Numerical Analysis of Fracture Failure Behavior of Refractory Lining in Coal-Water Slurry Gasifier

Jinghong Gao, Yuchen Shi, Weiguang Su,* Xudong Song, Jiaofei Wang, and Guangsuo Yu*

ABSTRACT: Fatigue crack fracture is one of the main reasons for the failure of a refractory lining in a coal-water slurry gasifier. To explore the fracture failure behavior of a refractory lining during the operation of a gasifier, the stress intensity factor (SIF) and J-integral at crack front were calculated by the finite element method, and a crack growth model for the refractory was established. At the same time, the effects of different crack length, depth, and angle on the stress and SIF, as well as J-integral distribution around the crack-tip, were presented. The simulation results demonstrated that very large stresses occurring at the crack tip and the distribution regulation of K and J-integral along the crack front for surface cracks were similar. The maximum values occurred near the two ends of the crack (θ = 0°, 180°), and the minimum values appeared near the deepest crack front (θ = 90°). K and J-integral values at the same position increase with increasing crack length and depth and decrease with the angle of crack when the a/c was kept constant. Furthermore, J-integral results indicated that excessive crack depths were likely to cause destabilizing crack growth. These results have provided a reliable theoretical basis for fracture analysis and life prediction of the refractory lining in a gasifier.

1. INTRODUCTION

Coal-water slurry (CWS) gasification is the most critical technology for clean and efficient utilization of coal. Due to its wide adaptability of raw materials, high carbon conversion rate, large capacity of single gasifier, and environmental friendliness, this technology has been widely used in electric power, petroleum, chemical, and other industries.1-3 The refractory lining is a key component of a CWS gasifier, which can isolate heat, restrict the flow field, and resist corrosion by particles, slag, and gas.6,7 During long-term service in a CWS gasifier, the refractory lining will inevitably initiate fatigue cracks due to the cyclic thermal shock caused by repeated heating and cooling of the gasifier. Fatigue crack growth has always been the main failure mechanism for a refractory lining serving at elevated temperature and high pressure conditions, leading to early failure of the refractory lining prior to the design life.8-10 This will not only affect the operation cycle and stability of the gasifier, but also cause production accidents. Therefore, determining the fracture failure of refractory lining under service loads for guiding the safe operation and timely maintenance of a CWS gasifier will be of paramount importance.

The concept of stress in classical mechanics cannot be well applied to the calculation of crack growth because the crack front has singularity, and the stress tends to be numerically infinite.11 Fracture mechanics is the basis for studying surface cracks in refractories. Relevant studies have shown that the crack growth was mainly evaluated by the stress intensity factor (SIF) and J-integral at the crack tip.12,13 It is well-known that SIF can characterize the singularity of the stress field strength at the crack tip in the linear elastic fracture mechanics (LEFM), which is an important parameter to determine the fracture of the cracked structure and calculating the crack growth rate.14-16 The J-integral denotes a method to calculate the strain energy release rate that characterizes near-crack tip stress and strains under elastoplastic material behaviors.17 Combined with the variation regularity of SIF and the J-integral, the fatigue fracture life and crack initiation of components could be better studied and explored.

In the past, a considerable number of analytical works has been carried out on the thermal shock cracks of ceramic materials through experimental test and model prediction.18-23 Papathanasiou et al.11 proposed a finite element procedure and developed a MATLAB code to study the development of thermal stress inside refractory ceramics subjected to severe thermal shock. The finite element code was validated and can
be used to estimate the thermal shock of refractories. Andreev et al. simulated the fracture behavior of refractory materials under tension by Hillerborg’s fictitious crack model. Their results showed that the cyclic temperature led to repeated crack growth in refractories during the whole service period. Kong et al. studied the crack tip stress–strain field by J-integral and established the crack safety relationship for ladle refractories under thermal and steel loading. Their results were in good agreement with the theoretical values obtained by the weight function method. Souad et al. calculated the SIF of ceramic matrix and fiber/matrix interface cracks under an applied load by finite element method (FEM), and the crack growth was studied by LEFM principles. Li et al. carried out the interaction between thermal shock crack evolution and heat conduction, and its influence on the thermal shock behavior of ultrahigh temperature ceramics by FEM. Chen et al. quantitatively analyzed the effect of pore space on SIF at the crack tip by J-integral numerical method, which provided a reliable theoretical basis for the design of porous ceramics with better performance. From the above studies, it can be observed that most of the research on the crack growth of refractories was mainly focused on the metallurgical and steelmaking industries. The refractory lining in a CWS gasifier services in an environment of high pressure and high temperature as well as strong reducing atmosphere, accompanied by huge changes in temperature and pressure during start-up and shutdown. However, the knowledge about the fracture failure behavior of refractories for a CWS gasifier exposed to high temperature and chemical corrosive environments is still very scarce. Further and deep study is much needed to provide some basic data for ensuring the safe operation of a gasifier.

In the present work, a numerical model was developed to calculate the SIF and J-integral for a surface crack of the refractory lining in a CWS gasifier based on the fracture mechanics theory. The effects of crack length, depth, and angle on the distribution of SIF and J-integral have been examined, and the crack growth characteristics of the refractory lining for a CWS gasifier were preliminarily analyzed. The results provide a reliable theoretical basis for fracture failure analysis and life prediction of the refractory lining in a CWS gasifier.

2. THEORETICAL APPROACH

In fracture mechanics, the stress intensity factor, J-integral, and strain energy release rate are the three basic parameters for studying the crack tip. In linear elastic materials, these three parameters are interrelated through material parameters, and the J-integral corresponds to the strain energy release rate.

According to the stress on the crack growth plane, cracks are divided into three modes: tensile opening mode (mode I), in-plane shearing mode (mode II), and out-of-plane shearing or tearing mode (mode III). The growth surface of the mode I crack is perpendicular to the loading load, while the growth surface of modes II and III crack is parallel to the load. When the crack growth surface is at an oblique angle to the force direction, there may be three crack states in which the cracks coexist. The displacement of the front edge of the three-dimensional crack is shown in Figure 1. The first normal of the crack front is set to \( n \) and the second normal to \( b \). The tangent direction \( r \) can be determined by the vector product of \( b \) and \( n \). When \( \theta = -\pi \), the expression of stress intensity factor described by crack front displacement is as follows:

\[
K_i = \frac{E}{8(1-\mu^2)} \left\{ \frac{2\pi}{r} \text{lim}_{r \to 0} [\mu_1(\theta = +\pi) - \mu_2(\theta = -\pi)] \right\}
\]

\[
K_{II} = \frac{E}{8(1-\mu^2)} \left\{ \frac{2\pi}{r} \text{lim}_{r \to 0} [\mu_1(\theta = +\pi) - \mu_1(\theta = -\pi)] \right\}
\]

\[
K_{III} = \frac{E}{8(1-\mu^2)} \left\{ \frac{2\pi}{r} \text{lim}_{r \to 0} [\mu_3(\theta = +\pi) - \mu_3(\theta = -\pi)] \right\}
\]

where \( K_i, K_{II} \) and \( K_{III} \) are the stress intensity factors of the mode I, mode II, and mode III cracks, respectively, \( \mu_{c1}, \mu_{c2}, \mu_{c3} \) and \( \mu_{s1}, \mu_{s2}, \mu_{s3} \) are the displacements in the \( b, n, r \) directions of the crack front, respectively.

The J-integral was first developed by Rice in 1968, which was used to describe the energy absorbed by the existence of the crack and to measure the stress–strain field strength at the crack tip. In the finite element software, the J-integral is solved by defining the element strain energy and integral on the circumference of stress–strain displacement path, and its accuracy can meet the engineering applications. The equation is as follows:

\[
J = \int_{\Gamma} W \, dx_2 - T_i \frac{\partial u_i}{\partial x_1} \, ds
\]

The strain energy density is calculated from

\[
W = W(\varepsilon_{eff}) = \int_0^{\varepsilon_{eff}} \sigma_{ij} \, d\varepsilon_{ij}
\]

where \( \Gamma \) is any counterclockwise path around the crack tip that starts on the lower crack surface and stops on the upper crack surface, \( ds \) is the length increment along the contour \( \Gamma \), \( T_i \) is the traction vector, \( W \) is the strain energy density, \( u_i \) is the displacement vector at any point in the contour \( \Gamma \), and \( \sigma_{ij} \) and \( \varepsilon_{ij} \) are the stress and strain tensors, respectively.

In linear elastic case, the SIF and J-integrals of composite cracks are related to each other by material parameters with the following equation:

\[
J = \frac{1 - \nu^2}{E} (K_{I}^2 + K_{II}^2) + \frac{1}{2\mu} K_{III}^2
\]

where \( \nu \) is the Poisson’s ratio, \( E \) is the modulus of elasticity, \( \mu \) is the shear modulus, and \( K_I, K_{II}, \) and \( K_{III} \) are the stress intensity factors for the above-mentioned three mode cracks, respectively.
3. FINITE ELEMENT ANALYSES

3.1. Finite Element Model. The refractory lining of a CWS gasifier is composed of the hot-face brick, backup brick, heat isolation brick, ceramic fiber, and steel shell.\textsuperscript{32} The environment of the inner refractory layer is much more severe than that of the outer layer in the actual operation process of gasifier. The preliminary analysis shows that the hot-face brick is highly susceptible to fracture during the operation of the gasifier, and the service life is usually shorter than 5000 h,\textsuperscript{33} while fracture failure of the outer refractory layer is negligible. The K-brick is a hot-face brick located at the uppermost part of the sidewall area in the gasifier, and its original thickness is 230 mm. The average corrosion rate of the sidewall area is about 0.076 mm/h, and the K-brick is the most seriously damaged. Therefore, the K-brick was selected as the object. To make the simulation results as close as possible to the actual values, this paper constructs the model based on the specimen by a ratio of 1/1, as shown in Figure 2.

Nonthrough cracks in engineering structures are usually simplified as semielliptical cracks. The finite element software ANSYS was used to establish a finite element model of a cracked hot-face brick as displayed in Figure 3. X axis is the direction of the crack front edge, Y axis is the normal direction of the crack front edge, and Z axis is parallel to the crack front edge. The crack depth and length are denoted by $a$ and $2c$, respectively. Alphabet $t$ indicates the thickness of the hot-face brick, $\theta$ is the angular parameter taking the center of the ellipse as its coordinate origin, and $\theta = 90^\circ$ denotes the deepest point of the crack front while $\theta = 0^\circ$ or $180^\circ$ indicates the two ends of the crack. The deepest point along the crack front is denoted A, and the crack tip location on the surface is denoted B. The wide-ranging geometrical dimensions of $a/t = 0.1, 0.2, 0.3,$ and $a/c = 0.6, 0.8, 1.0, 1.2, 1.4$ were selected to study the distribution of the crack-tip fracture parameter SIF and $J$-integral with the different geometrical dimensions.

One of the main problems in solving SIF with a conventional coordinated element is that it cannot reflect the...
singularity of the crack tip, so the mesh must be divided very finely. The tetrahedral element is used to divide the mesh, and the mesh is refined near the crack tip to obtain more accurate results, as depicted in Figure 4.

Figure 4. Schematic diagram of grid division of cracked refractories.

3.2. Material Properties. Cr$_2$O$_3$–Al$_2$O$_3$–ZrO$_2$ bricks are frequently used as K-brick for CWS gasifier on account of their excellent heat stability and corrosion resistance. Table 1 indicates the chemical composition and some of physical properties of the Cr$_2$O$_3$–Al$_2$O$_3$–ZrO$_2$ brick. Typical chemical composition includes 86.7 wt % of Cr$_2$O$_3$, 8.7 wt % of Al$_2$O$_3$, and 4.6 wt % of ZrO$_2$. The Young’s modulus and Poisson’s ratio of K-brick are measured by the impulse excitation technique.

3.3. Load Conditions. In fact, the fatigue crack growth in the hot-face brick of the coal-water slurry gasifier mainly occurs during the temperature drop after the gasifier has been stopped. This is because the temperature of the hot-face brick drops faster than that of the back-up brick after the gasifier stops. This causes the cracks to be subjected to tensile stresses on both sides of the crack, resulting in crack destabilization and expansion. Therefore, the variation of the temperature field at the crack should be analyzed before calculating the SIF and J-integral for the crack, as shown in Figure 5. Then, the stress change due to the temperature change is analyzed, and the value of the calculated maximum stress is applied to the crack surface as a load to obtain the value of SIF and J-integral at the crack. As the size and angle of the fatigue crack affects the change in the stress field around it, the stress change at the fatigue crack needs to be calculated separately depending on the size and angle of the crack, which will be discussed in detail in the next section.

4. RESULTS AND DISCUSSION

4.1. Numerical Verification. The calculated value of J-integral obtained by eq 4 is compared with the simulation value of the J-integral obtained by ANSYS finite element software through the line integral method. It can be seen from Figure 6 that the simulation value is very close to the calculated value. The relative error between the value of J-integral obtained by simulation and the value of J-integral obtained by calculation gradually decreases from the two end points of the crack surface to the deepest part of the crack front. The simulation value is almost coincident with the calculated value at the deepest part of the crack front, and the error near the two ends of the crack is slightly large. The maximum error between the simulation value and the calculated value of J-integral is less than 5% in the whole normalized crack front, which further verifies the reliability and accuracy of the ANSYS numerical simulation.

4.2. SIF for Surface Cracks. A typical distribution of the SIF along the crack fronts for surface cracks in refractory lining is shown in Figure 7. It is obvious that the value of K$_I$ is symmetric about the normalized length of the crack front ($\theta = 90^\circ$). The maximum value of K$_I$ along the crack front increases with decreasing the ratio of crack depth to length $a/c$ when $a/t$ remains constant. For all the crack curves, the value of K$_I$ gradually decreases from the two end points of the crack ($\theta = 0^\circ, 180^\circ$) to the middle of the crack front, and the

Table 1. Chemical Composition and Physical Properties of K-brick

| chemical composition  | density/ (g·cm$^{-3}$) | thermal conductivity / (W·m$^{-1}$·K$^{-1}$) | coefficient of the thermal expansion $\times 10^5$/°C$^{-1}$ | Young’s modulus/ GPa | Poisson’s ratio |
|-----------------------|-------------------------|---------------------------------|---------------------------------|----------------------|----------------|
| Cr$_2$O$_3$           | 86.7                    | 4.2                             | 4.2                             | 7                    | 105            |
| Al$_2$O$_3$           | 8.7                     |                                 |                                 |                      |                |
| ZrO$_2$               | 4.6                     |                                 |                                 |                      | 0.18           |

Figure 5. Temperature change curve at the crack.

Figure 6. Comparison of simulated and calculated values of J-integral.
Figure 7. Distribution of $K_I$ along the crack front for surface cracks: (a) $a/t = 0.1$, (b) $a/t = 0.2$, (c) $a/t = 0.3$, (d) $a/c = 1.4$.

Figure 8. Equivalent stress distribution of crack tips at different lengths: (a) $a/c = 0.6$, (b) $a/c = 0.8$, (c) $a/c = 1.0$, (d) $a/c = 1.2$, (e) $a/c = 1.4$. 
minimum value of $K_I$ occurs at the deepest point of the crack front ($\theta = 90^\circ$). Figure 7d shows the distribution of $K_I$ along the crack front for surface cracks with different depth $a/t$ at a specific $a/c$ of 1.4. For all crack curves, $K_I$ first decreases and then increases with increasing of the normalized crack front length, and the value of $K_I$ is the largest at two ends of the crack. When $a/c = 1.4$ (short crack), the minimum value of $K_I$ varies little among cracks of different depths, and the minimum value of $K_I$ is usually about the same near the deepest point of the crack front ($\theta = 90^\circ$). When $a/c = 0.6$ (long crack), the variation of $K_I$ at the crack front is relatively flat, and the $K_I$ value increases with the increase of the crack depth $a/t$. In addition, the value of $K_I$ along the crack front increases as the crack depth $a/t$ increases at the same $a/c$. Since the $K_I$ parameter is generally used to characterize the singularity of the stress field strength of the crack front, so the crack may initiate from the place with the maximum $K_I$ value. This demonstrates that the cracks with larger crack depth may first initiate due to the higher $K_I$ values along the crack front for cracks with the same ratio of $a/c$.

When the SIF of mode I crack is known, the predicted crack growth angle can be estimated under the applied load. Figure 8 depicts the equivalent stress distribution of cracks at different lengths. It can be seen that the stress centralization at the crack tip is significant, while away from the cracks there is low stress values. With the increase of the crack length, the equivalent...
stress value and the opening degree of the crack tip gradually increase, so the value of $K_I$ also gradually increases.

Figure 9 shows the equivalent stress distribution of cracks at different depths. An increase in crack depth and applied load results in an increase in equivalent stress, and maximum stress of the crack tip can be reach up to 13 376 MPa. It is also observed that elastic deformation at the crack faces increases as the crack depth increases. However, the longer is the crack depth, the less obvious is the stress concentration at the crack tip. The opening degree of the crack tip does not vary much, and therefore the range of variation of its stress intensity factor value is also not significant.

The distribution of surface crack fronts $K_I$ with different orientation angles is shown in Figure 10. The value of $K_I$ gradually decreases with an increase of crack angle when $a/t$ and $a/c$ remain constant. The larger the crack angle is, the faster the value of $K_I$ decreases. When $\theta = 45^\circ$, the value of $K_I$ at the crack front gradually tends to be negative by increasing of crack depth. The main reason is that the vertical load that initiates a mode I crack can be expressed as $\sigma \sin^2 \theta$, and the vertical load is not a affected at $\theta = 45^\circ$, so the value of the crack front $K_I$ gradually decreases. The negative value of $K_I$ means that the crack is closed away from the interface and under the action of external load. Furthermore, it is clear that the values of $K_I$ along the crack front increase as the crack depth $a/t$ increases at the same $a/c$ and crack angle $\theta$. The above results show that the larger is the crack angle, the smaller is the
possibility of crack growth, and the longer is the service life of the refractory lining.

Figure 11 shows the equivalent stress distribution of cracks at different orientation angles. It is observed that the higher stresses are located at the crack tip, and the equivalent stress value of the crack tip is the biggest at $\theta = 45^\circ$, which is 16295 MPa. With the increase of the crack orientation angle, the equivalent stress value of crack tip also increases gradually. The equivalent stress value of the crack tip reaches the maximum and the crack tip is almost closed at $\theta = 15^\circ$. It is further demonstrated that the larger is the crack angle, the smaller is the value of SIF, and the crack grows with more difficulty.

### 4.3. J-Integral for Surface Cracks

Figure 12 shows the distribution of the $J$-integral along the crack front for surface cracks with different geometrical dimensions. The distribution of the $J$-integral is similar to that of SIF ahead of crack front. The maximum value of the $J$-integral increases with the increase of $a/c$ under the same crack depth ratio $a/t$. Moreover, the position of the maximum $J$-integral value is also dependent on the crack dimensions. With the increase of
the crack length, the decrease of J-integral value in the middle area of the normalized crack front length was more obvious. The maximum J-integral value occurs at both ends of the crack ($\theta = 0^\circ, 180^\circ$) and the minimum J-integral value occurs at the deepest point of crack front ($\theta = 90^\circ$) for all cases. As shown in the eq 4, the stress level ahead of the crack tip is related to the SIF and J-integral. Hence, it can be concluded that the higher J-integral level always means the higher stress level around the crack front.

Figure 13 depicts the distribution of the J-integral ahead of the crack front for surface cracks with various geometrical dimensions at $a/c = 0.6$ and $a/c = 1.4$. The J-integral values increase with increasing crack depth $a/t$. It can be seen that J-integral decreases gradually with the increase of normalized distances and reaches the minimum value at the deepest point of the crack front. For the long cracks ($a/c = 0.6$), the J-integral values decrease first and then gradually increase, with the maximum J-integral values appearing at both ends of the crack ($\theta = 0^\circ, 180^\circ$). For short surface cracks ($a/c = 1.4$), the depth of the crack has little effect on the depth point of crack front but has great effect on the point near the crack surface. Moreover, the minimum values of J-integral for cracks with different depth at the same $a/c$ of 1.4 (short crack) are generally the same near the deepest point of the crack front.

Figure 14 indicates the distribution of the J-integral of surface cracks along the crack front at different angles. For all cracks, most of the variation is for both ends of the crack ($\theta = 0^\circ, 180^\circ$), while the value of the J-integral for the front part of the crack ($\theta = 90^\circ$) is less influenced by the angle. The J-integral values gradually decrease with the increase of crack angle when $a/t$ and $a/c$ remain constant. In addition, it is observed that the values of J-integral along the crack front increase as the crack depth $a/t$ increases at the same $a/c$ and $\theta$. The results indicate that excessive crack depth is likely to lead to destabilizing crack growth. The dangerous position and direction of cracks in the refractory lining can be found by J-integral, which provides guidance for solving the hidden dangers of the refractory lining.

4.4. Fatigue Crack Growth Rate and Life Prediction.

Based on the variation pattern of the SIF derived above, the remaining service life of the refractory lining could be estimated in conjunction with the fatigue crack growth equation. For ceramic materials, Zheng et al.\textsuperscript{36} proposed a crack-tip passivation cracking model and the Zheng-Hirt formula.

\[
\frac{da}{dN} = B(\Delta K - \Delta K_{th})
\]

\[
B = \frac{1}{2\pi(0.1E)^2}
\]

where $\frac{da}{dN}$ is the fatigue crack growth rate, $\Delta K$ is the magnitude of the loading stress intensity factor, $\Delta K_{th}$ is the crack growth threshold value, $B$ is the crack growth coefficient.

With the in-depth study of fatigue crack growth, many factors affecting fatigue crack growth have been proposed, but the decisive influences are the three basic factors of modulus of elasticity $E$, fatigue crack growth threshold value $\Delta K_{th}$ and fatigue fracture toughness value $K_{IC}$. The values of $\Delta K_{th}$ and $K_{IC}$ of refractories measured in relevant literature are approximately 3.5 MPa$\cdot$mm$^{1/2}$ and 10 MPa$\cdot$mm$^{1/2}$, respectively. The fatigue crack growth of the refractory is divided into three parts: the near-threshold region, the central steady-state growth region, and the rapid growth region. On this basis, Yuan et al.\textsuperscript{37} proposed an equation that can describe the crack growth behavior in three regions.

\[
\frac{da}{dN} = \frac{4.8}{E^2}(\Delta K - \Delta K_{th})^{1/2}\left(\frac{1}{\Delta K} - \frac{1}{(1-R)K_{IC}}\right)^{-3/2}
\]

\[
R = \frac{K_{min}}{K_{max}}
\]

where $R$ is the stress ratio and $K_{max}$ and $K_{min}$ are the maximum and minimum stress intensity factors at the crack tip, respectively.

These coefficients are obtained by least-squares fitting based on experimental data for a wide range of ceramic materials at higher stress ratios. The advantage of the above equation is that it has the same magnitude on both sides of the equation and is applicable to almost all ceramic materials. It is a good representation of the interaction between the three basic factors influencing crack expansion, which could be used as a basis for predicting the projected life of refractory bricks.

Equation 7 can be integrated in the following form:

\[
N = \int_{a_0}^{a_{th}} \frac{da}{\frac{4.8}{E^2}(\Delta K - \Delta K_{th})^{1/2}\left(\frac{1}{\Delta K} - \frac{1}{(1-R)K_{IC}}\right)^{-3/2}}
\]

where $N$ is the number of cycles, $a_0$ is the initial crack size, $a_{th}$ is the critical crack size. According to eq 9 the remaining service
life of the refractory lining can be roughly predicted so that it can be replaced in time to ensure safe operation of the gasifier.

The residual life prediction diagrams of refractory lining based on crack length and depth are shown in Figure 15. When the initial crack depth \( a/t \) is fixed at 0.1, the fatigue crack residual life is shown as a function of the initial surface crack length \( a/c \). In Figure 15a, the fatigue crack life decreases as \( a/c \) decreases (i.e., the crack length increases). In addition, the change in residual life is small when the initial crack length changes, and it can be seen that the fatigue crack residual life is not sensitive to the crack length. On the contrary, the fatigue crack residual life is strongly dependent on the crack depth. In Figure 15b, the fatigue crack residual life is shown as a function of the initial crack depth \( a/t \) when the initial crack length \( a/c \) is fixed. The residual life of the refractory lining decreases as the crack depth \( a/t \) increases and has a greater impact on the residual life as the crack depth varies. This means that accurate measurement of crack depth during inspection is critical to ensure safe operation of the gasifier.

5. CONCLUSIONS

The crack growth behavior of the refractory lining in coal-water slurry gasifier with surface cracks served at elevated temperature was studied by the finite element method. The crack growth effects along the crack front were characterized using fracture mechanics parameter \( SIF \) and \( J \)-integral, and the crack growth behavior was also predicted. The main results obtained are summarized as follows:

1. For surface cracks, the distribution regulation of \( J \)-integral was similar to that of \( K_I \). The maximum value of \( K_I \) or \( J \)-integral occurred near the two end points of the crack (\( \theta = 0^\circ, 180^\circ \)), while the minimum value occurred near the deepest crack front (\( \theta = 90^\circ \)). For cracks with the same ratio of crack depth to length \( a/c \), the \( K_I \) or \( J \)-integral increases with increasing crack depth \( a/t \) and decreases by increasing crack angle.

2. The distribution of equivalent stress in the refractory lining indicates the maximum stress concentration in the vicinity of crack tips, while away from the cracks there is low stress values.

3. The values of \( K_I \) and \( J \)-integral present an approximate parabolic distribution at the normalized crack front. The distribution of the values of \( K_I \) and \( J \)-integral has the same trend when only the initial crack parameters of the same type are changed. Combined with the trends of \( SIF \) and \( J \)-integral, the fracture of the refractory lining can be better studied and explored. This provides a reliable theoretical basis for fracture analysis and life prediction of the refractory lining in the CWS gasifier.

■ AUTHOR INFORMATION

Corresponding Authors

Guanguo Yu — State Key Laboratory of High-efficiency Utilization of Coal and Green Chemical Engineering, College of Chemistry and Chemical Engineering, Ningxia University, Yinchuan 750021, China; Institute of Clean Coal Utilization of Coal and Green Chemical Engineering, College of Chemistry and Chemical Engineering, Ningxia University, Yinchuan 750021, China; Email: guanguo@nxu.edu.cn

Weiguang Su — State Key Laboratory of High-efficiency Utilization of Coal and Green Chemical Engineering, College of Chemistry and Chemical Engineering, Ningxia University, Yinchuan 750021, China; Phone: +86 951 2062061; Email: weiguangsu@nxu.edu.cn

Authors

Jinghong Gao — State Key Laboratory of High-efficiency Utilization of Coal and Green Chemical Engineering, College of Chemistry and Chemical Engineering, Ningxia University, Yinchuan 750021, China; orcid.org/0000-0003-4124-9438

Yuchen Shi — State Key Laboratory of High-efficiency Utilization of Coal and Green Chemical Engineering, College of Chemistry and Chemical Engineering, Ningxia University, Yinchuan 750021, China

Xudong Song — State Key Laboratory of High-efficiency Utilization of Coal and Green Chemical Engineering, College of Chemistry and Chemical Engineering, Ningxia University, Yinchuan 750021, China

Jiaofei Wang — State Key Laboratory of High-efficiency Utilization of Coal and Green Chemical Engineering, College of Chemistry and Chemical Engineering, Ningxia University, Yinchuan 750021, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c01487

Notes

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■ NOMENCLATURE

\( a \) = crack depth (mm)  
\( a_0 \) = initial crack size (mm)  
\( c \) = crack length (mm)  
\( b \) = second normal direction of the crack front  
\( B \) = crack growth coefficient  
\( R \) = stress ratio  
\( t \) = thickness of the hot-face brick (mm)  
\( T_r \) = traction vector  
\( u_i \) = displacement vector at any point in the contour \( \Gamma \)  
\( \nu \) = Poisson’s ratio  
\( W \) = strain energy density (g·cm\(^{-3}\))  
\( \Delta K \) = magnitude of the loading stress intensity factor (Mpa·mm\(^{1/2}\))  
\( \Delta K_{th} \) = crack growth threshold value (Mpa·mm\(^{1/2}\))  
\( \sigma_i \) = stress tensors  
\( \epsilon_i \) = strain tensors  
\( \mu \) = shear modulus (GPa)
\( \mu_c \), \( \mu_d \), and \( \mu_s \) =displacements in the b, n and r directions of the crack front, respectively (mm).

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