Study on fracture mode of spot weld joint using continuum damage mechanics model*

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Recently, weight saving of car bodies have been required due to the enhancement of regulations for emissions of CO₂, and to improve collision safety, high tensile steel is widely used on car bodies. However, joint strength may decrease on high tensile steel. In addition, joint strength depends on fracture mode. Therefore, it is necessary to predict crack propagation direction and investigate the factors which influence the crack propagation direction. In this research, the author has proposed ductile crack analysis method based on continuum damage mechanics. In ductile crack propagation analysis, various potential models have been proposed as damage term. However, in such models, it is difficult to obtain convergence on the calculation of nonlinear constitutive relation. Therefore, in this study, a simplified ductile fracture evaluation method, which is based on the elastic-plastic analysis considering large deformation and strain, was proposed. The proposed method was applied to the analysis of cross tension test on spot weld joints. As a result, it was found that crack propagates along the outer periphery of the weld nugget on larger nugget diameter. These fracture modes are called plug fracture and higher cross tensile strength can be obtained in plug fracture. However, in smaller nugget diameter, crack propagates across the internal nugget. It is called interface fracture and joint strength decreases in this fracture mode. These tendencies agree with the results obtained by experiments. Therefore, in this study, it can be said that crack propagation direction can be predicted on cross tension test on spot weld joints by using the proposed method.

Key Words: Continuum damage mechanics, Fracture mode, Cross tension test, Spot welding, Finite element analysis

1. Introduction

Recently, weight saving of car have been required due to the enhancement of regulations for emissions of CO₂, and to improve collision safety, high tensile steel is utilized on car bodies. In the joining of car bodies, spot welding is widely employed due to its advantage in use and efficiency.

It is known that the strength of spot weld joint may decrease on high tensile steel and it depends on the fracture mode¹⁾. Fracture of spot weld joint is classified into two major modes. One is so-called plug fracture. In the plug fracture, crack propagates along the outer periphery of the weld nugget and this type of fracture tends to occur on larger nugget diameter. The other is called as interface fracture. In the interface fracture, crack propagates across the internal nugget. In general, cross tensile strength is larger in plug fracture than that in interface fracture. However, the mechanism of fracture is complicated and numerical simulation can be useful tool to discuss the mechanism.

It is effective to analyze ductile crack propagation based on continuum damage mechanics to investigate the fracture mode on spot weld joints. Currently, many damage models are proposed to

simulate ductile crack propagation problems using Finite Element Method (FEM). By using these damage models, elastic-plastic behavior considering damage of material is modeled and the initiation and propagation of ductile crack is directly predicted. So, it can be possible to predict the fracture mode of weld joint by applying these models to the analysis of fracture behavior on weld joint.

In this research, to predict the fracture mode of the spot weld joints, an investigation is carried out based on the continuum damage mechanics. In the investigation, it can be assumed that the analysis may be unstable due to the non-linearity of the damage model. Then, in this research, a simplified evaluation method for the damage of material is developed based on the damage model proposed in the literature²⁾ by one of the authors. Using this method, the fracture behavior is predicted and the influence of the shape of weld joint and material property is investigated.

2. Ductile crack propagation analysis

In this chapter, the existing ductile crack propagation analysis method, which models the elastic – plastic behavior of a damaged material to directly simulate the initiation and propagation of a ductile crack, is briefly described. And a simplified crack propagation analysis method, which can evaluate the damage using ordinary plastic potential, is proposed.

In the initiation and propagation of ductile crack, ductile crack

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Fig. 1 Schematic illustration of damage.

propagates with the formation of void in a material. In the existing method²⁾, progress of damage is classified as the following three stages as shown in Fig. 1.

- (I) The occurrence of nano-submicron size of void and it grows up to micro void.
- (II) At stage II, the strain increases to the level at which micro voids begin to form. (just before fracture)
- (III) In stage III, the damage accelerates due to the occurrence of plural micro voids and crack is formed.

In this model, initial damage D_0 is assumed and the damage increase gradually in stage I. The critical damage D_c , after which voids can coalesce, is assumed and the damage increases drastically after the damage D reaches D_c . Finally, a material collapses when D reaches D_{cr} .

To model the above fracture behavior, the damage is defined as follows using the volume component of plastic strain $\Delta\varepsilon_p$.

$$\Delta D = (1 - D)\Delta\varepsilon_p \quad (1)$$

Considering the damage defined in the Eq. (1), the following plastic potential ϕ in which yield stress depends on stress triaxiality and damage, is assumed.

$$\phi = \left(\frac{q}{\sigma_0} \right)^2 + a_1 D^* \exp \left(a_2 \frac{p}{\sigma_0} \right) - 1 = 0 \quad (2)$$

Where q is equivalent stress, p is hydrostatic stress, σ_0 is yield stress, D^* is effective damage, a_1, a_2 are material constants. Effective damage is represented by Eq. (3). By using the effective damage, the damage is accelerated rapidly after it exceeds critical damage D_c .

$$D^* = \begin{cases} D & \text{for } D < D_c \\ D_c + (D - D_c) & \text{for } D \geq D_c \end{cases} \quad (3)$$

Fig. 2 Stress triaxiality dependent ductility.

By using the above damage potential, the initiation and propagation of ductile crack can be analyzed. Here, Eq. (4) shows the relationship between the increment of plastic components of volumetric strain $\Delta\varepsilon_p$ and equivalent plastic strain $\Delta\varepsilon^p$ based on associated flow rule. Eq. (5) can be obtained by rearranging Eq. (2) and Eq. (4).

$$\Delta\varepsilon_p \frac{\partial \phi}{\partial q} - \Delta\varepsilon^p \frac{\partial \phi}{\partial p} = 0 \quad (4)$$

$$\Delta\varepsilon_p = a_1 a_2 D \exp \left(a_2 \frac{p}{\sigma_0} \right) \frac{\sigma_0}{2q} \Delta\varepsilon^p \quad (5)$$

Substituting Eq. (1) to Eq. (5) yields Eq. (6) which defines the relation between the increment of damage dD and equivalent plastic strain $d\varepsilon^p$.

$$\frac{1}{(1-D)D} dD = \frac{1}{2} a_1 a_2 \exp \left(a_2 \frac{p}{\sigma_0} \right) \frac{\sigma_0}{q} d\varepsilon^p \quad (6)$$

Since it can be assumed that the damage is very small if it is less than D_c , it can be considered that the stress including damage equals stress without damage ($\sigma_0 = q$). So, Eq. (7) can be obtained.

$$\int_{D_0}^{D_c} \frac{1}{(1-D)D} dD = \int_0^{\varepsilon^p} \frac{1}{2} a_1 a_2 \exp \left(a_2 \frac{p}{\sigma_0} \right) d\varepsilon^p \quad (7)$$

Therefore, Eqns. (8) and (9) can be obtained.

$$\varepsilon^p = A \exp \left(B \frac{p}{q} \right) \quad (8)$$

$$A = \frac{2}{a_1 a_2} \ln \left(\frac{(1-D_0)D_c}{(1-D_c)D_0} \right), \quad B = -a_2 \quad (9)$$

Assuming that the materials are unconditionally broken after the damage D exceeds the critical damage D_c , Eq. (8) can be criteria of fracture as shown in Fig. 2. Considering Eq. (8) as a criterion of fracture, the fracture is evaluated from stress triaxiality and

Fig. 3 Computing flow of considering crack propagation.

equivalent plastic strain. In this study, a simplified simulation method is proposed based on the above consideration. Figure 3 shows computing flow of considering crack propagation in this study. In this method, elastic-plastic analysis is performed. The fracture is evaluated for each element using Eq. (8). Once an element is determined as fractured, its stiffness is set to 0. In the elastic-plastic analysis, the Idealized Explicit FEM³⁾ proposed by one of authors is applied for the efficient computation.

3. Analysis of crack propagation on spot weld joint

3.1 Influence of nugget diameter on fracture mode

Figure 4 (a), (b) shows analysis model. Cross tension test on spot weld joints is modeled in this analysis. The assumed material

Fig. 4 Analysis model for cross tension test.

is a high tensile steel. Its Young's modulus is 210 GPa, Poisson's ratio is 0.3, yield stress is 830MPa. The yield stress is uniform in this model.

Figure 5 shows influence of nugget diameter on fracture mode. Figures 5 (a) to (c) show distribution of equivalent plastic strain before and after fracture for the nugget diameter $d = 3.8\text{mm} (3\sqrt{t})$. Figures 5 (d) to (f) show those for $d = 5.1\text{mm} (4\sqrt{t})$. And Figures 5 (g) to (i) show those for $d = 6.3\text{mm} (5\sqrt{t})$. These results show that fracture mode is influenced by nugget diameter. The fracture mode in the case of small nugget ($d = 3\sqrt{t}, 4\sqrt{t}$) is interface fracture in which crack propagates across the internal nugget. The fracture mode in the

Fig. 5 Influence of nugget diameter on fracture mode.

Fig. 6 Relation between stress triaxiality and equivalent plastic strain at point A and B.

case of large nugget ($d=5\sqrt{t}$) is plug fracture in which crack propagates along the outer periphery of the weld nugget.

Figure 6 shows relation between stress triaxiality and equivalent plastic strain at point A and B. From Fig. 6 (a), it is found that crack propagates into the nugget due to large stress triaxiality in the case of interface fracture. On the other hand, in the case of plug fracture, crack propagates into the thickness direction due to the large equivalent plastic strain. These results show plug fracture can be obtained by choosing the welding conditions in which the large nugget diameter can be obtained.

3.2 Influence of sheet thickness on fracture mode

In this section, the effect of sheet thickness on fracture mode and cross tensile strength is investigated. Figure 7 shows zoomed view of welded part. The shape of the model is as same as previous section as shown in Fig. 4. In this investigation, 7 cases of sheet thickness are considered: $t=1.2$ mm, 1.4 mm, 1.6 mm, 2.2 mm, 2.4 mm, 2.6 mm, 3.0 mm. In these cases, the same

Fig. 7 Zoomed view of welded part.

Fig. 8 Distribution of equivalent strain in the central cross section.

nugget diameter of $d=7.6$ mm ($6\sqrt{t}$) is used. The following material constant are assumed; Young's modulus is 210GPa, Poisson's ratio is 0.3, yield stress is 830MPa, the work-hardening coefficient is 0.

Figures 8 (a) - (f) show equivalent plastic strain distribution at sheet thickness $t=1.2$ mm, 1.6 mm, 2.6mm. From Figs. 8(b) and (d), it is shown that crack propagates into the thickness direction at sheet thickness $t=1.2$ mm, 1.6 mm and Fig. 8 (f) shows crack propagates into the nugget at sheet thickness $t=2.6\text{mm}$. This result shows that crack propagates into the nugget when sheet is thick. The reason of this tendency can be assumed as follows: as the sheet is thicker, the ratio of nugget diameter to sheet thickness decreases and stress concentration at the crack tip increases. Figure 9 shows load-displacement curve for all cases. In this figure, crack initiated at the broken line. This shows that as the sheet is thinner, crack propagation can occur at lower load. The successive disappearing of elements after crack initiation causes the fluctuation of load-displacement curve in this figure. In spite

Fig. 9 Load-displacement curve in several sheet thickness.

of considering no work-hardening, the load values in Fig. 9 gradually increases after the initiation of crack. This can be assumed that larger load is necessary until all cross section of the sheet to deform plastically. As shown above, the effect of sheet thickness on fracture mode and cross tensile strength is investigated. As a result, the interface-fracture in which the crack propagation into the nugget, is found in thicker sheet.

4. Conclusions

In this study, a simplified ductile fracture evaluation method based on continuum damage mechanics was proposed. And the proposed method was applied to the analysis of cross tension test on spot weld joints to investigate fracture modes. The following results were obtained.

- 1) It was shown that the fracture mode of the cross tension test on spot welding can be predicted by using the proposed method.
- 2) It was found that the size of nugget diameter affects fracture mode; fracture mode was interface fracture in the case of small nugget diameter, fracture mode is plug fracture in the case of large nugget diameter.
- 3) Through the comparison of the fracture behavior, it was found that crack propagates into the nugget due to large stress triaxiality in the case of interface fracture. On the other hand, crack propagates along the outer periphery of the weld nugget due to the large equivalent plastic strain in case of plug fracture.
- 4) It was found that the sheet thickness affects fracture mode; fracture mode is interface fracture in the case of thick sheet, fracture mode is plug fracture in the case of thin sheet.

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