Numerical Simulation of Hydrogen Diffusion and Accumulation Behavior under Residual Stress Distribution in Resistance Spot Welds

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Hydrogen related delayed fracture is a critical issue to be solved to enhance the application of high-strength steels. This holds true with the high-strength steels and its welds used in automotive applications. The trend of the increase of the strength of steels used will continue, therefore, it is important to investigate the hydrogen related fracture of high-strength automotive steels. In this study, hydrogen diffusion and accumulation behavior in the high-strength steel welds has been investigated by numerical simulation. The residual stress distribution of the resistance spot welds was considered as the driving force of hydrogen diffusion. The hydrogen diffusion was simulated under residual stress field with different initial hydrogen distributions and boundary conditions. When the diffusible hydrogen distributed uniformly in the weld metal just after welding, hydrogen diffused rapidly after welding and retained slightly at the center of the weld metal. When the diffusible hydrogen was introduced through the surface of the welded joint, diffusible hydrogen accumulated in the area of high tensile stress. In addition, the rate of increase of the hydrogen concentration was dependent on the distance from the surface of the welded joint.

Key Words: Resistance spot welding, Delayed fracture, High-strength steel, Residual stress, Numerical simulation, Hydrogen diffusion simulation

1. Introduction

The use of high-strength steels has been increasing in order to reduce the weight of automotive body. However, along with the increase in the steel strength, delayed fracture sensitivity increases. Automotive steel sheets are usually welded by resistance spot welding, therefore, causes of the delayed fracture, such as the hardened microstructure induced by quenching, residual stress, and stress concentration in the corona bond area, occur inevitably. If diffusible hydrogen exists in the welded joint, there is a possibility of delayed fracture. There are two possible sources of diffusible hydrogen; (1) the hydrogen derived from water or oil adhering to the material surface and involved in the weld metal, and (2) the hydrogen generated by surface corrosion or present in the environment. It is expected that the diffusion and accumulation behavior of hydrogen in the welded joint is influenced by the stress field. In this study, hydrogen diffusion and accumulation behavior in high-strength steel welds was investigated by performing a numerical simulation. The hydrogen diffusion was simulated under the residual stress field by taking into account the above-mentioned situations. In addition, the hydrogen diffusion simulation was performed under the stress field for the case where the load is applied to the welds assuming under loading with residual stress during use.

2. Numerical simulation model

2.1 Numerical formulation of hydrogen diffusion

Hydrogen diffusion was numerically simulated based on Eq. (1)\(^1\) by using the finite element method. By assuming that the mass diffusion is driven by the gradient of the chemical potential \(\mu\), the concentration flux \(J\) is described by Eq. (1):

\[
J = -\frac{Dc}{RT} \frac{\partial \mu}{\partial x}
\]

(1)

where \(D\) is the diffusion coefficient \((D = 9.242 \times 10^{-5} \text{ mm}^2/\text{s})\), \(c\) is the concentration, \(R\) is the gas constant \((8.314 \text{ J/K mol})\), \(T\) is the temperature, and \(x\) is the position vector. The chemical potential is defined by Eq. (2):

\[
\mu = \mu^0 + RT \ln \phi + pV_H
\]

(2)

where \(\mu^0\) is the standard chemical potential, \(\phi\) is the normalized concentration \((= c/s\), where \(s\) is the solubility, \(s = 0.0708 \text{ ppm mm/N}^0.5\)), \(p\) is the hydrostatic pressure, and \(V_H\) is the partial molar volume of hydrogen in the solid solution \((V_H = 2.0 \times 10^{-6} \text{ m}^3/\text{mol})\). Equations (1) and (2) yield Eq. (3):

\[
J = -sD \left( \frac{\partial \phi}{\partial x} + \phi \frac{\partial \ln T}{\partial x} + \frac{\phi V_H}{RT} \frac{\partial p}{\partial x} \right)
\]

(3)

The terms on the right side of Eq. (3) represent the driving force of diffusion due to the concentration, temperature, and hydrostatic stress gradients, respectively. The numerical simulation in this study was performed using the finite element method.
residual stress, and stress concentration in the corona bond area, reduce the weight of automotive body. However, along with the influenced by the stress field. In this study, hydrogen diffusion occur inevitably. If diffusible hydrogen exists in the welded joint, increase in the steel strength, delayed fracture sensitivity and accumulation behavior in high-strength steel welds was investigated by performing a numerical simulation. The hydrogen sources of diffusible hydrogen; (1) the hydrogen derived from resistance spot welding, therefore, causes of the delayed fracture, water or oil adhering to the material surface and involved in the hydroge or present in the environment. It is expected that the diffusion and accumulation behavior of hydrogen in the welded joint is therefore, it is important to investigate the hydrogen related fracture of high-strength automotive steels. In this study, hydrogen diffusion and accumulation behavior under Residual Stress Distribution in Resistance Spot Welds

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1. Introduction

Hydrogen related delayed fracture is a critical issue to be solved to enhance the application of high-strength steels. This hold true with the trend of the high strength steels and its welds used in automotive applications. The trend of the hydrostatic stress gradients, respectively. The numerical simulation model and introduced hydrostatic pressure field.

**Axis of symmetry**

Fig. 1 Numerical simulation model and introduced hydrostatic pressure field.

**Axis of symmetry**

Fig. 2 Hydrostatic pressure field when 0.01-mm of forced displacement in sheet separating direction was applied to the edge of model.

software Abaqus, in which the above formulation was incorporated.

2.2 Simulation model and hydrostatic pressure used in the simulation

In this study, 1.6-mm-thick resistance-spot-welded 980 MPa-class high-strength steel sheets were modeled for the range of 0 to 4.98 mm from the center (Fig. 1). The hydrostatic pressure shown in Fig. 1 reached to zero at the edge of the model; therefore, the model had enough size to discuss the hydrogen diffusion driven mainly by the hydrostatic pressure gradient. The resistance spot weld was modeled by using an axisymmetric model based on the assumption that the residual stress was distributed axisymmetrically. A hydrostatic pressure component was introduced as the residual stress field. This hydrostatic pressure field was selected on the basis of the results of the hydrostatic pressure field when 0.01-mm of forced displacement in sheet separating direction was applied to the edge of the model and the hydrostatic pressure was obtained (Fig. 2). In this case, the displacement in the sheet separating direction was applied keeping the displacement in the radial direction fixed.

2.3 Initial hydrogen distributions and boundary conditions

In the hydrogen diffusion simulation under the residual stress field, three cases, Case 1 (Fig. 3(a)), Case 2 (Fig. 3(b)), and Case 3 (Fig. 3(c)) were used. In Case 1, the initial hydrogen distribution in the weld metal was set to 1 ppm as the initial condition in order to model the hydrogen derived from water or oil adhering to the plate surface, and the surface hydrogen concentration was fixed at 0 ppm to model the discharge via the surface. In Cases 2 and 3, the diffusible hydrogen does not exist in the model initially and the hydrogen concentration at the surface was fixed at 1 ppm in order to model the introduction of hydrogen generated by corrosion or contained in environment through the surface of the welded joint. Introduction of hydrogen from the upper and lower surfaces was considered in Case 2, and that from the upper, lower, and slit surfaces was considered in Case 3. These conditions were set to consider the difference in the hydrogen environment to which spot welds are subjected. In each case, the hydrogen diffusion proceeded under the hydrostatic pressure field presented in Fig. 1.

In the hydrogen diffusion simulation under the load environment, Case 2 (Fig. 3(b)) was used assuming the introduction of hydrogen generated by corrosion or contained in
environment through the surface of the welded joint. The hydrogen diffusion proceeded under the hydrostatic pressure field presented in Fig. 2.

3. Results and discussion

3.1 Hydrogen diffusion under residual stress field

In Case 1, the diffusible hydrogen at nodes M1 to M4 diffused rapidly after welding, while the hydrogen concentration at nodes S1 to S4 increased temporarily, as shown in Fig. 4. The diffusible hydrogen was consequently discharged from the welds but a small amount was retained at the center of the weld metal for a short duration immediately after welding, as shown in Fig. 7. In Case 2, the rate of increase in the hydrogen concentration was dependent on the distance from the top and bottom surfaces of the model, i.e., the hydrogen concentration at S1 to S4 increased faster than those at M1 to M4, as shown in Fig. 5. Diffusible hydrogen accumulated in the area with a high tensile stress, as shown in Fig. 8. In Case 3, the rates of increase in the hydrogen concentration at nodes in the middle of the welds (M1 to M4)
were uniform as shown in Fig 6. This is because in Case 3, hydrogen is not introduced from the slit in between welded plates; therefore, M1 to M4 are located at almost same distance from the top and bottom surfaces. On the other hand, in Case 2, hydrogen is also introduced from the slit; therefore, the increase in the hydrogen concentration was dependent on the distance from the slit as shown in Fig. 5.

In the area with a high tensile stress, diffusible hydrogen accumulated in higher concentration compared to Case 2, as shown in Fig. 9. This is because the diffusible hydrogen concentration is fixed to 1 ppm in Case 2, however, the limitation is not applied in Case 3. In addition, the hydrogen concentration distribution reached a steady state at 172 800 s in both Case 2 and Case 3. These results show that the hydrogen diffusion and accumulation behavior in the resistance spot welds is strongly influenced by initial hydrogen distributions and boundary conditions.

3.2 Hydrogen diffusion under stress distribution after loading

Shown in Fig. 10 is the evolution of hydrogen concentration at nodes in the middle of the welds (M1 to M4) when the hydrogen diffusion proceeded under stress distribution after loading. The hydrogen concentration at node M4 was higher than that in the case where only the residual stress field was taken into consideration (Fig. 5). The node M1 is located in the stress concentration area caused by the applied load as shown in Fig 2, and the diffusible hydrogen was accumulated as shown in Fig. 11. The hydrogen concentration distribution reached a steady state at 172 800 s.

4. Conclusions

In this study, the hydrogen diffusion and accumulation behavior in the resistance spot welds has been investigated by performing a numerical simulation. The hydrogen diffusion was simulated under the following different stress fields: (i) the welding residual stress field and (ii) the stress field by applied load in addition to residual stress distribution. The following results were obtained:

(1) When the diffusible hydrogen distributed uniformly in the weld metal just after welding and discharged through the surface, hydrogen concentration decreased rapidly after welding, but a small amount of hydrogen was retained at the center of the weld metal.

(2) When diffusible hydrogen was introduced through the surface of the welded joint after welding, it accumulated in the area with a high tensile stress. In addition, the rate of increase in the hydrogen concentration was dependent on the distance from the surface of the welded joint. In addition, when there is no introduction of hydrogen through the slit of the sheets, diffusible hydrogen accumulated in higher concentration in the area with a high tensile stress.

(3) The hydrogen diffusion simulation under the load environment was performed under the hydrostatic pressure field when the forced displacement of sheet separating direction was applied to the edge of the model. Diffusible hydrogen was accumulated in the stress concentration zone caused by the applied load.

Reference
