Acoustic emission studies for characterization of fatigue crack growth behavior in HSLA steel

Jalaj Kumar\textsuperscript{a}, S. Ahmad\textsuperscript{a}, C.K. Mukhopadhyay\textsuperscript{b}, T. Jayakumar\textsuperscript{b} and Vikas Kumar\textsuperscript{a}

\textsuperscript{a}Defence Metallurgical Research Laboratory, Hyderabad, India; \textsuperscript{b}Metallurgy and Materials Group, Indira Gandhi Center for Atomic Research, Kalpakkam, India

1. Introduction

Knowledge of the fatigue crack growth (FCG) characteristics of materials is important for designing of components and applying life prediction methodologies. A cyclic plastic strain is developed at the crack tip when a material experiences fatigue load. Fatigue crack growth rate (FCGR) of a material undergoing fatigue cycling is correlated with the stress intensity factor range ($\Delta K$), which acts as a driving force for the crack growth. A plot of the FCGR $da/dN$ where $a$ is the crack length and $N$ is the number of fatigue cycles, with $\Delta K$ is divided into three stages. The stage I is the threshold where the crack growth rate is negligible and strongly influenced by microstructure and environment. In the middle region or in stage II, the curve is essentially linear. The stage III is the unstable crack growth regime which is independent of environment. In fatigue cycling studies of different materials, a wide variety of experimental data is found to fit a relation of the following form in stage II of the $da/dN$ vs. $\Delta K$ plots, known as Paris law [1]:

\begin{align*}
\frac{da}{dN} & \propto (\Delta K)^{n}
\end{align*}
\[ \frac{da}{dN} = C(\Delta K)^m \] (1)

where \(\Delta K = (K_{\text{max}} - K_{\text{min}})\), \(K_{\text{max}}\) = maximum stress intensity factor, \(K_{\text{min}}\) = minimum stress intensity factor, \(C = \text{constant}\) and \(m = \text{exponent}\). The magnitude of the exponent \(m\) in Equation (1) can be determined from the slope of the linear portion of log–log plot of \(da/dN\) vs. \(\Delta K\). However, FCG in the linear Paris region is reported to follow double slope behaviour in some investigations.\(^{[2–4]}\) It was suggested that the stage II of the FCG can be divided into two sub-stages, IIA and IIb.\(^{[3,4]}\) Stage IIA corresponds to structure sensitive slow crack growth regime and constitutes a micro-crack advance after a certain number of cycles. Whereas crack growth in stage IIb is insensitive to submicroscopic structural features and crack advance takes place with every cycle. FCG study of low carbon steel (C-0.08%) showed that transition from stage IIA to stage IIb occurs at a critical value of stress intensity when the ratio of plastic zone radius to ferrite grain diameter is approximately four, and this was attributed to the relaxation of constraint at the crack tip as the crack length increases.\(^{[2]}\) In the study on ductile structural steel, it was shown that striation spacing coincides well with the \(da/dN\) over the range 0.1–70 \(\mu\text{m}/\text{cycle}\) and suggested that the striation is formed by plastic blunting at the crack tip.\(^{[3]}\)

High strength low alloy (HSLA) steels are a group of low carbon steels that utilise small amounts of alloying elements to attain high yield strength in the as-rolled or normalised conditions. These steels are used in oil and gas pipelines, automotive components, offshore structures and shipbuilding. These steels possess better mechanical properties than as-rolled carbon steels, largely by virtue of grain refining and precipitation hardening. Due to their superior mechanical properties, HSLA steels and micro-alloyed steels allow more efficient design with improved performance, reduction in manufacturing costs and weight reduction of components to be produced.

FCG studies of HSLA steels were reported in the literatures \(^{[5–10]}\). It is known from these studies that the correlation between \(da/dN\) and \(\Delta K\) in these steels in the linear Paris region can also be divided into two sub-stages. The slope between \(da/dN\) and \(\Delta K\) at lower values of \(\Delta K\) in the power law region above threshold is about 4. This is called the intermittent crack growth regime. In contrast, the slope of the relation between \(da/dN\) and \(\Delta K\) in the higher \(\Delta K\) region is 2 and corresponds to continuum crack growth.\(^{[5–8]}\) Fatigue striation measurements were used to support the changeover of the FCG mechanism from intermittent to continuum crack growth regime upon increasing \(\Delta K\), which causes a change in the slope of the crack growth curve in the power law region from 4 to 2.\(^{[5,6]}\) But overlapping of these two sub-stages sometimes makes them indistinguishable, and stage II FCG appears as a single power law regime.\(^{[5]}\)

Acoustic emission (AE) is widely used for the study of crack growth behaviour in materials.\(^{[11]}\) AE is defined as the class of phenomenon whereby transient elastic waves are generated by rapid release of energy from localised sources in a material (Figure 1).\(^{[11]}\) An AE sensor coupled to a sample undergoing dynamic changes detects the energy emitted in the form of elastic waves and provides information about the nature of dynamic changes taking place in the sample.\(^{[11–13]}\) A typical burst-type AE signal is shown in Figure 2. Different parameters associated with the AE signal are explained in the annexure A.

The AE technique has been used for FCG studies of various steels.\(^{[14–17]}\) AE signals generated during the FCG provide information about the opening/closure of the crack, and micro-mechanisms of damage accumulation as well as fracture. In an investigation...
on FCG in solution annealed AISI type 316 stainless steel (SS),[16] stage II Paris region was divided into two sub-stages, plane strain dominant and plane stress dominant, with the help of AE, by a change in the rate of AE activity with increase in crack growth rate. AE due to fatigue crack closure was studied in a few investigations.[18,19] In SS 316(N), crack closure loads on weld compact tension (CT) specimens determined by AE were compared to those determined by global crack mouth opening displacement method and a good agreement was reported.[18] A few studies on the FCG behaviour in micro-alloyed steel using AE have been reported.[20,21] Three stages of AE generation during fatigue crack propagation were revealed in micro-alloyed steel and its weld, and the AE source
mechanisms for different stages were proposed as the crack initiation, plastic activities ahead of the crack tip and shearing of ligaments between micro-voids and micro-cracks, respectively.[20] In another study [21], the effects of the changes in microstructure due to heat treatments and welding on fatigue and corresponding AE behaviour were investigated. The results showed that the microstructural constituents including inclusions and precipitates could significantly influence the fatigue crack propagation behaviour, which in turn influence AE source mechanisms.[21] It is also known from these studies that as compared to the variation of $da/dN$ vs. $\Delta K$, AE count rate vs. $\Delta K$ variation enables identification of the transition from stable crack growth (stage II) to unstable crack growth (stage III) of the FCG.[20,21] Micro-alloyed steel is one of the important categories of HSLA steel. But the micro-alloyed steel referred to in the above studies [20,21] is a C–Mn steel with strength values (yield strength and ultimate tensile strength 360 and 560 MPa, respectively) much lower than the HSLA steel used in the present investigation. In view of this, this study on the FCG behaviour in a HSLA steel using AE was undertaken. Another objective of the present investigation is to explore the possibility of using AE for identifying the transition between the two sub-stages in the Paris region in HSLA steel.

The effect of loading ratio on the FCG behaviour is known from many earlier investigations conducted by different authors, and a few of them are mentioned.[22–24] There exists a strong correlation between the crack growth rate and the loading ratio $R$, with increasing crack growth rates observed for increasing $R$.[22–24] Low-strength steels are relatively insensitive to $R$ ratio in stage II region. This effect is more pronounced at stages I and III of the Paris curve.[24] Concepts such as residual compressive stresses and environment effects have been applied to explain the stress ratio effect on the FCGR.[24] In the present investigation, AE has been used to study the FCG behaviour of HSLA steel with two different $R$ ratios. In-situ AE signals have been captured by mounting two piezoelectric sensors on CT specimens while performing the FCG tests. This article presents the results of the investigation carried out by AE monitoring during FCG of HSLA steel.

2. Material
The material used for the FCG experiment is HSLA steel. The HSLA steels normally include one or more of the following elements: boron, vanadium, titanium and niobium. Their additions combined with close control of coiling temperatures ensure that minimum yield and tensile properties are achieved in the HSLA steel strip.

The chemical composition (wt.%) of the HSLA steel used in this investigation is as follows: C – 0.1%, Mn – 0.3%, Si – 0.3%, Cr – 0.5%, Ni – 2.0%, Cu – 0.5%, Mo – 0.3%, Al – <0.02%, V – <0.02%, S – <0.02% and P – <0.02%. The addition of molybdenum produces a fine grain structure of acicular ferrite and substantially enhances the precipitation hardening effects achieved with other alloying elements. The microstructure of the HSLA steel, shown in Figure 3, consists of pearlite (black) in ferrite (white) matrix. The values of 0.2% offset yield strength, ultimate tensile strength and total elongation of this steel at ambient temperature are 600 MPa, 700 MPa and 20%, respectively.

3. Experimental
3.1. FCG test
CT specimens of 25.4 mm thickness and machined notch in the longitudinal direction prepared from the HSLA steel were used for this investigation. Dimensional details of the CT
specimens used in this study are shown in Figure 4. The specimens were fatigue precracked as per the ASTM standard E 647 (2010).[25] FCG testing of the precracked specimens was carried out under cyclic loading with specific stress ratios (0.3 and 0.5) using INSTRON 8500 plus test system at a frequency of 15 Hz.[25] Input parameters for this test are frequency, modulus, maximum stress and stress ratio. The crack growth was monitored using a MTS crack opening displacement gauge. Crack length vs. number of fatigue cycles and crack growth rate vs. Δ$K$ curves were obtained from the tests.

3.2. AE monitoring of the FCG
An 8-channel AE system (M/s. PAC, USA) with digital data acquisition and processing facility was used in this study. AE signals were recorded using two resonant (10 mm
dia × 12 mm ht) piezoelectric sensors having frequency response in the range of 100–600 kHz. with resonant frequency at 210 kHz. These sensors were mounted on the surface of the FCG test specimen using vacuum grease as a couplant, as shown in Figure 5. The sensors were mounted in a linear location mode using the location algorithm provided in the AE software. In this mode, the arrival time difference for the AE signal at two sensors is measured. The procedure followed in this investigation can be understood by considering the source location in one dimension (for example on a pipe line) as can be seen from Figure 6. If the source is located beyond the region between the two sensors, but close to sensor 2 relative to sensor 1, the first hit sequence is at sensor 2 and then the second is at sensor 1. The time difference between the two hits is equal to the time taken to cross the entire separation of the sensor pair, i.e. \( \Delta T_{\text{max}} = D/V \) where \( D \) = distance between the sensors, \( V \) = wave velocity and \( \Delta T_{\text{max}} \) = maximum time difference. If the source is located inside the region between the two sensors, the source location distance \( d \) can be given by

\[
d = \frac{1}{2}(D - \Delta T.V)
\]

Figure 5. Acoustic emission test set-up.

Figure 6. Linear source location of acoustic emission.
where ‘$d$’ is measure from the first hit sensor ($S_2$).

The distance between the sensors along the axial direction in this investigation was 61 mm. The coupling and the sensitivity of the sensors before the test were checked by simulating with pencil lead break at different places in the region between the two sensors. The lead break is considered to be a repeatable event that produces a stress wave similar to the stress waves normally generated during a dynamic event like crack growth. The difference in relative sensitivity between the sensors was maximum 3 dB. By simulation study, accuracy of source location was checked which was found to be within ±5% of the distance between the sensors. By mounting two sensors, the region between the sensors could be covered to detect the signal arising between the two sensors and also to ensure that no AE signals outside the covered region are recorded by the sensors. In this study, source location was based on Rayleigh wave velocity and distance between the two sensors which is given as input to the source location software. Since these values remain almost constant during the FCG studies, difference due to attenuation of the wave can be considered minimum.

Teflon-coated loading pins were used in order to reduce noise due to the pins. The acquired AE signals were amplified by a 40 dB fixed gain preamplifier and passed through a band pass filter having a bandwidth of 10–2 MHz. The preamplified and filtered AE signals were further amplified and analysed. For this, the overall gain and threshold selected were 80 and 40 dB, respectively. The signal-to-noise ratio can be stated in Decibel (dB) which is the log ratio and is defined as $\text{dB} = 20 \log (V_o/V_i)$ where $V_o = \text{output voltage}$ and $V_i = \text{input voltage}$. Using this formulae, for 80 dB gain, the $V_o/V_i$ value works out to be 10,000.

A dummy CT specimen without a notch was fatigue cycled to the same load range and at the same frequency. From this dummy test, it was observed that the interference from mechanical noises such as rotating pins and grip noise is insignificant under the experimental conditions selected. In CT specimens, clevis and pin assembly are used to allow in-plane rotation as the specimens are loaded. In some of the clevis design, holes with small flats are made to provide rolling contact between the loading pins and the holes. This results in more rotation of the pin as compared to that for the specimens with circular hole as used for the specimens in this study. Thus, rotation of the pin is less in the CT specimens used. The dummy CT specimen was also tested several times to ensure maximum rotation of the pin and to check the noise from the loading pins. The purpose of the dummy specimen without notch was also to allow higher load in the trial tests so that the load experienced during the FCG test would be lower. As per Kaiser effect of acoustic emission, any noise signal once appeared, will not occur during subsequent loading unless the previous maximum load is exceeded.

AE counts and peak amplitude of AE hits (events) recorded during the tests were used for analysing the results. In AE studies, counts are related to the damage process in the material and classically counts have been used to correlate with the crack growth rate in fatigue. In several recent studies also, counts and energy of AE signals are used for the correlation of the FCG process.[20, 21] In ASTM standard, count and energy are defined as effective parameters for correlating damage processes in materials. The use of these time domain parameters enhances the understanding of the deformation and crack growth behaviour in materials, and also, the results can be compared with the numerous literatures existing in this field. Because of this, count and energy are used
in this investigation. In this study, same sensor was used for all the tests and hence any variation from sensor was not there.

3.3. Fractographic study
The fracture surfaces were examined using FEI scanning electron microscope (SEM). The locations of the fractographic samples on the CT specimens were marked using the crack growth data. Fractured samples were selected for different $\Delta K$ locations, and SEM investigations were performed.

4. Results and discussion
Figure 7 shows the variation in crack length vs. fatigue cycles for the two specimens ($R = 0.3$ and 0.5) where it is seen that the crack length increases with cycles. It can be seen that the crack propagated more rapidly in the specimen with $R = 0.5$ as compared to the specimen with $R = 0.3$. The crack growth curves were converted into crack growth rate vs. $\Delta K$ curves and plotted in Figure 8. Two specimens for each stress ratio were studied, and the results
were found to be similar. Hence, the result from one of the specimens for each stress ratio has been reported in this article. It can be seen that there is no appreciable difference in the crack growth rate curves for the two specimens. Figure 8 also shows that \( \frac{da}{dN} \) does not vary linearly with \( \Delta K \) for the entire region. Instead, it obeys two slope behaviour. But it is difficult to resolve at which values of \( \Delta K \), the change in the slope takes place, as this changeover was observed to be gradual.

The AE results from the two specimens were analysed. Figure 9(a) and (b) show the variation of cumulative count as a function of \( \Delta K \) for the two stress ratios. The variation of \( \frac{da}{dN} \) with \( \Delta K \) is also included in the plots for comparison. It is seen that substantial AE is generated during FCG in the HSLA steel, where cumulative count increases with \( \Delta K \) for both the stress ratios. FCG during stage II occurs by crack tip blunting and resharpening mechanism during loading and unloading part of the fatigue cycle, respectively. The crack growth mechanism is associated with plastic deformation, crack closure and crack jump near the crack tip. All these phenomena would contribute to the AE generation during the FCG process.

It can be seen from Figure 9(a) and (b) that, as compared to the variation of \( \frac{da}{dN} \) with \( \Delta K \), the change in slope in the cumulative count vs. \( \Delta K \) plots is more distinct and indicates two sub-stages (IIa and IIb) in the linear Paris II region. The points of the slope change are
marked by lines A and A′ in Figure 9(a) and (b). The ΔK values corresponding to the slope change are found to be 24 MPa m$^{1/2}$ for $R = 0.3$ and 18 MPa m$^{1/2}$ for $R = 0.5$. These values are also marked in Figure 8 by the lines A and A′.

The ΔK values at changeover from stage IIa to stage IIb are given in the literature by the following equation $[4,26,27]$:

$$\Delta K_0 = 10Eb^{1/2}$$

(3)

where $\Delta K_0$ is the stress intensity factor at the point of changeover in MPa m$^{1/2}$, $E$ is Young’s modulus in MPa and $b$ is Burger’s vector in m. Equation (3) was developed based on the observation that when $da/dN$ is normalised by Burger’s vector [i.e. $(da/dN)/(1/b)$] and ΔK is normalised by Burger’s vector and Young’s modulus (i.e. $\Delta K/Eb^{1/2}$), and the normalised values of $da/dN$ and ΔK are plotted, the resulting plot yields an intersecting point at a particular value of the abscissa where all curves of a class of material representing different crack growth rates intersect each other. $[26]$ The value of ΔK at the point of intersecting is known as changeover point from stage IIa to stage IIb and denoted as $\Delta K_0$. $[26]$ Equation (3) was reported to be valid for a wide range of materials such as steels, copper, magnesium, aluminium and titanium alloys. $[26,27]$ It was noted that for ΔK values less than $\Delta K_0$, the number of striations is not equal to the number of fatigue cycles suggesting that the crack does not propagate in every cycle, but for ΔK values greater than $\Delta K_0$, each loading cycle forms one striation and the striation spacing matches with that of the macroscopic crack growth rate. $[26]$ It was also noted that the value of $\Delta K_0$ is dependent on experimental conditions. $[27]$

The value of $\Delta K_0$ for HSLA steel is estimated from Equation (3) using the value of $E$ as $1.86 \times 10^5$ MPa m$^{1/2}$ and $b$ as $2 \times 10^{-10}$ m. It is found to be 26 MPa m$^{1/2}$. This is closer to the $\Delta K_0$ value for $R = 0.3$ (24 MPa m$^{1/2}$) as compared to the $\Delta K_0$ value for $R = 0.5$ (18 MPa m$^{1/2}$) found by AE in this study. This observation that $\Delta K_0$ value for $R = 0.3$ experimentally found by AE matches well with that estimated theoretically from Equation (2) and is higher than that for $R = 0.5$, signifies that AE predicts the transition from slow stable crack growth (i.e. stage IIa) to fast crack growth (i.e. stage IIb) at lower value of ΔK for higher stress ratio. This is further discussed by comparing peak stress intensity ($K_{\text{max}}$) values at the crack tip later in this article.

The variation of cumulative count with ΔK corresponding to the two sub-stages found by AE was further analysed, and the resulting values of intercept and slope along with correlation coefficient are given in Table 1. It can be seen that, slope values in stage IIa are 2.4 and 4.7 for $R$ of 0.3 and 0.5, respectively, while both the slope values are very close, i.e. 0.71 and 0.72 in stage IIb. The present AE results are in agreement with the earlier investigation on AISI type 316 SS that the stage II Paris region can be divided into two sub-stages

| $R$ | Intercept | Slope | Correlation coefficient | Intercept | Slope | Correlation coefficient |
|-----|-----------|-------|-------------------------|-----------|-------|-------------------------|
| 0.3 | 0.49      | 2.4   | 0.96                    | 2.84      | 0.71  | 0.81                    |
| 0.5 | −2.71     | 4.7   | 0.90                    | 2.33      | 0.72  | 0.91                    |
NoNDESTRUCTIVE TESTING AND EVALUATION

Corresponding to the variation of cumulative count with $\Delta K$, the variation of $da/dN$ with $\Delta K$ was correlated and the results are given in Table 2. It is seen that the values of the slopes are around 4 (3.6–4.1) and 2 (2.2) for the stage IIa and IIb, respectively, for both stress ratios. This bi-linear behaviour of crack growth is in agreement with the reported values of FCG in HSLA steel and indicates that these two sub-stages correspond to the intermittent and continuum crack growth regimes, respectively, as described in the literature.[5–10]

In investigations on 7075-T6 Al alloy and 4140 steel,[28] a peak in the variation of AE count rate with the energy release rate due to crack extension was observed and this was attributed to the plane strain to plane stress transition as the crack extended with increasing $\Delta K$. The values of energy release rate due to crack extension ($E_{rr}$) were determined as per the following equation [28]:

$$E_{rr} = \left[ \frac{B \times da/dN}{E} \right]^{1/2} \left( \frac{\Delta K}{(1 - R)} \right)$$

where $da/dN$ is the fatigue crack growth rate, $B$ is the specimen thickness and $E$ is the Young’s modulus. In the present investigation, the AE cumulative count was also correlated with the energy release rate due to crack extension, as determined by Equation (4). The variations of $da/dN$ with $\Delta K$ are also included in the plots. The resulting plots are shown in Figure 10(a) and (b) for the $R$ ratio of 0.3 and 0.5, respectively. Figure 10(a) and (b) show results similar to that depicted in Figure 9(a) and (b) that the changes in the slopes of cumulative count vs. $E_{rr}$ plots occur at almost similar values of $\Delta K$ (28 MPa m$^{1/2}$ for $R = 0.3$ and 19 MPa m$^{1/2}$ for $R = 0.5$). This value of $\Delta K$ at the transition from stage IIa to stage IIb for $R = 0.3$ (28 MPa m$^{1/2}$) found by AE also matches well with that estimated theoretically from Equation (2) for $\Delta K_0$, i.e. 26 MPa m$^{1/2}$. This also follows the same trend observed earlier for cumulative count vs. $\Delta K$ plot that the $\Delta K$ value at the transition is lower for $R = 0.5$ than that for $R = 0.3$. It can thus be concluded that the changes in the slopes of AE cumulative count vs. $\Delta K$ or $E_{rr}$ plots are due to changes in the stress state (plane strain to plane stress) as $\Delta K$ increases. It can also be concluded that the experimentally determined $\Delta K$ values at the changeover point obtained by AE (either by cumulative count vs. $\Delta K$ or by cumulative count vs. $E_{rr}$ plot) are closer to the theoretically estimated $\Delta K_0$ for $R = 0.3$ and shows the validity of $\Delta K_0$ for lower stress ratio. This also indicates the stress ratio dependency of $\Delta K_0$ as revealed by acoustic emission.

Figure 9(a) and (b) further indicate that, while crack growth rate varies with $\Delta K$ for the entire FCG curve as two slope behaviour, the variation of cumulative count with $\Delta K$.

Table 2. Values of intercept and slope for the variation of $da/dN$ vs. $\Delta K$.

| $R$ | Intermittent regime (stage IIa) | Continuum regime (stage IIb) |
|-----|-------------------------------|-------------------------------|
|     | Intercept | Slope | Correlation coefficient | Intercept | Slope | Correlation coefficient |
| 0.3 | −8.8      | 3.6   | 0.99                    | −6.8      | 2.2   | 0.99                    |
| 0.5 | −9.3      | 4.1   | 0.99                    | −6.9      | 2.2   | 0.99                    |
beyond line A shows another transition corresponding to line B for both the stress ratios, beyond which the variation of cumulative count with $\Delta K$ shows higher slope. This can be attributed to the change in damage process from stable to unstable crack growth as stage III sets in. This is also attributed to the onset of fully plastic yielding. These are shown by lines B and $B'$ in Figure 8. The changes in such slopes in the cumulative count vs. $\Delta K$ plots (Figure 10(a) and (b)) at almost similar values of $\Delta K$ are also seen. The $\Delta K$ values corresponding to the changes in the slopes from stage IIa to stage IIb and stage II to stage III as

\[
\begin{array}{cccccccc}
\text{Stage IIa to stage IIb} & \text{Cumulative count vs. } \Delta K \text{ plot} & \text{Cumulative count vs. } E_{\text{rr}} \text{ plot} & \text{Stage II to stage III} & \text{Cumulative count vs. } \Delta K \text{ plot} & \text{Cumulative count vs. } E_{\text{rr}} \text{ plot} \\
R & \Delta K & K_{\text{max}} & \Delta K & K_{\text{max}} & \Delta K & K_{\text{max}} & \Delta K & K_{\text{max}} \\
0.3 & 26 & 37 & 31 & 44 & 38 & 54 & 37 & 53 \\
0.5 & 21 & 42 & 21 & 42 & 31 & 62 & 30 & 60 \\
\end{array}
\]

Figure 10. Crack growth rate and AE cumulative energy vs. $\Delta K$ for (a) $R = 0.3$ and (b) 0.5.
obtained from cumulative count vs. $\Delta K$ plots (Figure 9(a) and (b)) and cumulative count vs. $E_{cr}$ plots (Figure 10(a) and (b)) are shown in Table 3. Two specimens were tested for each load ratio, and the results were found to be similar. In Table 3, average values of the two specimens are given. The stable crack and unstable crack propagation during the FCG are generally identified by different slopes in the log–log plots of $da/dN$ vs. $\Delta K$. But, in this investigation, no such transition was identified from the $da/dN$ vs. $\Delta K$ plots. However, with the help of AE, the change in damage process corresponding to the transition from stage II to stage III could be identified.

The onset of stage III is defined as the rapidly increasing crack growth rates, but this is not observed in the present investigation. But the AE results clearly reveal a change in the damage process giving rise to the transition in AE due to the transition from stage II to stage III. Acoustic emission, being highly sensitive to micro-mechanistics of damage in materials, could bring out the changes in the damage processes in advance before the transition takes place. Similar results were reported in micro-alloyed steel.[20,21] It is known from these studies that the AE generated in this type of steel depends on the region of FCG. Following stage I of the FCG process which corresponds to rapid increase in AE in a short period in the beginning of the test due to crack initiation, increase in AE activity occurs slowly over a longer period in stage II due to plastic activities ahead of the crack tip, and finally, sudden increase in AE in stage III occurs until final fracture due to micro-fracture events. It was reported that the formation of micro-cracks and fracture of ligaments between the micro-cracks give rise to AE signals marking the beginning of stage III [20,21]. The AE results obtained in the present investigation for the HSLA steel are in line with the results of micro-alloyed steel reported.[20,21] Identification of the transition from stage II to stage III is important and useful from the point of view of providing an early warning of impending failure for components and/or structures undergoing fatigue cycling.

It is seen from Figure 9(a) and (b), Figure 10(a) and (b) and Table 3 that the $\Delta K$ values at which the transitions occur from stage IIa to stage IIb and stage II to stage III as found by acoustic emission, are lower for the specimen with $R = 0.5$ as compared to the specimen with $R = 0.3$. This can be attributed to the increased damage processes at the crack tip for the higher stress ratio.[22–24] It is known that FCG involves two crack driving forces: stress intensity factor range $\Delta K$ and peak stress intensity $K_{max}$.[29] One of these two will be controlling factor during FCG in a given stress ratio. While $\Delta K$ induces fatigue damage at the crack tip by cyclic load, $K_{max}$ is related to the fracture process in a cyclically damaged region ahead of the crack tip. Since $\Delta K = K_{max} - K_{min}$ and $R = K_{min}/K_{max}$, $K_{max}$ can be expressed by the following equation [29]:

$$K_{max} = \frac{\Delta K}{1 - R}$$  \hspace{1cm} (5)

The values of $K_{max}$ were determined corresponding to the $\Delta K$ values from the two slope changes in AE and included in Table 3. The theoretically estimated value of $\Delta K$ (i.e. $\Delta K_0$) was reported to be valid for a particular material irrespective of $R$ [4,26,27], and hence, $K_{max}$ value for this $\Delta K$ could not be determined. The change in the slope is attributed to the change in damage process during transition from stage II to stage III. It can be seen from Table 3 that although $\Delta K$ value at the slope change (first slope) is different for two stress ratios, $K_{max}$ corresponding to the slope change (first slope) is almost same for the two stress ratios.
Corresponding to the change in the second slope, although $\Delta K$ is lower, $K_{\text{max}}$ is higher for higher stress ratio. This increased $K_{\text{max}}$ for the same applied $\Delta K$ results in increased severity of damage process at the crack tip for the higher stress ratio. At low stress ratios, due to low $K_{\text{max}}$ value, the crack growth process is predominantly fatigue dominated, while at high $R$ ratios due to high $K_{\text{max}}$ value crack growth is fracture dominated.\cite{29} The present results are in line with the results of an ASTM A572 grade structural steel that with increase in $R$ ratio in the range between 0.02 and 0.7, the $\Delta K$ value at which transition from stage II to stage III occurs, decreases.\cite{30}

Apart from cumulative count, energy of the AE signals has also been determined and correlated with $\Delta K$ and energy release rate. The resulting plots (Figure 11(a) and (b) and Figure 12(a) and (b)) are similar to the AE counts plots. The absolute values of counts and energy are different, but the trend of variations for both counts and energy are similar. It may be noted that the energy is directly proportional to the area under the AE waveform. Since the AE activity is attributed to the rapid release of energy in a material, the energy content of the AE signal can be related to the energy release.

The increased damage processes for the specimen with $R = 0.5$ are also supported by location analysis of the AE signals. Figure 13 shows the results of the linear source location

**Figure 11.** AE cumulative count vs. energy release rate due to crack extension ($E_{\text{rr}}$) for (a) $R = 0.3$ and (b) 0.5.
of AE signals generated during the FCG which was obtained by determining the arrival time difference of the signals between the two sensors. This shows that AE was mainly generated from the centre of the specimens, where the crack propagated during the FCG process. The AE data which were generated in the above location were taken for analysing the results, and the signals generated outside this region were not included in the analysis. Higher number of events (~3 times) are generated in the specimen tested at stress ratio of 0.5 as compared to the specimen with R ratio 0.3 and can be attributed to the increased rate of damage processes at the crack tip for the higher stress ratio.

The linear location was based on Rayleigh wave velocity. In a steel plate of 25.4 mm thickness, Rayleigh wave is generated at the crack faces during growth process and propagates to the plate surface.[31] For any source generated in the specimen, the possibility for the Rayleigh wave to continue to propagate to the plate surface depends on whether the plate is thick enough to support a Rayleigh wave according to the equation \[ f = \frac{c_T}{(t \pi)} \] where \( f \) is the frequency below which for a given plate thickness, \( t \), Rayleigh waves cannot propagate and \( c_T \) is bulk shear velocity.[32] For a steel plate of 25.4 mm thickness, the frequency of Rayleigh is determined to be 323 kHz. The piezoelectric sensors used in

Figure 12. AE cumulative energy vs. energy release rate due to crack extension (\( E_{rr} \)) for (a) \( R = 0.3 \) and (b) 0.5.
the present investigation having frequency response in the range of 100–600 kHz can thus considered to be acquiring the Rayleigh wave from the crack growth sources.

Figure 14(a) shows the representative fractographs of the fractured samples for Δ\(K\) values of 15, 20 and 25 MPa m\(^{-1/2}\) for the specimen with \(R = 0.3\). The fracture surface at 15 MPa m\(^{1/2}\) shows transgranular faceted fracture. At 25 MPa m\(^{1/2}\) corresponding to stage IIb, the fracture surface contains dimples resulting from static fracture process, and this occurs due to increased damage at the crack tip at higher values of Δ\(K\). The fractographs for the specimens tested at \(R = 0.5\) (Figure 14(b)) showed similar behaviour except that at 20 MPa m\(^{1/2}\), it shows transgranular faceted fracture which may have contributed to larger AE event at this stress ratio.

**Figure 13.** Location plots of AE Events for the specimens with \(R = 0.3\) and 0.5.
5. Conclusions

(1) AE generated during FCG in CT specimens of HSLA steel has been monitored. AE counts obtained have been correlated with \( \Delta K \) and energy release rate due to crack extension.

(2) AE is useful to reveal the presence of two sub-stages in the linear stage II Paris region of the FCG clearly, possessing two different slopes. Correspondence of these sub-stages with intermittent and continuum crack growth regimes in HSLA steel described in the literature has been confirmed.

(3) The transition from stage II to stage III of FCG can be identified by increasing slope of cumulative count vs. \( \Delta K \) and cumulative count vs. energy release rate due to crack extension plots, which otherwise not feasible from \( da/dN \) vs. \( \Delta K \) plots.

(4) Experimentally determined \( \Delta K \) value by AE at the transition from stage IIa to stage IIb is closer to the theoretically estimated value of \( \Delta K_0 \) only for the lower stress ratio \( (R = 0.3) \).
K_{\text{max}} values corresponding to the transition from stage IIa to stage IIb are almost similar for two stress ratios and can be used for characterising the transition instead of $\Delta K$, which depends on $R$ ratio.

(6) For the transition from stage II to stage III, $\Delta K$ is also lower for higher $R$. But $K_{\text{max}}$ value is higher for higher stress ratio, and this is attributed to higher rate of damage at the crack tip and supported by generation of higher AE events.

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**Disclosure statement**

No potential conflict of interest was reported by the authors.
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