INVESTIGATION OF PIPELINE STEEL FRACTURE OF USING ACOUSTIC EMISSION MONITORING

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Abstract

T*he acoustic emission (AE) monitoring technique is widely used in mechanical and materials research for detection of plastic deformation, fracture initiation and crack growth. However, the quantitative dependences of the AE signal parameters on material fracture parameters are not completely understood. This paper presents recent research results on AE monitoring of the fracture behavior of X80 line pipe steel, a critically important material for the oil and gas transportation industry. Fracture of this steel was studied using tensile testing of small scale specimens coupled with AE monitoring and high speed video camera. The dependence of fracture behavior and AE parameters on loading conditions (strain rate and presence or absence of a notch) was investigated. The AE parameters were analyzed using the "Average Hit" features and "Wave Form and Power Spectrum" methodologies. The fracture surface was characterized using scanning electron microscopy and a dependence of the AE parameters on the average void size has been obtained*.

Keywords: acoustic emission monitoring, tensile testing, fracture, pipeline steel

1. INTRODUCTION

Acoustic Emission (AE) is a phenomenon in which transient stress/ displacement waves are generated following rapid release of energy from localized sources such as crack initiation sites, fracture propagation and dislocation motion in metals [1, 2].The elastic energy is transmitted through the material in the form of transient elastic waves and can be detected by sensors on the surface of a specimen. The sensor converts elastic waves to the electric signals which are then processed and analyzed by special hardware and software. AE signal analysis is often complicated due to background noise generated by friction or machine work [3]. AE monitoring has been widely used to investigate the fracture behaviour of metals. Mukhopadhya et al. [4] studied AE generated by the dislocation movement in an austenitic stainless steel sample. Chuluunbat at al [5] investigated the effect of loading conditions on fracture behaviour of aluminium alloy using AE monitoring during tensile testing. Yusof at al [6] studied AE activity of X70 pipeline steel subjected to fatigue. The crack initiation was found to increase the AE count value at positive peak stress. Capelle at al [7] compared the local fracture of pipeline steels, such as X52, X70 and X100, using three-point bending tests to analyse the effect of hydrogen concentration on fracture while simultaneously recording AE. The AE technique was used to identify the onset of fracture. Drew at al [8] used AE during tensile testing of X42, X60 and X65 pipeline steels. It was found that the amplitude of events was relatively small and the number of events was low. Most of AE activity detected at around yield point was for the high strength X65 steel. Chuluunbat at al [9] applied the AE monitoring technique to study the effect of loading conditions (temperature and strain rate) on fracture initiation and propagation during tensile testing of X70 pipeline steel. The crack initiation and propagation was observed by a high speed video camera. It was shown that the fracture mode and relative magnitude of mode-dependent AE signatures are affected by the strain rate, low temperatures and features of the sample notch simulating a crack.

Some researchers studied the relationship between AE features (such as signal amplitude, frequency, energy and duration) and mechanical parameters (load, stress and crack growth) during tensile deformation of notched or plain specimens [10-13]. However, the quantitative influence of AE parameters on the fracture parameters is not completely understood to date. In the present study, the effect of loading conditions on fracture behaviour was studied using AE monitoring of the tensile testing of X80 pipe line steel samples. The fracture initiation and crack propagation were observed using high speed video camera. The load-displacement curves were correlated to the AE parameters to obtain a dependence of the AE features on the fracture propagation parameters.

2. EXPERIMENTAL PROCEDURE

Tensile testing. A pipe line API-X80 steel was used in this study (Table 1). The tensile tests to failure were carried out using a Kammrath and Weiss GmbH tensile stage. The samples were prepared from a pipe with 25 mm wall thickness and 1067 mm diameter and the tensile direction was parallel to the rolling direction. Tensile specimens were of 5 mm width, 0.6 mm thickness and 13 mm gauge length and single edge notch tensile specimen had initial crack of 1 mm length. The 0.3 mm wide notch was cut using wire cutting. The crack (notch) length was equal to 0.2 of the specimen width. The crack propagation and crack path during tensile testing was observed using a stereo optical microscope Leica M205A with video recording capability. The test conditions are shown in Table 2. Three specimens were tested for each condition. Only one typical result will be shown and discussed below for each condition.

Table 1. Composition of X80 pipeline steel.

C	Si	Mn	P	S	Cu	Alt	Nb	Ni	Cr	Ti	Ceq	Pcm

0.064	0.22	1.72	0.006	0.002	0.23	0.027	0.068	0.206	0.22	0.0158	0.42	0.18

Table 2. Testing conditions.

Testing condition	A	B	C	D
Strain rate	$0.3x10^{-3}$ s^{-1}	$0.3x10^{-3}$ s^{-1}	$0.9x10^{-3}$ s^{-1}	$0.9x10^{-3}$ s^{-1}
Specimen type	Plain	SENT	Plain	SENT

AE monitoring. During the tensile test, the AE was recorded using an AE acquisition system manufactured by Physical Acoustics Corporation (USA).The system consisted of a single channel AE Digital Signal Conditioner (card) with a built-in low noise preamplifier and a USB connection to a computer. One general purpose wideband sensor (WSα) was used in this study. Its operating frequency range was100-1000 kHz and temperature range was -65°C to + 175 °C. During testing the sensor was mounted on the specimen using ultrasound treatment gel as a coupling material to improve the signal quality. The experimental setup is shown in Fig.1. The variations in AE parameters were analyzed using the 'Average Hit Features' and 'Wave Form and Power Spectrum' methodologies and correlated to the load-displacement curves obtained during testing.

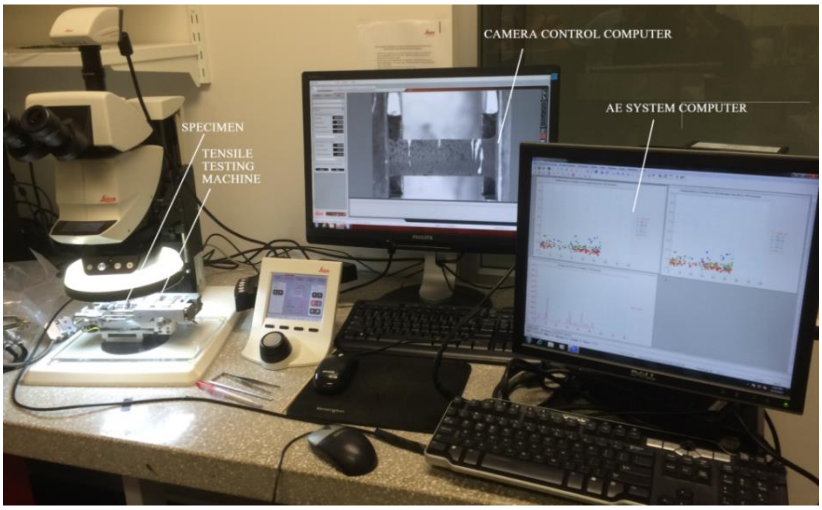
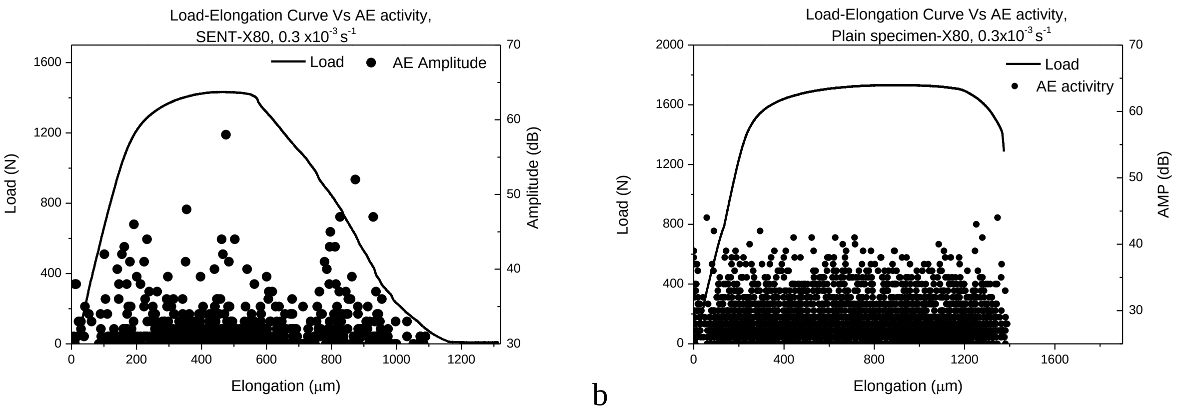


Fig.1.The experimental setup of the tensile testing coupled with AE monitoring.

3. RESULTS AND DISCUSSION

Variation in AE parameters along the load-displacement curve

For the AE signal analysis, the load displacement curve was divided into three regions: 1- before the yield point, 2- between the yield point and the peak stress, and 3- after the peak stress. During testing of the notched specimen at a slow strain rate, the AE activity was recorded as shown in Fig. 2a. In region 1several hits were recorded before yielding due to the stress concentration around the notch tip leading to fast crack growth via small increments. In region 2 the AE hit density decreased, compared to Region 1, as the crack growth rate decreased. In region 3 the AE activity (hit density and signal amplitude) increased again, following an increase in the crack growth rate. This increase in AE activity continued until the final fracture. The main AE signals observed in region 3 were of up to 60 dB amplitude and up to 500 kHz average frequency.



a b

Fig. 2Load-displacement curves vs AE amplitude at 0.3E-03 s^{-1} strain rate: a) single edge notched specimen, b) plain specimen.

During testing of the plain (without a notch) specimen at a slow strain rate, the AE activity was different compared to that for the notched specimen, as shown in Fig. 2b. In region 1 few AE hits were recorded before the yield point, which can be explained by the weakness of signals coming from the elastic tension and the absence of fracture. In region 2 the AE activity was growing due to plastic deformation in this region. The main signals had up to 50 dB amplitude and up to 250 kHz average frequency. In region 3 the necking was observed, the AE activity was weak. However, a strong ~100 dB signal was generated by the final fracture of the specimen.

For the notched specimen with an increase in strain rate the AE hit density significantly increased in all the regions of the load-displacement curve (compare Figs. 2a and 3a). This can be related to an increase in crack growth rate with an increase in strain rate. The AE activity trend with strain, i.e. a higher hit density around the yield point followed by a decrease in it after the peak stress and an increase in it during final fracture, was similar to the test with slower strain rate. This reflects a similarity in the crack growth rate variation with strain for both strain rates. The amplitude of some hits reached 50dB, which is slightly higher compared to the slow strain rate tests. No significant variation in the AE average frequency was observed. For the plain specimen with an increase in strain rate the AE hit density increased significantly during the work-hardening period (Fig. 3b). This can be explained by a higher deformed volume of the plain specimen compared to the notched specimen. The AE signal amplitude slightly decreased down to a maximum of 50 dB, compared to the 70 dB signals recorded at slower strain rate. The average frequency increased to up to 300 kHz, compared to the maximum 200 kHz signals recorded at slower strain rate.

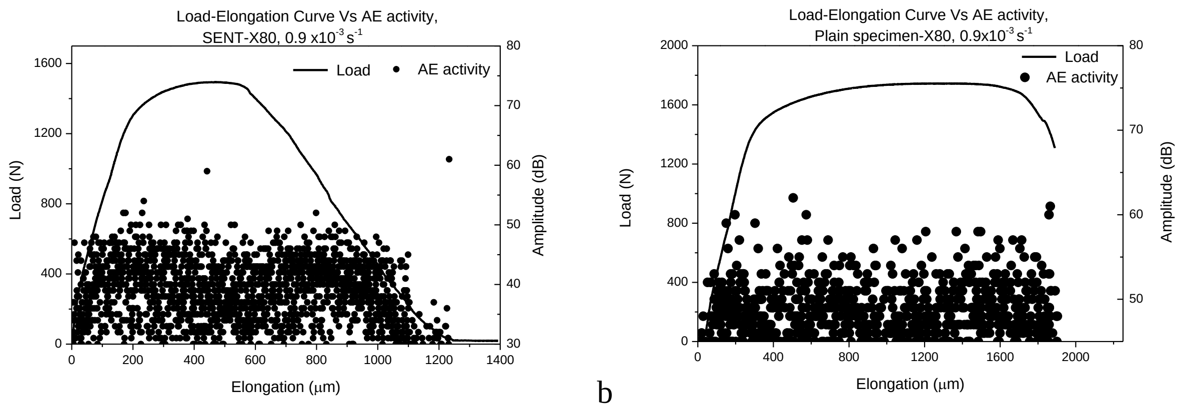


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Fig. 3Load-displacement curves vs AE amplitude at 0.9E-03 s^{-1} of strain rate: a) single edge notched specimen, b) plain specimen.

Fracture surface analysis

In all the tests conducted in this work, the fracture was ductile. From fracture mechanics, it is known that the ductile crack growth is characterized by micro void nucleation, growth and coalescence. As the specimen is loaded, local strains and stresses at the crack tip become sufficient to nucleate voids and these voids grow as the crack blunts, and link with the main crack [14]. Scanning electron microscopy (SEM) has been used to observe the fracture surfaces for all four studied conditions (Fig. 4).

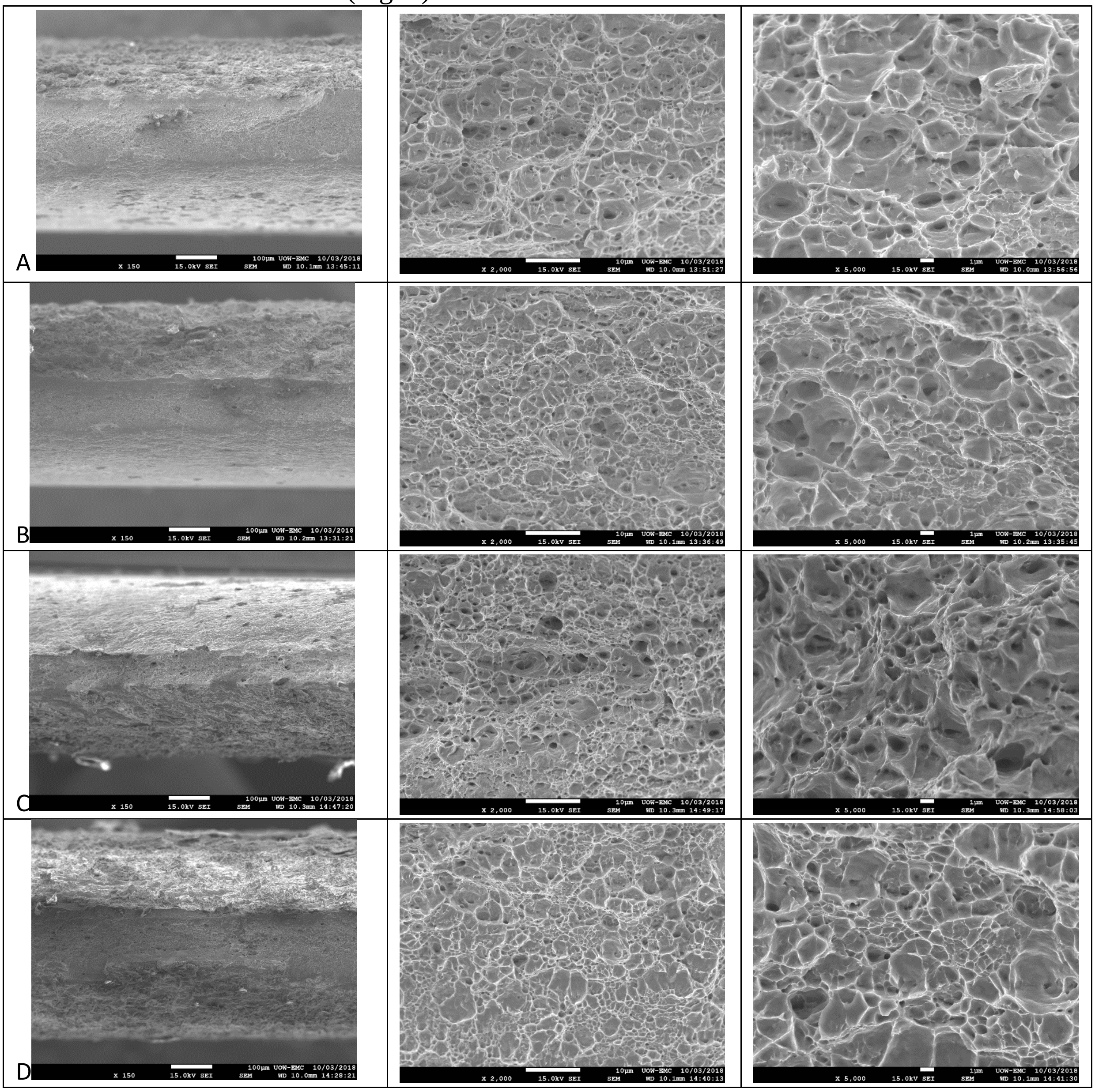

Fig. 4SEM imaging of fracture surfaces for four studied conditions (A, B, C and D according to Table 3) at three magnifications: x150, x2000 and x5000.

The average void size decreased with an increase in strain rate for both specimen types (Table 3). This corresponds to previously reported results [15] and may indicate a transition towards a more brittle fracture behavior with an increase in strain rate. The average void size was larger for plain specimens compared to this for the notched specimens. This corresponds to a larger fraction of <1 μm voids and a lower fraction of >1.5 μm voids for the notched specimens observed on the void size distributions (Fig. 5). A notch is known to increase the stress concentration leading to increased crack growth rates. Thus, for SENT specimens the time available for voids coalescence prior to local fracture was shorter, compared to the plain specimens, and the void size appeared being smaller.

Table 3 Average void size with a various testing condition.

Testing condition	A	B	C	D
Strain rate	$0.3x10^{-3}$ s^{-1}	$0.3x10^{-3}$ s^{-1}	$0.9x10^{-3}$ s^{-1}	$0.9x10^{-3}$ s^{-1}
Specimen type	Plain	SENT	Plain	SENT
Average Void size	1.58 µm	1.23 µm	1.46 µm	1.19 µm

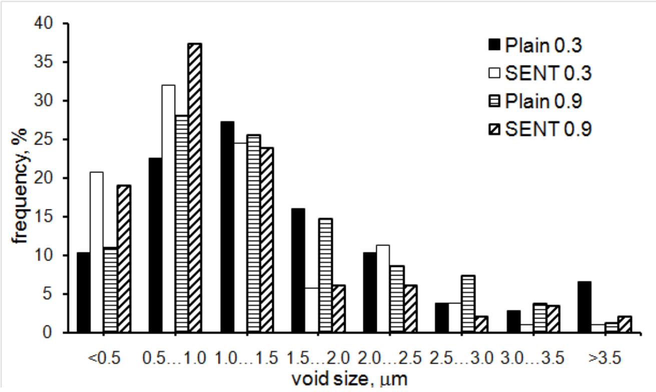

Fig. 5.The void size distributions for fourstudied test conditions.

AE waveform and power spectrum analysis

Table 4 Waveform parameters at strain rate of $0.9x10^{-3}$ s^{-1}.

Specimen type	Region	Suggested cause of AE	Amplitude, dB	FFT power spectrum frequency peak, kHz
Single edge notch	I	Elastic tension, void nucleation	30	80-150
	II	Plastic deformation (voids growths and coalescence)	<35-70	>150
	III	Ductile crack growth, final fracture	>40	>200
Plain specimen	I	Elastic tension	<40-60	70-120
	II	Dislocation pile-up	<30	>100
	III	Ductile crack growth, final fracture	>30	>250

Observation of the AE waveforms did not show a significant variation in their shape for specimens of different type (Fig.3a and Fig.3b) However, the power spectra corresponding to the loading Regions I and II showed a larger number of high frequency peaks for the notched specimen, compared to that for the plain specimen (Table 4). This can be explained by the variation in deformation development: in the notched specimen, crack growth is the dominant deformation mode, and the plain specimen deforms predominantly via the dislocation motion. During the final loading stage (Region III in Figs.3a and Fig. 3b) the power spectra looked similar for both specimen types, this can be related to the similarity in their fracture modes. As can be seen from Table 4, the power spectrum peaks occur at slightly higher frequencies for the notched specimen compared to these for the plain specimen.

4. CONCLUSION

AE monitoring of tensile testing of X80 pipe line steel has shown the following:

1. The AE activity starts before the yield point for the notched specimen, due to stress concentration at the crack tip, and after the yield point for the plain specimen, due to dislocation motion. An increase in strain rate leads to increased AE activity, i.e. an increase in the AE hit density.

2. The fracture initiation point can be identified by the AE monitoring technique. For the notched specimen the fracture initiation led to an AE signal with 60 dB and 300 kHz.
3. For the tested pipe line steel the peak frequency of power spectrum for the ductile fracture was lower than 150 kHz.
4. Scanning electron microscopy helped to investigate the dependence of void sizes on test parameters. With an increase in strain rate the void sizes decreased. Notched specimens exhibited smaller voids. The void sizes can be used to characterize transition from ductile to brittle fracture behavior.

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