Mechanism and Effect of Stress-induced Transformation on Improvement of Fracture Toughness †

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Abstract

To study the influence of expansion under phase transformation on ductility of the material, a finite element method employing interface element is developed. It is applied to the fracture problem of a rectangular specimen with a center crack and a three point bending of specimen with initial crack. The effectiveness of the expansion accompanied by the phase transformation is clarified from the aspects of toughness level of a reference material.

KEY WORDS: (Phase Transformation) (Expansion under Transformation) (Toughness) (Interface Element) (Crack Growth)

1. Introduction

To develop a high performance steel, both strength and toughness are the primary properties to be achieved. Strength is for the performance against the plastic collapse while toughness is that against the failure accompanying the formation and the growth of the crack. The former is represented by yield stress. The latter is represented by fracture toughness parameters, such as K, G, J and CTOD. Charpy impact energy is also used as a convenient parameter.

Comparing the strength and the toughness, the strength is a relatively easy concept to understand. But the toughness is difficult. The clear difference between them is that the toughness is connected to the mode of failure accompanying the formation and the growth of the crack. Thus, to study the toughness of the material, a mechanical model which directly represents the formation and the growth of the crack is necessary. One such mechanical model is the interface element proposed by the authors[1,2].

As it is commonly understood, materials with high strength or hard materials are generally brittle and the strength and the toughness are thus mutually conflicting properties. The high performance steels are developed from the delicate balance between these two parameters. For the further improvement of steels, control of other factors, such as the strain hardening properties, micro structures and phase transformation is necessary. One of such attempts is the dual phase steel that consists of Martensite and retained Austenite. The Martensite is for the strength and the Austenite for the toughness. Austenite is the phase unstable at room temperature. When the dual phase steel is subjected to mechanical loading, the retained Austenite transforms to the Martensite. This is known as stress-induced transformation. In this transformation process, the Austenite expands and deforms due to the difference of lattice constants. The compressive stress produced by expansion is expected to improve the toughness.

In this study, the effectiveness of the volumetric expansion associated with the transformation on the toughness of the steel is investigated using the mechanical model in which the interface element is introduced.

2. Mechanical Model using Interface Element

The mode of failure is roughly divided into plastic deformation dominant and crack growth dominant modes and they are controlled by whichever is larger between the yield strength and the bonding strength of the material. For example, if the bonding strength is larger than the applied stress which is represented by the sum of the tri-axial stress and the yield stress, the crack

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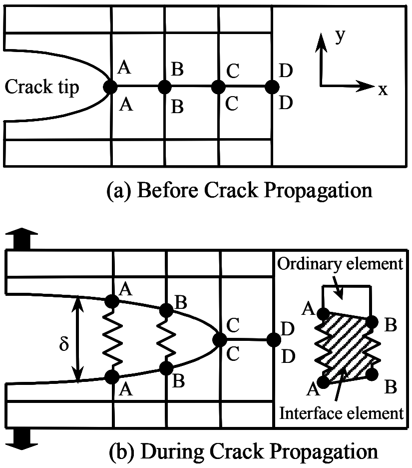

Fig. 1 Schematic illustration of interface element.

may not be produced nor grow. Thus the failure becomes a plastic type. On the contrary, if the bonding strength is smaller, the crack is formed and failure mode becomes a fracture type.

To describe these two possible failure modes, both the plastic deformation produced in bulk and the formation of the crack must be taken into account. The plastic deformation can be described using the standard elastic-plastic finite element scheme and formation of the crack can be described by the interface element.

Essentially, the interface element employed in this research is the distributed nonlinear spring existing between surfaces forming the interface or the potential crack surfaces as shown by **Fig. 1**. The relation between the opening of the interface δ and the bonding stress σ is shown in **Fig. 2**. When the opening δ is small, the bonding between the two surfaces is maintained. As the opening δ increases, the bonding stress σ increases till it becomes the maximum value σ_{cr}. With further increase of δ, the bonding strength is rapidly lost and the surfaces are completely separated. Such interaction between the surfaces can be described by the interface potential. There are rather wide choices for such potential. The authors employed the Lennard-Jones type potential ϕ because it explicitly involves the surface energy γ, which is necessary to form new surfaces, i.e.

$$\phi(\delta) = 2\gamma \cdot \left\{ \left(\frac{r_0}{r_0 - \delta} \right)^{2N} - 2 \cdot \left(\frac{r_0}{r_0 - \delta} \right)^{N} \right\} \quad (1)$$

where, constants γ, r_0, and N are the surface energy per unit area, the scale parameter and the shape parameter of the potential function. The derivative of ϕ with respect to the opening displacement δ gives the bonding stress σ acting on the interface.

$$\sigma = \frac{\partial \phi}{\partial \delta} = \frac{4\gamma N}{r_0} \cdot \left\{ \left(\frac{r_0}{r_0 + \delta} \right)^{N+1} - \left(\frac{r_0}{r_0 + \delta} \right)^{2N+1} \right\} \quad (2)$$

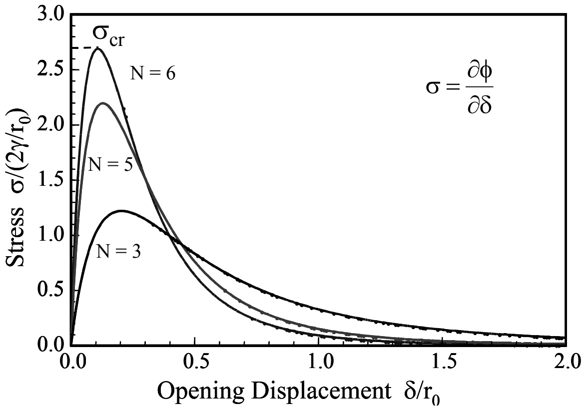

Fig. 2 Relationship between opening displacement and bonding stress.

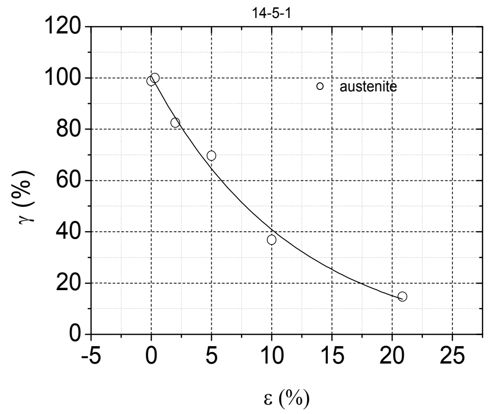

Fig. 3 Relation between retained autenite and applied strain.

When the opening δ becomes the critical value δ_{cr} which is given by the following equation, the bonding stress becomes the critical value σ_{cr}.

$$\delta_{cr} = \left\{ \left(\frac{2N+1}{N+1} \right)^{1/N} - 1 \right\} r_0 \quad (3)$$

As it is seen from **Eq. (2)**, the bonding stress σ is proportional to the surface energy γ and inversely proportional to the scale parameter r_0. By arranging such interface elements along the crack propagation path as shown in Fig. 1, the growth of the crack under the applied load can be analyzed in a natural manner. In this case, the decision on the crack growth based on the comparison between the driving force and the resistance as in the conventional methods is not necessary.

3. Phase Transformation Model

Figure 3 is the relation between the applied strain ε and the retained Austenite γ obtained by Hiraoka *et al.* using the magnetic measurement. The material measured is 100% Austenite. As shown in Fig. 3, the fraction of the Austenite decreases with the applied strain and it becomes almost zero when the applied strain is about

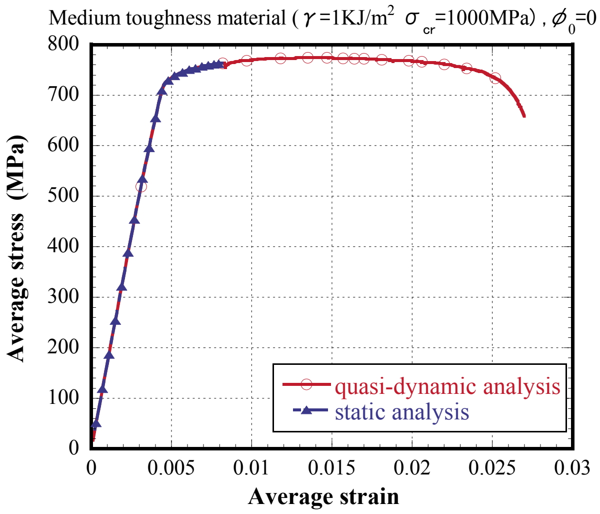

Fig. 4 Comparison between static and quai-dynamic analyses.

30%. These measured data are approximated using a quadratic function given by the following equation.

$$F(\varepsilon^p) = (\varepsilon^p - 0.3)^2 / 0.09 \qquad (4)$$

where, $\varepsilon^p < 0.3$

Since the material considered in this research is the dual phase steel consisting of Austenite and Martensite, the expansion of the material $\varepsilon^T(\varepsilon^p)$ due to the phase transformation under the applied plastic strain ε^p is assumed to be given by **Eq. (5)**.

$$\varepsilon^T(\varepsilon^p) = \phi_0 \cdot \varepsilon_0^T \{1 - F(\varepsilon^p)\} \qquad (5)$$

Where, ϕ_0 is the initial fraction of the Austenite and ε_0^T is the expansion of the material due to the transformation from Austenite to Martensite. Further, the relation between the increment of expansion $\Delta\varepsilon^T$ and that of the applied plastic strain $\Delta\varepsilon^p$ is derived by differentiating Eq. 5.

$$\Delta\varepsilon^T = -\phi_0 \cdot \varepsilon_0^T \frac{dF}{d\varepsilon^p} \Delta\varepsilon^p \qquad (6)$$

In the finite element analysis, the increment of the phase transformation strain $\Delta\varepsilon^T$ given by **Eq. (6)** is applied.

4. Quasi-dynamic Solution Procedure

To evaluate the toughness of the material, it is necessary to chose appropriate measures. The load at which

(1) crack start to grow

(2) crack growth becomes unstable

can be taken as measures. In this research, the second measure is selected. The situation when the static equilibrium is not reached or when the solution diverges in computation may be an indication of the unstable crack growth. However, this type of numerical instability may happen due to a small fluctuation of the solution path. To overcome this problem, a quasi-dynamic solution procedure is applied for the step at which the convergence of the solution can not be reached. If the convergence is reached with the dynamic solution procedure, the procedure is returned to the static one. In this way, the stable crack growth can be traced and the toughness is evaluated as the load at which the crack starts to grow rapidly. **Figure 4** shows the comparison between the straightforward static analysis and the proposed quasi-dynamic analysis applied to the same crack growth problem of the model with a center crack. As it is clearly shown in the figure, the solution stops at fairly early stage in the case of static analysis. If the quasi-dynamic solution procedure is employed, the full path of stable crack growth is traced up to the onset of the rapid decrease of the load accompanying the crack growth.

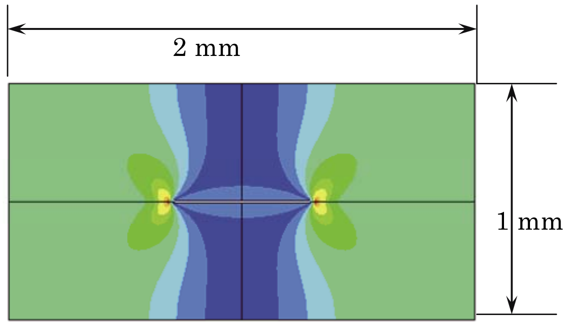

Fig. 5 Model with center crack.

5. Computed Results

5.1 Simple model with center crack

The model considered is a square specimen with a center crack subjected to the tensile load as shown in **Fig. 5**. The size of the model is 1 mm x 2 mm and the length of the initial crack is 0.6 mm. The tensile load is applied through the uniform displacement applied along the top and the bottom edge of the specimen and the problem is solved assuming a plane strain state. Since the initial fraction of the Austenite may be different among the steels to be studied, the expansion associated with the phase transformation is varied from -1 % to 1 %. The reason why negative expansion or contraction, which is not observed in real material, is included is to observe the general trend of the mechanical response. Though material properties changes with the process of phase transformation, these are assumed to be unchanged. The yield stress σ_Y for the Austenite and the Martensite are assumed to be the same and it is given by

$$\sigma_Y = \sigma_{Y0}(1 + 50\varepsilon^p)^{0.02} \qquad (7)$$

where, ε^p is the equivalent plastic strain and σ_{Y0} = 900 MPa. The Young's modulus E and the Poisson's ratio ν are assumed to be

$$E = 200\ GPa \qquad (8)$$

$$\nu = 0.3 \qquad (9)$$

Table 1 Property of interface element.

	Surface energy γ (K_{1C})	Bonding strength σ_{cr}
High toughness	1.0 kJ/m^2 (28 MPa·m$^{1/2}$)	2000 MPa
Medium toughness	1.0 kJ/m^2 (28 MPa·m$^{1/2}$)	1000 MPa
Low toughness	0.5 kJ/m^2 (20 MPa·m$^{1/2}$)	1000 MPa

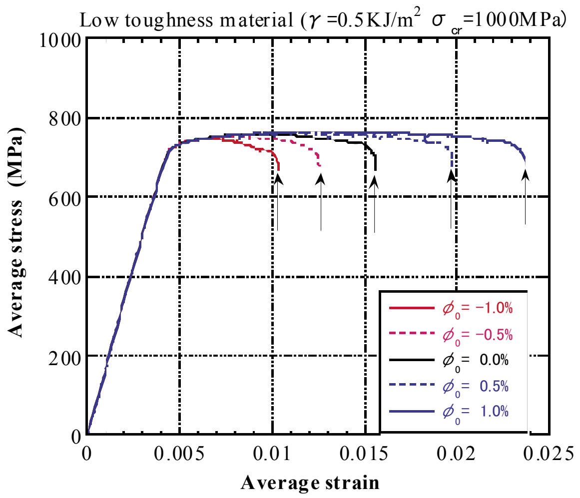

Fig. 6 Stress-displacement curve (low toughness).

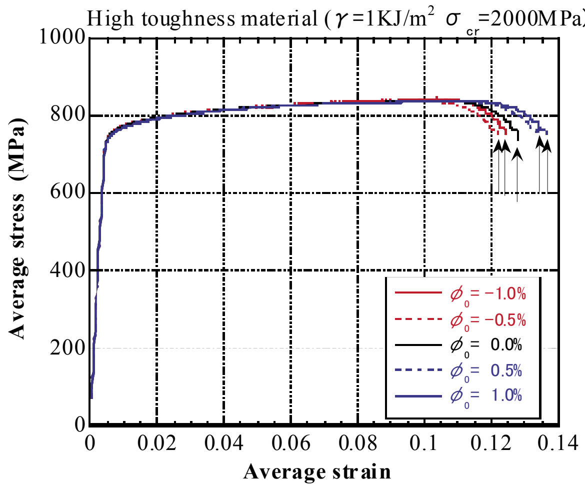

Fig. 8 Stress-displacement curve (high toughness).

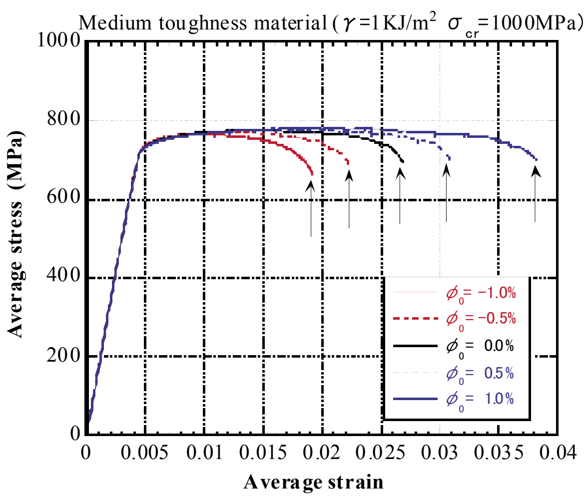

Fig. 7 Stress-displacement curve (medium toughness).

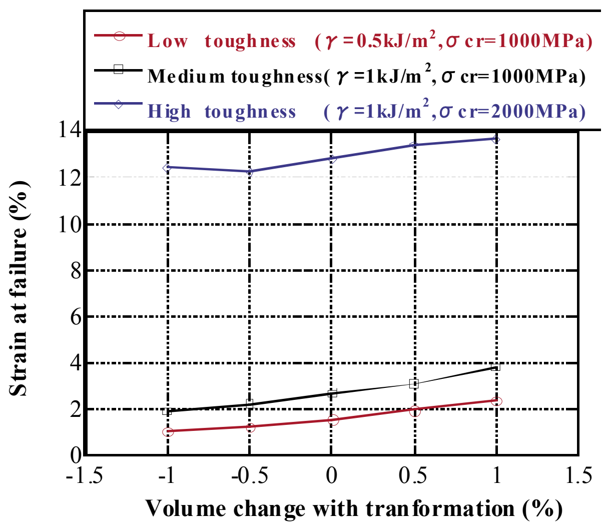

Fig. 9 Influence of volume change on ductility of specimen with crack.

On the other hand, to simulate the crack growth, the interface elements are arranged along the path of crack growth. Three types of materials, namely high toughness, medium toughness and low toughness materials, are assumed. The toughness of the material modelled using the interface element changes with the surface energy γ and the critical bonding stress σ_{cr}. The toughness becomes larger when the surface energy γ and the critical bonding stress σ_{cr} are large. The values of these parameters are assumed as shown in **Table 1**.

The computation is continued until the growth of the crack becomes unstable. The displacement or the load at the onset of unstable crack growth is defined as the failure displacement or the failure load. **Figures 6**, **7** and **8** show the average stress-strain curve for the three materials when the magnitude of the expansion due to the phase transformation is changed from -1 % to 1 %. The arrow in the figure indicates the fracture point. Regardless of the level of toughness, the strain at the failure increases when the expansion due to the transformation is large. The influence of the phase transformation strain on the toughness of the material is summarized in **Fig. 9**. As seen from the figure, the influence of the transformation is relatively large when the toughness of the material is small while that for the high toughness material is small. This may be explained from the fact of the level of strain at fracture. In case of high toughness material, it is about 10 – 20 % which is very large compared to the expansion due to the transformation. The phenomenon that the strain at the failure slightly increases when the material shrinks with the transformation may be explained by the mechanism that the contraction occurs in the area away from the crack tip and produces compressive stress at the crack tip.

The distributions of the stress component in the tensile direction, the equivalent plastic strain and the phase fraction at the fracture are shown **Fig. 10**. The plastic strain up to 30 % is emphasized in the figure. It is clearly seen that significantly large plastic deformation is developed during the growth of the crack if the material exhibits expansion during phase transformation. On the contrary if the material contracts during transformation, the crack grows without the development of significant plastic deformation.

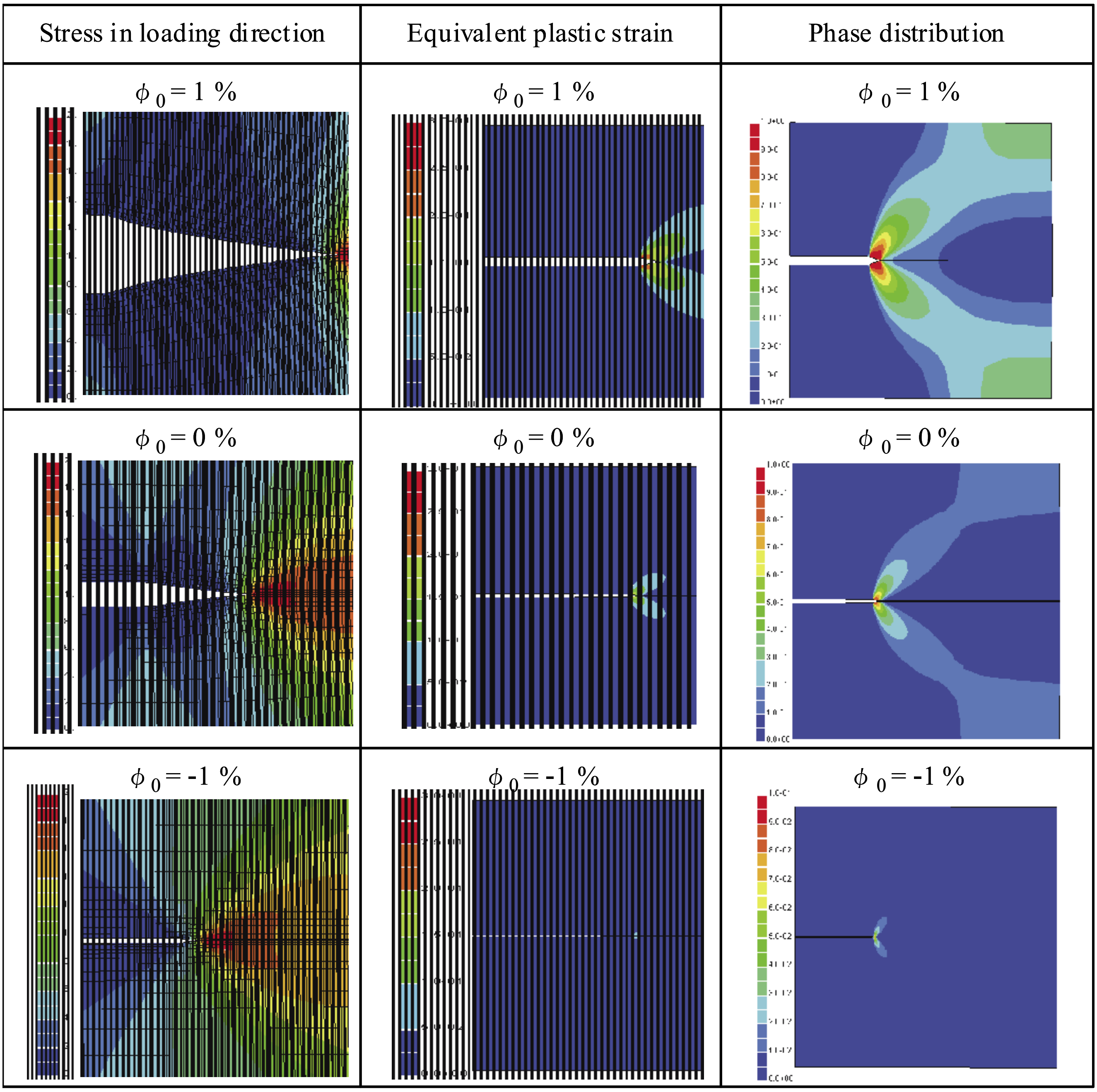

Fig. 10 Influence of transformation on stress and strain field under crack extension (low toughness).

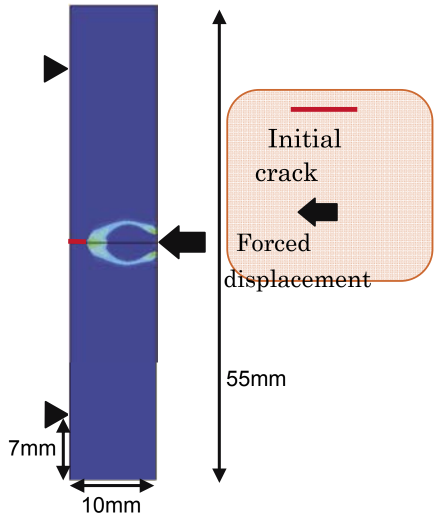

Fig. 11 Three-point bending model.

5.2 Three point bending of cracked specimen

The Charpy impact test is widely employed to measure the toughness of the material because of its convenience. Generally, the phenomenon in the Charpy test is dynamic and very complex. The influences of the strain rate, heat generation at the crack tip and the inertia need to be considered. However, the problem is treated as a simple static problem because the primary objective of this study is to clarify the influence of the phase transformation on the crack growth. As a simple example, a Charpy type specimen with an initial crack shown in **Fig. 11** is studied. The length of the initial crack is assumed to be 2 mm and three point bending load is applied.

In this example, three different toughness levels are assumed as in the previous example. To select appropriate values of surface energy γ and critical bonding strength σ_{cr} for high, medium and low toughness materials, serial computations are conducted. The computed results are summarized in **Fig. 12**. For these computations the material is assumed to show no transformation. The mode of failure can be categorized into three, namely elastic unstable crack growth, unstable elastic-plastic crack growth and the stable plastic crack growth as illustrated in **Fig. 13**. These three modes are mapped on Fig. 13. Based on Fig. 13, 6 kJ/m^2 is selected as the surface energy γ. The value of the critical bonding strength is selected to be 1150 MPa, 1200 MPa and 1250 MPa, respectively for low, medium and high toughness material. The elastic-plastic properties of the material are assumed to be the same as in the previous example.

The influence of the phase transformation on the crack growth in the specimen under three point bending is studied using three materials with different levels of toughness selected in the above. The computed results are presented in the same manner as in the previous example. **Figures 14**, **15** and **16** show force-displacement curves for materials with different values of expansion accompanied by the phase transformation ranging from -1 % to 1 %. It is generally seen that the deformation at the failure increases with the magnitude of transformation strain. The results are summarized over three levels of toughness in **Fig. 17**. In cases of materials with high and medium toughness, the ductility of the material, thus the energy absorbing capability, is improved significantly due to the phase transformation. In case of high ductility material and the magnitude of expansion is 1 %, the deformation at the failure is increased by 80 % compared to the material without transformation. Comparing Fig. 9 and Fig. 17, clear difference is observed between the materials with low toughness. The influence of the transformation in Fig. 17 is small compared to that shown in Fig. 9. This may be explained by the fact that the low toughness models in Fig. 17 fail without significant development of the plastic strain and the transformation as its consequence. To clarify the relation between the mechanical state, such as the distribution of the stress and the plastic strain, and the crack growth, the distributions of stress component

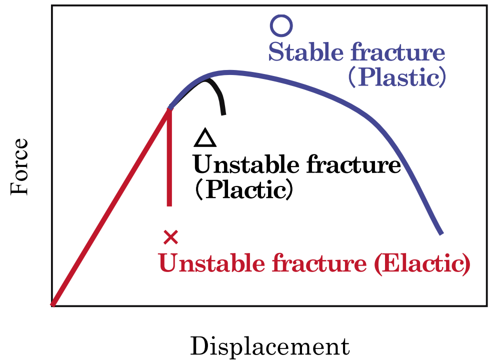

Fig. 12 Typical stress-displacement curve for three fracture types.

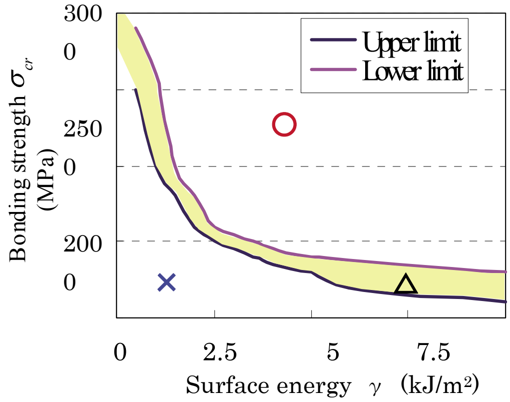

Fig. 13 Map of fracture.

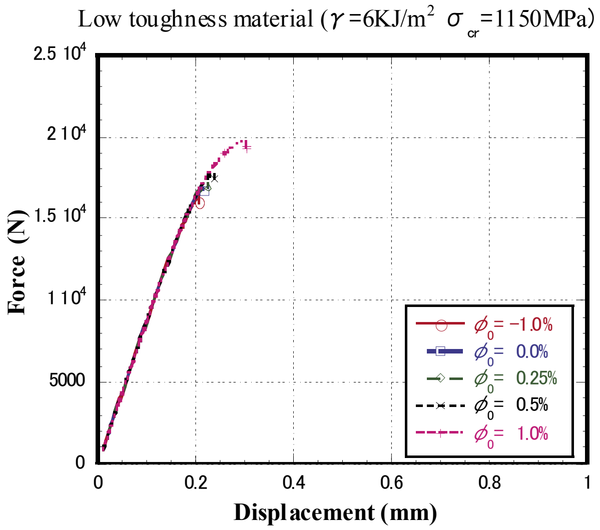

Fig. 14 Force-displacement curve (low toughness).

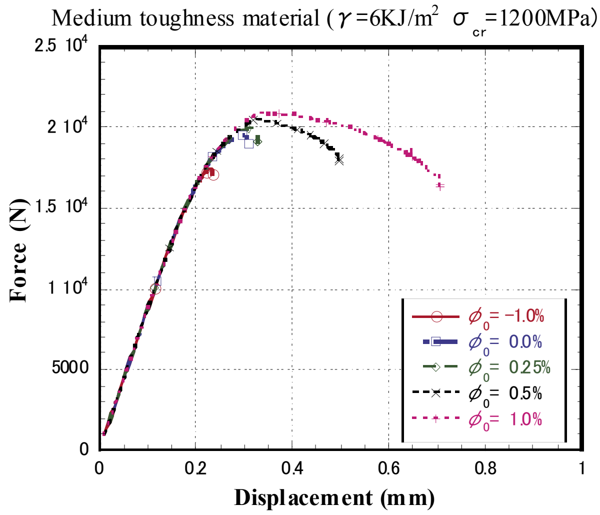

Fig. 15 Force-displacement curve (medium toughness).

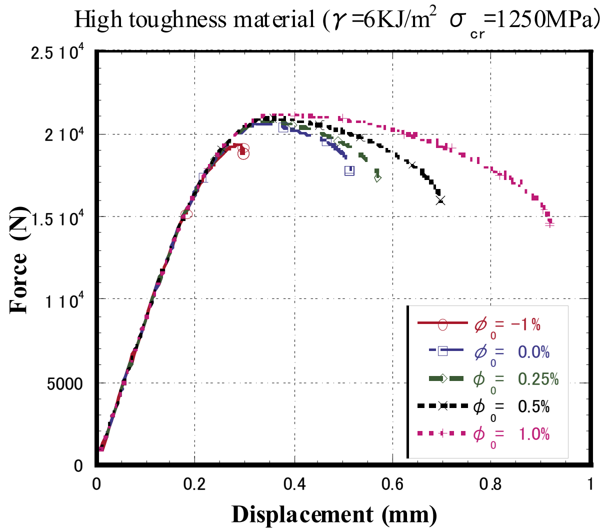

Fig. 16 Force-displacement curve (high toughness).

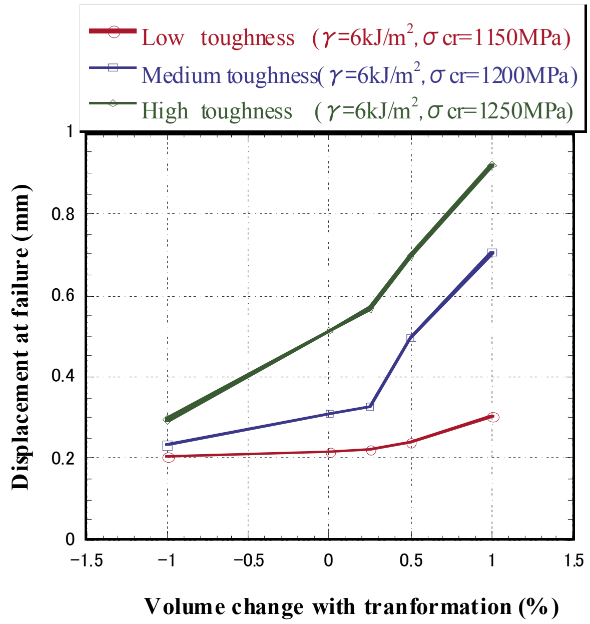

Fig. 17 Influence of volume change on ductility of specimen under three-point bending.

in tensile direction, the equivalent plastic strain and the phase fraction when the crack growth length is 1.88 mm are plotted in **Fig. 18**. As it is shown in the figure, significant difference is not observed in the stress distribution. However, a clear difference is observed in equivalent plastic strain and the phase fraction. The plastic strain distributes in a larger area and the opening of the crack becomes large when the material expands with the transformation.

6. Conclusions

To clarify the influence of stress-induced transformation in dual phase steel consisting of Austenite and Martensite on the fracture strength of the structure with initial cracks, the interface element is introduced to the finite element method. This method is applied to two simple problems. One is the rectangular specimen with a center crack under tensile load and the other is the three point bending of a cracked specimen. From the numerical results for these problems the following conclusions are drawn.

(1) Though degree of influence changes with the level of plastic strain at the failure, the deformation at the failure or the ductility generally increases through the expansion accompanying the phase transformation. Improvement of the ductility is observed even when the magnitude of expansion is less than 1 %.

(2) Compared to the material without phase transformation, the length of the stable crack and the opening of the crack become larger and the

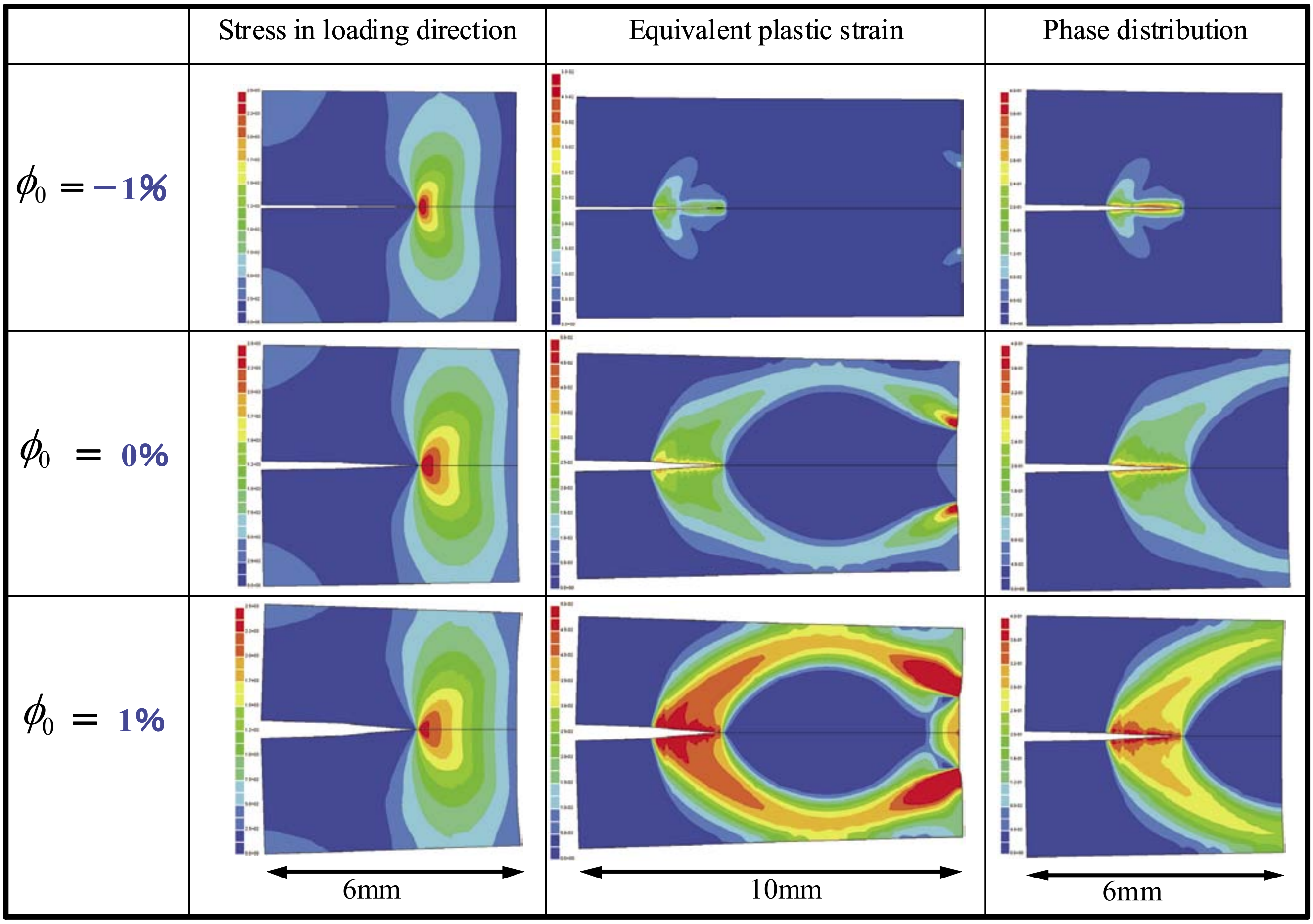

Fig. 18 State of stress and strain field under crack extended 1.88 mm (High toughness).

distribution of the plastic strain becomes wider when the material exhibits the expansion accompanied by the transformation.

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