Mechanical Behavior during SR-treatment of Welding Residual Stress Through the Thickness†

You Chul KIM*, Teruhisa YAMAKITA** and Han Sur BANG***

Abstract

Welding residual stress often makes deteriorate quality of the welded joint. So, PWHT (post weld heat treatment) is usually carried out for the purpose of relaxation of welding residual stress and softening of the welded joint.

In this paper, the mechanical behavior during SR (stress relief annealing), which is the most popular treatment among the PWHT, is elucidated based on the results of three-dimensional thermo-elasto-plasto-creep analysis. The main results are as follows:

According to the results of three-dimensional creep analysis, at the early stage during SR-treatment, creep strain tends to be easily accumulated in weld metal and HAZ (heat affected zone). Therefore, stress relaxation is considerable in weld metal and HAZ. Welding residual stress is mainly relaxed in the heating stage. The configuration of the stress distribution does not change and plastic strain is not produced during SR-treatment. Predicting creep strain and stress during and after SR-treatment from the results of two-dimensional plane-deformation thermo-elasto-plasto-creep analysis, the accuracy depends upon how actually represents the distribution and the magnitude of welding residual stress, which is one of the mechanical measures represented the severity of mechanical condition. If the stress concentration such as a notch, defects of welding etc. exists in parallel with weld line, the accumulation of the creep strain component perpendicular to a notch becomes great, but the stress component in the same direction is hard to be relaxed. Then, in the case that the characteristic of stress relaxation is inferior in base metal, though creep strain is greatly accumulated in weld metal and HAZ, the stress component perpendicular to weld line is hard to be relaxed.

KEY WORDS: (Residual stress) (Plastic strain) (Post weld heat treatment) (Stress relief annealing) (Creep strain) (Three-dimensional analysis) (Stress concentration) (Strain concentration) (FEM)

1. Introduction

It is well known that welding residual stress often makes deteriorate the quality of the welded joint; the buckling strenght, the brittle fracture strength and the fatigue strength etc. So, PWHT (post weld heat treatment) is usually carried out in order to relax welding residual stress and to soften the welded joint. Among various PWHT, SR (stress relief annealing) is generally done, which is performed so that stress may be relaxed by heating a portion of the welded joint or a whole of the machinery and holding high temperatures. However, a crack (namely SR-crack) at a notch of the coarse grained zone in HAZ (heat affected zone) of the welded joint may occur anew by SR-treatment although it improves the quality of the welded joint.

In this paper, the mechanical behavior during SR-treatment is elucidated to propose the method for deciding the condition of initiation of the SR-crack from a mechanical point of view.

First, what mechanical behavior happens during SR-treatment is elucidated from the results of three-dimensional thermo-elasto-plasto-creep analysis. Moreover, the mechanical significance with the results of two-dimensional plane-deformation thermo-elasto-plasto-creep analysis, which is easily obtained various mechanical measures, is elucidated based on those of three-dimensional one. Then, influences of the existence of a notch on the mechanical behavior during SR-treatment are investigated with the results of two-dimensional analysis.

2. Results of Three-dimensional Analysis

Here, welding residual stress through thickness is obtained by three-dimensional thermo-elasto-plasto-stress analysis. And then, three-dimensional thermo-elasto-plasto-creep analysis is carried out on welding residual stress as initial one. From the results of the analyses, the mechanical behavior during SR-treatment is elucidated.

2.1 Model for analysis

The model for analysis and the coordinate system

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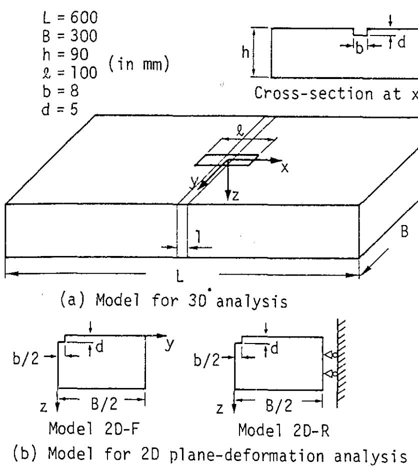

Fig. 1 Model for analysis.

are shown in **Fig. 1**. The single pass welding is performed in a slit assuming the last pass (breadth $b=8$ mm, depth $d=5$ mm, length $l=100$ mm) along x-direction with heat input $Q=3.4$ kJ/mm and travel speed $v=5.5$ mm/sec.

Material of the specimen is 2 1/4 Cr-1Mo steel. Temperature dependence of physical constants, mechanical properties and creep constants of material used in a series of analyses are described in references 1) and 2) respectively.

SR-treatment is carried out under the following condition, that is, heating rate 100°C/h, holding temperature 600°C and holding time 1 h or 3 h.

Concerning to creep law for three- and two-dimensional thermo-elasto-plasto-creep analysis, the transient-state creep law is applied in the case that transient-state creep rate is larger than steady-state creep one, as shown in the following equation,

$$\{\dot{\varepsilon}^c\} = 3/2\, mA^{1/m}\bar{\sigma}^{\gamma/m}(\bar{\varepsilon}^c)^{1-(1/m)}\{\sigma'\} \qquad (1)$$

Conversely, the steady-state creep law is applied in the case that transient-state creep rate is smaller than steady-state creep one as follows:

$$\{\dot{\varepsilon}^c\} = 3/2\, \beta\bar{\sigma}^n\{\sigma'\} \qquad (2)$$

where, $\{\dot{\varepsilon}^c\}$: creep strain rate
$\bar{\sigma}$: equivalent stress
$\bar{\varepsilon}^c$: equivalent creep strain
$\{\sigma'\}$: stress deviation
m, A, γ, β, n: creep constant[1)]

It is assumed in the creep analyses that no creep strain is produced in temperature under 400°C, where it is very small, and that creep strain rate is same in weld metal, HAZ and base metal. A series of analyses in this study is performed by the finite element method.

2.2 Welding residual stress and plastic strain by three-dimensional stress analysis

The distribution of welding residual stress and plastic strain in weld metal ($y=3$, $z=8$ (mm)) along weld line, which is obtained by three-dimensional thermo-elasto-plasto-stress (with moving heat source) analysis, is shown in **Fig. 2**. Then, the distribution of them through the thickness ($y=3$ (mm)) at the middle cross section ($x=0$, yz-plane) is shown in **Fig. 3**.

As the details of the characteristics of welding residual stress and plastic strain and their production mechanism have been reported[3)], they are omitted here.

2.3 Accumulation of creep strain and stress after SR-treatment by three-dimensional creep analysis

Three-dimensional thermo-elasto-plasto-creep analysis is performed on welding residual stress, which is shown in Fig. 2 and Fig. 3, as initial stress.

The distributions of the accumulation of creep strain and stress after SR-treatment along weld line in weld metal ($y=3$, $z=8$ (mm)) are shown in **Fig. 4**.

The distributions of the accumulation of the creep strain components, ε_x^c (along weld line), ε_y^c (perpendicular to weld line) and ε_z^c (in thickness direction), are almost uniform along weld line except the welding edges.

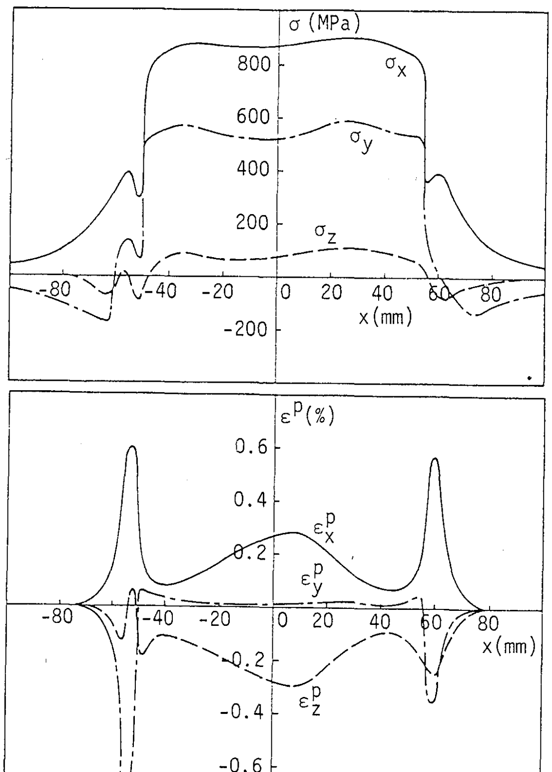

Fig. 2 Distributions of welding residual stress and plastic strain along weld line.

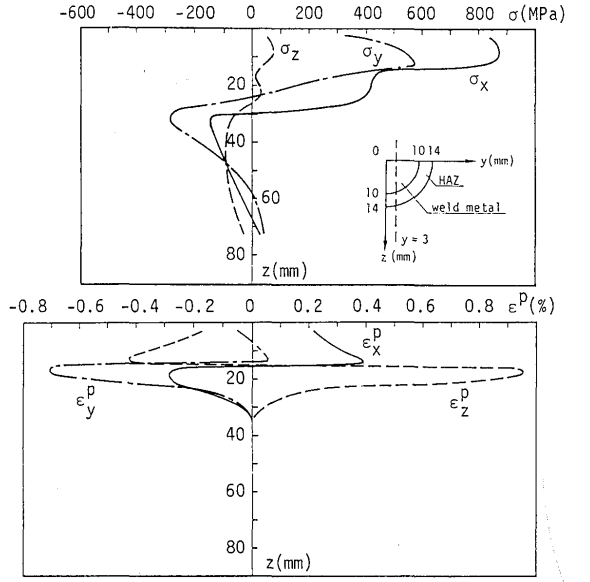

Fig. 3 Distributions of welding residual stress and plastic strain through thickness (at middle cross section).

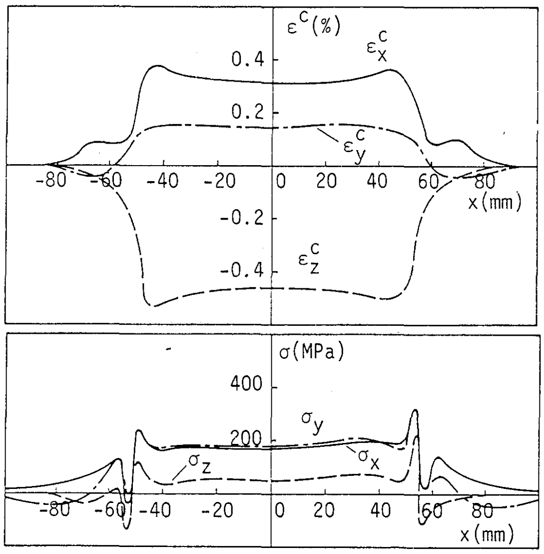

Fig. 4 Distributions of creep strain and stress along weld line after SR-treatment.

Paying attention to the creep strain component, ε_x^c and ε_y^c, they are both tensile. So, the stress components σ_x (along weld line) and σ_y (perpendicular to weld line) are largely relaxed by SR-treatment. Contrary to this, the stress component σ_z (in thickness direction) is relaxed a little, though the creep strain component ε_z^c is entirely compressive.

Considering the reason why ε_z^c was largely compressive, creep strain has been treated as it is incompressibility. That is, in thickness direction, where the mechanical restraint condition is most weakest, it is largely compressive so as to satisfy the condition of volume constant.

Equivalent creep strain $\bar{\varepsilon}^c$ produced by SR-treatment through the thickness (y=3 (mm)) at the middle cross section (x=0, yz-plane) is shown in **Fig. 5**, with transition and accumulation of each creep strain component. The distribution of transition of equivalent stress $\bar{\sigma}$ and stress components, σ_x, σ_y and σ_z, and their magnitudes after SR-treatment are shown in **Fig. 6.**

Concerning to the distribution of transient stress shown in Fig. 6, Young's modulus usually goes down as a temperature rises. As a result, stress becomes small even if creep strain is not produced.

Here, however, in order to elucidate the history of stress relaxation accompanied with the accumulation of creep strain, stress are revised with disregarding the decrease of stress caused by the temperature dependence of Young's modulus as shown in Eq. (3).

$$\{\sigma\} = (E_R/E_T)\{\sigma_T\} \tag{3}$$

where, E_R, E_T: Young's modulus of a room temperature and a temperature T

Furthermore, as creep strain is generally accumulated in a cooling stage from holding temperature to a room temperature, stress is relaxed a little. But, in this paper, stress after SR-treatment is obtained regardless of the accumulation of creep strain in a cooling stage from holding temperature.

2.4 Accumulation of creep strain and behaviors of stress relaxation

Based on Fig. 5 and Fig. 6, the accumulation of creep strain and the behaviors of stress relaxation are discussed here.

First, consider the distribution of transient equivalent creep strain $\bar{\varepsilon}^c$ and equivalent stress $\bar{\sigma}$. According to the creep-law applied in this paper, creep strain rate $\{\dot{\varepsilon}^c\}$ is proportional to the γ/m power of equivalent stress $\bar{\sigma}$, in the region of transient-state creep, and to n-th power of $\bar{\sigma}$ in the region of stready-state creep. From the results (Fig. 6) of three-dimensional stress analysis, welding residual equivalent stress $\bar{\sigma}$ is 700 MPa in weld metal and HAZ, and 380 MPa in base metal close to HAZ (in either case, produced stress is same as yield stress σ_Y of material). Calculating γ/m and n, creep strain to be accumulated in weld metal and HAZ is more than ten times as large as those in base metal.

Consequently, stress relaxation at the early stage during SR-treatment is considerable in weld metal and HAZ. Then, stress is relaxed all over the object after the difference of the magnitude of stress in weld metal, HAZ to base metal is vanished.

Secondly, paying attention to each component, creep strain increment $\{\Delta\varepsilon^c\}$ is proportional to stress devia-

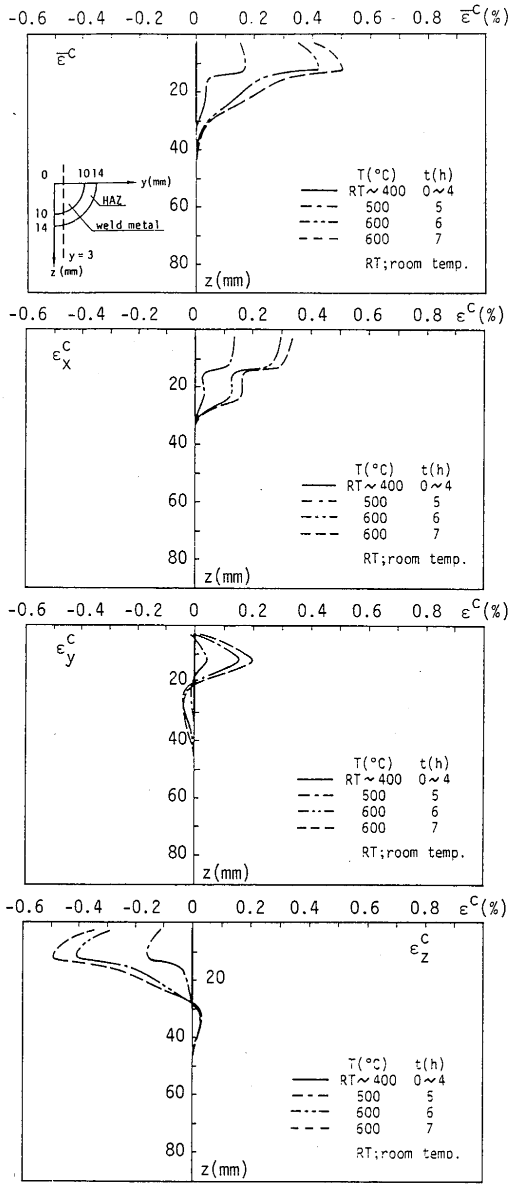

Fig. 5 Distributions of creep strain through the thickness during SR-treatment (at middle cross section).

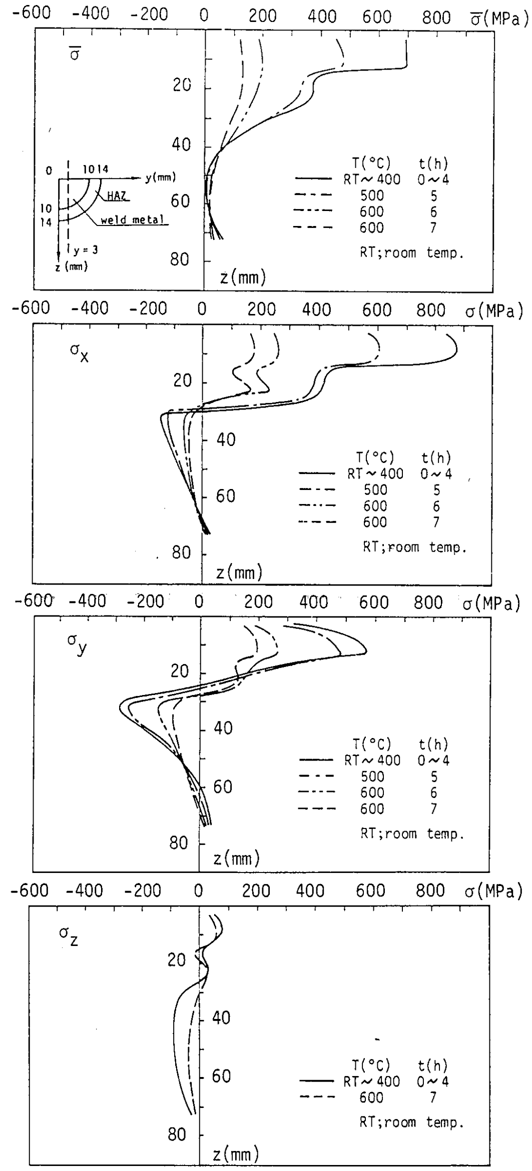

Fig. 6 Distributions of stress through the thickhess during SR-treatment (at middle cross section).

tion $\{\sigma'\}$. The components of $\{\Delta\varepsilon^c\}$ are shown as follows:

$$\begin{aligned}
\Delta\varepsilon^c_x &\propto 2\sigma_x-\sigma_y-\sigma_z \\
\Delta\varepsilon^c_y &\propto 2\sigma_y-\sigma_z-\sigma_x \\
\Delta\varepsilon^c_z &\propto 2\sigma_z-\sigma_x-\sigma_y
\end{aligned} \tag{4}$$

According to the results of three-dimensional stress analysis, the magnitude of the welding residual stress components: σ_x σ_y and σ_z produced in weld metal and HAZ was $\sigma_x>\sigma_y\gg\sigma_z\doteqdot 0$ (see Fig. 2 and Fig. 3).

Therefore, in the initiation of SR-treatment (Fig. 5: the heating stage T=400~500°C), the increment of the creep strain components becomes $\Delta\varepsilon^c_x>0$, $\Delta\varepsilon^c_y\doteqdot 0$ and $\Delta\varepsilon^c_z<0$ from Eq. (4) respectively. In consequence, as ε^c_x (the accumulation of $\Delta\varepsilon^c_x$) increases in tensile, the stress component σ_x is largely relaxed in weld metal and HAZ (Fig. 6). On the other hand, since ε^c_y (the accumulation of $\Delta\varepsilon^c_y$) scarcely increases, the stress component σ_y is not relaxed so much (Fig. 6).

Next, in the case of T=500°C, the magnitude of σ_x and σ_y (Fig. 6) is almost same in HAZ, so that increment of the creep strain components in HAZ is $\Delta\varepsilon^c_x>0$, $\Delta\varepsilon^c_y>0$ in T=500~600°C (Eq. (4)). Therefore, the accumulation of $\Delta\varepsilon^c_x$ and $\Delta\varepsilon^c_y$ becomes large in tensile in HAZ (Fig. 5). As a result, the stress components, σ_x and σ_y are largely relaxed in HAZ (Fig. 6).

While, notwithstanding the heating and holding stage, ε^c_z (the accumulation of $\Delta\varepsilon^c_z$) is largely compressive (Fig. 5). As mentioned in Section 2.3, the reason why ε^c_z is largely compressive, ε^c_z is largely produced so as to satisfy the condition of volume constant in the direction where the mechanical restriction is weakest.

By the way, among the welding residual stress components produced in weld metal and HAZ, a degree of relaxation of the stress component σ_y is not so large compared with that σ_x.

In spite of the heating and holding stage, stress is relaxed without changing of a shape of the distribution of them (Fig. 6). Now, stress is mainly relaxed in heating stage. Besides, no plastic strain is produced during SR-treatment.

As mentioned hereinbefore, the mechanical behavior during SR-treatment, that is, the accumulation of creep strain and stress relaxation is largely affected by the magnitude of i) equivalent welding residual stress $\bar{\sigma}$, and that of ii) deviation stress $\{\sigma'\}$ (effect of tri-axes stress state). In addition, as iii) stress is self-equilibrating, the characteristics of stress relaxation of base metal must be paid attention to[4]. This is discussed in the next chapter.

3. Consideration

The results of three-dimensional creep analysis are compared with those of two-dimensional plane-deformation one. Then, the mechanical significance with the result of two-dimensional creep analysis is elucidated based on that of three-dimensional one. Now, SR-treatment among various PWHT are widely performed for the purpose of relaxing of the welding residual stress and softening of the welded joint. However, SR-crack may occur anew at a notch of the coarse grained zone in HAZ of the welded joint by SR-treatment though it improves quality of the welded joint. Therefore, two-dimensional creep analysis is carried out to the model with a notch. From the result, the influence on the mechanical behavior during SR-treatment with a notch is examined in detail. Moreover, the characteristics of stress relaxation in base metal, which influence on the accumulation of creep strain and stress relaxation are studied.

3.1 Mechanical significance with results of two-dimensional analysis

Two-dimensional stress analysis has been performed at middle cross section ($x=0$, yz-plane: Fig. 1(b); Model 2D-F) of the assumed model for three-dimensional analysis. The distributions of the welding residual stress components through the thickness are shown in **Fig. 7** with a dotted line. Then, two-dimensional creep analysis is carried out on them as initial stress.

The history of stress relaxation during SR-treatment

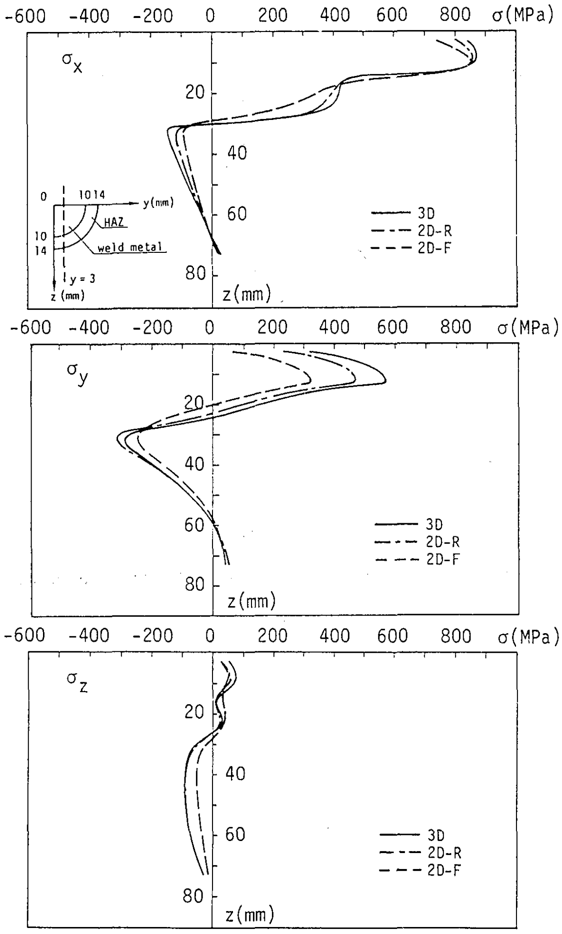

Fig. 7 Comparison of two-dimensional plane-deformation analysis (2D) with three-dimensional analysis (3D) on welding residual stress through the thickness (at middle cross section).

in weld metal ($y=3$, $z=8$ (mm)) is shown in **Fig. 8(a)** with a thin line. Besides, a bold line in the same figure expresses the results of three-dimensional creep analysis. From the results, equivalent creep strain $\bar{\varepsilon}^c$ and the stress component σ_y after SR-treatment can not be estimated so accurately from the results of two-dimensional creep analysis to the model 2D-F. The reason why the accuracy of prediction of the stress component σ_y after SR-treatment is low is attributed to the welding residual stress component σ_y is small comparing to that by three-dimensional stress analysis, which is because the effect of the welded portion is not considered in Model 2D-F, though the welded portion restricts the contraction of the observing point in three-dimensional problem taking the effect of moving heat source[5].

Therefore, in order to easily represent the effect of the welded portion which restricts the contraction of weld metal, two-dimensional creep analysis is carried out to the model 2D-R assumed that the displacement of y-direction is restricted at the edge of the middle

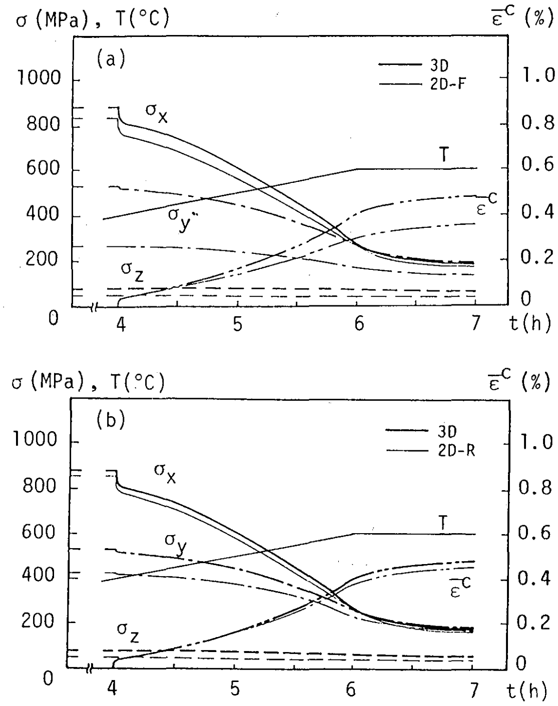

Fig. 8 Comparison of two-dimensional plane-deformation analysis (2D) with three-dimensional analysis (3D) on stress and equivalent creep strain in weld metal during SR-treatment (at $y=3$, $z=8$ (mm)).

cross section (shown in Fig. 1(b)). The distributions of the welding residual stress components through the thickness are illustrated in Fig. 7 with a chain line. The history of stress relaxation in weld metal ($y=3$, $z=8$ (mm)) during SR-treatment obtained by two-dimensional creep analysis is shown in **Fig. 8(b)** with a thin line. A bold line in the same figure expresses the result of three-dimensional creep analysis.

Naturally to say, when three-dimensional problem is replaced by two-dimensional one, the confidence of the results depends upon how accurately the mechanical restraint condition of three-dimensional problem is represented. Consequently, by means of the model 2D-R (Fig. 7) which has a high accuracy of representing welding residual stress obtained by three-dimensional stress analysis, the history of the stress relaxation during SR-treatment, the accumulation of equivalent creep strain $\bar{\varepsilon}^c$ and stress after SR-treatment, etc. can be estimated accurately by two-dimensional analysis.

From the above-mentioned results, in case that the mechanical behavior during SR-treatment, the accumulation of creep strain and stress after SR-treatment could be predicted by two-dimensional analysis, the accuracy of predicition is decided how actually welding residual stress in three-dimensional problem is represented. Because, the distribution and the magnitude of welding residual stress are one of the mechanical measures which shows the severity of mechanical restraint condition in three-dimensional problem[3].

3.2 Influence of Existence of a Notch on Mechanical Behavior during SR-treatment

Comparing the mechanical behavior during SR-treatment between with a notch and without one at the coarse grained zone in HAZ of the welded joint, the influence of the existence of a notch on stress-strain is elucidated.

Now, a notch is set up at the coarse grained zone (the location where the maximum temperature reaches 1350°C, $y=11$ (mm)) in HAZ. The size of a notch is as follows; depth $d=0.8$ (mm), radius curvature $\rho=0.2$ (mm) and the degree of the stress concentration $K_t=5$.

Besides, a series of analyses is performed on the model 2D-R (Fig. 1 (b)).

3.2.1 *Welding residual stress and plastic strain*

Two-dimensional stress analysis is performed on the model 2D-R with a notch (the stress concentration) and without one. The distributions of welding residual stress and plastic strain through the thickness at $y=11$ (mm) (corresponding to the location of a notch) of each model are shown in **Fig. 9**.

Without a notch, among the distribution of welding residual stress through the thickness, σ_x is the largest at the location corresponding to a bottom of a notch ($y=11$, $z=0.85$ (mm)) and the order of the magnitude of the welding residual stress components is $\sigma_x>\sigma_y>\sigma_z$. Contrary to this, with a notch, it becomes $\sigma_y\fallingdotseq\sigma_x>\sigma_z$ (Fig. 9(a), (a')). As the stress component σ_y is largely influenced by the stress concentration, the order of the magnitude is guessed to be $\sigma_y\gg\sigma_x>\sigma_z$. However, it is considered that it became $\sigma_y\fallingdotseq\sigma_x>\sigma_z$ owing to the restricted condition which the magnitude of produced stress had not been able to become larger than that of yield stress of material.

Among the distributions of residual plastic strain through the thickness, pay attention to a bottom of a notch ($y=11$, $z=0.85$ (mm)). Without a notch, the plastic strain component ε_y^p(perpendicular to weld line) is compressive (Fig. 9(b)). The other hand, with a noсth, ε_y^p is largely tensile (Fig. 9(b')) and ε_z^p (in thickness direction) is largely compressive. This is because similar to the above-mentioned creep strain, it is produced so as to satisfy the condition of volume constant in thickness direction where the mechanical restraint condition is weakest.

3.2.2 *Accumulation of creep strain and stress after SR-treatment*

Two-dimensional creep analysis is performed on welding residual stress (Fig. 9(a), (a')) as initial one, which was obtained from the stress analyses to both of the models with a notch and without one. The accumulation of creep strain and stress through the thickness after SR-treatment are shown in **Fig. 10**.

First, pay attention to the accumulation of creep strain through the thickness after SR-treatment (Fig. 10(a), (a')). With a notch, the accumulation of the creep strain component ε_y^c is more considerable at the location corresponding to a bottom of a notch ($y=11$, $z=0.85$ (mm)) than that without a notch. Besides, the creep strain component ε_z^c is largely compressive. This is because similar to the above-mentioned plastic strain, it is produced so as to satisfy the condition of volume constant.

The history of the accumulation of creep strain at the location corresponding to a bottom of a notch is shown in **Fig. 11(a), (a')**. It is found that the accumulation of the creep strain component ε_y^c with a notch is more considerable than that without a notch. Considering

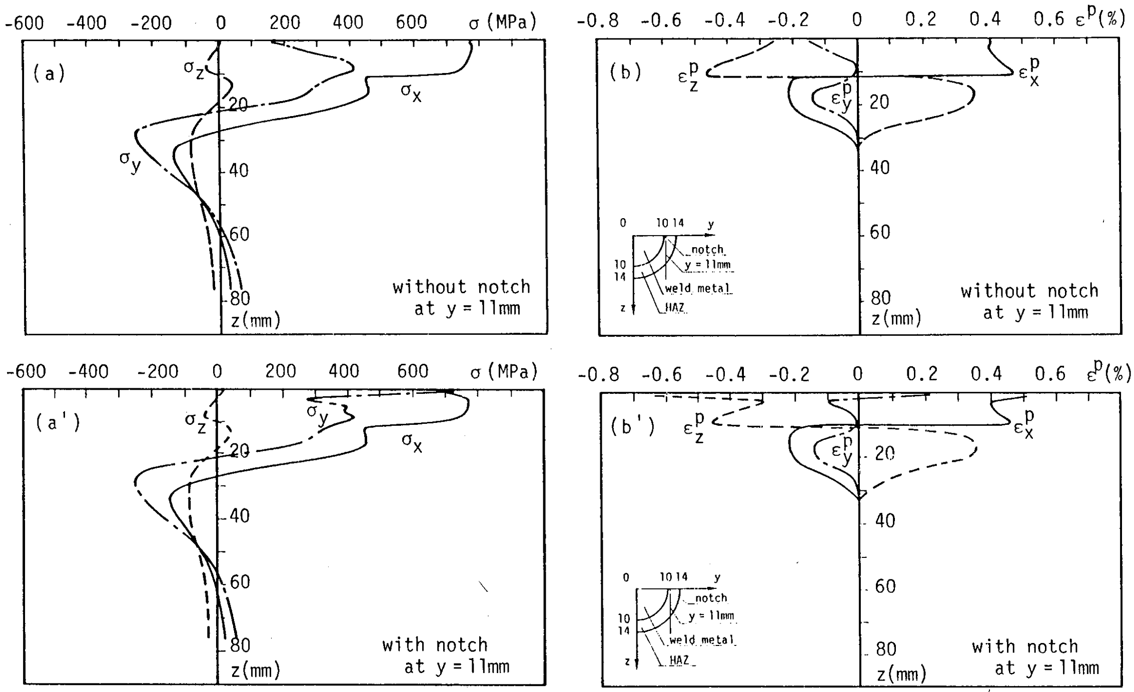

Fig. 9 Distributions of welding residual stress and plastic strain through the thickness (by two-dimensional plane-deformation analysis).

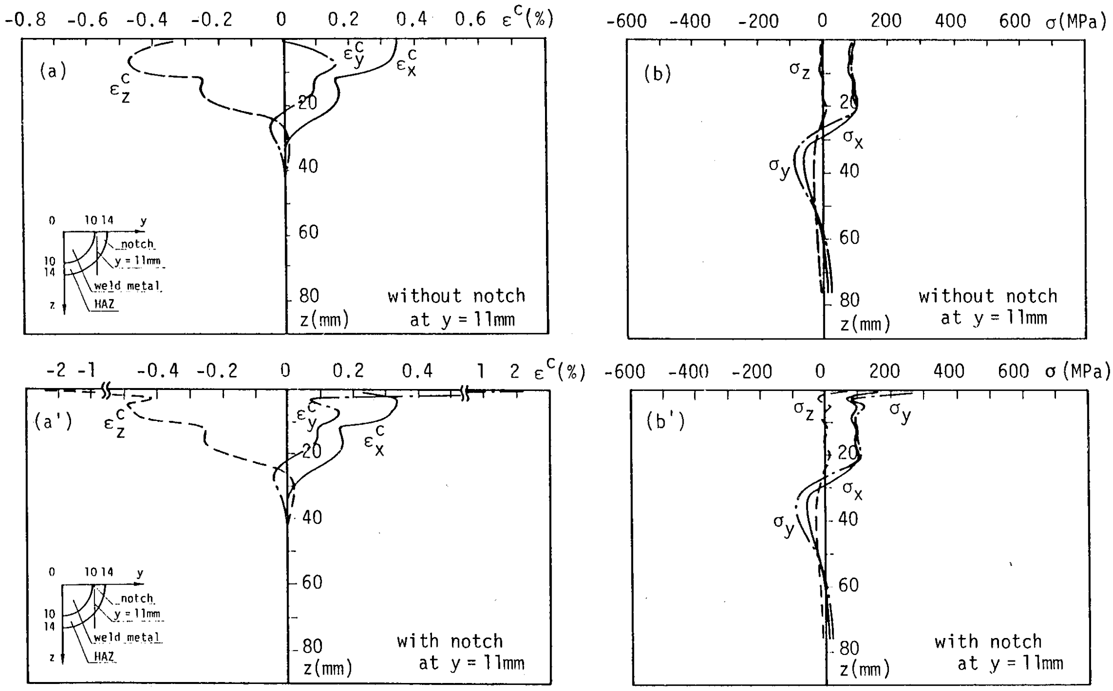

Fig. 10 Distributions of creep strain and stress through the thickness after SR-treatment (by two-dimensional plane-deformation analysis).

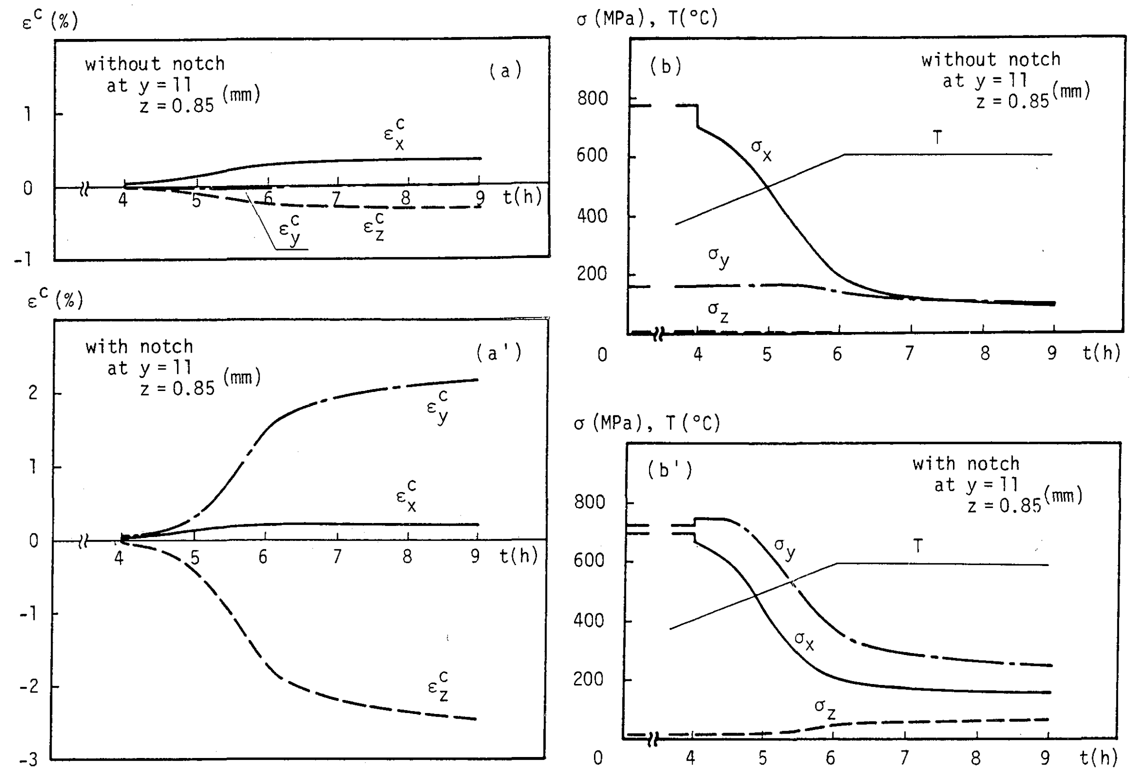

Fig. 11 Transient creep strain and stress during SR-treatment (by two-dimensional plane-deformation analysis).

the reason of that, no produced stress is able to be over yield stress of material under any conditions. However, there is no restricted condition for strain such as that for stress. Therefore, as predicted from Neuber's law, a bottom of a notch is largely affected by the strain concentration due to an existence of a notch. The component ε_y^c is most influenced by it.

Furthermore, the accumulation of creep strain is considerable in weld metal and HAZ (Fig. 10(a), (a')), though there is a difference of the accumulation of creep strain whether with a notch or without one. No plastic strain is produced irrespective of the existence of a notch in creep analysis.

On the other hand, without a notch, at a location corresponding to a bottom of a notch ($y=11$, $z=0.85$ (mm)), the order of the magnitude of the welding residual stress components during SR-treatment (Fig.11 (b')) is $\sigma_x > \sigma_y > \sigma_z$ and the ones after SR-treatment is $\sigma_x \fallingdotseq \sigma_y > \sigma_z \fallingdotseq 0$. With a notch, the order of the magnitude of welding residual stress components is $\sigma_y \fallingdotseq \sigma_x > \sigma_z$, but that of the stress components during and after SR-treatment is $\sigma_y > \sigma_x > \sigma_z$. Among others, at temperature 400°C where creep strain is produced, though σ_x is relaxed to some extent, σ_y becomes a little larger. So it is found that the stress component perpendicular to a notch is largely affected by the stress concentration. Therefore, it is considered that the component perpendicular to weld line σ_y is hard to be relaxed attributed to the stress concentration.

Generally, without a notch and if the accumulation of ε_y^c is considerable, σ_y is largely relaxed. However, with a notch, σ_y is hard to be relaxed nevertheless the accumulation of ε_y^c becomes considerable at a bottom of a notch. This is considered because the strain and stress concentration due to the existence of a notch largely influence on the direction perpendicular to a notch.

3.3 Characteristics of base metal to influence stress relaxation

Regarding to the accumulation of creep strain and stress relaxation, welding residual stress produced in welded joint without any external forces must be self-balanced. Then, stress during SR-treatment is changing with holding the self-equilibrium. Owing to this, the characteristics of stress relaxation in base metal should be also noted[4].

Here, applying to the model 2D-R which accurately approximated the results of three-dimensional analysis, two-dimensional creep analysis is performed with the same creep rate ($\dot{\varepsilon}_{WM}^c = \dot{\varepsilon}_{HAZ}^c$) in weld metal and HAZ, and with the changing creep rate ($\dot{\varepsilon}_{BM}^c$) in base metal into as tenfold and one hundred times as fast as $\dot{\varepsilon}_{WM}^c$ ($=\dot{\varepsilon}_{HAZ}^c$). The history of the accumulation of equivalent creep strain $\bar{\varepsilon}^c$ and relaxation of each stress component at $y=3$, $z=8$ (in mm) are shown in **Fig. 12**.

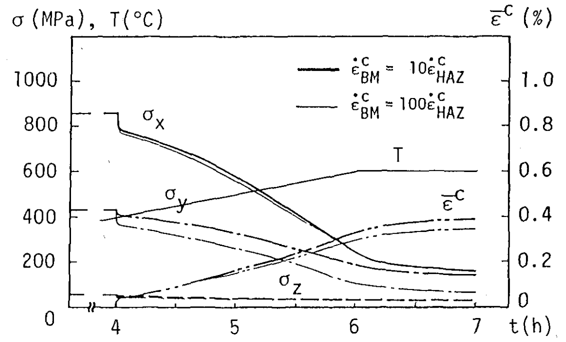

Fig. 12 Effect of creep strain rate in base metal on stress relaxation and accumulation of equivalent creep strain (at $y=3$, $z=8$ (mm)).

From the results of the analysis, if the characteristics of stress relaxation in base metal becomes good, the accumulation of $\bar{\varepsilon}^c$ becomes small and the stress component σ_y is considerably relaxed. In other words, it is found that σ_y is hard to be relaxed though the accumulation of creep strain in weld metal and HAZ is considerable, if the characteristics of stress relaxation in base metal is inferior.

4. Conclusions

The obtained main results are as follows:

From the results of three-dimensional thermo-elasto-plasto-creep analyses:

(1) At the early stage during SR-treatment, creep strain tends to be greatly accumulated in weld metal and HAZ, where welding residual stress is larger than in base metal. So, stress relaxation is considerable in weld metal and HAZ. After the difference between the magnitude of stress in weld metal and HAZ and that in base metal is disappeared, stress relaxation progresses all over the body.

(2) Welding residual stress is mainly relaxed in the heating stage. Then, the configuration of the distribution of stress does not change regardless of the heating and holding stage, no plastic strain is produced during SR-treatment.

Comparing the results of three-dimensional analysis with those of two-dimensional plane-deformation thermo-elasto-plasto-creep analysis:

(3) Predicting the accumulation of creep strain and stress during and after SR-treatment from the results of two-dimensional analysis, the accuracy depends upon how actually represents the distribution and magnitude of welding residual stress.

From the results of two-dimensional analyses:

(4) Without a notch, at a location corresponding to a bottom of a notch, the order of the magnitude of the welding residual stress components and the stress component during SR-treatment is $\sigma_x > \sigma_y > \sigma_z$ and that after SR-treatment is $\sigma_x \fallingdotseq \sigma_y > \sigma_z \fallingdotseq 0$. On the contrary, with a notch such as defects of welding ect., the direction perpendicular to a notch (y-direction) is greatly affected. The order of the magnitude of welding residual stress components is $\sigma_y \fallingdotseq \sigma_x > \sigma_z$, but that of the stress components during and after SR-treatment is $\sigma_y > \sigma_x > \sigma_z$.

(5) With a notch, as y-direction is greatly affected by the stress-strain concentration at a bottom of a notch, the accumulation of creep strain becomes considerable and the stress components in the same direction are hard to be relaxed by the influence of the stress concentration.

(6) Whether a notch exists or not, there is a difference of the accumulation of creep strain. However, the accumulation of creep strain is considerable in weld metal and HAZ comparing with base metal regardless of existence of a notch.

(7) If the characteristic of stress relaxation is inferior in base metal, though creep strain is greatly accumulated in weld metal and HAZ, the stress component perpendicular to weld line is hard to be relaxed.

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