Fracture Toughness Evaluation of 316LN Stainless Steel and Weld Using Acoustic Emission Technique

Mengyu CHAI,1) Quan DUAN,1)* Xinglong HOU,1) Zaoxiao ZHANG1) and Lichan Li2)

1) School of Chemical Engineering and Technology, Xi’an Jiaotong University, No. 28 Xianning West Road, Xi’an, 710049 China. 2) State Nuclear Power Engineering Company, No. 888 Tianlin Road, Shanghai, 200233 China.

(Received on October 19, 2015; accepted on January 12, 2016)

Fracture toughness behaviors of 316LN stainless steel (SS) base metal and weld were investigated using Acoustic emission (AE) technique. Four point direct current potential drop (DCPD) method has been used to measure the crack initiation and extension, aiming at generating evidence for determination of the point of crack initiation by AE methods. Fracture toughness $\Delta K$ values were estimated using AE characteristics with simultaneous ASTM standard E1820. The results in this investigation showed that 316LN SS weld exhibited lower fracture toughness than that of base metal. The points of crack initiation in 316LN SS base metal and weld could be characterized by the first peak of cumulative energy rate, the sudden increase of AE cumulative energy counts or amplitude coupled with peak amplitude signals. The fracture toughness values of 316LN SS base metal and weld estimated using AE technique were lower than those obtained by ASTM procedure.

KEY WORDS: acoustic emission; fracture toughness; 316LN; weld; crack initiation.

1. Introduction

316LN stainless steel (316LN SS) is a low carbon austenitic steel which has been selected as candidate reactor coolant piping materials in AP1000 nuclear power plants due to its excellent combination mechanical strength and corrosion resistance. For the design of new structures and for the safety and reliability analyses of operating components, fracture toughness data of the materials play an essential role. The ability of material to carry loads or resist deformation under the condition of a crack is defined as the fracture toughness. A great number of standards are currently available to determine fracture toughness value of structural materials, which need many procedures for evaluating fracture toughness of the material using analysis of load-displacement plots.

Lately, acoustic emission (AE) has emerged as a potential non-destructive evaluation (NDE) method for testing materials. It is based on the rapid release of energy within a material generating transient elastic wave. Due to its advanced detection and location ability to dynamic defects, AE technique possesses the ability for presenting directly the point of crack initiation during fracture toughness test of a specimen. For utilizing this ability of AE, several investigators have performed extensive fracture toughness tests by AE technique to estimate the fracture toughness values.1–11) However, the approaches are different. In some investigations, changes in the slope of AE parameters versus fracture mechanic parameters such as crack opening displacement (COD), stress intensity factor (K) or J integral curve were used to determine the fracture toughness.1–3) Arli et al.,1) in an early work, concluded that the point of crack initiation could be described as the significant change in the slope of total AE counts versus COD value. In the case of two grades of medium and high strength steels, the crack initiation during fracture toughness tests was determined by the sudden change in the slope of total AE energy versus J curve.2) Meanwhile, Blanchette et al.3) gained the point of crack initiation from the sudden change in the slope of total AE counts versus K curve. Nevertheless, in other works, the maximum value of AE parameters such as amplitude and frequency spectra was used to evaluate the fracture toughness.4–10) In A533B pressure vessel steel, the first appearance of high amplitude emissions appeared to be associated with crack initiation and extension, which involved the rapid shear linkage of growing void.10) In C–Mn structural steels, two distinct peaks in the variation of total AE events with time were observed during fracture toughness tests.7) The first peak was attributed to the crack initiation whereas the second peak was ascribed to the final fracture. In another instance, frequency spectrum of AE signals was used to evaluate the fracture toughness and the onset of crack initiation was characterized by the first strong AE peak spectra.8) Roy et al.7) have studied AE behavior during fracture toughness tests of four kinds of steels exhibiting varying ductility. They provided the recommendation that the point of crack initiation could be obtained by identifying the sudden rise of cumulative energy/counts along with high amplitude signals. Moreover, in the case of 304LN weldments, AE behavior was investigated during monotonic and cyclic fracture toughness tests and the sudden rise in AE
energy associated with high amplitude signals was taken as the crack initiation.\(^8\) In addition, double differential based on AE count was used to evaluate the fracture toughness of SA333 Gr.6 steel for the first time. The maximum rate of occurrence of AE at a point had been correlated with the crack initiation point.\(^9\)

It is obvious from the above discussion that the evaluation of fracture toughness by AE technique was based on the evident changes in the slope of cumulative AE parameters versus fracture mechanic parameters or on the appearance of AE signals which exhibited high amplitude or frequency spectra. However, these approaches were chaotic and guidelines were seldom provided for determination of fracture toughness by AE technique. On the other hand, the point of crack initiation characterized by these methods was physically seldom verified. No evidence or quantitative basis showed that the sudden jumps of cumulative AE parameters or signals with high amplitude or frequency spectra were attributed to the crack initiation. In view of this, four point direct current potential drop (DCPD) method has been taken in this investigation to measure the crack initiation and extension, which generate evidence for determination of physical crack initiation by AE methods.

As one of the nondestructive methods for the detection of defects, the DCPD method is based on an occurrence of a potential drop caused by a discontinuity in a specimen, like cracks, when a homogeneous direct current of a sufficient value passes through the whole cross-section of a specimen.\(^12\) This method is very sensitive to crack and has been widely used in the crack growth.\(^12\)–\(^14\) In this study, analyses of DCPD and AE during fracture toughness tests of 316LN SS base metal and weld were made synergistically to determine the point of crack initiation. Subsequently, the critical load values corresponding to the crack initiation were calculated to determine the fracture toughness. Finally, the results were compared with those obtained by conventional ASTM procedure. The aim of this investigation is to verify the physical crack initiation determined by AE approach and to provide some available guidelines for estimation of fracture toughness.

2. Experimental Details

2.1. Materials and Microstructures

The 316LN SS plates were joined by the shielded metal arc welding process (SMAW) using type ER316L electrode of 3.2 mm diameter. The welding electrodes were soaked for 1 h at 623 K before the commencement of welding. During the welding, the voltage, current and travel speed were maintained at 25.2 V, 130 A and 2.5 mm/s, respectively. The geometry of the welding plates is illustrated in Fig. 1. After welding, the steel plates were solution-treated at 1 323 K for 2 h and then water quenched as the post-weld heat treatment. The chemical compositions and microstructures for 316LN SS base metal and weld in this investigation are presented in Table 1 and Fig. 2, respectively. The microstructure of base metal was found to exhibit an austenitic structure with ferrite bands, while the microstructure of

![Fig. 1. Geometry of welding plates and cut-out of fracture toughness test specimens.](image)

![Fig. 2. Microstructure of 316LN SS for: (a) base metal and (b) weld.](image)

| Table 1. Chemical compositions of 316LN stainless steel (Wt.%) |
|------------------|---------|---------|-------|-------|-------|-------|-------|-------|
| Composition      | C       | Cr      | Ni     | Mo    | Mn    | Si    | N     | P     | S     |
| Base metal       | 0.023   | 16.43   | 11.33  | 2.25  | 1.45  | 0.46  | 0.16  | 0.024 | 0.001 |
| Weld             | 0.023   | 18.30   | 11.30  | 2.02  | 1.50  | 0.42  | –     | 0.026 | 0.014 |
weld metal revealed the presence of ferrite with a fine vermicular morphology.

2.2. Fracture Toughness Test Coupled with DCPD Monitoring

Single edge bend (SEB) specimens in thickness 9 mm (Fig. 3) were machined from the as-received material with notches to determine fracture toughness of 316LN SS base metal and weld. The specimens were then fatigue pre-cracked to achieve a/W ≈ 0.5 following the ASTM standard E647-03. All pre-cracking experiments were carried out at a stress ratio of 0.1 using a frequency of approximately 100 Hz. Crack tip opening displacement (CTOD) fracture toughness tests were performed on an Instron machine (model 1195) using a constant crosshead displacement rate of 0.5 mm/min at ambient temperature. A clip gauge was attached to the mouth of each specimen during the tests to monitor the crack mouth opening displacement (CMOD). The load (p) and CMOD data for each of the specimens were recorded for subsequent evaluation of fracture toughness values. These tests were carried out following the guidelines recommended in ASTM standard E1820.16) The potential drops of specimens were recorded by DCPD method during the test, as shown in Fig. 3. The crack lengths were then calculated by the linear relationship between the crack and potential drop.

2.3. Acoustic Emission

The AE signals generated from fracture toughness tests were recorded by SAMOS AEwin system, made from Physical Acoustic Corporation (PAC). Two narrow band transducers (R15a) with an operating frequency from 50 kHz to 200 kHz and two 2/4/6 preamplifiers with 40 dB were used to monitor the AE signals. The transducers were mounted on the surface of the specimen using vacuum grease as couplant. Attached position of the AE transducers on the specimens is shown in Fig. 3. The peak definite time (PDT), hit definite time (HDT) and hit lookout time (HLT) were set at 300 µs, 600 µs and 1 000 µs, respectively. Before starting the tests, the AE signals generated during a test of dummy SEB specimen without a notch were monitored to check the friction noises under the same loading conditions. Based on this dummy test, the threshold of 32 dB and the compatible filter of 100–400 kHz were maintained to eliminate the extraneous noises. The AE tests were carried out until the final fracture of the specimen emerged. Different parameters of AE signals viz. counts, energy, amplitude were considered for analyzing the results.

2.4. Fractography Investigation

The tested specimens were subjected to high frequency fatigue to grow the crack further for the convenience of optical measurement of crack growth and fractography investigation. The initial and final crack lengths were measured optically by a travelling microscope using a nine point averaging method, as specified in ASTM E1820 standard. Subsequently, fractography examination using scanning electron microscope (SEM) was performed on the fractured surface of each tested specimen to identify the fracture mechanism.

3. Results and Discussion

3.1. Fracture Toughness Tests Results

The fracture toughness tests data were analyzed to establish δ-R curves for each of the tested specimens using the single specimen technique according to the ASTM standard E1820. The value of δ was usually determined from the δ-R curves using a theoretical blunting line, whose equation is given by

\[ \delta = M_e \Delta a \]  

where \( M_e = 1.4 \) and \( M_b \) is the slope of the blunting line, \( \Delta a \) is the crack extension.

The estimated values of δ and the corresponding crack extension \( \Delta a \) for 316LN SS base metal and weld have been plotted to obtain the δ-R curves, as shown in Fig. 4. In the present investigation, \( \delta_b \) was taken as the value at which the power law curve fitting the δ-Δa values intersects the blunting line at 0.2 mm offset. The corresponding \( \delta_b \) values are given in Table 2. The average fracture toughness of 316LN SS base metal and weld were calculated as 0.6375 and 0.4800 mm, respectively. The estimated fracture toughness values of base metal were similar with the results reported in an earlier work, which ranged from 0.5 to 0.64 mm. The similarity was attributed to the similar thickness considered in the two considerations. The specimen thickness in the present study is 9 mm and that reported in the literature was 10 mm. Moreover, it is evident from Table 2 that the weld possesses lower fracture toughness than that of base metal, which is consistent with the results reported by Refs. 18, 19. Same results have also been obtained for another austenitic stainless steel by Baek et al. and they found that the base metal of 304 SS showed superior resistance to crack growth relative to weld over the entire testing temperature range. The difference may be ascribed to the fact that in a duplex structure of base metal the macroscopic crack initiation can be impeded by ferrite bands, while in a single phase structure of weld the resistance to macro propagation is lower. Therefore, it is worth noting that the weld of 316LN SS exhibits lower fracture toughness and NDE on weld need to be paid high attention to during the operation and maintenance of equipments.

The fracture toughness \( \kappa_b \) is a thickness-independent material toughness property corresponding to the highest crack tip constraint conditions. The ASTM E1820 standard

![Fig. 3. Schematics of the specimen and experimental apparatus.](image-url)
indicates two criteria:
1. The maximum $\delta$ capacity for a specimen is given by $\delta_{\text{max}} = b_0/20$, and
2. Qualification of $\delta_Q$ as $\delta_{IC}$, which requires $\delta_Q \leq b_0/35$
where $b_0$ is the initial ligament.

The values according to the two criteria are calculated as 0.45 and 0.257 mm, respectively. It may be noted that values of $\delta_Q$ estimated here do not qualify as $\delta_{IC}$ by these criteria and cannot be considered as a material property. However, these $\delta_Q$ values could be used only for components of thickness equal to or less than 9 mm.

3.2. Acoustic Emission
3.2.1. AE Characteristics and Identification of Crack Initiation by AE and DCPD Method

Typical plots of AE amplitude and cumulative parameters such as cumulative counts, energy and amplitude versus time for the base metal and weld specimens are shown in Figs. 5 and 6, respectively. Three regions were observed from the above illustrations. In region 1, the cumulative counts, energy and amplitude increased slowly and weak amplitudes occurred at the beginning due to the plastic deformation in the ductile material. However, a sudden increase of cumulative counts, energy and amplitude, and peak amplitude emerged at 105 and 75 s for base metal and weld specimen, respectively. Several authors have attributed this sudden rise of cumulative parameters with high amplitude signals to crack initiation. However, the crack initiation was not physically verified. In this investigation, the potential drop of specimens during fracture toughness tests were obtained to provide some evidences, as presented in Fig. 7. It can be seen that the potential had dramatic fluctuations at the beginning and maintain a steady growth after the point of peak amplitude, which indicated that crack initiated and started to propagate. Therefore, the consistency of the AE and potential results proved that the point of crack initiation could be identified by the sudden increase of AE cumulative energy, counts or amplitude with peak amplitude signals. The typical waveform and frequency spectrum of crack initiation were also analyzed and the results are shown.

Table 2. Comparison of fracture toughness values estimated from ASTM standard procedure ($\delta_Q$) and AE test ($\delta_{AE}$).

<table>
<thead>
<tr>
<th>Specimen no.</th>
<th>$\delta_Q$ (mm)</th>
<th>$\delta_{AE}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>1 0.5973</td>
<td>0.0969</td>
</tr>
<tr>
<td></td>
<td>2 0.6298</td>
<td>0.2312</td>
</tr>
<tr>
<td></td>
<td>3 0.6890</td>
<td>0.1722</td>
</tr>
<tr>
<td>Weld</td>
<td>1 0.4493</td>
<td>0.0962</td>
</tr>
<tr>
<td></td>
<td>2 0.4821</td>
<td>0.1924</td>
</tr>
<tr>
<td></td>
<td>3 0.5087</td>
<td>0.1573</td>
</tr>
</tbody>
</table>

Fig. 4. Typical $\delta$-R curves of 316LN SS for: (a) base metal and (b) weld.

Fig. 5. Typical plots of AE amplitude and cumulative energy versus time for: (a) Base metal and (b) Weld.
in Fig. 8. It is obvious that the waveform is in a burst type and the spectral energy mostly distributed at the frequency zone of 25–165 kHz. The peak energy appeared at the frequency of about 110 kHz. The features were significantly consistent with those of crack growth signals. In addition, several authors have concluded that the waveform of plastic deformation is a type of continuous signal, and signals for crack closure resulted from the contacting friction of the crack surfaces showed relatively higher spectral frequency at 200–400 kHz. Thus, the analyses of waveform and frequency spectrum also generate evidences that the peak amplitude signals originated from crack initiation. Furthermore, the point of crack initiation obtained from the AE results of weld emerged at an earlier time when compared with that of base metal specimens. It indicated that the crack resistance of weld was lower than that of base metal, which agreed with the results gained from conventional ASTM standard.

In region 2, signals with lower amplitude were found compared with those during crack initiation process in region 1. Mukhopadhyay et al. have studied the AE behavior during fracture toughness tests of SA333 Gr.6 steel and they found that during the crack initiation, AE hits generated were of higher peak amplitude as compared to those generated before and after crack initiation, which was accordance with our results. Moreover, the cumulative

![Fig. 6. Typical plots of AE cumulative counts and amplitude versus time for: (a) Base metal and (b) Weld.](image)

![Fig. 7. Typical plots of AE amplitudes and potential drop versus time for: (a) base metal and (b) weld.](image)

![Fig. 8. Typical AE waveform (a) and frequency spectrum (b) of crack initiation.](image)
counts, energy and amplitude increased slowly until the final fracture. This was related to the stable crack propagation and a large number of plastic deformation at the crack tip of specimens. The relatively low AE activity during this region corroborated the earlier results reported by Refs. 8, 25 that ductile crack growth is a relatively silent process. In region 3, the cumulative energy and amplitude showed a sudden increase again and amplitude reached the maximum value. This was attributed to the final fracture caused by the quick and unstable crack propagation. Though the point of fracture in weld specimens was not associated with jumps in cumulative counts, it was found to be related to the jumps in cumulative energy and amplitude.

3.2.2. Determination of Fracture Toughness Using AE Technique

Because the AE monitoring continued to the final fracture of specimen, so the time were longer than that of P-CMOD measurement. The load, related to the point where cumulative counts, energy and amplitude had a first sudden increase with peak amplitude signals, was taken as the critical load \( P_{QAE} \) corresponding to the crack initiation for determination of fracture toughness of 316LN base metal and weld. Typical variations of amplitudes and load with respect to time for estimating the critical load \( P_{QAE} \) for specimens of base metal and weld are shown in Fig. 9. Fracture toughness \( (\delta_{QAE}) \) values were then calculated using the critical load from Fig. 9 following Eq. (A1.12) of Ref. 16. The estimated fracture toughness values \( \delta_{QAE} \) are presented in Table 2. The average fracture toughness of base metal and weld were calculated as 0.1667 and 0.1486 mm, respectively.

3.2.3. AE Sources

The above analysis has shown that the main AE sources during the three regions of fracture tests are plastic deformation at the crack tip, crack initiation and propagation. However, the AE source mechanisms of 316LN base metal and weld still require investigations. Typical SEM fractographs of base metal and weld are shown in Fig. 10. It is evident that both fracture surfaces revealed micro-voids with tearing ligaments. The micro-mechanism of fracture was predominantly governed by micro-voids nucleation, growth and coalescence as indicated by general dimple formations on their fracture surfaces. As the plastic deformation zone and stress at the crack tip increased, the local stress concentration led to the formation of micro-voids. Further loading caused the fracture of ligaments between these micro-voids, as illustrated in Fig. 10. The shearing of ligaments would generate several AE signals giving rise to an increase of cumulative counts, energy and amplitude.26 Therefore, AE sources during the fracture toughness tests for 316LN SS base metal and weld were the plastic deformation, crack initiation, crack extension and shearing of ligaments.

3.3. Comparison between the Results of Fracture Toughness Tests and AE

It can be seen from Table 2 that the fracture toughness values obtained from AE characteristics were consistently

![Fig. 9](image-url). Typical variations of load and AE amplitudes versus time for: (a) base metal and (b) weld.

![Fig. 10](image-url). SEM fractographs of: (a) base metal showing micro-voids and tearing ligaments, (b) weld showing dimple feature.
lower than those estimated from the conventional ASTM procedure. The average $\delta_{\text{AEE}}$ values were lower by about 73% and 69% for the specimens of base metal and weld, respectively. The difference in the critical values of $\delta$ estimated using ASTM standard and AE technique could be attributed to the following arguments. First, the fracture toughness $\delta_0$ determined by ASTM method is ascribed at the intersection of a blunting line with the power law curve where the crack extension of 0.2 mm is considered. AE technique, on the other hand, has a higher sensitivity to reveal the micro-fracture processes at the crack tip, and thus indicates more precisely the point at which the crack initiates or occurs in a much smaller length. Therefore, a lower value of $\delta_{\text{AEE}}$ is naturally achieved. Second, the higher value of $\delta_0$ estimated by the standard method is also associated with the blunting line and the lower slope of the blunting line could lead to a higher value of $\delta_0$. Mukhopadhyay et al.\(^{5)}\) have calculated the fracture toughness $J_0$ by using the different value of slope of blunting line $M$. According to the results, the $J_0$ values obtained following ASTM standard for $M=4$ were substantially lower than those obtained for theoretical $M=2$. The $J_{\text{QAE}}$ values estimated by AE technique were found to be 4–41% lower than those estimated using $M=2$, however, were similar to those obtained for $M=4$. In fact, the Chinese standard procedure recommends the use of a higher value of slope of blunting line for a more conservative estimation of fracture toughness.

The lower values of the fracture toughness estimated by AE technique in comparison to the conventional approaches were also reported by other authors.\(^{5,7,8,25,27)}\) In 7075-T651-Al alloy, the critical values of $K$ and $J$ determined with the help of AE technique were approximately 6–10% lower than the values estimated by the conventional procedure.\(^{25)}\) Ohira et al. have reported that the fracture toughness $J_{\text{QAE}}$ of A533B pressure vessel steel was nearly 36% lower than that obtained by conventional J-integral test.\(^{27)}\) Camerini et al.\(^{7)}\) have investigated the relation between AE behavior and CTOD testing for a structural steel and they found that the critical CTOD values corresponding to the first AE peak were three to nine times lower than the conventionally estimated CTOD values for the initiation of stable crack propagation. In another instance, Roy et al.\(^{7)}\) have reported that the fracture toughness values estimated using AE technique for SA333 and 304LN steels were almost 15–25% lower than those obtained by ASTM procedure. In 304LN weldment, a comparison between $J_{\text{QAE}}$ and $J_0$ indicated that the former ones were nearly 54% and 16% lower than the latter ones, for monotonic and cyclic fracture tests, respectively.\(^{9)}\) The obtained results from these investigations were in good agreement with those in this study. It is worth noting that AE technique lead to a conservative estimate of fracture toughness value. The fracture toughness values based on AE technique once used in mechanical engineering design will reduce the factor of safety applied and decrease the risk of fracture.

In D2 tool steels, however, the plain strain fracture toughness $K_{IC}$ values obtained by AE technique were very close to those determined by ASTM standard E399.\(^{10,11)}\) In these studies, critical loads corresponding to the maximum of cumulative counts rate and energy rate were used to estimate the fracture toughness values and the authors believed that the two methods were more accurate than conventional AE method based on the sudden increase of cumulative counts. However, the maximum value of cumulative counts rate and energy rate emerged closely to the end of fracture tests. The point might belong to the crack extension or the final fracture process and should not be considered as the crack initiation. In the present investigation, the first peak of cumulative energy rate appeared during the crack initiation and the maximum value occurred at the end of the tests for both specimens, as shown in Fig. 11. Therefore, the fracture toughness values estimated using the maximum of cumulative energy rate and counts rate are definitely higher than those determined by the point of crack initiation. Though the fracture toughness values obtained by AE technique in Refs. 10, 11) were similar to those estimated by conventional ASTM procedure, the two methods that based on the maximum of cumulative energy rate and counts rate should not be recommended for estimation of fracture toughness. Instead, the first peak of cumulative energy rate, the sudden increase of cumulative counts, energy and amplitudes coupled with peak amplitude signals, which corresponded to the point of crack initiation, should be considered comprehensively for determination of fracture toughness.

It also should be noted that the fracture toughness values estimated by AE technique were much lower than those calculated by ASTM standard. The AE based fracture toughness values once used in mechanical design will

![Fig. 11. Typical cumulative energy rate versus time for: (a) base metal and (b) weld. (Online version in color.)](image-url)
significantly affect the factor of safety adopted in the structural design and reliability analysis. However, it has been proved that AE technique could recognize the onset of crack initiation, monitor the fracture process and determine the fracture toughness online. Therefore, further study should be conducted to accumulate more data for investigating the feasibility of the application of AE on fracture toughness evaluation and establishing the corresponding standards.

4. Conclusions

Fracture toughness behavior of 316LN SS base metal and weld were investigated using AE and DCPD monitoring. The following conclusions can be drawn:

1) 316LN SS weld exhibits a lower fracture toughness than that of base metal and thus non-destructive evaluation on weld need to be paid high attention to during operation and maintenance of equipments.

2) Three regions are observed on AE amplitude and cumulative counts, energy and amplitude plots. Region 1 is associated with crack initiation, region 2 is related to crack extension and region 3 is concerned with the final fracture. AE sources during the fracture toughness tests for 316LN SS base metal and weld have been attributed to the plastic deformation at the crack tip, crack initiation and extension, and shearing of ligaments.

3) The points of crack initiation in 316LN SS base metal and weld can be identified by the first peak of cumulative energy rate, the sudden increase of AE cumulative energy, counts or amplitude coupled with peak amplitude signals. It is recommended that these determination methods should be considered synthetically for identification of crack initiation.

4) The average fracture toughness $\delta_{\text{AE}}$ values estimated using AE characteristics are found to be 73% and 69% lower than the values obtained using ASTM standard procedure for 316LN SS base metal and weld, respectively. Therefore, it can be contended that AE technique results in a conservative estimate of fracture toughness.

Acknowledgements

This study was supported by the National Basic Research Program of China (No. 2015CB057602).

REFERENCES