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Pitting Corrosion Monitoring Using Acoustic Emission

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1. Introduction

Damage from corrosion represents one of the most important problems in existing structures. Various types of traditional nondestructive testing (NDT) for example, Ultrasonic ThicknessMeasurement (UTM) or Magnetic Flux Leakage (MFL) are implemented to measure the growth of corrosion; each method, however, has its particular limitations. For the last two decades Acoustic Emission (AE), an advanced NDT method, has been used to monitor the severity of corrosion. Compared to the conventional NDT methods, it is less intrusive and has the advantage of real-time measurement. In this chapter, the development of pitting corrosion monitoring using AE is reviewed.

AE refers to the generation of transient elastic or stress waves during the rapid release of energy from localized sources within a material. The source of these emissions in metals is closely related to the dislocation movement accompanying plastic deformation and the initiation and extension of cracks in a structure under stress. AE systems are comprised of an AE sensor, an amplifier and filter, an acquisition and a data display. In the corrosion process, an AE parameter is extracted and then the relation with corrosion grading is determined. The parameters commonly used in corrosion applications include AE HIT, Even and AE energy.

The accurate forecast of corrosion level assists in maintenance planning. For instance, a storage tank or pipeline in the petroleum industry could fail as a result of pitting. In general, the severity of pitting corrosion is presented with two factors: the maximum pit depth and the pitting factor. A wide variety of methods were used to measure the severity of pitting corrosion. In this chapter, AE sources corresponded to the maximum pit depth are explained. The AE source generated from the pitting corrosion related to its mechanism is exposed. Experimental setup, results and discussions are briefly described. Research works in AE sources are deliberately reviewed. Three AE sources – hydrogen bubbles, breakage of passive film and pit growth – are proposed. The average frequency of the AE parameter was used to define the hydrogen bubbles. The oscillation, movement, and breakage of hydrogen bubbles generate acoustic stress waves in the same frequency band, which is related to the bubble diameter. An acoustic parameter, namely the 'duration time', can be used to classify the AE signal sources generated from the breakage of the passive film into two groups: the rupture of passive films and the pit growth signal. The results were explained based on the corrosion mechanism and the electrochemical analysis.

In practice, the location of the pitting can be calculated by using the difference in the arriving time of each pair or group of sensors. In this chapter, a novel source location system using an FPGA-PC system was utilized to calculate the arrival time difference from signals received from an array of three AE sensors on the specimen. The system consists of the AE sensors, pre-amplifiers, a signal conditioning unit, an FPGA module, a PC and a data acquisition. Experimental results and errors are shown.

2. Acoustic Emission testing (AE)

Nondestructive Testing can be defined as the development and application of methods to examine materials or components, in ways that do not impair future usefulness and serviceability, in order to detect, locate, measure and evaluate flaws; to assess integrity, properties and composition; and to measure geometric characteristics (American Society for Testing and Materials (ASTM E1316, 2001).

Acoustic emission (AE) is a powerful method for non-destructive testing and material evaluation. Older NDT techniques such as radiography, ultrasonic, and eddy current detect geometric discontinuities by beaming some form of energy into the structure under test. AE is different: it detects microscopic movement, not geometric discontinuities. AE, by definition, is a class of phenomena whereby transient stress/displacement waves are generated by the rapid release of energy from localized sources within a material, or the transient waves so generated (ASTM E1316, 2011). AE is the recommended term for general use. Other terms that have been used in AE literature include (1) stress wave emission, (2) microseismic activity, and (3) emission or acoustic emission or emission with other qualifying modifiers. These elastic waves can be detected by microphones or transducers attached to the surface of the specimen. AE techniques have been used in many applications such as in material degradation, leak and flow, solidification, and machining.

AE is a passive technique. The growing defect makes its own signal and the signal travels to the detecting sensors. The main benefits of AE compared to other NDT methods are that AE is a real-time method and it is less intrusive. The discontinuities of defects can be detected by AE at an early stage when they are occurring or growing. AE techniques can be used as a warning system before the testing material is severely damaged. AE requires access only at the sensors; while on the other hand, most other NDT techniques require access to all regions inspected.

In order to detect AE events, a transducer is required to convert the very small surface displacement to a voltage. Displacements as small as 10^{-14} metre [(Course Handbook for SNT-TC-1A (1991)] can be detected by the use of the most sensitive sensors. The most common type of transducer is piezoelectric, which is sensitive, easy to apply, and cheap. A couplant is needed for good transmission, and is usually achieved by grease or ultrasonic couplants, together with some means of applying force to maintain contact.

2.1 AE systems

An AE system consists of AE sensor, cable and pre-amplifier, and AE data-acquisition, as illustrated in Figure 1. There are two types of piezoelectric transducer: resonant transducers and broadband transducers. The principal or resonant frequency of a piezoelectric element depends on its thickness. The piezoelectric element is unbacked or undamped in a resonant transducer, but a broadband transducer has an element that is backed with an attenuating medium. The frequencies of most AE-resonant transducers lie in the range of 100 kHz to 1 MHz. However, it was found that the frequency of 30 kHz is often used for corrosion detection. Resonant sensors are more sensitive than broadband types because of the gain provided by mechanical resonance. Broadband sensors are used when the object of interest has the frequency spectrum of AE, but they do not have as high sensitivity as resonant transducers. Because of the reliance on mechanical resonance, resonant sensors can be used to detect preferentially a frequency range which has been shown from previous experience to give a good indication of the AE changes. Alternatively, a broadband sensor can be used and the required frequency is selected by filters.

Fig. 1. Component of AE system (Prateepasen A., 2007)

Elastic waves emitted from materials can be divided into 2 types based on their appearance: burst and continuous. A burst emission is a signal, oscillatory in shape, whose oscillations have a rapid increase in amplitude from an initial reference level, generally that of the background noise, followed by a decrease, generally more gradual, to a value close to the initial level. Acoustic emission released from pitting corrosion is of the burst type. A continuous emission is a qualitative term applied to acoustic emission when the bursts or pulses are not discernible. (A pulse is an acoustic emission signal that has a rapid increase in amplitude to its maximum value, followed by an immediate return.)

2.2 AE waveform parameters

The parameters commonly used to predict severity in the corrosion process are AE ring down count, AE HIT, AE Even and AE energy or AErms. An AE burst, the typical AE signal from the corrosion process, is shown in Figure 2 and can be described by the parameters as follows.

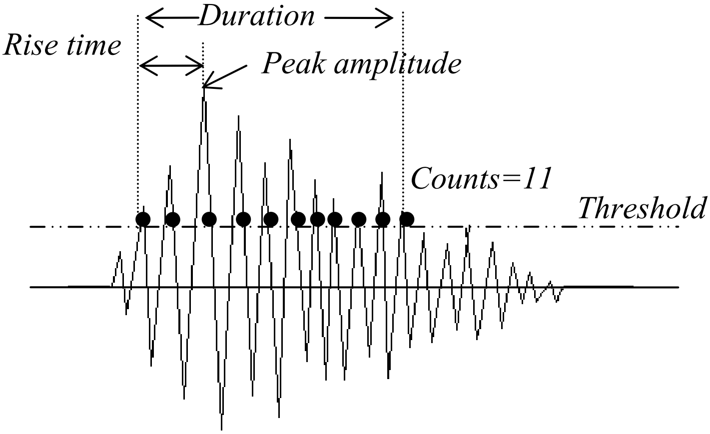


Fig. 2. Definition of AE waveform parameters

Ring down count is the number of times a signal exceeds a pre-set threshold. This is a simple measure of the signal size, since larger signals typically give more counts. Electronically, this is a very easy measurement, and it was the first to come into widespread use. By summing the counts from all detected emissions, one has a convenient measurement of the total emission from the specimen or structure. The number of counts (N) can be calculated by (Ronnie K.,1987)

$$N = \frac{\omega}{2\pi B} \ln \frac{V_0}{V_t} \tag{1}$$

where ω = angular frequency
B = decay constant (greater than 0)
V_0 = initial signal amplitude
V_t = threshold voltage of counter

AErms is the root mean squared value of the input signal. Since acoustic emission activity is attributed to the rapid release of energy in a material, the energy content of the acoustic emission signal can be related to this energy release. AErms can be defined as

$$V_{rms} = (\frac{1}{T}\int_0^T V^2(t)dt)^{\frac{1}{2}} \tag{2}$$

where V(t) = signal voltage function
T = period of time

AE HIT is the detection and measurement of an AE signal on a channel (ASTM 1316, 2011).

AE EVEN is an occurrence of a local material change or mechanical action resulting in acoustic emission.

AE ENERGY is the energy contained in an acoustic emission signal, which is evaluated as the integral of the volt squared function over time.

AE Duration time is the time between the point at which the event first exceeds the threshold and the point at which the event goes below the threshold. This parameter is closely related to the ring down count, but it is used more for discrimination than for the measurement of emission quantities. For example, long duration events (several milliseconds) in composites are a valuable indicator of delamination. Signals from electromagnetic interference typically have very short durations, so the duration parameter can be used to filter them out. In this chapter, duration time will be used to divide the AE source from pitting corrosion into two groups.

3. Corrosion

Corrosion is the disintegration of material into its constituent atoms due to chemical reactions with its surroundings. The type of corrosion mechanism and its rate of attack depend on the exact nature of the environment (air, soil, water, seawater) in which the corrosion takes place.

3.1 Corrosion process

The corrosion process is an ion transfer between anode and cathode poles which are on the material surface of one piece or a different piece depends upon the corrosion form and property of corroded material. The result of an electrochemical corrosion process on stainless steel is shown below. The corrosion process of metal comprises an oxidation and reduction reaction. At the anode pole, the oxidation reaction can be expressed by:

$$\mathrm{M} \rightarrow \mathrm{M}^{2+} + 2\mathrm{e}-$$

and at the cathodes pole, the reduction reaction can be presented as:

$$2\mathrm{H}+ \ + \ 2\mathrm{e}- \rightarrow \ \mathrm{H2}\,; \ \mathrm{O2} + 4\mathrm{H}+ + 4\mathrm{e}- \rightarrow 2\mathrm{H_2O};\ \mathrm{M}^{3+} + \mathrm{e}^- \rightarrow \mathrm{M}^{2+}$$

In the reaction, the hydrogen bubble is formed:

$$\left(\mathrm{Mn}^+ + \mathrm{nCl}^-\right) + \mathrm{nH_2O} \rightarrow \mathrm{M}\left(\mathrm{OH}\right)_\mathrm{n} + \mathrm{nM}^+ + \mathrm{nCl}^-$$

The chloride ion is absorbed on the material surface and breaks the passive film.

3.2 Acceleration of corrosion by electrochemical process

To study the relation between AE parameters and corrosion severity, pit growth is accelerated by the electrochemical process. Electrochemical polarization methods can be classified into two types: controlled potential (potentiostatic and, potentiodynamic) and controlled current (galvanostatic). The method used to accelerate pitting corrosion in the experiments in this chapter is potentiostatic and potentiodynamic. The applied polarizing current to control potential between working electrode (WE) and reference electrode (REF) at any prescribed value was adjusted by a potentiostat automatically. The diagram in Figure

3 shows the potentiostatic circuit, which consists of a potential and a current measuring element. The current (I) polarizes the WE to the prescribed potential with respect to REF, which remains at a constant potential with little or no current passing through the potential measuring circuit. The polarization curve from the potentiodynamic method allows the study in detail of the important parameters affecting formation and growth of passive films (Ecorr) and corrosive propagation (Epit).

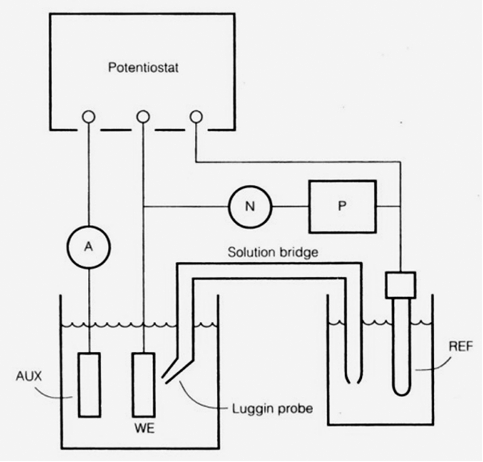


Fig. 3. Schematic circuitry diagram of potentiostatic and potentiodynamic methods

3.3 Monitoring and prediction of corrosion severity

The severity of pitting corrosion is measured by two factors: the maximum pit depth and the pitting factor. The pitting factor is the ratio of the depth of the deepest pit. At present, there are various methods to monitor corrosion (Jirarungsatian& Prateepasen, 2010) such as (1) failure records and visual inspection, (2) weight loss coupons, (3) spools and subs, (4) brine analyses, (5) deposit analyses, (6) three-electrode measurement technique, (7) electronic resistance instruments, (8) hydrogen patches and probes, (9) inhibitor residual analyses, (10) caliper surveys, and (11) A/C impedance and electrochemical noise instruments. Generally, the main aim of corrosion measurement is to find out the corrosion severity in order to forecast the test object's remaining life. However, each method has its limitation, such as the lack of real-time and difficulty in accessing all of the examination area. Nowadays, the Acoustic Emission method, which is a real-time NDT technique, is less intrusive and can inform of the severity of the corrosion.

3.4 Mechanism of pitting corrosion

In order to understand the AE source released from the pitting corrosion process, the mechanism of pitting corrosion will be explained. The elementary pitting process is divided into three steps as shown in Figure 4.

1. Pit nucleation: in this stage a small area of bare, un-filmed, passive surface of metal is formed.

2. The development of a metastable pit: either the formation of a stable pit or the repassivation has occured.
3. The growth of a stable pit: the metal is damaged and the pit is propagated in this stage.

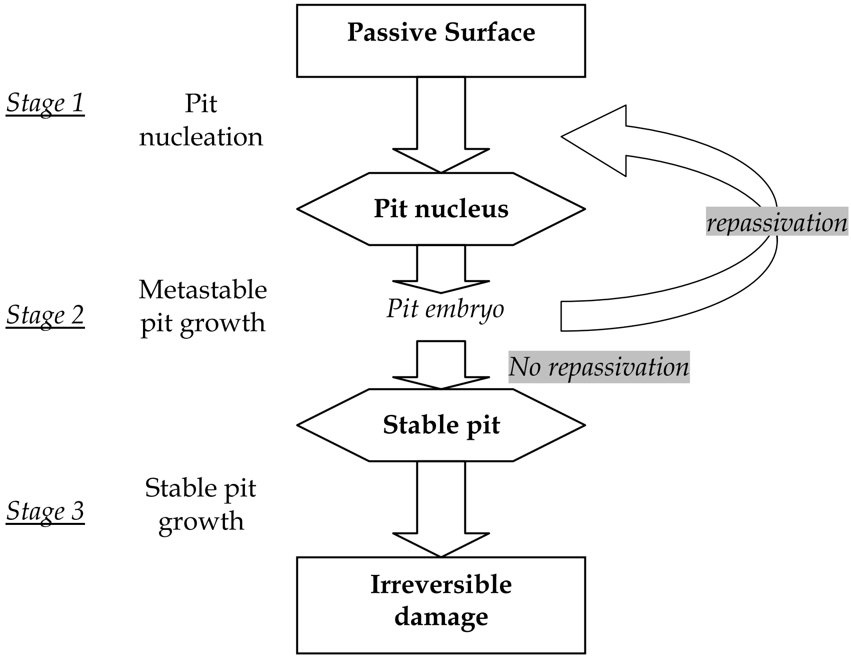


Fig. 4. Multistep mechanism for the onset of a stable pit (Jirarungsatian& Prateepasen, 2010)

4. Detection of pitting corrosion by AE

Researches in the area of pitting corrosion monitoring by AE have been the focus of several research groups. AE source generated from corrosion has been reported.

4.1 Literature review of the identification of AE source in corrosion process

A variety of corrosion types including uniform corrosion, pitting corrosion, crevice corrosion, stress corrosion cracking (Bosch, 2000; Cakir, 1999; Leal & Lopez, 1995; Xidong, 2005, Yoon et al., 2000), abrasion corrosion and erosion corrosion (Burstein & Sasaki, 2000; Ferrer & Labeeuw, 2000; Sasaki Oltra et al., 1995), has been studied and found to be correlate with AE. All of previous works presented the analogous conclusion that the AE technique can detect corrosion efficiently. However, the major disagreement is the corrosion mechanism that releases the acoustic wave. AE count number can be related with the corrosion rate in various corrosive conditions. In addition, the AE sources are corrosion activity and the hydrogen bubble occurrence on an electrode (Mansfield & Stocker, 1979). The frequency analysis of AE signals in the abrasion corrosion process was studied and it was concluded that the sources of AE are the impact of glass beads and gas bubbles (Ferrer, 1999).

Recently, researches in AE for source identification were proposed. Passive film breakage, bubble formation and the other actions in the corrosion process were considered as sources of the AE signal (Mirakowski, 2010). Experimental setup to eliminate AE source from gas bubble activity has been attempted in order to study the correlation between AE signal, which is AE count, and pitting corrosion in the electrochemical method (Mazille & Tronel, 1995; Mazille et al., 2001). The experiment used to study the acoustic emission generated by heating the metals and alloys confirmed that the AE signal was released during the phase transformation of specimens, and the AE parameter , 'count', was selected to explain the relation (Liptal, 1971). In the controlled potential of crevice corrosion monitoring, the research concluded that the AE signal in the monitoring was detected from all activity sources in the corrosion process including gas bubble formation (Kim & Santarini, 2003). The gas bubble activity also releases the acoustic wave. Therefore, the researches of the corrosion process which generated the gas bubble presented the identical discussion concluding that the AE source was bubble activity by comparison of AE counts with and without bubbles (Rettig & M. J. Felsen, 1976; Ferrer & Andrès, 2002). The AE event in an investigation of pitting corrosion using potentiodynamic methods expressed the relationship of the corrosion process with the AE source such as bubble activity (Darowicki, 2003). Numerous researchers have investigated the source of AE in the corrosion process. AE parameters were selected to correlate with the pitting process. In this chapter, the source of AE will be presented. The experiment was designed to find out the AE source and implemented to predict the pit growth.

4.2 Development of research work in AE for corrosion monitoring in ANDT

The Acoustic Emission and Advanced Nondestructive Testing Center (ANDT), King Monkut's University of Technology (KMUTT) has been studying the detection of corrosion by using AE since 2001. The first research work was to study and confirm that AE can detect corrosion. The relationship between AE and the mechanism of the corrosion damage was discovered (Jirarungsatean et al., 2002a). The accuracy of source location based on a general commonly used concept, namely the difference of arriving time interval, was studied (Jirarungsatean et al., 2002b). Accordingly, a low-cost system used to locate the corrosion location using FPGA was developed (Jomdecha et al., 2004, 2007). The classification of corrosion severity was subsequently the focus in ANDT's researches. Corrosion severity was evaluated by acoustic emission and a competent classification technique was implemented (Saenkhum et al., 2003). Consequently, a novel classification technique was developed to increase prediction performance (Prateepasen et al., 2006a). The effect of sulfuric acid concentration on AE signals obtained from uniform-corrosion was presented (Prateepasen et al., 2006b). Acoustic emission sources released from both uniform and pitting corrosion processes were investigated (Prateepasen et al., 2006c). More details of AE source recognition obtained from pitting corrosion will be mentioned in the next section.

4.3 Experimental work to validate the detection of corrosion by AE

The first step of the ANDT research group in the area of corrosion was to show that AE could detect pitting corrosion. High-concentration acid was used to produce pitting corrosion (Jirarungsatean et al., 2002a). The experimental work was developed by using electrochemical control (Prateepasen et al., 2006c). A specimen made of stainless steel

(SS304) was subject to accelerated pitting by electrochemical control equipment as shown in Figure 5. The surface of the specimen was ground with 1200 grit silicon carbide paper, rinsed with distilled water, and dried in cool air. The electrochemical environment was 3% NaCl solution mixed with HCl to control its pH of 2, and the electrochemically applied constant current was controlled with a Solartron 1284. In this experiment, the specimen acted as a working electrode, a platinum mesh worked as the counter-electrode, and a Ag/AgCl (sat. KCl) worked as a reference. AE sensor R15 (PAC) was mounted at the surface of the specimen. The crystal's resonance frequency was 150 kHz. An AE signal captured by the sensor was fed to a preamplifier for 60dB gain. A wide-band filter was embedded in the preamplifier. Data acquisition used to record and analyze the AE signal was done by LOCAN 320. The frequency waveform was recorded by a spectrum analyzer (HP 89410A).

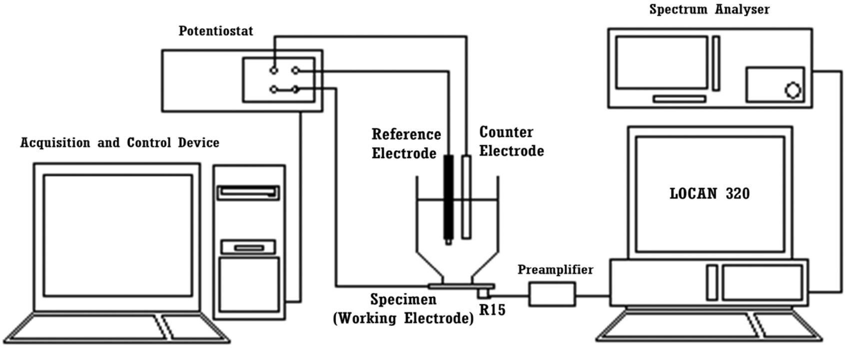


Fig. 5. Set up of AE system and electrochemical control equipment (Prateepasen et al., 2006c (pH of 2))

The pitting corrosion rate was controlled by the potentiostat that applied a constant potential on the specimen for twenty hours. Data received from the sample of SS304 was analyzed. The average frequency and time waveforms were collected every ten minutes. The relationship between the time and voltage was recorded by the potentiostat.

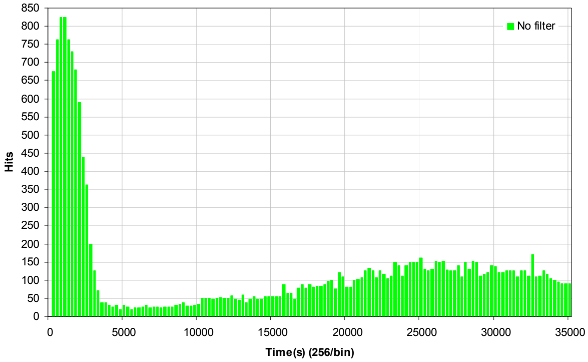


Fig. 6. Hit parameters in time domain (Prateepasen et al., 2006c)

The Epit value was identified from the polarization curve of potentiodynamic tests. The electrical noise was detected by the AE sensor. However, it was a small signal and was filtered out by the threshold setting. The frequency response of the AE in this experiment is illustrated in Figure 6 where the average frequency of corrosion signals in frequency domain analysis is around 110 kHz. The time domain analysis was shown. AE parameter hits and amplitude showed correlation with pit growth. There were high numbers of hits in the initial corrosion period; then the number of hits decreased, and rose again in the next stage of pitting. Figure 7 shows a pitting corrosion in the specimen.

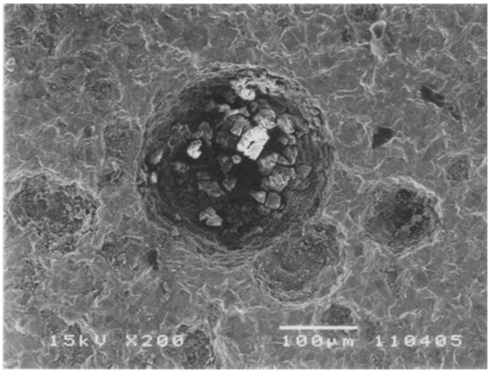


Fig. 7. Pitting corrosion in the specimen

5. AE source recognition in pitting corrosion process using acoustic parameter

Continuing researches have been performed, and AE source recognition in the pitting corrosion process was proposed by Jirarungsatian & Prateepasen (2010). The AE source was assumed to divide into three groups. The mechanism of pitting corrosion shown in Figure 4 and the theory of cut-off frequency of the bubble activity including the results from the experiment were used to support the assumption. Three AE sources are as follows:

1. Bubble activities by using the resonance frequency (formation oscillation and collapse).
2. Primary passive film and repassive film breakage by using duration time relating to the initial time of metastable pit formation according to electrochemical analysis.
3. Pit growth or pit propagation related to the time of occurrence and pitting corrosion mechanisms.

Experimental work has been done to validate the cut-off frequency. The electrochemical potential was set up and kept constant with the potential level of 0.3041 V (Ag/KCl) using the potentiostat. Its level was chosen from a potentiodynamic test. The specimen, austenitic stainless steel (SS304) sized 4×6×0.05 cm^3, was used as the working electrode. The test was set in two conditions; one, the AE signal with bubble signal, and the other, a separate bubble signal.

Experiment setup in Figure 8 shows that the AE sensor was mounted under the container located near the hydrogen bubble. In this case, AE breakage of the hydrogen can be captured by the sensor.

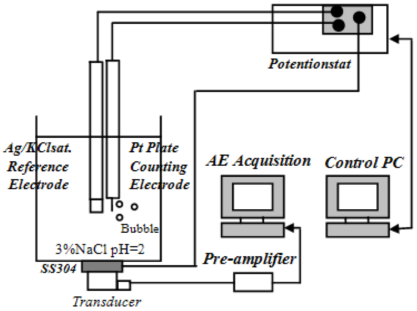


Fig. 8. Experimental setup for corrosion analysis *with bubbles* by AE (Prateepasen & Jirarungsatian, 2011, (pH=2,potential level =0.3041V))

The experiment was set up to eliminate the signal released from bubbles. The counting electrode was moved away from the AE sensor by using an Electrolyte Bridge (shown in Figure 9).

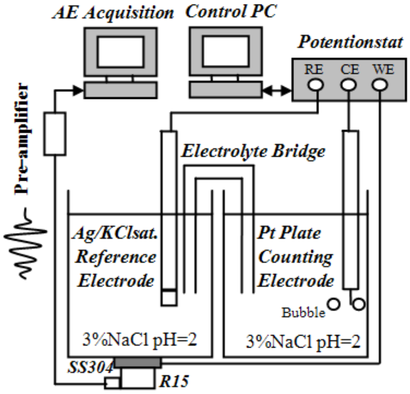


Fig. 9. Experimental setup of corrosion analysis *without bubble signals* by AE (Prateepasen & Jirarungsatian,2011, (pH=2,potential level =0.3041V))

In the theory of cutoff frequency of the bubble, the cutoff frequency of the bubble breakage can be calculated by the following equation (Leighton, 1994).

$$\nu_0 \approx \frac{1}{2\pi D}\sqrt{\frac{3\gamma P_0}{\rho_0}} \tag{3}$$

From the experimental results, the largest bubble diameter obtained from pitting corrosion was approximately 0.9 millimeters (stable bubble size, D). Typical bubbles are shown in Figure 10. The value of the liquid density (ρ_0) was 1000 kg/m^3. The bubbles were assumed to be filled with an ideal gas, with a specific heat coefficient γ = 1.4, and the liquid was assumed to be nearly incompressible with static pressure P_0 = 3.110×107 kg/m.s^2.

The cut-off frequency calculated from equation 3 is 125 kHz. It is shown that the AE activity above 125 kHz is released from bubble activity.

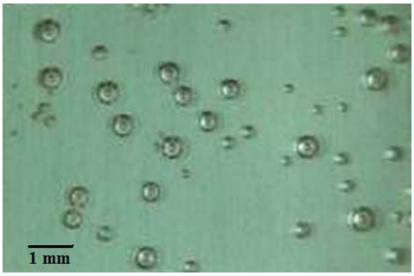
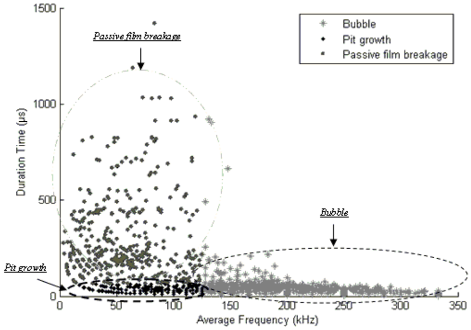
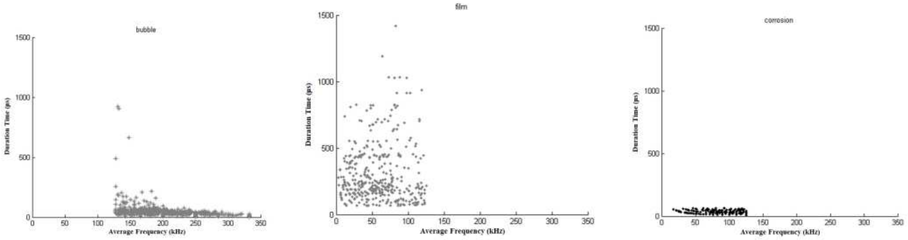


Fig. 10. Examples of hydrogen bubbles on the test specimen in a pitting corrosion process

Results from the experiment showed that the frequency of most AE activities in the time domain collected from the setup of AE with bubble is above 125 kHz. In addition, AE data captured from the setup of the separated bubble exhibited the frequency below 125 kHz. The AE signal of all three sources (with bubble breakage) in the time domain was plotted. A scatter plot of AE duration time and average frequency is shown in Figure 11. Figure 11b shows the AE signal obtained from the bubble breakage. The calculated cut-off frequency at 125 kHz was used to separate the bubble source from all AE sources in Figure 11a.



a) All AE sources (Jirarungsatian& Prateepasen, 2010)



b) Bubble (*) c) Passive film rupture (♦) d) Pitting corrosion (♦)

Fig. 11. Source identification of pitting corrosion by AE parameter (Jirarungsatian& Prateepasen, 2010)

In order to classify the AE signal sources obtained from pit growth and passive film breakage, AE duration time of 65 microseconds was used as a threshold. AE released from breakage of passive film decreased at the time of the initial metastable pit formation. In this stage, re-passivating took place, and then the amount of film rupture was reduced (Jirarungsatian& Prateepasen, 2010). The AE signals obtained from the pit growth or propagation had an average duration of below 65 microseconds and frequency between 3-125 kHz. The cumulative total of detected signals (cumulative hits) of AE from pit growth was lower than that from film rupture during the pit nucleation stage.

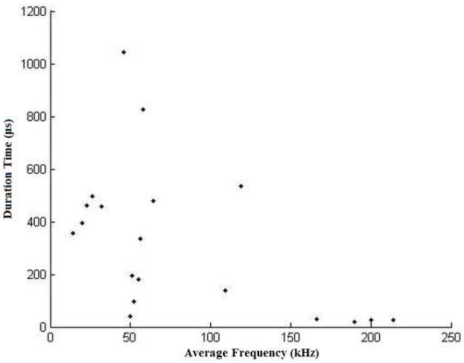


Fig. 12. AE signal from pitting corrosion tests of an undetectable acoustic bubble (Jirarungsatian& Prateepasen, 2010)

6. Novel work in acoustic emission for pitting monitoring

The development of pitting corrosion monitoring will be presented in three parts: implantation of AE source recognition, classification of severity, and location prediction by using FPGA.

6.1 Implementation of acoustic emission source recognition for corrosion severity prediction

Knowledge of source recognition for corrosion severity was implemented by Prateepasen & Jirarungsatian, (2011). To show the relationship between each AE source and the corrosion rate, the AE hit rate in the time domain was used to predict the corrosion rate. The total AE sources of pitting corrosion were divided into two groups: bubble breakage and metal corrosion including rupture of a passive film. Consequently, each AE source was plotted to show the relationship between the hit rate and the severity of pitting corrosion, represented by the pit depth (Figure 13). In this research, the severity of corrosion varied from 0.1 to 0.5 mm of pitting.

Both the progression of pitting with rupture of the passive film, and bubble breakage alone, showed a high correlation with the pit depth. In the other words, each AE source can be used to predict the corrosion rate. The benefit of source recognition can be utilized in the corrosion field test. The environmental noise can be avoided by selecting the AE source at a frequency range that is different from the background noise.

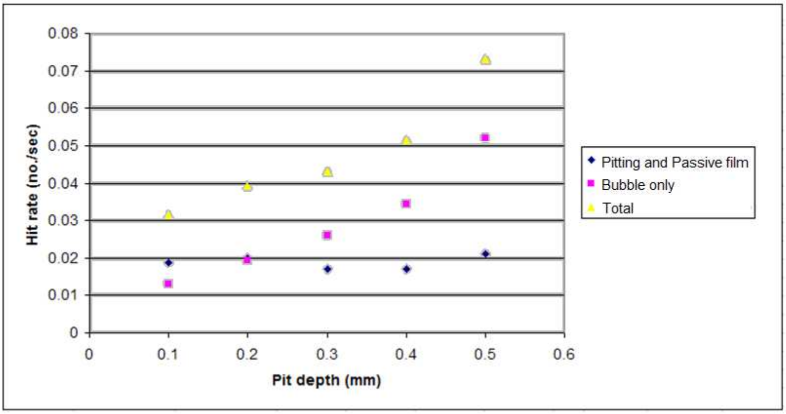


Fig. 13. The relationship between the AE hit rate and pit depth of various AE sources Prateepasen & Jirarungsatian, (2011)

6.2 Classification of corrosion detected by AE signal

The corrosion severity is ranked roughly into five levels based on the depth of corrosion by using a Feed-Forward Neural Network (Saenkhum et al., 2003) and Probabilistic Neural Network (Jirarungsatean et al., 2003]. The classification performance is very good. The error prediction rate is low. After that, the practical classification techniques based on Bayesian Statistical Decision Theory, namely Maximum A Posteriori (MAP) and Maximum Likelihood (ML) classifiers, were presented. A mixture of Gaussian distributions is used as the class-conditional probability density function for the classifiers. Although the mixture model has several appealing properties, it still suffers from model-order-selection and initialization problems. A semi-parametric scheme for learning the mixture model is therefore introduced to solve the difficulties. The result of its performance was compared with a Conventional Feed-Forward Neural Network and Probabilistic Neural Network. The results show that our proposed methods gave much lower classification-error rates and also far smaller variances than those of the classifiers.

Classifier	Overall Performance			
	Minimum	Maximum	Average	Variance
MAP	98.97	99.74	99.26	0.010
ML	98.68	99.52	99.03	0.014
FFNN (Saenkhum et al., 2003)	84.73	98.85	90.65	3.115
PNN (Jirarungsatean et al., 2003]	89.62	99.13	97.33	1.418

Table 1. Overall Performance of Classifiers

6.3 FPGA-PC AE low-cost system for source location

The AE system generally can inform of the location of the AE source. The technique uses the measurement of time differences for acceptation of the stress wave at a number of sensors in an array. There are three types of location techniques, which are linear location, two dimensions, and three dimensions. In the application of corrosion, the two-dimensional technique is generally used.

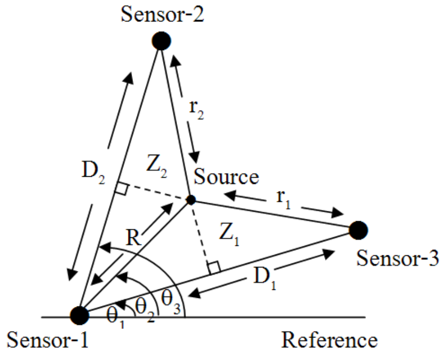


Fig. 14. Three-sensor array in two dimensions (Jomdecha et al., 2007).

In Figure 14, the distance and angle of the AE source from sensor 1 can be determined by solving the following set of equations (McIntire, 1987) (Jomdecha et al., 2007).

$$R = \frac{1}{2}\frac{D_2^{\,2} - \Delta t_2^{\,2} V^2}{\Delta t_2 V + D_2 \cos(\theta_3 - \theta_0)}, \text{ and } R = \frac{1}{2}\frac{D_1^{\,2} - \Delta t_1^{\,2} V^2}{\Delta t_1 V + D_1 \cos(\theta_0 - \theta_1)} \tag{4}$$

where Δt_1 and Δt_2 are the time differences between sensors 1 & 2 and 1 & 3, respectively.

The time difference parameters can be obtained by simple thresholding or cross-correlation techniques. Solving the set of equations gives the location of the source in a polar form (R, θ) as illustrated in Figure 14.

A novel low-cost location system, namely FPGA, was proposed by Jomdecha et al. (2004, 2007). It was designed for multi-channel high speed counters with serial communication using VHDL (Very High Speed Integrated Circuit Hardware Description Language). When all the AE sensors were triggered, the counting data from the FPGA-based electronic front-end was sent to the PC via an RS-232 port. The FPGA was operated at approximately 30 ms per cycle. The PC was employed for analysis of the arrival time differences of sensors and, finally, the coordinates of corrosion could be estimated.

In order to prove the accuracy of identifying the location of pitting corrosion, an experiment was performed. The electrochemical environment was a 3% NaCl solution with pH 2 to facilitate the pitting corrosion mechanism. The pitting potential (E_{pit}) was controlled electrochemically with a potentiostat (Solartron 1284) to accelerate pitting corrosion. The arrival time difference of the AE signal received from the array of three AE sensors on the specimen was determined by the FPGA-PC system. The system consisted of the AE sensors, pre-amplifiers, signal conditioning unit, FPGA module, PC, and LOCAN320 AE analyzer. A two-dimensional or planar representation was used to demonstrate the results of corrosion location. Figure 15 shows a diagram of the experimental setup for corrosion source localization.

Figure 16 shows the comparison of pitting location between the real location and the location detected by FPGA. It was shown that the locations of pitting and crevice corrosion were spread around the region of the corrosion sources.

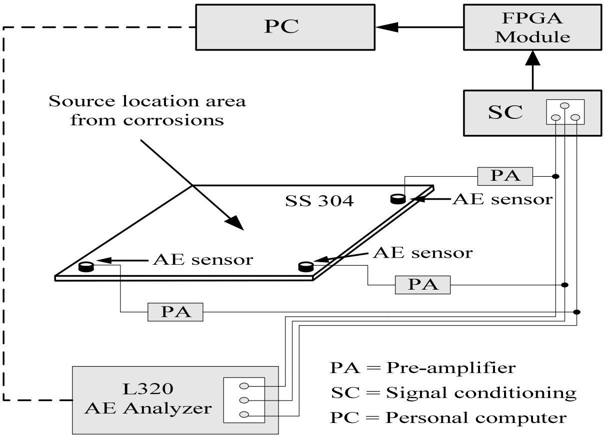


Fig. 15. Three AE sensor array and the system for source location (Jomdecha et al., 2007)

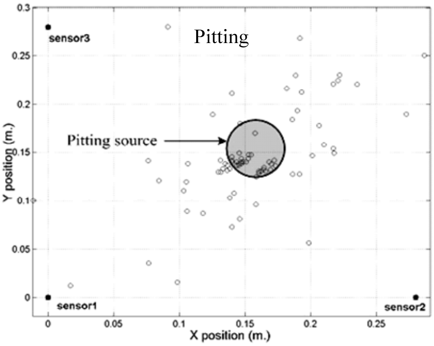


Fig. 16. Comparison of pitting location between real location and location detected by FPGA (Jomdecha et al., 2007)

7. Conclusions

Pitting corrosion detected by AE was explained. AE sources released from the pitting corrosion process were studied to determine the mechanism, and explained. Experiments were performed to classify types of AE source into three groups: bubble activities, primary passive film and repassive film breakage, and pit growth or pit propagation. Subsequently, each type was used to plot the relation with pitting growth. It is a novel technique and provides important benefit to implement in corrosion field test. An artificial network was utilized to classify pitting severity. A neural network was first used and then a SEMI PARAMETRIC technique was developed. The location of pitting was shown by the novel low-cost technique, FPGA. The advantage of AE compared to other techniques is that AE is a real-time and less intrusive technique.

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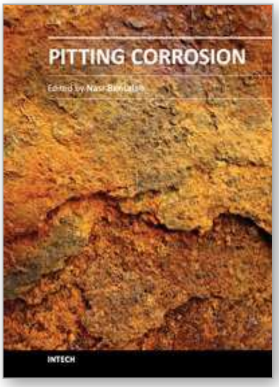

Pitting Corrosion
Edited by Prof. Nasr Bensalah

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Taking into account that corrosion is costly and dangerous phenomenon, it becomes obvious that people engaged in the design and the maintenance of structures and equipment, should have a basic understanding of localized corrosion processes. The Editor hopes that this book will be helpful for researchers in conducting investigations in the field of localized corrosion, as well as for engineers encountering pitting and crevice corrosion, by providing some basic information concerning the causes, prevention, and control of pitting corrosion.

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