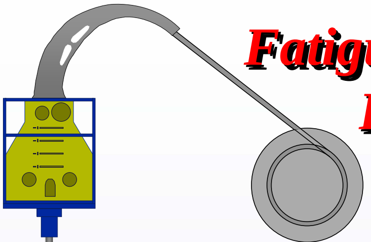

Fatigue Integrity Analysis of Rotating Coiled Tubing

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Abstract

Conventional coiled tubing endures severe above-ground bending and straightening cycles that cause low-cycle fatigue to be the predominant factor limiting its useful life. For conventional coiled tubing, downhole bending events associated with wellpath curvature are negligible since the strains generated are orders of magnitude less severe than strains caused by above-ground cyclic bending, and are applied with a very low cycle count.

A new drilling rig is under development that rotates coiled tubing (CT) downhole, reportedly at rates on the order of 20 RPM, resulting in numerous operational benefits. However, rotation will impose additional rotating-bending events in the high-cycle fatigue regime as sections of CT pass through regions of high dog leg severity. This paper presents a study of the influence of downhole rotation on the fatigue durability of CT. In this study, fatigue data taken in the high and low cycle regimes from a variety of sources are used to assess the potential high-cycle fatigue damage that may be caused by downhole rotation. The results indicate that the damage is below the endurance limit and thus negligible relative to fatigue damage accumulated from above-ground bend-straighten cycles for conventional CT. This analysis also took into account another area of potential concern: circumferential abrasion that could occur when rotating coiled tubing contacts with the casing and/or wellbore. Surface roughness factors were estimated and used to modify life estimates. Results still indicate that sub-surface rotation-induced fatigue cycles should not detrimentally influence fatigue life relative to above surface fatigue cycles.

Experimental results are presented which validate the conservatism of the assumptions made for surface roughness factors. The results also demonstrate that the abrasion process causes compressive residual surface stresses that somewhat offset the detrimental effect of a rougher surface.

The Problem

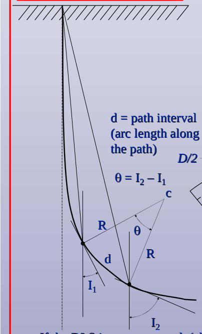
Curved wellpaths place tubing in bending. Rotation thus induces sinusoidal, fully-reversed strain/stress variation around the entire circumference.

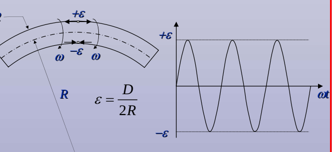
The radius of curvature can be computed from the "dogleg severity" (DLS) of the well profile.

$$DLS = \frac{\theta}{d} \qquad \theta = DLS(100\,ft)\frac{\pi}{180^\circ} \qquad R = \frac{100\,ft}{\theta}$$

d = path interval (arc length along the path)

$\theta = I_2 - I_1$





Bending strains imposed on curved section of rotating tubing.

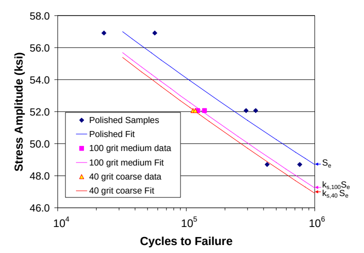
If the DLS is severe enough (above the endurance limit) additional high cycle fatigue (HCF) can be imposed, along with the low cycle fatigue (LCF) damage caused by conventional CT spooling/deployment hardware.

The severe bending strains caused by spooling induces residual tensile stresses in the tubing, which can potentially reduce the fatigue limit.

Circumferential abrasion caused by contact with the wellbore can roughen the surface, which can further lower the fatigue limit.

Full-Scale Results

90 ksi, 1.25" samples with medium and coarse surfaces were tested and compared to polished samples to compute the surface roughness factors.



The surface correction factors given by these results compare favorably to the Johnson curves, and are much higher than the conservative estimate of 0.6 used in the analysis (see "Analytical Results").

$k_{s,100} = 0.970$

$k_{s,40} = 0.963$

Conclusions

- A system to rotate coiled tubing imposes rotational-bending cycles on tubing deployed in directional wells.
- Sub-surface rotational-bending cycles are shown to lie well below the endurance limit for 90ksi grade coiled tubing.
- Based on conservative assumptions, the threshold DLS corresponding to the fatigue limit is well above 25°/100ft.
- Rotating-bending fatigue data on full-scale 1.25" diameter CT samples with and without circumferential abrasion validated the conservatism of the predictions.
- Additional rotating-bending data from small coupon samples showed that compressive residual stresses caused by surface abrasion somewhat offsets the detrimental effect of a rougher surface.
- Additional research is being conducted to model the HCF behavior of CT and to identify the threshold fatigue limit DLS more definitively.

Analytical Results

The Manson-Coffin relation is used to define the strain-life relation for LCF behavior:

$$\varepsilon_a = \frac{\sigma_f'}{E}(2N)^b + \varepsilon_f'(2N)^c$$

sf' = fatigue strength coefficient
b = fatigue strength exponent
ef' = fatigue ductility coefficient
c = fatigue ductility exponent

These properties have been assessed for the 90 ksi CT alloy under investigation.

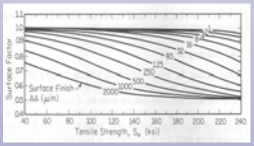
The Manson-Halford equation can be used to assess the influence of mean stress, σ_m.

$$\varepsilon_a = \frac{\sigma_f' - \sigma_m}{E}(2N)^b + \varepsilon_f'\left(\frac{\sigma_f' - \sigma_m}{\sigma_f'}\right)^{c/b}(2N)^c$$

The slope of the elastic portion of the strain-life curve, (b, the fatigue strength exponent) can be modified to account for surface roughness influence by:

$$b_s = -\frac{\log\left(\frac{\sigma_f'}{k_s S_e}\right)}{\log(2N_e)}$$

Where k_s is the surface roughness correction factor used to reduce the fatigue limit. Empirical curves such as this one (from R.C. Johnson) can be used to estimate k_s.



Using these equations, life predictions can be made assuming different values for mean stress, σ_m, and surface factor, k_s.

Using a DLS of 25°/100ft, the following predictions are made:

	Life Estimate (cycles)	
	$K_s = 0$	$K_s = 0.6$
$\sigma_m = 0$	102,866,660	2,151,423
$\sigma_m = 0.2S_y'$	59,155,134	1,386,299

With even the most conservative predictions of mean stress and surface roughness, all predictions lie above the endurance limit life of 10^6 cycles.

The surface factor of 0.6 is very small compared to the Johnson curves. The small value was selected for sake of conservatism.

Experimental Investigation

To study the effect of surface roughness caused by circumferential abrasion, two sets of experiments were conducted using full scale 1.25" diameter 90ksi CT samples and small scale 4130 steel coupon samples.

The purpose of the tests was to quantify (a) the k_s fatigue surface roughness factors and (b) the influence of residual stresses caused by the surface abrasion process on fatigue behavior.

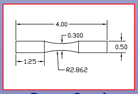
Both sets of tests were generated under rotating-bending loading as shown.

Emery cloth was used to induce the circumferential abrasion and a surface profilometer was used to measure the corresponding roughness

Full-scale CT rotating-bending fatigue testing machine, shown with 1.25" diameter sample.

Surface Condition	Cloth Grit	Ra roughness
A – Polished	N/A	3.4 μin
B – Fine	120	24.3 μin
C – Medium	100	57.5 μin
D – Coarse	40	78.8 μin

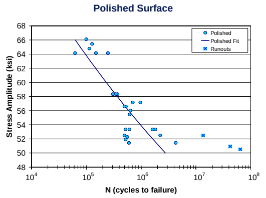
Small coupon rotating-bending fatigue test machine.

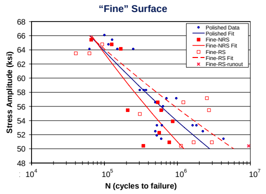


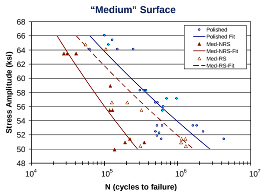
Coupon Sample Dimensions

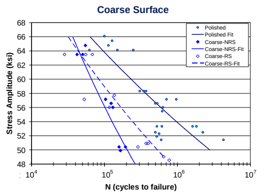
Small Coupon Results

Groups of small 4130 coupon samples were prepared with emery per the table below. Three other groups were left as machined. All were stress-relief heat-treated by soaking at 1150ºF for one hoar. After heat treating, the three as-machined groups were abraded, producing sets of fine, medium and coarse surfaces with residual stresses induced by the abrasion process (RS). The other sets had identical surface roughness, but no residual stresses (NRS). The polished data are shown below, and as a reference with the other sets of fine, medium and coarse surface finish data.









The surface roughness factors computed from these data are tabulated below.

Surface Condition	k_s - RS	k_s - NRS
B – Fine	>1	0.95
C - Medium	0.96	0.84
D - Coarse	0.88	0.81

The effect of residual compressive stresses is apparent in these graphs, as the dashed lines lie above the solid tendlines in every case.

In fact, the samples with the "fine" abraded surface finish slightly outlast the samples with polished surfaces.

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