Monitoring of Low Cycle Fatigue Damage with Eddy Current

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Abstract. Structural and technical components may experience high stress cycles beyond the yield stress during operation. Under extreme weather conditions components of offshore installations are subject to large displacement cycles with possibly high strain amplitude fatigue or low cycle fatigue, respectively. Another example is the operation of coiled tubing which goes through several plastic deformation cycles through its usage in and out of the wells so that it is subject to ultra low cycle fatigue.

Though, the fatigue life of the a.m. components can be assessed with special calculation methods, an additional monitoring of areas with stress concentrations (e.g. in the case of offshore structures) or an integral monitoring (e.g. in the case of coiled tubing) with a suitable non-destructive method would be beneficial for a safe operation.

In the framework of a feasibility study we performed basic investigations how eddy current is suitable for the detection of crack initiation and for monitoring the crack propagation and growth. Carbon steel plates (S355) were prepared with low cycle fatigue damage by cyclically bending in the low cycle fatigue regime. These samples were investigated at different degrees of fatigue with eddy current and magnetic particle inspection. Subsequently, these samples were tested destructively with tensile testing, Charpy impact testing and metallography. Thus, we could correlate the eddy current readings at different degrees of fatigue with the corresponding fatigue related degradation of the mechanical properties.

1. Introduction

Despite of a tremendous number of scientific studies in the field of fatigue mechanism, today’s dimensioning methods and technical regulations are not sufficient to eliminate any risk of fatigue damage [1]. Thus, monitoring of components which are subject to cyclic loading is important for a safe operation. This is all the more important the stronger the cyclic loading is. Under extreme conditions structural and technical components may experience high stress cycles even beyond the yield stress. This may happen accidentally when e.g. offshore structure are exposed to extreme weather conditions and are subject to large displacement cycles with possibly high strain amplitude or low cycle fatigue (LCF) respectively, where the numbers of cycles to fracture ranges from $10^2$ to $10^4$ [2]. Also intentionally, e.g. at the operation of coiled tubing which goes through several plastic deformation cycles through its usage in and out of a well, components may be subject to LCF. Coiled tubing is bended that strongly that it may be subject to extreme low cycle...
fatigue with numbers of cycles to fracture of $10^2$ and below. Though, the fatigue life of e.g. offshore components can be assessed with special calculation methods [3], a monitoring of areas with stress concentrations like nodes or an integral monitoring in the case of coiled tubing with a suitable non-destructive method for crack detection and sizing would however be beneficial for a safe operation.

In principle, eddy current suggests itself for this task. Aim of our investigations was to test if a conventional eddy current approach, i.e. using notches of different depths as reference features, is suitable for a monitoring / sizing of LCF cracks. The feasibility of this approach depends very much on the dimensions of the initial fatigue cracks and the further development of these cracks w.r.t. density, propagation and coalescence. If the frequency of the crack coalescence is rather small, a generation of few dominating cracks is less likely than at a high frequency. In the first case the conventional approach might not be suitable in the second case it should work. Furthermore, the eddy current system should detect cracks as early as possible. As benchmark how early a detection is possible we chose the magnetic particle inspection (MPI) method for comparison.

Using flat steel bars, samples with cracks as realistic as possible were prepared by cyclically bended in the low cycle fatigue regime. These samples were then investigated at different degrees of fatigue first with magnetic particle inspection to have a reference for the earliest point of crack formation and then with eddy current. Beyond a degradation caused by cracks, at low cycle fatigue also a degradation of the mechanical properties may occur. In [4] it is stated that at the use of coiled tubing even after a few cycles, the bending and straightening of the tube leads to a loss of yield strength caused by the Bauschinger Effect, i.e. the decrease of the technical elastic limit after an initial plastic deformation and a subsequent deformation in opposite direction [5]. To correlate the eddy current readings at different degrees of fatigue with the corresponding fatigue related degradation of the mechanical properties the samples were tested finally also destructively with tensile testing, Charpy impact testing and metallography.

2. Experiments

2.1 Sample preparation

The tested flat bar samples had dimensions of 50 mm x 5 mm and were of steel grade S355J2+M according to EN10025-2. The bending tests were carried out with a fatigue testing machine Zwick Roell Amsler HB 250. To realize a bending load, the sample was fixed into a special device with a circular shaped element on top corresponding the bending radius to be applied on the sample, see fig. 1. The samples were bended by ca. 3% (outer fiber referred to the neutral fiber) in one direction and then moved back to the starting position each. The maximum deflection amplitude was constant for all cycles.
A set of 3 samples each was bended with a certain number of cycles. The first set was bended with 15 cycles, followed by 50 cycles and then continuing by increments of 50 cycles until reaching the number of cycles to fracture. Out of the same material (batch) samples with 1mm and 2mm deep eroded notches as reference feature were prepared.

2.2 Investigations of prepared samples

First, the bended plates were all tested with magnetic particle inspection as reference for crack initiation and for visualization of all emerged cracks. Both, the top side, i.e. the side with the concave bending, and the bottom side were tested. Then the investigations with eddy current testing followed. As the magnetic permeability of ferromagnetic materials limits the depth of penetration of induced eddy current and the permeability variations inherent in those materials often cause anomalous test result it was decided to work with magnetic saturation. Applying this technique, the magnetic characteristics of permeability, hysteresis, etc. is suppressed, so that the material under examination is effectively rendered nonmagnetic [6]. For the tests a eddy current probe with 8mm coil diameter and an excitation frequency of 500kHz was chosen. The samples were scanned along the centre lines with a sampling rate of 1mm each while the samples were magnetized with an electro yoke, see fig. 2. The plates with the reference notches were scanned correspondingly. Both the samples and the reference plates were scanned along the top and the bottom side.
For the mechanical investigations sections with the originated cracks in the centre were cut out of the plates: dog bone samples for tensile test, V-notched samples for Charpy testing and a further samples for metallography, see fig. 3.

3. Results and Discussion

3.1 Non-destructive testing

The first crack indications with MPI were observed on the top side at the samples with 150 cycles. The crack indications were very fine, short and densely arranged (> 50 / cm²). At the bottom side no MPI indication were detected. With increasing number of cycles the density of cracks did not increase whereupon the existing cracks grew in length or by coalescence correspondingly. Furthermore, the longest cracks showed the strongest MPI indications which advert to a growth into depth. In particular at all samples with 250 cycles and 300 cycles, one dominating strong crack was observed having a minimum length of 10 mm each. Fig. 4 shows this development. Altogether, at the bottom side a similar MPI indication pattern was observed as on the top side, however with a delay of 50 cycles.
For the eddy current testing, initially the phase angle was adjusted in such a way that lift-off changes deflected in x-direction (channel 1) in the impedance plane. Reference measurements were then performed at the 1 and 2 mm deep notches. Fig. 5 shows the notch signals in the impedance plane representation when moving across the notches, which deflect mainly in y-direction (channel 2). Additionally, in fig 6 (left) the signal sequence of the crack sensitive channel (channel 2) is plotted versus distance when moving across the notches. The scans of the opposite (bottom) side of the notches showed no eddy current signals due to the insufficient penetration depth.

Both, top and bottom of the fatigued samples were then tested with this instrument setting. In the following only the results of the top side are presented. In fig. 6 (right) the signal sequence of channel 2 versus distance when moving across the complete crack area of the samples with 150, 200, 250 and 300 cycles are shown. Though, at 150 cycles a weak eddy current signals appears, the detection limit is rather at 200 cycles. Above the plots in fig. 6, photos of the 2mm notch and of a sample with 300 cycles after MPI are shown on the same scale.
Fig. 6. Left: Signal sequences of the crack sensitive channel 2 when moving across the reference notches. Above the plot a photo of the 2mm notch is shown. Right: Signal sequences of channel 2 when moving across the cracks. Above the plot the crack field after 300 cycles is shown. The crack field is encircled.

From the left plot in fig. 6 the effective signal width of the sensor as defined in [7], i.e. the full width half maximum of the signal sequence at the movement across a notch, can be determined. It is ca. 8mm, which corresponds with the coil diameter of the eddy current probe. Looking at the signal sequences when moving the sensor across the crack fields of the LCF cracks, at the samples with 150 and 200 cycles similar full widths half maxima of the signals are observed reasoning that the signal is mainly caused by one single deep crack. This confirms the observations of the MPI testing. At the samples with 250 and 300 cycles the corresponding values are a few millimetre larger, obviously due to the influence of small adjacent cracks which have grown also slightly. However, also in these cases one single prominent crack dominates the signal sequence and the maximum of it can be assigned clearly to this crack.

Fig. 7 shows furthermore that also w.r.t. the phase angle the cracks are comparable with the reference notches. The signal of the 1 mm notch matches best with the deepest crack of the samples with 250 cycles and the 2mm notch with the one with 300 cycles. According to these results the deepest crack after 250 cycles should be between 1 and 2 mm and the deepest crack after 300 cycles a bit below 2mm deep.

Fig. 7. Impedance plane presentation of crack signals compared with notch signals.
Altogether, these results show that in this case eddy current testing with a conventional notch based evaluation is an adequate approach for crack detection and monitoring.

3.2 Destructive Testing

Consistent with the non-destructive testing results also at the metallographic inspection the dominance of few individual cracks is observed. Fig. 8 and 9 show an overview of digitally merged pictures out of 24 individual cross-section polished pictures along the crack field each. Furthermore, the maximum depths of the cracks visible in the pictures are in agreement with the above estimated depth sizing results from the eddy current probe.

![Fig. 8](cross-section.png)

**Fig. 8.** Cross section of a samples after 250 cycles (merged out of 24 pictures). Only cracks at the top side were measured.

![Fig. 9](cross-section.png)

**Fig. 9.** Cross section of a samples after 300 cycles (merged out of 24 pictures). At the top side one dominant crack with a large opening is observed. Cracks at the bottom side were also measured.

At the mechanical tests the most striking observation is a decrease of the yield strength starting at the first few cycles until 50 cycles, which is a known phenomenon (Bauschinger effect) and e.g. considered in the recommended practice for care, maintenance and inspection of coiled tubular product [4].

At those samples where the first cracks appear (150 cycles) the effective cross section is reduced. The cross section decreases further with increasing number of cycles, see fig. 8 and 9. Correspondingly, a continuous decrease of the tensile strength and the Charpy toughness respectively is observed from 150 cycles until break, see fig. 10.

![Fig. 10](mechanical.png)

**Fig. 10.** Mechanical testing results at different numbers of cycles
Apart from the early decrease of the yield strength, basically the destructive testing results are consistent with the results of the non-destructive investigations, i.e. a decrease of the corresponding characteristic values starts when the first cracks are detected non-destructively. The detection of material degradation w.r.t. yield strength is indeed beyond the capability of the tested eddy current system which was construed for crack detection and sizing.

4. Summary

We investigated the capability of eddy current testing for monitoring of low cycle fatigue (LCF) cracks. Flat steel bars were bended in the LCF regime to obtain samples with LCF cracks. In addition to eddy current testing the investigations included also magnetic particle inspection (MPI), mechanical tests and metallography. A set of 3 plates were bended up to a certain number of cycles (first with 15 and 50 cycles followed by increments of 50 cycles) and then tested each. The respond thresholds of the different testing methods, i.e. the number of cycles at which a significant change compared to an unfatigued sample was observed, is summarized in table 1 for the different investigation technologies.

<table>
<thead>
<tr>
<th>Tab. 1. Comparison of the respond thresholds of all tested measuring methods in dependence of the number of cycles</th>
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<tr>
<td>Number of cycles</td>
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<tr>
<td>Magnetic particle inspection</td>
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<tr>
<td>Eddy current</td>
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<tr>
<td>Yield strength</td>
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<tr>
<td>Tensile strength</td>
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<td>Toughness (Charpy)</td>
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Apart from the yield strength which shows a special behaviour and decreases already after a few cycles (Bauschinger effect) and then remains after 100 cycles on a constant level until fracture, all other methods respond more or less simultaneously at 150 or 200 cycles corresponding the detection of the first cracks with MPI. Furthermore, from that number on, a continuous worsening of tensile strength and toughness and a continuous increase of signal strength or amplitude of the non-destructive methods is observed. Eddy current responds with a delay of 50 cycles compared to MPI. This is ca. 150 cycles before break and still considered to be sensitive enough for an early crack detection.

In particular, it could be demonstrated, that the conventional eddy current approach which we tested here, i.e. applying reference measurements at notches for depth sizing, was feasible for monitoring of LCF cracks at the prepared samples. This was possible because with increasing number of cycles individual deep cracks developed by coalescence from initially originated densely arranged small cracks.
5. References


[4] API 5C8, Recommended Practice for Care, Maintenance and Inspection of Coiled Tubular Product, Nov. 2004

