UNDERSTANDING ROD LOADING

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Understanding rod loading is vital to reducing failure rates in reciprocating rod lift systems. By changing the minimum stress and using the modified stress analysis instead of the modified goodman diagram, manufacturers are "tricking" you into using high tensile strength and/or premium sucker rods in your rod designs. This presentation will attempt to explain rod loading and why most rod lift applications do not require or need high strength and/or premium sucker rods.

BRIEF HISTORY OF ROD LOADING CALCULATIONS

In the 1960's API developed a conservative method for rod load calculations based on the Goodman diagram. The Goodman diagram was originally developed using empirical data which accurately predicted the fatigue life (in air) of steel components. The API Task Force agreed upon a Modified Goodman Diagram (MGD) with a safety factor of two due to the lack of testing data for sucker rods in corrosive environments. The modified Goodman diagram was first published March 1969 in the API RP 11BR. This standardized loading calculations across all sucker rod manufacturers. Figure 1 shows the resulting diagram and equation.

DEVELOPMENT OF HIGH STRENGTH SUCKER RODS

Currently, high strength sucker rods are non-API. Typically, high strength rods meet API dimensional requirements but exceed API mechanical requirements. Oilwell introduced the first high strength case hardened sucker rod, which was patented in 1970. By 1974 the EL (case hardened sucker rod) was advertised as a 50,000 psi rod using the following alternate stress analysis (ASA) equation:

$$S_a = 50{,}000 \times SF$$

$$\%\ Rod\ Loading = (S_{Max} \div S_a) \times 100$$

By contrast using the MGD (T/4, 115,000/4), the maximum available stress for the API Grade D sucker rod is only 28,750 psi.

This allowed the EL to be used in applications where load calculations show that API rod grades are overloaded per the API 11BR MGD. Because this rod was patented by Oilwell their competitors had very few options that would enable them to develop a comparable sucker rod capable of higher loads. In the mid 1980's, Norris released the N97 high strength sucker rod to compete with the EL. The N97 was developed with a minimum tensile of 140,000 psi. If Norris used the MGD, they would be required to divide 140,000 psi by four, giving the T/4 value of 35,000 psi, still far below the EL's 50,000 psi. The lower stress value was still a problem for Norris. With the help of some fatigue testing, they developed their own equation, the modified stress analysis (MSA), to compete against the EL.

$$S_a = \frac{T}{2.8} + 0.375 \times S_{min}$$

If we take that 140,000 psi and divide by 2.8, we get:

$$S_a = 50{,}000 + 0.375 \times S_{min}$$

Changing the formula gave Norris a 50,000 psi rod to "compete" with the EL rod. This modified stress analysis (MSA) was adopted by other sucker rod manufacturers for their competing high strength rods. Today, the current manufacturer of the EL rod uses an updated version of the ASA:

$$S_a = (55{,}000 \div 0.2143 \times S_{min})$$

STEEL FATIGUE RESISTANCE

High strength rods were developed to handle higher loads, and in-air fatigue testing indicates that the increase in tensile strength will give a better fatigue/endurance life. Higher tensile strength steels can have a longer endurance life, but as the hardness increases, the endurance life of the material will only increase to a point. Once the steel has reached a specific hardness, steel fatigue life decreases, as shown in Figure 2.

Developing higher strength steels requires additional alloying elements, especially carbon. Carbon is the most important alloy element and is used to increase the tensile strength, yield strength and hardness of steel. However, with increasing carbon content, comes a decrease in the percentage of elongation, reduction of area and a decrease in the impact resistance of the steel. This results in a reduction of toughness and ductility i.e., the ability of the steel to tolerate a stress riser. This is illustrated in Figure 3.

SUCKER ROD OPERATING STRESS

API 11BR, Ninth Edition, 3.1-3.3 states:

> *"The selection of API grade sucker rods for a beam pump installation depends on a variety of factors, including stress effects, environmental effects, and rod grade.*
>
> *Sucker rods need to be selected based on applied stresses. API 11L, Design Calculations for Sucker Rod Pumping Systems provides a procedure for calculating the applied loads or stress on a sucker rod string design.*
>
> *Sucker rod strength is limited by the fatigue performance of the rod's metal. This useful strength is dependent on the metal's tensile strength as shown by Goodman (Goodman, "Mechanics Applied to Engineering" and Kommers, "Effect of Range of Stress and Kind of Stress on Fatigue Life"). This relationship is the basis for Section 4 of this document. According to the Goodman diagram shown in Figure 1, sucker rods operating in a non-corrosive environment and in the proper stress range will theoretically exceed 10 million load reversals. However, the fatigue life can be dramatically decreased by improper installation, design, handling or operation even without corrosion."*

The Modified Goodman Diagram is utilized in modern wave equation design programs such as SROD™, Rodstar™ and QRod™. Since these programs utilize the MGD for API grade sucker rods, they give a conservative value for rod stress. Since high strength sucker rods are non-API, manufacturers of these products utilize the other stress loading calculations such as the ASA or the MSA. Figure 4 illustrates the chemical and mechanical requirements for API grade rods in *Specification for Sucker Rods, Polished Rods and Liners, Couplings, Sinker Bars, Polished Rod Clamps, Stuffing Boxes, and Pumping Tees, API 11B*, Twenty-Seventh Edition, May 2010. If we were to apply a modified stress calculation such as the MSA to API grade rods, we would see a significant reduction in percent of rod loading and a significant reduction in the need for high strength rods.

INFLUENCE OF CORROSION

API 11BR, Ninth Edition, 4.1 recommends using service factors to derate rod stress values in corrosive environments.

> *"Since all well fluids are corrosive to some degree, if not inhibited 100%, and since the corrosivity of well fluids varies greatly, it is of extreme importance that the stress values determined from this diagram be adjusted by an appropriate service factor, based on the severity of the corrosion. This service factor should be selected by each user as his experience indicates. It could be greater than one, although normally it will be less than one, varying inversely with severity of corrosion."*

This recommendation in *API 11BR*, Ninth Edition, 4.1 causes an increase in the percentage of rod loading for API grade rods and influences end users to utilize high strength sucker rods in more applications. However, all high strength sucker rods are more susceptible to corrosion fatigue due to the higher tensile strength and corresponding increase in notch sensitivity of the steel. This causes smaller stress risers, such as very small corrosion pits, to initiate cracks more rapidly as indicated in Fontana, Mars G. *Corrosion Engineering,* McGraw-Hill, 1987*,* pg 142:

> *"Corrosion fatigue can be prevented by a number of methods. Increasing the tensile strength of a metal or alloy improves ordinary fatigue but is detrimental to corrosion fatigue. In the case of ordinary fatigue resistance, alloys with high tensile strength resist the formation of nucleating cracks. It should be noted however, that once a crack starts in a high strength material, it usually progresses more rapidly than a material with a lower tensile strength. During corrosion fatigue, a crack is readily initiated by the corrosive action; hence the resistance of high tensile strength material to corrosion fatigue is quite low."*.

FAILURE HISTORY

Understanding the MGD, the influence of high strength rods, steel fatigue resistance, and the influence of corrosion, summarizes what experience has shown in most sucker rod applications. Failure analysis of thousands of high strength sucker rods typically show small or very small corrosion pits acting as stress risers, causing premature corrosion fatigue failures in high strength rods. An example of small corrosion pits causing a failure in a HS rod is illustrated in Figure 5. Because API D special (DS, also known as KD sucker rods) rods have a lower carbon content, higher chromium and nickel, and lower hardness, DS rods are less susceptible to corrosion fatigue. The question is: can these rods support higher loads (high strength applications) without premature failure? In the early 1990's several West Texas oil production companies, worked with a manufacturer to substitute grade DS sucker rods in high strength applications. This substitution resulted in a significant increase in run time and the determination that service factors were not beneficial to run life when designing a rod string for a corrosive environment.

Due to the success of this trial, grade DS rods became the standard substitution to high strength rods when loadings were within the maximum percentage of available stress utilizing the MSA:

$$S_a = \frac{T}{2.8} + 0.375 \times S_{min}$$

As an example, when the MSA is applied equally to API grade rods, the need for high strength rods decreases. Figure 6 shows stress calculations values using MGD versus MSA.

CONCLUSION

With field experience and knowing the limitations to increasing the tensile strength and hardness of sucker rods to values over current maximum API values, API grade sucker rods can be utilized for higher load applications than what is recommended in the current API 11BR. Although there is a need for high strength sucker rods, most end users are not aware of the application limitation of design programs using the modified goodman diagram for API rods. Using the MGD (T/4) users can safely use service factors up to 1.3 on API grade rods before utilizing high strength rods. This is equivalent to using the MSA (T/2.8) with a service factor up to 0.90 on API grade rods. The authors have utilized this method for almost 30 years with great success and have been able to help end users lower their failure rate and decrease operational costs. It is highly recommended that that when a sucker rod does fail, the cause of the failure is correctly identified, and a solution is determined that will prevent recurrence of the failure. Using the correct grade of sucker rod for your application may be the first step in preventing corrosion related failures.

REFERENCES

1. For more information see Norman W. Hein, Jr and Russell Stevens. 2010. *Sucker Rod String Service Factors*, Southwest Petroleum Short Course
2. *Recommended Practice for the Care and Handling of Sucker Rods*, API 11BR, August 2008, pg 1.
3. Chart is found in *Recommended Practice for the Care and Handling of Sucker Rods*, API 11BR, August 2008, pg 3.
4. Boyer, Howard E, Atlas of Fatigue Curves, American Society of Metals, 1986, pg 84
5. *Metals Handbook Desk Edition*, Second Edition, JR Davis, Editor, pg 164

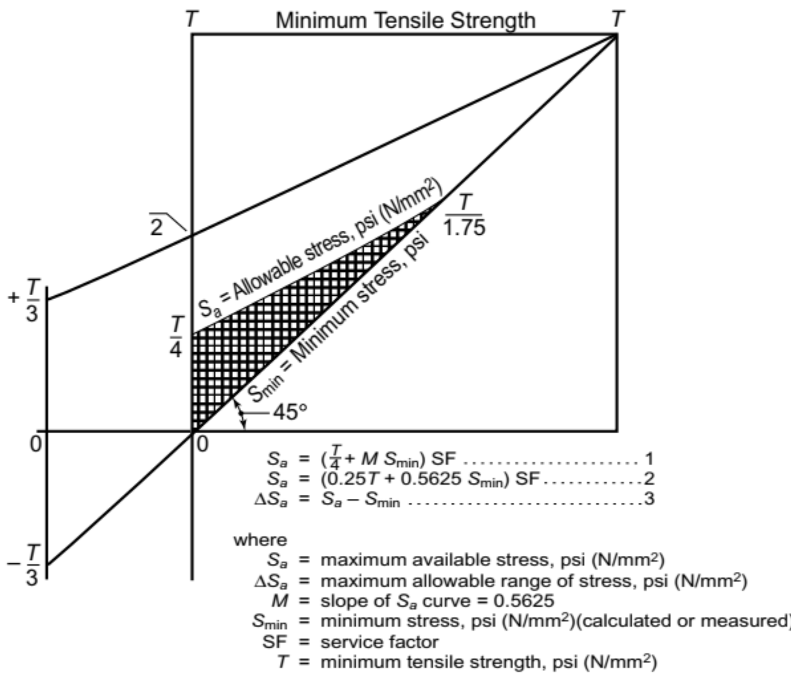
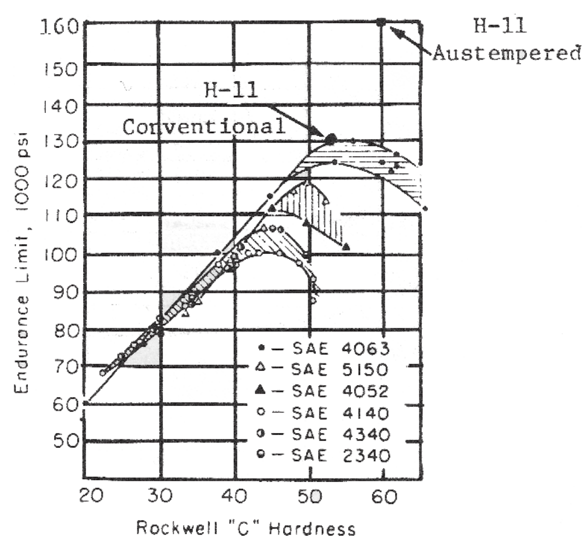


Figure 1. API Modified Goodman diagram.

4-2. Medium-Carbon Alloy Steels, Six Grades
Hardness vs Endurance Limit



Relation of hardness and fatigue strength for several steels.

Figure 2. Endurance life of hardness (HRC) vs. steel.

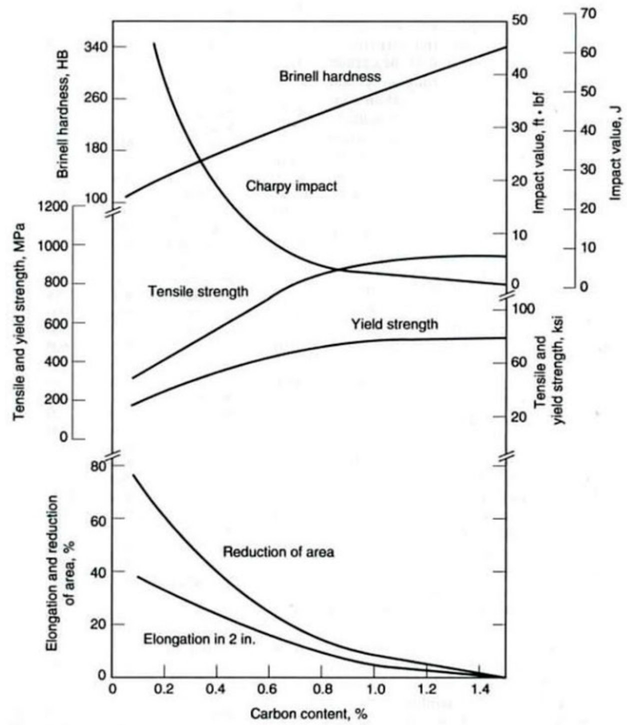


Figure 3. Chart showing % carbon content vs hardness, tensile, yield, elongation, impact and R of A.

API Grade	Chemical Composition	Minimum Yield 0.2% Offset (psi)	Minimum Tensile (psi)	Maximum Tensile (psi)
K	AISI 46XX	60,000	90,000	115,000
C	AISI 10XX AISI 15XX	60,000	90,000	115,000
D Carbon	AISI 10XX AISI 15XX	85,000	115,000	140,000
D Alloy	AISI 41XX	85,000	115,000	140,000
D Special	Special alloy with total combined minimum of 1.15% of nickel, chromium, and molybdenum	85,000	115,000	140,000

Figure 4. API 11B sucker rod steel requirements.

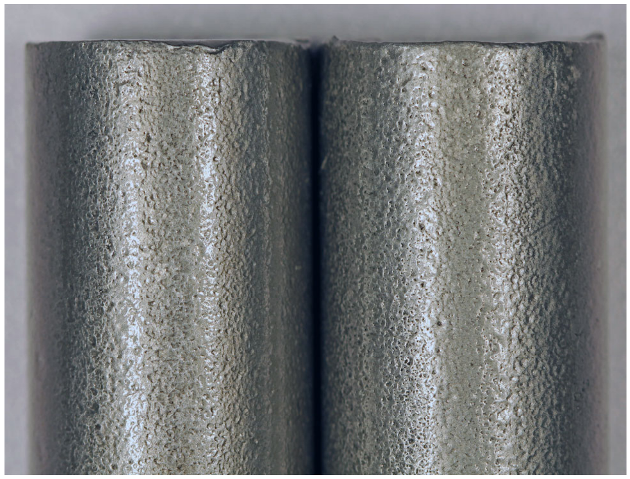


Figure 5. Rod part on a high strength sucker rod. Note small corrosion pitting.

Grade DS (115,000 / 4)		Grade DA (120,000 / 4)		Grade DS (115,000 / 2.8)		Grade DA (120,000 / 2.8)		Grade DXS (125,000 / 2.8)		Grade HA/HS (140,000 / 2.8)	
SF	% Rod Load	SF	% Rod Load	SF	% Rod Load	SF	% Rod Load	SF	% Rod Load	SF	% Rod Load
1.0	**126**	**1.0**	**119**	**1.0**	**88**	**1.0**	**83**	**1.0**	**79**	**1.0**	**69**
0.9	150	0.9	141	0.9	102	0.9	97	0.9	92	0.9	79
0.8	186	0.8	174	0.8	123	0.8	116	0.8	110	0.8	94
0.7	244	0.7	227	0.7	154	0.7	144	0.7	136	0.7	115
API MGD (T/4)				Non-API MSA (T/2.8)							

Where S_{max} = 42,507 and S_{min} = 13,981

Figure 6. Comparison of MDG vs MSA