THE INSPECTION OF STEEL COILED OILFIELD TUBULARS

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ABSTRACT

Coiled oilfield tubulars up to length 32,000-ft. are now being manufactured. Their NDE has evolved to where standards are requiring advanced form of magnetic flux leakage and phased array ultrasound. This presentation covers recent developments in these techniques, including a non-contact magnetic method for measuring wall thickness, phased array methods for flaw assessment, especially in butt welds, and the use of an internal untethered robot. Examples of NDE results are given, including 2 strings that were submerged by hurricane Katrina.

PUBLISHED STANDARDS

Coiled steel oilfield tubulars are (a) coiled line pipe (CLP), and (b) coiled tubing (CT). Both are seam welded materials. CLP is used as flow-lines and hang-off, and its manufacture is now standardized into published grades, sizes, and masses/unit length under API Specification 5LCP. CT is used as work strings, and suffers severe accumulation of ultra-low cycle bending fatigue. ASTM 606/7 HSLA steels hot-rolled into coils are used to assure high fatigue lives for CT. API’s Resource Group for Coiled Tubulars is working towards a standard for CT (draft API Spec 5ST). API Recommended practice RP 5C7 has now been re-approved twice since its introduction in 1996, but the material there-in will eventually transferred to other documents.

MANUFACTURING NDE

NDE is critical to the success of API coiled tubular strings. The old adage that if a string passes a hydrostatic test, it must be acceptable, represents older and unacceptable thinking. In cases involving seam welded pipe, the hydrostatic test can do more harm than good in that it can cause smaller (undetected) defects to grow, but not burst. In coiled tubulars, these smaller defects still need to be defined, but we have had to set standards based upon known detection methods and their reference indicators. Here is the present position.

Skelp-End Welds

Strips are welded end to end to make the length of the string, often as much as 32,000 ft. All skelp-end welds are radiographed (after dressing), using a 2T hole as a standard. Purchasers then have the option of having RT-accepted welds re-inspected with UT, searching for the planar defects that might escape RT, and enlarged grain colonies that cause brittleness. Small EDM notches are used as standards. The welds are also hardness tested. The welding + NDE procedures should aim at obtaining a weld (in tube form) that will have a cycle life of 80% of the tube itself.

Strip (Skelp)

Strip should be full body inspected. It is easier to do this during the string make-up than in the original metre-wide coil form. Removal of defects and imperfections at this stage eliminates them from passing into the string, and possibly causing premature failure. Saturated-field eddy current systems for this inspection have been reported.

Tubing (Pipe) In-Line

API standards (5LCP, RP 5C7) permit UT or electromagnetic inspection of the tube during the manufacturing process. Experience suggests that eddy current methods are just not sensitive enough to detect the very small planar flaws (such as hook cracks – a steel defect – and penetrators – a steel edge preparation/welding defect). The seam weld of tubing should thus be inspected by advanced ultrasound during the manufacturing process. A phased array system has been reported. The difficulties that arise for NDE are those associated with (a) leaving the inside flash in the tubing, and (b) the changing wall thickness of CT from one end of many of the strings to the other. Missed penetrators are one cause of premature leaks in the seam weld, especially when cycled and acids are run in the pipe. [Penetrators arise basically from poor edge preparation].

The detection of 10% of ID and OD test flaws of length 0.25-in. are recommended of an inspection system.
Butt Welds
Some strings have butt welds. They are either permitted (as in CLP, hang-off) or discouraged (long, high-pressure, high temperature work strings), and often done in the field as a repair to remove deep defects or heavily cycled sections of CT. Butt weld quality is often questionable. While RT is used and has been standardized, recent advances in phased-array UT have meant that butt welds in relatively thin-walled tubulars can now be readily performed. Typically 10 MHz sound between 45 and 70 deg is used, with a standard that contains a 5% x 0.125-in. long EDM reference indicator. This is appropriate for lack of fusion problems that are not detected by X-ray, and these are probably the worst defects that such butt welds can harbour. Ends to be butt-welded should also be demagnetized to as low a level of residual magnetism as possible.

Final Inspection at Mill
Indications detected on in-line inspection need to be investigated off-line as soon as possible. Rules have been reported in earlier papers. The only way (at present) to re-inspect a finished string is to use a small version of a conventional EMI unit that was built for small diameter OCTG tubing inspection. In this equipment, the steel is magnetized axially and circumferentially so that defects in all directions can be found using magnetic flux leakage (MFL). Reference standards include 0.25 and 0.50-in. long x 10% ID surface EDM notches, and 1/32nd and 1/16th-through-drilled holes.

Occasionally, only a longitudinal magnetization is used, but this method has little sensitivity to longitudinal seam-weld defects such as tight penetrators, and other than setting baseline wall thickness measurements, this method provides little information.

Prove Up
The usual MT and PT are useful for OD-surface tight defects. Compression wave ultrasonics (UT) is used to measure remaining wall after OD surface flaws are removed. Shear wave techniques have evolved that (a) permit the seam weld to be inspected without getting reflections from the internal flash column, (b) permit the skelp-end weld to be inspected in tube form.

The same reference indicators as above are used.

OD Surface Flaw Removal
Flaw removal is governed by the need not to have a butt weld, since they do not have anywhere near the bend-cycle life of the virgin tubes. Research at the Coiled Tubing Mechanics Research Consortium at the U. of Tulsa has indicated that removal of defects up to about 10% of the tubing wall is not particularly detrimental, and preferable to a butt weld. This represents good practice.

FIELD NDT
Three forms of field inspection have evolved; all employ MFL rather than UT. No full body UT unit for used CT inspection currently exists.

1) In the first, the EMI unit above is used. It contains a rotating gamma-ray source for wall thickness measurement. This method has been used for inspections of over 100 CT and CLP strings, both new and used, and was used for the strings reported below.

2) In the second, the tbg is magnetized longitudinally, and checked for flaws with a transverse component. The method also uses a magnetic reluctance technique for non-contact wall thickness measurement. An eddy current stand-off method is used for measurement of tubing ovality, which seriously affects the collapse resistance of the tbg. Very much used tbg has been inspected by this method, and it is being standardized in draft API RP 5C8 (Care, Maintenance and Inspection of Coiled Tubulars). The device is relatively portable, and may be attached to the CT rig, so that the tbg can be inspected as it is pulled out of the hole.

3) In the third, a robot is sent through the tubing while it sits on the storage reel. (This eliminates the one fatigue cycle often consumed by the above methods). The robot uses permanent Nd-B-Fe magnets to saturate the tube wall longitudinally, and hall-effect elements are used to scan MFL from defects on both walls, and measure the tangential field strength that has been shown to be related to the wall thickness in the vicinity of the sensor. (This is not a small “spot” measurement as is compression-wave UT, but rather an average over a region of pipe, but is useful for detecting grinds and extended areas of wear or corrosion on the tbg.)

COILED TUBING MECHANICS

Problems Associated With Coiled Tubing
Several articles have been written regarding what happens to CT and how it degrades in field operations. Summarizing:

1. Mill Residuals: The worst appears to be incomplete fusion of the seam weld. It may contain cold welds and penetrators, which may subsequently leak at high pressure, in acids, and
after only a few cycles.

2. **OD Surface Marks**: These include chafing marks (the tbgs wrap moving tightly against themselves & the side of the reel), gouges, and injector ring marks.

3. **OD Corrosion**: Tubing must be protected before and after jobs with a layer of coating materials, and preferably kept out of rain- and seawater, and acids. All cause corrosion if left unattended.

4. **ID Corrosion**: Acids and seawater (used to flush out the tbgs) cause pitting and eventually hydrogen-induced cracking, including embrittlement if left inside. These problems generally occur at the 6-00 o’clock position wrt to the tubing on the reel.

5. **Ovalling and Ballooning**: Continual cycling lowers the yield strength, and subsequent pressure causes the tubing to oval or to swell. Tension may then cause ballooning or collapse.

6. **Abrasion**: Tubing abrades against the sides of the well, either going in (buckling) or coming out. Passing sand through the tubing abrades the ID in the curved part of the string on the reel.

7. **HIC and SOHIC**: In H₂S, HIC and SOHIC may occur and cause serious problems. They can originally initiate at inconsistencies in the steel such as laminations and mid-wall segregations.

**CT Mechanics Research**

Based upon work at U Tulsa, fatigue curves were established for virgin tubes, skelp-end welds, and butt-welds. These curves predicted tubing life in the absence of defects. Because tubing was reportedly breaking in the field at defects, further research lead to a programme (Flexor TU05) that covers the detrimental effects of OD surface defects. As might be expected, shorter, wider defects lead to lower fatigue lives, while smoothing them out raises it.

We have used both NDE and this programme to determine the suitability of the use of used strings.

**EXAMPLES OF EMI AND FLEXOR**

1. **Katrina String 1**: Inspection of a 28,240-ft. string of CT90 manufactured for the Thunderhorse wells (Gulf of Mexico) was performed in Houston after the string had been delivered to Venice (S. LA) and then flooded by hurricane Katrina. Numerous OD pits were found, doubtless caused by seawater, the deepest of which were 0.050-in. The pits often occurred where the tubing contacted itself and the sides of the reel. Flexor TU05 was then used to calculate

   (a) the number of trips to failure at 3000 psi internal pressure (we had to select a value and this is as good as any!) for perfect pipe,

   (b) the no. of strips to failure at the same pressure with the defects present, assuming they were hemi-spherical, which many were.

   (c) The number of trips if the defects are then sanded out, and

   (d) The 95% confidence level in the calculations.

   To estimate the effect of a butt weld, the undamaged tubing results were divided by 4. It was found that flaw removal would always have been a better option than replacing pitted sections with butt welds.

2. **Katrina String 2**: Similar results were found on a second sister string of CT90 submerged under Katrina.

3. **Tahiti String**: Similar results were found with a CT-110 string manufactured for the Tahiti (G o M) well, which had 2 butt welds. EMI and Flexor revealed only a few shallow pits, (the deepest being 0.020-in.) to be of no serious consequence. The butt welds were the obvious problem in this string, since their cycle life would be far less than that of the tubing.

**PHASED ARRAY BUTT WELD INSPECTION**

In order to test butt welds in CT, an “Omniscan” was used at 10 MHz with entry angles 40-70 deg. from a contoured probe. This technique is ideal for the detection of lack-of sidewall fusion. Zero degree scans were also performed to both look at the ID bead, and check for LoF between the 1st and 2nd weld metal layers. The reference notch of 0.125-in. long x 5%t (in this case 0.009-in.) was easily detected and it’s A-scan set at 80% FSH. The S-scans are particularly revealing.

Inspections of butt welds in CT have now been performed in the field (far easier than taking radiation to an offshore rig!) and the method has been included into at least two CT standards.

**ROBOTIC INSPECTION**

A robot has been developed that will travel inside CT of diameter 2.875-in. Data from field tests in Norway.
indicate that the system is responsive to internal and external pitting, and that wall thickness can be measured from the inside of the tube. The robot knows exactly where it is and in which direction it is going. It is totally untethered. Data are collected at approximately 1 mm intervals, stored in memory, and reviewed when the robot is returned.

It has now been developed to negotiate 1-D bends in furnace and other tubing. At larger diameters, techniques other than MFL can be used, so that material other than ferromagnetic tubes can be inspected.

CONCLUSIONS

1. CT inspection is much improved from the situation 15 years ago. Minimum production standards are now written, and customers are requiring additional state-of-the inspections such as phased-array UT.

2. Final inspection of CT has been introduced and now finds its way into API standards.

3. Internal robots have been introduced that can inspect CT from the inside, and may be used for steel tubing products.

Note: A detailed version of this paper can be found in “Inspections of 100 Coiled Tubing Strings,” R. K. Stanley, ASNT Intl. Chemical and Petroleum Insp. Conf., Houston, June 2007.

References


2. API Recommended Practice RP 5C7, “RP for Coiled Tubing Operations in Oil and Gas Well Services.”


Inspection of Steel Coiled Tubulars

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Abstract

- CT strings are generally for high-pressure/high temperature use, and made by ERW/HFI methods.
- Lengths are up to 32,000 ft
- Internal flash column is not removed – makes NDE “interesting”.
- We calculate the effect on the fatigue life of the tubing using a computer programme – Flexor TU05.
- Roughly 100 coiled tubing strings have been final-inspected in Houston (after hydro test)
- This paper covers some of the inspections
Standards for Coiled Tubing?

• Where do standards and specifications come from?
• There is no published (API) specification for CT.
• Currently, the buyer must perform “Contract Review” on commercial grades..
• And look at tests and inspections over and above those that are conventionally performed in the mill.
• „Such as a “Final Inspection after Hydro-test”

Final Inspection of coiled tubing for use as a riser offshore Africa. The inspection unit is between the 2 reels.
Current Standards for Coiled Tubing

Recommended Practice API RP 5C7

• Covers CT70, CT80 and CT90 Grades only

API are working on a *Specification for Coiled Tubing* (API Spec 5ST) that will cover grades CT70, CT80, CT90, CT100, CT110 and…..

A Recommended Practice for *Care, Maintenance and Inspection of Coiled Tubulars.* (API RP 5C8)

• and there are some customer standards

.........So it can get confusing out there……..
Coiled Line Pipe

- However, there **is** an API Specification for coiled *line pipe*, covering grades X52C-X90C (almost the same grade symbols as in API Spec 5L)
- *2nd Ed. publ Apr 2007*
Needs for NDE for HPHT Coiled Tubulars

- Mill “Final inspection” of tube (EMI or UT)
- Better and non-radiative inspection of seam welds and butt-welds (if present in tubes)
- Better Field Inspection of entire strings, inc, butt welds
- Tying NDE to Fatigue and life loss as the pipe is cycled

So, in this paper we discuss

- Fatigue considerations
- Final Electromagnetic Inspection (EMI)
- UT prove up for Longitudinal Seam Welds
- Phased-Array Butt Weld Inspection
What Happens to CT?

- Coiled Tubing spends it life being bent and straightened, & having nitrogen, acids, cement and other stuff pushed through it.
- May or may not contain a wire-line.
- It will have (a) Residual mill defects, and (b) Service-induced defects in it as it is used.
- Some pictures follow.....
Typical Defects 1

- Typical defects on OD of tube from rig operations.
- Cracks form in the roots of these defects when the pipe is bent and straightened, often without your knowledge.
- Pipe can (and has) broken in hole and caused fishing jobs running at $M.
- One failure cost one N. Sea Oil Company about $8M in lost production; could have been avoided if the pipe had been inspected.
- CT failures, especially offshore, are not cheap.....

See the need for non-contact defect detection?
Typical Defects 2

- Pitting and scrapes in tubing

See the need for detection of defects on internal and external surfaces?
Typical Defects 3

- Results of a sand-frac (Canada), and acid left in the tubing (Colombia)

See the need for wall thickness measurement of pipe with rust?
Typical “Longitudinal” Defects

- Fatigue cracks
- Open seam in electric weld pipe, with internal flash present.
- Long crack that split the pipe at the root of the flash column after acid work.

2 pictures courtesy Dr B Luft, BJ Services
How They Tell the Condition of the CT.....

- Count the running feet......scrap after X-ft. (X is, of course, a variable....)
- Scrap after 3 years....(if it hasn’t broken).
- Scrap after surviving 2 winters....
- Buy a Fatigue Model and calculate the accumulated bending fatigue
- Until recently, none of these models accounted for the presence and growth of defects.
- Until recently, rarely was NDE used, and great risks were taken
Fatigue Life Models

- Tubing fatigue life is theoretically modelled.
- There are several models…no 2 give the same result.
- Most models do not include the effects of imperfections.
- The model described here (Flexor TU) from the U of Tulsa, contains the effects of OD surface damage.
- This model is the result of company participation at the Coiled Tubing Mechanics Research Consortium, and the Idaho National Engineering Lab.
Flexor TU05 Cycle Life Model

- Data that are collected on fatigue machines are used to compute rig performance of the tbg with OD surface defects.

- Cycles/trips without the defect are **495 cycles** and **104 trips** respectively. With this defect present, **197** and **41** respectively.

This programme is recently up-dated with 95% confidence levels.
Predictions of Flexor Model with Defects

Quote “The tubing failed at 20% of its rated life”
Response “More likely it failed at 100%. What or who caused the other 80%?”

Cycle life and trips gets smaller as:

• (a) defect gets deeper (width & length the same)
• (b) defect gets axially shorter (depth and width the same)
• (c) defect gets transversely wider (depth and length the same)
• (d) internal pressure increases.

Picture shows the result of cycling a 10% EDM notch on a fatigue machine to failure
NDE Techniques for CT Strings

..in addition to what the mill does on *any* string.....

- “Final” EMI inspection (*Because there is no final full-body Ultrasonic Testing......yet....*). Done at the mill, or as “receiving inspection”.
- The usual MT and PT for tight surface imperfections
- Ultrasonic *Shear Wave* Inspection for Longitudinal Seam Weld
- Shear Wave Inspection for Butt Welds. *This is a very useful inspection for in-service butt welds*. Good results have been obtained with phased array UT.
- EMI for in-service strings (Magnetic wall thickness, MFL for pitting & gouges, cracks, and an ovality measurement)
Techniques - EMI

Transverse flaw inspection/longitudinal magnetization

This Inspection meets API 5LCP SR 21 & ASTM 570

Longitudinal flaw inspection, circular magnetization with rotating poles

Sensors in rotating inspection
EMI-Transverse Flaw Only

System measures wall, ovality, and detects transverse flaws

Field Experience

- Over 14.5 million feet inspected.
- Total of > 240 strings.
- Spooling, onshore and offshore operations.
- Several evaluation tests.

Courtesy Rosen Inspection
Use of Neural networks to assess defects in tubing in real time

Courtesy Rosen Inspection
EMI Transverse Flaw only 2

- Small diameter tubing from the OD
- Fold-out map of MFL signals, along with more traditional presentation.
- Wall thickness

Courtesy Tuboscope
Reference Standards for EMI and UT

- Pipe is made to have several EDM notches, 2 TDHs, and a butt weld.
- Pick the ones you want during “contract review”.
- Set up the unit on the agreed reference indicator(s),
- Test with RIs at 12, 6, 3, 9 o’clock, then run the tubing string.

- Then evaluate all signals, not just those that exceed the reference indicator signal.
Indication Prove-Up

- UT Wall measurement
- Dimensions (ovality)
- The usual Magnetic Particle Inspection for tight OD defects
- Ultrasonic **Shear Wave** for Seam Welds
- Advanced **Phased-Array Ultrasonic Shear Wave** for Butt welds
Shear Wave – Seam Weld

• Simple trigonometry reveals distance to flaw and wedge angle. We use angles calculated from coiled tubing tables so as to avoid reflections from internal flash.
• This Level II guy is inspecting the weld of spiral-weld pipe.
• This is faster than RT and sees planar stuff that RT would tend to miss.
Current Butt Weld Inspection

• Currently we use *double-wall RT* Mill – *X-Rays* Field - *Gamma rays*

• OK for *volumetric* flaws, but not responsive to *planar* problems, e.g. Lack Of Fusion.

• There is a need a lightweight, accurate non-radiation method, esp. for offshore use.

• **We are studying Phased Array UT at 5-10 MHz**

• Note: Butt welds are *not* critically inspected by current EMI/MFL methods because the butt weld signal hides the MFL from much smaller planar flaws in the weld

Elliptical image on film is necessarily through 2 walls
Advanced UT of Butt Welds 1

- **RT is not acceptable** for planar defects (which have high stress concentrations at their ends under bending loads, and fail quickly)

- Planar defects (e.g. sidewall lack-of-fusion) are better detected by ultrasound, but conventional UT methods are hard to implement in thin-walled material. Phased-array works very well...........

- There is much evidence for this from pipeline weld inspection.

- **UT is Easier, cheaper, and faster than RT, and doesn’t need a radiation safety programme**, but does need a good Level II.
- 5-10 MHz *Phased Array*
- 16 transducer system instead of 1
- Small reference indicator (5% of wall, 0.125-in.)

*Rapid* scans possible from both sides of weld

- OD Surface prep is important to eliminate spurious reflections
- Can be performed as acceptance *after mill RT*

- Perform *easily* in field to monitor welds, esp. offshore, because weight is negligible, and calibration can be done before you get on the helicopter.

**Advanced UT of Butt Welds 2**

Unit and calibration notch weighs about 10 lb
Phased Array?...

- Multi-element pulses of sound, controlled by computer.
- Sound comes together right where you want it to.
- Beam angles from 40-70 and $\frac{1}{2}$ degree intervals. (60 beams!)
- Vary defect sensitivity by changing the frequency.
- Many presentation modes are possible, to suit the inspection.

Screen of PA unit
PA Equipment For CT Butt Welds

- RD-Tech “Omniscan” at 5 MHz
- Computer does everything, including storing the standardization from one job to the next.
- Highly portable and no radiation!
- 16 element UT probe looking 40° deg to 70° from either side of smoothed weld.
- Detects both 2D and 3D imperfections in and close to butt-weld, or anywhere else……

Courtesy RD-Tech
Phased Array Display for Shear Wave Weld Inspection – Ref Ind.

- Reflection from EDM notch from 50-60°, max at 56°.
- 80% FSH set at “red”.
- This EDM Notch depth is 0.009-in., length 0.125-in.

These data were taken by Q-Pro (Houston), and stored in memory, before heading to Oklahoma to inspect a butt weld.
Typical Data – ID Indication

- A-scan at 56.5° (L) and S-scan (R) from 40-70 deg with an ID indication.
- Defect at ID
- Defect on 2nd leg

Data were collected at Q-Pro (Houston), before going out on a job.
Weld Signal – 2.375-in. Tube Weld

- Field inspection of butt weld
- Some noise from weld metal on 1st leg.
- Possibly enlarged grains in weld which scatter sound

Data were collected by Q-Pro in the field
Cracks in Pipe

- Small secondary cracks in a fatigued sample are easily detected.
- Ideal for field prove-up

16-element transducer
Examples of EMI Inspection

• We have inspected over 100 strings by EMI.
• The following examples of NDE were done with the EMI system with the rotating pole described above.
• Two of the strings had been manufactured for use on *BP Thunderhorse*, but were submerged during hurricane Katrina.
• A third string had been stored for 2 years, and the owner want to know if it was usable.
2006-String 1(Katrina)

- 28242-ft. of 2-in. tubing
- 0.050-in. (28%) OD pit at 12,000-ft in 0.156 wall.
- **Flexor TU05** predicts cycles drop from 541 to 139 at 3 kpsi, on a 72-in. radius bend block. 302 cycles if flaw is removed.
- The rest are mainly 0.010-0.027-in. deep OD salt-water pits.

Note that the pits are in bands, related to the outer edges of the storage reel.
*Over 50 pits between 10-15 mils deep, from salt water, at lower end of string.*

*We computed the effect of the flaw using Flexor-TU05 (number to failure, & 95% confidence level.)*

*One 46 mil deep pipe flaw at 7815-ft. reduces life drastically at this point.*

*String could have been repaired and used*
2006 string 3 – CT110 grade

- 27,000-ft. with 2 butt welds
- 1.75-in. (0.204-0.156)
- Built 2003
- Inspected new and in 2006.
- Used a 1/16\textsuperscript{th}-in. TDH reference indicator, since we had already inspected it “new”, and passed the string.
- 15 indications
- One at 20\%t, 2 at 18\%t
- *String could have been repaired, then monitored in service.*
  General surface condition shows OD surface pitting
Conclusions

• We have presented examples of techniques developed for inspecting HPHT and other tubing strings, and coiled line pipe, both in addition to mill inspection, and in the field (EMI and UT).

• We have found that setting up an inspection programme to monitor CT strings in the field can be very effective in making strings last longer.

• An inspection programme may provide the confidence to keep strings in service, avoiding failures, and indicating when new strings, butt welds, etc., are required.

• Flexor is very effective in telling when to weld or repair a string.