FULL-SCALE TRIBOCORROSION AND ABRASIVE TESTING TO MITIGATE ROD AND TUBING WEAR

Guillermo Emiliano Ghione, Matias Gustavo Pereyra, Pablo Zupanc,
Esteban Oliva, and Francisco More
Tenaris

ABSTRACT

The relative motion between sucker rods and tubing in rod-lifted wells, particularly in corrosive fluids, leads to degradation mechanisms that often cause material loss, commonly referred to as wear. In U.S. unconventional wells, this wear mechanism accounts for over 50% of the operational expenditure (OPEX) in rod-lifted systems.
Through the application of Root Cause Analysis, the primary mechanisms responsible for this wear—Tribocorrosion and three-part abrasion—were identified. These mechanisms can occur individually or in combination.

To better understand these processes and assess the performance of materials and components, Tenaris developed two distinct full-scale testing methods: (1) the Tribocorrosion Sliding Test and (2) the Abrasive Sliding Test. Both testing methods allow for the manipulation of environmental conditions, lateral loads, and key fluid or abrasive components.

Upon completion of the testing protocols, wear levels in each component were quantified using state-of-the-art imaging techniques. This data was carefully analyzed to evaluate the relative performance of materials and identify optimal combinations to mitigate wear, ultimately enhancing the run life of rod-lifted systems.

PROBLEM STATEMENT

Sucker Rod pumping applications have changed substantially since 2008 unconventional revolution. Deeper wells and the need to produce higher flow rates has continuously pushed all the system components to their limits. Specially for the sucker rods and tubulars, there is an increased occurrence of holes in tubing (HIT) cause by the relative motion between rods and tubulars wear.

This challenge prompted the initiation of the Rod & Tubing Wear project nearly three years ago, which involved an in-depth study of the interaction between the components involved in this failure mechanism: tubing, guides or couplings, and the abrasive medium.

Using Root Cause Analysis (RCA) methodology as an approach for identifying the underlying causes of holes in tubing (Figure 3). A sampling of 6 different HITs was selected from various wells in the Bakken, run life and conditions. The analysis of the information allowed for the identification of common wear patterns in at least 3 samples, where the marks were subsequently erased due to severe damage primarily caused by two mechanisms: 1) Tribocorrosion, and 2) Three-part abrasion. Nearly three years after its launch, the two research directions, on one hand, the **Tribocorrosion Sliding Test**, and on the other, the **Abrasive Sliding Test,** joint efforts between Tenaris and independent laboratories specialized in this field are showing promising results regarding their combined mechanism interaction.

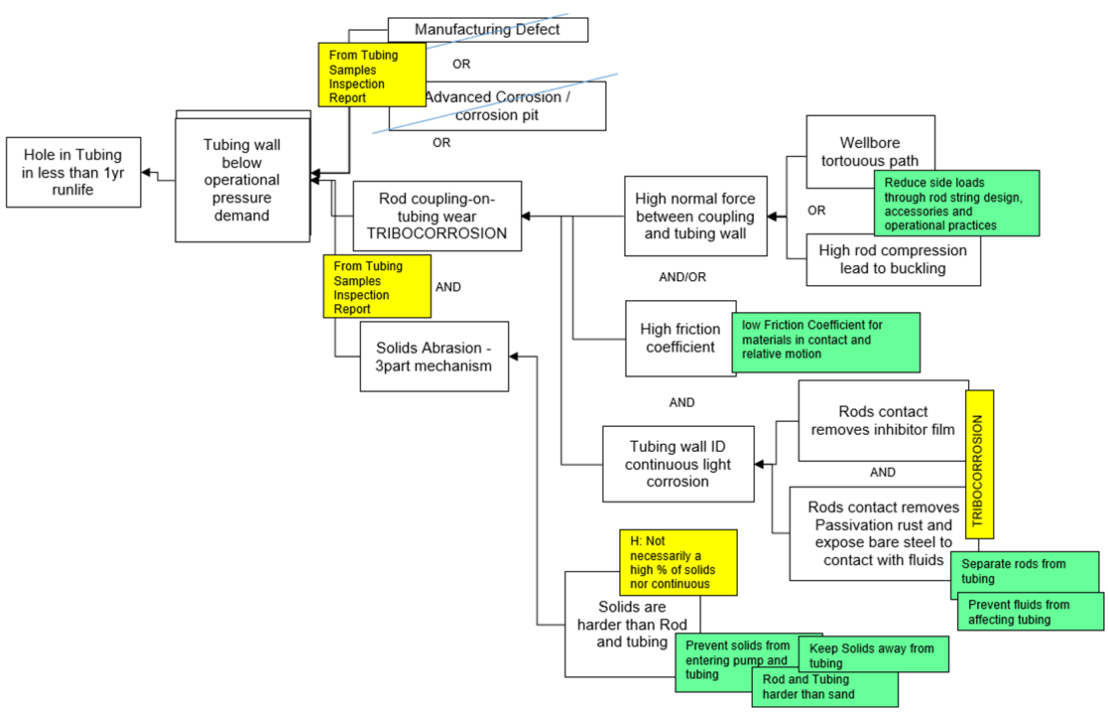


Figure 1. Cause Map Analysis – Holes in Tubing

Sample No.	Well	Installation date	Failure Date	Run life (days)	Failure Depth (ft)	Grade
1	A	8/8/2021	5/27/2022	292	8711	Unknown
2	B	12/28/2020	3/31/2022	458	8773	Unknown
3	C	10/31/2017	1/12/2022	1534	9226	L-80 New
4	D	2/8/2021	4/7/2022	423	9624	L-80 New
5	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
6	F	2/21/2018	3/31/2022	1499	9086	L-80 New

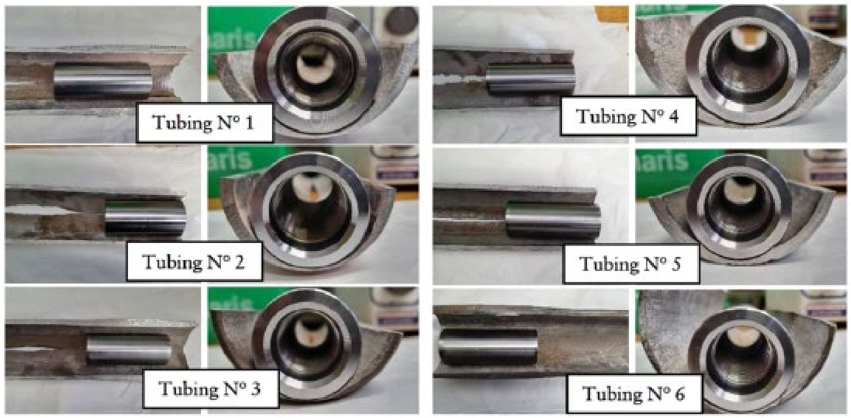


Figure 2. Sampling of Holes in Tubing

Figure 3. Typical Holes in Tubing.

1) TRIBOCORROSION TESTS METHODOLOGY

Tribocorrosion is an irreversible transformation of materials resulting from simultaneous action of mechanical loading (e.g., friction, abrasion) and chemical/electrochemical interactions with the surrounding environment (corrosion attack). It combines two major scientific areas: tribology and corrosion. The first comprises the study of friction, wear, and lubrication, whereas the latter is related to the chemical aspects of material degradation.

Under these conditions, a low coefficient of friction for materials in contact and relative movement, avoiding contact of the rods with the tubing, avoiding fluids that affect the pipe and reducing lateral loads, are all variables that extend the useful life of the tubing.

Tenaris performed wear-corrosion tests to characterize the performance of selected combinations of tubing, SR-couplings, guides and/or Liner materials.
The laboratory test rig, slides a SR-coupling against a Tubing (or Liner) in a CO_2 corrosive environment, Figure 4.

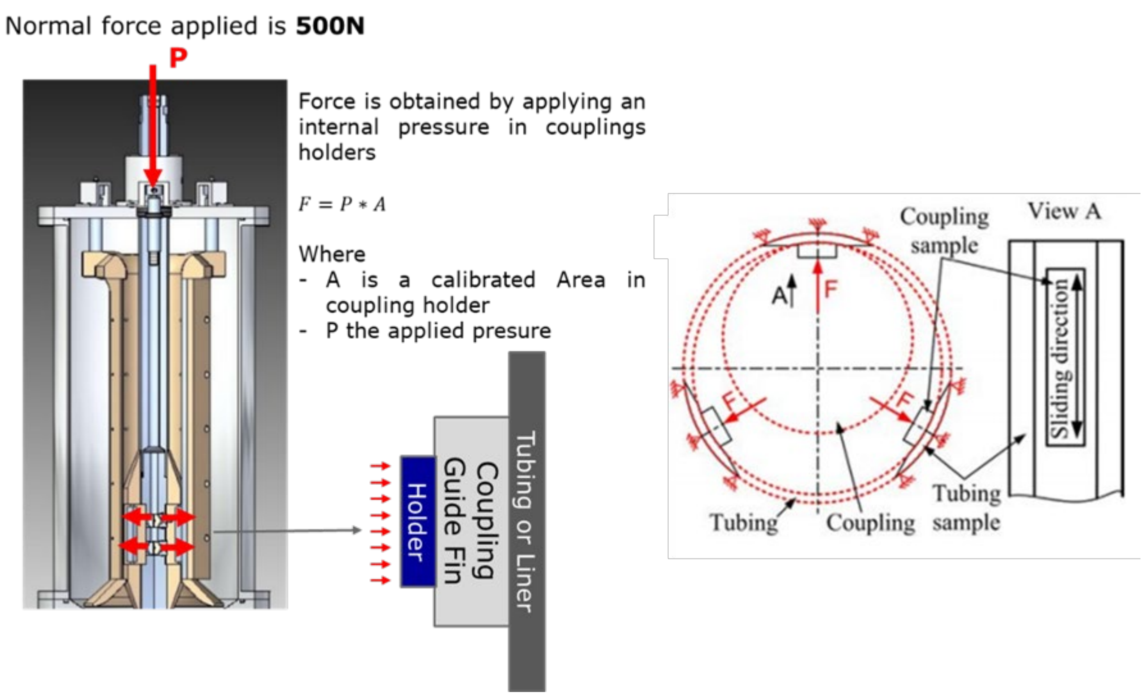


Figure 4. Test-rig.

The experimental conditions were the following:

- Environment:
  - 4.5 bar of $ppCO_2$
  - Brine: 3% NaCl
  - pH: 4.5

- Test temperatures:
  - 60°C, 100°C, 135°C: bare materials
- Number of cycles coupling: 37,5K
- Number of cycles guides: 300K and 600K
- Path: 500mm

Main testing output:
- Material loss of tubing and coupling by 3D scanning
- Friction coefficient
- Qualitative evaluation

SAMPLE PREPARATION AND METHODOLOGY

The tubing is cut and then milled to ensure the parallelism of both faces. Surface cleaning is done using a solution of hydrochloric acid, water, soap, and finally ethanol, which helps remove surface residues and prevent adverse effects during the test (Figure 5).

Figure 5. Tubing before the experiment.

As for the guides, prior to the experiment, they undergo autoclave aging for 15 days at 120°C in a saline solution with CO_2 at 1300 psi. After aging, the fins of the guide are cut, cleaned with water, soap, and ethanol. After cleaning, a reference mark is made on the area that does not contact the tubing. The injection fin is used as the reference, and the other three fins are the ones tested (Figure 6). Data is recorded during entire experiment (Figure 7).

Figure 6. Guides segments before the experiment.

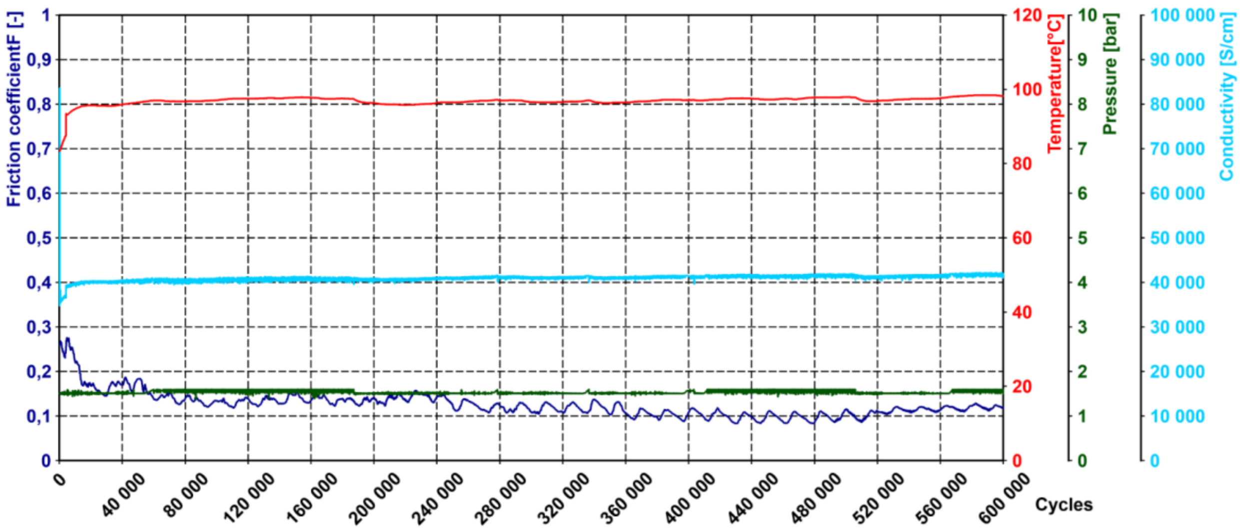


Figure 7. Real-time Data Recording (Friction, Temperature, Pressure vs. Cycles)

Before and after the experiment, the samples are scanned using high-precision software. The samples are then compared, and the depth and volume of wear on each material are calculated.

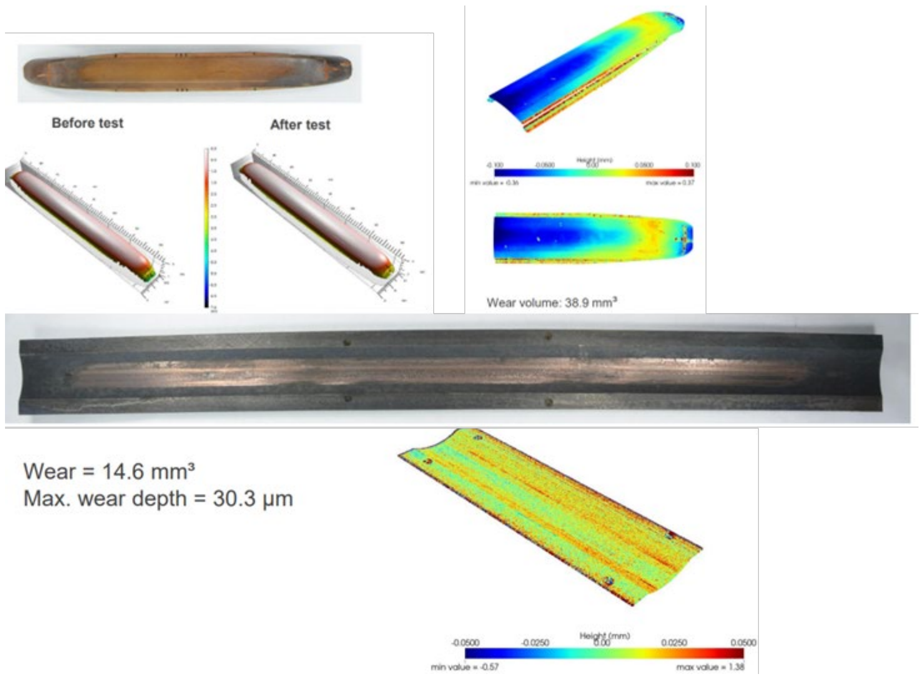


Figure 8: Samples before and after experiment.

RESULTS

Tribocorrosion results are shown in Table 1.

Test Materials		J55
Tenaris Couplings	API T	Done
	API Spray Metal (SM)	Done
	LaserShield® (LS)	Done
Other Manufacturers	Coupling A	Done
	Coupling B	Done
	Coupling C	Done
	Coupling D	Done
Tenaris Guides	PEEK20	Done
	PA600	Done
	PPA33	Done
	PPA00	Done
	PPS30	Done
	PPS20	Done
	PK1-PK3-PK4	Done
	PK2 - Tenaris' proprietary blend	Done
	PPSC4 and PPSC3	Done

Table 1. Tribocorrosion Test Matrix.

Competitor couplings A through D include the following characteristics:

- Copper-nickel-tin alloy coupling
- Metallic alloy on coupling substrate by nanolaminating process
- Thermal boron diffusion coupling
- Tungsten with nano-structured Tungsten Carbide applied by chemical vapour deposition process

The Tribocorrosion test results are shown in two different charts. Figure 9 displays the results of tubing vs. coupling, and Figure 10 shows the results of guide vs. tubing.

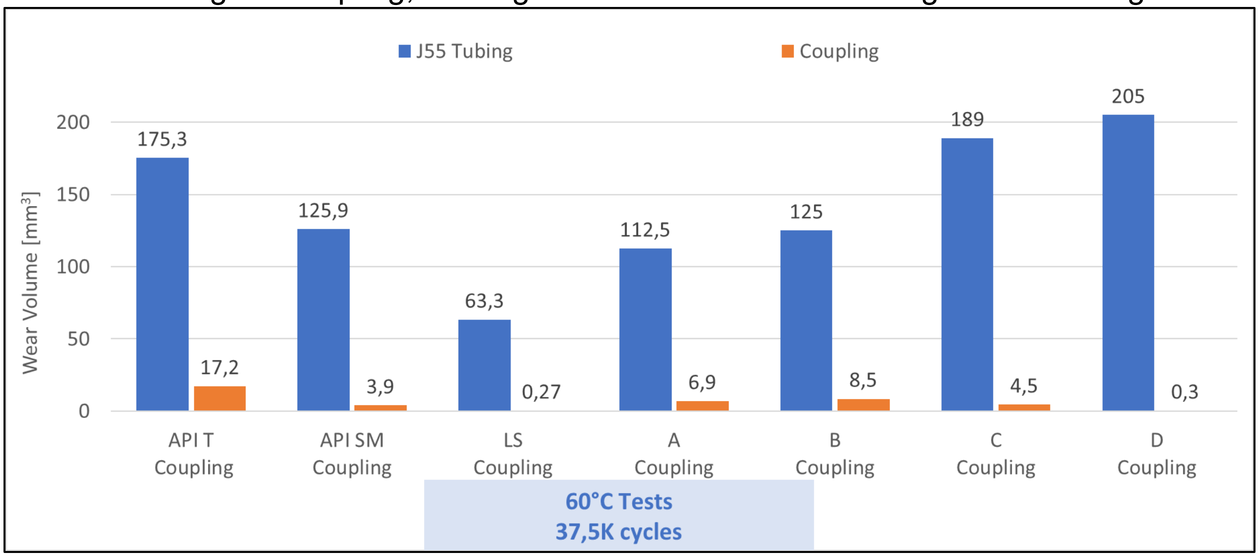


Figure 9. Tribocorrosion Test Results, Tubing vs Coupling.

The LaserShield® couplings showed the best performance after 37.5K test cycles, wearing less and causing less wear on the J55 tubing. The D coupling showed similar performance to LaserShield® in terms of wear but generated significant wear on the tubing.

LaserShield® technology utilizes an Extreme High-speed Laser Material Deposition (EHLA) process, where coating material supply and consolidation occur in one step. This not only opens up to a wide range of coating materials and compositions to pick specific properties but also results in a very uniform layer with low porosity, low roughness and Low Friction Coefficient compared to other coupling surface coating or conditioning solutions. Further details on the technology are provided in the Proposed Solution section below.

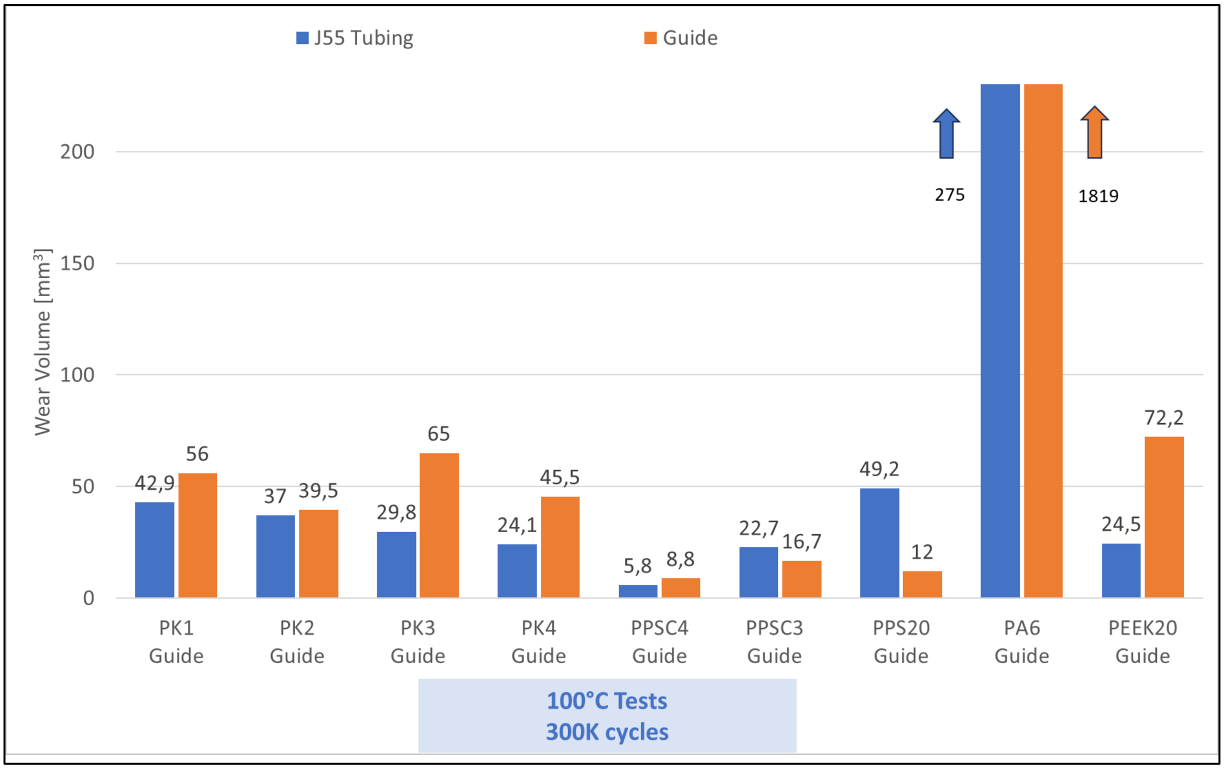


Figure 10. Tribocorrosion Test Results, Tubing vs Guide.

Regarding the guide vs. tubing, after 300K test cycles, the PPS guides showed the best performance, with the PPSC4 exhibiting the least wear on both the guide and tubing. The other polymers remained below 80 mm³, except for PA6, which showed significantly higher wear on both the guide and tubing.

Based on these results, the 5 guides with the best performance were selected, and the Tribocorrosion test was continued up to 600K cycles. The worn volume shown in Figure 11 represents the total volume worn. It can be seen that the PK2 guide reduced its wear rate and caused the least wear on the tubing compared to the other guides. Additionally, the volume of tubing worn in the first 300K cycles was greater than the total wear observed in the 600K cycles.

Microscopy revealed a polymer layer of approximately 30 µm strongly adhered to the tubing surface, which explains the significant reduction in volume readings of the worn tubing, as shown in Figure 12. While field validation is still needed, the adhesion of this polymer layer to the inner surface of the tubing during the last 300K cycles would deliver protection to the tubing, thereby reducing the wear on both components in contact."

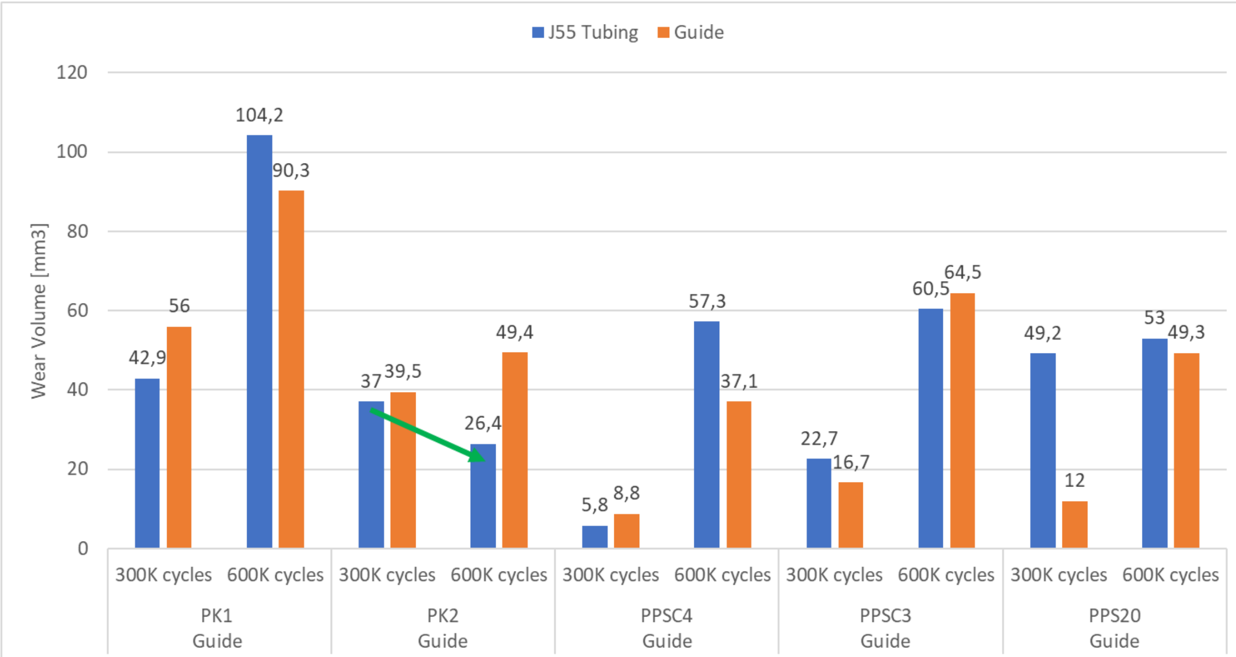


Figure 11: Tribocorrosion Test Results, Tubing vs Guide after 600K Cycles.

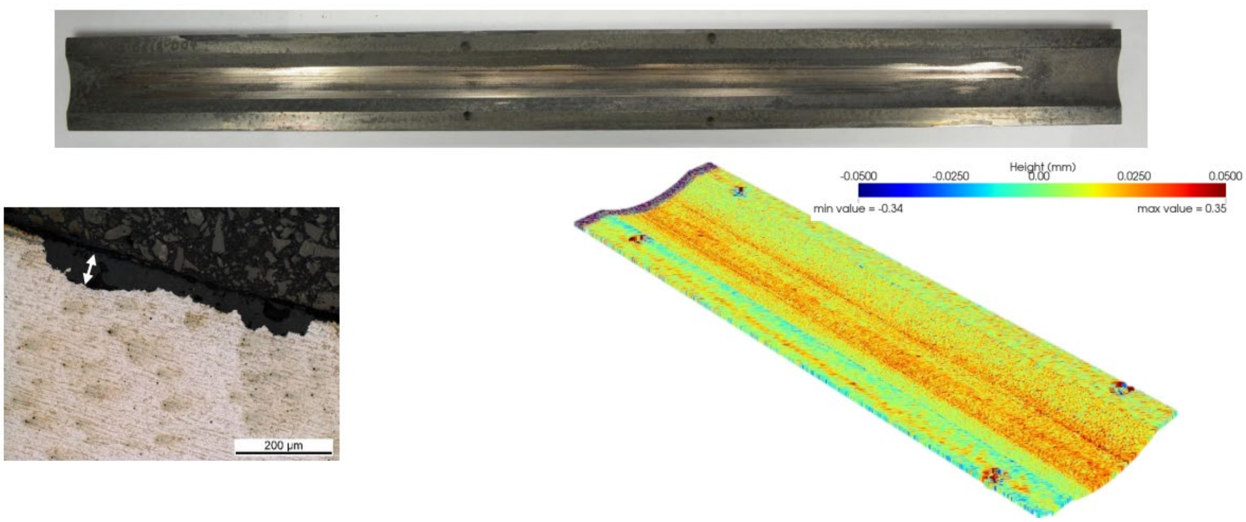


Figure 12. Protective Shield on Tubing ID.

GUIDE AND TUBING LIFE

Figure 13 shows the service life of the guides under Tribocorrosion conditions, according to the tests conducted.

Using the wear rates of a 7/8 TenFlow® guide for 2 7/8” tubing obtained in the Tribocorrosion test, and considering a well with an 8 SPM, Stroke length of 168", the time required to consume the erodible volume of the guide fin (EWV) was calculated.

Traveled Distance in Tribocorrosion tests:

$$TTD = n° \; cycles \times path \; length \times 2$$

TTD: Total test distance [km]
N° cycles: 300.000 and 600.000
Path length: 500 [mm]

Daily distance in well:

$$DDW = Stroke \; length \times SPM \times 60 \times 24$$

DDW: Daily distance in well [km]
Strokes per minute (SPM): 8
Stroke length: 168”

Service life of the guide:

$$GL = \frac{TTD \times {}^{EWV}/_{4}}{TWV \times DDW \times 365}$$

EWV: Guide erodible wear volume [mm^3]
TWV: Test worn volume (of guide) [mm^3]
GL: Guide life [years]

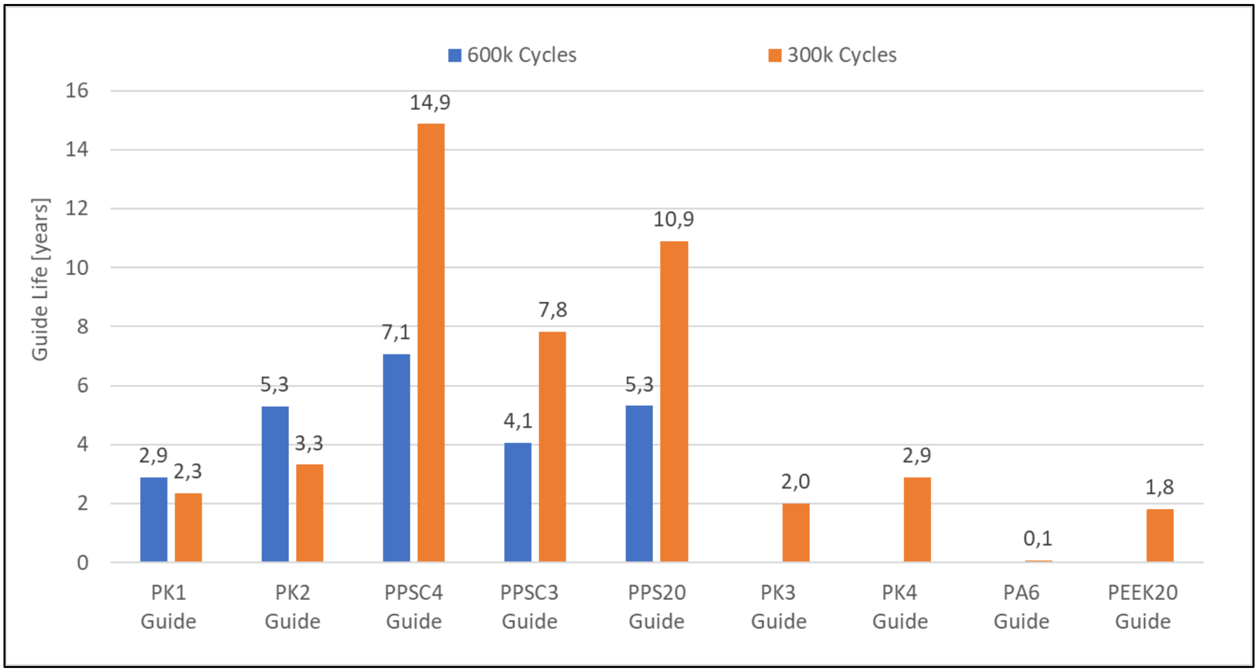


Figure 13: Lifetime of a 7/8" x 2 7/8" guide (years).

In Table 2, the service life of the tubing is shown at different percentages of wall thickness wear (WT). It was determined using the wear rate from the Tribocorrosion test for each tested combination, considering a well with 8 SPM, a stroke length of 168", tubing with a diameter of 2 7/8" and a wall thickness (WT) of 5.5 mm, and a 7/8" string. A schematic of the considered section is shown in Figure 14.

Service life of the tubing:

$$TL = \frac{WVL \times n° \; cycles}{TWV \times SPM \times 60 \times 24 \times 365}$$

WVL: Tubing wall volume loss [mm^3]. This value was calculated with the worn profile to achieve XX% of wall thickness loss.
TWV: Test worn volume (of tubing) [mm^3]
Strokes per minute (SPM): 8
TL: Tubing life [years]

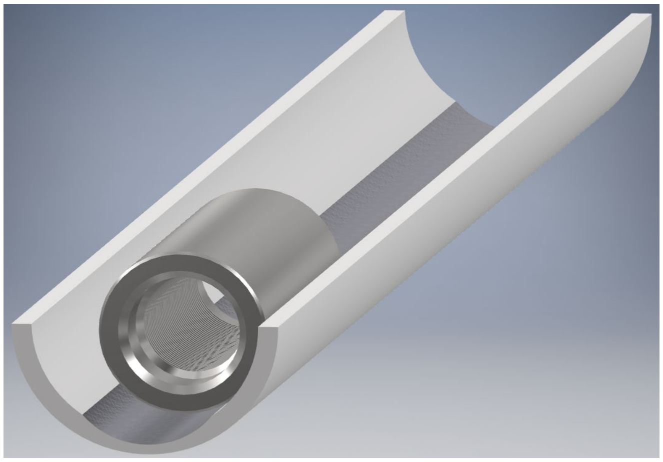
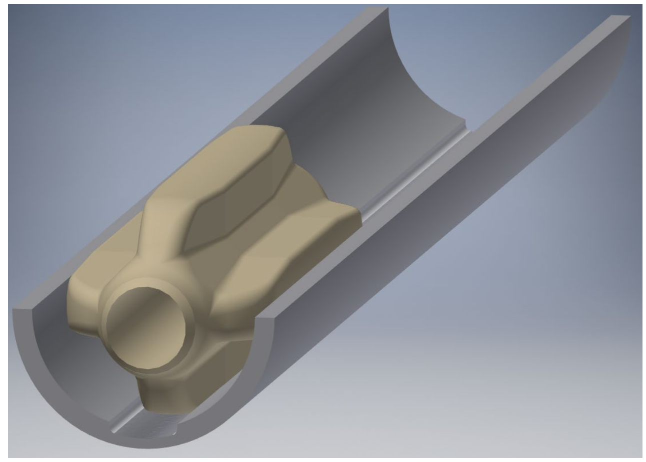
 

Figure 14. Contact of the Tubing with the coupling or guide.

Test material	15% WT lost	30% WT Lost	50% WT lost	100% WT Lost
API T Coupling	0,3	0,9	1,8	4,5
API SM Coupling	0,5	1,2	2,5	6,3
LaserShield® Coupling	0,9	2,4	5	12,6
A Coupling	0,5	1,4	2,8	7,1
B Coupling	0,5	1,2	2,5	6,4
C Coupling	0,3	0,8	1,7	4,2
D Coupling	0,3	0,8	1,5	3,9
PK1 Guide	9,8	20,5	34,8	71,7
PK2 Guide	38,8	80,9	137,4	283,1
PPSC4 Guide	17,9	37,3	63,3	130,4
PPSC3 Guide	16,9	35,3	60	123,5
PPS20 Guide	19,3	40,3	68,4	141

Table 2. Tubing Life in years.

According to Tribocorrosion Tests results, the most favorable condition would be to use PK2 guides and LaserShield® couplings. While the tubing is in contact with the guide, the wear produced is very low. However, as shown in Figure 11, the guide experiences wear, and when it loses its Erodible Wear Volume, the tubing encounters the coupling, causing its service life to decrease significantly (see later in Figure 24).

2) ABRASIVE SLIDING TEST - METHODOLOGY

The abrasive fluid sliding test consists of sliding the sucker rod guide or coupling on a sliced liner or tubing. An abrasive fluid consisting of water and silicon sand is applied between the two test pieces. The fluid is heated and continuously recirculates. The wear is quantified:

- By weight difference before and after the test.

- By surface comparison of the samples (3D scanned before and after the test). The comparison is made with the GOM Inspect Software.

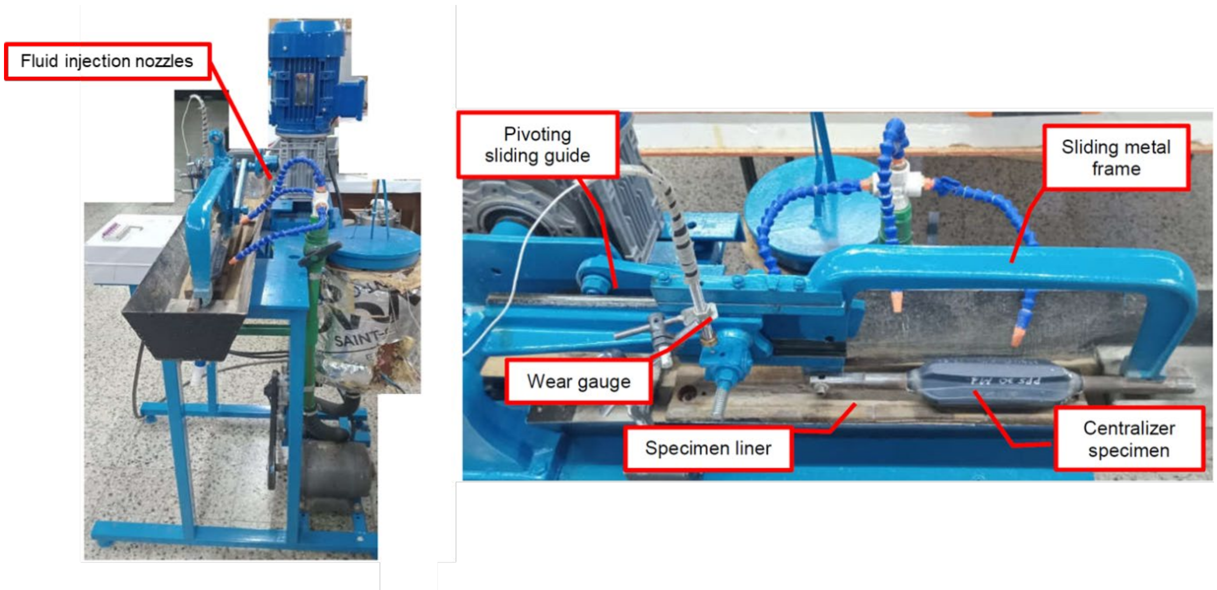
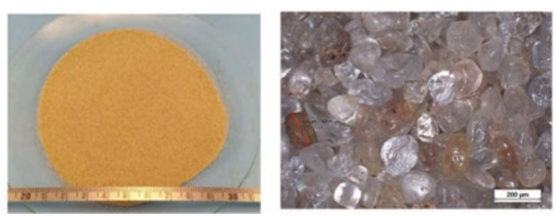


Figure 15. Reciprocating tribometer.



Particle average size 150 µm

Figure 16. Left: Image of the sieved sand / Right: 50x detail of the sieved sand.

<table>
<tr><th colspan="2">Parameter description</th><th>Value</th></tr>
<tr><td colspan="2">Fluid temperature [°C]</td><td>90</td></tr>
<tr><td colspan="2">Stroke length [mm]</td><td>252</td></tr>
<tr><td colspan="2">Normal load applied [Kgf]</td><td>4,1</td></tr>
<tr><td colspan="2">Test duration [min]</td><td>120 continuous</td></tr>
<tr><td colspan="2">Test frecuency [cycles/min]</td><td>78</td></tr>
<tr><td colspan="2">Abrasive granulometry</td><td>Passes sieve 60</td></tr>
<tr><td rowspan="2">Abrasive/Water Ratio</td><td>[kg/l]</td><td>0,067 or 0,033</td></tr>
<tr><td>[lb/gal]</td><td>0,559 or 0,279</td></tr>
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Table 3: Parameters of Abrasion Test with sliding motion.

Dimensional analysis:

For dimensional wear analysis, all the guides and liners, were scanned before and after the Abrasion test.
In the case of the guides, the before and after scanned 3D models were superimposed, showing the wear on the surface over the entire length of the fin. The worn volume was reconstructed in 3D taking different section profiles along the fin.
The procedure for the liners was similar, but it was impossible to match the before and after scans due to deformations that were observed after the tests. Only the worn samples scans were used for the analysis. The reconstruction of the worn volume was performed taking the profile of the cross section in the center and every 10mm towards each side, covering the central 100mm of the liner.

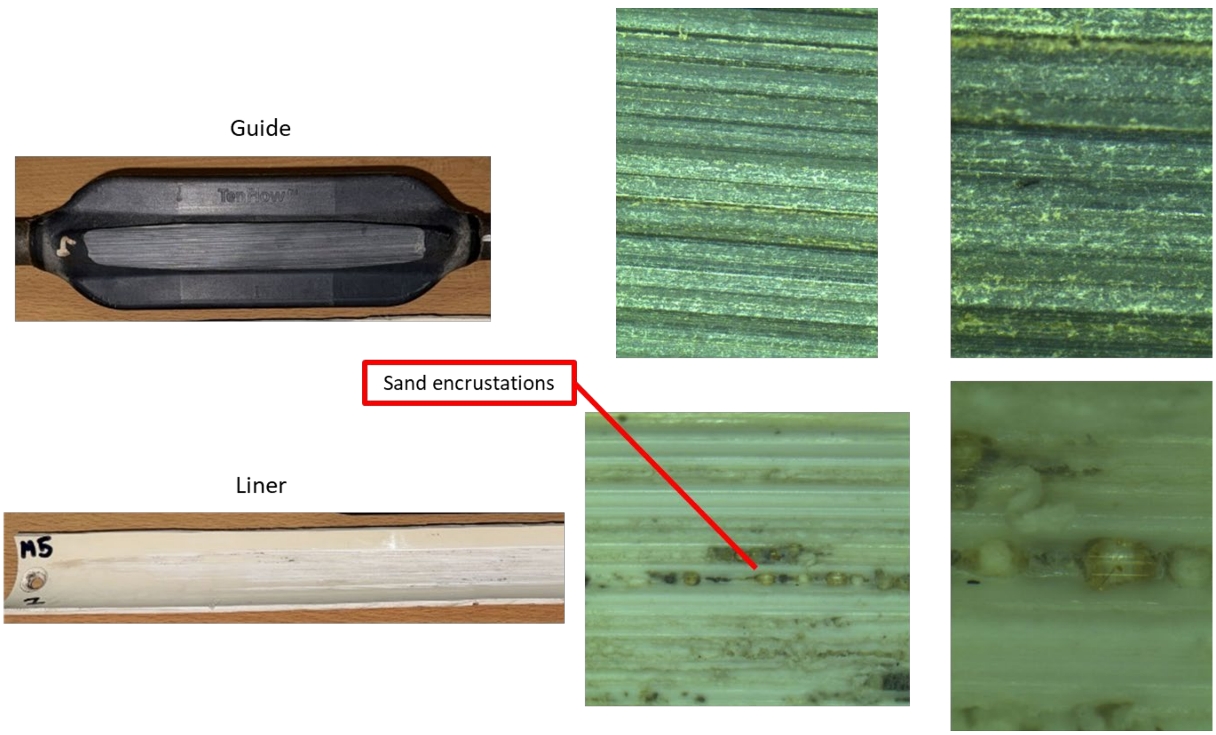
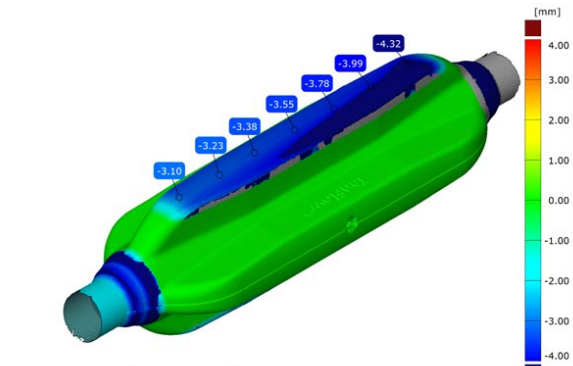
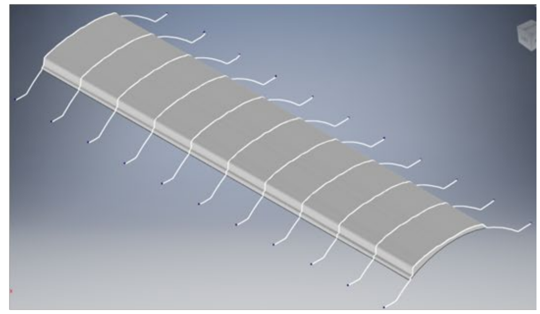


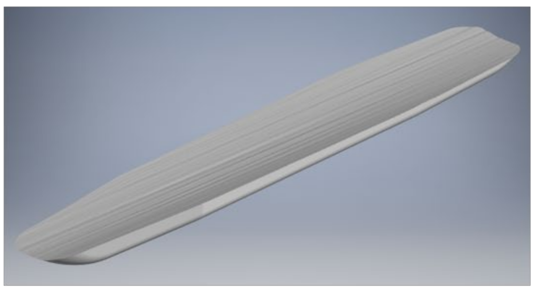
Figure 17: Guide and Liner after Abrasion Test sample.



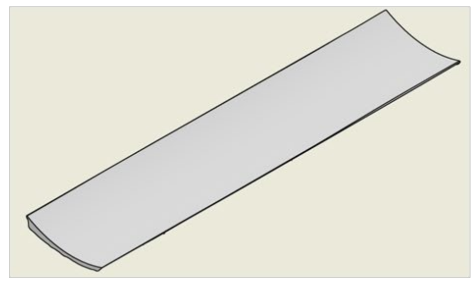
Guides Surface comparison
before and after test



Liner Cross section profiles
every 10mm from the center
towards each side



Guide worn
volume



Liner Worn volume
3D reconstruction

Figure 18: 3D scanning and analysis.

Test N°	Material combination		Sand concentration [kg/l]
1	Guide PPS30	Liner PPS FX	0,067
2	Guide PPS30	Liner PPS FX	0,067
3	Guide PPS20+PTFE	Liner PPS FX	0,067
4	Guide PK2	Liner PPS FX	0,067
5	Guide PPS20+PTFE	Liner PK	0,067
6	Guide PK2	Liner PK	0,067
7	Guide PPS30 (aged)	Liner PPS FX	0,067
8	Guide PK2 (aged)	Liner PK	0,067
9	Guide PPS30 (aged)	Bare Tubing J55	0,067
10	Guide PK2 (aged)	Bare Tubing J55	0,067
11	Guide PPS30 (aged)	Bare Tubing J55	0,033
12	Guide PK2 (aged)	Bare Tubing J55	0,033
13	LaserShield® coupling	Tubing – TenCoat™ 8000	0,067
14	LaserShield® coupling	Tubing – TenCoat™ 8000	0,033
15	Guide PPS30	Tubing - TenCoat™ 8000	0,067
16	LaserShield® coupling	Bare Tubing J55	0,033
17	T coupling	Bare Tubing J55	0,033
18	Guide PPS20+PTFE 4,5%	Bare Tubing J55	0,033
19	Guide PEEK 20% FG	Bare Tubing J55	0,033

Table 4: Test program.

Results:

Figure 19 below shows the worn volume results for Liner vs. Guides, while Figure 20 shows the worn volume results for Tubing vs. Guides.

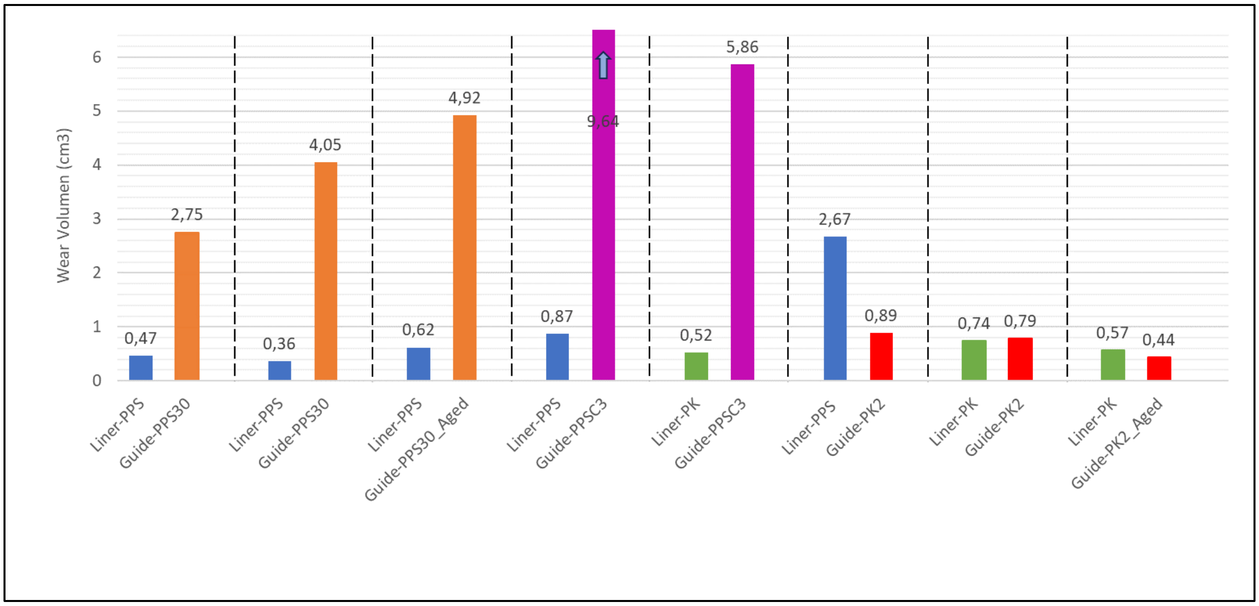


Figure 19: Liner vs Guides.

The best combination was PK liner with PK2 guide, resulting in lowest wear on both liner and guide.

PPS liners performed well combined with PPS30 guide, but the guide wear is high. If combined with PK2 guide, the liner shows higher wear.

PPSC3 guides showed very high wear combined with both PPS and PK liner.

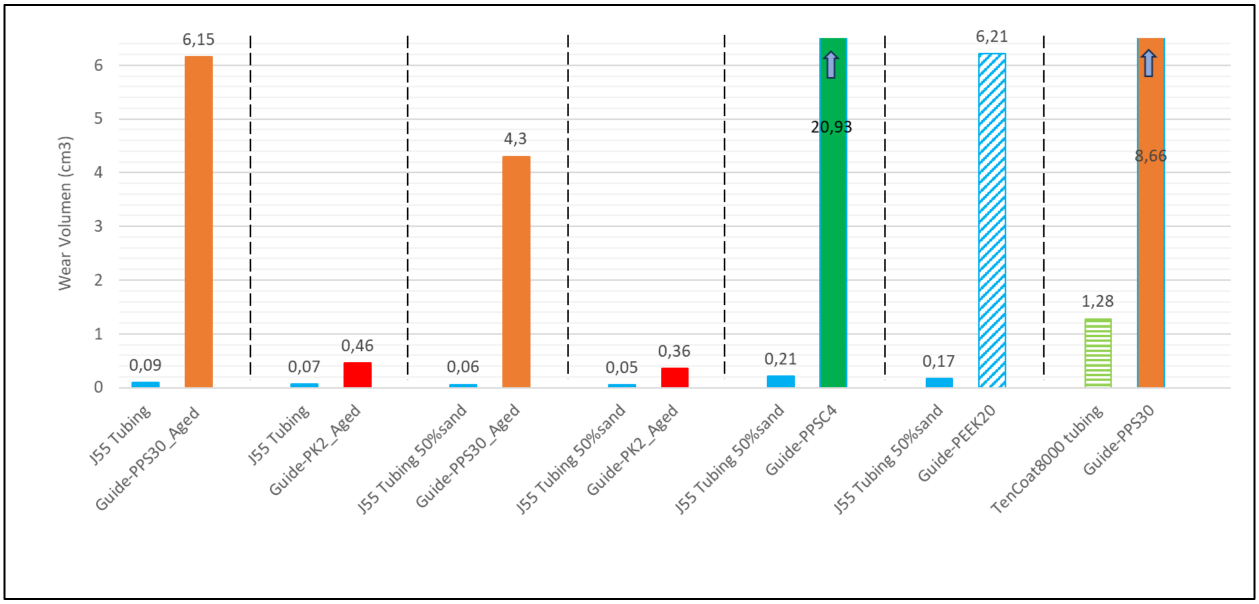


Figure 20: Tubing vs Guides.

The PK2 guide was the one that showed lowest wear on both guide and tubing.
PPSC4 guide suffered very high wear as did the tubing.
PPS30 guide showed high wear in all cases. Combined with TenCoat™ 8000 tubing, it completely wore the coating and part of the metal base.
PEEK20 guide showed high wear and produced higher wear to the J55 tubing than the PPS and PK2 guides.

These results indicate that Polyketone is the material that performs best under abrasion conditions with sand, both with guides and with liners. The hypothesis is that being the softest material, it better adapts to the surfaces it slides over, generating a sweeping effect on the solids and significantly reducing wear.

Figure 21 below shows the worn volume results for Tubing vs. Coupling, while Figure 22 shows the worn volume results for J55 Tubing vs Guides and Couplings.

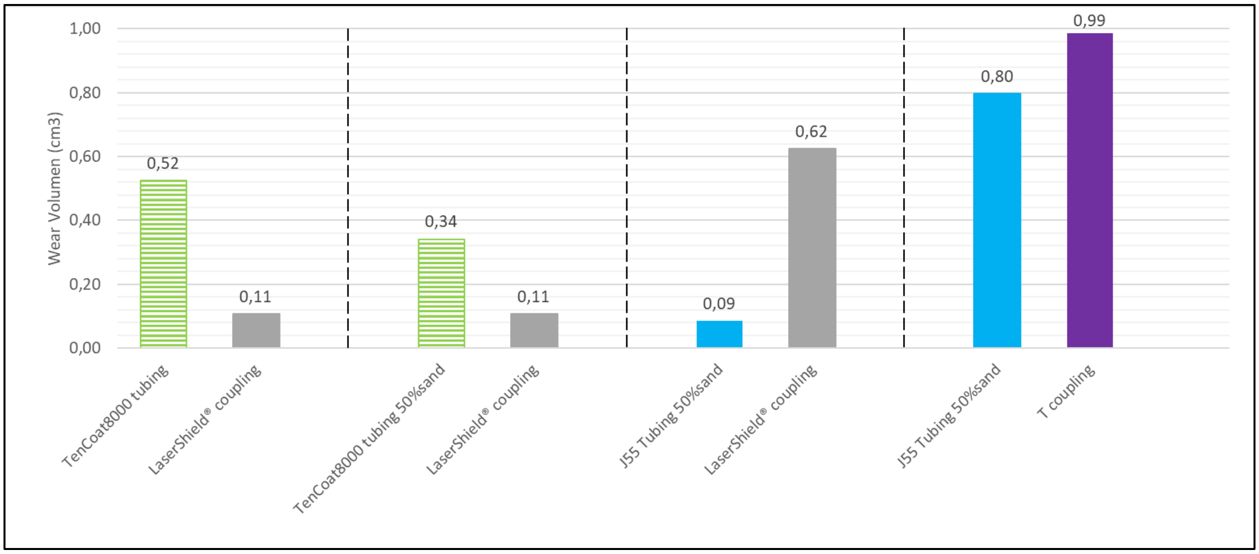


Figure 21: Tubing vs Coupling.

T-coupling shows the highest wear of all combinations both on coupling and tubing. LaserShield® coupling showed high wear against J55 tubing and lower wear against TenCoat™ 8000 tubing.
TenCoat™ 8000 tubing shows higher wear than J55 tubing when combined with LaserShield® coupling.
Previous hypothesis was again validated, a soft material (TenCoat™ 8000) better adapts to the surfaces, generating a sweeping effect on the solids and reducing wear.

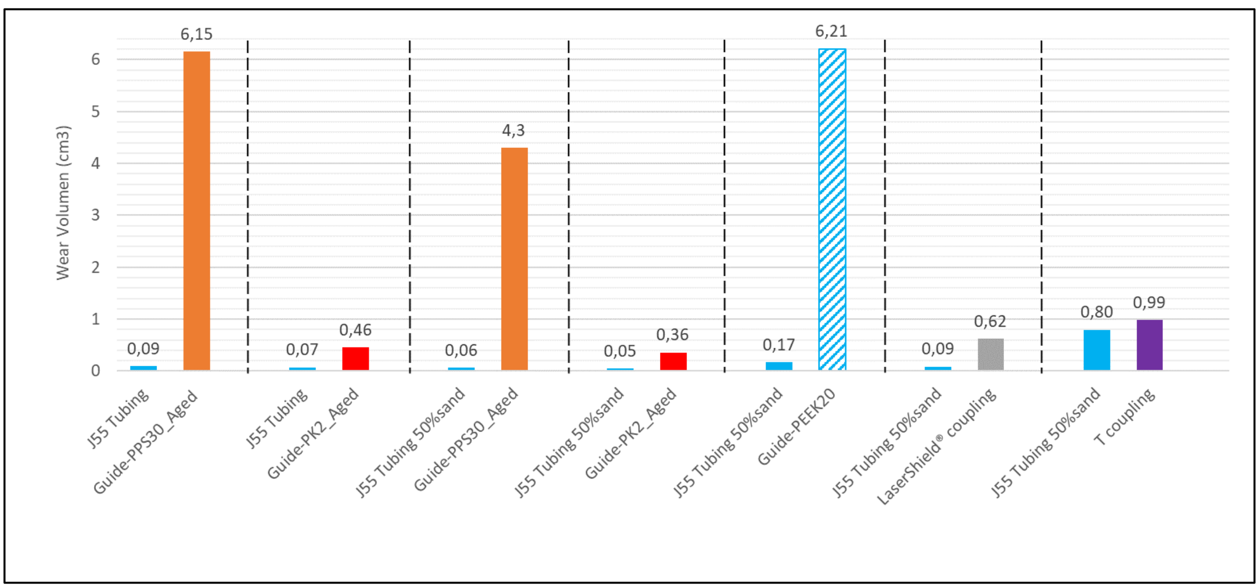


Figure 22: J55 tubing vs Guides & Couplings.

The PK guide showed the lowest wear on the tubing while having very low wear itself, even lower than the LaserShield® coupling.

Figure 22 again shows that the use of guides reduces tubing wear, while also delaying the contact and wear of the coupling.

Figure 23 shows the service life of the tubing under sand abrasion conditions. It was determined using the wear rate for each tested combination in a well with 8 SPM, a stroke length of 168", tubing with a diameter of 2 7/8” and a wall thickness (WT) of 5.5 mm, and a 7/8” rod string.

Service life of the Tubing:

$$TL = \frac{WVL \times n^{\circ}\ cycles}{TWV \times SPM \times 60 \times 24 \times 365}$$

WVL: Tubing wall volume loss [mm^3]. This value was calculated with the worn profile to achieve XX% of wall thickness loss.

TWV: Test worn volume (of tubing) [mm^3]

Strokes per minute (SPM): 8

TL: Tubing life [years]

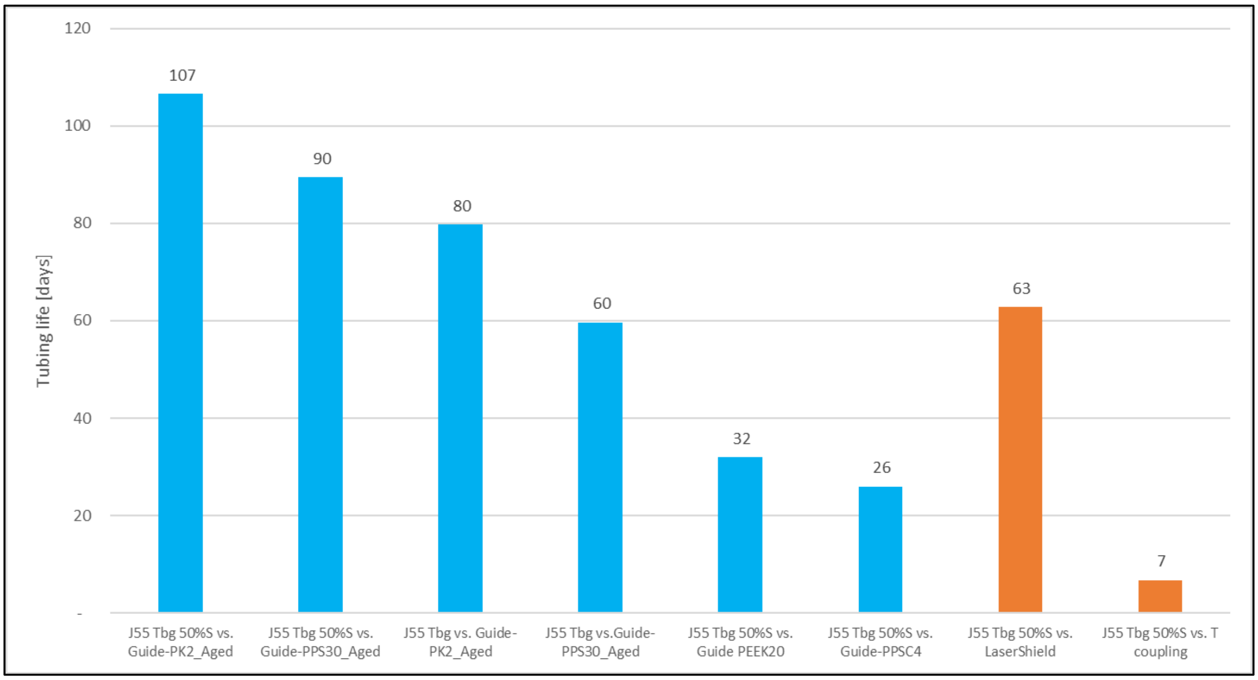


Figure 23: J55 Tubing life.

According to Abrasion Tests results, the most favorable condition would once again be to use PK2 guides and LaserShield® couplings.

PROPOSED SOLUTIONS

The best strategy is to use Suker Rod Guides which delay the contact of the couplings with the tubing, extending the life of both tubing and string.

To maintain optimal performance, it's essential to refresh Erodible Wear Volume (EWV) by replacing the guides before they are fully worn out. However, predicting the precise timing of this wear is quite challenging (Figure 24).

If the EWV is completely depleted and the coupling starts contacting the tubing, we need to consider two potential scenarios:
A) The T-couplings represents the more aggressive scenario for tubing. It poses higher risks due to both Tribocorrosion and abrasive mechanisms.
B) The LaserShield® couplings technology is the optimal solution for minimizing tubing wall loss.

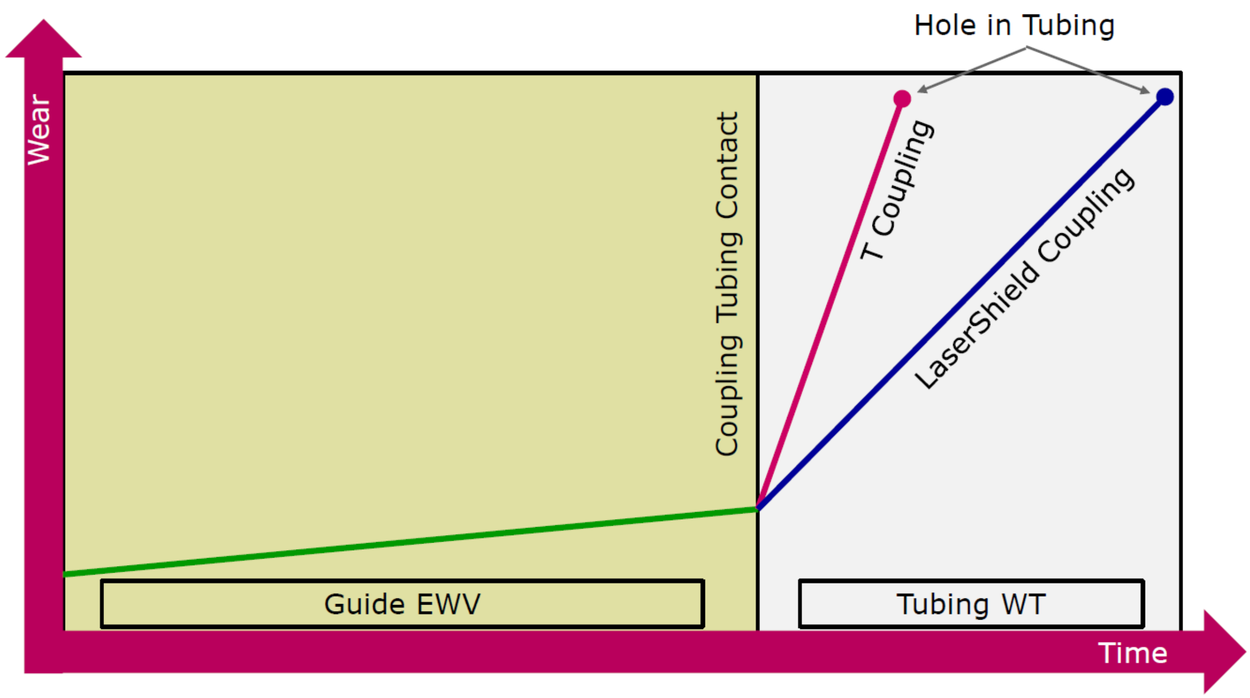


Figure 24. Hole in Tubing timeline.

INCREASING ERODIBLE WEAR VOLUME AT THE EXTREMES (EWV)

Tenaris Sinker Rods, 1” x ¾” pin or 1 1/8” x 7/8” pin, are already a proven solution through added material and Optimized for Compresion (OfC) strategy. This design increases the EWV in the guide by reducing the OD of the coupling, Figure 25 (*Sinker Section Design to Reduce Buckling-Related Failures; Anderson, Oliva; SPSC 2024,*). However, guides at the middle of the rod can be eroded as far as the valley level of the fins, while guides close to the connection only can be eroded up to the coupling OD, meaning the available EWV in the guides at the ends is lower than in the center guides. An additional 20% of EWV can be considered in the guides at the center of the rod compared to the ends, taking into account wear at the coupling level, provided the rod rotator is functioning properly. The new Sinker Rod design with a 9-per distribution concentrates 3 guides near each side of the connection and increases the EWV from 0.05 to 0.095 in³/in at the ends and to 0.07 in³/in in the center. This represents a 100% increase in EWV at the ends compared to the previous 8-per design (Figure 26).

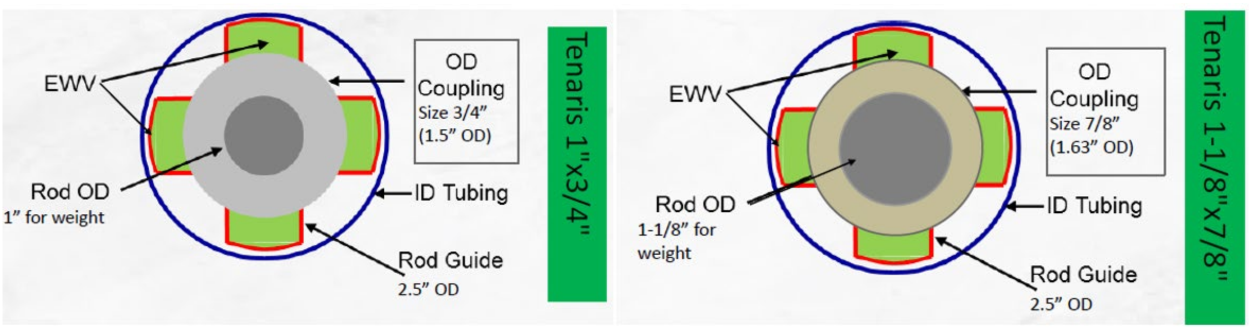


Figure 25. 1” and 1 1/8” Sinker Rods EWV Visualization.

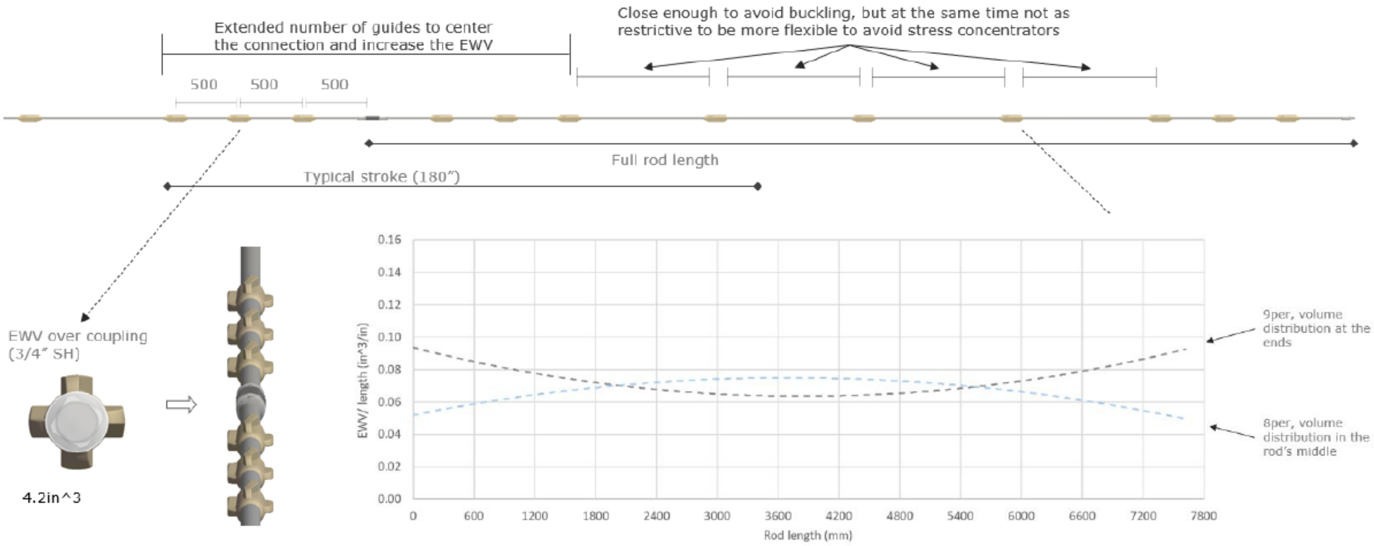


Figure 26. 8per vs 9per EWV distribution.

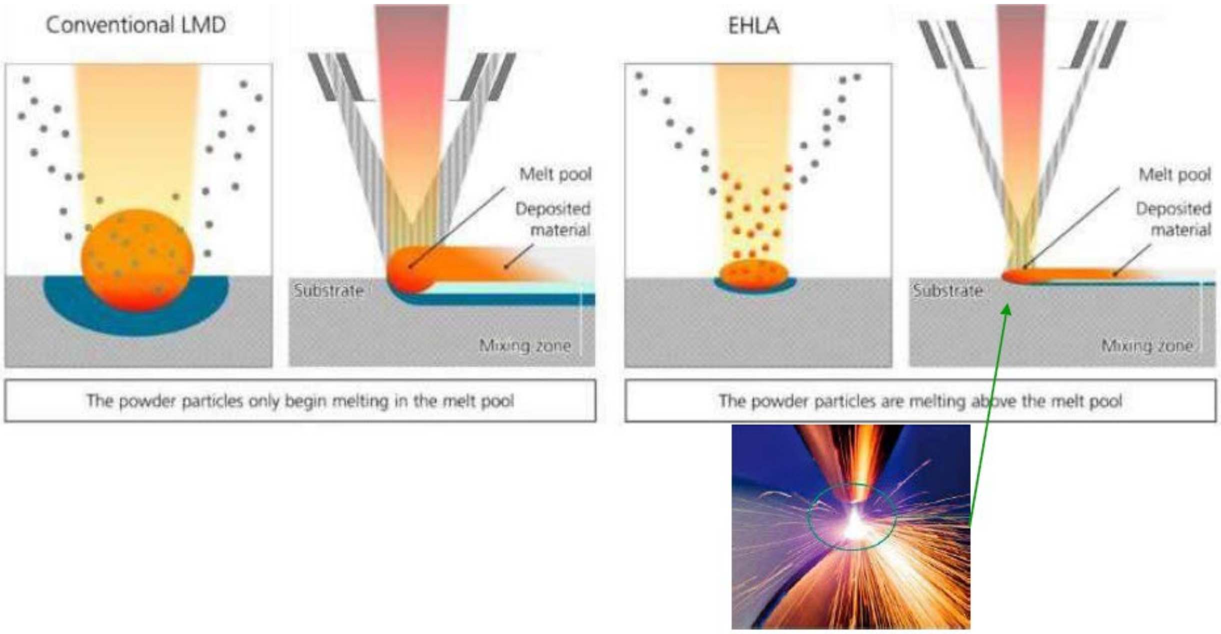
LASERSHIELD® COUPLINGS

LaserShield® technology utilizes an Extreme High-speed Laser Material Deposition (EHLA) process, where coating material supply and consolidation occur in one step. This not only opens up to a wide range of coating materials and compositions to pick specific properties, but also results in a very uniform layer with low porosity, low roughness and Low Friction Coefficient compared to other coupling surface coating or conditioning solutions.

LaserShield® technology process minimizes the Heat Affected Zone (HAZ) in the base steel to less than 500µm (Figure 27). Hence, LS deposition provides an extremely consistent coating with enhanced mechanical properties, such as reduced porosity and increased fatigue resistance (Figure 28). This is particularly critical for Slim Hole coupling configurations in high load applications, especially ¾", 7/8" and 1".

LaserShield® coating is a nickel-based material with maximum roughness of ~15 µin. The friction coefficient in Tribocorrosion testing is 0.18 and 0.2 on J55 and L80 tubing, respectively- much lower than the 0.3 friction coefficient typically seen in conventional SM. LaserShield® High Strength Full Size performed twice the fatigue limit versus the standard SM FS (486 versus 227 MPa lower fatigue limit alternative stress) during testing on the Tenaris corrosion-fatigue machine in R&D.

Figure 27. Conventional versus Extreme High-Speed Laser Material Deposition



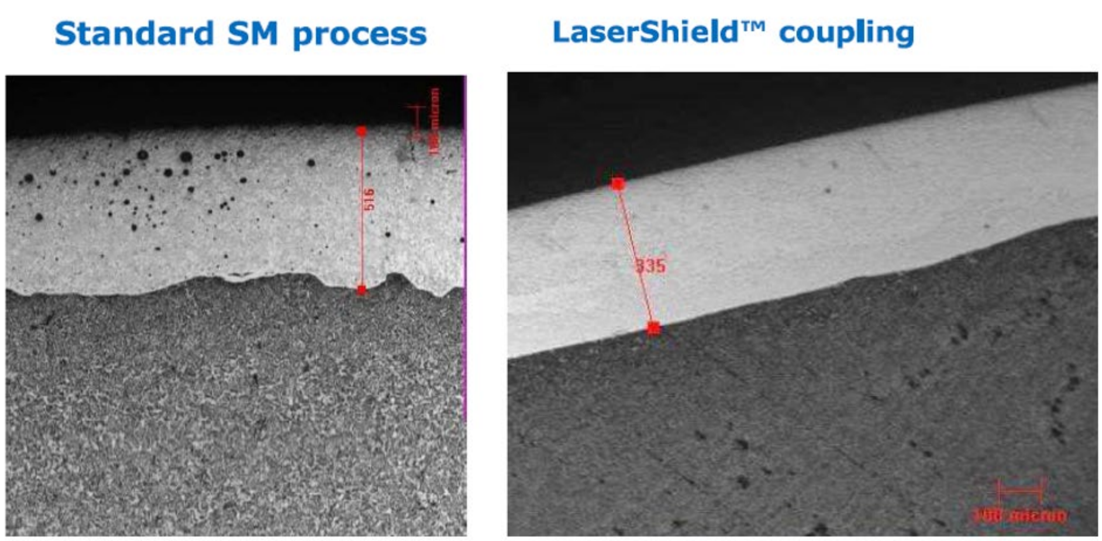


Figure 28. LaserShield® Enhanced Layer Quality.

NEXT STEPS:

- PK2 field trials.
- Implement the integrated strategy with EWV management and coupling selection

CONCLUSIONS

Tribocorrosion Tests:

- LaserShield® couplings were the best performing ones when combining tubing and coupling duration.
- Guides induce negligible wear on J55 tubing in Tribocorrosion tests when compared to couplings. PK2 Guides showed the best performance.

Abrasive Sliding Tests:

- Guide induce negligible wear on J55 tubing in Sand Abrasion wear tests against tubing comparing the wear imparted to liners.
- Overall, PK guides handle sand in a more effective way when compared to PPS30.
- PK and PPS liners have similar performance in wear rate in Sand Abrasion Tests.

Strategy for the Combined Abrasion and Tribocorrosion Mechanism:

- To minimize this mechanism, it is key to delay coupling and tubing contact.
- Improve Erodible Wear Volume (EWV) duration via adding guides and Optimized for Compresion (OfC) strategy.
- Develop a program to evaluate EWV reduction in the well and replace the guides before it has fully worn out.
- If contact between coupling and tubing is expected, use LaserShield® couplings.
- Field validation is recommended to validate PK2 as the best option.