*Romanian Journal of Petroleum & Gas Technology*
*VOL. IV (LXXV) • No. 1/2023*

# SUCKER RODS STRING DESIGN – RODS FATIGUE BEHAVIOR INTERPRETATION USING GOODMAN DIAGRAM

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**DOI: 10.51865/JPGT.2023.01.02**

## ABSTRACT

During the standard pumping of an oil well, the sucker rods are subjective to alternative stress (tensile and compression). Certain steel grades have different behavior, taking into consideration their mechanical properties, like tensile strength. While most operators consider that, the higher the ultimate tensile strength (UTS) of a material is, it will behave better when subjected to loads. This paperwork shows that, comparing three different steel grades, they may have different results on the Goodman diagram, than expected.

We are going to show that, even the steel grades have the same tensile strength (115 ksi), when calculating the %Goodman, the steel have different behavior, and this results from the manipulation of coefficients “A” and “b” involved in the formula, that each sucker rods manufacturer validates.

**Keywords:** sucker rods, string design, Goodman diagram, rods failure mechanism, sucker rods selection

## THEORETICAL CONSIDERATIONS

In the lifecycle of an oil well, it reaches a moment when it is not able to flow naturally anymore, an artificial lift system is installed in the well. By using different technologies of lifting, the oil is brought to the surface. There are several artificial lift systems used in the oil and gas industry: gas lift, plunger lift, electric submersible pumps, but the most used system is the sucker rods pumping.

The sucker rods pumping system consists of surface unit, wellhead, tubing string, sucker rods string and the downhole pump (fig. 1).

The sucker rods string connects the surface unit to the downhole pump, its main purpose being to transmit the movement generated by the surface unit to the downhole pump (fig. 1).

A typical sucker rod string contains polished rods, short sucker rods (pony rods), standard sucker rods, sinker bars (heavy sucker rods), couplings.

A sucker rod is a steel bar, 25 or 30 ft long, with mechanically deformed ends and threaded pins. The rods are connected through couplings and form the sucker rods string. When transmitting the movement from the surface units to the downhole pump and lifting the oil to surface, the sucker rods are subjected to different loads, thus need to comply with certain mechanical properties.

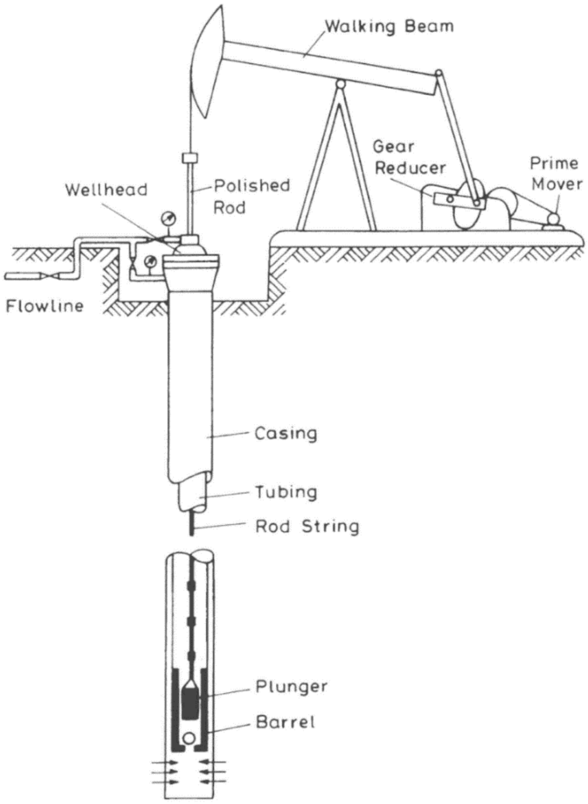


***Fig. 1*** *Sucker rods pumping system [1]*

The industry requirements for sucker rods characteristics (dimensional, steel grades and mechanical properties) are presented in the API 11B standard, as shown in Table 1.

***Table 1***. *Chemical composition of sucker rods steel grades [2]*

| Grade | Chemical composition |
|---|---|
| K | AISI 46XX series steel[a] |
| C | AISI 10XX series steel[a] |
| | AISI 15XX series steel[a] |
| D Carbonf | AISI 10XX series steel[a] |
| | AISI 15XX series steel[a] |
| D Alloy | AISI 41XX series steel[a] |
| D Special | Special alloy shall be any chemical composition that contains a combination of nickel, chromium, and molybdenum that total a minimum of 1.15% alloying content |
| a Or an equivalent international series number steel | |

The mechanical properties of the steels mentioned in Table 1 are presented in Table 2.

***Table 2.*** *Mechanical properties of sucker rods steel grades [2]*

| Grade | Minimum yield (0.2% offset) | | Minimum Tensile | | Maximum Tensile | |
|---|---|---|---|---|---|---|
| | psi | MPa | psi | MPa | psi | Mpa |
| K | 60000 | 414 | 90000 | 621 | 115000 | 793 |
| C | 60000 | 414 | 90000 | 621 | 115000 | 793 |
| D | 85000 | 586 | 115000 | 793 | 140000 | 965 |

The industry has become more and more demanding, requiring for the pump to be placed at higher depths, thus, during the pumping cycle, to withstand higher loads. The sucker rods manufacturers address this need by developing high strength sucker rods, designed reservoirs fluids, that can be corrosive or efficiently inhibited.

This paperwork presents the main considerations for sucker rods selection and string design, with special attention on the materials fatigue resistance behaviour and interpretation on Goodman diagram.

## SUCKER RODS FATIGUE ANALYSIS USING GOODMAN DIAGRAM

In non-corrosive environments, the lifespan of a sucker rod string is determined by the fatigue resistance of the rods steel grades. A fatigue failure represents a type of failure which occurs in structures and components when they are subjected to dynamic or alternating stresses, therefore, in the case of sucker rods, the fatigue resistance depends on the stress applied during the pumping cycle.

Failure characteristics:

- Failure occurs at a stress level considerably lower than the tensile or yield strength for a static load.
- The failure usually takes place after a long period of repeated stress cycling. The material becomes "tired"

The fatigue failure is generated when plastic (permanent) deformations occur the structure of the material. These deformations start generally in the steel grains next to the material surface by stress concentrations caused by deformations on it and they are propagated through cracks. When the area remaining is not able to withstand the loads that it is subjected to, it generates a failure.

The failure is produced suddenly and with just few deformations on the metal surface but having a failure origin, a propagation zone and the final fracture (fig. 2).

During the pumping cycle, the sucker rods string is subjected to a series of loads and stress, which vary along the string length. Some of the loads are static, generated by the weight of the string itself, fluid column that acts against the pump and by friction forces, while other loads are dynamical generated by the systems that are moving. [4]

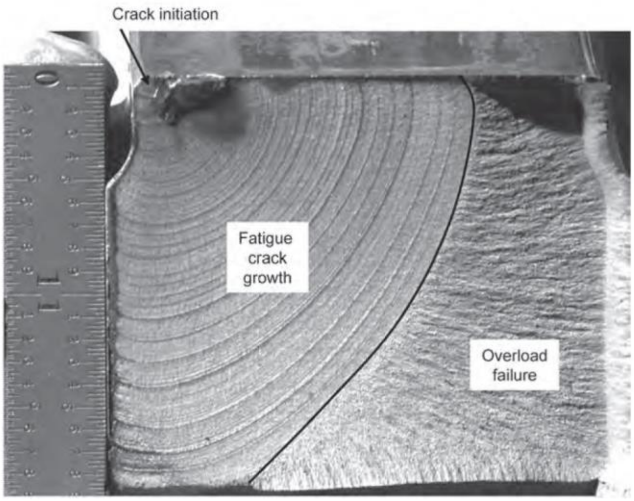


***Fig. 2*** *Failure stages [2]*

To prevent the appearance of fatigue failures during the pumping cycle, the stress on the sucker rods body is evaluated by using Goodman diagram. This method is also presented in the API RP 11BR - Recommended Practice for Care and Handling of Sucker Rods, which recommends the usage of modified Goodman diagram for determining the allowable stress on steel sucker rods, which is taking into consideration only the mechanical properties of the steel grade. For corrosive reservoirs, the outcomes from the application of Goodman diagram are no longer feasible, as other factors like corrosion; fluid turbulences, erosion, wearing, etc affect the steel.

The fatigue performance of the materials can be characterized through an S-N curve, also known as a Wohler curve. This is often plotted with the cyclic stress (S) against the cycles to failure (N) on a logarithmic scale. S-N curves are derived from tests on samples of the material to be characterized (often called coupons or specimens) where a regular sinusoidal stress is applied by a testing machine which also counts the number of cycles to failure. This process is sometimes known as coupon testing. For greater accuracy but lower generality component testing is used.[1]

Analysis of fatigue data requires techniques from statistics, especially survival analysis and linear regression. A series of test samples are put under a symmetric alternate cycle and the number of cycles to failure is measured. When reducing the load, the sample will resist a greater number of cycles (without samples or cycle modification).

The graphic of this results is what is called the ***Wöhler diagram*** (fig. 3). Steels have an asymptotic behaviour when reducing stresses (Fatigue Limit - $\sigma_D$). [2]

Figure 3 shows that, theoretically, under the same applied stress, the steel grades reach a certain point called “Fatigue limit”. After reaching that point, and under the absence of external factors, they could withstand an infinite number of cycles.

But, during the pumping cycle, the sucker rods may not be always subjected to positive stress. In some cases, due to design characteristics, the sucker rods can be compressed.

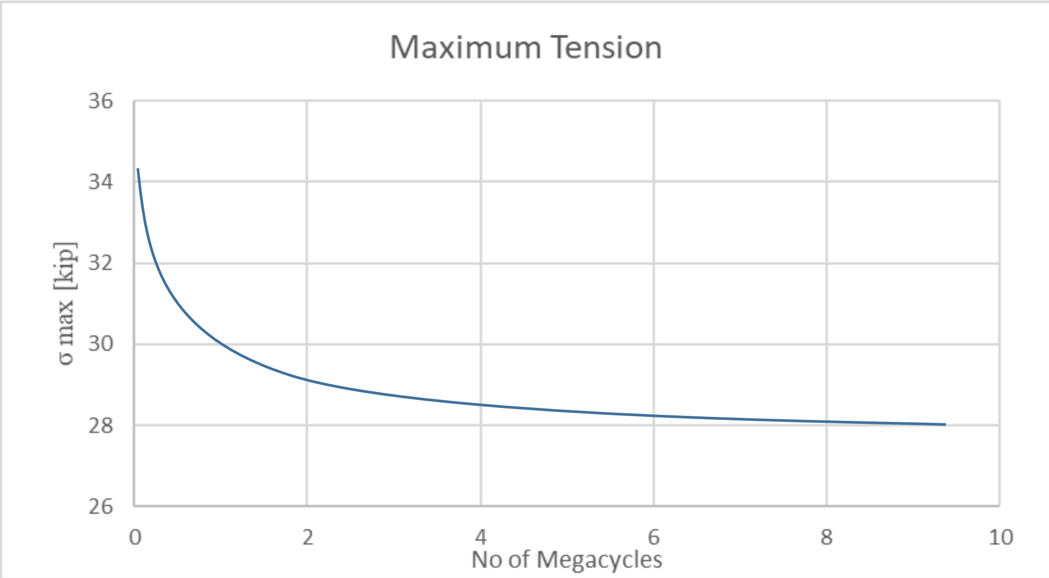


***Fig. 3.*** *S-N Curve [2]*

Below is presented how the compression influences the fatigue limit, through the usage of Stress Ratios (fig. 4):

R=Stress Ratio,

$R=S_{min}/S_{max}$,

$S_{min}$ – minimum stress; $S_{max}$– maximum stress

The stress ratio R becomes negative when the material is placed in compression.

Effect of the stress ratio (R) on the fatigue limit:

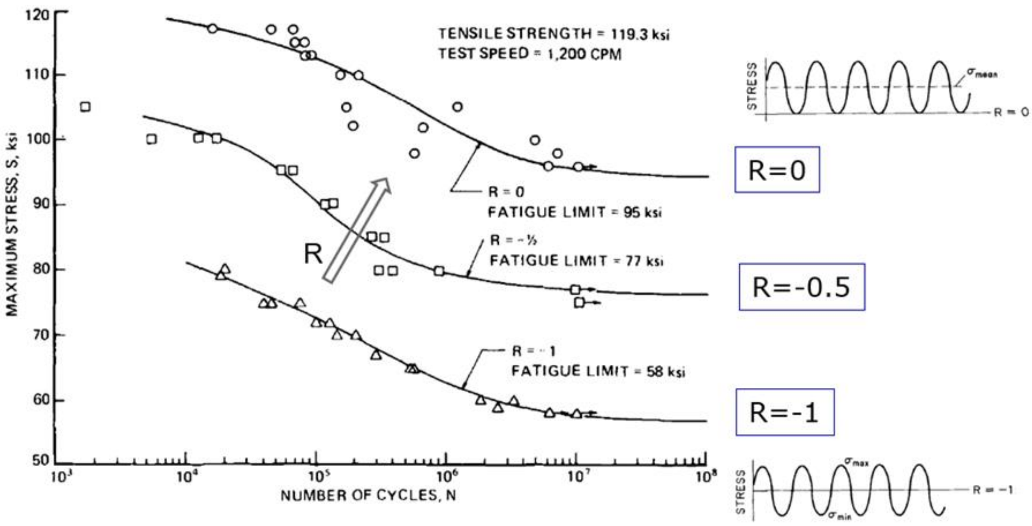


***Fig. 4*** *Stress ratio impact [3]*

Another important aspect when performing a sucker rods string design is for the material not to be in negative stress. When the sucker rods are subjected to compression, their fatigue limit decreases considerably. (fig. 4, R=-1)

Goodman gathered and generalized all Wöhler tests results and made the Goodman diagram that establishes a secure working area for every material depending on the stress cycle.

The Goodman diagram has been modified considering Hardy considerations:

- $S_{max}$ < YS
- $S_{min}$ < 0 not allowed

  (to avoid buckling)
- Includes a SF (have in mind environments)
- Establishes the Admissible Stress Curve (**$S_{adm}$**). An $S_{max}$ vs $S_{min}$ diagram is used.

YS=Yield Strength [psi]

In order to calculate the Allowed Working Area it's necessary to calculate Admissible Stress for the used Sucker Rod Grade.

This allows us to determine the stress level (%) for the sucker rods.

The calculations are the following. For API 11B Grades:

$$S_{adm} = \left(\frac{UTS}{A} + b * S_{min}\right) * SF \tag{1}$$

$$\%\ Goodman = \frac{(S_{max} - S_{min})}{(S_{adm} - S_{min})} * 100 \tag{2}$$

$S_{adm}$: Max. Admissible Working Stress (psi)

UTS: Ultimate Tensile Strength (ksi)

$S_{min}$: Minimum Stress – to be identified on dynamometer card (psi)

$S_{max}$: Maximum Stress – to be identified on dynamometer card (psi)

SF: Service Factor

A, b: Coefficients, defined by API as:

A=4;

b=0.5625

We are going to show a calculation example, using the Admissible Stress and Goodman formulas.

The $S_{min}$ and $S_{max}$ are specifically values for a certain oil well and can be read on the dynamometer card. An example of a polished rod dynamometer card is shown in fig. 5, from which the Peak Load and Min Load can be read and based on the rod size (7/8"), the stress $S_{max}$ and $S_{min}$ can be calculated.

- OD for 7/8" rod = 22.23 mm

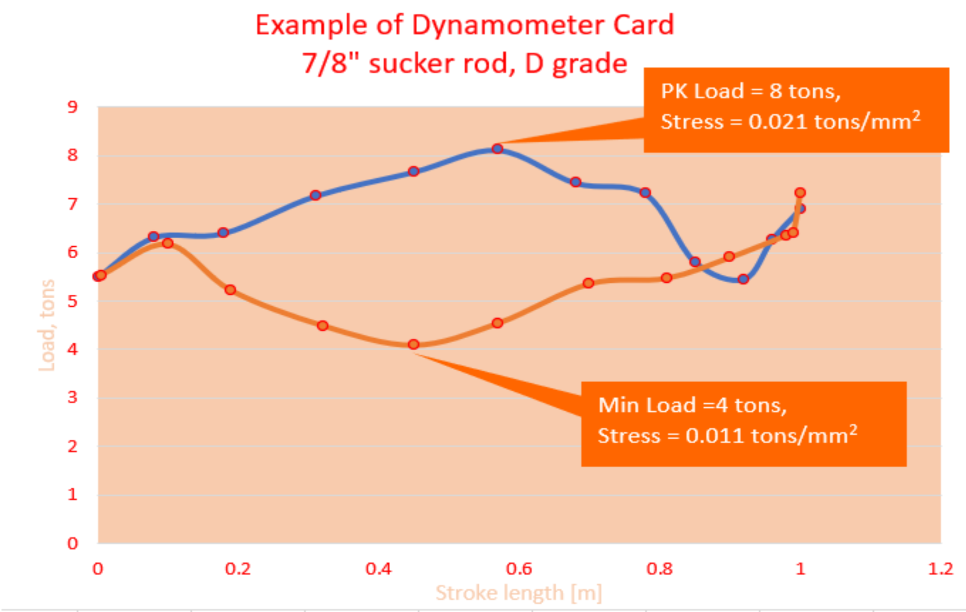


***Fig. 5*** *Dynamometer cards for polished rod*

Using the Goodman formula, the Working Diagram for a sucker rod D grade, having the mechanical properties according to the API 11B standard and the coefficients according to API 11BR – Recommended Practice, has the representation from fig. 6.

Data:

UTS= 115 ksi

YS=85 ksi

A=4; b=0.5625

SF=1

Applying the Goodman formula, through the Admissible Stress ($S_{adm}$), we define the safe working Area for the D grade, considering different values for S min:

$$S_{adm} = \left(\frac{UTS}{A} + b * S_{min}\right) * SF \tag{3}$$

The following points have been represented:

| $S_{min}$ | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 65 | 71.5 | 77 |
|---|---|---|---|---|---|---|---|---|---|---|
| $S_{adm}$ API | 30.0 | 35.6 | 41.3 | 46.9 | 52.5 | 58.1 | 63.8 | 66.6 | 70.2 | 73.3 |

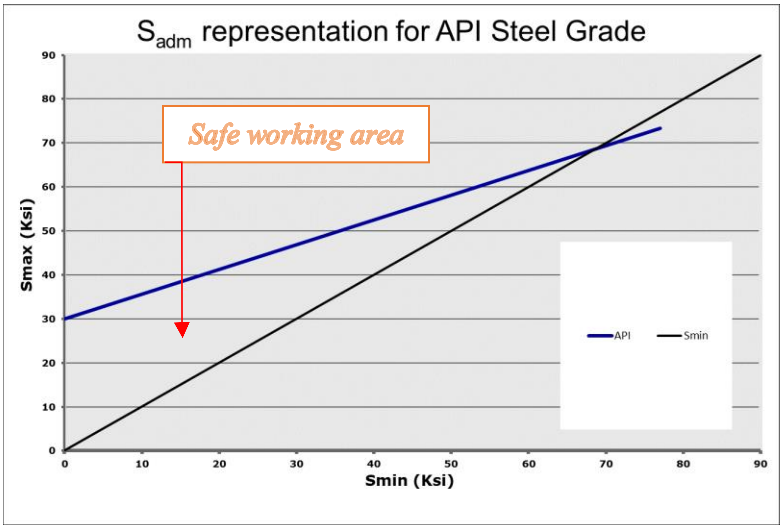


***Fig. 6*** *Admissible Stress for an API D Rod*

The diagram (fig. 6) has been created in Microsoft Excel and defines the working area where the sucker rods might perform without failure, therefore in elastic behavior, under a certain range of stress. For the sucker rods, the % of stress resulting from using Goodman formula, to be below 100%, the admissible stress $S_{adm}$ must be in the safe area (fig. 6).

If we are considering a minimum load $S_{min}$=15100 psi and a Maximum Stress $S_{max}$ = 29700 psi we place them in fig. 6, resulting the fig. 7 below:

$S_{min}$ = 15100 psi

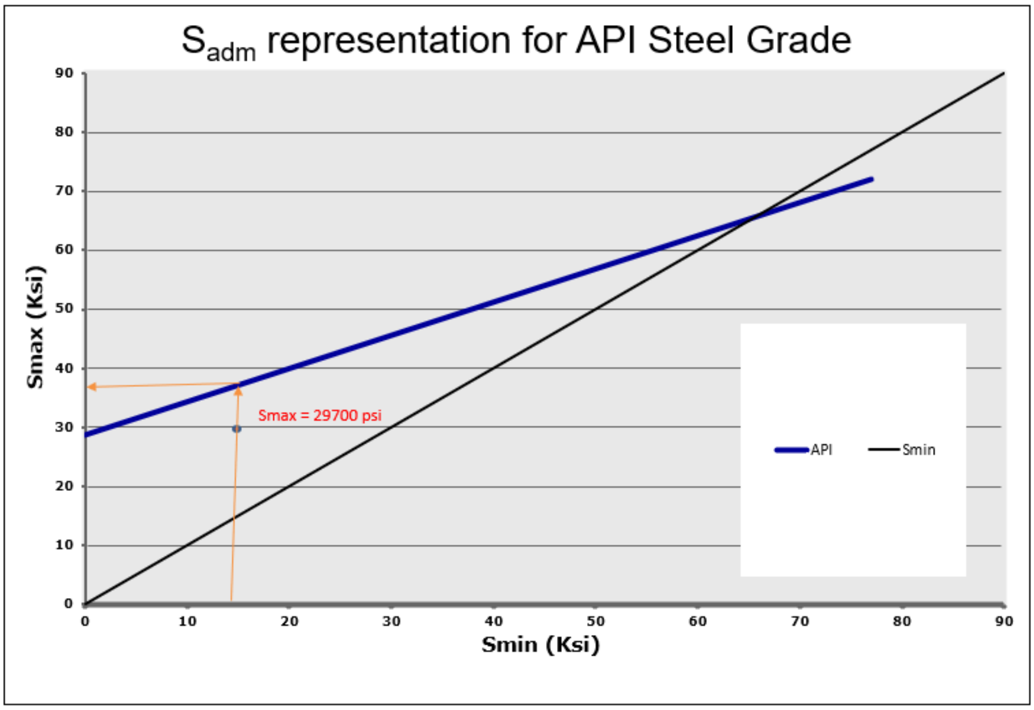


***Fig. 7*** *Calculation example on the diagram*

The data represented in fig. 7 is calculated below:

- First, the $S_{adm}$ is calculated:

$$S_{adm} = \left(\frac{UTS}{A} + b * S_{min}\right) * SF \tag{4}$$

It results:

$$S_{adm} = \left(\frac{115000}{4} + 0.5625 * 15100\right) * 1 = 37243\ psi \tag{5}$$

By applying the Goodman formula,

$$\%\ Goodman = \frac{(S_{max} - S_{min})}{(S_{adm} - S_{min})} * 100 \tag{6}$$

It results:

$$Rod\ Loading = \frac{29768 - 15100}{37243 - 15100} = 66\% \tag{7}$$

## GOODMAN FORMULA – INFLUENCE OF COEFFICIENTS "A" AND "b" IN ADMISIBLE WORKING AREA

The coefficients involved in the $S_{adm}$ calculation can be modified, therefore, the Goodman method has suffered, over the years, different modifications. The coefficients are playing a major role in determining the $S_{adm}$ for a steel grade, therefore, there will be different results among steel grades having similar mechanical properties range.

Below, we have built presented a comparison among 3 steel grades: an API grade, a Steel grade 1 and a Steel grade 2. Their Ultimate Tensile Strength (UTS) remains the same = 115 ksi, but the "A" and "b" coefficients are modified.

Coefficients "A" and "b" are pre-defined for the API Steel grades. For Steel Grade 1 and Steel Grade 2, we have considered lower values. There is no restriction in terms of selecting the coefficients, if there have been performed mechanical tests of the steel grades and they are validating the results, so for the below analysis, the coefficients have been decreased.

***Table 3.*** *Steel grades features – different factors*

| Feature | API Steel grade | Steel grade 1 | Steel grade 2 |
|---|---|---|---|
| **YS** | 85 | 110 | 110 |
| **UTS** | 115 | 115 | 115 |
| **Factor A** | 4 | 2.6 | 2.8 |
| **UTS/A** | 29.5 | 45.4 | 42.1 |
| **Factor b** | 0.5625 | 0.375 | 0.375 |
| **SF** | 1 | 1 | 1 |

Using the Excel file already mentioned, we have calculated the Admissible Working Area ($S_{adm}$) for each of the above-mentioned Steel Grades, and are presented in Table 4.

***Table 4.*** *Steel grades features – different factors*

| $S_{min}$ | $S_{adm}$ | | |
|---|---|---|---|
| | **API** | **Steel Grade 1** | **Steel Grade 2** |
| **0** | 28.8 | 44.6 | 41.1 |
| **10** | 34.4 | 48.4 | 44.8 |
| **20** | 40.0 | 52.1 | 48.6 |
| **30** | 45.6 | 55.9 | 52.3 |
| **40** | 51.3 | 59.6 | 56.1 |
| **50** | 56.9 | 63.4 | 59.8 |
| **60** | 62.5 | 67.1 | 63.6 |
| **65** | 65.3 | 69.0 | 65.4 |
| **71.5** | 69.0 | 71.5 | 67.9 |
| **77** | 72.1 | 73.5 | 69.9 |

The diagram shows that, for the Steel Grade 1 (Green line), there is a larger window of application in terms of stress, as it has the lowest "b" coefficient.

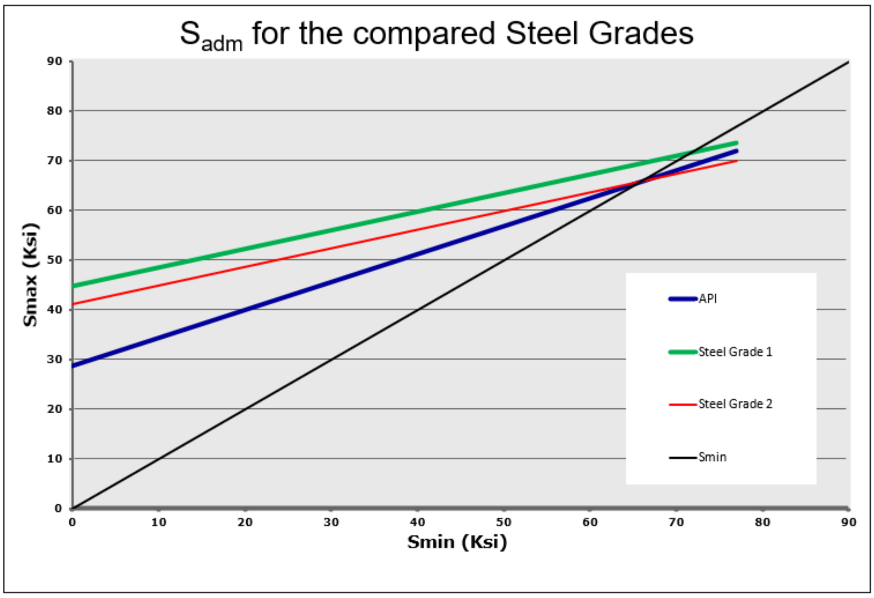


***Fig. 8*** *Goodman diagram for the compared steel grades*

To understand the behavior of each steel grade in certain points in the Admissible Stress Diagram from fig. 8 – Points A, B and C have been selected, that are inside Safe Working area for Steel Grade 1 and Steel Grade 2, but outside of the Safe Working Area for API D grade, as shown in fig. 9:

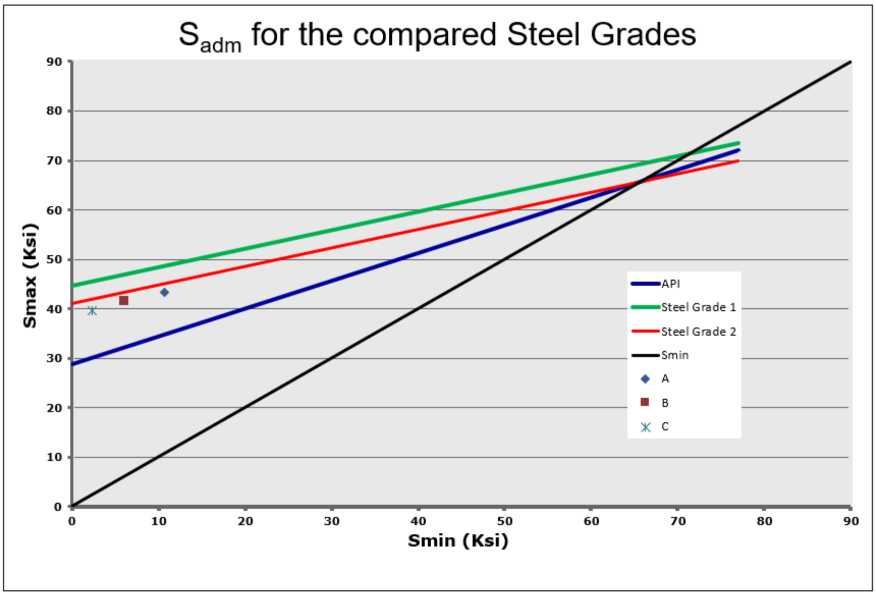


***Fig. 9*** *Goodman diagram for the compared steel grade – with 3 points selected*

The value of the points are presented the Table 5, and for these points we are going to calculate the percent of loading for each steel grade, using the Goodman formula (Table 6).

***Table 5.*** *Points selected on the diagram to verify the %Goodman*

| Point | $S_{min}$ (ksi) | $S_{max}$ (ksi) |
|---|---|---|
| **A** | 10.7 | 43.3 |
| **B** | 6.1 | 41.5 |
| **C** | 2.3 | 39.6 |

The loading values calculated by using Goodman method are the following:

***Table 6.*** *%Goodman calculated for each steel grade, considering points A, B and C*

| %Goodman | | |
|---|---|---|
| **API Steel Grade** | Steel grade 1 | Steel grade 2 |
| **135%** | 85.8% | 95% |
| **136%** | 86.7% | 95% |
| **135%** | 86.4% | 94% |

When applying the Goodman formula, to the selected points, we have noticed Steel grade 1 withstands the stress better than API and Steel grade 2, and much better than API D Grade, even though all steel grades have similar Tensile Strength (115 ksi). This demonstrates the fact that, when selecting a sucker rod steel grade for a certain application, in terms of stress resistance, it is not necessary to select a steel grade with high tensile strength (UTS), but to bear in mind that there are other mechanical features that may influence the material behavior of the sucker rods in deep wells, when they are subjected to dynamic loads.

It is important to mention that the coefficients "A" and "b" cannot be modified for API Steel Grades, but the sucker rods manufacturers have the possibility of adjusting these coefficients for their proprietary steel grades, if there are laboratory tests that show improvement in the sucker rods fatigue behavior.

Not included in this analysis, but it worth mentioning that the stress resistance of a material can be increased by applying a certain heat treatment, that will generate an improved microstructure. During the pumping cycle, the material is subjected to different types of stress: tension and compression. Therefore, the thinner microstructure a steel has, it requires more energy to break the connections among the grains, thus the material will behave better under stress and fatigue conditions.

## CONCLUSIONS

- During pumping cycle, the sucker rod string is subjected to tensile and compression forces.
- Dynamometer cards and software usually give us the stress level for the upper sucker rod of each taper (the most stressed one).
- Modified Goodman diagram gives a secure working area for each sucker rod steel grade.
- This diagram represents the tensions and not with loads.
- What can be noticed is that, even though the tested materials are having similar mechanical properties (same UTS = 115ksi), there are sucker rods which can behave better under stress – Steel Grade 1, thus, based on field results, the coefficients "A" and "b" that are part of the Admissible Stress formula can be modified. Therefore, the percentage of stress shown when using Goodman formula, will be different.
- Every sucker rod working in a well has a place in this diagram that belongs to a stress level (% of Goodman).

## REFERENCES

[1]. Gabor Takacs, Sucker-Rod Pumping Manual, PennWell Books, Tulsa, Oklahoma, ISBN: 0-87814-899-2, 2003.

[2]. API 11B: Specification for sucker rods, polished rods and liners, couplings, sinker bars, polished rod clamps, stuffing boxes and pumping tees, pages 21, 22, 83. 2010.

[3]. Tenaris Technical Assistance, OMV Petrom String Design Workshop, April 2017

[4]. https://petrowiki.spe.org/Sucker_rods/

Received: December 2022; Accepted: January 2023; Published: January 2023