A STUDY OF STRESS CORROSION CRACKING IN HIGH STRENGTH STEELS USING ACOUSTIC EMISSION TECHNIQUES

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ABSTRACT

High levels of acoustic emission activity have been observed during stress corrosion cracking of high strength steels. Under controlled laboratory conditions, quantitative relationships can be obtained between the amount of acoustic emission and the extent of fracture. The characteristics of the acoustic emission are influenced by the crack morphology, transgranular cracking producing less acoustic emission activity than intergranular cracking for steels of similar strengths. In the case of intergranular fracture the acoustic emission during stress corrosion cracking increases with increasing grain size.

Tests have also been conducted in hydrogen gas at low pressure. Similar cracking is found in this environment as observed during stress corrosion cracking. In both environments it is considered that it is the hydrogen atom which is responsible for cracking and that the detailed differences in cracking and acoustic emission activity are associated with the distribution and availability of hydrogen in the region of the crack tip.

KEYWORDS

Acoustic Emission Tests, Stress Corrosion Cracking, High Strength Steels, Hydrogen Embrittlement.

INTRODUCTION

The operation of structures in contact with aggressive environments can sometimes lead to premature failure, due to the conjoint action of stress and an aggressive environment. This type of fracture is called stress corrosion cracking. Cathodic corrosion reactions occurring at a metal surface produce hydrogen atoms, which may diffuse into the metal and cause embrittlement. High strength steels can be particularly susceptible to stress corrosion and the fracture mechanism often involves the hydrogen atom. Acoustic emission techniques offer the possibility of studying the details of stress corrosion cracking, since some of the elastic energy released during fracture is transmitted in the form of elastic waves which travel through the lattice of the metal and can be detected by a suitable transducer located on an external surface.

The work described in this paper has examined acoustic emission during stress corrosion cracking in high strength steels under controlled laboratory conditions. Attention has been paid to the influence of metallurgical variables, environment and cracking morphology on the characteristics and quantity of acoustic emission during stress corrosion cracking. This has helped to establish the factors governing the generation of acoustic emission during stress corrosion cracking and to obtain an insight into the detailed mechanisms of crack extension.

MATERIALS AND EXPERIMENTAL PROCEDURES

Details of the composition and mechanical properties of the high strength low alloy steels used are given in table 1. After precracking by fatigue in air, the test pieces were tested in either a solution of 3.5% NaCl in deionised water, which was introduced into the notch region of the test piece, or in hydrogen gas at pressures in the range .025-0.1 MPa (190-760 torr). Crack extension was monitored by the direct current electrical resistance technique.

TABLE 1 Materials Used for Stress Corrosion studies

Steel	Element, wt.%									0.2% Proof Stress MPa	K_{IC} $MNm^{-3/2}$
	C	S	P	Si	Mn	Ni	Cr	Mo	V		
817M40	0.34	0.045	0.030	0.23	0.55	1.60	1.13	0.30	0.01	1440	56
897M39	0.33	0.010	0.013	0.35	0.54	0.22	3.00	0.87	0.21	1440	69
835M30	0.31	0.024	0.012	0.24	0.49	4.11	1.21	0.24	-	1350	75
AISI 4340	0.40	0.007	0.004	0.29	0.73	1.77	0.85	0.23	-	1450	54

Acoustic emission measurements were made with commercially available equipment. In some tests, only the total number of acoustic emissions with amplitudes above a pre-set threshold level were recorded as a function of the crack length. In others, the energy associated with emissions possessing amplitudes over a 26dB dynamic range above the background noise level was recorded. Simultaneous measurements of the amplitude of the emissions were also made during some of the tests to establish how the amplitude of the emissions is influenced by the environment, the microstructure and fracture path of the steel, and the stress intensity acting at the crack tip.

After testing fractographic examinations were conducted by scanning electron microscopy.

EXPERIMENTAL RESULTS

The Initiation of Stress Corrosion Cracking in High Strength Steels

During stress corrosion tests substantial incubation periods were sometimes observed prior to the detection of the onset of activity at the crack tip by the electrical resistance method. When this occurred, significant and increasing levels of acoustic emission activity were often recorded before any crack extension was indicated.

In order to examine the source of this acoustic emission a test piece was loaded in air. The acoustic emission activity was found to be transient in nature and soon returned to the level of the background noise. This indicates that the acoustic emission during the early stages of the stress corrosion tests is not associated with noise produced during the loading process, but by localised cracking in favourably oriented grains.

Correlation of Acoustic Emission Parameters with the Extent of Stress Corrosion Cracking

Close similarity was found between the variation of the number of ringdown counts and crack length with time and the variation of total acoustic energy and crack length with time during the stress corrosion testing of all the steels examined. Typical examples are shown in Figs.1 and 2. The sensitivity of the technique is further illustrated by comparing the rates of acoustic energy release with simultaneously measured crack growth rates for the steels examined, as shown in Figure 3. Good correlation between acoustic emission and crack length was observed and rapid increases in both the rate of acoustic energy release and the crack growth rate occurred as the conditions for unstable crack propagation were attained.

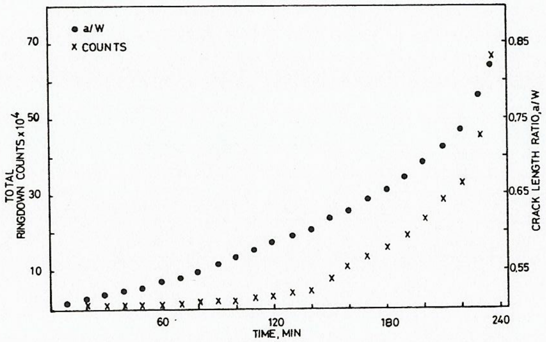

Fig. 1. Acoustic Emission Ringdown Counts During Stress Corrosion of 817M40 Steel

Acoustic emission energy measurements produced better agreement with the crack length monitoring measurements than ringdown counting methods (see Figs.1 to 3). This is perhaps not surprising in view of the approximately linear relationships between the sums of the squares of acoustic emission amplitudes (a measure of the acoustic emission energy) and the incremental area of crack growth during stress corrosion cracking, indicated by Hartbower & co-workers (1968) and Bartle (1975). Linear relationships between cumulative acoustic emission energy and the area of crack growth during the early stages of stress corrosion cracking were observed for the steels examined in this work, as seen for example in Fig.4 Note the non-linearity in the data for the large grain steel corresponding to a crack increment of approximately 1 grain (2.5 mm^2). This is due to the greater sensitivity of the acoustic emission technique to the initial stages of cracking.

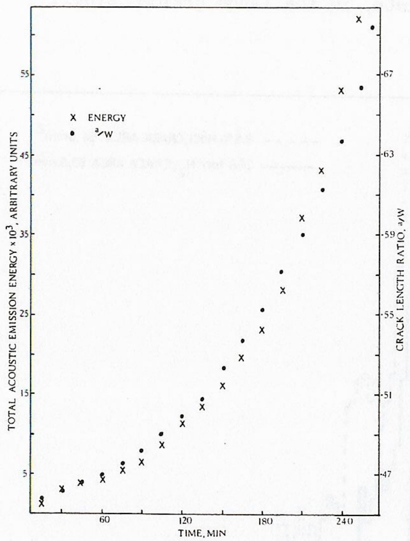

Fig. 2. Acoustic Emission Energy During Stress Corrosion Cracking in 817M40 Steel.

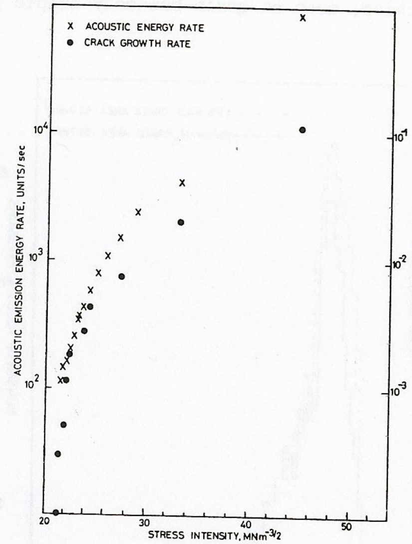

Fig. 3. Acoustic Emission Energy Release Rate and Crack Growth During Stress Corrosion in 817M40 Steel.

Acoustic Emission during Stress Corrosion Cracking in 3.5% NaCl Solution

Previous work (McIntyre 1973) had shown that the K_{ISCC} value for each of the steels in 3.5NaCl solution was in the range 10-20MNm$^{-3/2}$. Table 2 shows the level of acoustic emission energy during the early stages of crack propagation in each of the steels. For steels of similar strength levels, transgranular stress corrosion cracking appears to produce less acoustic emission than intergranular cracking. This is supported by a decrease of an order of magnitude in the number of ringdown counts associated with stress corrosion cracking in 897M39 steel compared with 817M40 steel, which crack transgranularly and intergranularly respectively. Acoustic emission amplitude measurements shown in Figure 5 demonstrate that fewer and lower amplitude acoustic emissions are generated during transgranular stress corrosion in 897M39 steel, than in the intergranular cracking in AISI 4340 steel.

Increasing the grain size produces higher levels of acoustic emission during intergranular stress corrosion cracking, as shown in Table 2 and Fig.4. Higher amplitude acoustic emissions are generated during cracking in large grained steels, as shown in Fig.6.

Acoustic Emission during Stress Corrosion Cracking in Gaseous Hydrogen

All the steels have K_{ISCC} values in hydrogen gas similar to those found in NaCl solution (McIntyre 1973). Crack growth rates at similar crack tip stress intensities are found to be at least an order of magnitude greater than in

sodium chloride solution and identical fracture mechanisms operate during stress corrosion cracking in both environments.

Linear relationships are found between cumulative acoustic emission energy and the extent of stress corrosion cracking; the values obtained being given in Table 2.

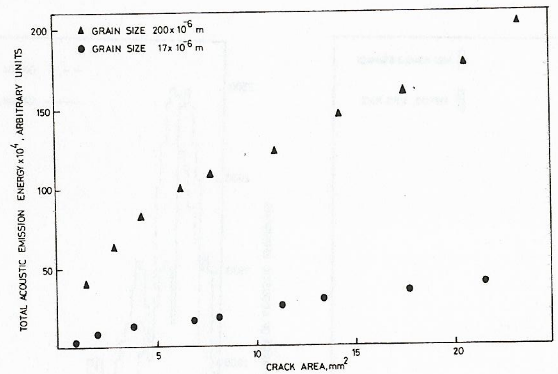

Fig. 4. Acoustic Emission Energy During Stress Corrosion in AlSl 4340 Steel

In the case of 817M40, 835M30 and AISI 4340 steels, which fracture in an intergranular manner, the acoustic emission energy assoicated with fracture in hydrogen gas is found to be greater than that in sodium chloride solution. Acoustic emission amplitude measurements made during the stress corrosion cracking of AISI 4340 steel shown in Fig.7 demonstrate that a greater number of higher amplitude acoustic emissions are generated during stress corrosion in hydrogen gas than in sodium chloride solution.

897M39 steel, in which the predominant fracture mechanism during stress corrosion cracking is transgranular, generates less acoustic emission during stress corrosion cracking in gaseous hydrogen than in sodium chloride solution, although the crack growth rate increases. This observation is supported by acoustic emission amplitude measurements (see Fig.8). Increasing the hydrogen gas pressure increases the crack growth rate, but decreases the amount of acoustic emission generated (see Table 2).

DISCUSSION

The Sensitivity of Acoustic Emission Techniques to the Initiation of Stress Corrosion Cracking

The greater sensitivity of acoustic emission techniques to the initiation of stress corrosion cracking can be attributed to non-uniform crack propagation during the early stages of cracking. Simultaneous measurement by ultrasonic and electrical resistance techniques during stress corrosion cracking in 835M30 steel showed that cracking initiated in mid-thickness (McIntyre 1974). The extent of tunneling is limited and eventually the crack front must broaden until cracking occurs across the whole test piece thickness. The crack front then propagates as a whole. Until this stage, the extent of crack opening is limited and the electrical resistance technique underestimates the amount of crack growth. The acoustic emission techniques, being sensitive only to the elastic waves generated in the test piece does, however, detect this initial growth.

The high sensitivity of the acoustic emission technique makes it a valuable tool in the study of the initiation of stress corrosion cracking.

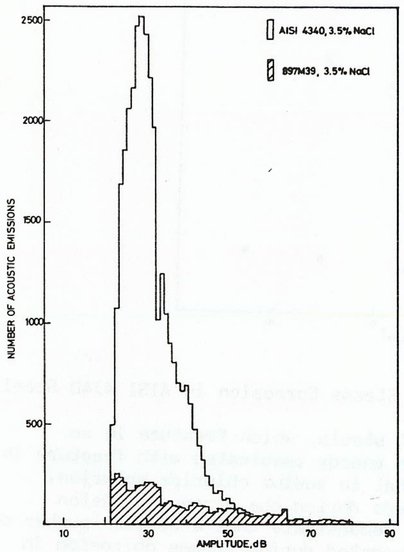

Fig. 5. Acoustic Emission Amplitude Distribution during Stress Corrosion.

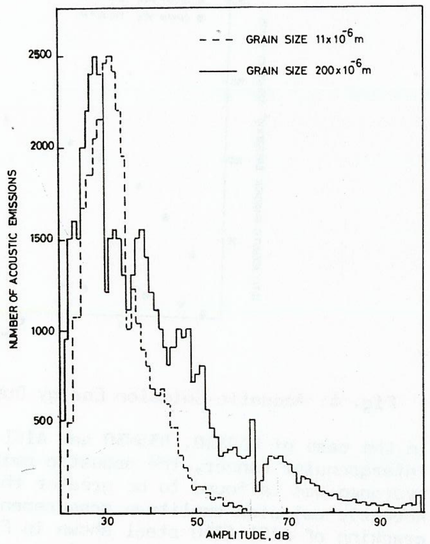

Fig. 6. Acoustic Emission Amplitudes During Stress Corrosion in AISI4340 Steel.

Influence of Crack Path on Acoustic Emission During Stress Corrosion Cracking

The experimental evidence indicates that for similar high strength steels, higher levels of acoustic emission energy are generated during intergranular stress corrosion cracking than when transgranular stress corrosion occurs. This is supported by acoustic emission amplitude measurements. If the amplitude of an acoustic emission is related to the magnitude of the cracking event producing it, then these observations suggest that the size of the cracking increments is smaller when transgranular cracking occurs than when intergranular cracking occurs. Increasing the grain size in steels which crack intergranularly shows that the basic mechanism of cracking is unaffected by grain size, but the probability of larger crack increments is increased. Earlier studies (McIntyre 1973) have shown that it is the hydrogen atom which is responsible for crack growth in both the aqueous and gaseous environments. The influence of crack path on the size of crack increment may be attributed to the greater availability of hydrogen atoms in the grain boundary regions which may act as preferential sites for hydrogen diffusion. Similarly, the influence of grain size on the size of crack increment may be explained by the increase in hydrogen concentration at grain boundaries and by the smaller number of impediments to cracking, such as grain boundary triple points, in the large grained steel.

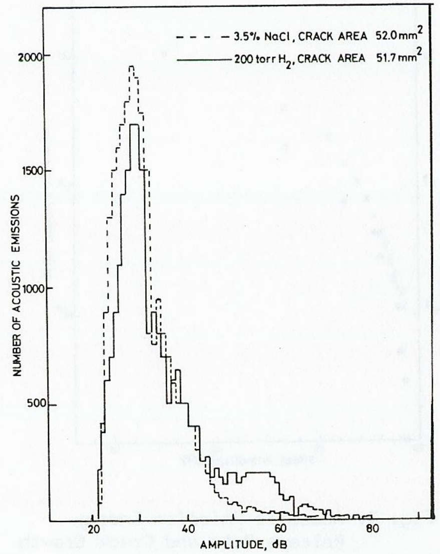

Fig. 7. Acoustic Emission Amplitudes during Stress Corrosion in AISI 4340 Steel.

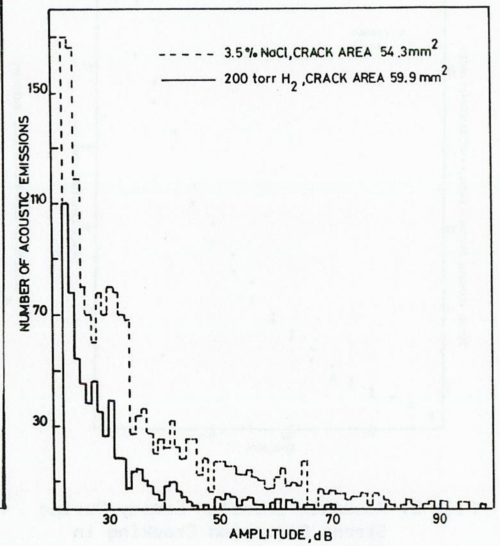

Fig. 8. Acoustic Emission Amplitudes during Stress Corrosion in 897M39 Steel.

Influence of Environment on Acoustic Emission During Intergranular Cracking

Greater levels of acoustic emission are generated when intergranular cracking occurs in hydrogen gas than for similar cracking occurring at lower velocities in sodium chloride solution. However, the acoustic emission amplitude distributions for both environments indicate generally similar characteristics. The only significant difference is the presence of a secondary peak at a larger amplitude of approximately 55dB occurring during tests in hydrogen. It now appears possible for larger crack increments to occur in hydrogen gas. This may be because of the greater availability of atomic hydrogen in the triaxially stressed region ahead of the crack tip in hydrogen gas compared with tests in sodium chloride solution.

Influence of Environment on Acoustic Emission During Transgranular Cracking

The evidence of reduced detectable acoustic emission energy, and of lower acoustic emission amplitudes indicate that crack growth in hydrogen gas occurs in smaller increments than transgranular cracking in sodium chloride solution, assuming that the acoustic emission frequencies remain similar in both environments. Since the crack velocities are much higher in hydrogen gas these smaller events must occur significantly more frequently on testing in hydrogen.

The results indicate that more severe hydrogen concentration gradients may occur close to the crack tip during tests in hydrogen gas than for tests in sodium chloride solution. The critical hydrogen concentration required for the formation of stable microcracks in the triaxially stressed region ahead of the crack tip may therefore be more easily satisfied closer to the crack tip, producing smaller increments of cracking.

The differences in behaviour in hydrogen gas and sodium chloride solution during transgranular and during intergranular fracture may well be attributable to the relative ease with which hydrogen atoms can diffuse to the triaxially stressed regions in the material via grains in the case of transgranular fracture and via grain boundaries in the case of intergranular fracture.

Table 2 Acoustic Emission Energy as a Function of Fracture Path and Test Environment for the Steels Studied

Steel	Grain Size μm	Fracture Path	Environment	$\frac{dE}{dA}$ ($10^{-5}V^2S/mm^2$)
817M40	17	INTERGRANULAR	3.5% NaCl Solution	9×10^3
	100	INTERGRANULAR	3.5% NaCl Solution	70×10^3
	17	INTERGRANULAR	H_2 at 200 torr Pressure	31×10^3
897M39	10	TRANSGRANULAR	3.5% NaCl Solution	5×10^3
	10	TRANSGRANULAR	H_2 at 190 torr Pressure	2×10^3
	10	TRANSGRANULAR	H_2 at 760 torr Pressure	1.5×10^3
AISI 4340	11	INTERGRANULAR	3.5% NaCl Solution	31×10^3
	200	INTERGRANULAR	3.5% NaCl Solution	210×10^3
	11	INTERGRANULAR	H_2 at 200 torr Pressure	87×10^3
835M30	13	INTERGRANULAR	3.5% NaCl Solution	6×10^3
	13	INTERGRANULAR	H_2 at 760 torr Pressure	3×10^3

CONCLUSIONS

Acoustic emission measurements on stress corrosion tests on high strength steels in hydrogen gas and 3.5% sodium chloride solution have shown that the technique can provide valuable insight into the processes of crack propagation. Acoustic emission data relating to crack growth for various steels and environments can be compared quantitatively with a high degree of reproducibility.

Where environmentally enhanced intergranular cracking occurs, the level of acoustic emission is higher than in the case of transgranular cracking and this may be because the size of increment by which discontinuous crack propagation occurs is larger during intergranular cracking. Increasing the grain size greatly increases the amount of acoustic emission because the formation of larger crack increments is facilitated.

The influence of environment on the crack growth process and the associated acoustic emission is strongly dependent on the fracture path. Where intergranular fracture occurs, a change from sodium chloride solution to a more aggressive hydrogen environment accelerates crack growth and larger crack increments are facilitated. In constrast for transgranular cracking, although testing in hydrogen accelerates crack growth, the acoustic emission behaviour indicates that the crack increment decreases. These observations can be explained on the basis that atomic hydrogen is responsible for cracking in both environments and that the detailed mechanism depends upon the distribution of hydrogen in the highly constrained region ahead of the crack tip, the level of triaxial stress ahead of the crack tip and the preferred crack path.

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