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ACOUSTIC EMISSION BEHAVIOR DURING STRESS CORROSION CRACKING OF INCONEL 600

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Abstract

Acoustic Emission (AE) technique was applied to stress corrosion cracking of Inconel 600 to investigate the AE capability of detecting crack growth and to obtain the relation between AE characteristics and crack mechanism. The specimens were heat-treated in two conditions (600℃ for 30 hrs or 700 ℃ for 1 hr) and undergone CERT at two extension rates (2.5×10^{-5} or 1.25×10^{-4} (mm/s)). It was found that the AE peak amplitude from plastic deformation was generally smaller than about 48dB (0.25mV), while Intergranular stress corrosion cracking (IGSCC) and ductile fracture produced higher values of 49 to 70dB (0.3mV to 3mV). The slopes of cumulative amplitude distribution (b-values) were linearly dependent on IGSCC susceptibility and the higher the susceptibility, the smaller the b-value. The monitoring of combined AE parameters such as event rate, amplitude, count and energy can provide effective means to clearly identify the transition from crack initiation and small crack growth to rapid growth of dominant cracks.

1. Introduction

Acoustic Emission (AE) technique provides unique advantages of early detection of subcritical crack growth and of recognizing when and where crack is growing. Some studies (1-4) have been conducted to investigate the capability of AE technique for monitoring environmentally assisted crack growth such as Stress corrosion cracking (SCC) and corrosion fatigue in various metals.

In this study, AE technique is applied to SCC of Inconel 600 to investigate the AE capability of detecting crack growth and to obtain the relation between AE parameters and crack mechanism such as fracture mode and crack growth rate during SCC.

2. Experimental procedure

Quantitative conditions for SCC in Inconel 600 were investigated by Was, et al..(5) who conducted

Table 1. Summary of SCC test conditions and results

Test case	ER [1] (mm/s)	HT [2]	Elong. (%)	Max. force (kN)	No. of events	% of IGSCC	S_{IGSCC}	b-value		
								Total	non-SCC	SCC
1	2.5×10^{-5}	630	1.47	0.69	142	100	0.94	1.65	-	-
2	2.5×10^{-5}	701	13.4	1.54	1301	70	0.46	2.20	3.43	2.03
3	1.25×10^{-4}	630	9.21	1.07	604	80	0.63	2.03	3.07	1.97

1) ER : Extension Rate 2) HT : Heat Treatment, 630 (600 °C for 30 hrs), 701 (700 °C for 1 hr)

a study on effects of heat treatment (HT) and extension rate (ER) on SCC through a series of electrochemical, immersion and constant extension rate test (CERT). Those conditions were applied in this study. The heat treatment of Inconel 600 specimens was conducted in two different conditions such as reheating at 600℃ for 30 hrs (630) or 700 ℃ for 1 hr (701) after annealing at 1100 ℃ for 1 hr so as to give rise to the different degrees of sensitization (DOS) at grain boundaries. The specimens were undergone CERT at two ERs , namely, 2.5×10^{-5} and 1.25×10^{-4} (mm/s) to study the effect of ER on SCC and AE response. The 0.01 M solution of sodium tetrathionate ($Na_2S_4O_6$) was used as the corrosion medium. The electrochemical potential of 200mV was applied.

The size of plate-type specimens was 220mm in length and 1.6 mm in thickness, and the gauge section was 20mm in length and 2.5mm in width. Piezoelectric AE transducers were mounted at both sides of the specimen, 50mm apart from the center of gauge section. AE data acquisition, monitoring and analysis were performed with LOCAN 320 System of Physical Acoustic Co.. The fixed amplitude threshold of 40dB (0.1 mV at the sensor) was selected to trigger AE events, considering the background noise level of 38 to 39 dB . The time difference of signal arrival at each sensor, 10μs, was set as the discriminating criterion to eliminate unnecessary AE hits due to test circumstances or the loading device. Prior to SCC testing, the specimens were loaded to 1.1 yield stress (approximately 0.7 kN) in air to eliminate , the Kaiser effect (6), namely, spurious AEs due to elastic deformation of the gauge section and at the specimen holders.

3. Results and Discussion

The test conditions and results are summarized in Table 1. The overall behavior of AE parameters obtained during the process of initial crack formation to sample failure was investigated. Table 1 shows that the test results from this study on elongation, the maximum loading force, the percent of IGSCC at the fractured surface and IGSCC susceptibility (S_{IGSCC}) with respect to the HT and ER conditions have similar trends with Was' results (5). The test results are here analyzed and evaluated from an AE behavior point of view.

The number of AE events, peak amplitude, and loading force for the case of no. 1 during SCC test are plotted in Fig.1(a). The number of events and peak amplitude in Fig.1 are the summed and the averaged values in each bin, respectively. The x-axis of Fig.1 consists of 100 bins regardless of the total elongation value. Most AE events in the case of no.1 are supposed to be originated from

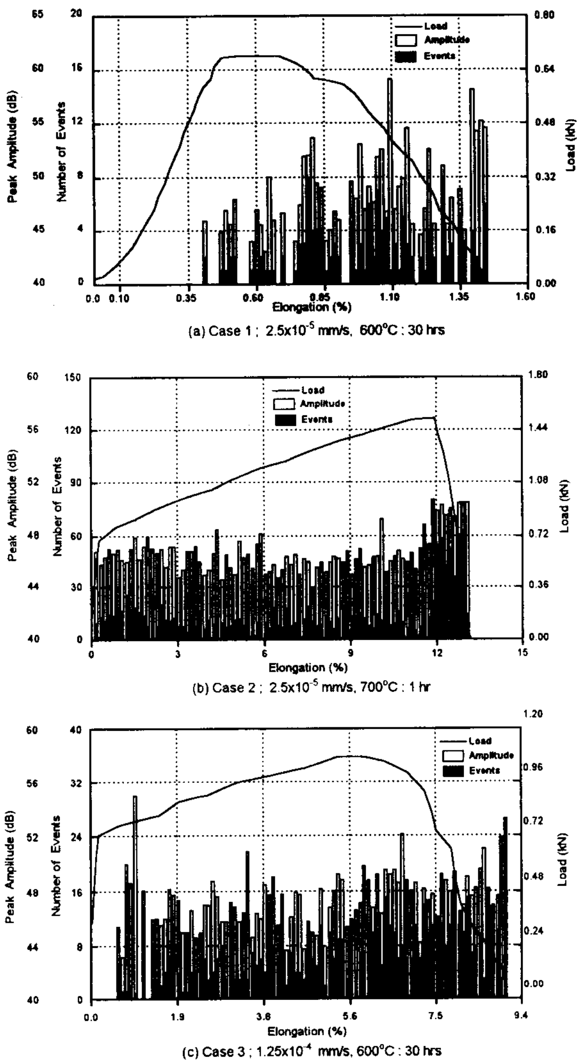

Fig.1 Number of events, peak amplitude, and load vs elongation for the case of no.1, 2 and 3

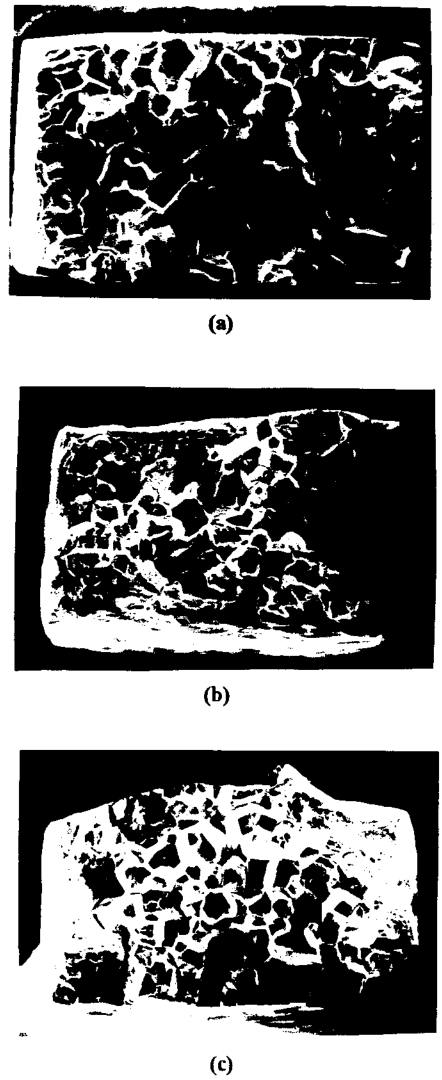

Fig.2 SEM micrographs of the fractured surface for the test case of no.1, 2 and 3

IGSCC growth, but not from elastic and plastic deformation. The reason for this is based on the facts that the maximum load is below 1.1 yield stress (0.7 kN) and no AE events were detected prior to 80 % of the maximum force. Fig.2(a) that shows 100 % intergranular(IG) SCC at the fractured surface , also obviously verifies the above fact. It was also found that multiple AEs having relatively lower peak amplitude below 48dB were detected prior to the decrease of load, while AEs having higher amplitude were produced right after the decrease of load.

The maximum force and elongation of the case of no.2 are much higher than those of the case of no.1. Since loading force exceeded prior loading force (0.7 kN), many AE events were generated not only from SCC growth but also from mechanical deformation and ductile fracture. Fig.1(b) shows that AE events and peak amplitude abruptly increase near the moment of decreasing load. It is supposed that AEs before maximum load were primarily generated due to plastic deformation while AEs after maximum load were produced by the both of IGSCC and ductile fracture. This could be confirmed by the SEM photograph of the fractured surface (Fig.2(b)), which shows almost 70 % of IGSCC. It was also found that the magnitude of peak amplitude arising dominantly from plastic deformation falls in the range of 44 to 48 dB (0.16 - 0.25 mV at the sensor) while that from IGSCC and ductile fracture is above 48 dB , which could be a good clue for identifying AE sources.

Higher ER was applied to the case of no.3. As the load exceeded 1.1 yield stress , similarly to the case of no.2, most events were thought to be originated not only from SCC growth but also from mechanical deformation and ductile fracture. However, the difference between the case of no.2 and no.3 seems that AEs during load increase in the case of no.3 were originated from some IGSCC as well as from plastic deformation , while AEs during load increase in the case of no.2 were from only plastic deformation. Infrequent AE signals with high amplitudes during load increase ,as shown in Fig.1(c), indicates the occurrence of IGSCCs. The fractured surface showed almost 80 % of IGSCC, referring to Fig.2(c).

It was found from Fig.1 that the peak amplitude level of plastic deformation was generally less than 48dB (0.25mV), while IGSCC and ductile fracture gave rise to higher values of 49 to 70dB (0.3mV to 3mV), which means that the peak amplitude much depends on AE source mechanism. Cumulative amplitude distribution (CAD) analysis is recognized as a powerful means for distinguishing different fracture mechanisms. One of the most useful models of CAD analysis is the power law model (7) which is mathematically expressed as $F(V) = (V/V_t)^{-b}$ where F(V) is the normalized cumulative distribution function to represent the probability that an emission's amplitude exceeds V ; thus $F(V_t) = 1$ if V_t is the lowest amplitude considered in the model. The b-value represents the slope of CAD. Pollock (7) showed that the lowest b-values are associated with discontinuous crack growth process in brittle high-strength metal, while the growth of plastic zone prior to crack extension gives relatively high b-values. The b-value for each case in this study is given in Table 1. The non-SCC in Table 1 is here defined as the range in which the plastic deformation is dominating, i.e., from the initial to maximum load, 11.7% and 5.6% of elongation for the case of no. 2 and 3, respectively. The remainders were regarded as the SCC region. The

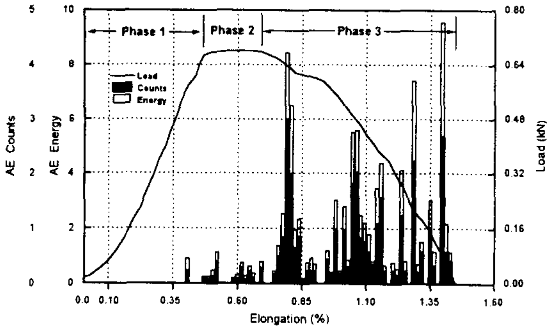

Fig.3 SCC susceptibility vs. b-value for each test case

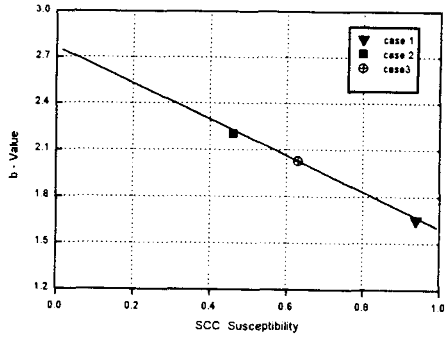

Fig.4 AE energy, count, and load vs. elongation for the case of no.1

b-values for apparent IGSCC were below 1.7, while the processes including plastic deformation had relatively higher values of 2.0~2.2. For the case of no. 2 and no.3, the b-values in the non-SCC region were higher than those in the SCC region, which indicates clear difference in peak amplitude distribution between plastic deformation and IGSCC growth. This result shows similar tendency observed in a previous work (7) although b-values for SCC lied in a higher range than those from the previous work. It was also found that the b-value of the cases of no. 1 was lower than those for the SCC regions of no. 2 and 3. The SCC regions of no.2 and 3 include AEs generated due to IGSCC as well as due to ductile fracture. It means that the peak amplitude in ductile fracture was statistically distributed at lower level than that in apparent IGSCC. Fig.3 showed that the b-values were linearly dependent on susceptibility to IGSCC and the higher the susceptibility, the smaller the b-value. This relation could be applied to determine susceptibility of materials to SCC.

Measuring the crack growth rate and identifying the transition from subcritical to critical growth have been major subjects for studies of AE application. AE parameters such as event rate, amplitude, count, and energy have been considered in these studies. Although quantitative crack growth rate was not measured in present study, the behavior of IGSC crack growth could be qualitatively explained on the basis of the loading force and AE parameters processed. The result of the case of no.1 could be regarded as a typical IGSCC behavior since the fracture was 100% of IGSCC. As shown in Fig.4, the crack growth behavior of the case of no.1 was assumed as consisting of three phases such as 1) the generation of small cracks at the surface (0-0.48 % of elongation), 2) the growth of small cracks and the formation of dominant cracks (0.48-0.7 %), and 3) the growth of dominant cracks and fracture (0.7-1.47 %). In phase 1, initial IGSC cracks are formed by a proper load and sufficient corrosion at grain boundaries . It could be verified by the observation of multiple small cracks at the surface after detection of initial several AE events. Also, some AE events with low values of event rate, amplitude, count, and energy were detected in phase 1 as shown in Fig.1(a) and Fig.4. Even after initial crack formation, the loading force continuously increased , since the crack opening rate was not enough to offset the elongation rate of the gauge section . In phase 2, it seemed that small cracks grew to dominant cracks whose crack opening rate was almost equal to the elongation rate of the gauge section. It could be inferred from the constant loading force. AE event rate and amplitude in phase 2 were slightly higher than those in phase 1. Dominant cracks were not visually observed through a magnifying glass during phase 2. In phase 3, the load continuously decreased due to rapid growth rate of dominant cracks exceeding the elongation rate. The sudden increase of peak amplitude, count, and energy was observed at the transition from phase 2 to phase 3. As a result, the monitoring of combined AE parameters can provide effective means to identify the transition from crack initiation and growth of small cracks (phase 1 and 2) to dominant crack growth (the beginning of phase 3).

4. Conclusions

It was found that the AE peak amplitude level of plastic deformation was generally smaller than 48dB (0.25mV), while IGSCC and ductile fracture gave rise to higher values of 49 to 70dB (0.3mV to 3mV). The slopes of cumulative amplitude distribution (b-value) for apparent IGSCC in Inconel 600 were below 1.7, while the processes including plastic deformation had relatively higher values of 2.0~ 2.2. The b-values were linearly dependent on IGSCC susceptibility and the higher the susceptibility, the smaller the b-value.

The monitoring of combined AE parameters such as event rate, amplitude, count and energy can provide effective means to clearly identify the transition from crack initiation and growth of small cracks to rapid growth of dominant cracks.

It was demonstrated that AE technique is capable of detecting early stages of IGSC crack growth in Inconel 600, and has a potential as a nondestructive test method. It also could be a useful tool for studying SCC mechanism.

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