Structural Integrity and Health Monitoring of Road and Railway Tanks based on Acoustic Emission

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Abstract: Development of corrosion or/and fatigue crack propagation are the most common causes of structural degradation in road and railway tank vessels. An acoustic emission based monitoring procedure in conjunction with follow-up non-destructive testing is here proposed as a promising alternative to the conventional inspection processes enabling continuous health monitoring of the tank structures. Thereby, finite element analysis taking the respective ADR and RID tank design loads into account is proposed as a capable tool to be applied in early stages of development to reveal the hot spot areas, where acoustic emission sensors have to be positioned. The developed health monitoring procedure is successfully validated on tank structures providing degradation in terms of natural and artificial corrosion and fatigue cracks. The results pinpoint the capability of acoustic emission testing to reliably detect and identify each individual degradation mechanism in early stages under operational loading conditions.

Keywords: Health Monitoring, Structural Integrity, Acoustic Emission, Tanks, Corrosion, Fatigue Cracks

1 Introduction

Fatigue crack growth and corrosion processes are the main causes leading to structural degradation and eventual breakdown of structures if no countermeasures are performed. Especially for surface transport products (road tankers, railway tank cars and ships) structural failure would yield damaging of the transport product, loss of goods and, in case of hazardous goods, environmental pollution or even threaten human lives. To prevent such incidents leading to diminishing of reputation and high costs structural inspection is necessary.

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International regulations such as ADR (2008) and RID (2011) combined with the European standards EN 13445 (2002), EN13094 (2008), EN 14286 (2007), BS PD 5500 (2011) point out preventative maintenance activities that have to be carried out on the basis of periodic inspections. For purposes of visual inspection and other Non-Destructive Testing (NDT) the transport means for cargo, such as crude oil and pressurized gases, have to be taken out of service.

The main disadvantages of the established inspection procedures are the large timeconsume, the high costs and their instantaneous nature, which means that certain risk of not detecting the onset of a defect still remains and the possibility of failure within the time period until the next inspection is apparent. According to Tscheliesnig (2010), an effective alternative to the current inspection process may be provided by the idea of continuous health monitoring of the transport tanks on the basis of acoustic emission testing (AT). Degradations in the components would be detected and analyzed as soon as they occur. Thereby an increased reliability combined with reduction of maintenance costs would be assured.

The present paper illustrates the basic principles of a continuous health monitoring concept for road and railway tanks based on AT. It allows the detection and identification of different degradation processes such as fatigue cracking or corrosion. For this, appropriate testing procedures have been developed within the framework of a European Project (CORFAT, FP7) and acoustic emission (AE) equipment has been adapted and redesigned for application in transport products, especially for those carrying dangerous goods (pressurized gases, fuel, crude oil etc.) or operating under hazardous environment. The paper shows and discusses the developed AT methodology including the prior steps required to facilitate the efficient application of the proper AE sensors to a given tank structure as well as the follow-up NDT to confirm the AT indications. Moreover, to validate its capability for detection of structure degradation, the proposed procedure is here applied on road and railway tanks providing corrosion and/or fatigue cracks subject to operational loads. The application of this methodology to ship structures is discussed by Jagenbrein, Baran, Nowak, Buglacki (2012).

2 State of the art on Acoustic Emission Testing

For various industrial applications, e.g. storage tanks for gaseous or liquid media, diverse pressure equipment, drying cylinders, chemical reactors, gas cylinder, AT is nowadays the standard non-destructive, non-invasive and integral testing method. Depending on measuring conditions, the structure and material of the test object and the inside medium (air, gas, water, oil, fuel) corrosion, fatigue cracking and/or leakage can be detected. By means of few sensors mounted regularly on the surface the whole structure can be covered during monitoring with AT (integral method),

while with other NDT methods, e.g. ultrasonic testing (UT), radiographic testing (RT), penetrate testing (PT), eddy current (ET) and magnetic powder testing (MT), only parts of a structure can be inspected (e.g. only line per line). In contrast to e.g. UT and RT (active emission of acoustic and electromagnetic waves, respectively), AT is a passive method, because of only "listening" into the structure without emitting any waves. Acoustic emission (AE) is a phenomenon whereby transient elastic waves in solid materials are generated when they undergo fast local stress changes, e.g. during plastic deformation, crack growth, corrosion, impact, friction, leakage etc. The standard EN1330-9 (2009) contains the principles of AT. Interested readers may find in the works of Miller and Hill (2005), Rogers (2001) and Ono (2011) valuable overviews on the AE principles. The work of Teti, Jemielniak, O'Donnel, Dornfeld (2010) and Grosse, Ohtsu (2010) provides an up-to-date comprehensive evaluation of advanced monitoring technologies focusing on AT and its future trends.

During AT monitoring existing defects have to be stimulated for excitation of AE waves due to e.g. application of load(s). Industrial devices are usually pressurized using often the regular working medium. Stressing of road and railway tanks in-service is caused e.g. during filling, discharging or driving/moving. Accordingly, these objects may permanently be monitored by AT during service conditions, when operational loads are applied to the structure.

The amplitude of an AE event is independent on the spatial extent of a defect or damage. In the case of degradation by e.g. crack growth, the wave amplitude (dynamic surface displacement) only depends on the material strength of the fracture on the level of microstructure, the velocity of the crack tip propagation and the corresponding area of the newly-created fracture surface. Baran, Nowak and Schmidt (2010) presented successful fatigue testing on ship materials by means of acoustic emission. Consequently, AT, as real-time method, always needs conditions of stress concentration that activate dynamic micro-processes. However, it gives usually no information about the shape or absolute size of emitting defects, e.g. lengths of flaws or residual wall thickness within corroded areas. Thus, follow-up NDT performed with e.g. UT, RT, PT, ET or MT for validation of indications found by AT is needed.

Theoretically, micro-fracture events are of high bandwidth up to the Megahertz or even Gigahertz frequency range. Usage of AE sensors with low eigenfrequencies for technical applications is necessary to detect AE sources over longer distances of wave propagation. On the other hand, low frequency sensors make the distinction of "false" indications (often noise events of low frequency) from "true" indications (crack growth or corrosion events with contents of high frequencies) more difficult. It should be considered that background noises are always apparent during service conditions, especially in the case of road and railway tanks. To be able to detect corrosion and fatigue cracking, high sensitivity (i.e. low detection threshold) of the acquisition system is necessary. Hence, that will rise the measuring of AE from service and environmental background (noise). In two-dimensional ("plate-like") structures acoustic waves propagate in the form of plate waves. They are detected using resonant piezoelectric sensors usually whereat acoustic waves stimulate electric burst signals in the piezo-crystal. Regarding the fact that frequency components higher than 300 kHz in steels are strongly attenuated, AE sensors are used with typical eigenfrequencies in the range of 70 kHz to 200 kHz. They are attached to the surface of the test object. A good and stable acoustic coupling by the use of grease and magnet holders must be ensured.

Wachsmuth, Malikoutsakis, Savaidis and Bohse (2012) studied the effects of fatigue loading and background noise under laboratory conditions. Welded metal plates providing both corrosion and fatigue cracks were tested under four-point cyclic bending. The obtained results showed that AE signals from different degradation mechanisms can be clearly identified and separated from the background test rig noises.

Moreover, AE measurements on tanks performed by Jagenbrein, Tscheliesnig, Wachsmuth and Bohse (2012) under operational load conditions proved that background noises occurring during different environmental and service conditions can be separated from ones resulting from structure degradation. For this, advanced software tools including pattern recognition for discrimination of real damage processes from background noise have been developed and presented by Vallen and Ruske (1998) and are continuously improved until today. They are based on the pattern recognition with respect to the waveforms of AE signals to define classes of signals. Relevant reference data of waveforms related to the different AE sources (fatigue cracking, corrosion and background noise) have been taking into account to build up a classifier.

The AE signals measured by the data acquisition system AMSY-5 developed by Vallen (2001) are analyzed and reduced to a set of features. Some essential features extracted from AE burst signals are the arrival time at the sensor, the maximum peak amplitude (in dB_{AE} = 20 log (U₁/U₀) with U₁ = actual signal voltage at preamplifier input and U₀ = 1 μ V = reference voltage for dB scale of AE amplitudes) and the signal energy. Notice that there are various approximations to calculate the AE burst signal energy; most frequently it is expressed in energy units (eu = 10⁻¹⁴ V²s) or Attojoule (1 aJ = 1.10¹⁸ J = 1.10¹⁵ V²s/kΩ). A set of external test parameters, e.g., load, deformation, temperature etc., can be recorded simultaneously and linked to the data set of each AE signal.

A suitable number of sensors with known positions together with determined arrival

times of burst signals and measured wave velocity are used for localization and clustering of AE sources. Acoustic waves are attenuated during travelling in the test object from source to sensor location. Therefore, only these source events are detected that still have amplitudes high enough to cross the set detection threshold (A_d) of the AE measuring system and generate so-called AE burst signals. For the evaluation of AE results a distance correction of burst signal amplitudes is a precondition. Re-calculation of first hit amplitudes at the location of source is done by means of measured attenuation curve and computed distance of the source from the closest, first hit sensor.

If a transient recorder module for storage of waveforms of AE signals is available, a spectral analysis in the frequency domain (FFT: Fast Fourier transformation) or frequency-time domain of signals (WT: wavelet transformation, STFFT: short-time FFT) of AE burst signals can be performed. Such advanced analyses are necessary for identification of source mechanisms led to the corresponding AE signals.

3 Procedure for AE health monitoring of road/rail tank cars

Based on series of successive theoretical investigations performed by Malikoutsakis, Savaidis and Savaidis (2011) regarding the determination of degradation hot spots of road tanks, laboratory tests performed by Wachsmuth and Bohse (2011) and Wachsmuth, Malikoutsakis, Savaidis, Savaidis and Bohse (2012), and tests on real tanks presented by Tscheliesnig (2012) and Jagenbrein, Tscheliesnig, Wachsmuth and Bohse (2012), a complete procedure for AE based health monitoring of road and railway tanks has been developed and proposed here. It contains the following basic tasks:

- Knowledge/determination of all potential degradation hot spots in the structure under investigation
- Application of AE sensors near the hot spots
- On-line structural health monitoring during operation
- Follow-up NDT in case of degradation indication during AT

The following subsections pinpoint the works and duties to be successively performed within the developed structural health monitoring procedure.

3.1 Hot spot determination for application of AE sensors

Often, hot spots of tank structures are well-known by experience gathered by similar tanks and/or similar operation fields.

In the very early stage of development of new tanks, it is helpful to evaluate hot spots by means of Finite Element (FE) analyses based on the technical drawings and manufacturing characteristics. To do this, knowledge of the operational loads and conditions of the tank is essential, to simulate its behaviour and allow previewing those locations more prone to damage. Precedence should be given to individual operational load and/or stress measurement data as far as they are available. However, to the authors' knowledge, such data are not reported in the literature. Wachsmuth, Malikoutsakis, Savaidis, Savaidis and Bohse (2012) showed that the design loads given in the ADR (same as the ones given in RID for railway tank cars) are capable to reveal hot spots in class 3 road tanks, i.e. the ones carrying dangerous goods.

3.2 Application of AE measuring equipment

The AE acquisition system is to be arranged at an appropriate location, e.g. in the driver's cabin of a truck. Cabling and sensors are to be installed to the outer face of the tank shell. Sensor arrays should include the specific hot spots in particular. The surfaces of the areas defined for mounting of the sensors must be cleaned. Secured paths for the cabling running from the mounted sensors to the location of the acquisition system are to be defined. Cabling is to be fixed e.g. by cable straps, adhesive tapes or other appropriate measures.

At this preparatory phase, it is necessary to ensure that all the accessories that could be connected to the tank will not interfere the measuring result. Cables from electric devices like instruments for metering, pneumatics and hydraulics for flow control, valves and actuators or handles, tools on the metering box of the tank, all this should be considered to not interfere with the measurements.

3.3 Check of AE measuring equipment and measuring chain

Standardised checking of the AE measuring system has to be done, e.g. with Hsu-Nielsen source (short HSU = pencil lead break). In addition automatic sensor test available at the acquisition systems can be used. HSU is a standardised source, see Fig. 1.

By means of the *Guidering* the pencil has to be contacted to the surface of the test object with the lead touching the surface. Light-hardened pencils of hard-grade 2H are to be used. Then, the lead has to be broken by tipping the pencil. So an acoustic wave is generated, which propagates in the wall and along the surface of the tested structure. Location results delivered by the measuring system are to be compared with the real position for checking.

These tests ensure that acoustic coupling of the sensors to the surface of the struc-



Figure 1: Hsu-Nielsen source (pencil lead break)

ture is well, cabling is configured in the correct way and the measuring chain is not interrupted. Additionally, the location process has to be checked by means of HSU carried out at specific locations at the structure, e.g. hot spots, welds.

3.4 AT of tanks – acquisition of AE signals, storage of data and localisation of AE sources (indications)

Tanks should be monitored by AT during various conditions, e.g. empty, filled, standing, moving, pressurized, non-pressurised. Thus, the measuring system is to be adapted with respect to the tank and the measuring conditions. Measuring conditions and relevant events are to be reported during monitoring for documentation. The measuring system is to be watched during monitoring by the operator, who may undertake appropriate adaptations and/or inform the owner/user, if necessary. Measuring data get stored automatically by the system and backed up. Locations of indications from AT should be validated by HSU and subsequently their positions should be marked at the surface of the structure for follow-up NDT. Notice that an additional task for the near future research activities is to store - besides the measuring data - warnings based on automatic online classification of data and submit them to the operator and/or owner.

3.5 Data analysis and evaluation of AT indications

In addition to standard displays for indications available at the screen of the measuring system, supplementary software tools and processes (e.g. filters) for further analysis can be used. The development of a classifier for measuring data based on pattern recognition has been initiated and successfully introduced by Vallen and Ruske (1998) and is since then in successful use in several applications. Different source mechanisms (e.g. corrosion, fatigue, background noise) originate dissimilar AE, i.e. correlated AE signals have differences in the energy and frequency distribution. By means of the software "VisualClass" developed by Vallen and Ruske (1998) special features are derived from the time-frequency-pattern of AE signals from known source mechanisms and used to train a classifier. A trained classifier is able to assign one of the trained source mechanisms to an AE signal of an unknown source mechanism. In this way, measuring data can be related to specific AE sources (corrosion, fatigue, background noise). The developed classifier has been used here for the experimental validation described in section 5.

3.6 Follow-up NDT and results evaluation

AT results obtained during monitoring of a structure yield information regarding AE sources (indications), about their local concentrations on the structure, their activity (indications per time), their intensity (low or high amplitude or energy) and the type of source (restricted classification). But for more specific and detailed results (e.g. remaining wall thickness, crack length, crack depth) follow-up NDT is suggested to be applied at marked positions of indications. Based on the measuring and object conditions the NDT expert defines in cooperation with the tank owner the appropriate NDT method, e.g. UT, RT, ET or Phased Array UT. Other potential techniques may be used in the future like Guided Waves and Alternating Current Field Measurement (ACFM); that is an emerging electromagnetic technique for detecting and sizing small surface breaking defects in metallic structures.

In general, NDT corrosion inspection is required both on the internal and the external structure surfaces. However, uniform corrosion on the inside face of the shells on steel made type of pressure tanks is not common to occur mainly due to the absence of oxygen on the internal atmosphere. Local corrosion may occur as worm holes, selective attack of welds or the heat affected zone and nearby attachments. Both the sill and tank are subject to external corrosion, which frequently occurs under insulation. External corrosion can also occur around nozzles or in areas where the car is exposed to the transport product.

Fig. 2 contains a flow diagram showing the complete inspection procedure to be followed during AT based online monitoring of road or railway tank cars including the measures (follow up NDT and repairs, if necessary) to be done depending on the level of degradation.

4 FE pre-studies for hot spot determination of road/rail structures

Health monitoring of a road or railway tank car would require a relatively large number of AE sensors if the entire structure were to be monitored. Nevertheless, in operational conditions only several locations are prone to catastrophic failure



Figure 2: Overview of the developed AT inspection procedure

due to fatigue and/or corrosion. Identifying these locations will become a routine operation once the proposed health monitoring concept will become a standardized technique. In the research stage or in cases of new tank designs, however, these locations which are also called "hot spots" can be identified by Finite Elements Analysis (FEA) or by statistical means based on similar structures already in or out of service.

Statistics can be used for relatively old models of road/railway tank cars, from which considerable number is already withdrawn from service, by inspecting the type and location of critical damages as these cars are sent to recycling. This case is not the most relevant, since the economical advantages of the health monitoring

technique become obvious for long service life, which is the case for new models. Linear FEA would quickly and accurately facilitate the allocation of degradation hot spots as shown by Malikoutsakis, Savaidis, Savaidis (2011) and Wachsmuth, Malikoutsakis, Savaidis, Savaidis, Bohse (2012). Therein comprehensive FE modelling methodology is proposed based on the directives given in the guideline of the International Institute of Welding edited by Hobbacher (2007), along with an exemplary case study of a road tanker.

In the absence of operational load spectra, the common ADR (2008) and RID (2011) regulatory load assumptions may be taken into account for road and rail structures, respectively, especially for those carrying dangerous goods. Even though the magnitude of these load assumptions suggest their appearance only during extreme and accidental-like cases, the load directions and relative magnitude to each other, can be considered to represent the basic load situations appearing during normal operation. Due to the linear elastic nature of the FEA, the magnitude of the applied loads is only of secondary importance for the hot spot determination; since stress re-distributions that may occur from local elastic-plastic behavior at very high load levels, e.g. the ADR/RID ones, do not have any effect in the case of linear calculation.

4.1 Load assumptions

Both ADR and RID regulations demand the calculation and/or experimental determination of the structural integrity of the respective transport means, against some common gravity loads. These loads arise from the earth acceleration, G, of the fully laden vessel along its vertical, longitudinal and lateral axes. Moreover, the filling medium is considered to be water, in order to produce the worst case scenario conditions, due to the water's higher density in comparison to the actual transported substances such as gasoline, petroleum, etc. In case of pressurized fluid tankers, maximum operation pressure should superpose the gravity load cases.

Additionally, the fore mentioned regulations refer to international standards for the integrity checks in case of pressurization of the transportation vessel. These checks require the application of both over- and under-pressure conditions in the whole vessel and in each compartment separately, in case of multi-compartment vessels.

Fig. 3 gives an illustration of both the gravity (left side of Fig. 3) and pressure (right side of Fig. 3) loads typically applied for the FE pre-study of a road tanker. According to RID, the same gravity loads have to be considered for railway tank cars.



Figure 3: (a) gravity load 2G in the direction of driving, (b) gravity load 2G vertically downwards, (c) gravity load 1G vertically upwards, (d) gravity load 1G in the lateral direction (sideways), (e) overpressure of the whole vessel, (fi) overpressure of each compartment i for multi-compartment tanks, (g) under-pressure of the whole vessel.

4.2 FE results/Hot spots

Comprehensive FEA on various types of LGBF and LPG tanks, similar to the road and railway tanks used here for the experimental validation (see section 5), have been performed applying the methodology proposed by Malikoutsakis, Savaidis and Savaidis (2011) and Wachsmuth, Malikoutsakis, Savaidis, Savaidis and Bohse (2012), along with the respective application examples. Fig. 4 and Fig. 5 show exemplarily the qualitative hot spots of an LPG road and railway tank structure, respectively, for each load case given in ADR and RID.

The supports are assumed fixed at their contact areas with the car bodies. The gravity loads are calculated by the weight of the water (instead of the actual transportation means) occupying the whole volume of the tanker multiplied by the corresponding accelerations in any of the four directions indicated in ADR/RID, and the pressure, which has two components, the nominal pressure and the hydrostatic pressure due to the fluid inside the vessel. In Figures 4 and 5, the circles pinpoint the areas of high stress concentration. As expected, the failure critical areas lay on the vicinity of the support sub-structures, occupying the weld connections between different sheet metals. Therefore it becomes clear that the dominant role for the integrity and durability of the structure is played by these weld connections and their resistance against fatigue and corrosion mechanisms accumulated during service.

Malikoutsakis, Savaidis and Savaidis (2011) showed that in the case of single- or multi-compartment LGBF tanks the weld connecting the upper protection system with the hull of the structure as well as the welds connecting the tank hull with the manholes may be additional degradation hot spots, that should be taken into account for AT.



Figure 4: FEA results for LPG road tank subjected to (a) gravity load 2G in the direction of driving, (b) gravity load 2G vertically downwards, (c) gravity load 1G vertically upwards, (d) gravity load 1G in the lateral direction, (e) overpressure of the whole vessel, (g) underpressure of the whole vessel.



Figure 5: FEA results for LPG railway tank subjected to (a) gravity load 2G in the direction of driving, (b) gravity load 2G vertically downwards, (c) gravity load 1G vertically upwards, (d) gravity load 1G in the lateral direction

5 Experimental validation on tank structures

Various railway tank cars and road tankers were made available by different tank owners to validate the proposed AT health monitoring procedure within the framework of the current research investigation. Nevertheless, in order not to overfill the capacity of the present paper, details on AT and characteristic results referring to corrosion and fatigue cracking from one road tanker and one railway car, respectively, are exemplarily shown and discussed.

While power supply for the measuring equipment is normally not a problem for monitoring of stationary test objects, monitoring of road tankers and railway tank cars during travel requires much more effort. At trucks the acquisition system was arranged in the driver's cab and power was delivered by the batteries of the trucks via DC-AC-converter. At railway tank cars usually there is no power supply. Thus, the acquisition system can be powered by the locomotive or by separate power supply during moving. The acquisition system can be arranged either in the locomotive or an additional wagon.

5.1 Road and rail structures with corrosion – Description

Figure 6 shows the investigated 9m-long semitrailer with multi-compartment tank that has been shortly taken out of service for the purpose of the experimental validation.



Figure 6: Semitrailer with mounted AE sensors

For monitoring corrosion processes by AT, the AE sensors were mounted regularly around the tank shell. The circles show the locations, at which AE sensors were applied. The numbers label the individual AE sensor. Location of and distance between the sensors were defined regarding parameters of the test object, e.g. material of tank, position of hot spot welds, medium in the tank, attenuation of acoustic waves. Further AE sensors were applied to the rear side of the structures which are not visible in the view shown in Fig. 6.

Note that the road tankers tested here are commercially in-service and free of corrosion. Therefore, artificial corrosion sources have been designed and applied to the tank shell, see left image in Fig. 7.

It is a squared and closed tube containing acid liquid (mixture containing water, sodium chloride, nitrid acid, sulphuric acid) inside. The corrosion process works only inside the tube. Nevertheless, once coupled to the tank structure, AE waves are able to propagate into it and captured by AE sensors. To cover a "worst case scenario", the artificial source was applied in severe distances from AE sensors. The right image in Fig. 7 shows the artificial corrosion source applied at the top of the



Figure 7: left: Artificial corrosion source, right: Artificial corrosion source with directly attached separate sensor mounted at the tank shell

semitrailer. It is mounted by magnets at the tank shell, applying acoustic coupling agent to ensure wave propagation from the source to the tank shell. In addition to the sensor array mounted for monitoring of the tank, one separate sensor is directly mounted at the artificial corrosion source, to monitor in parallel the activity of the corrosion source.

Notice that HSU has been applied at the position specified for mounting of the artificial corrosion source for comparison.

Fig. 8 shows one of the tested railway tank cars (design type Zaest3), exemplarily.



Figure 8: Railway tank car with mounted sensors

The tank was manufactured in year 1987 for a design life of 30 years. Its volume amounts to 60000 lt. Its material corresponds to structural steel grade S355J2G3 according to EN 10025, and its working pressure amounts to 2,5 bar. The minimum thickness of the shell is 7 mm. It was used for transportation of glue until 2005. Then, it has been converted to transportation of Methanol, after evaluation of its

structural health. Due to the yearlong transportation of glue, the tank was corroded inside. Fig. 9 shows the corroded inner tank shell.



Figure 9: Typical corrosion inside the railway tank car under investigation

In opposition to the road tankers investigated, monitoring of real corrosion process by AT could be studied at the railway tank car.

5.2 Road and railway structures with artificial cracks – Description

Notice that it was not possible to find operating road or railway tankers with existing fatigue cracks in the shell within the duration of the present investigation. This is mainly because a crack in an in-service tank shell gets usually repaired as soon as it is detected.

To overcome the aforementioned drawback, it was decided to install coupons providing fatigue cracks at the tank shells. For this, windows have been first cut out of the tank structures and then, coupons providing pre-cracks manufactured in the laboratory were welded at the tank shell, at the locations where the windows were cut out. However, due to the intervening operation required, only out-of-service tankers could be made available by the owners for the AT measurements. As a consequence, driving out-of-service tankers on public road and rail tracks is not possible due to safety regulations.

To overcome this restriction and simulate fatigue crack growth, the individual coupons were equipped with artificial AE sources with electromagnetic periodic stimulation (AFAES-EM) and applied to the tank shells. Fig. 10 shows the design of such a coupon, and Fig. 11 its weldment at the tank shell.



Figure 10: Technical scheme of the coupon with V-notch



Figure 11: Welded coupons at the semitrailer (left) and the railway tank car (right)

It provides machined V-notch with an artificial fatigue pre-crack in the notch root. The coupons are designed with the same curvature (radius R) as the corresponding tank shell. The coupons are curved in order to be "integrated" in the corresponding tank structures by welding in corresponding window cuts into the individual structure's shell. The fatigue pre-cracks were induced into the coupons' notch roots by cyclic loading, in order to be able to monitor the fatigue crack growth in the tank structures' shells within a reasonable period of time. The wall thickness of the coupon was reduced at the inner side to 2.0 mm (nominal thickness of the tank shell 12 mm) and the notch (length 60 mm, depth 1.5 mm) was machined at its outer side. The electro-magnetic (AFAES-EM) device was installed with the supports on the coupon to apply cyclic loading in parallel to the static overpressure on the inside, applied by means of an external pump.

Fig. 12 and Fig. 13 show the investigated road semitrailer and the railway tanker,



Figure 12: Semitrailer tank with coupon welded at the tank shell, mounted sensors (circles) at the tank shell and the electro-magnetic (AFAES-EM) device



Figure 13: Railway tank with coupon welded at the tank shell and the electromagnetic (AFAES-EM) device

respectively, with integrated artificially cracked coupons and electro-magnetic (AF AES-EM) devices for application of the cyclic loading.

Every weld joining the individual coupon with the corresponding tank shell has been inspected by PT. Then the tank was filled fully with water and pressurized slowly up to 3 bar and then, stepwise (0.5 bar per step), to higher pressure. After reaching each pressure level the pump was stopped, while the pressure was kept constant.

During this period of constant pressure, cyclic loading was generated by the electromagnetic (AFAES-EM) device. Power and cycle time was set via control unit. Hence, the coupon was bended cyclically by magnetic force. During all actions, i.e. pressurization of the tank and cyclic loading of the coupon, the tank was monitored simultaneously by AT. Breakthrough of the coupon was reached during cyclic loading at a pressure of 5.5 bar.

5.3 AE-Sensors, application, testing procedure

Fig. 14 contains the block diagram showing the configuration of an AE system for road and/or railway tank car monitoring.



Figure 14: Block diagram of AE equipment for road and/or railway tank car monitoring: ATEX certified intrinsically safe sensor ISAS3 (left) and signal isolator SISO3 (right)

Intrinsically safe sensors, series ISAS3 developed by Vallen Systeme GmbH (Vallen and Thenikl (2012)) for special applications in hazardous areas (ATEX Zone 0 or 1) have been used. The ATEX (Appareils destinés à être utilisés en ATmosphères EXplosives) regulation consists of two EU directives describing the equipment and the work environment, which are allowed in an environment with an explosive atmosphere. On the left side of the block diagram, sensors ISAS3 pick up the surface movement of an AE wave from the wall of the tank, a location usually classified as potential explosive zone 1. To ensure intrinsic safety of cabling to meet the requirements for fluid hazardous materials, signal isolator, SISO3, was developed, which is interconnected between the acquisition system and the intrinsically safe sensor ISAS3. The sensors convert the surface movement to an electrical AE signal that is transferred by cable to the signal isolator SISO3 in a non-hazardous control room, e.g. the driver's cabin, usually classified as potential explosive zone 2. Thus, the cabling between the signal isolator and the sensor is intrinsically safe. The sensor arrays were defined and mounted taking the measuring conditions and parameters of the test objects into account. The signal isolator transfers the signal to the AE system, which operates under control of a PC.

However, within the present test, neither hazardous cargo nor hazardous environment existed, hence non-intrinsically safe version of the sensors was used. The mechanical setup and measuring characteristics are the same, but its installation needs less effort.

After installation of the sensors and the acquisition system, standard survey, as shortly described hereafter, was carried out. The correct setup of the measuring chain (i.e. acoustic coupling of sensors, cabling and sensitivity) was checked by means of HSU. Furthermore, HSU was applied at specified areas (e.g. welds, supports) of the tank shell to check the accuracy of location process, which works correctly only for a well designed sensor array (positioning of sensors at the tank shell) and proper settings of the software tools, e.g. wave velocity.

Monitoring tests were performed regarding corrosion as well as during pressurisation of the tank with activated electro-magnetic (AFAES-EM) device for defined periods. These tests could be carried out at the test site, because moving of the test object on road/rail was not necessary for these tests. Hence, also standard power supply could be used.

5.4 Results of AE monitoring

All diagrams contained in the following subsections show the shell of the individual tank unreeled to a plane, whereas the ridge of the tank is represented by X = 0. The sensors are marked by small crosses and labelled by numbers. The positions of AE events localized during monitoring are plotted in the diagrams. Different symbols (colour and shape) are defined to mark the indications (see individual figure legends) with respect to the distance corrected amplitude of the signal and the related class. For the classification of AE signals (relation to defined classes) the classifier "VI3B5" described in the work of Jagenbrein, Tscheliesnig, Wachsmuth and Bohse, (2012) was used. Therein, the defined classes mentioned in the figure legends are: class 1 (background of truck), class 2 (background of railway car), class 3 (background of ship), class 4 (corrosion), class 5 (fatigue cracking with wave propagation in the metallic structure) and class 6 (fatigue cracking with wave propagation through water).

Clustering process illustrates the number of AE events within a defined area by coloured circles. Those colours are related to a minimum number of AE events (see legends in the individual plots).

5.4.1 Structures with corrosion

Results of AE monitoring of corrosion processes caused by artificial corrosion sources as well as by inside real corrosion using low detection thresholds (as de-

rived for testing of unmoved tanks) are demonstrated in Fig. 15 and Fig. 16 for the semitrailer and the railway tank car, respectively. They are part of typical displays available at common AE measuring systems. Considering the quite large length of the semitrailer's tank, approx. 9 m, and in order to keep clarity of the results, only a typical part of measurements at the front of the tank is shown in Fig. 15, where the artificial corrosion sources were mounted.



Figure 15: Located AE events caused by artificial corrosion sources mounted at semitrailer; top: distance corrected amplitudes of AE signals; bottom: relation to classes

The artificial corrosion sources were mounted close to the positions (X = ± 70 cm, Y = 140 cm). The different corrosion processes inside the corrosion sources lead to unequal results during monitoring. In particular, stronger corrosion inside the left artificial corrosion source (X = -70 cm, Y = 140 cm) caused few measured AE signals with distance corrected amplitudes greater than 70 dB_{AE} and majority of the AE signals with distance corrected amplitudes between 50 dB_{AE} and 70 dB_{AE}. Less indications are found for the other weaker (right) artificial corrosion source



Figure 16: Located AE events caused by inside corrosion in railway tank car; top: distance corrected amplitudes of AE signals; bottom: relation to classes

(X = +70 cm, Y = 140 cm). Both artificial corrosion sources were monitored simultaneously. Most of the AE signals are related to class 4 (corrosion) by the classifier and the others mainly to class 1 (background of truck).

In Fig. 16 is well depicted that AT delivered mostly indication in a particular area of the tank. Nearly all distance corrected amplitudes of the measured AE signal are greater than 50 dB_{AE} and about the half greater than 70 dB_{AE}. Nearly 25% of AE signals are related by the classifier to class 4 (corrosion), others to class 2 (background of railway car), but also to class 1 (background of truck).

5.4.2 Structures with artificial fatigue crack

To verify sensor setup and location processor and for later comparison with data from monitoring, HSU was applied along the weld connecting the coupon with the tank shell of the semitrailer and at the notch machined into the coupon (coupon details are shown in Fig. 10). Reference data acquired during HSU at the tank without pressure (Fig. 17) and AT results monitored during constant pressure at

specific pressure levels in the tank and with cyclic stressing of the coupon by the electro-magnetic device were measured using low detection threshold due to stationary testing of the tank (Fig. 18). Data received during pressure rise (increase of pressure by pumping from one pressure level to the next, i.e. 0.5 bar steps) are not included to the AT results shown in Fig. 18.



Figure 17: HSU carried out along the weld of the coupon (left) welded into the tank shell and at the notch machined into the coupon (right)



Figure 18: Located AE events received during monitoring of the semitrailer tank during constant pressure and cyclic stressing of the coupon by the electro-magnetic device; left: distance corrected amplitudes of AE signals; right: relation of AE signals to classes

It is obvious, that the majority of indications, delivered by AT during monitoring of the cyclic stressing of the coupon by the electro-magnetic device with simultaneous pressure application inside the tank, are located at the coupon. The distance corrected amplitudes of the measured AE signals are nearly all greater than 50 dB_{AE} and about 1/3 of them is greater than 70 dB_{AE}. The AE signals are associated with the fatigue crack process. The classifier relates most of the AE signals to class 1 (background truck) and few to class 6 (fatigue cracking with wave propagation through water).

Thus, there have been some effects. The tank was filled fully with water. Hence, wave propagation was partly through water. This version of the classifier does not account for the distance of the AE sources and is based on limited measuring data. Improvement of the classifier can be achieved by recording more measuring data and calibrating properly the classes. Further, the possibility of considering the wave propagation effects on forms and spectral contents of AE signals has to be checked. Follow-up NDT was not performed, since the locations of degradation events (artificial, natural) in the studied tanks were pre-known.

6 Conclusions

A continuous acoustic emission based health monitoring concept has been developed that can be applied to ensure the structural integrity of road and railway tanks. First accurate versions of all necessary hardware and software devices are also developed. The concept has been validated on road tankers and railway tank cars with natural and artificial degradation products (corrosion, fatigue cracks).

The degradation mechanisms could be detected and reliably located during monitoring with AT. The distance corrected amplitudes from AE signals due to corrosion have been in the range from 50 dB_{AE} to more than 70 dB_{AE}, i.e. part of them can be detected also with a higher detection threshold (e.g. 50 dB_{AE}) if needed in case of increased background noise.

While AE signals originated by corrosion have been related by the classifier mostly to the correct class, AE signals recorded during cyclic stressing of the coupon by the electro-magnetic device, were mainly related to class 1 (background truck) and only few to class 6 (fatigue cracking with wave propagation through water).

The results pinpoint the capability of acoustic emission testing to separate background noises and reliably detect and identify individual degradation mechanisms in early stages under operational loading conditions.

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References

ADR (2008): European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), Economic Commission for Europe, Committee on Inland Transport; United Nations; New York and Geneva.

Baran, I.; Nowak, M.; Schmidt, J. (2010): Fatigue Testing of Ship Building Material with Acoustic Emission, In: *Proc. 29th European Conference on Acoustic Emission Testing (EWGAE)*, Vienna/Austria.

BS PD 5500 (2011): Specification for unfired fusion welded pressure vessels.

RID (2011): International Carriage of Dangerous Goods by Rail.

EN 13094 (2008): *Tanks for the transport of dangerous goods. Metallic tanks with a working pressure not exceeding 0,5 bar. Design and construction.* European Committee for Standardization, Brussels.

EN 1330-9 (2009): *Non-destructive testing – Terminology – Part 9: Terms used in acoustic emission testing*, European Committee for Standardization, Brussels.

EN 13445 (2002): *Unfired Pressure Vessels*, European Committee for Standardization, Brussels.

EN 14286 (2007): Aluminium and aluminium alloys. Weldable rolled products for tanks for the storage and transportation of dangerous goods. European Committee for Standardization, Brussels.

Grosse, U.G.; Ohtsu, M. (2010): Acoustic Emission Testing. Springer Verlag, Berlin, Heidelberg.

Jagenbrein, A.; Baran, I.; Nowak, M.; Buglacki, H. (2012): Acoustic emission monitoring of structural elements of a ship detection of fatigue and corrosion damages, In: *Proc. EWGAE 2012*, Granada/Spain.

Jagenbrein, A.; Tscheliesnig, P; Wachsmuth, J.; Bohse, J. (2012): Detection of corrosion processes and fatigue cracks by means of acoustic emission monitoring.

Materials Testing, vol. 54, pp. 769-778.

Hobbacher, A. (2007): Recommendations for fatigue design of welded joints and components. *IIW document XIII-2151-07 / XV-1254-07*.

Malikoutsakis, M.; Savaidis, G.; Savaidis, A. (2011): Unified FE simulation of road tanks for ADR and fatigue assessments. *2nd Int. Conf. Engineering against Fracture (ICEAF II)*, Mykonos, Greece.

Miller, R.K.; Hill, E. (2005): Acoustic Emission Testing, Nondestructive Testing Handbook, 3rd Edition, vol. 6, American Society for Nondestructive Testing.

Ono, K. (2011): Acoustic Emission in Materials Research – A Review, *J. Acoustic Emission*, vol. 29, pp. 284-308.

Rogers, L.M. (2001): Structural Engineering Monitoring by Acoustic Emission *Methods - Fundamentals and Applications*, Lloyd's Register, Technical Investigation Department, London.

Teti, R.; Jemielniak, K.; O'Donnel, G. Dornfeld, D. (2010): Advanced monitoring of machine operations. *CIRP Annals: Manufacturing Technology*, vol. 59, pp. 717-739.

Tscheliesnig, P. (2010): Cost effective fatigue and corrosion monitoring by means of acoustic emission on transport products, In: *Proc. EWGAE 2010*, Vienna.

Tscheliesnig, P. (2012): Detecting corrosion and fatigue cracks during service. *Projects Magazine*, vol. 30, Insight Publishers Ltd, pp. 62-65.

Tscheliesnig, P. (2012): Acoustic emission (AE) monitoring on transport products, In: *Proc.* 7th *International Conference on Acoustic Emission*, Granada/Spain.

Vallen, H. (2001): Schallemissionsprüfung: Grundlagen - Gerätetechnik - Anwendungen, *DGZfP-Jahrestagung* (in German).

Vallen, H.; Thenikl, T. (2012) New Intrinsically Safe Acoustic Emission Sensor System for Use on Tank Ships, In: *Proc.* 7th International Conference on Acoustic Emission, Granada/Spain.

http://www.ndt.net/article/ewgae2012/content/papers/96_Vallen_Rev1.pdf

Vallen, J.; Ruske, G. (1998): Frequency based Source Classification of AE signals, *Proc.* 23rd European Conference on Acoustic Emission Testing, Vienna, pp. 249-254.

Wachsmuth, J.; Bohse, J. (2011): Schallemissionsanalyse von Schadensmechanismen an Feinkornstahl. *DGZfP Jahrestagung*, Bremen, 2011.

Wachsmuth, J.; Malikoutsakis, M.; Savaidis, G.; Savaidis, A.; Bohse, J. (2012): Corrosion and fatigue crack monitoring by means of acoustic emission for application in transportation. *Int. J. Terraspace Science and Engineering*, accepted. Wachsmuth, J.; Malikoutsakis, M.; Savaidis, G.; Savaidis, A.; Bohse, J. (2012): Corrosion and fatigue crack monitoring by means of acoustic emission for application in transportation. 14th Int. Cong. Mesomechanics, Budapest, Hungary, pp. 193-205.