FATIGUE-ENHANCING PERFORMANCE PROCESS INCREASES THE OPERATIONAL RANGE OF SUCKER RODS

Tony O'Neal and Rodrigo Ruiz

TRC Services Inc.

ABSTRACT

The fatigue performance of sucker rods is directly influenced by their manufacturing processes and material properties. Shot peening has emerged as a key enhancement technique, offering significant improvements in fatigue resistance. Over the past decade, this process has been increasingly recognized for its potential to enhance sucker rod performance, prompting discussions on its inclusion in the API 11BR modified Goodman diagram. TRC Services has been a leader in implementing shot peening, particularly in remanufactured rods, compiling extensive data through laboratory and field testing.

Historically, shot peening has been associated with increasing fatigue life within a fixed stress range. However, a shift in evaluation criteria has led to a deeper exploration of how shot peening impacts stress tolerance at a predetermined fatigue life expectancy. Recent testing has shown that properly optimized shot peening can significantly expand the operational stress range of sucker rods, surpassing the limits of standard new rods. These findings suggest that advanced shot peening techniques contribute to a broader application scope for sucker rods, improving operational performance and reducing failure risks.

This paper details the testing methodology, fatigue life evaluation, and the operational advantages of adopting advanced shot peening technology.

INTRODUCTION

Sucker rods play a crucial role in sucker rod pumping systems, operating under continuous cyclic loading, making fatigue failure a significant concern. Enhancing fatigue resistance is key to improving efficiency, reducing failures, and lowering operational costs. Shot peening has emerged as a widely recognized method for increasing fatigue resistance in various industries, including artificial lift applications.

Shot peening introduces beneficial compressive residual stresses into the rod surface, counteracting the tensile stresses responsible for fatigue failure. This process has been widely adopted in aerospace and automotive industries due to its ability to enhance fatigue performance. In the sucker rod industry, its effectiveness has driven discussions about modifying the API 11BR Modified Goodman diagram to account for these improvements[4].

This study builds on previous research[2,3], expanding the evaluation of shot peening from extending fatigue life to improving load tolerance at a fixed fatigue life expectancy with the latest MPACT shot peening recipe. Comparative testing between shot-peened and untreated rods, new and used, demonstrates the operational benefits and potential modifications to standard rod design criteria.

SHOT PEENING TECHNOLOGY AND ITS EFFECT ON FATIGUE LIFE

Understanding Shot Peening

Shot peening is a controlled surface treatment process that enhances fatigue resistance by introducing a layer of compressive residual stress. This is achieved by bombarding the surface with spherical media, inducing plastic deformation that counteracts tensile stresses, which are the primary cause of fatigue failures.

The process involves precisely controlling several parameters, including shot size, material, velocity, and coverage. The primary goal is to develop a uniform layer of compressive stress that delays crack initiation and mitigates fatigue propagation. The effectiveness of shot peening depends on factors such as the material properties of the rods, the hardness of the shot media, and the peening intensity. In optimized conditions, shot peening introduces a surface stress state that significantly improves the endurance limit of sucker rods, allowing them to withstand more demanding operational conditions.

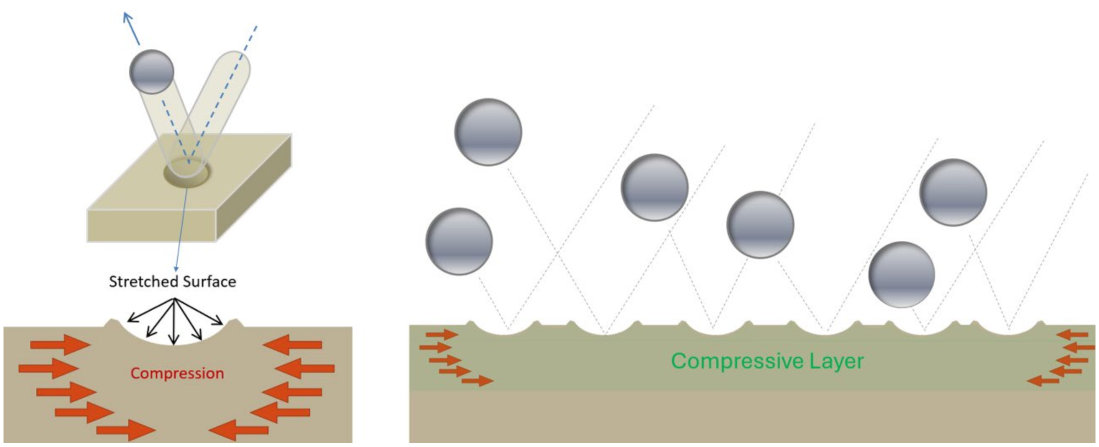


Fig 1. Schematic of shot peening process inducing a residual compressive stress.

One key advantage of shot peening is its ability to improve fatigue resistance without altering the base material composition or heat treatment process. By refining the residual stress profile, it increases the operational life of components that experience cyclic loads.

In sucker rods, shot peening has been applied to reduce fatigue failures, particularly in high-stress applications. The technique has proven effective across multiple industries and continues to gain adoption in artificial lift applications.

Advancements in Shot Peening for Sucker Rods

Over the years, advancements in shot peening technology have resulted in significant improvements in fatigue resistance, specifically for sucker rods. These advancements have been driven by deeper research into the mechanics of residual stress development and optimization of processing parameters, which combined results in a specific recipe. Some of the most notable improvements include:

- Advanced Media Selection
- Precision Peening Intensity Control
- Optimized Surface Coverage
- Process Customization for Sucker Rod Applications
- Residual Stress Profiling and Validation
- Fatigue Testing

These advancements collectively enable sucker rods to operate at higher stress levels while maintaining fatigue resistance. By refining the peening process, the industry continues to expand the limits of what can be achieved with shot peening, making it an essential tool in extending the operational lifespan of sucker rods and reducing failure rates in demanding applications.

Recent advancements in shot peening technology have resulted in significant improvements in fatigue resistance:

- **Enhanced Process Control:** Optimized shot size, velocity, and impact distribution ensure consistent application and improved fatigue performance.
- **Optimized Stress Profiles:** Proper management of peening parameters reduces stress concentrations, leading to better load-bearing capacity.
- **Higher Stress Tolerance:** Advanced shot peening techniques allow sucker rods to operate under increased loading conditions without sacrificing fatigue life.

EXPERIMENTAL TESTING AND DATA ANALYSIS

Testing Methodology

To assess the impact of advanced shot peening, **rotating bending stress tests** were conducted. This testing method provides controlled cyclic loading conditions, offering a comparative analysis between shot-peened and untreated rods.

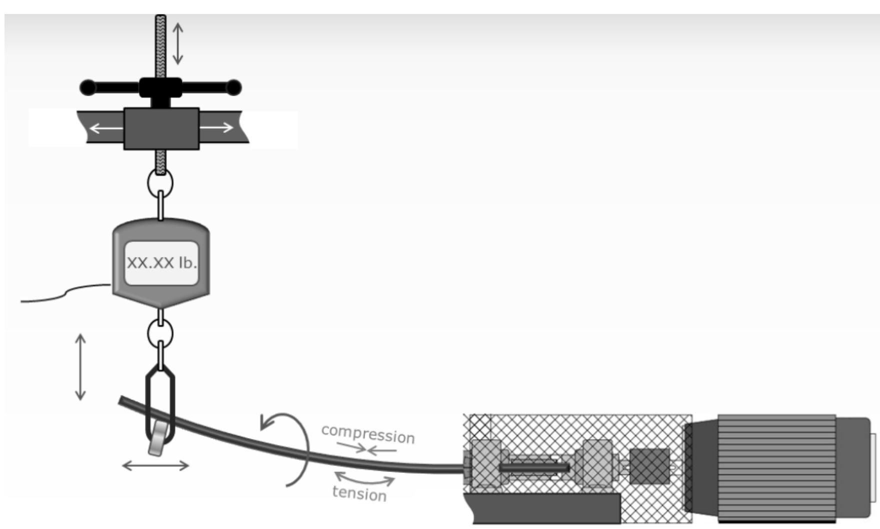


Fig 2. Schematic of the rotating bending stress fatigue machine used for the evaluation.

Results and Discussion

The test results highlight a substantial improvement in fatigue life for shot-peened rods compared to untreated rods. These findings are based upon previous research conducted in Tony O'Neal's 2012 study[1], which demonstrated the effectiveness of shot peening in increasing fatigue life.

In O'Neal's initial study, rotating bending fatigue tests showed that shot-peened new sucker rods exhibited an average of **67% increase in fatigue life** compared to untreated rods under identical loading conditions. The data confirmed that introducing compressive residual stresses through shot peening significantly delayed crack initiation and propagation. In the case of used sucker rods, the average was about **72% increase in fatigue** life.

Testing Scope Change: Evaluating Load Capacity at Fixed Fatigue Life

Building on O'Neal's results, the testing method was redirected to explore the other intrinsic shot peening benefits and **evaluate stress tolerance at a set fatigue life expectancy**. Testing was conducted under controlled conditions, maintaining a constant fatigue life while increasing applied stress (building S-N curves to determine each rod's fatigue endurance limit).

Key observations include:

- **Stress Increase for Constant Life:** when compared to the best performer "KD" new sucker rod in a constant stress fatigue life test, the MPACT shot-peened rods demonstrated an **average stress capacity increase of 32%** at the same fatigue life compared to "as received" new rods (shot peened by the manufacturer recipe).

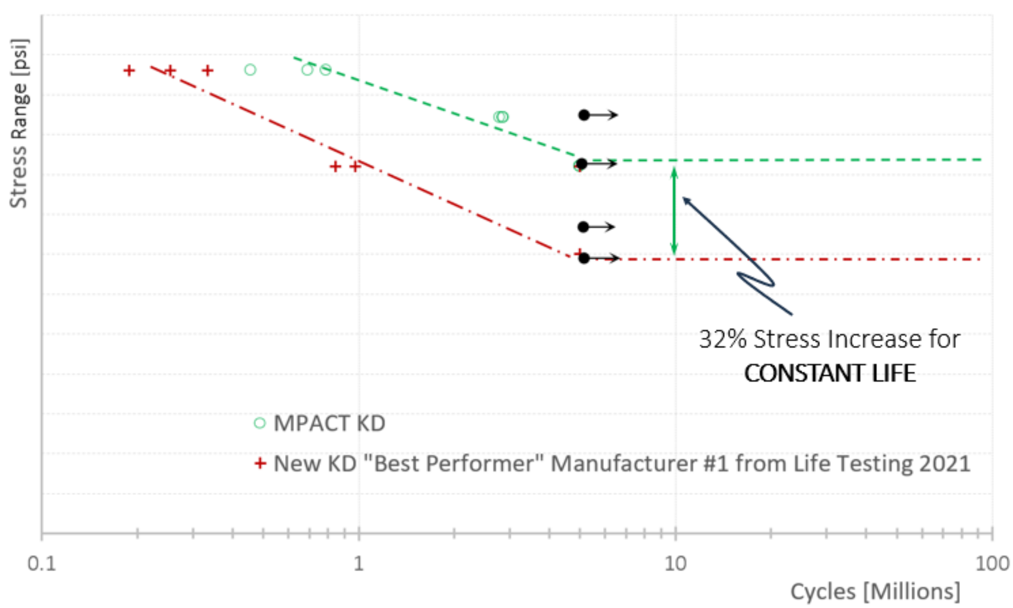
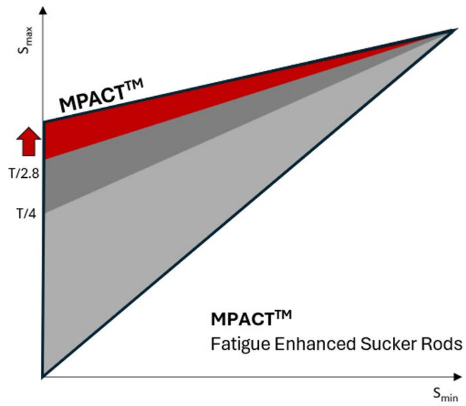


Fig 3. Constant Fatigue Life (S-N) Testing: Best new rod fatigue life performer KD versus MPACT KD.

- **Expansion of the Modified Goodman Diagram Range:** The ability to sustain higher alternating loads while maintaining expected cycle performance supported the development of a new Modified Goodman Diagram (MGD). The testing results were used to develop a unique MGD admissible load equation for each rod grade.



$$S_{adm} = MPACT_{Constant\#1} + MPACT_{Constant\#2} * S_{min}$$

***Equation constants defined by Fatigue Testing for*

Fig 4. New Proposed Modified Goodman Diagram describing the expansion in the loading capacity due to the introduction of the MPACT fatigue testing results.

The combination of these results with the original findings from O'Neal's study reinforces the role of advanced shot peening in enhancing sucker rod durability and stress performance. The test results highlight a substantial improvement in fatigue life for shot-peened rods compared to untreated rods.

- **Extended Fatigue Life:** Shot-peened rods exhibited a significantly higher cycle count before failure.
- **Increased Load Capacity:** Peened rods demonstrated a higher tolerance to operational stress, allowing for optimized string design.

APPLICATION IN ROD STRING DESIGN

Modified Goodman Diagram Evolution

The Modified Goodman Diagram has traditionally been used to define allowable stress ranges for sucker rods. However, the introduction of advanced shot peening has supported the opportunity to expand these safe fatigue stress limits. Testing results show that shot-peened rods can sustain higher stress range while maintaining expected fatigue resistance, justifying potential modifications to API design criteria.

String Design Cases

Sucker rod string design is the technical technique used to address load requirements in a sucker rod pumping system, with an emphatic focus on the limitations of the sucker rod string capacity to lift fluids at a certain depth. String design commercial software utilizes a solution to a unidimensional wave equation to assess the cyclic nature of the load on a sucker rod string. The Modified Goodman Diagram is then utilized at the end of the process to verify the loading exposure for the string is within the recommended load capacity defined by either a manufacturer or the API.

Below is a series of comparative rod string designs highlighting the benefit of implementing the new MPACT MGD on typical operating examples.

Example#1:

- Operating Parameters: 10,000 ft, 1 1/2” pump, 192in stroke at 6 SPM -> 200 bpd
- String Design Software Used: RODSTAR
- Well Type: Deviated

Case#:

1. **API D or KD (T/4) vs. MPACT-C/K:** MPACT-C/K demonstrated a reduction in load demand of an average of 25% for this example. When the same case is compared to D or KD using T/2.8 MGD the MPACT-C/K is close but showing around a 10% overload. C or K sucker rods present themselves as a viable alternative as they are less susceptible to sulfide stress cracking, a common initiator of cracks that lead to a progressive corrosion fatigue process.

Rod string design (rod tapers calculated)				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	D (API)	2675	115000	123.3%	43356	17170	11022	API MG
0.875	D (API)	2700	115000	123.5%	41403	12841	8751	API MG
0.75	D (API)	4175	115000	123.8%	39594	8723	951	API MG
@ 1.5	C (API, SB)	450	90000	55.7%	11176	-1784	-340	API MG

Rod string design (rod tapers calculated)				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	TRC MPACT - C	2525	90000	98.7%	-24.6% 43027	16986	11145	Straight Line
0.875	TRC MPACT - C	2600	90000	98.3%	-25.2% 41904	13085	9155	Straight Line
0.75	TRC MPACT - C	4425	90000	98.2%	-25.6% 40895	9417	1058	Straight Line
@ 1.5	C (API, SB)	450	90000	55.4%	11159	-1724	-340	API MG

Example#2:

- Operating Parameters: 10,000 ft, 1 3/4” pump, 192in stroke at 8 SPM -> 400 bpd
- String Design Software Used: RODSTAR
- Well Type: Deviated

Case#

2. **KD T/2.8 vs. MPACT-KD**: MPACT-KD shows a reduction in loading demand of 22% compared to New KD rods at T/2.8 MGD. Implementations of this benefit go into not needing to go into a harder steel (KDP, HS), increasing the production range of the whole

system or re-design it to lower the load requirements to the point that allows the operator to reduce the size of the pumping unit.

Rod string design				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	KD (4320)	3025	120000	107.2%	50646	14214	7632	API MG T/2.8
0.875	KD (4320)	3175	120000	106.9%	48533	8217	4536	API MG T/2.8
0.75	KD (4320)	3350	120000	107.2%	46756	2506	387	API MG T/2.8
@ 1.5	Flexbar C	450	90000	76.9%	15904	-2101	-340	API MG

Rod string design				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	TRC MPACT KD	3025	115000	85.8% -21.4%	50248	13996	7440	Straight Line
0.875	TRC MPACT KD	3175	115000	85.0% -21.9%	47980	7967	4514	Straight Line
0.75	TRC MPACT KD	3350	115000	85.2% -22%	46368	2476	601	Straight Line
@ 1.5	C (API, SB)	450	90000	76.1%	15797	-1981	-340	API MG

3. **HS (41XX series) vs. MPACT-D**: MPACT-D could replace any need to use High Strength sucker rods, especially the 41XX HA series. The loading capacity of MPACT-D exemplified in the case below shows both designs with similar loading ratio.

Rod string design				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	HS (41XX)	3025	140000	88.6%	50646	14214	7632	API MG T/2.8
0.875	HS (41XX)	3175	140000	89.9%	48533	8217	4536	API MG T/2.8
0.75	HS (41XX)	3350	140000	91.4%	46756	2506	387	API MG T/2.8
@ 1.5	Flexbar C	450	90000	76.9%	15904	-2101	-340	API MG

Rod string design				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	TRC MPACT DA	3025	115000	91.8% +3.2%	50248	13996	7440	Straight Line
0.875	TRC MPACT DA	3175	115000	90.9% +1.0%	47980	7967	4514	Straight Line
0.75	TRC MPACT DA	3350	115000	91.2% -0.2%	46368	2476	601	Straight Line
@ 1.5	Flexbar C	450	90000	76.1%	15797	-1981	-340	API MG

4. **DS (4330 KDP) vs. MPACT KD:** MPACT-KD Demonstrated an 11% increase in stress capacity under the same design parameters without the need to increase hardness like in the case of KDP.

Rod string design				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	WFD KDP	3025	125000	95.4%	47875	13126	7321	API MG T/2.8
0.875	WFD KDP	3175	125000	95.3%	45701	7812	4346	API MG T/2.8
0.75	WFD KDP	3350	125000	97.5%	44389	2249	948	API MG T/2.8
@ 1.5	Flexbar C	450	90000	73.3%	15275	-1786	-340	API MG

Rod string design				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	TRC MPACT KD	3025	115000	85.8% -9.6%	50248	13996	7440	Straight Line
0.875	TRC MPACT KD	3175	115000	85.0% -10.3%	47980	7967	4514	Straight Line
0.75	TRC MPACT KD	3350	115000	85.2% -12.3%	46368	2476	601	Straight Line
@ 1.5	C (API. SB)	450	90000	76.1%	15797	-1981	-340	API MG

5. **HS (43XX series) vs MPACT-KD**: MPACT-KD shows an average 5% less load demand allowing use of them interchangeably but enjoying the benefits of softer material, tougher with better corrosion-fatigue behavior than high strength rods.

Rod string design				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	HS (43XX)	3025	140000	88.6%	50646	14214	7632	API MG T/2.8
0.875	HS (43XX)	3175	140000	89.9%	48533	8217	4536	API MG T/2.8
0.75	HS (43XX)	3350	140000	91.4%	46756	2506	387	API MG T/2.8
@ 1.5	Flexbar C	450	90000	76.9%	15904	-2101	-340	API MG

Rod string design				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	TRC MPACT KD	3025	115000	85.8% -2.8%	50248	13996	7440	Straight Line
0.875	TRC MPACT KD	3175	115000	85.0% -4.9%	47980	7967	4514	Straight Line
0.75	TRC MPACT KD	3350	115000	85.2% -6.2%	46368	2476	601	Straight Line
@ 1.5	C (API. SB)	450	90000	76.1%	15797	-1981	-340	API MG

Example#3:

- Operating Parameters: 10,000 ft, 2.5" pump, 366in stroke at 3.41 SPM -> 600 bpd
- String Design Software Used: RODSTAR
- Well Type: Deviated

6. **HS (43XX) vs MPACT-HS**: MPACT-HS is a viable alternative for those wells with effective chemical treatment or no risk of corrosion to expand the production range even in the most demanding applications with a 20% reduced loaded requirement in the case presented here.

Rod string design				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	HS	4300	140000	115.0%	63765	22316	10458	API MG T/2.8
0.875	HS	4450	140000	115.6%	60888	11192	2827	API MG T/2.8
0.75	HS	650	140000	115.6%	57411	-1313	740	API MG T/2.8
# 1.5	C (API, no neck)	600	90000	63.4%	13655	-832	-340	API MG

Rod string design (rod tapers calculated)				Rod string stress analysis (service factor: 1)				
Diameter (in)	Rod Grade	Length (ft)	Min. Tensile Strength (psi)	Stress Load %	Top Maximum Stress (psi)	Top Minimum Stress (psi)	Bot. Minimum Stress (psi)	Stress Calc. Method
+ 1	TRC MPACT HS	4300	140000	95.5%	63447	22082	10213	Straight Line
0.875	TRC MPACT HS	4450	140000	95.9%	60519	10873	2833	Straight Line
0.75	TRC MPACT HS	650	140000	96.1%	-20% 57305	-1305	813	Straight Line
# 1.5	C (API, no neck)	600	90000	63.2%	13637	-814	-340	API MG

Application based use cases for this advance shot peening technique.

- **Use KD sucker rods instead of high-strength rods** (mitigating premature corrosion-fatigue risk).
- **Reduced pumping unit load** – MPACT rods properly designed can lower the overall mechanical load on the pumping unit, potentially allowing for downsized equipment and reduced operational costs.
- **Increased production rate** – Enhanced fatigue resistance and stress tolerance enable increased fluid recovery.
- **Cost reduction through material selection** – Enables the use of **C or K grade rods** instead of more expensive high-strength rods while maintaining corrosion resistance.
- **D Grade Substitution** – Replaces **HS/HA rods** with **D grade rods** for **cost-effective performance** without sacrificing operational capabilities.
- **Heavy-Duty Applications** – MPACT-treated rods improve performance in **high-load, non-corrosive environments**, where fatigue failure is a primary concern.
- **Fatigue resistance in deviated wells** – Enhanced fatigue resistance at **forged ends** helps reduce failures in wells with deviations and directional drilling conditions.
- **Tracking & Performance Monitoring** – The **MPACT process** enables real-time tracking and evaluation of rod performance, allowing operators to optimize maintenance schedules and improve rod string management.

CONCLUSIONS

Advanced shot peening technologies, exemplified by the MPACT process, show a notable shift in sucker rod fatigue evaluation criteria, extending beyond life-cycle improvement to higher operational stress tolerances at specified fatigue life expectancies. Controlled fatigue tests indicate a 67–72% enhancement in rod longevity over untreated specimens, along with a 32% increase in stress capacity under constant cycle requirements.

These results drive a potential evolution of the Modified Goodman Diagram, giving operators greater flexibility in rod string design and allowing the substitution of conventional high-strength rods in certain applications. Field examples highlight up to 25% reductions in load demand, improved reliability, and potential material cost savings.

From a practical standpoint, applying this process in deviated wells or high-load scenarios reduces downtime and mitigates fatigue-related failures. Implementation, however, must consider proper operator training and monitoring to ensure correct rod handling. Ongoing studies will further quantify long-term performance gains and refine shot peening parameters suitable for diverse well conditions.

Overall, advanced shot peening represents a step forward in extending rod capabilities and addresses fatigue challenges in a cost-effective, operationally robust manner, supporting the industry's pursuit of higher efficiency in artificial lift systems.

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