Effect of residual stresses on ductile crack growth resistance

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Abstract

It is well known that residual stresses influence the ductile fracture behaviour. In this paper, a numerical study was performed to assess the effect of residual stresses on ductile crack growth resistance of a typical pipeline steel. A modified boundary layer model was employed for the analysis under plane strain, Mode I loading condition. The residual stress fields were introduced into the finite element model by the eigenstrain method. A sharp crack was embedded in the center of the weld region. The complete Gurson model has been applied to simulate the ductile fracture by microvoid nucleation, growth and coalescence. Results show that tensile residual stresses can significantly reduce the crack growth resistance when the crack growth is small compared with the length scale of the tensile residual stress field. With the crack growth, the effect of residual stresses on the crack growth resistance tends to diminish. The effect of residual stress on ductile crack growth resistance seems independent of the size of geometrically similar welds. When normalized by the weld zone size, the ductile crack growth resistance collapses into one curve, which can be used to assess the structural integrity and evaluate the effect of residual stresses. It has also been found that the effect of residual stresses on crack growth resistance depends on the initial void volume fraction \( f_0 \), hardening exponent \( n \) and T-stress.

1. Introduction

It is widely accepted that the presence of residual stresses can influence the failure characteristics of components and structures. A significant influence due to the residual stress on the failure and load bearing capacity of components under predominantly elastic conditions was demonstrated by Ainsworth et al. [1], who also showed that the effect on load-bearing characteristics reduced with the increasing plasticity within the component. A quantitative understanding of how residual stresses affect the failure behaviour is thus required to provide accurate integrity assessment and reduce the conservatism inherent in many assessment codes.

Ductile crack growth plays an important role in the analysis of the fracture behaviour of structures [2]. Crack extension reduces the load-bearing ligament and will influence the capacity of the structures. Ductile crack growth may also change the near-tip stress/strain fields and promote the transition to unstable cleavage fracture. The mechanism of ductile fracture in metallic materials may be considered as a three-stage process: nucleation, growth and coalescence of microvoids. The ductile fracture process is influenced by the local conditions of stress triaxiality and plastic strain within the vicinity of a stress concentrator such as a notch or a crack-tip [3]. Liu et al. [4] and Ren et al. [5] have demonstrated that residual stresses can induce an additional crack-tip constraint, and a parameter \( R \) was defined based on the difference between the full stress...
field and the reference field to quantify the residual stress-induced crack-tip constraint. It is thus interesting to further investigate how residual stresses influence the local failure mechanisms and global ductile crack resistance.

Panontin and Hill [6] predicted the brittle and ductile initiation by micromechanical models and showed that the effect of residual stress on the ductile fracture initiation toughness is negligible. Sherry et al. [3] demonstrated that a high strength low toughness aluminum alloy Al2024-T351 showed a marked reduction in initiation and tearing toughness for specimens containing a mechanically induced residual stress field. It should be noted that the fracture behaviour of Al2024-T351 remains in ductile fracture regime. Experimental work undertaken by Sharples et al. [7] on wide plate specimens has also demonstrated that residual stress can significantly influence the ductile tearing behaviour of engineering materials. However, the experiments performed by Mirzaee-Sisan et al. [8] on the AISI Type 361 H stainless steel indicates a negligible impact on ductile tearing toughness at load ratio $L_r$ close to 1, i.e. close to the plastic collapse of the specimen. The observation is in contrast to their previous experiments performed on the A533B unstable cleavage fracture in ferritic steels at −150 °C [9]. A reduction of approximately 46% was observed in apparent fracture toughness for specimens containing a residual stress field compared with specimens in the as-received condition. Mahmoudi et al. [10] employed a local out-of-plane compression method to introduce residual stresses into C(T) specimens for aluminum alloys A12650 and A12024. Their experimental results showed that tensile residual stresses reduced the initiation cleavage fracture toughness of A12650 by about one half, and the ductile tearing resistance of A12024 also decreased when tensile residual stresses present. To date, the fundamental understanding of the effect of the residual stresses on ductile fracture resistance remains an open challenge. To this end, we utilized a micromechanical damage model in a Modified Boundary Layer (MBL) model to investigate the problem. The MBL model has been widely used to investigate the crack problems [11], and the transferability to real components can be well handled by simply changing the boundary conditions.

In recent years, damage mechanics models have become widely used in numerical simulation of ductile crack growth. The Gurson model [12] is often used to assess ductile tearing behaviour under primary loading, where the effect of the void growth is taken into account in the constitutive model. The Gurson model has later been modified by Tvergaard and Needleman [13–15], thus, it is most often referred to as the Gurson–Tvergaard–Needleman (GTN) model. The GTN model is in fact a void growth model. The effect of void coalescence can be considered with the introduction of a so-called critical void volume fraction, which is not a physical mechanism-based coalescence criterion. Thomason [16] proposed a plastic limit load model for coalescence, which was easy to implement and very accurate [17,18] compared with the finite elements results by Koplik and Needleman [19]. This work has been further improved by considering the plastic strain hardening [20]. By combining the GTN model for void growth and Thomason’s plastic limit load model for coalescence a so-called “complete Gurson model” has been proposed by Zhang et al. [21], with which ductile fracture is exclusively linked to the void nucleation parameters and the mesh size.

Two scenarios have been considered to study the effect of the residual stresses on the crack growth resistance in this paper. Firstly, the effect of residual stresses on ductile crack resistance in a large round weld region was investigated. In such a way, the final crack growth length still locates in weld region. Secondary, a much smaller rectangular weld region was constructed, where the crack can propagate through the whole weld region. The effect of the weld zone size was also taken into account and studied. In addition, the effects of initial void volume fraction and material hardening have also been studied.

2. Numerical procedure

2.1. Problem description

This study concerns an ideal problem. A large cylinder with a weld in the center was studied. The cylinder was simulated by a 2D plane strain MBL model with a remote boundary governed by the elastic $K$-field and $T$-stress. A sharp crack was embedded in the weld region. The analysis procedure, as illustrated in Fig. 1, consists of the following steps: (1) enforce a welding procedure in un-cracked body, which introduces a residual stress field; (2) introduce a sharp crack; and (3) apply the external load. The contact between the upper and lower free surfaces of the crack is considered when the residual stress was introduced.

![Fig. 1. Illustration of the problem. (a) The round cylinder; (b) welding at the center and a sharp crack is introduced; and (c) apply the external load.](image-url)
2.2. Finite element model

The present analyses were carried out for the conditions of small-scale-yielding. The MBL model used for this study consists of a weld region located in the center of the model, an outer base metal region, and a sharp crack in the center of weld. The load was applied to the remote edges of the model through a displacement field \((u, v)\) controlled by the elastic asymptotic stress field of a plane strain Mode I crack:

\[
\begin{align*}
    u(r, \theta) &= K_I \frac{1 + v}{E} \sqrt{\frac{r}{2\pi}} \cos \left( \frac{1}{2} \theta \right) (3 - 4v - \cos \theta) + T \frac{1 - v^2}{E} r \cos \theta \\
    v(r, \theta) &= K_I \frac{1 + v}{E} \sqrt{\frac{r}{2\pi}} \sin \left( \frac{1}{2} \theta \right) (3 - 4v - \cos \theta) - T \frac{1 + v}{E} r \sin \theta
\end{align*}
\]

where \(K_I = \sqrt{\frac{EJ}{(1 - v^2)}}\) under plane strain condition, \(E\) is Young’s modulus, \(v\) is Poisson’s ratio, and \(r\) and \(\theta\) are polar coordinates centered at the crack tip with \(\theta = 0\) corresponding to the crack tip.

The finite element computations were performed using ABAQUS [22]. Due to symmetry, only the upper half of the geometry is modeled. The mesh is shown in Fig. 2. The radius of the MBL model is taken as 1000 mm to ensure the small-scale-yielding condition is fulfilled. Close to the crack tip, there is a rectangular region (9.4 mm ahead of the initial crack tip and 1.6 above the symmetry line) with uniform mesh sizes of 0.1 × 0.05 mm for the first layer and 0.1 × 0.1 mm for the rest of the layers are created. In following context, \(L_c = 0.1\) mm represents the size of the uniform elements. Full integration four-node 2D plane strain elements are used. The finite element model has 2616 elements. Nonlinear geometry effects (NLGEOM in ABAQUS) are accounted for in the analyses. An initial opening of 0.02 mm is applied for the upper half model. When the residual stresses are introduced into the model, the crack faces can be partly closed. Thus, a rigid analytical plane is defined in the model to simulate the contact of the crack surfaces.

2.3. Materials

As described in Section 1, the complete Gurson model is utilized to simulate the crack growth, which is implemented into ABAQUS using a set of generalized-midpoint algorithms developed by Zhang via the material user subroutine UMAT [23–25]. Both the weld metal and base metal are modeled as a power-law hardening material.

\[\text{A free copy of the ABAQUS UMAT Fortran code can be obtained from the corresponding author.}\]
where $\sigma_f$ is the flow stress, $\bar{\varepsilon}^p$ is the equivalent plastic strain, the Poisson’s ratio $\nu$ is 0.3, Young’s modulus is 200,000 MPa, yield stress $\sigma_0$ is 400 MPa, $\sigma_0 = \sigma_0/E$ is the yield strain and $n$ is the plastic strain hardening exponent. The yield function of the Gurson model has the following form:

$$\phi(q, \sigma, f, \sigma_m) = \frac{q^2}{\sigma_f^2} + 2q_1f \cosh\left(\frac{3q_1\sigma_m}{2\sigma_f}\right) - 1 - \left(qf\right)^2 = 0$$

(3)

where $f$ is the void volume fraction, $\sigma_m$ is the mean macroscopic stress, $q$ is the von Mises stress. $\sigma_f$ is the flow stress, and $q_1$ and $q_2$ are parameters introduced by Tvergaard [13,14]. Fixed values of $q_1 = 1.5$ and $q_2 = 1.0$ have been used in this study.

In this study, a cluster void nucleation model has been used [21]. The critical void volume fraction ($f_c$) is automatically determined by Thomason’s plastic limit load criterion [16,20]. The post-coalescence deformation behaviour of the Gurson model is numerically simulated by an artificial acceleration of void growth, as suggested by Tvergaard and Needleman [15]:

$$f^* = \begin{cases} f & \text{for } f \leq f_c \\ f_c + \frac{f_c - f}{f_c} (f - f_c) & \text{for } f > f_c \end{cases}$$

(4)

where $f_c = 1/q_1$ and $f_c$ is the void volume fraction at the end of void coalescence. Here, $f_c = 0.15 + 2f_0$, where $f_0$ is the initial void volume fraction. When the coalescence starts and $f > f_c$, $f^*$ replaces $f$ in Eq. (3).

2.4. Eigenstrain method

Different thermal expansion coefficients of the base metal ($\alpha_b$) and weld metal ($\alpha_w$) were used to introduce residual stresses into the model by the so-called eigenstrain method. It should be noted that the thermal expansion coefficients here are not physical thermal coefficients, but are used to introduce residual stresses into the FE model. The eigenstrain method was also called “inherent strain” method when first introduced by Ueda et al. [26]. The concept of the eigenstrain method is that the source of residual stress is an incompatible strain field caused by plastic deformation, thermal strains and phase-transformation etc. [27]. Thus, if the distribution of the eigenstrain is known, the distribution of residual stresses can be obtained through linear elastic calculation by using the finite element method. Our approach is to set the eigenstrain values equal to the thermal expansion coefficients for different regions. The model is then loaded by applying a unit temperature decrease, thereby introducing the residual stress field of interest. Similar approaches were also applied in the literature [28,29], and their results showed that the distributions of residual stresses obtained by such approaches agreed well with the experimental results.

2.5. The crack driving force

In fracture mechanics, the $J$-integral [30] or Crack Tip Opening Displacement ($\delta$, CTOD) are used to characterize the crack-tip driving force of a cracked body made of an elastic-plastic material. The $J$-integral is a path-independent integral based on the assumption that the strain energy density is a single-valued function of the strain (or stress) [31]. However, non-proportional loading may occur in the region where the $J$-integral is evaluated and lead to path-dependence, for example, in the case of ductile crack growth [2], or in the presence of a residual stress field [32]. In this study, the $J$-integral is evaluated on contours far away from the zone of highly non-proportional loading, and displays practically path independence in both cases with and without residual stresses. Residual stresses as an additional stress field induce an initial $J$-integral. However, the residual stress-induced $J$-integral is negligible compared to the final $J$-integral caused by the combination of residual stress and external load. Also, under the small-scale-yielding conditions, the difference between calculated $J$-integral and applied $J$-integral is less than 2.78% for the case without residual stress, and 3.25% for the case with residual stresses [5]. Thus, $J$-integral should be applicable in the present study, and the $J$ in the following context represents far-field $J$-integral.

3. Results and discussion

3.1. Residual stress fields

As described in Section 2.4, we used the eigenstrain method to introduce residual stresses into the finite element model. A round weld region was introduced in the center of the model, as illustrated in Fig. 3. According to the eigenstrain method, the thermal expansion coefficients of both the weld metal ($\alpha_w$) and base metal ($\alpha_b$) were assumed to be isotropic and equal to the eigenstrain values respectively. In this section, we assume $\alpha_w=0$. Four residual stress fields were generated by setting $\alpha_w=$ -0.001, 0.001, 0.002, and 0.003 and designated as RsField0, RsField1, RsField2, and RsField3 respectively. Fig. 4 shows the distribution of the residual stresses both before and after the crack was inserted. Note that the stresses are normalized by the yield stress, and the distance from the crack tip $x$ is normalized by the size of the uniform element $l_c$.
It can be seen that the negative eigenstrain value introduces the compressive residual stress at the weld region while the positive ones generate tensile residual stresses. Both tensile and compressive residual stresses parallel to the crack front converge to zero far from the crack tip. The opening residual stresses are self-balanced ahead of the crack tip. There is a sharp turning point in the distribution of the opening residual stress, which is the region where eigenstrain discontinuity has been introduced into the FE model, namely the weld metal-base metal boundary. The tensile residual stresses also show similarity, and the level of the tensile residual stress increases with the increasing $a_w$. Due to the singularity, $\sigma_{11}$ is about 800 MPa and $\sigma_{22}$ is about 1200 MPa at the crack tip for RsField2. Fig. 4 also shows that residual stress components are smaller than the yield stress before the crack was inserted.

3.2. Effect of residual stresses on ductile crack resistance

Ductile crack growth resistance is important for structural integrity assessment, and it is interesting to investigate the effect of residual stresses on it. In this section, effects of residual stress fields on the crack growth resistance were studied. The initial void volume fraction $f_0$ is fixed to be 0.1% and the strain hardening exponent $n = 0.1$. The crack growth resistance described by the $J$-integral is showed in Fig. 5.

For the cases chosen, the residual stresses seem to have significant effects on the ductile crack growth resistance. Fig. 5a shows that the compressive residual stress enhances the crack growth resistance while the tensile residual stresses have the...
opposite effect. With the increase of tensile residual stress, the crack growth resistance decreases. The absolute difference between the case with and without residual stress increases with the increase of crack growth. Fig. 5b presents the normalized crack growth resistance. The resistances with residual stresses were normalized by the resistance at the same crack growth without residual stresses. The distance from the original crack tip was normalized by $l_c$. It can be seen that the tensile residual stresses significantly decrease the initiation toughness while the compressive residual stress increases it. With advancing crack growth, the effect of the residual stresses decreases and approaches to a constant value. Note that the current crack grows only to 3 mm, which is very small compared to the size of the residual stress dominant length scale shown in Fig. 4. As shown in Fig. 4, beyond the singularity affected zone ($x/l_c > 30$, i.e. 3 mm), the residual stress fields approach a hydrostatic stress state. Thus, the residual stresses cannot be easily released by the crack growth, and the effect of residual stresses retains.

In order to better understand the effect of residual stress on crack growth resistance, a smaller rectangular weld region was constructed, as illustrated in Fig. 6. In this section, $a_b=0$, and $a_w$ was assumed to be orthogonal and characterized by $a_{11}$ and $a_{22}$ in following context. The ratio $a_{11}/a_{22}$ was fixed to be 2. Four residual stress fields with $a_{22}=-0.001$, 0.001, 0.002, and 0.003 were generated and represented by RsField0, RsField1, RsField2, and RsField3 respectively, as shown in Fig. 7. It should be noted that the eigenstrain values selected here are taken from experimental measurement results in literature [33,34]. The residual stress fields generated by the selected values have similar distribution as the residual stress fields showed in Ref. [35]. To obtain accurate distributions of the residual stress fields by the eigenstrain method, one should carry out the experiments to measure the distribution of the eigenstrain. However, the main objective of this study is to investigate the effect of the residual stresses, and prediction of the real distribution of the residual stress field is outside of the scope.

The absolute and normalized crack growth resistances are shown in Fig. 8. It can be seen that the compressive residual stress increases the crack growth resistance while tensile residual stresses decrease the crack growth resistance, as shown in
Fig. 8a. Fig. 8b shows that the reduction of the crack growth resistance converges with crack growth to the case without residual stress. As known, the quantity \( r_m/r_e \) defines a convenient measure of triaxiality linked to the growth rate of micro-scale voids consistent with the subsequently introduced damage measures [36]. Therefore, we investigated the distribution of triaxiality ahead of the crack tip. Fig. 9 presents the triaxiality values on the ligament ahead of the original crack tip for different crack growth. The distance from the original crack tip are scaled by \( J/r_0 \), or equivalently \( (K_I/r_0)^2 \), which defines approximately the value of crack-tip opening displacement and provides a physical meaningful length scale for normalization.

It can be seen that tensile residual stresses enhance the triaxiality values while the compressive residual stress reduces the triaxiality value at the crack initiation, see Fig. 9a, which corresponds to our previous findings [4,5]. However, the effect of residual stress on triaxiality tend to be negligible when the crack advanced to 3.5 mm, as shown in Fig. 9b. Higher stress triaxility corresponds to a smaller plastic zone. Thus, the energy dissipated by the plastic deformation is smaller, which in turn result in a lower crack growth resistance.

3.3. Effect of weld zone size on crack growth resistance

The length scale of the residual stress field may play an important role on the effect of residual stress on ductile crack growth resistance, as shown in Section 3.2. To better demonstrate this, four geometrically similar rectangular weld regions were constructed, as illustrated in Fig. 10. The size of the weld is designated as \( c \). The orthogonal thermal expansion coefficient was used with a value of \( 11/11 = 0.004 \) and \( 22 = 0.001, 0.001, 0.002, \) and \( 0.003 \).

Fig. 7. Residual stress distribution in MBL model with a rectangular weld after the crack was inserted, (a) components parallel to the crack plane and (b) normal to the crack plane. Four different residual stress cases were considered, where RsField0 is compressive and the remaining 3 are tensile. \( 11/11 = 2; 22 = -0.001, 0.001, 0.002, \) and \( 0.003 \).
Fig. 12a presents the absolute crack growth resistance. In Fig. 12b, crack growth length was normalized by $l_c$. It can be seen that the residual stresses generated in the larger welds influence more significantly the crack growth resistance. With increasing crack growth, the effect of the residual stresses on the crack growth resistance converges to the case without residual stresses. However, an interesting pattern emerges when normalizing the crack growth length by the weld zone size $c$, as shown in Fig. 12c. Surprisingly, the normalized crack growth resistances collapse into one curve, which indicates that the effect of the residual stresses on the crack growth resistance is nearly independent of the weld zone size. For the cases specified in this section, when the crack grows approximately to 3 times of $c$, the effect of residual stresses can be neglected.

For geometrically similar welds, the uniform curve can be used to roughly predict the length scale of residual stress-affected region beyond which the effect of the residual stress can be neglected. In our previous study [5], it has been shown that residual stress fields generated in round weld regions with three sizes respectively can be normalized by the weld zone size and collapsed into a uniform field. Thus, the “master” curve as shown in Fig. 12c can be expected.

3.4. Effect of residual stresses on crack growth resistance for different hardening exponents

It has been shown that the effect of strain hardening on the ductile crack resistance is not fully understood. Xia and Shih [37] demonstrated that the ductile resistance increases with increasing hardening capacity. However, Eikrem et al. [38] and Østby et al. [2,39] reported that decreasing the hardening exponent will significantly raise the resistance curve. In this study, the effect of strain hardening on the crack growth resistance was investigated for cases both with and without residual stress. It should be noted that in this particular study, the initial volume fraction $f_0$ was fixed to be 0.05%, and the residual stress field was introduced by the rectangular weld with orthogonal thermal expansion coefficient $\alpha_{11} = 0.004$ and $\alpha_{22} = 0.002$, i.e. RsField2 in Fig. 7. The crack growth resistance was plotted as a function of hardening exponent $n$ in Fig. 13.

Fig. 13a shows that with decreasing hardening exponent the crack growth resistance increases for both with and without residual stress cases, which corresponds to the results demonstrated in Ref. [2,38,39]. For a given hardening exponent, residual stresses reduce both the initial toughness and crack growth resistance. Also, the effect of residual stress on the ductile resistance becomes stronger for stronger hardening material, as shown in Fig. 13b. With increasing crack growth, the reduction of the crack growth resistance decreases and tends to converge to the case without residual stress. Residual stresses reduce the equivalent plastic strain significantly at crack initiation, which indicates smaller plastic deformation. Hence,
lower crack growth resistance curves can be expected. With the crack growth, the effect of residual stresses on the equivalent plastic strain becomes negligible for different hardening exponents.

3.5. Effect of residual stresses on ductile crack resistance for different initial void volume fraction

The initial void volume fraction $f_0$ represents the degree of damage in the material. The larger the initial void volume fraction is, the larger damage the material has. In this section, the effect of residual stress fields on crack growth resistance was
investigated for three initial void volume fractions, \( f_0 = 0.05\%, 0.1\% \) and 0.2\%. The residual stress was introduced into a rectangular weld with \( a_{11} = 0.004 \) and \( a_{22} = 0.002 \), i.e. RsField2 in Fig. 7. The crack growth resistance curves are shown in Fig. 14.

As shown in Fig. 14a, for both with and without residual stress cases, the crack growth resistance increases with the decrease of initial void volume fraction, which can be expected because the ductility becomes better when initial void volume fraction decreases. Also, it can be observed that the residual stress reduces the crack growth resistance for fixed \( f_0 \). Normalized crack resistance curves shown in Fig. 14b indicate that with increasing crack growth, the effects of residual stresses decrease and become less dependent on \( f_0 \). The residual stress enhances the opening stress beyond the larger strain effect region compared with the case without residual stress at crack initiation, which induces an increase of crack-tip constraint [4,5], and a lower fracture toughness can then be expected. However, it has been found that the effect of the residual stress on opening stress becomes negligible when crack growth becomes larger.

3.6. Effect of residual stresses on ductile crack resistance for different \( T/\sigma_0 \)

Crack tip constraint effects on fracture toughness have received considerable attention recently. In our earlier work [5], we have found that the residual stress–induced crack-tip constraint is lower for a higher geometric constraint. Xia and Shih [37], Tvergaard and Hutchinson [40] studied the effect of \( T \)-stress on the crack growth resistance and showed that a negative \( T \)-stress results in a rapidly rising resistance curve while the positive \( T \)-stress lowers the fracture resistance. It is thus interesting to investigate how residual stress combined with varying \( T \)-stress affect the crack growth resistance. In this paper, \( T/\sigma_0 = -0.5, 0, \) and 0.5 were studied. The initial void volume fraction is fixed to be 0.1\%, and the residual stress with \( a_{11} = 0.004 \) and \( a_{22} = 0.002 \), i.e. RsField2 in Fig. 7, was introduced. The absolute and normalized resistance curves are shown in Fig. 15.

It can be seen that the tensile residual stress reduces the crack growth resistance for all \( T/\sigma_0 \) cases, as shown in Fig. 15a. Fig. 15b shows that the normalized crack growth resistance is lower for smaller \( T \)-stress. However, the differences between

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**Fig. 13.** Effect of residual stresses on crack growth resistance for different hardening. (a) absolute crack growth resistance curves and (b) normalized crack resistance curves. \( a_{11} = 0.004; a_{22} = 0.002; f_0 = 0.05\%; E/\sigma_0 = 500.\)

**Fig. 14.** Effect of residual stresses on crack growth resistance for different initial void volume fraction, (a) absolute crack growth resistance curves and (b) normalized crack resistance curves. \( a_{11} = 0.004; a_{22} = 0.002; n = 0.1; E/\sigma_0 = 500.\)
2. Under certain circumstances, the effect of the residual stresses on ductile crack growth resistance can be normalized by the size of the geometrically similar weld, and the normalized crack growth resistance curves collapse into a single curve. One can use this curve to evaluate the effect of the residual stress on the structural integrity and simplify the assessment procedure. It can also be used to predict the length scale of the residual stress-affected range beyond which the effect of the residual stresses can be neglected. For the cases specified in this study, when the crack grows to a length of 3\(c\) the effect of the residual stresses can be neglected.

3. The reduction of the crack growth resistance caused by residual stresses is smaller for weaker hardening materials, and the influence of the residual stresses decreases with crack propagation.

4. Residual stress reduces the crack growth resistance more significantly for the materials with larger initial void volume. The influence of the residual stresses decreases with the crack growth and becomes independent of \(f_0\).

5. The reduction of the crack growth resistance induced by the residual stress increases with increasing \(T/\sigma_0\) at the early stage of crack growth and then tend to be negligible when the crack growth is larger. The results are in line with our earlier findings that the effect of residual stress on the crack-tip constraint becomes weaker for higher \(T/\sigma_0\).

The present study indicates that residual stress as an additional stress field can alter the stress state near the crack tip and further influence the ductile crack growth resistance. Triaxility or crack-tip constraint was shown to play an important role in the ductile fracture behaviour. Therefore, the residual stress-induced crack-tip constraint is a very important factor to consider in structural integrity assessment. In our previous studies [4,5], we have defined a parameter \(R\) to quantify the residual
stress-induced crack-tip constraint. However, the effect of residual stress on the ductile crack resistance has not been linked with R by a quantitative way in this study. The reason for this is that the residual stress field in reality is very complicated, hence one should find an efficient way to standardize the distribution of the residual stresses for typical weld joints. To reduce the conservatism of current integrity assessments, a proper description of the residual stress field is very important. Once a proper description of the residual stress is obtained, the “master” curve, though obtained from the MBL model, can be applied to real engineering structures and components that contain similar residual stress fields under small-scale-yielding conditions. The transferability of the results from MBL studies to real structures should be verified in further studies.

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