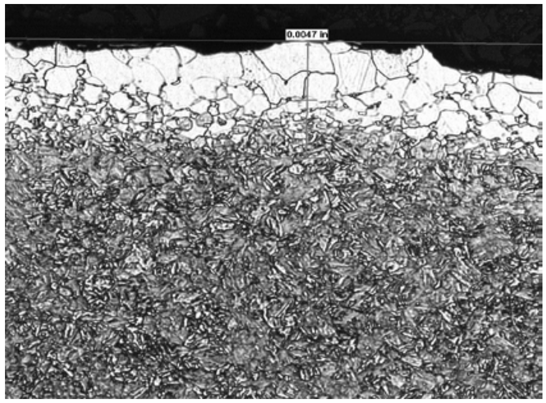
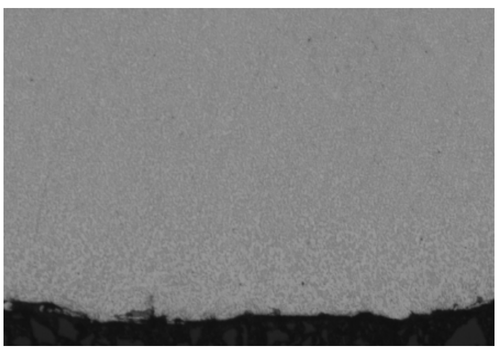
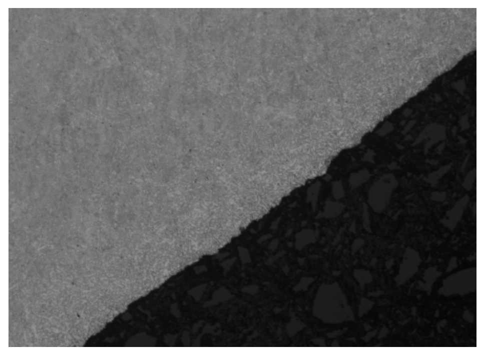



Figure 9 – The Microstructure of an Overseas Grade D Competitor Sucker Rod with Decarburization Layer of 0.0047”



Forged End Heat Treated



As-rolled Condition

Figure 10 – Decarburization Measurement of Norris Sucker Rod via Scanning Electron Microscope Evaluation

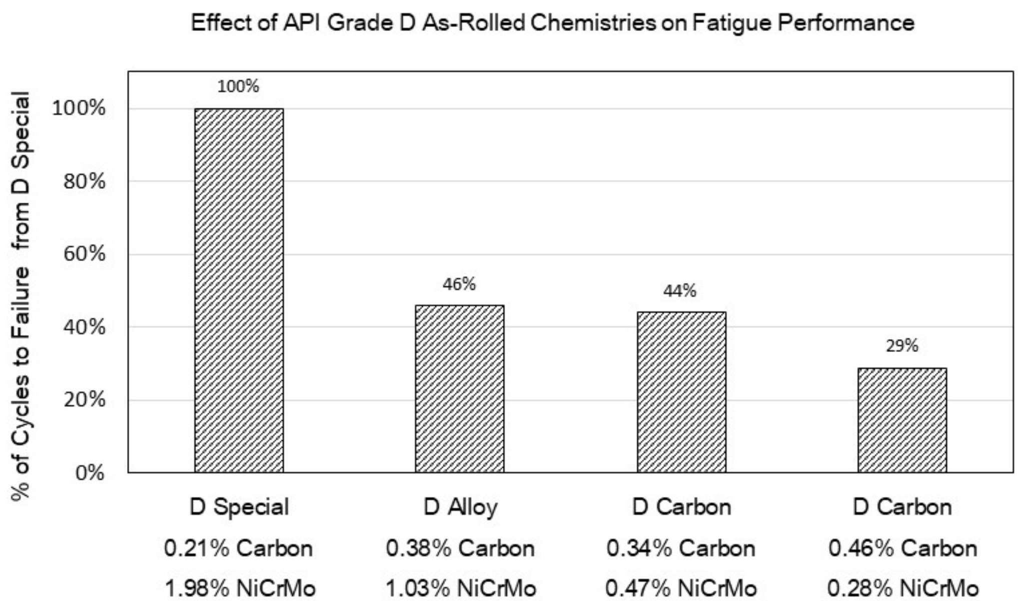



Figure 11 – Effect of As-Rolled API Grade D Chemistries on Fatigue Performance