Coiled tubing is subject to wear and fatigue during each trip in and out of a wellbore. A new wellsited scanning system helps operators minimize premature tubing failures through continuous monitoring of tubing anomalies as they evolve.

Advances in drilling and stimulation technologies are opening new plays for development of unconventional resources. The success of these plays hinges largely on an operator’s ability to maximize wellbore exposure to the reservoir and then open that reservoir to production. These strategies rely on horizontal or extended-reach drilling followed by hydraulic stimulation. To convey tools and stimulation treatments downhole in high-angle wells, operators increasingly call on the capabilities provided by coiled tubing.

Coiled tubing (CT) is designed to be flexible and ductile enough to withstand winding and unwinding from its storage reel while remaining strong enough to convey and retrieve tools downhole. The tubing is made of low-carbon alloy steel...
in diameters ranging from 0.75 to 3.5 in. and may exceed 9,100 m [30,000 ft] in length. From onshore to offshore and from drilling and completions to workovers, coiled tubing has proved its versatility. Coiled tubing is used for reentry drilling, logging, fishing, perforating, fracturing, acidizing, wellbore cleanouts, unloading of wells, electric submersible pump installations and other applications. A typical CT job will subject the tubing to numerous and varied types of stresses, which, over time, subtly weaken the pipe and ultimately lead to its withdrawal from service.

During each CT deployment, diverse forces act in concert to degrade the service life of the coiled tubing string. On its way into the wellbore, the string is led off its storage reel, bent over a guide arch then straightened as it is pulled through the injector head to enter the wellbore; downhole, the tubing must bend to extend beyond the heel of a lateral wellbore (right). Bending stresses tend to be highest at the guide arch and on the reel, where they can exceed the steel tubing’s elastic yield strength, thus subjecting the CT string to plastic deformation.

Once the downhole tasks are completed, the process is reversed as the tubing is extracted from the wellbore and spooled back onto the reel. Repeated bending, unbending and tensional stresses exert cyclic loads on the pipe. The resulting strains impart low-cycle fatigue, cumulative damage that leads to the formation of microcracks and ultimately forces the tubing string to be removed from service. In addition to low-cycle fatigue, certain operating conditions exacerbate the typical stress loads: a tight bending radius, high temperature or high internal pressure can cause a tubing string to be retired after only a few hundred cycles.

Numerous other factors affect CT fatigue life. Metallurgical composition dictates the tensile strength of the pipe and the types of environments in which it can operate. Defects may be caused by inclusions or poor welds. Fluids pumped downhole, such as those for acid treatments or brine completions, can cause corrosion, as can residual moisture left in the pipe during storage. Corrosion causes pitting and degrades tubing wall thickness. Mechanical damage—a result of routine CT operations caused by contact with the reel, injector head, blowout preventers, wellhead internals and downhole well completion equipment—manifests itself in the form of surface flaws such as scratches, gouges or dents. Chrome production tubulars are particularly abrasive to carbon steel tubing.

To prevent problems associated with tubing wear and fatigue, the CT industry has instituted pipe management practices for the handling and treatment of coiled tubing. Most pipe management systems estimate the progression of CT fatigue over time by tracking the number of bending cycles imposed by the reel and the guide arch, or gooseneck, in addition to tracking various operating parameters. Industry standards set limits on the size of external mechanical damage that is acceptable for CT operations; most ratings are based on damage depth, expressed as a percentage of nominal wall thickness. The tubing is typically retired when metal loss exceeds 10% of the wall thickness.

Damage and imperfections are typically identified during periodic pipe inspections when nondestructive evaluation (NDE) techniques can be

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3. Fatigue life is expressed in terms of the number of loading cycles required for a crack to initiate and then propagate to a specific critical size that will render the tubing unserviceable. In general, low-cycle fatigue is defined as failure of a material in 1,000 cycles or fewer; however, coiled tubing failure may result after only a few hundred load cycles, depending on the severity of deformation accumulated over time.
5. If metal loss occurs within a small section of tubing, that section may be cut out, and the rest of the tubing is welded together before it is returned to service; if metal loss is extensive along the tubing string, the entire string may be retired.
Welding of coiled tubing. Early manufacturing processes used a butt weld (left) to join lengths of tubing together. After a number of tubing failures were found at the heat-affected zone adjacent to the weld bead, tubing makers developed a new approach to manufacturing. Flat strips of sheet steel are joined end to end before being curled into tubular form. These strips are cut on an angle and joined by a bias weld (right). This weld forms a helix when the strip is rolled into a tube (middle). The bias weld distributes stresses in the weld zone over the length of the helix rather than concentrating it within a narrow band as would a butt weld.

This article reviews a CT inspection system that operates at the wellsite in real time. Mounted near the storage reel, the CoilScan RT real-time pipe inspection system incorporates a series of sensors that allows the operator to monitor the condition of the CT string as it is spooled in and out of the well. The inspection system establishes the location and extent of internal and external anomalies that point to pipe defects and damage. This technology enables CT crews to identify flaws and monitor how they evolve over the working life of the pipe.

Problems in the Making
Under the stress and strain of wellsite operations, minor tubing defects and imperfections may develop into major problems that can undermine the integrity of the CT string and compromise operations. These flaws can be attributed to three primary sources: manufacturing defects, corrosion and service-induced mechanical damage.

Manufacturing of coiled tubing starts at the mill, where rolls of sheet steel are laid flat and cut into strips, known as skelps. Each skelp is cut on a bias, typically at 45°. The bias edges of several skelps are welded together to form a continuous strip of sheet steel, and the mechanical properties of the bias weld nearly match those of the skelp. Next, the strip of sheet steel is rolled formed into a tubular shape while a high-frequency induction welding machine fuses its two edges together to form a continuous longitudinal seam. When the sheet steel is formed into a tube, the 45° bias weld winds helically around the tubing and is evenly distributed over a greater length of the tubing than would be the case for a butt weld (above). The mill removes the bead of welding flash from the external side of the seam to obtain a smooth OD on the tubing. The inside of the tubing is flushed to remove scale or other loose material; in some cases, excess welding flash inside the tubing must also be removed.

Although tubing companies take measures to prevent their occurrence, two types of problems have been encountered during the manufacturing process. Nonmetallic inclusions, such as calcium oxide, may sometimes be introduced into the steel strip at the steel mill. Such impurities and inclusions can lead to delamination of the tubing wall, degradation of the mechanical properties of the steel and an increase in the risk of corrosion. The other type of problem is caused by any interruption to the welding process. Welding interruptions produce a partial or complete lack of fusion that can result in porosity, underfilling of the weld area and open gaps along the bias and seam welds.

Corrosion can pose a significant problem throughout the life of a CT string. Through deployment in the wellbore, the tubing may be exposed to acid treatments, brine completion fluids, water, hydrogen sulfide [H2S] and carbon dioxide [CO2]. Such exposure promotes corrosion, which results in pitting and reduction in tubing wall thickness. To combat these problems, tubing manufacturers and end users have instituted a variety of measures. While running hydrostatic pressure tests, tubing companies maintain the testing fluid at slightly alkaline pH levels between 8 and 9. After testing, they drain and wipe the inside of the tubing to remove any fluids. Some companies pump nitrogen into the tubing and maintain a slight pressure to eliminate as much oxygen as possible during storage and transport. Corrosion inhibitors may also be used to coat the inner and outer surfaces of the pipe.
Perhaps the most common threats to tubing integrity arise from damage incurred during routine wellsite operations (above). Normal handling at the wellsite subjects the CT to mechanical damage—scratches, abrasions, dents or gouges—through contact with the injector, wellhead, casing and completion equipment as well as through contact with abrasive formations in openhole settings. Other operational damage may take many forms (previous page bottom). These include the following:

- ballooning: localized expansion of the tubing caused by high pressures while tripping
- necking: stretching and thinning caused by application of excessive tensile force
- erosion: wearing away of the inner or outer tubing surface as a result of high flow rates or abrasion
- injector damage: transverse gripper marks or longitudinal gouges created as the CT is injected downhole may be caused by improper operation of the injector, misalignment of injector gripper blocks or foreign objects between the gripper blocks and the coiled tubing.

Manufacturing defects, corrosion and service-related damage result in surface flaws that affect the tubing's capability to handle cyclic stress loads: They concentrate stress. Ideally, when a load is applied to a piece of tubing, the resulting stress will be distributed uniformly. However, scratches, gouges, pits or pinholes produce voids in the surface of the metal tubing, and these voids are incapable of bearing loads. The stress must then be redistributed over the remaining metal. This creates an uneven distribution of stress that is highest at the edges of the void, which causes stress concentration. Furthermore, these stress risers accelerate the formation of fatigue cracks.

When tubing has been subjected to stress cycles, fatigue cracks may form where stress is concentrated. Fatigue cracks usually initiate at the surface of the tubing; therefore, surface flaws such as abrasion, pitting or scratches can decrease fatigue life. Conversely, smooth surfaces increase the time required for fatigue cracks to form.

Because CT is ductile, such defects do not normally cause failure at their onset and do not

7. Calcium oxide helps remove impurities such as phosphorus and sulfur from the steel. When calcium oxide is added, these impurities form a slag on the surface of the molten metal, which can then be skimmed for removal.
necessarily result in condemnation of the entire CT string. Minor surface blemishes can be dressed with a grinding tool and brush. Sometimes, whole sections must be cut out of the pipe, leaving the undamaged sections on either side of the cut to be rejoined by welding. Over time, however, even minor blemishes can evolve into major flaws that threaten the structural integrity of the pipe.

The CT Scanning System

The CoilScan real-time pipe inspection system consists of an inspection head, a data acquisition system and monitoring software. This system employs two proven nondestructive evaluation techniques for detecting flaws in the tubing: magnetic flux leakage (MFL) and eddy current testing. These techniques are well suited for oilfield operations, requiring neither a clean tubing surface nor any type of coupling agent between the sensors and the tubing. Because the CoilScan RT system uses noncontact sensors, it can accommodate CT strings with rough, dirty, wet or muddy tubing surfaces. The only parts that touch the tubing during normal operations are the stainless steel guide rollers and the odometer wheels. The MFL sensors locate defects and determine wall thickness; eddy current sensors measure the OD and ovality of the tubing string. This system provides continuous real-time monitoring at an operational speed up to 40 m/min [130 ft/min].

Magnetic flux leakage is the basis for detecting magnetic anomalies in the tubing string. The anomalies typically originate from gouges, pitting, metal loss or other imperfections, including material damage or manufacturing defects. The MFL device employs strong magnets to induce a magnetic field in the steel wall of the coiled tubing. This magnetic field flows from its south, or negative, pole—where it enters the steel—to its north, or positive, pole, where it exits. Any break or void in the magnetized tubing will have a similar polar orientation; when the magnetic field encounters a break—a crack, for example—the field will exit the north pole of the crack and reenter at its south pole. The air gap between edges of the crack cannot support as much magnetic flux as steel can, so the magnetic field will spread out, or leak (above left). This flux leakage is detected by Hall effect sensors in the inspection head.\(^{10}\) Measurements of the intensity and distribution of magnetic flux leakage infer an underlying defect in the steel. This method can also be used to determine CT wall thickness.

Eddy currents. An eddy current probe is used to measure outside diameter and ovality of a CT string. Current flows through the primary coil of the probe, generating a magnetic field. This field creates eddy currents in the conductive tubing. The eddy currents generate their own magnetic fields, which are out of phase with the original primary coil’s magnetic field.

\(^{10}\) Magnetic flux leakage. The magnetic flux in a piece of tubing may be interrupted by any type of break or discontinuity along the inner or outer surfaces of the tubing. The air gap at the surface discontinuity cannot support the same flux magnitude as can steel. This causes the magnetic field to leak out of the metal and spread outward from the defect.
Eddy currents are circular electric currents induced within a conductor by changing magnetic fields in that conductor. In an eddy current probe, alternating electric current flows through a wire coil and generates an oscillating magnetic field. When the probe nears the CT, eddy currents are generated on the tubing surface. The eddy currents generate their own magnetic field, which opposes the magnetic field originating from the wire coil. As a result, the electrical impedance of the wire coil will be altered. From measurements of the change in electrical impedance in the coil, the distance between the coil eddy current probe and the conductive CT surface can be determined. Using these measurements, the CoiIScan RT system determines the tubing OD and the ovality of the CT string.

The two halves of the CT inspection head form a clamshell that is placed around the tubing, and measurements are obtained as the CT is spooled off and on the reel. The head consists of an MFL subsystem, an OD-ovality subsystem and an odometer subsystem.

The MFL subsystem is located at the center of the inspection head. It employs permanent magnets and Hall effect sensors to screen for CT wall thickness and detect anomalies on the inner and outer tubing walls. The MFL sensor data are processed through digital filters specially designed for detecting fatigue cracks, corrosion, holes, notches, gouges and pitting, and the processed data are also used to quantify metal loss over time.

The OD-ovality subsystem measures the outside diameter of the tubing. These measurements are used to calculate ovality. The OD measurements are obtained from eddy current displacement probes arranged in opposing pairs over the circumference of the tubing.
High-definition 3D magnetic flux leakage (MFL) signature plot for a typical bias weld anomaly. Bias welds are used extensively during the manufacturing process and are found in nearly every coiled tubing string. An anomaly associated with such welds is caused primarily by localized changes in material properties, particularly changes in steel permeability between two skelps. On some CT strings, bias welds join skelps of differing thickness, and this change in thickness may play a role in causing magnetic flux leakage as well. This display shows an aggregation of MFL amplitude readings from all Hall effect sensors. The same anomaly is mapped in 2D and 3D. Colors correspond to MFL values in gauss from low (blue) to high (red). The map view can be rotated for better visualization of the data.

The odometer subsystem measures the depth, length and position of the tubing as it is being inspected. Two odometer subassemblies provide redundancy and reliability in distance measurement. Each subassembly has a measuring wheel and a high-resolution rotary encoder to convert wheel rotation into linear distance.

A data acquisition subsystem interfaces with the inspection head, processes and interprets the MFL and eddy current sensor data and depth encoder counts then outputs the results to the monitor for display. This independent data acquisition and processing subsystem can be placed up to 30 m [100 ft] from the inspection head.

Essential capabilities under normal operating conditions include the following:

- measurement of wall thickness to an accuracy of ±0.127 mm [±0.005 in.]
- measurement of outside diameter to an accuracy of ±0.254 mm [±0.01 in.]
- detection of through-hole defects as small as 0.79 mm [0.031 in.]
- detection of wall thinning, blind holes, transverse notches and longitudinal notches on the outer and inner surfaces of the tubing string
- calculation of ovality and measurements of MFL amplitude, wall thickness and outside diameter obtained every 1.2 cm [0.5 in.] along the CT axis.

All measurements are integrated with 3D modeling and interpretation software that helps the operator detect, identify, visualize over 360° and track anomalies over time.

Pipe damage identification and the defect library. The red curve is derived from the upper boundary of the measurements from all MFL sensors; the blue curve is derived from their lower boundary. The red and blue curves together constitute the MFL defect signature. The MFL plots from a CoilScan RT system inspection of a 2-in. OD string reveal severe pipe damage. The software correctly identified the defect as a gouge on the pipe surface and also provided severity information. This identification was accomplished without having to stop the CT operation to prove up the defect. The CT defect (top left) can be compared with a similar defect from the predefined library (top right). Corresponding MFL amplitude signatures from the defect and library also showed a good match (bottom).
The CoilScan AP technology software retains a record of all alarm-triggering events in its alarms record table. During a job, the CT operator may enter notes into the comments field of that table. All comments are saved with the main data to become a permanent attachment to the inspection data. Selecting any row in the table will pull up an MFL amplitude display of the associated anomaly (previous page, top). The CT engineer can evaluate the MFL signatures at the wellsite and archive the data for further review after the job.

As the tubing is spooled in and out of the hole, the CT crew monitors MFL amplitude and various job parameters using the log plot. For used tubing, tens or even hundreds of spikes are not uncommon on the amplitude chart of a typical string. Each spike corresponds to a magnetic anomaly and thus a potential defect (above). To address the high number of spikes and the difficulties associated with stopping the CT operation to perform prove up—physically locating the defect that caused the MFL alarm then investigating it further using various nondestructive evaluations—Schlumberger researchers developed a program to automatically identify and track the recorded anomalies.

Using advanced pattern identification, recognition and matching algorithms, the program identifies the underlying defect type and provides useful information regarding severity of the flaw. Just as important, the program tracks defect initiation and growth at various times in the life of the tubing. Automatic defect identification is based on a library of defects that has been preloaded into the program. This library pairs MFL signatures with photographs of numerous defects collected from yard and field inspections. The software can identify newly discovered defects by matching their MFL signatures with patterns in the predefined benchmark library (previous page, bottom).

This process of automatic defect tracking enables CT crews to maintain a history of important defects for each string, characterized by their similarity to catalogued MFL signatures, depths and wall thicknesses. The tracking of MFL signatures as they evolve can shed light on...
The evolution of a defect. Numerous inspections were carried out on a CT pipe over its service life. The MFL (magnetic flux leakage) amplitude, measured in gauss, provides a normalized measure of defect severity. Within the coilstring, the entire evolution of a particular defect can be reconstructed.

Continuous Inspection

Through continuous MFL monitoring of pipe—first from use to the end of its service life—defects can be identified, isolated, and tracked, leading to improved evaluations of a CT string's condition and future serviceability. By integrating these features into a portable device suitable for real-time inspection, the CoilScan RT system significantly improves the ability to monitor overall pipe integrity.

Once the sensors locate a defect, the next priority is to evaluate the severity of the defect in relation to its effect on CT integrity. Defect severity can be determined by obtaining its length, width, and depth. Schlumberger researchers are using finite element analysis (FEA) to model magnetic flux leakage for specific mechanical defects in CT. The FEA models, followed up by laboratory tests of MFL responses on actual pipe, indicate that defect geometry can be accurately measured using MFL. Researchers continue to make progress in defining the relationships between MFL measurement profiles and the corresponding geometric characteristics of defects. Researchers are also making progress in evaluating the impact of defects on pipe fatigue. By identifying and grouping defects into different types—transverse or longitudinal dents, fatigue. By identifying and grouping defects into different types—transverse or longitudinal dents, researchers are able to establish a correlation between the MFL signals of the defects and the fatigue life of the pipe.

Pipe management can now be based on job-to-job, continuous, physical measurements with an object-oriented tracking system that allows CT operators to monitor defects over time with minimal interruption to normal wellsite operations. Coiled tubing crews will be able to understand the circumstances that cause defects and that promote further tubing degradation as well as devise mitigation techniques. Defects will be tracked and recorded simultaneously with CT characterizations and critical job parameters. The integration of the CoilScan RT real-time pipe inspection system into CT operations promises to redefine pipe management practices.

—MV