A Method for Determination of Stress and Fatigue in Risers and Wellheads
Harald Horn, Ferr AS; Arild Saasen, SPE, Det norske oljeselskap ASA and University of Stavanger; Arnjot Skogvang, Lundin Norway AS

Abstract
The paper presents a new and novel non-destructive method for measuring deterioration and cracks in steel structures. Results from stress and fatigue tests with different full scale structures are presented and related to real applications with respect to life-time prediction. Conventional cyclic loading test of riser-pipe elements are documented herein for confirmation of the method.

The subject method functions as follows: The material properties magnetic permeability and electrical conductivity, and changes in these, are determined by analyzing the measured voltage response to injected electric pulses. The response is transient voltage drop signals, measured under various conditions, and is the basis for calculating parameters representing the stress, fatigue and crack nucleation and crack development in the materials. The degree of material degradation can be used to calculate operational lifetime.

The method has been tested and verified for different types of stress and fatigue loads in different steel alloys. High sensitivity to elastic stress and early detection of permanent changes for high-cycle fatigue testing have been demonstrated with fatigue tests of workover riser pipes. High sensitivity to remanent stress, i.e. the steel’s ability to “remember” stress (elastic) is a feature that is proportional to the maximum stress occurred since last measurement. On risers, measurement devices can be installed to give the actual condition of the steel for the most exposed locations. Additionally, this information can be used to calibrate the mathematical models for estimating the condition of the whole riser in order to reduce the uncertainty of estimates.

Introduction
Monitoring fatigue in structures is today based on calculation of stress from strain measurements as well as on monitoring of the movement of the structure. These data are then used to estimate degradation in the structure based on standard engineering tools, for example in the form of statistical stress life data (known as the Wöhler or S-N curve). There is usually large scatter in such data and the resulting fatigue estimates are usually very conservative.

In ferromagnetic steel, magnetic properties and electrical resistance depend on changes in both microstructure and macroscopic damage related to cyclic loading. Measurements based on
electromagnetic principles are therefore applicable in monitoring actual fatigue degradation both before and after crack initiation.

In the following a method is presented that is based on measuring changes in magnetic permeability and electrical resistance at different depths and at multiple locations within a monitored area (Horn, 2011). An application of the method is to monitor changes in the material due to fatigue during cyclic loading in order to detect and monitor early degradation.

One application can be onsite inspection of riser joints, which has been focused upon in a revised edition of API's recommended practice for drilling risers (API RP 16Q, 1993). In this document it is recommended that “Field inspection and maintenance are to be scheduled regularly and performed for all riser components”, and that “a shorter interval specified for those joints subjected to highest levels of fatigue damage”.

The subject inspection method is in line with these recommendations when comparing results from actual steel condition for critical areas that have seen the largest fatigue loads. Typically, two or three riser joints are instrumented and thus accurate condition data for these points can be achieved by inspection onsite. Furthermore, the measurement values from these points can be used to calibrate models for fatigue estimation for the complete riser. Such measurements can thus reduce the need for sending the riser onshore for inspection and hence, reduce the operational costs and extend the period of safe operation.

Theoretical Background

Four-Point Potential Drop Measurement Principle

The presented electromagnetic method, based on the potential drop method, is sensitive to changes in ferromagnetic materials that influence the electrical impedance. This impedance consists of the steel’s magnetic permeability and electrical resistance. Stress and material deterioration change these parameters. This behavior of the steel parameters is well documented in the literature as for example described by Jiles (1998, 1988) or Bi et al. (1997). This method’s responses to such changes have been demonstrated by many tests with small specimens and full scale structures and pipes. The sensor arrangement is based on a four-point potential drop technique comprising one pair of electrically connected electrodes for injection of an excitation current and one or more pairs of electrically connected sensing electrodes between the excitation pair (Jiles 1988) as illustrated in Fig. 1. A and B in the figure below are connections for excitation current, and C and D make a sensing pin pair for measuring the potential drop response signal. Normally, many potential drop pin pairs are applied per current excitation pair. However, in the present set-up there is only one such pair.

![Fig. 1. General layout of four-point potential drop sensor.](image)

The electric Excitation current, Response signal (Potential drop) and finally the Deviation are shown in Fig. 2. The Excitation current pulse has a typical duration of 0.5s. Two Response signal transient curves
measured at two different states of the steel are shown. Here is shown the transient voltage response, $a(t)$, of the monitored object and the transient voltage response, $n(t)$, measured at the evaluated material condition, in this case when being exposed to higher stress. The curve to the right in Fig. 2 shows the Deviation $d(t)$ between the two response transients: $d(t) = [n(t)/a(t) - 1]1000$ [ppt] (parts per thousand). The deviation $d(t)$ shows the deviation of transient $n(t)$ to transient $a(t)$, and by subtracting 1 from the fraction, $d(t)$ will be zero as long the transients are equal. By multiplying with 1000 we get parts per thousand.

![Conceptual waveforms](image)

**Fig. 2. Conceptual waveforms.** Excitation current pulse, Response signals $a(t)$ and $n(t)$, which are two transient curves measured at the pin pairs for two different steel conditions, and Deviation $d(t)$ between the two Response signals.

The transient shape of the response signal is due to the skin effect when injecting a current step in ferromagnetic steel. The transients shown in Fig. 2 are characterized by their time constants $\tau$ which are related to the steel parameters presented in Equation 1:

$$\tau \approx \frac{1}{4} t^2 \sigma \mu_0 \mu_r$$  \hspace{1cm} (1)

where $t$ is the wall thickness, $\sigma$ is the electrical conductivity, $\mu_0$ is the magnetic permeability of free space and $\mu_r$ is the relative magnetic permeability.

**Measurement principle**

**General**

The purpose of this section is to describe relations between fatigue and the electromagnetic properties of steel. Magnetic permeability and electrical resistance are the main parameters of steel influencing these measurements. We discuss how measuring changes of these parameters can be used to monitor material degradation prior to crack initiation during fatigue.

The initial material changes during a fatigue process will be the growth of dislocations and micro-cracks in the surface. These will cause a reduction in permeability and then an increased electrical resistance in the surface. These changes in the outer surface and beneath are monitored by the transient voltage response. This response changes in accordance with the degree of changes in the material. I.e., when the micro-cracks grow to more continuous cracks, a different response is measured, and this degree of material degradation can thus be detected before any crack is visible.
Fatigue and microstructure of steel

Fatigue refers to irreversible changes in a material or component that is exposed to cyclic loading. These changes are crack initiation, growth and microstructural changes before the onset of macroscopic crack growth. Changes in microstructure are closely related to changes in the density and structure of dislocations. The fatigue process is commonly divided into three stages (Klesnil and Lukáš, 1992) corresponding to first, accumulation of cyclic plastic deformation, second, formation of slip bands and nucleation and growth of micro-cracks, and third, growth of a macroscopic crack to failure. The first stage is closely related to bulk material properties and is most commonly characterized by cyclic stress-strain behavior. In the second stage changes are more localized, for example towards free surfaces and areas of stress concentration. This leads to nucleation of micro-cracks which in turn may grow, and possibly coalesce, to form macroscopic cracks. In a typical fatigue process on smooth surfaces, the material should be in the first phase for the majority of fatigue life. On rough surfaces with the presence of stress concentration points, this phase is almost completely absent and the fatigue process starts directly with crack initiation and propagation.

Fatigue monitoring based on changes in magnetic properties of steel

The electromagnetic properties of ferromagnetic steel depend strongly on the metal’s microstructure (Jiles, 1998). Magnetic measurements therefore have a long tradition of being applied in non-destructive evaluation (NDE) of steel metals (Jiles, 1988). Several laboratory works have demonstrated that measurement of changes in magnetic properties can be used to monitor the progression of fatigue damage (Lo et al., 1999; Bi et al., 1997; Chen et al., 1994; Govindaraju et al., 1993; Lo et al., 2000; Bose, 1986). The essential results from these works is that rapid changes are measured during early fatigue cycles, followed by more gradual changes until rapid changes are again observed imminent to fatigue failure. This development correlates with the different stages of fatigue as outlined above. Large initial changes are expected due to the cyclic stress-strain behavior, which affects bulk microstructure and therefore also the bulk magnetic properties. Later, more localized changes take place during the second fatigue stage which leads to more gradual changes in magnetic properties. Large changes near the fatigue failure are usually related to crack growth and failure of the structure.

The strong dependence of magnetic properties on the microstructure of steel is mainly due to interactions between the dynamics of the magnetization process and microstructural features. Each crystal grain in a piece of ferromagnetic material is internally composed of several magnetic domains. These domains are separated by boundaries called domain walls. When the material is exposed to a magnetic field, for example due to an electromagnet or injected electrical currents, magnetization occurs by growth of domains whose magnetization is aligned with the magnetizing field. This growth of domains requires movement of domain walls. However, domain walls do not move freely because they are obstructed by microstructural imperfections. The effect of these imperfections can be regarded as a type of friction that works against the magnetizing force, thus making it harder to magnetize the material due to reduced magnetic permeability. A well known example of this phenomenon is decreased magnetic permeability with increased dislocation density (Astie and Degauque, 1981).

Although several of the magnetic methods used in laboratory research are sensitive to changes in microstructure, most have limitations for use in practical monitoring applications. Some methods measure only bulk magnetic properties like hysteresis measurements. Others measure properties such as conventional Barkhausen noise or eddy currents that are sensitive mainly to a thin surface layer. However, it is important to discriminate between changes in the bulk material and changes on the surface of this material. To measure fatigue damage, the significance lies in whether changes occur in bulk or a localized region like on the surface. This again depends on the stage of the fatigue. Additionally, having sensitivity to different depths, including inside and outside surfaces, improves the ability to discriminate between different phenomena influencing the magnetic properties. Finally, pure magnetic methods have limitations when it comes to detecting and quantifying more severe damage such as cracks, which mainly result in increased electric resistance.
Electrical resistance-based methods

Measuring electrical resistance is a widely established technique for detecting and monitoring crack growth (Merah, 2003; Černý, 2001). Electrical resistance measurements are most commonly made using the well-known four-point potential drop method where the potential drop due to an injected electrical current is measured. An advantage of the potential drop technique is that it is suitable for use in a wide range of environmental conditions, such as high temperature large-scale testing (Černý, 2004). It has also been suggested that the Direct Current Potential Drop (DCPD) method is ideal for structural health monitoring (Chung, 2001). Recent published work has also concluded that changes in the electrical resistance of steel during cyclic loading can be related to the fatigue-induced increase in the density of defects, such as micro-cracks (Starke et al., 2011).

Traditional potential drop methods

Traditional PD techniques are based on injecting either alternating or direct current, corresponding respectively, to Alternating Current Potential Drop (ACPD) or DCPD. DCPD depends only on the electrical conductivity and geometry of a material. ACPD has an additional frequency-dependence due to the electromagnetic skin effect, which causes the injected current to flow in a thin surface layer at high frequencies. Recent studies have demonstrated in lab scale that such multi-frequency ACPD measurements can be used as a tool for material characterization (Bowler et al., 2008; Bowler, 2011).

Transient potential drop method

The transient potential drop combines the features of both ACPD and DCPD and provides a technique that is simpler to realize for field applications than ACPD. In transient potential drop, pulsed current is used as the excitation source and the resulting transient voltage response is measured. The advantage of this technique is that a single transient response contains information from multiple depths in the material, because the pulsed current is composed of multiple frequencies.

Monitoring of fatigue with transient potential drop

This method to monitor fatigue is based on measuring the transient potential drop at multiple probe locations within the monitored area. Changes in electromagnetic properties are monitored by comparing measurements taken at different points in time. The use of fixed sensors ensures high repeatability and sensitivity to small changes in material parameters, obtained by having a large signal to noise ratio. Other electromagnetic methods using portable sensors rely on the operation such that the results depend on the skill of the user or the particular sensor in use. The potential drop method has an advantage in this sense due to the simplicity and robustness of the sensors, leading to simpler interpretation of the measurements compared with other techniques, as described by Bowler (2011). An advantage of the transient potential drop method is that the different stages of the fatigue process can be monitored continuously. The transient phase of the signal is used to measure the depth profile of changes in both electrical resistance and magnetic permeability due to changes in microstructure.

The start of the transient has high sensitivity to any material changes in the outer surface and is used for detection of crack initiation in the surface since the current at this point flows in a thin surface layer. The steady phase of the signal, equivalent to DCPD, is independent of magnetic properties, but is sensitive to discontinuities such as fatigue cracks. In other words, the transient potential drop is sensitive to both changes in material microstructure and flaws, which means it can be used both to monitor degradation before crack initiation and to detect and monitor crack growth after initiation. In essence, sensitivity to changes in electrical resistance and magnetic permeability at different depths as well as high sensitivity to damage, gives a more complete monitoring of integrity of steel structures.
Experimental results

As outlined in the previous sections, the ability to measure changes in electromagnetic properties at different depths in a material is essential to the characterization of changes in a material caused by fatigue. An example of how transient potential drop signals can be characterized in terms of changes in material properties at different depths is shown in the following. These measurement data are taken from a dataset from monitoring fatigue during testing of a riser pipe section in a four-point bending rig. Basic interpretation of measurements can be made qualitatively with knowledge of how changes in electrical resistance and magnetic permeability influence the signal.

In an attempt to improve the characterization of signals, a physical model for the transient potential drop is used that takes into account how the signals are affected by the electromagnetic parameters at different depths in a layered plate. The model parameters used here are a layered conductor of thickness 15.5mm which corresponds to the nominal wall thickness of the tested riser pipe. Three layers are used in the model. The interfaces between the layers occur at depths of 1 mm and 2 mm, corresponding to two surface layers of thickness 1 mm. The use of two surface layers was necessary to obtain sufficient agreement between the model and measurement results.

Modelled deviation signals are based on first modelling a reference signal. Here, a homogeneous reference is assumed, with parameters \( \mu_r = 100 \) and \( \sigma = 2.82 \text{ MS/m} \). These parameters were chosen in order for the modelled transient to have similar length and DC level as the measured reference transient from the riser pipe.

In Fig. 3 is shown a measured deviation signal corresponding to changes accumulated over 10 000 fatigue cycles. The deviation in potential is shown as a function of time. The results from the first 10 ms are shown in Fig. 4. Also shown is a modelled deviation signal corresponding to a 30 % decrease in conductivity in the top 1 mm layer, and a decrease in relative magnetic permeability of 8 % and 40 % in the two next layers. The modelled conductivity decrease in the top layer can be interpreted as an increase in the electrical resistance in the surface. The changes introduced by the fatigue cycles can therefore be attributed to a combined increased electrical resistance in the surface and decreased relative magnetic permeability in the lower part of the pipe wall.

![Experimental measurements and theoretical predictions (dashed curves) for changes in electrical resistance and magnetic permeability in a layered conductor.](image)
The effects of electrical resistance and magnetic permeability on the modelled deviation signal are shown in Fig. 5. Showing the individual contributions from the surface resistance and the magnetic permeability and how these sum up. Note that the increased electrical resistance in the surface dominates the early part of the signal. The middle part of the deviation is dominated by the permeability changes. The final DC part of the deviation signal is determined by the resistance changes only since it is not sensitive to magnetic permeability.

**Laboratory testing of riser pipe fatigue**

The main objective of this conventional fatigue loading laboratory test was to evaluate the method’s sensitivity to fatigue and crack detection by monitoring a high-cycle fatigue test of a piece of riser pipe element. Instrumentation used for fatigue monitoring of the test was identical with systems designed for the field application and a circumferential overlay weld was monitored. Measurements were taken at short intervals during the high-cycle fatigue testing. The rig was constructed for one-sided loading only, and the bending was downwards with cyclic loads oscillating between 15kN to 325kN in Phase 2 (Table 1). This caused different stress level distribution around the circumference. On top of the pipe, defined as 12 o’clock position, was seen maximum compression stress, and on the bottom of the pipe, defined as 6 o’clock position, was measured maximum tension stress.
The test was run in two steps, Phase 1 with cyclic loads = 12.5% of Re (material yield stress), and Phase 2 with cyclic loads = 48% of Re. Initially in Phase 1 shake down bending was run to reduce the residual stresses in the weld and Heat Affected Zone (HAZ).

Before the start of the cyclic fatigue loading in Phase 2, shake down bending with a load designed for this test phase was done. The purpose of this bending was to reduce the residual stresses in the monitored area and it was mainly effective at the 6 o’clock position, where the tensile stress was highest. The first measurement taken after the shake down was after cycle 90 003 and taken at no stress, which also was the case for all the following measurements. The cyclic loads were designed to give fatigue failure after approximately 100 000 cycles in Phase 2. However, fractures were observed after applying 37 000 cycles in addition to the 90 000 cycles from Phase 1. The reason for the relatively low fatigue life was anticipated to be the irregular profile of the weld caused by the manual welding process, compared to automatic welding. However, the fatigue life was within the scatter band being ± two standard deviations of the fatigue life of welds.

The test pipe was a piece of a workover riser. The specifications for this tested riser pipe were as follows:

- Pipe OD = 219.1 mm
- Wall thickness = 15.5 mm,
- Length = 4.3 m
- Tensile strength Rm > 827 MPa
- Yield stress Re = 758 MPa (110 ksi)
- Circumferential overlay weld

![Fig. 6. Sketch of test rig, 4-point bending. Pipe length = 5 m. One-sided loading was applied.](image)

![Fig. 7. Block diagram of instrumentation used during the fatigue test.](image)
Table 1. The test was run with two different load programs

<table>
<thead>
<tr>
<th>Cycle Freq. (Hz)</th>
<th>Stress when measure (MPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 - 85.5</td>
<td>47.3</td>
<td>0</td>
</tr>
<tr>
<td>15 - 325</td>
<td>170</td>
<td>0</td>
</tr>
</tbody>
</table>

The test was carried out in a four-point bending test rig that was specifically designed and built for this type of testing. A schematic drawing of this rig is shown in Fig. 6. The rig was constructed for one-sided loading only, and the bending was downwards with cyclic loads as defined in Table 1. The span length L was 1.2 m. The length of the mid-span with constant bending moment was 1.2 m. The test was run in load-controlled mode with a load cell that was calibrated to a nominal accuracy of 0.5%. Stresses were calculated from elementary beam theory.

The block diagram of the instrumentation system used for the test is shown in Fig. 7. The system is a dedicated system for transient potential drop measurements and for this test the capacity was 28 pin pairs, which gave good resolution for monitoring the 8.5/8” pipe’s circumferential weld. Pictures from the tests are shown in Fig. 8. To the left is shown the instrumentation of the butt weld, and to the right the 8.5/8” pipe in the test rig. For the testing a soft soldering technique was applied for the electrical connections of the sensing pins and the current excitation to the pipe. In field operation both soft soldering and a clamp-on device will be considered to make the system robust. Both designs will avoid any material changes in the steel or the introduction of any hot spots, and both have been through comprehensive environmental testing.

Measurements were taken before any loading and also after the shakedown bending. The data presented here are deviations to the measurements taken after the shakedown and thus only show the effect of cyclic loads. Measurements were mainly performed at a time without any external load when the test rig was stopped, and data presented are from measurements without stress. Changes in electromagnetic properties are monitored by comparing measurements taken during the test with the first measurement after shakedown.

The transient phase of the signal is used to measure the depth profile of changes in both electrical resistance and magnetic permeability that are due to changes in microstructure. The start of the transient has high sensitivity to changes in the outer surface since the current at this point flows in a thin surface layer. The steady phase of the signal (equivalent to DCPD and here called DC Deviation) is independent of magnetic properties, but is sensitive to discontinuities such as fatigue cracks that change the electrical
resistance. The response signal thus has sensitivity to changes in electrical resistance and magnetic permeability at different depths.

**The riser pipe fatigue test results**

The material deterioration during a fatigue process is considered to start with the growth of dislocations and micro-cracks in the surface. These material changes cause reduced permeability and also increase the electrical resistance in the surface. These two parameters make up the electrical impedance of the steel and the changes in the pipe surface and the body beneath the surface are monitored by the transient voltage response. This response changes with changes in these parameters, such as when micro-crack density increases and becomes continuous cracks, and the degree of material degradation can be characterized.

![Deviation Curves](image)

**Fig. 9.** Example of deviation curves for Phase 2 for pin pair at 6 o’clock with the highest tensile stress. These curves show response to material deterioration development including crack initiation. Each curve is relative to measurement at cycle 90 003.

An example of deviation curves for Phase 2 is shown in **Fig. 9**. The top of the pipe is defined as the 12 o’clock position and the bottom of the pipe is defined as the 6 o’clock position. These curves show response to material deterioration development including crack initiation. Each curve is relative to the measurement at cycle 90 003. The leftmost side of the graph, called Peak Deviation, is the deviation between the transients’ peaks, and represents material changes in the outer surface. To the right of the Peak, the influence of material changes deeper in the wall is measured. At the far right, the DC deviation represents resistance changes in the bulk material, which in this case are related to crack development. Based on the shape and development through the whole deviation curve it can be concluded that the crack is in the outer surface.

The increase of Peak Deviation is a result of the increase in resistance in the surface caused by material degradation there. The decrease of deviation up to approximately 35 ms is due to reduced magnetic permeability, which is mainly related to the increase in dislocation density at the surface and deeper. From cycle 108 280 (- 90 003) the permeability is more or less constant and the whole curve is lifted due to the increase of resistance caused by crack growth.

One criterion for the detection of cracks, is when the DC part of the deviation data is significant (>0.5 ppt). The DC part for this installation starts after approximately 90 ms. This criterion is valid for cracks both on the inside and the outside of the pipe surface. Using the information from the signal at Peak Deviation, a significantly higher sensitivity to crack initiation is obtained.

The measurement of the initiation and development of cracks in the outer surface is shown in **Fig. 10**. The data points in this curve are taken from the deviation curves in **Fig. 9** at approximately 31 ms on each of the curves, indicated with a vertical red line in this figure. The data points show changes in the electrical
impedance relative to the measurement at cycle 90 003, and show changes in the surface as an effect of material degradation due to cyclic loads. The impedance consists of the sum of $\mu$ and $\sigma$. The shape of this curve is typical for monitoring of weld and fatigue development in the outer surface. The impedance decreases in the start because the decrease of permeability dominates. When the amount of surface micro-cracks grows and the micro-cracks coalesce to cracks, the surface resistance increases and dominates the change in the impedance.

![Diagram](image)

**Fig. 10.** Example of deviation for Phase 2 for pin pair at 6 o'clock with the highest tensile stress. These curves show response to material deterioration development including crack initiation. The x-axis show the number of cycles relative to cycle 90 003.

The characterization of material degradation before cracking is based on estimated changes of magnetic permeability and electrical resistance in the surface based on measured deviation from the original status. The development of magnetic permeability is shown in **Fig. 11**. The left plot’s x-axis is the number of load cycles starting with 90 003, the y-axis is the clock position around the pipe’s circumference, and finally, the z-axis is the deviation in ppt. The plot on the right shows the bulk permeability deviation for the pin pair at the 6 o’clock position. A rapid decrease to measurement 12 can be observed (measurement numbers are defined in Table 2). After approximately measurement 15 the estimated permeability values are less reliable because the crack size changes the conditions the calculation algorithm is based on.

![Diagram](image)

**Fig. 11.** Estimated development of magnetic permeability for all pin pairs and all measurements in Phase 2.
The development of deterioration in the surface is shown in Fig. 12. The left figure shows the estimated increase of resistance in a 1 mm surface layer for all pin pairs around the circumference. The figure to the right shows the surface resistance deviation for pin pair 25 at the 6 o’clock position. These data are related to growth of micro-cracks in the surface and crack initiation at the 6 o’clock position. Already for measurement number 12 the deviation is 12 ppt which is 12 times the sensitivity level for such data. For measurement number 13, when it is measured a crack based on the 3 ppt DC deviation, the surface resistance deviation is 22 ppt. The numerical values of the estimates for the last measurements are less reliable due to disturbance from the growing crack.

In the tests, the increased number of accumulated material deteriorations during cyclic loading was monitored and crack initiation was detected before any crack was visible. Fig. 13 shows that the development of the DC deviation which is directly proportional to the bulk resistance changes. As these data are related to the crack size growth, the crack size is calculated based on the estimated change of the bulk resistance.

Fig. 12. Deterioration in the surface

Fig. 13. Crack size growth.
Fig. 14 shows the bulk resistance deviation data for each of the pin pairs around the pipe. Pin pair 25 is at the 6 o’clock position where the initial crack started. The left plot show the deviation data for measurement number 15 when the initial crack first was visible. Related to the fact that the detection sensitivity is 0.5 ppt, the deviations for the pin pairs to the left of pin pair 25 are significant, and a secondary crack was later detected there. The plot on the right shows deviation data for the last measurement, and these data show that the crack length has increased. The algorithm for estimation of the crack size uses the pin pair data with maximum deviation together with adjacent pin pairs to estimate the maximum depth of the crack.

A picture of the fracture surface is shown in Fig. 15. Multiple initiation spots along the weld are apparent. The Initial Crack to the left is the primary crack. The crack to the right started to develop when the initial crack had reached a depth of approximately 10 mm. From the beach marks that are visible on the crack surface, and the observations of the surface length of the crack, the crack development is described in Table 2. The numbers based on observed crack dimensions are approximate. As shown in the table, the crack developed very rapidly after approximately 30 000 cycles. The apparent reason is that the secondary crack had started to develop, and coalesced with the initial crack.

<table>
<thead>
<tr>
<th>Measurement no.</th>
<th># Load cycles from 90 003</th>
<th>Estimate by tester</th>
<th>Measured Peak Deviation (ppt)</th>
<th>Measured DC deviation (ppt)</th>
<th>Estimated depth (mm)</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>11</td>
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<tr>
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<td>--</td>
<td>10</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

Fig. 14. DC deviation for all pin pairs around the circumference. Pin pair 25 is at 6 o’clock. The x-axis shows pin pair no., the y-axis shows the deviation in ppt/1000.

Fig. 15. Photo of the cracked surface.
Table 2. Crack growth related to number of load cycles from cycle 90 003 in Phase 2.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Load Cycles</th>
<th>Crack Length</th>
<th>Crack Depth</th>
<th>Deviation</th>
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<tr>
<td>13</td>
<td>10 000</td>
<td>0</td>
<td>--</td>
<td>33</td>
<td>3</td>
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<tr>
<td>14</td>
<td>16 399</td>
<td>0</td>
<td>--</td>
<td>54</td>
<td>10</td>
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<tr>
<td>15</td>
<td>18 280</td>
<td>25</td>
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<td>66</td>
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<tr>
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<td>415</td>
<td>672</td>
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</table>

In Table 2 observations and measurement results for Phase 2 are presented. Measurement deviation data is relative to the first measurement after Phase 1 and Phase 2 shake down bending and taken at no stress. The crack’s length and depth were observed by the operator running the test. The lengths were observed during the test and the depth was based on the beach marks on the cracked surface. The measured deviation values are for pin pair 25 at the 6 o’clock position. The peak deviations are deviations between the peak values of the transients and have the highest sensitivity for early degradation in the surface. Crack depth estimates are based on DC deviation values.

Conclusion
A method is described that detects crack formation potential in material prior to the appearance of cracks. The method uses a combination of
- Transient potential drop
- Changes in magnetic permeability
- Changes in electrical resistance
at different depths in a material. Measurements at multiple locations within a monitored area and different points in time result in a mapping of changes which can be interpreted as changes in material properties due to early degradation.

The theoretical basis and how changes of the electromagnetic properties relate to material degradation and fatigue have been described. These capabilities have been demonstrated by monitoring material degradation prior to crack, and also crack growth during monitoring a high cycle fatigue test with riser pipe. A very sensitive, early detection of deterioration in pipe wall outer surface was validated during the fatigue test, and hence, the potential for detecting cracks prior to their appearance was confirmed.

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References


