Defect Detection by Acoustic Emission Examination of Metallic Pressure Vessels

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Abstract

There are only relatively few publication which give hints to the questions, when acoustic emission examination should be applied and which defects can be detected? This paper addresses flaws, cracks, and crack-like defects in pressure vessels made of ductile steel. Mechanisms which enable defect detection are identified, and the characteristics of these mechanisms are described. Based on the identified mechanisms and their characteristics, examples of conditions which lead to good or bad ability of defect detection are given.

This could be the basis for a quantitative grading system for defect detection by acoustic emission examination. Such a scheme could be further developed for the evaluation of probabilities of detection (POD), which are necessary for quantifying the benefit of acoustic emission examinations in reliability analyses and risk based inspections.

Introduction

There are many standards dealing with acoustic emission examination of metallic pressure vessels, e.g. [1, 2]. In these standards, only very fuzzy answers are given to the question, which defects can be detected by acoustic emission examination. The problem that plastic deformation and crack growth in ductile pressure vessel steels may be only a weak acoustic emissions source [3, 4, 5, 6] leads to frequent discussions about the effectiveness of acoustic emission examination.

This paper concentrates on flaws, cracks, and crack-like defects in metallic pressure vessels. Because usually high ductility is required for pressure vessel steels, such defects in ductile steels (elongation after fracture A≥14% and Charpy-V-notch impact energy not less than 27 J) are considered here. Of course, material embrittlement in combination with the considered defects is possible.

To reduce the complexity of the problem, mechanisms which may activate acoustic emission sources during acoustic emission examination are classified according to the following criteria:

- Within one group of mechanisms the acoustic emission characteristics should be similar.
- Based on the known operating conditions of a vessel, it should be possible to decide whether or not a mechanisms is relevant for the considered vessel.
- The expected total acoustic emission is the sum of the acoustic emission from the different mechanisms.

One of the most important parameters is the loading at which the acoustic emission occurs. Because of the Kaiser effect, it has to be distinguished between first and subsequent loading. The loading at the defect is increased if the pressure is increased but also if the defect size is increased. As single loading parameter, which reflects both influences, the rate of the pressure to the burst pressure is used. The burst pressure is pressure when the considered defect fails by burst.

Description of the considered Flaws, cracks, and crack-like defects

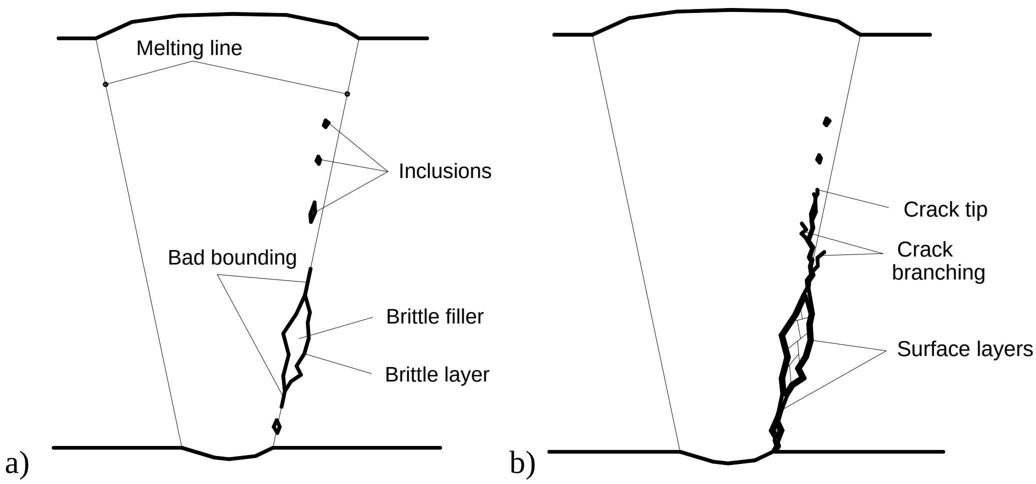

Figure 1: Weld flaw; a) initial flaw after welding; b) flaw after operating period

To show what defects may look like, a cross section of a flaw in a weld is sketched in Fig. 1. A flaw near to the melting line is shown. There may be slag or a brittle surface layer in the flaw. The flaw may end in a zone of badly bound material. Other smaller inclusions may be present. After a period of operation, at one side the connection of the flaw may be open to the surface of the vessel due to crack propagation. At the opposite side of the flaw, the badly bound material may be fractured, und crack initiation may have taken place. Due to deformation, brittle fillers (slag) and surface layers are broken. Also smaller brittle inclusions may be broken. If the flaw is open to the surface, the operating medium may penetrate into the flaw. Corrosion or other layers may be built at the crack or flaw surface. A combination of such flaws and cracks with material embrittlement is probable.

For situations similar to the one described, the following source mechanisms for acoustic emission activities are identified: Most of the described mechanisms can also arise in flows and cracks at the base material.

Plastic deformation of ductile material

Here, for the zone where the plastic deformation occurs, material with good quality (comparable to material of usual tension test samples) is considered. Material deficiencies, e.g. embrittlement and inclusions, are handled separately. Local plastic deformation of ductile pressure vessel steels may be a very weak acoustic emission source (see [4, 5]).
Large number of low amplitude signals are expected. At the first loading the acoustic emission activity will increase (Fig. 2) until cross section yielding, afterwards the activity will decrease. In the case of subsequent loading or loading of cold formed material, the activity will be very small.

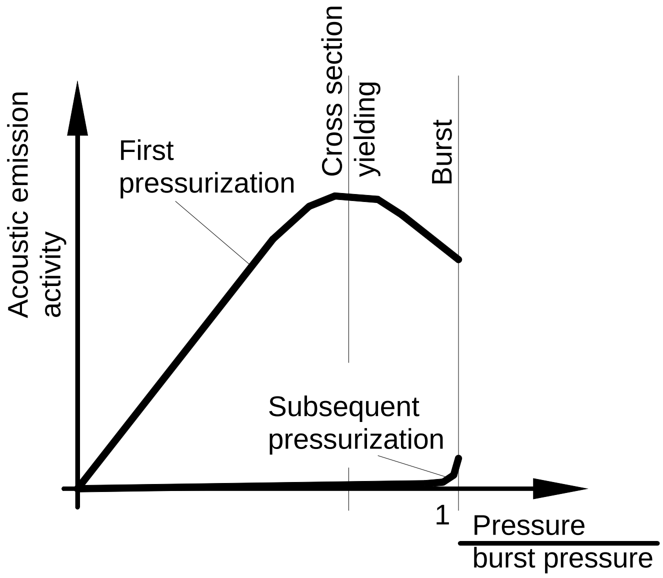

Figure 2: Activity due to plastic deformation of defect free material depending on the load level

Crack initiation or crack propagation in ductile material

Here for the material in the ligament, good quality (comparable to material of usual fracture mechanical test samples) is considered, material deficiencies are handled separately. Crack initiation and crack growth in ductile pressure vessel steel is dominated by the mechanism of void coalescence, which may be a very weak acoustic emission source [4, 6]. Acoustic emission may be expected from brittle microfracture events, which may take place, depending on the material quality and stress state, more or less frequently. Depending on the material, a small number of medium and high amplitude signals is to be expected.

Stable crack growth in ductile material takes place at relatively large loadings, after crack blunting and crack initiation [7, 8, 9]. Therefore, acoustic emission must be expected at the first loading at relatively high ratios of the loading to the limit load (Fig. 3). At subsequent loading stable crack growth may only be expected if the loading approaches to the maximum value of the previous loading. If the pressure of the actual pressure test is not larger than the one of a previous pressure test, a larger ratio of the pressure to the limit pressure can only be reached if the defect had grown during the operating period.

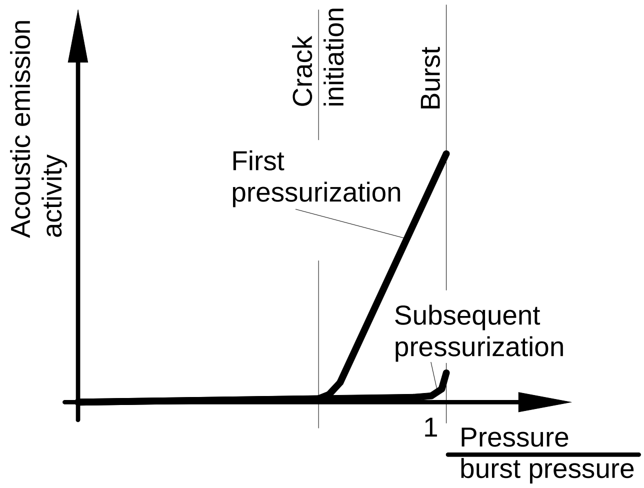

Figure 3: Activity due to stable crack growth in ductile material depending on the load level

Fracture, decohesion or friction of fabrication caused brittle fillers or layers, and opening of badly bound zones

In the case of fracture, decohesion or friction of fabrication caused brittle fillers or layers, and opening of badly bound zones, high amplitude signals can be expected [10], friction may cause low amplitude signals.

Fracture and decohesion of brittle fillers, layers and bad bounded zones takes place at relatively small loadings [10] (Fig. 4). Such inclusions and layers fracture only once, therefore, acoustic emission is expected mainly during the first loading, and for relatively small ratios of the loading to the limit load. Due to the small loading required for fracture, or decohesion of such fillers or layers, small defects can be detected.

Due to the fracture, such inclusion and layers may split into parts, which may be wedged together. During subsequent loading acoustic emission from friction at the contact surfaces of this parts can be expected. This activity will start with low amplitude signals at small loadings - signals which are caused by the usual friction of the defects surfaces. Because these fracture surfaces may be wedged together, burst signals due to release of wedged surfaces (Fig. 6) can be expected when the crack is opened. These burst signals may have larger amplitudes and this acoustic emission activity is increased, if the crack opening is increased. The activity stops when the crack is opened in a way that the fracture surfaces are not wedged together anymore.

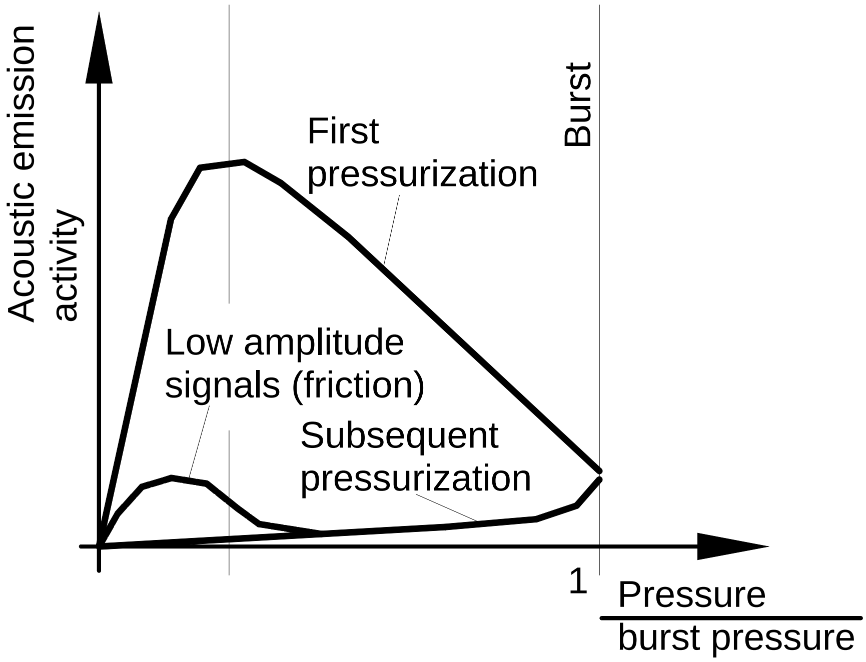

Figure 4: Activity due to fabrication caused brittle fillers, layers, and badly bound zones as function of the load level

Fracture, decohesion, or friction of inclusions in the ligament

The difference between brittle fillers at the flaw itself and smaller inclusions is mainly the size. Brittle fillers are at the main part of a flaw, inclusion may be present in the highly stressed ligament. Due to fracture of the material between inclusions larger flaws may be built.
The intensity of the acoustic emission sources depends mainly on the size and strength of the inclusion. Larger size and strength of inclusions leads to larger amplitudes.
The number of events correlates with the number of inclusions. If the density of inclusions is constant, the number of acoustic emission events is proportional to the volume of the (plastically) deformed material.
The loading and/or deformation, at which inclusions fracture, depends mainly on the strength and size of the inclusions. Inclusion with low strength may fracture before plastic deformation starts. The largest rate of acoustic emission events due to such events can be expected at the beginning of plastic deformation. Therefore a distribution of the acoustic emission signals over the loading similar to the one for plastic deformation is expected (Fig. 2).

Fracture, decohesion, or friction of layers and fillers built due to operation

Layers and fillers built during the operation period are different to the ones built during the fabrication process. Layers built due to operation are not present in the pressure test after fabrication, because they are built during the operation period. If the crack or flaw is open to the inside of the vessel, the operating medium can penetrate into the flaw or crack; if it is open to the outside surface, the environmental

air may penetrate into it. At flaws or cracks which are not open to the surface, such layers or fillers are not to be expected.
High amplitude signals can be expected, friction may cause low amplitude signals. These layers are built during operation and will be stress-free at the loading at which they are built. Below the loading at which they are built, they will be mainly in compression, resulting mainly in acoustic emission due to friction (Fig. 5). For loadings larger than the one at which these layers or fillers are built, fracture and decohesion of these layers and fillers may cause burst signals with large amplitudes. Subsequent loading will cause mainly acoustic emission due to friction. Such layers and fillers may fracture due to changes in the operating load, and, therefore, large variations of the operation pressure may decrease the acoustic emission in a pressure test.

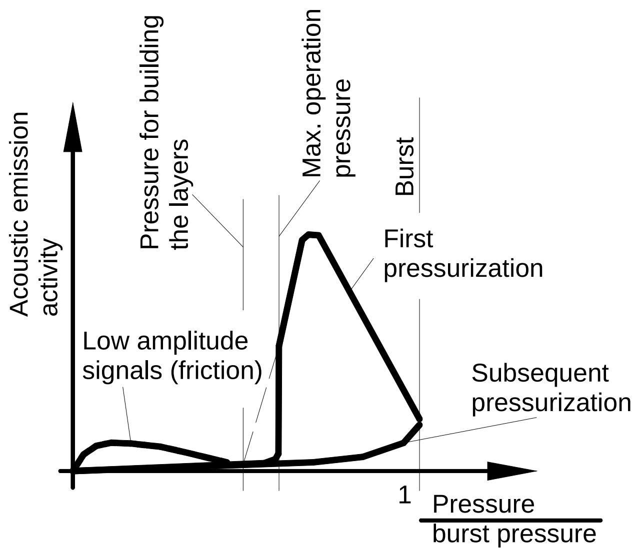

Figure 5: Activity due to operation caused brittle fillers and layers as function of the load level

Material embrittlement in ligament

Material embrittlement in the ligament will lead to an enhanced rate of brittle microfracture events at the crack front and at the ligament. High amplitude signals can be expected long before burst [11] especially if hydrogen embrittlement is included [12, 13].
If the concept of linear fracture mechanic applies also at the microscale, fracture at the microscale occurs if $K = K_c$. Following this concept, microfracture occurs mainly during the first loading. In subsequent loadings considerable acoustic emission can only be expected, if something has changed, e.g. further embrittlement, crack growth.

Friction at crack surface

Here friction at the crack surfaces without brittle layers or fillers is considered, e.g. fatigue cracks without any corrosion or other layers.
Low amplitude events may be expected at small loadings if crack surfaces lose contact. Larger amplitudes are expected when wedged connections (due to larger irregularities of the fracture surface of surfaces are released).
Typical small amplitude events from friction at the fracture surface will occur at small loadings. At larger loadings, when the crack opens, further events with larger amplitudes from the release of wedged connections (Fig. 6) may be expected. Such

events occur during the first as well as in subsequent loadings. Due to the decreased plastic deformations in subsequent loadings, the acoustic emission activity due to friction may also be decreased.

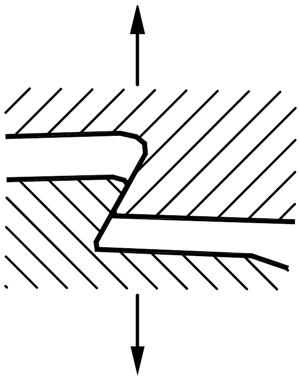

Figure 6: Release of wedged surfaces

Conclusions

From the different mechanisms for the detection of cracks and crack-like defects in ductile material by acoustic emission examination, it is obvious, that details of the defect are important for the detectability.

Some examples for good detectable defects:

- Flaws or badly bound regions caused by the welding process: They can best be detected during the first pressure test after the fabrication.
- Cracks or crack-like defects with layers and fillers built due to the operational environment, e.g. corrosion layers
- Cracks and crack-like defects which have their crack tip in material with insufficient ductility
- Cracks with irregular fracture surface, cracks with multiple branches

Conditions which lead to a small probability of detection of cracks and crack-like defects in ductile material:

- Ductile material with low probability of brittle microfracture in the ligament, e.g. low strength steel, base material
- Non-corrosive environment, or in corrosive environment which does not lead to corrosion layers or material embrittlement, e.g. acid corrosion
- Plane fracture surface and low surface roughness of the fracture surface, e.g. high cycle fatigue cracks, cracks which started from a single sharp notch.

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