

Care, Maintenance, and Inspection of Coiled Tubing

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Care, Maintenance, and Inspection of Coiled Tubing

1 Scope

This recommended practice covers the care, maintenance, and inspection of used low alloy carbon steel coiled tubing. Commonly manufactured coiled tubing outside diameters range from 25.4 mm (1.000 in.) to 88.9 mm (3.5 in.).

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Specification 5ST, *Specification for Coiled Tubing*

ASTM A370¹, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*

H. Haga, K. Aoki, and T. Sato (1980a), Welding Phenomena and Welding Mechanisms in High Frequency Electric Resistance Welding—1st Report, *Welding Journal* 59(7), pp. 208–212

H. Haga, K. Aoki, and T. Sato (1980b), The Mechanisms of Formation of Weld Defects in High-Frequency Electric Resistance Welds, *Welding Journal* 59(7), pp. 103s–109s

For a list of other documents associated with this standard, see the Bibliography.

3 Terms, Definitions, Acronyms, and Abbreviations

3.1 Terms and Definitions

For the purpose of this document, the following definitions apply.

3.1.1

Bauschinger Effect

A phenomenon that occurs in polycrystalline metals (including steel), that results in a decrease of the yield strength in one direction due to plastic deformation in another direction such as is caused by service loads, coiling, or straightening.

3.1.2

bed wrap

The wraps of coiled tubing that are adjacent to the cylindrical core of the shipping or usage reel.

3.1.3

cold work

Plastic deformation at such temperatures and rates that substantial increases occur in the strength and hardness of the metal.

NOTE Visible structural changes include changes in grain shape and, in some instances, mechanical twinning or banding.

3.1.4

critical weld(s)

Primary connections in coiled tubing where failure would jeopardize the safety of personnel or equipment and/or be detrimental to the integrity of the coiled tubing string or operation.

NOTE Critical welds include, but are not necessarily limited to, tube-to-tube girth joints and high-pressure end-fitting welds for union connections to swivel joints on coiled tubing reels.

¹ ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org

3.1.5**cycle**

One complete bend and straightening event that the coiled tubing experiences during manufacture, operation, and use.

3.1.6**defect**

An imperfection of sufficient magnitude to warrant rejection of a product or the part of the product containing the defect, according to an agreed specification.

3.1.7**diametral growth**

The increase in tubing outside diameter observed following coiled tubular operations.

3.1.8**electro-discharge machining****EDM**

Method for producing reference indicators for nondestructive testing (NDT) cut into part surface using the spark-erosion technique.

3.1.9**electromagnetic inspection**

Either the generic term for all NDT performed using electromagnetic methods, such as eddy current and magnetic flux leakage, or the oilfield tubular inspection term for various combinations of eddy current and magnetic flux leakage inspections commonly performed on such tubulars.

3.1.10**flash (OD/ID)**

A fin of metal formed at the sides of a weld when a small portion of metal is forced out between the edges of the forging or welding dies.

3.1.11**fleet angle**

The angle at which the coiled tubing goes on to or comes off the storage reel measured from the adjacent tubing already on the reel.

3.1.12**fluorescent magnetic particle inspection**

The magnetic particle inspection process employing a finely divided fluorescent ferromagnetic inspection medium that fluoresces when activated by ultraviolet light.

3.1.13**high frequency induction welding**

A welding method in which metal is heated to softness by eddy currents and pressed together forming a continuous material without addition of filler metal.

3.1.14**image quality indicator****IQI**

A reference standard for radiography.

3.1.15**lamination**

An internal metal separation creating layers generally parallel to the surface.

3.1.16**Level I**

A person trained to a written practice in the NDT methods employed in testing product but not necessarily capable of interpreting results.

3.1.17**Level II**

A person trained to a written practice in the NDT methods employed in testing product, capable of interpreting procedures, results, procedures, and supervising Level I inspectors.

3.1.18**Level III**

A person trained to a written practice in NDT methods employed in testing a product and capable of interpreting the results, writing test procedures, and qualifying and certifying Level I and Level II inspectors.

3.1.19**liquid penetrant inspection**

An inspection process in which fluids are attracted into tight flaws by cohesive surface forces, partially leached out, and developed for visibility.

3.1.20**magnetic flux** Φ

The amount of magnetism, measured in Webers, or lines of magnetism.

3.1.21**magnetic flux leakage****MFL**

An inspection process that consists of magnetizing a ferromagnetic product and detecting flaws using the magnetic flux they expel into the surrounding air.

3.1.22**magnetic induction****B**

The amount of magnetism per unit of cross-sectional area (A), measured in Tesla (Weber/square meter), lines per square centimeter.

3.1.23**magnetic particle inspection/testing****MT**

An inspection process that consists of magnetizing the material and applying a prepared magnetic powder that adheres along the lines of flux leakage.

3.1.24**magnetic permeability**

The ratio of the magnetic induction to the intensity of the magnetizing field.

3.1.25**maximum outside diameter** $D_{\max}$

The maximum outside diameter is the largest measured outside diameter at any location of the coiled tubing.

3.1.26**maximum permitted outside diameter** $D_{p,\max}$

The maximum permitted outside diameter is the largest outside diameter that can be accepted on the job for which the coiled tubing will be used.

3.1.27**microhardness**

Measurement of bulk hardness using a small load.

3.1.28**microhardness test**

The average of three values taken at the measurement location, with obvious inaccurate readings repeated.

3.1.29**minimum outside diameter**

$D_{\min}$

The minimum outside diameter is the smallest measured outside diameter at any location of the coiled tubing.

3.1.30**minimum permitted outside diameter**

$D_{p,\min}$

The minimum permitted outside diameter is the smallest outside diameter that can be accepted on the job for which the coiling will be used.

3.1.31**nondestructive inspection****nondestructive testing****NDT**

Evaluation of the tubular to detect any surface, internal, or concealed defects or flaws by using techniques that do not damage or destroy the product.

3.1.32**ovality**

Difference in outside diameters of the tubular of a single cross section of the tubular.

3.1.33**penetrator**

A weld seam defect that goes from inner or outer diameter into or through the weld.

3.1.34**radiography**

A nondestructive test method in which high energy electromagnetic radiation (generally X-rays) are passed through an object and a shadow of variations within the product captured on film or digitally.

3.1.35**reeling**

Transferring tubing or pipe from one reel to another.

3.1.36**reference indicator**

A defined imperfection that is used for setting the sensitivity level of nondestructive evaluation equipment.

3.1.37**reference standard**

A block or tube containing machined imperfections used as a base for comparison or for the standardization of inspection equipment.

3.1.38**sensitivity**

The size of the smallest discontinuity detectable by a nondestructive test method with a reasonable signal-to-noise level.

3.1.39**skelp**

The rolled steel sheet used in making of high-frequency induction welding or laser-welded tube.

3.1.40**spooling**

The act of transferring tubing from one storage (shipping) reel (spool) to another by means of unwinding the payoff string and rewinding the take-up string.

3.1.41**ultrasonic inspection**

A nondestructive method of inspection of a product for wall thickness or the presence (or absence) of imperfections or defects employing high-frequency sound.

3.1.42**ultrasonic shear waves**

Short wavelength, high-frequency waves in which the energy flows in a direction perpendicular to the particle motion.

3.1.43**ultrasonic testing****UT**

A nondestructive method of inspecting material by the use of high-frequency sound waves.

3.1.44**used coiled tubing**

Coiled tubing that has passed from a storage reel past the injector into a well.

3.1.45**wiper ball**

A compressible and disposable sponge ball that is propelled through the tubing to remove as much of the hydro test or other fluid as possible.

3.1.46**yield radius**

The minimum radius above which, when coiled tubular product is wound upon a reel, it will not experience any plastic yield.

3.1.47**yoke**

A device for magnetizing a small area of a ferromagnetic part surface so that magnetic particle inspection can be performed.

3.2 Acronyms and Abbreviations

AWS	American Welding Society
BHT	bottomhole temperature
BOP	blowout preventer
CWB	Canadian Welding Bureau
EC	environmental cracking
EDM	electro-discharge machining

EW	electric weld
FSH	full screen height
GTAW	gas tungsten arc welding
HAZ	heat-affected zone
HIC	hydrogen-induced cracking
IQI	image quality indicator
LCF	low cycle fatigue
MFL	magnetic flux leakage
mpy	mils per year (1 mil = 0.001 in.)
MT	magnetic particle inspection/testing
NDE	nondestructive examination
NDT	nondestructive testing
NORM	naturally occurring radioactive material
OEM	original equipment manufacture
PQR	procedure qualification record
PT	liquid penetrant testing
PWHT	postweld heat treatment
RT	radiographic testing
SG	specific gravity
SOHIC	stress-oriented hydrogen-induced cracking
SSC	sulphide stress cracking
TIG	tungsten inert gas
UT	ultrasonic testing
WPS	welding procedure specification

4 General Information

4.1 Applications of Coiled Tubing

4.1.1 General

Coiled carbon steel tubing can be used, but not limited to, the following applications.

4.1.2 Workstrings

Workstrings are specifically designed for servicing specific wells or specific fields but are often used in other wells and fields. Certain regions of workstrings may receive heavy bending and experience considerable

fatigue. They may or may not contain means of communicating with tools attached to the end of the tubing, such as electric or fiber optic cables. They may be used to transport acids, liquid nitrogen, cement, and sand for well service operations.

4.1.3 Drill Strings

Coiled tubing drill strings are used with rotary bits that are driven by mud motors and bottomhole electric motors. The tubing itself does not rotate other than as a flexural response to the drilling operation.

4.1.4 Siphon and Velocity Strings

Siphon strings are introduced into wells in order to provide a channel for the introduction of fluids at pressure to the producing section of the well in order to raise well fluids to the surface inside the production tubing. Velocity strings are introduced into wells to restrict the annular flow area in wells that employ conventional tubing, thus promoting higher flow rates for the produced fluids. Such strings are not generally cycled in this mode of use. Older strings may be retired into this type of service.

4.1.5 Sucker Rod Systems

Coiled carbon steel tubing may be used as coiled sucker rods. In this application, the produced fluid flows up the bore of the coiled tubing.

4.2 Responsibility of the Purchaser

4.2.1 Purchaser Responsibility

It is the responsibility of the purchaser of the inspection, maintenance, and repair services to inquire if the companies employed to perform the work have quality systems in place to conform to this recommended practice. In this context, “system” is taken to mean the combination of equipment, equipment performance, operator training, and a quality system under which the company operates. The quality system should include written procedures for equipment operation and recalibration, operator training, and certification and should take as the model the requirements of API Q1 or the ISO 9000 series of quality standards.

4.2.2 Purchaser Access

4.2.2.1 Access to Quality System

The purchaser should have access to the quality system of the service provider and may perform periodic audits thereon for the purpose of qualifying or requalifying the service provider.

4.2.2.2 Access to Provider Facility

Upon agreement, the purchaser should have access to monitor the work of the provider, provided that the representative of the purchaser meet and comply with all the necessary safety standards in operation under the auspices of the provider and any legal and governmental requirements.

4.3 Naturally Occurring Radioactive Materials (NORMs)

Coiled tubing strings that have been in service in certain areas may develop a coating of NORM. The coiled tubing strings should be checked for the presence of NORM prior to performing the service work herein.

Guidelines for operations involving NORM on tubulars are provided in API E2.

Unless otherwise agreed between the owner of the coiled tubulars and the service provider, all work performed as services in this document shall be on coiled tubulars that have NORM in accordance with appropriate local regulations.

4.4 Properties of Coiled Tubing

Annex A provides information on coiled tubing properties.

5 Welding Coiled Tubing

5.1 General

Welds in coiled tubing are used for repair and modifications such as extending the length, removing damaged sections of the coiled tubing, or for attaching temporary or permanent end-fittings. Unlike welds in conventional process piping or tubing, tube-to-tube girth welds (butt welds) in coiled tubing are subjected to plastic bending cycles and therefore shall exhibit both sufficient strength and plasticity so as to provide acceptable low cycle fatigue (LCF) performance. Experience has shown that the LCF life may vary from 25 % to 75 % of the base tubing, depending upon the welding process used. Since the LCF life of these welds is highly dependent upon their welding procedure specification (WPS) and quality of workmanship, it is of critical importance to pay special attention to welding procedure control such as fit-up, edge preparation, filler metal selection, thermal cycle control, and dressing of the as-welded connection. This section is intended to provide guidelines to achieve sound welds in carbon steel coiled tubular operations with emphasis on achieving acceptable plastic bend fatigue performance.

Welders of coiled tubing manufactured to API 5ST should meet the requirements in Table 1.

Table 1—Welds with Filler Metal (Tube-to-Tube Weld)

Condition	Special Process
Weld	90° tube-to-tube weld
	Heat treatment of tube-to-tube weld
	NDT of tube-to-tube weld
Tube wall	NDT

This section is concerned only with welds in new and in-service coiled tubing involving tube-to-tube girth welds of equivalent or dissimilar CT strength grades, wall thicknesses and/or loading history, and welded end-fittings involving fillet weld connections between new or used CT and other heat-treatable high-strength low-alloy carbon steels.

Welding of corrosion-resistant alloy coiled tubing is outside the scope of this document. Joining by amorphous diffusion bonding is outside the scope of this document. If looking for additional information not identified in this document, refer to ASME *BPVC* Section IX.

5.2 Type of Welds Used in CT Products

5.2.1 Tube-to-Tube Welds

A tube-to-tube weld is a girth butt weld that joins two lengths of existing coiled tubing of equal outside diameter. The two ends to be joined are cut square, carefully aligned and welded from one side without backing around the circumference. The resulting weld is perpendicular to the coiled tubular string axis. Butt welds in coiled tubing should meet the requirements of API 5ST.

5.2.2 Coiled Tubing to Fitting Welds

End-fittings are welded to coiled tubing for connections to swivel joints on the CT reel and, in some cases, for attachment to bottomhole assemblies. Welding of fittings for swivel joint connections is generally performed at the coiled tubing manufacturer and is therefore governed by the specifications and quality control of the coiled

tubing manufacturer. However, whenever slip on type fittings are involved, the use of two fillet welds in tandem is recommended.

Since fittings are generally made of different steel grades including air-hardenable alloys, a special WPS is required for these connections.

5.2.3 Flag Welds on Coiled Tubing

Flag welds are welds made around the tubing at certain positions specified by the operator. These welds may both reduce the fatigue life of that local section of the tubing, preferentially corrode in acid service, and are not recommended.

5.3 Welding Processes

Welding processes for coiled tubing usually entails both manual and mechanized (orbital) gas tungsten arc welding (GTAW) also referred to as tungsten inert gas (TIG). Manual GTAW is the most common welding process used for tube-to-tube connections. Orbital GTAW welding processes are also used for field welds but are less common due to their higher costs and more critical joint fit-up and specialized operator training requirements. However, made in carefully controlled conditions and with the repeatability and consistency of automation, the fatigue life of orbital GTAW welds can be expected to be about twice that of manual GTAW welds. Since the quality of manual welds is inherently more variable, orbital GTAW or other processes that result in more consistent and superior LCF performance are preferred for tube-to-tube welds.

Manual shielded metal arc is another process commonly used for welding coiled tubing products, but it is not recommended for tube-to-tube welds.

5.4 Welding Procedure and Qualification

5.4.1 General

All carbon steel coiled tubing welds should be performed only by qualified welders in accordance with a written WPS. A WPS may be qualified by a procedure qualification record (PQR). The coiled tubing service provider shall maintain a permanent file of all welding procedures, procedure-qualification test results and PQRs. Copies of all or parts of this file should be available upon request by customers of the service provider.

5.4.2 WPS

A WPS is a set of written instructions and welding parameters designed to enable the welder to make a sound weld. It consists of a WPS datasheet and a welding engineering standard. For a given welding process, the WPS provides detailed information on the following:

- a) base material,
- b) applicable standards and codes,
- c) joint type,
- d) thickness range,
- e) edge preparation,
- f) welding position and progression,
- g) filler metal (consumable) classification and size,
- h) welding wire feed speed (if applicable),

- i) preheat and inter-pass temperatures,
- j) postweld heat treatment (PWHT),
- k) shielding gas type and flow rate,
- l) electrical characteristics (polarity, amps, volts),
- m) arc travel speed,
- n) welding technique,
- o) pass sequence,
- p) PQR, and
- q) other information that may be relevant.

A typical WPS format is given in a document for the preparation of tube-to-tube welds that has been published by the International Coiled Tubing Association (ICoTA) (see [39]) and is recommended for the detailed preparation of WPSs for coiled tubular strings.

WPSs should be prepared by a welding engineer with the guidance of [39], [45], [46], and [61].

5.4.3 Welding PQR

5.4.3.1 A PQR is a supporting document on test weld coupon results to verify that the weldment exhibits the required physical properties and desired material performance when welded according to a particular WPS datasheet. The PQR for coiled tubular welds should include the following:

- a) yield and tensile strength,
- b) ductility tests (% elongation, side bend tests),
- c) micro and macro etch photography,
- d) microhardness survey,
- e) nondestructive examination (NDE), and
- f) plastic bend fatigue testing (in the case of tube-to-tube welds).

5.4.3.2 In special circumstances such as low-temperature or corrosive environments, the following may also be required by the customer:

- a) Charpy impact tests,
- b) fracture toughness tests,
- c) plastic bend cycle tests,
- d) preferential corrosion resistance testing.

5.4.3.3 The PQR serves to qualify a given WPS. It is recommended that all coiled tubular welding be performed only with a pre-qualified WPS. All WPSs for critical welds in coiled tubing shall be pre-qualified by a PQR. A typical PQR format and record sheet is given in [39] and [61]. Qualification of welding procedures should be performed under the supervision of a welding engineer with the guidance of [39], [43], [45], and [61].

5.5 Tube-to-Tube Weld Procedure Specification

In addition to the requirements of [61] for the preparation of a WPS for tube-to-tube welds in coiled tubulars, special attention should be paid to the following aspects of preparing a girth weld connection in coiled tubing.

a) Tube End Preparation

Coiled tubing ends may be flame cut or rough sawn cut. Ends that have been flame cut should be cut back by mechanical means far enough to assure that any thermal effects from the flame cut are removed. At least 3 in. should be removed. Prior to welding groove or edge preparation, rough cut tubing ends should be cut square and perpendicular with the tubing axis using mechanical pipe cutters or similar tooling. The angular deviation from perpendicular should be checked at four locations or more with a straight edge. Should a surface be found that is more than $\frac{1}{32}$ in. from square, the tube end should be reworked until this criterion is satisfied.

Edge preparations (welding groove) should be located at least 3 in. from torch cut ends. The weld groove should be prepared in accordance with the pre-qualified WPS and welding engineering standards.

b) Internal Flash Removal

The electric resistance weld flash on the inside of both tubing ends to be joined should be tapered back with the inner tubing surface to a length of at least 1 in.

Appropriate tools that do not leave circumferential grinding marks or cause heat checking should be used to remove internal flash. Use of a pencil grinder for this operation may cause accidental gouging of the coiled tubing surface adjacent to the electric resistance weld seam. Grinding can also cause heat check defects that act as fatigue initiation cracks, especially in coiled tubing. The finished inside surfaces should not have any transverse scratch marks and shall be smooth to a surface roughness value of less or equal 60 $\mu\text{in. rms}$.

c) Demagnetization

Welding magnetized materials can cause problems with arc-blow, and result in weld defects. If necessary, demagnetization may be effected by application of appropriate direct or strong alternating coil fields for a distance of at least 3 ft (1 m) at each end to be welded. The use of the type of AC yokes used in magnetic particle inspection is not permitted.

The reading of a gauss-meter (Tesla-meter) probe held so as to measure the maximum value of the magnetic flux density emergent from either prepared end of the tube should be less than 5 Gauss at all points around the circumference of the end of the tubing. Demagnetization should be performed after all end preparation.

Demagnetization is generally required at location to be tube-to-tube welded, after coiled tubing have been inspected by electromagnetic methods.

d) Welding of Dissimilar Strength Grades

Coiled tubular strength grades are designated by their specified minimum yield strength in thousands of pounds per square inch (ksi). Coiled tubing strength grades within API 5ST include CT70, CT80, CT90, CT100, and CT110.

Tube-to-tube welds of dissimilar strength grades are permitted in coiled tubing provided that the welding is performed in accordance with a pre-qualified WPS. However, loss of LCF may occur depending on the degree of mismatch in local CT yield strength. (See 3.3.1 of [61].)

Tube-to-tube welds of dissimilar strength grades are not suggested for use in coiled tubing.

e) Welding Consumables

For elastically stressed weldments, filler metal welding wire for the TIG process is generally specified by AWS A5.18 and AWS A5.28 in which the ultimate tensile strength of the filler metal is matched with that of the base metal. For plastically strained girth welds in coiled tubing performed with the orbital TIG process, research has shown^[45] that improved LCF life can be obtained by matching the tensile strength of the filler metal with the specified minimum yield strength of the coiled tubing. The increased LCF life is achieved at the expense of a small (10 %) loss in axial yield strength capacity of the tube-to-tube welded connection.

Under-matching of filler metal with coiled tubing tensile strength is not recommended for manual TIG tube-to-tube welds because the benefits of more uniform plastic strain distribution across the weld joint is offset by the nonflush internal weld profile typically obtained with manual welding.

f) Welding Technique and Pass Sequence

Multi-pass stringer beads are recommended for tube-to-tube girth welds because they result in a lower heat input and grain refinement of previously deposited weld beads. Orbital TIG welding is capable of depositing extremely small stringer beads and weld metal layers that result in a grain size of similar magnitude as the coiled tubing base material. Welding stops and starts should be staggered from layer to layer.

g) Preheat and Inter-pass Temperature

Tube-to-tube welding of coiled tubing steels performed at room temperature, typically 21 °C (70 °F), or higher generally does not require preheating to preclude hydrogen-induced cold cracking. At lower ambient temperatures, preheating to 10 °C (50 °F) for a distance of at least 3 in. from the weld edge preparation is recommended. When welding in ambient temperatures of less than 0 °C (32 °F), the coiled tubing ends should be preheated to 36.5 °C (100 °F) for a distance of at least 3 in.

Inter-pass temperatures shall be controlled to the maximum permitted by the WPS to preclude excessive loss of yield strength in the deposited weld metal or heat-affected zone (HAZ). Inter-pass temperatures can be limited by allowing the weldment to cool between successive weld bead deposits or with the use of chill blocks.

When welding to other than CT alloys, refer to the appropriate WPS for preheating requirements. Preheat and inter-pass temperatures should be determined with the use of thermal crayons or similar means.

h) PWHT

While many welds are supplied in coiled tubing manufactured from grades ASTM A606 or A607 modified steels without PWHT, cases arise where PWHT is employed. This should be controlled by the WPS.

5.6 Tube to End-fitting WPS

5.6.1 General

Separate pre-qualified weld procedure specifications are required for end-fittings to coiled tubing weld joints. Welding of end-fittings to coiled tubing generally involves dissimilar alloys and the use of fillet welds in a lap joint configuration. Hence there is no welding groove preparation or EW flash removal requirement.

5.6.2 Preheat and Inter-pass Temperature (End-fittings)

Depending on the steel grade used for coiled tubing end-fittings, preheating and control of maximum inter-pass temperature may be required as specified on the appropriate WPS. If preheating is necessary, it should be applied separately to the end-fitting before mating with the coiled tubing for welding.

5.6.3 PWHT (End-fittings)

Because PWHT is detrimental to ASTM A606/607 modified coiled tubing steels and once joined together, end-fittings cannot be selectively heat-treated without affecting the coiled tubing, end-fitting materials should be selected such that PWHT is not required. Commonly used fittings made from air-hardenable alloys, e.g. 4130/4140 steels, should be wrapped in a thermal blanket to slow cool the weldment to 93.5 °C (200 °F) before removing the blanket. The PWHT should be defined in the WPS.

5.7 Qualifying Weld Procedure Specifications

The basic PQR requirements are given in [39] and [61]. It is not necessary to individually qualify every coiled tubing weld. A WPS incorporating a number of varying welding parameters can be qualified by a single PQR. Re-qualification of a WPS is required only when one or more of essential variables have been changed. For tube-to-tube coiled tubing welds, these variables are defined in Table 3.1 of [61].

In addition to the requirements of [61], the following PQR testing and essential variables shall apply to welds in coiled tubing.

a) Mechanized Welding Process

A separate PQR shall be prepared for either the manual or orbital GTAW process.

b) Tensile Testing

Tensile testing of full body coiled tubing test specimen shall be performed in accordance with the 1 % pre-strain method described in H. Haga et al. (1980a, 1980b).

c) Hardness Testing

Hardness measurements for tube-to-tube, pipe-to-pipe, and end-fitting welds should be made for the deposited weld metal, HAZ, and base metal. For field tube-to-tube welds, measurements are made with a portable field hardness tester. For coiled tubing, all readings shall be below the maximum specified for the grade, when new.

d) Tube-to-Tube PQR

When weldments in coiled tubulars are designed to function in fatigue cycling operations, qualifications may include low cycle plastic fatigue bend testing of multiple welded connections along with multiple samples of the parent coiled tubing.

Testing for the qualification of tube-to-tube welds shall include low cycle plastic bend fatigue testing of the welded connection. Generally, the working fatigue life of manual tube-to-tube welds in coiled tubing is in the range of one quarter to one third of the working life of the coiled tubular. For orbital TIG welds, a working life roughly equal to one half of the coiled tubular can be expected. Acceptable ultra-low cycle fatigue life of tube-to-tube welds in coiled tubing is a matter of tubing string management and/or agreement between customer and coiled tubing service provider.

5.8 Welder and Welding Operator Qualification

Welding of steel coiled tubing requires welders and welding operators with advanced qualifications and specialized training.

A welder performance test is required to verify that the welder is capable of following the written procedure specifications and producing a coiled tubular weld with the same quality expected from the PQR test results. The welder shall also demonstrate periodically that proficiency in welding coiled tubing has been maintained. For coiled tubing, reference should be used as a guide for re-qualification of welders.

In addition to performance evaluation, the coiled tubing welder shall have a clear understanding of the critical factors that affect the integrity of the weld. Often it is the correct fit-up, edge-preparation, weld dressing, and general quality of workmanship that determines the success or failure of a coiled tubular weld.

Section 4 of [61] should be consulted for qualification and re-qualification requirements of welders engaged in performing coiled tubing welds. In addition to these requirements, the following shall apply.

a) Tube-to-Tube Qualifying Tests

To qualify, a welder or operator shall produce at least three consecutive girth welds in full body coiled tubular specimens and welding positions representative of actual welding conditions. Acceptance of these test welds is generally determined by radiographic or shear wave ultrasonic examination for volumetric defects, and liquid penetrant or wet fluorescent magnetic particle testing for accessible surface defects.

b) Disqualification

If the test in 5.8 a) fails to meet the specified requirements, the welder or operator may make one only additional qualification weld. If this re-test fails, the welder or operator is disqualified from performing any tube-to-tube girth welds in coiled tubing until the welder has satisfactorily completed additional training.

c) Welding Engineering Standards

All coiled tubing welds should be performed in accordance with a consistent set of welding engineering standards. Each welding fabricator or service organization may have their own proprietary welding standards. Welding fabricators that are certified by the American Welding Society (AWS) or the Canadian Welding Bureau (CWB), for example, are required to adhere to welding standards that are approved by these licensing authorities. At minimum, welding engineering standards for coiled tubing welds should include the following.

d) Alignment and Fit-up

Proper alignment and fit-up of the weld groove preparation is critical for tube-to-tube joints for maximum LCF performance. This requires a welding fixture that is capable of rigidly securing both tubing sections to be joined, usually in the horizontal (5G) position. Welding fixtures shall not impose excessive axial restraint on the tubing so as to preclude high shrinkage stresses upon cooling of the weldment. Any rigid clamping for the tubing sections should be applied as far away from the faying surfaces (edge preparation) as possible.

The two ends to be welded should be straight for a minimum of 3 ft. Axial alignment may be checked by the use of a straight edge placed so that it straddles equally each side of the weld and adjusting the position of the tubing clamps so that no more than $\frac{3}{32}$ in. of air gap is observed at either end of the straight edge.

Where possible, the tubing ends should be aligned with the electric resistance weld seam offset to avoid states of high and localized triaxial stress at the intersection with girth welds.

e) Tubing Diameter

Only coiled tubing and pipe of the same outside diameter shall be welded together. The mismatch across outside diameters should not exceed 0.010 in. To achieve the desired outside diameter alignment, where possible the tubing may be rotated within the clamps in order to produce the minimum OD misalignment, as measured at four places around the proposed weld. Consideration should be given to cutting back the tubing until the mismatch is minimized.

An effective mismatch in tubing ID can also occur for tubing of equal wall thickness due to differences in ovality of the two mating tubing sections. The permitted step change in ID shall not exceed 10 % of the nominal wall thickness.

f) Wall Thickness

Wherever possible, the wall thickness of mating coiled tubing sections should be equal; however, variation in wall thickness should not exceed 5 % of the specified wall thickness. Whenever this is not possible, the owner of the tubing should be cautioned that the fatigue life of the proposed weld will be significantly reduced.

g) Tubing Ovality

Excessive out-of-roundness or ovality of the tubing cross section should be removed. This is especially critical for orbital TIG welding. Restoring the tubing to a near circular cross section is best accomplished with a special coiled tubular product circularizer. Alternatively, it may be possible to cut back the tubing until a more acceptable cross-section geometry for welding is found.

Maximum tubing wall offset due to tubing ovality should be limited to 0.010 in. Where this is not possible, a test should be performed on tube-to-tube welds in excessively ovalized coiled tubing, to determine its LCF performance. At minimum, the owner of the tubing string should be cautioned that the fatigue life of the completed weldment may be unacceptably low.

h) Surface Preparation and Cleaning (Before Welding)

LCF testing of tube-to-tube welds has shown a high sensitivity to the surface finish quality, cleanliness, and/or loss of wall section of the prepared surfaces from weld groove and flash removal operations. Transverse (circumferential) grinding or filing marks are particularly conducive to fatigue crack initiation. Similarly, local heat checks from contact of high-speed grinders with inner wall surfaces can act as hot spots for fatigue crack initiation. Great care shall therefore be taken to avoid surface damage from excessive filing, grinding, or gouging and to prevent other forms of mechanical damage to the inner tubing surfaces.

Surfaces prepared for welding should be free of filings and other debris. Both tubing ends should be cleaned with an emery cloth, wire brush, or similar means to remove rust and scale for approximately 6 in. from the edge preparation. Prior to welding, these surfaces shall be cleaned with denatured alcohol or similar quick evaporating solvents to remove all hydrocarbons and other contaminants that may provide a source of hydrogen atoms.

During welding, completed passes shall be cleaned by wire brush or grinding to sound metal prior to depositing successive weld beads.

i) Weld Profile and Dressing (After Welding)

The outer surface of tube-to-tube welds should be dressed flush with the coiled tubular outside diameter by removing the weld reinforcement (crown) prior to the performance of ultrasonic or radiographic NDE. Similar to the precautions to be taken in preparing the internal surfaces, great care shall also be taken to prevent damage to the outer surfaces or wall thinning by excessive grinding or filing. Transverse or

circumferential grinding marks shall be removed by draw filing in the axial or longitudinal direction followed by sanding with emery cloth to obtain a smooth finish. All weld spatter, if encountered, shall be removed. Weld spatter is an indication of improper welding conditions such as lack of gas shielding or improper arc current/voltage characteristics and shall be rectified.

Root pass penetration should be kept to a minimum. In the ideal case, which is generally achievable only with the orbital GTAW process, the root pass profile would be flush with the inner tubing surface. No undercut is permitted.

Fillet weld profiles shall ensure sufficient throat thickness for strength requirements and avoid undercuts and excessive convexity. The requirements of acceptable fillet weld profiles specified in AWS or CWB should apply to fillet welds in coiled tubulars and end-fittings.

j) **Welding Habitat**

Because gas metal arc welding processes such as TIG are sensitive to strong cross winds (that interfere with the shielding gas stream), rain, and snow, a suitable habitat is required to protect both the weldment and welder from inclement weather conditions.

k) **Chill Blocks**

Because coiled tubing steels are generally heat-treated alloys, the heat input from welding may reduce the yield strength of the HAZ, typically by 5 % to 10 %, with the greater loss being attributed to manual TIG welding. To avoid this loss, local heat sinks or “chill blocks” fabricated from a copper alloy may be used. Since chill blocks are not readily accommodated by orbital welding equipment, some loss of yield strength in the HAZ will occur. Alternatively, coiled tubing welds performed without chill blocks may be placed in service provided allowance is made for appropriate weld joint efficiency as determined from PQR tensile tests.

When used, chill blocks should be placed sufficiently far from the welding arc to preclude weld metal contamination with copper. The location, size, and auxiliary cooling method of chill blocks should be included in the WPS.

5.9 Inspection of Coiled Tubular Welds

5.9.1 General

NDE for imperfections or defects of coiled tubing welds, particularly critical welds, is indispensable to ensure the integrity and expected material performance of the weld joint. However, the extent of NDE to be performed on any particular coiled tubular weld is a matter of agreement between the coiled tubular provider and customer. NDE of coiled tubing welds entails one or all of the following: visual inspection, liquid dye penetrant (PT), magnetic particle inspection (MT), ultrasonic testing (UT), and radiographic testing (RT).

5.9.2 NDE of Tube-to-Tube Welds

Tube-to-tube welds should be inspected visually both with the naked eye for gross imperfections or defects and with the aid of a magnifying glass to ensure the absence of transverse (circumferential) grinding or filing marks. A short straight edge should be used to ensure a flush weld profile.

At least UT or RT for NDE of tube-to-tube and pipe-to-pipe joints should be applied for through-thickness inspection of the weld. It is recommended that both RT and UT be used in conjunction because one method can generally identify flaws that may be undetected by the other. Ultrasonic inspections should include measurements of local wall thickness variations for at least 3 in. on either side of the girth joint.

By agreement between the coiled tubular service provider and customer, NDE of tube-to-tube or pipe-to-pipe welds may include hardness survey measurements across the weld to confirm conformance with PQR requirements.

5.9.3 NDE of Coiled Tubulars to End-fitting Welds

Coiled tubular end-fittings using fillet welds should be inspected visually for gross flaws or defects, undercut, sufficient leg size, sufficient throat, and weld profile. MT or PT should be used to inspect for surface or near-surface cracks, respectively.

Since it is generally difficult to perform ultrasonic inspection on fillet welds, end-fitting welds should be examined by radiographic methods.

By mutual agreement between the coiled tubing service provider and customer, NDE of end-fitting welds may include hardness survey measurements to confirm conformance with PQR requirements.

5.9.4 Engineering Critical Analysis

The quantitative results obtained from a particular NDE method shall be evaluated against a specified code or standard. There are currently no generally accepted and published codes or standards against which indications obtained by NDE for tube-to-tube welds in coiled tubing girth joints can be evaluated.

It is recommended that the NDE results be subjected to an engineering critical analysis in order to decide whether to accept, reject or repair the coiled tubular weld. The engineering critical analysis may be facilitated with reference to acceptance standards and criteria published in ASME *BPVC* Section IX and/or API 1104.

Ongoing research, supported by the coiled tubing industry, is in progress to quantify the effects of surface damage on LCF of coiled tubulars including welded girth joints. Wherever available, these results should be used as a guideline for the engineering critical analysis.

Whatever codes, standards, or engineering critical analysis methodology is to be used is a matter of mutual agreement between the coiled tubing service provider and customer.

5.9.5 Local Coiled Tubing Weld and Grind Repairs

Research has shown ^[48] that local weld repairs of any imperfections found in coiled tubing or coiled tubing weld areas are ineffective with respect to ultra-low cycle fatigue performance. Therefore, any defects in tube-to-tube or pipe-to-pipe welds should not be ground out and repaired with local spot welding techniques. Defective welds should be completely removed and the tubular prepared for re-welding.

The same research has shown, however, that minor surface imperfections can be repaired by grinding a smooth and shallow crater that does not appreciably reduce the wall thickness. A measurable recovery in LCF life that is lost due to the presence of the original defect could be realized. It was shown that the net fatigue life corresponds, in general, to that of a coiled tubing string of wall thickness equivalent to that of the reduced wall from the grind repair. Surface defects may therefore be removed from the coiled tubular weldment by gentle grinding to an agreed minimum wall thickness. See 9.21.

5.10 Field Management of Coiled Tubular Welds

5.10.1 Coiled Tubular Weld Identification and Location

Welds in coiled tubulars represent inhomogeneity in the tubing string. Tube-to-tube girth welds have reduced LCF life compared to the base tubing and provide potential sites for preferential corrosion attack ^[46]. The loading history for each weld should be monitored accurately to preclude undesirable string failures associated with the weld joint.

Documentation should be maintained to identify the weld, welder or welding operator, and welding sub-contractor. The weld identification would include, but not be limited to, the date, location, conditions of welding environment, CT string identification, remaining fatigue life, and WPS and PQR numbers used to perform the repair weld. This is best accomplished with the aid of computer management programs.

If possible, tube-to-tube welds should be located in sections of the tubing string that are subjected to the least amount of bend fatigue loading.

5.10.2 Weld Failure Investigations

The weld identification will assist in any post failure investigations. Root cause(s) identified in any weld failure investigation should be used to modify WPS datasheets, upgrade welder training and/or qualification requirements, or help rectify deficiency(s) in any aspects of the welding operation that can be related to the root cause(s) of weld failure.

To maintain ongoing quality and tube-to-tube weld performance and improve the statistical basis on which allowable working cycles are based, one CT service company removes all tube-to-tube welds after a specified number of fatigue cycles and rejoins the string with a similar repair weld. Two adjacent sections of approximately 7 ft (2.13 m) are removed prior to rejoining, one containing the girth weld and the other consisting of bare tubing. The remaining LCF life obtained from each tubing section is compared and recorded for ongoing quality and performance monitoring of tube-to-tube repair welds.

5.10.3 Safety and Operational Considerations

Due attention shall be paid to all safety considerations associated with all aspects of coiled tubing welding operations. Section 6 of [61] should be made for more detailed discussions of coiled tubing welding safety.

To achieve the desired coiled tubular weld performance and quality, it is essential that the welder or welding operator be granted sufficient time to perform quality workmanship without excess duress or undue pressures that are inherent in periods of downtime.

5.11 Welds in CT Product for Sour Service

Sour environments can result in sulphide stress cracking (SSC) in tube-to-tube welds. Manual tube-to-tube girth welds are not recommended for coiled tubing operations involving sour wells. Orbital TIG and other automatic or semi-automatic welding processes may be used to perform repair welding in sour service coiled tubing other than under-balanced drilling operations, provided that the welding is performed in accordance with a qualified WPS.

5.12 Butt Welds and Fittings

5.12.1 Tube-to-Tube Butt Welds

Coiled tubing may be supplied with tube-to-tube butt welds that are manufactured to written procedures. The ability of these welds to sustain bend cycle loading is generally substantially less than that of the tube itself. The classification of coiled tubing as CT70–CT110 is not affected by the presence of tube-to-tube welds.

5.12.2 End-fittings

Many strings of coiled tubing are supplied with an end-fitting that is manufactured from a different steel than the tubing itself. Such fittings are applied to written welding procedures and inspected nondestructively when cold. Special fittings are required for high pressure and for sour service work.

6 Corrosion—Effects and Mitigation in Steel Coiled Tubing

6.1 General

In-service steel coiled tubing often corrodes between jobs, generally due to lack of protection or improper protection. The coiled tubing may also corrode during actual service jobs due to exposure to wellbore fluids and materials or the local environment. Various forms of corrosion can have such detrimental effects as reduced axial load capacity, reduced pressure integrity (collapse and burst), reduced fatigue life, and an increase in susceptibility to sudden and unexpected premature failures. This section outlines types of corrosion mechanisms found in coiled tubulars and remedies for corrosion mitigation.

6.2 General Comments

The following are considerations for CT corrosion.

- a) Safe and successful completion of coiled tubing service tasks and maximization of string life may be assisted by good storage habits and good pre- and post-job maintenance practices that minimize corrosion.
- b) Exposure of unprotected coiled tubing to humid atmospheres produces iron oxides (rust) that can interfere with proper functioning of the injector gripper blocks and wellhead stripper and promote pitting of the steel coiled tubing.
- c) Internal pitting corrosion can be caused by aqueous fluids left inside the tube after a job. It is extremely difficult to remove all fluids with wiper balls since some fluid will always stick to the wall of the tubing and run back down to the lowest level under gravity. Small pools of fluid form that can be highly corrosive.
- d) The potential for steel coiled tubing problems increases with lack of utilization if the tubing is not properly protected during storage.
- e) The operator should be aware of the nature of the downhole and flowline conditions and take appropriate measures. For example, if H_2S is expected, some higher strength steel coiled tubing may be inappropriate or stress-cracking inhibitors may be required.
- f) Effective inventory management should be employed to ensure that tubulars are kept in service as much as possible, and their condition monitored at regular intervals.
- g) Such procedures may vary depending upon location.

6.3 Corrosion and Environmental Cracking (EC) of Coiled Tubing

6.3.1 General

Corrosion damage and stress corrosion cracking together account for a major portion of reported carbon steel coiled tubing field failures, particularly when the interaction with other failure modes such as fatigue (e.g. corrosion fatigue), overloads (e.g. wall thinning), and manufacturing (e.g. localized attack in welds) are taken into account. Because of the complexity of variables involved, systematic derating of coiled tubing serviceability in corrosive service is often arbitrary and difficult, even when using full-length NDE. Therefore, this section provides only guidelines and best practices, which are likely to decrease the risk of steel coiled tubing failures in corrosive environments.

6.3.2 Corrosion

Types of corrosion damage applicable to coiled tubing are listed below.

a) General Corrosion

This manifests as uniform wall thinning of the coiled tubing. Though not common in coiled tubing operations involving short-duration exposures (<30 hours), wall-thinning corrosion is accelerated by the degree of cold work and the extent of galvanic coupling of the coiled tubing to more passive corrosion-resistant materials downhole.

General corrosion may be accelerated along the seam weld line in the region where the grain flow is preferentially toward the ID or OD of the tube.

b) Galvanic Corrosion

Like general corrosion, galvanic corrosion is not a problem for use of steel coiled tubing on wells containing low alloy steel components. It can be a serious problem when low-alloy carbon steel coiled tubing is used in corrosive wells containing corrosion-resistant alloys, such as duplex stainless steels, nickel-based super alloys, and titanium alloys. For such wells, electrochemical contact of the coiled tubing with the corrosion-resistant alloys in the presence of poorly inhibited well fluids, workover fluids, or acids can result in accelerated corrosion of the coiled tubing. The more passive alloy will increase the wall thinning of the more anodic carbon steel coiled tubing.

For example, 2205 duplex steel and alloy 718 have been shown to increase the corrosion rates of 4130 steels by up to 50 % in 25 % NaCl + 1.0 psi H₂S + 1200 psi CO₂ at 200 °C (392 °F) and by up to 400 % in 12 ppg CaCl₂ + 400 psi CO₂ packer fluid at 177 °C to 200 °C (350 °F to 392 °F). Such effects shall be minimized when designing coiled tubing jobs for corrosion-resistant alloy wells by use of inhibition, by limiting the duration of the exposure (<30 hours), or by using thicker wall coiled tubing.

c) Atmospheric and Filiform Corrosion

Coiled tubulars stored with remnant fluids in the ID, splashed fluid on the OD, or in areas of high humidity and warm climate with aerated conditions can suffer accelerated corrosion on the OD (rust) and localized randomly distributed corrosion streaks on the ID (filiform). Filiform corrosion appears as streaks of long, narrow pits.

Time-of-wetness is also a critical variable. Wetness is generally greater on the inside wraps than on the outer wraps of a spool. Fluids trapped in the inner wraps due to condensation with temperature changes can result in permanent wetness of the inner wraps. Condensing water solutions may contain carbon dioxide CO₂, forming carbonic acid, and certain chlorides, sulphates, and sulphides. Condensation may also occur inside the coiled tubing, washing salts from the ID to the bottom of the wrap under gravity.

Elimination of aqueous fluids from the tubing ID will eliminate filiform corrosion.

Sulphur compounds are a major cause of increased corrosion in industrial areas.

The ID corrosion manifests as sharp and narrow pits that grow deep within a short time during storage or transit and could result in leaks.

To minimize damage due to internal corrosion, during storage or transit, coiled tubing strings should be displaced with an inhibitor and blown dry with inert gas and seal capped. Various vapor corrosion inhibitors are commercially available for providing protection during storage and transoceanic shipments.

If the tubing is being placed in storage or not in use, an inhibitor should be utilized. This should be done as quickly as possible at completion of job. Ideally this process would take place during the last run out of the hole, where possible.

d) Pitting and Crevice Corrosion

Pitting and crevice corrosion of coiled tubing occurs primarily in hot acidic environments (low pH) and gets worse with increasing temperature. It can also occur in aerated brines under atmospheric conditions. These are more common forms of coiled tubing corrosion damage than general corrosion and result in leaks or premature fatigue life loss. Some forms of pitting can represent a more severe form of corrosion than uniform metal loss. This is due to extensive localized wall loss that may compromise the integrity of the string.

Effective inhibition is a necessary control for such damage, even for short-duration jobs, as pit depths are not reliably monitored during service. Also crevices formed by poor contact at seals, downhole connectors, or other downhole tools should be avoided.

High flow rates, such as those that occur in velocity strings or coiled tubing completions, may increase pitting rates.

e) Marine Corrosion

Corrosion of coiled tubing occurs through contact with marine salts, primarily sodium chloride (NaCl), but also with potassium (K^+) magnesium (Mg^{++}), calcium (Ca^{++}), and sulphate (SO_4^{--}) ions. Chloride salts are hygroscopic, and the chloride ion promotes pitting in carbon steels. Once pitting is established, penetration into the steel can occur at more accelerated rates. It has been observed that steel will corrode 12 times faster when located 24.4 m (80 ft) from the coastline than when it is located 244 m (800 ft) from the coastline due to the level of marine salts that are present at the two locations. Note, however, that sea-salt can be found at great distances from a sea coastline, typically 160 km (100 mi) inland, and can descend as both a dry dust and in rain-fall. Time of wetness becomes a critical factor in determining the level of corrosion caused in such circumstances. Salt tends to increase time-of-wetness by absorbing water at lower humidity.

6.4 Effects of Corrosion on Coiled Tubing Serviceability

6.4.1 Material loss due to the various forms of corrosion described above has several specific detrimental effects such as:

- a) reduced usable strength of coiled tubing due to wall thinning and pits,
- b) reduced pressure integrity—collapse, burst, and yield,
- c) reduced service cycles due to corrosion fatigue,
- d) increased susceptibility to premature fracture due to corrosion and pits acting as initiators for H_2S and/or CO_2 related stress corrosion cracks, and/or
- e) reduced service life in deviated wells due to increased erosion-corrosion.

6.4.2 Corrosion and rust on the OD surface have the following undesirable effects:

- a) poorer seal at the stripper and blowout preventers (BOPs),
- b) deterioration of the tubing surface weakens the mechanical integrity and provides sites for subsequent corrosion following exposure to wellbore or treatment fluids,

- c) elastomers used in well pressure control equipment may be damaged or rendered less effective by a rough tubing surface,
- d) accumulated rust or scale can affect the depth measurement and tubing monitoring equipment, and/or
- e) the snubbing force required to run the tubing through the stripper on a high-pressure well may be significantly increased by a rough tubing surface.

6.5 Corrosive Fluids in Coiled Tubing Service

Specific considerations for various fluids are as follows.

a) Production Fluids

In production fluids with acid gases ($\text{H}_2\text{S} + \text{CO}_2$), the pH of the aqueous phase can be very low. For temperatures of 68 °F to 212 °F, $\text{pH} \gg 3.4$ at $\text{PH}_2\text{S} + \text{PCO}_2 = 0.147$ ksi; $\text{pH} \gg 3.0$ at $\text{PH}_2\text{S} + \text{PCO}_2 = 1.47$ ksi, and $\text{pH} \gg 5.0$ at $\text{PH}_2\text{S} + \text{PCO}_2 = 0.147$ psi. Production water containing brines increase the corrosivity of production fluids. Multiphase fluids as well as fluid velocity are also critical considerations, particularly in the use of coiled tubing for production or velocity strings.

b) Workover and Completion Fluids

Brines used in workovers and completions increase corrosivity as temperature increases from 49 °C (120 °F) to 204 °C (400 °F). The effect increases with the specific gravity (SG) of the brine and the degree of aeration. For example, at 102 °C (216 °F), NaCl brine with SG = 1.05 corrodes low alloy steel at the rate of <5 mpy after 8 hours exposure when deaerated, but under aerated conditions, the corrosion rate can be up to 40 mpy.

Similarly, a high density brine such as $\text{CaBr}_2\text{-ZnBr}_2$, SG = 2.3, can produce a corrosion rate of $\gg 25$ mpy at 149 °C (300 °F), while $\text{CaCl}_2\text{-CaBr}_2$, SG = 1.45, produces a corrosion rate of <10 mpy at 149 °C (300 °F).

c) Acidizing Fluids

Stimulation and well cleanout acids used in coiled tubing jobs require special care to avoid aeration. Corrosion rates can increase by up to 5 to 7x due to aeration. The most danger of aeration occurs due to exposure of coiled tubing to air between coiled tubing runs, and between job locations, even though the acids used are deaerated. Spent acids are also more corrosive than fresh acids due to oxygen pickup as well as deterioration of the inhibitor. When acid cleanouts are enhanced with gas, such as during nitrified acid descaling, increased corrosion rates and loss of inhibitor effectiveness can result due to more turbulence and slug behavior of the acid inside the tubing.

6.6 Environmental Cracking

6.6.1 General

Coiled tubing strength and reliability can be seriously reduced by exposure to wet hydrogen sulfide (H_2S). Hydrogen sulfide is noncorrosive in the absence of moisture, so the risk of corrosion or cracking in dry gas wells containing H_2S is low. However, a highly corrosive environment occurs when moisture is present and this may affect coiled tubing integrity. Generally speaking, $\text{H}_2\text{S} + \text{Fe} + \text{H}_2\text{O} = \text{FeS}_x + 2\text{H} + \text{H}_2\text{O}$.

The released hydrogen atoms may enter the steel matrix and cause various forms of hydrogen-related damage, including hydrogen blistering and various forms of hydrogen cracking including hydrogen-induced cracking (HIC), stress-oriented hydrogen-induced cracking (SOHIC), surface fissuring, and SSC. Hydrogen in the steel matrix may also cause embrittlement that can reduce steel ductility, promote brittle fracture, and potentially reduce fatigue life in CT. Higher strength CT is, of course, more susceptible to EC than lower strength CT. The industry has learned through years of experience and by laboratory testing that the primary

environmental variables related to cracking of coiled tubing in H_2S containing aqueous fluids are the *in situ* pH of the water phase and H_2S partial pressure. Low pH (more acidic) and high H_2S partial pressure increase the likelihood of EC of CT. Coiled tubing cracking in wet H_2S environments may manifest itself in different ways, depending on the environmental severity, duration of exposure, steel and weld metallurgy, strength, chemistry, heat treatment, residual stress, pre-existing mechanical damage or cold work, and prevalent service stress.

It is recommended that users check the sour service properties of coiled tubing prior to use.

The service life for tubing used in sour service can be drastically reduced to about one-third of the service life in nonsour applications.

It is recommended that field repairs are not performed on materials that will be used in sour service.

6.6.2 Hydrogen Blistering

Surface bumps are caused by accumulated molecular hydrogen, which forms elongated subsurface voids. The molecular hydrogen is from coalescence of atomic hydrogen generated during corrosion, which diffuses into the steel. Blistering is independent of applied stress. Susceptibility increases with increase in content of nonmetallic inclusions (manganese sulfide), banded microstructure, and pre-existing delaminations in the steel. This damage is more common in lower strength coiled tubing grades (CT70). Control is achieved through selection of coiled tubing metallurgy and/or the use of corrosion inhibition.

6.6.3 HIC

HIC is similar to blistering but exists only subsurface and joins in a through-wall direction in a stepwise pattern to result in failure of the coiled tubing. HIC is principally responsible for axial (longitudinal) failures of coiled tubing, loss of burst and collapse properties, and is independent of the prevalent operating stress. HIC is common (but not exclusively) with moderate to high-strength coiled tubing grades (CT80 and above) and with coiled tubing that contains pre-existing mechanical damage or severe cold work. Control is achieved by: (1) limiting % Mn (<1.2 %), % S, and % C in the coiled tubing; (2) limiting the microhardness within the segregation bands in the coiled tubing to 300 VHN; and (3) limiting hydrogen absorption by using corrosion inhibition.

6.6.4 SOHIC

SOHIC is like HIC except that the HIC cracks are shorter in length, are stacked rather than stepped in the through-wall direction, and are oriented and propagate in response to the prevalent applied and/or residual stresses. Unlike HIC, inclusion stringers are not required initiation sites, rather grain boundaries, segregation bands, and in-homogeneities in the microstructure can initiate SOHIC cracks. Though measures that control HIC are beneficial for control of SOHIC, weld residual stress and operating stress are critical factors and should together be kept to << 80 % of specified yield strength.

6.6.5 Surface Fissuring

Surface fissures are cracks initiated as SSC by wet H_2S corrosion, but only penetrate the coiled tubing wall to about 5 mils (0.13 mm) deep, and the root gets blunted by corrosion. Surface fissuring manifests itself as shallow parallel surfaces that are perpendicular to the applied tensile loading. This type of cracking is influenced by the residual and operating stresses in the coiled tubing string, as well as surface cold work, and can occur in the ID or OD of the coiled tubing. The cracking can also occur selectively along welds in the coiled tubing.

6.6.6 Sulfide Stress Cracking

SSC is the most severe form of hydrogen-related cracking and results in brittle failure caused by applied or residual stresses along with significant hydrogen absorption from wet H_2S corrosion. High-strength coiled tubing grades are generally more susceptible to SSC than lower strength grades. And laboratory testing has

shown^[44] that the welds (seam weld, bias weld, and especially butt welds) are more susceptible to SSC than the parent metal or body of the CT. The amount of strain cycling (LCF) to which the CT has been subjected before H₂S exposure is also a factor but may not be significant until over 50 % utilization has occurred^[44]. Another study^[59] concluded that based on transverse SSC tests conducted at 50 % to 100 % of the specified minimum yield strength, no increase in susceptibility to SSC was observed with cyclic cold work.

Figure 1 of [44] shows the “No SSC Zone” and “SSC Zone” for CT90 with respect to the two main environmental conditions: (1) *in situ* pH of the water phase and (2) H₂S partial pressure. This figure indicates that CT operated in Domains 1 and 2 environments are unlikely to fail by SSC whereas SSC susceptibility is high in Domain 3 environments. The area of uncertainty in Figure 1 is where test laboratory samples exhibited surface fissuring.

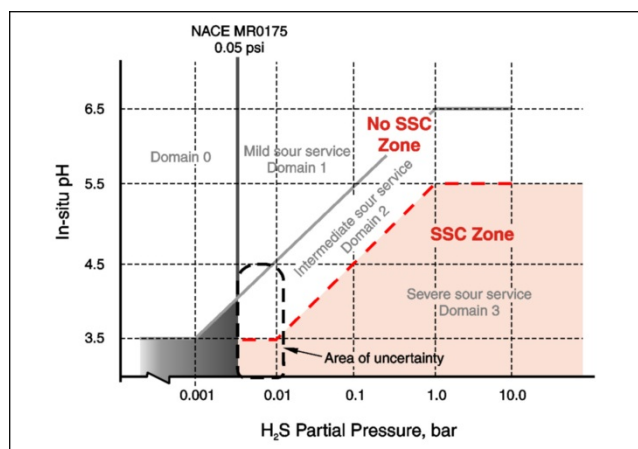


Figure 1—SSC Zoning (Excluding Tube-to-Tube Welds)

6.7 Specific Guidelines to Reduce the Risk of Coiled Tubing Environmental Cracking Failures in Wet Sour Wells

Use of coiled tubing in sour wells requires special care due to the factors discussed above. Some specific guidelines to reduce risk of EC are as follows.

- Always know the environment in which the CT may be operated. Control of the environment to which the coil tubing may be exposed may be necessary by, for example, introducing a brine to the wellbore and/or adding a chemical inhibitor. For additional protection, swab the OD of the coiled tubing with an appropriate inhibitor. Be aware that acid, which has an extremely low pH, mixed with H₂S downhole will significantly increase cracking susceptibility of the coiled tubing. Also, note that H₂S in brine, with or without CO₂, is more corrosive than H₂S in oil.
- Hardness and strength of the coiled tubing are obviously important parameters with respect to susceptibility of EC. However, be aware that used low-strength CT may contain OD mechanical surface damage (and therefore increasing local hardness), which therefore increases EC susceptibility.
- Tube-to-tube (butt) welds are more susceptible to SSC than bias welds or seam welds. Use of coiled tubing field tube-to-tube welds for sour service should be avoided if possible. If the use of tube-to-tube welds is necessary, then minimize cycling of tube-to-tube welds.
- Consider full-body NDE after significant H₂S exposure(s). H₂S can degrade the tubing (surface fissuring, for example), leading to pinholes at a later date. Hydrostatic pressure testing should be performed to assure pressure integrity.
- If full-body NDE is not available, it is recommended to perform a careful visual inspection of the coiled tubing outside diameter after the first 10 cycles when used in continuous H₂S service or in numerous acidizing or sour gas well jobs.

- f) Hydrogen bake-out treatments [e.g. 150 °C (300 °F) for 48 hours] may be performed after an extended duration of service in a sour well to extend the life of the coiled tubing string. The effectiveness of this treatment depends on whether there has been irreversible hydrogen damage to the coiled tubing.
- g) End connectors induce mechanical damage, which makes the coiled tubing more vulnerable to EC. It is recommended to cut off connector damaged portions after exposure to sour wells.
- h) Wet H₂S assisted damage of coiled tubing can be cumulative with respect to fatigue damage. Therefore, coiled tubing that has accumulated significant cycles in a sour well, e.g. during cleanouts and workovers, will be more degraded than coiled tubing used continuously, e.g. velocity string, in a sour well and should therefore be derated.

6.8 Corrosion Related to Inserts

Coiled tubing may be supplied with wireline or other inserts. Wireline, for example, may be pumped into the coiled tubing on the reel, and some water may remain inside the coiled tubing. Fluids trapped next to wireline or other insert may cause internal corrosion.

If tubing with wireline is to stand for any length of time, the insert should be removed from the tubing. The inside surface tubing should then be wiped with wiper balls to remove most of the fluid, and the inside surface of the tubing should then be passivated and dried with dry, warm nitrogen.

Where possible, wireline should only be re-inserted into coiled tubing strings immediately prior to performing service work with the tubing. It is also common practice to apply internal corrosion inhibitor after the wireline injection and displace with nitrogen.

7 String Protection

7.1 Protection for Coiled Tubing

7.1.1 Nitrogen Purge

To assist with preserving coiled tubing after use, it is recommended to displace internal fluids with wiper plugs and nitrogen. The volume (V_N) of nitrogen to be used may be calculated from:

$$V_N = L\pi d^2/96 \quad (1)$$

where

V_N is the volume of nitrogen (ft³);

L is the length of coiled tubing (ft);

d is the maximum ID (in.).

The minimum recommended amount of nitrogen for displacement is two times the internal string volume. Additionally, the amount of water vapor in the nitrogen passing out of the tubing may be measured with a relative humidity meter to be compared to the dryness of nitrogen going in.

When purging is finished, the tube ends should be capped or plugged.

7.1.2 Freeze-proofing and Internal Protection

Tubing shipped to colder locations should be flushed with anti-freeze. Tubing that will be stored for a long period after shipment should be internally protected by coating the internal surface with an appropriate coating.

This may be accomplished by entrapping a slug of the coating fluid between wiper pigs and blowing it through the tubing on the storage reel.

7.1.3 External Coatings

Coiled tubing may be coated with a nonpermanent external coating. These coatings may be washed from or evaporate from the surface over a period of time or during trans-shipment.

7.1.4 Wrapping and Crating

Tubing outer wraps may be protected by wrapping with plastic sheet and by adding slats around the outer edges of the shipping reel. Reels should be supplied with anti-movement attachments for shipment.

In cases where the shipping reel is to be lifted on to a boat or an offshore rig, it may be necessary to certify the lifting device and the reel lifting points.

7.1.5 Storage Prior to Use

Prior to use, coiled tubing should be stored under cover wherever possible. If a positive pressure is applied inside the tube, the gauge should be checked at regular intervals and the inert gas replenished if necessary.

7.2 Coiled Tubular Reel Dimension Effects

7.2.1 Yield Radius (R_Y) and Reel Dimensions

During manufacture, inspection, testing, removal of imperfections, coating, and while in use, coiled tubing strings are moved from one reel to another and suffer from ultra-low cycle fatigue during these operations. As the tubing is bent onto the reel, it is bent past the yield radius, which is defined by:

$$R_Y = (E/S_Y)(D/2) \quad (2)$$

where

R_Y is the yield radius (in.);

E is Young's Modulus for material (lb/in.²);

S_Y is the specified yield strength of material (lb/in.²);

D is the specified OD of tubing (in.).

Annex C compares yield radii (R_Y), shipping spool core radii (R_S), tubing reel core radii (R_{REEL}), and tubing guide arch radii (R_{TGA}) for various coiled tubing sizes. It is recommended that the smallest reel core diameter not be less than 40 times the diameter of the tubing.

7.2.2 Value of Young's Modulus

Values for Young's modulus (E) for steel coiled tubular materials have been found in the range 27×10^6 to 32×10^6 psi. A value of 30×10^6 psi is commonly used, but care should be taken in determining a value for used coiled tubing.

8 Inspection

8.1 Used Coiled Tubulars

Used coiled tubing is tubing that has been at least once over the CT unit guide arch and into the well. Changes in length, diameter, and wall thickness may introduce the following additional items when working with used coiled tubing.

a) Outside Diameter of Used Coiled Tubing

Maximum ($D_{p,max}$) and minimum ($D_{p,min}$) permitted outside diameters for used coiled tubing are determined by injector considerations and shall be agreed upon during contract review prior to the performance of an inspection or coiled tubing job.

In order to perform the computation, the average diameter (D_{av}) is computed using Equation (3) from a minimum of four diameter readings (D_1 , D_2 , D_3 , and D_4) as shown in Figure A.1, at approximately 90° intervals around the tubing, and averaged. For example:

$$D_{av} = (D_1 + D_2 + D_3 + D_4)/4 \quad (3)$$

where

D_{av} is the calculated average diameter for used coiled tubing (in.);

D_1 , D_2 , D_3 , and D_4 are four approximately equidistant outside diameter measurements (AA, BB, CC, and DD in Figure A.1) made at the same location along the tube and include the values of D_{max} and D_{min} .

The D_{av} is rounded to the closest 0.001 in.

b) Wall Thickness of Used Coiled Tubing

The minimum remaining wall thickness of used coiled tubing should be determined in contract review prior to inspection of the string. Measuring techniques for wall thickness are given in 9.7 and 9.8.

The average wall thickness ($t_{av,s}$) for used coiled tubing is computed from four or more wall thickness measurements that are made with a suitably calibrated gauge at roughly equal intervals around the tubing, with no measurements made that could be construed as including a contribution from internal flash. The average wall thickness is computed by:

$$t_{av,s} = (\sum t_i)/n \quad (4)$$

where

$t_{av,s}$ is the calculated average wall thickness for used coiled tubing (in.);

t_i are the wall thickness readings, which include t_m (the minimum wall thickness reading), taken at approximately equidistant locations around the circumference of the tubing at the same axial location (in.);

n is the number of readings taken around the tubing.

For t_i , measurements should not be made to the cap of any internal flash that may be present. The average wall thickness is rounded to the closest 0.001 in.

c) Pipe Metal Cross-sectional Area for Used Coiled Tubing ($A_{m,s}$)

The pipe metal cross-sectional area for used coiled tubing is computed from measurements made on the diameter and wall thickness in accordance with the techniques in 9.5.

The computed pipe metal cross-sectional area is calculated by (see A.2.2 for an example calculation):

$$A_{m,s} = \pi t_{av,s}(D_{av,s} - t_{av,s}) \quad (5)$$

The cross-sectional area of the tubing material is reported to the nearest 0.0001 in.².

d) Length of Used Coiled Tubing

Because of cycling, hanging under its own weight, and pulling during service, the tubing generally stretches and true lengths of tube sections between skelp-end welds may change during use. Pieces are also removed for various string maintenance operations.

The length of coiled tubing is measured by mechanical counters that depend upon contact between the tubular and a wheel (or wheels) in the counter. In cases where several counters are employed, the largest reading may be taken.

As a used string changes length, results from accurate length measurements, an inspection for the location of skelp-end and tube-to-tube welds may be used to update the as-manufactured locations of these welds.

Length measurements shall be recorded to the nearest 30 cm (1 ft).

8.2 Drifting of Used Coiled Tubing

8.2.1 Used coiled tubing should be drift tested whenever a reduction in ID that is detrimental to the required performance and functionality is suspected. Reasons for drifting used CT may include the following.

- a) The coiled tubing is suspected of containing high internal flash.
- b) The coiled tubing is suspected of containing sections of high ovality.
- c) The coiled tubing is suspected of containing dents or excessively crimped areas caused by prior operations with the tubing.
- d) Tube-to-tube welds have been placed in the tubing and a check for a minimum internal diameter is required.
- e) The coiled tubing has been pulled excessively and may have “necked.”
- f) When required by the end-user or owner of the CT.
- g) After pumping solid laden fluids or cement.

8.2.2 A tool of known diameter is passed down the tubing. Passage of a drift ball through tubing in a reel at the surface does not always indicate that a tool of a known outside diameter will pass down the tubing. Under these circumstances the operator should check that the tubing, when installed, will pass the tool.

Either steel or nylon drift balls may be employed.

a) Drifting of Used Coiled Tubing with Cylindrical Drift

In order to determine that a tool will pass through an installed coiled tubular, the operator should drift the tubing with a drift that has a diameter and a length that both exceed those of the tool to be used.

b) Relationship of Weld Flash and Drift Ball

Annex C, Table C.2 shows the relation between standard drift balls (column 3) and the inside bore of the coiled tubing (column 4).

c) Area Covered by Drift Ball

Column 5 of Table C.2 shows the ratio of the cross section of the drift ball to the flow area of the tubing, calculated from $(d_{ball}/d)^2$ and expressed in percent. Figure 2 provides an illustration.

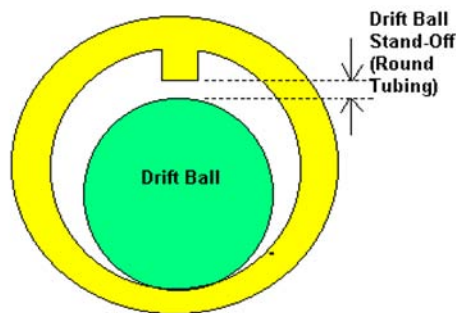


Figure 2—Drift-ball Standoff in Perfectly Round Coiled Tubing

8.3 Drift Ball Standoff for Flash-free Coiled Tubing ($S_{R,0}$)

8.3.1 General

The smallest standoff between the specified gauge ball and the distance across the inner diameter of the tubing at the location of the flash is given in column 6 of Table C.2.

This column is calculated for the worst case of a permitted internal flash column of 0.5 mm (0.020 in.).

8.3.2 Standoff for Round Tubing with Internal Flash Present (S_R)

The standoff for a drift ball for perfectly round tubing with the maximum permitted internal flash present is illustrated in Figure 3 and calculated by:

$$S_R = D - 2t - \text{MFH} \quad (6)$$

where

- D is the specified OD (in.);
- t is the specified wall thickness (in.);
- MFH is the maximum flash height (in.).