LABORATORY EXPERIMENTS FOR ASSESSING THE DETECTABILITY OF SPECIFIC DEFECTS BY ACOUSTIC EMISSION TESTING

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Abstract

For acoustic emission (AE) testing of pressure vessels during in-service inspection, special experiments must be performed to get the appropriate information in some cases. Design of such experiments, especially the loading history, is the focus of this paper. Limitations on the experimental load history, which result from the Kaiser-effect and the goal of the test, are given. Another important point is the generation of an appropriate defect. An example with an initial artificial weld defect and defect growth by pressure cycling is given. The measured low AE activity during this test shows that experimental verification for AE testing may be necessary, even if standard procedures are used.

Introduction

In the last decades acoustic emission (AE) testing was developed further [1], and many dangerous defects were found [e.g., 2-4], and probably accidents have been prevented. Frequently, economic reasons are the determining factor of whether or not AE testing is used during in-service inspection. To get an optimum on safety, the question whether or not defects and failure modes, which are probable in the specific case, can be detected by AE testing should dominate the decision. Of course, AE is an integral testing method and able to detect unforeseeable defects, which is a favorable property for inspection strategy.

Finding experimental evidence that a specific type of defect is detectable is difficult. One of the reasons why the transfer of results from experiments to AE testing is difficult is the complicated load history, which is applied to pressure vessels prior to AE testing. Therefore, this paper focuses on experimental loading histories for studying the AE characteristics of defects during AE testing of pressure vessels.

Here, AE testing during in-service inspection, not during pressure testing after fabrication, is mainly considered. The focus lies on local defects, like welding defects, cracks, pitting, etc., and global wall thinning and design failures are outside of the scope of this paper.

Loading History

Loading histories of pressure vessels (Fig. 1) start with the pressure tests after fabrication. AE testing during the first pressure test is not the focus of this paper. During service, the vessel is usually pressurized with more or less pressure variations, but pressure has to be below maximum allowable pressure $p_S$, which is the relief pressure of the safety valve. Because of limited tightness of safety valves near the relief pressure, operating pressures are usually below $p_S$. When the safety valve opens, according to the European Pressure Equipment Directive (PED), the pressure...
is allowed to exceed $p_s$ by 10%. For AE testing the pressure should be raised to a value higher than the maximum value reached during the operating period before the test, but the maximum pressure of the first pressure test is usually not exceeded.

Initial defects may be present after fabrication. If they are not detected before the vessel goes into service, they may grow during the service period. Other defects may be initiated and grow during service. The goal of the in-service inspection is to detect all dangerous defects before they lead to catastrophic failure.

![Fig. 1. Typical loading history of pressure vessel; $p$, pressure; $p_s$, maximum allowable pressure; $p_{test}$, test pressure; $p_{AE}$, maximum pressure at AE testing.](image)

**Plastic Deformation**

For the AE generation, plastic deformation is important. First yielding produces AE itself, and the resulting large deformations activate many secondary AE sources. To see the possible plastic deformations of vessels, in [5] a finite-element (FE) simulation was performed for an example vessel HSD01 (Fig. 2a). For this vessel, stress-strain curves for the base materials as well as for the welding materials were available because it was investigated during a European research project. It is a vessel made of high strength steel, and for the allowable pressure, the largest allowable one was evaluated. For details about the analysis see [5].

At the beginning of the simulation, some artificial shrinkage was introduced into the welding material to simulate residual stresses from the welding process. Afterwards the first pressure test up to the test pressure $p_{test} = 419$ bar (Fig. 2b 1-2) was simulated. The simulation continued with one operating cycle up to $p_s = 293$ bar (Fig. 2b 4-5) and a second pressure test (Fig. 2b 6). After reaching the maximum pressure of the pressure test the pressure was further increased to 486 bar (Fig. 2b 7). Figure 2c shows the von Mises equivalent stress vs. the circumferential strain at the Point A (Fig. 2a): Due to shrinkage of weld material, large stresses and some initial strain are present at the beginning (Fig. 2c 1). At the first pressurization, plastic deformation starts at the beginning (Fig. 2c 1-2). During unloading and the operating cycle, practically no plastic strain is accumulated (Fig. 2c 2-5). Also in the second pressure test, almost no plastic deformation occurs, as long as the maximum pressure of the first pressure test is not exceeded (Fig. 2c 5-6). Only if
the maximum pressure of the first pressure test is exceeded plastic deformation starts again (Fig. 2c 6-7).

Due to yielding the residual stresses are changed in a way that the subsequent unloading and reloading can take place without (or with very small) plastic deformation. Exceeding the first maximum pressure leads to considerable new plastic deformations. Like plastic deformation, AE activity is totally different whether or not the first load limit is exceeded (Kaiser effect - compare to Fig. 6). This has to be considered when specifying the loading history for verification experiments.

**Experimental Load History**

When designing experiments for studying AE testing, one has to consider that during AE testing for in-service inspection the maximum loading of the first pressure test is usually not exceeded. Only the maximum of the operating load, at which defect initiation and/or growth took place, should be exceeded during the AE testing.

![Diagram](image)

**Fig. 2.** Example HSD01, plastic strain in spherical vessel with residual stress [5]; a) FE model with point A shown, b) simulated cycles; c) circumferential strain vs. von Mises equivalent stress at point A.
Therefore, for finding an appropriate experimental loading history, the following procedure (Fig. 3) is proposed:
At first a load $L_S$, which corresponds to the load of the vessel at the maximum admissible pressure $p_S$, has to be specified. This can be a pressure, if a vessel is tested, or a force resulting in an appropriate stress level, if simple tension specimens are used. At this point the usual safety factors in pressure vessel design have to be considered (usually a safety factor of at least 1.5 to the appropriate proof or yield stress is applied at operating conditions). Starting from this load the following procedure can be applied:

a) If an initial defect from fabrication should be simulated, a sample with an initial defect can be used, or an initial defect can be introduced at the beginning (Defect introduction 1 at Fig. 3).

b) The test itself should start with a loading cycle, which simulates the first pressure test. The appropriate load $L_{test}$ can be evaluated by multiplying the load corresponding to $p_S$ ($L_S$) with the appropriate pressure test factor.

c) After this loading cycle, an optional reference cycle up to the load $L_{test}$ can be applied. This cycle gives some reference for the AE of the sample without defect or with the initial defect after the first pressure test.

d) If defect initiation during operation should be simulated, a defect can be introduced after the first pressure test (Defect introduction 2 at Fig. 3).

e) Now load variations should be applied. In this phase, the load has to be smaller than the maximum load, which will be reached at the vessel during operation. At least a few load cycles up to the maximum load, which can be reached at this phase, should be applied. Simulating defect growth by the investigated mechanism (fatigue, corrosion, etc.) would be optimal in this phase.

f) Now a loading cycle simulating the AE test can be applied. Here, it is clear that the load should only be increased up to a value $L_{AE}$ reached during the planned test. If the load is raised to a larger value, may be up to burst or fracture, AE above the load $L_{AE}$ would not arise at a comparable AE test. At least AE above the load $L_{test}$ is not comparable to AE during AE testing during in-service inspection.

g) Simulation of further defect growth and further AE tests are of course possible.

**Fatigue Cracks Starting from an Artificial Notch as Examples of Defects**

Saw cuts (Fig. 4a), which cause U-shaped notches, have been used in connection with gas cylinders made of high strength steel [5, 7]. These U-shaped notches cause fatigue cracks growing from both sides of the notch into the ligament. Frequently during crack opening, shear cracks are formed, which connect these two cracks. Increased friction at the crack surface may result.

V-shaped notches (Fig. 4b) cause crack initiation nearly in one plane, but the fabrication may be more complicated.

Introduction of welding defects in a defined way is difficult. In [6] a special procedure was used (Fig. 5c) to introduce a welding defect inside of an existing vessel. Here a notch was cut through the whole wall thickness. Afterwards a strip was pressed into the bottom of the notch. Onto this strip the weld was placed. The resulting crack-like notches are somewhat similar to welding defects like lack of fusion at the weld root.

The introduced notches have to be relatively deep to get fatigue crack growth within a practicable number of cycles, and with the usual nominal stresses in pressure vessels. Notches of 1/3 to 1/2 of the wall thickness in connection with cycle numbers of 10,000 full pressure cycles may be
Fig. 3. Load history for experimental testing; \(L_S\), load according to load at allowable pressure, \(L_{\text{test}}\), load according to load at pressure test.

Fig. 4. Examples of artificial defects: a) saw cut (U-notch), b) V-notch, c) artificial weld defect.

necessary. Careful monitoring of defect growth during cycling is needed to do the AE tests at appropriate time. In [6] online crack growth measurement based on strain gauge measurements was used.

The pressure cycling with pressure variations as large as possible and with the large defects (both necessary to get crack initiation and growth with a practicable number of cycles) causes large cyclic plastic deformation in the ligament, which causes brittle material components to break. Therefore, AE activity during pressure tests after this cycling may be low. This was seen in a test with a defect in ferritic weld material as described in the following:

**Example**

Within the following experiment [6] an old vessel ST6599 (Fig. 5a) was tested by means of pressure tests and cyclic pressurization. The vessel was made of St41KT (0.17%C, 0.018%P, 0.022%S), a material according to ÖNORM M3121. This material corresponds to P265GH of EN 10028-2. The vessel diameter was 800 mm and the wall thickness 15 mm.

As an initial defect, before the first pressure test, an artificial weld defect of the type given in Fig. 4c was introduced on the vessel. Therefore, a saw cut was introduced in the original longitudinal weld, a steel strip was placed into this cut, and the weld was placed on the strip (Fig. 5b). For reference, a second weld with the intention of having no defect (marked “New Weld” in Fig 5a) was placed on the vessel. In this case only a V-notch, which partially penetrated the wall thickness was introduced and filled up by welding.
The testing procedure started with a pressure test, consisting of three pressure cycles (Fig. 6) up to a pressure of 1.43pS (pS = 32 bar). After the pressure test, the vessel was cycled with sinusoidal pressure variation between 2 bar and pS until crack initiation was indicated (strain gauge measurements). Afterwards a pressure test and the next cycling followed. The procedure was repeated until the vessel failed at the 6th pressure test through leakage at the artificial weld defect (Table 1).

AE was measured with 5 SE150 sensors with a resonance frequency of 150 kHz and threshold settings between 31.2 and 35 dB$_{AE}$ (Table 2) were used. A 0.5-mm pencil-lead break results in an AE event of about 84 dB$_{AE}$ at 30 cm distance (distance of the artificial weld defect to the first hit sensor). Strain gauges were used for online crack growth detection (Fig. 5a). The indication was based on stiffness changes.

The micrograph (cross section a short distance from the leak) of the defect after the test (Fig. 7a) shows the crack starting at one side of the steel strip, almost in a single plane, and clear crack blunting at the 5th and 6th pressure tests. At the fracture surface (Fig. 7b) at least the crack tip at the last three pressure tests can clearly be seen.

a)

![Figure 5a: Test vessel with artificial weld defect](image)

b)

![Figure 5b: Artificial weld defect](image)

Fig. 5. Experiment ST6599 [6]: a) Test vessel, b) sketch of artificial weld defect,
Table 1: Experimental procedure.

<table>
<thead>
<tr>
<th>Experimental Step</th>
<th>Pressure</th>
<th>Cycles</th>
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<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; pressure test</td>
<td>$p_t = 45.8$ bar</td>
<td>3 Cycles</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; cyclic pressurisation</td>
<td>2 – 30 bar</td>
<td>5064 cycles</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; pressure test</td>
<td>$p_t = 45.8$ bar</td>
<td>3 Cycles</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; cyclic pressurisation</td>
<td>2 – 30 bar</td>
<td>4397 cycles</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; pressure test</td>
<td>$p_t = 45.8$ bar</td>
<td>3 Cycles</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; cyclic pressurisation</td>
<td>2 – 30 bar</td>
<td>1850 cycles</td>
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<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; pressure test</td>
<td>$p_t = 45.8$ bar</td>
<td>3 Cycles</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; cyclic pressurisation</td>
<td>2 – 30 bar</td>
<td>1222 cycles</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; pressure test</td>
<td>$p_t = 45.8$ bar</td>
<td>3 Cycles</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; cyclic pressurisation</td>
<td>2 – 30 bar</td>
<td>809 cycles</td>
</tr>
<tr>
<td>6&lt;sup&gt;th&lt;/sup&gt; pressure test</td>
<td>Leakage at 39.9 bar</td>
<td>Leakage at first pressurization</td>
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Table 2: Threshold settings.

<table>
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<tr>
<th></th>
<th>Threshold [dB]</th>
<th>Waveform recorded for $A &gt; [dB]$</th>
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<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; pressure test until 8 bar</td>
<td>31.2</td>
<td>43</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; pressure test after 8 bar</td>
<td>35.6</td>
<td>49.8</td>
</tr>
<tr>
<td>Cyclic pressurisation</td>
<td>35.6</td>
<td>49.8</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; pressure test</td>
<td>31.2</td>
<td>49.8</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; to 5&lt;sup&gt;th&lt;/sup&gt; pressure test</td>
<td>31.2</td>
<td>33.7</td>
</tr>
<tr>
<td>6&lt;sup&gt;th&lt;/sup&gt; pressure test</td>
<td>31.2</td>
<td>31.2</td>
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</table>

During the pressure tests and cycling considerable acoustic emission activity was acquired from the investigated weld defect, the “New Weld” and from a position called “Circumferential weld defect” (Fig. 5a). With radiography in the “New Weld” and “Circumferential weld defect” also considerable defects were found. Micrographs at the locations with the largest indications showed insufficient penetration at “Circumferential weld defect” and bad bounding at “New Weld”. Details of this can be found in [6]; here only signals from the investigated weld defect are further discussed:
The most important phase during AE examination is the phase of increasing pressure, including the hold periods, of the first pressure cycle of a pressure test – this is the period from start of the pressure test until start of pressure release. For this phase of the pressure tests 1 – 6, the numbers of AE events within the investigated region, i.e. the longitudinal weld defect, are given in Table 3. For comparison also the sum for the whole vessel is given. Figure 8 summarises the acquired events from the investigated defect during the last pressure test until leakage.

Description of the values in Table 3:

≥80 dB, located: Here the number of located events with amplitudes larger than 80 dB at the first hit sensor is given. The numbers of events that are located within the considered regions are given. Hsu-Nielson sources (0.5 mm) at the investigated regions reach at the first hit sensor amplitudes between 80 and 85 dB, therefore, amplitudes larger than 80 dB have intensities similar or larger than the Hsu-Nielson source (0.5 mm).

60 dB, located: Here the number of located events with amplitudes larger than 60 dB at the first hit sensor are given. The amplitude of 60 dB is 20 dB smaller than the one reached by Hsu-
Nielson sources. Above this amplitude, with the arrangement used, location processing with good reliability is possible.

**TR-page available:** Here the number of events is given for which at least for the 1st hit sensor the waveform data was acquired. Only the events, which are assigned to the considered region according to the channel sequence criteria, are considered. This number is important for further evaluation, because more sophisticated data evaluation is only possible if the waveform is acquired.

**40 dB, according to channel sequence:** Here the number of events is given which reach at the 1st hit sensor an amplitude of 40 dB. Only the events, which are assigned to the considered region according to the channel sequence criteria, are considered here. The considered amplitude of 40 dB is about 40 dB smaller than the one which would be reached by the Hsu-Nielson source (0.5 mm).

Table 3: Pressure tests 1 - 6, first pressure cycle, increasing pressure: Number of events at the considered regions.

<table>
<thead>
<tr>
<th></th>
<th>At whole vessel</th>
<th></th>
<th>Longitudinal weld defect</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>&gt;=80db, located</td>
<td>=60db, located</td>
<td>TR-Pages available</td>
<td>&gt;=40db, all events</td>
</tr>
<tr>
<td>1. PT</td>
<td>3</td>
<td>383</td>
<td>5300</td>
<td>19900</td>
</tr>
<tr>
<td>2. PT</td>
<td>0</td>
<td>6</td>
<td>25</td>
<td>73</td>
</tr>
<tr>
<td>3. PT</td>
<td>0</td>
<td>3</td>
<td>143</td>
<td>54</td>
</tr>
<tr>
<td>4. PT</td>
<td>1</td>
<td>2</td>
<td>92</td>
<td>36</td>
</tr>
<tr>
<td>5. PT</td>
<td>0</td>
<td>2</td>
<td>115</td>
<td>37</td>
</tr>
<tr>
<td>6. PT</td>
<td>0</td>
<td>2</td>
<td>111</td>
<td>47</td>
</tr>
</tbody>
</table>

Fig. 8: Longitudinal weld defect; 6th pressure test; channel sequence filter at the top; location filter at the bottom.
During the first pressure test, large AE activity was measured. The acoustic emission during the pressure tests two to six can be characterised in the following way: There were very few signals with large amplitudes. Only at the 4th pressure test, in the region of the longitudinal weld defect, one event with amplitude near to the one of a pencil lead break was acquired. In two pressure tests, in the region of the longitudinal weld defect, no events with amplitudes larger than 60 dB were acquired. When considering low amplitude signals the activity decreased until the 4th pressure test, and increased in the 5th and the 6th pressure test again. This increase of the activity with low amplitudes correlates with crack propagation at these last two pressure tests.

For the base material, comparable small AE activities can also be found in the literature [e.g. 8]. Here the weld material, which forms the ligament for the considered crack, has a fine-grained microstructure (Fig. 7 c and d), which may be one of the reasons for the small AE activity.

The applied procedure may possibly not detect the applied type of fatigue crack (pure fatigue, without corrosion) in weld metal of low carbon steel. Most pressure vessels have only a small number of fatigue cycles and failure modes due to corrosion and interaction between corrosion and mechanical action dominate. When doing experimental verification for AE testing, which focuses on theses failure modes, the corrosion effects have to be included in the experimental testing.

Conclusion

Limitations on the loading history for experiments in connection with AE testing were demonstrated. One experiment following the guidelines was conducted with an initial artificial weld defect in connection with fatigue crack growth. AE activity during the simulated AE tests was small. This shows that standard procedures of AE testing are not always appropriate. Analysis of probable defects and the possibility to detect these defects by AE testing is necessary. For some types of defects experimental verification is necessary. In the experiments the investigated defects have to be reconstructed in a proper way. Using fatigue cracks instead of cracks from stress corrosion or corrosion fatigue interaction may not be sufficient. Procedures of verification experiments, which include corrosion in an appropriate manner, are not established.

References