Title	An Efficient Method for Estimation of Reduction of Welding Residual Stresses from Stress-Relief Annealing (Report II) : The Characteristics of Reduction of Welding Residual Stresses in Very Thick Joints during SR Treatment(Mechanics, Strength & Structural Design)
Author(s)	Nakacho, Keiji; Ueda, Yukio
Citation	Transactions of JWRI. 1994, 23(1), p. 79-84
Version Type	VoR
URL	https://doi.org/10.18910/12237
rights	
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An Efficient Method for Estimation of Reduction of Welding Residual Stresses from Stress-Relief Annealing (Report II) †

— The Characteristics of Reduction of Welding Residual Stresses in Very Thick Joints during SR Treatment —

Keiji NAKACHO* and Yukio UEDA**

Abstract

Stress-relief annealing (SR treatment) is included in the fabrication process of welded structures such as pressure vessels. This study aims to develop a simple analytical method which facilitates the calculation of transient and residual stresses during SR treatment, in order to easily determine reasonable conditions of SR treatment for the recent large-size structures constructed of high quality thick plates.

In the first report, estimating equations in an uni-axial stress state were formulated for relaxation tests at changing and constant temperatures. In this report, the stresses relaxed by SR treatment in the thick welded joint are analyzed accurately by the finite element method based on thermal elastic-plastic-creep theory. The characteristics of the changes of the welding residual stresses in multi-axial stress state are studied in detail for further development of the estimation method.

KEY WORDS : (Simple Estimating Method) (Stress-Relief Annealing) (Welding) (Thick Welded Joint) (Transient Stress) (Residual Stress) (Thermal Elastic-Plastic-Creep Analysis)

1. Introduction

Stress-relief annealing (hereinafter called SR treatment), whose main purpose is to relieve welding residual stresses, is included in the fabrication process of welded structures such as pressure vessels. Standard conditions for SR treatment are specified in JIS, ASME code, etc. For the recent large-size structures constructed of high quality thick plates, the specified conditions may require keeping the structures at a high temperature near 700 °C for a long time, in proportion to the thickness. Repeating this treatment in the fabrication and repair processes may deteriotate the qualities of the steel and the joint. The main reason for the difficulty in specifying rational conditions for SR treatment is that the effect of SR treatment on stress relief (that is, the change of welding residual stresses during SR treatment) is not fully known, especially for thick joints. So the severe conditions for SR treatment are specified for safety from the viewpoint of residual stress.

On the other hand, the available theory [1), 2)] of thermal elastic-plastic-creep analysis based on the finite element method had been developed, and with the theory, the changes of stresses in the welded joint of a very thick plate due to SR treatment were analyzed [2)]. However, the theory and computer program for analysis are so complicated that it is not easy to perform the analysis. Furthermore, for the three-dimentional problem, very long CPU time is necessary for computation even with a super computer. Each analyzed result does not always have essentials of the behavior or the mechanism.

This study aims to develop an analytical method (as simple as hand calculation) which facilitates the calculation of transient and residual stresses during SR treatment in order to easily determine reasonable conditions for SR treatment by parametric study. For this purpose, the various relations between stresses and strains during SR treatment are idealized, and the estimating equations are developed. In the first report [3)], estimat-

† Received on July 11, 1994
* Assistant Professor
** Professor

Transactions of JWRI is published by Welding Research Institute, Osaka University, Ibaraki, Osaka 567, Japan

ing equations in an uni-axial stress state were formulated for relaxation tests at changing and constant temperatures, which present a phenomenon similar to the stress relaxation phenomenon during SR treatment. It was shown that the analytical results of simple calculations using these equations are highly accurate.

In this report, the stresses relaxed by SR treatment in the thick welded joint are analyzed accurately by the finite element method based on thermal elastic-plastic-creep theory. The characteristics of the changes of the welding residual stresses in multi-axial stress state are studied in detail for further development of the estimation method.

2. Specimen and Process of Welding

The specimen in this study is shown in **Fig. 1**. Two long plates of 100 mm thickness and 195 mm width are welded with a 10 mm groove width by multipass welding. The welding method is narrow gap arc welding. The welding starts from the bottom and finishes with 20 passes and 20 layers. After the welding, stress-relief annealing is performed.

The material of the specimen is ASTM A336F22 (2 1/4 Cr - 1 Mo steel), and the wire is US521AxMF29A (made by Kobe Steel , Ltd.). Their physical, mechanical and creep properties are indicated in **Figs. 2, 3 and 4**, which have been used in the analyses (Reference 2, for

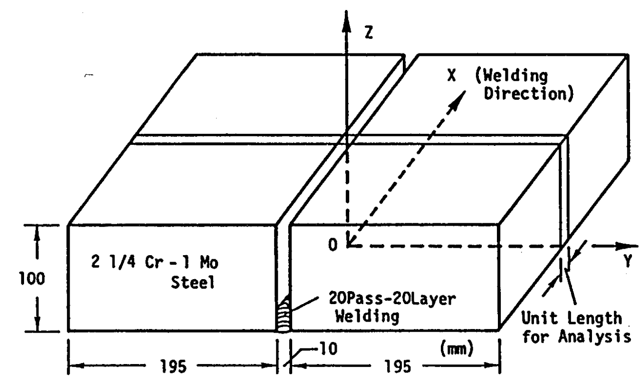


Fig. 1 Specimen of thick welded joint for analysis

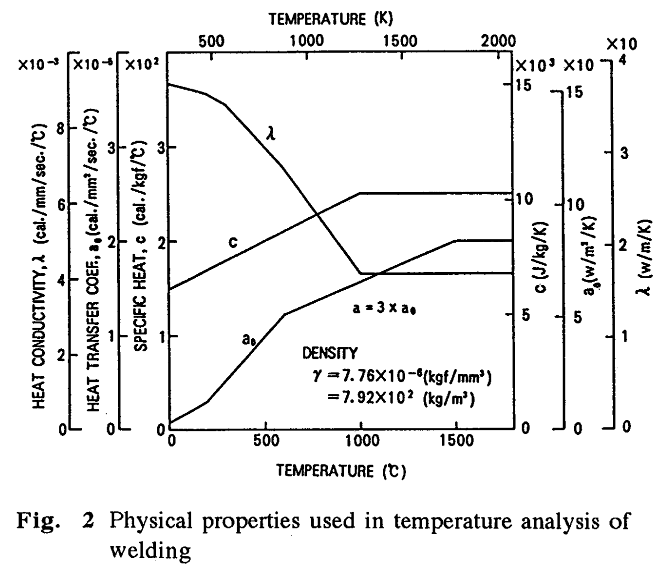


Fig. 2 Physical properties used in temperature analysis of welding

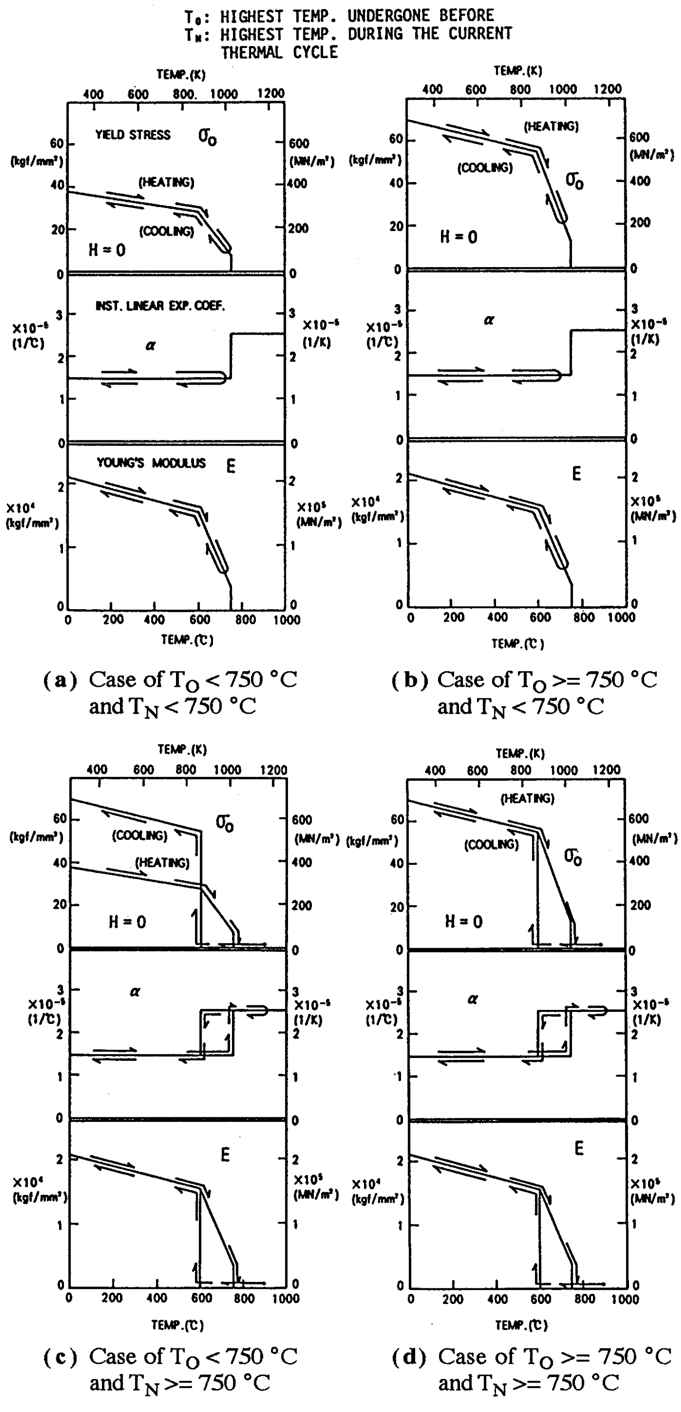
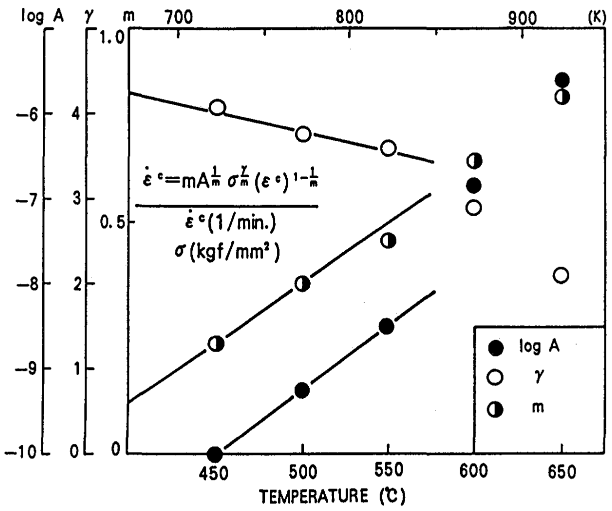
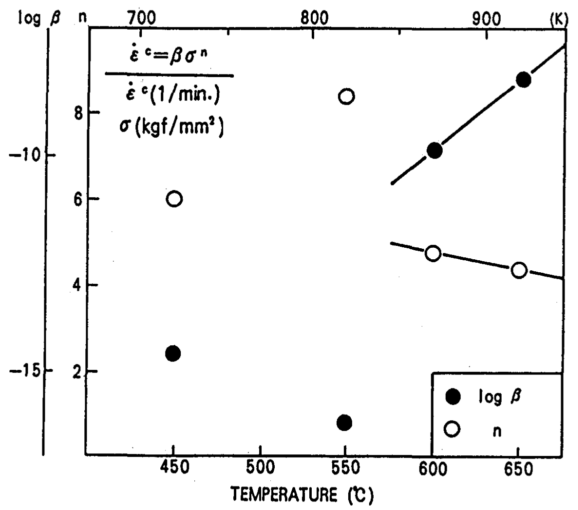


Fig. 3 Mechanical properties used in stress analysis of welding and stress-relief annealing (SR)



(a) For strain-hardening creep law (below 575 °C)



(b) For power creep law (above 575 °C)

Fig. 4 Creep properties used in stress analysis of stress-relief annealing (SR)

example). The mechanical properties change depending on the history of temperature. The creep properties change depending on the temperature, that is below 575 °C or above 575 °C.

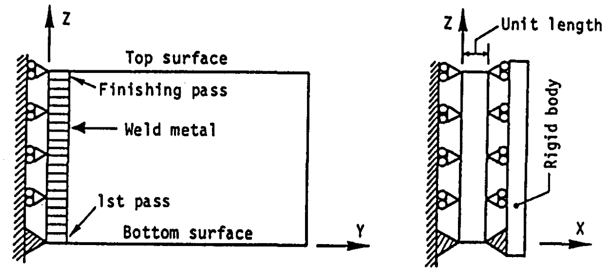
3. Conditions of Welding and Stress-Relief Annealing

The welding conditions are the same for all welding passes. The heat input is 35,000 J/cm, and the heat efficiency is 0.9. The preheating and inter-pass temperatures are 200 °C.

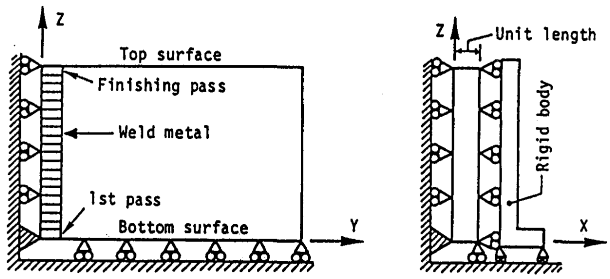
The conditions of stress-relief annealing for the welded specimen are as follows. The heating rate is slow, that is 30 °C/hr, because of the large thickness of the joint. The maximum heating temperature is 650 °C, and at that temperature the specimen is held for 1 hour.

4. Restraint Conditions of Specimen

As the restraint condition of the specimen, two conditions are adopted as shown in **Figs. 5 (a) and (b)**. In restraint condition A, no external restraint is loaded on the specimen during welding and SR treatment. In restraint condition B, longitudinal bending deformation (rotation around Y-axis) and angular distortion (rotation around X-axis) are restricted. In both restraint conditions, the displacement in the direction of plate width (along Y-axis) can occur. These restraint conditions are the two extreme restraint conditions for an actual butt joint.



(a) Restraint condition A



(b) Restraint condition B

Fig. 5 Restraint conditions of specimen

It is considered in this study that the specimen is sufficiently long and the welding speed is sufficiently fast. In such a case it is rational to assume that any YZ-plane in the specimen except near both ends is allowed to move, remaining as a plane (plane deformation). Based on the assumption, a three-dimensional stress state is realized in thermal elastic-plastic-creep analysis in this study.

5. Method of Analysis

The welding stresses of the specimen and the changes in them during SR treatment were analyzed continuously. The thermal elastic-plastic-creep analyses were performed by applying the finite element method whose theory was developed by the authors [1), 2)]. The analysis as a plane deformation needs only the same memory capacity and CPU time as two-dimensional analysis. The material properties of 2 1/4 Cr - 1 Mo steel and the weld metal shown in Figs. 2, 3 and 4 were used in the analysis.

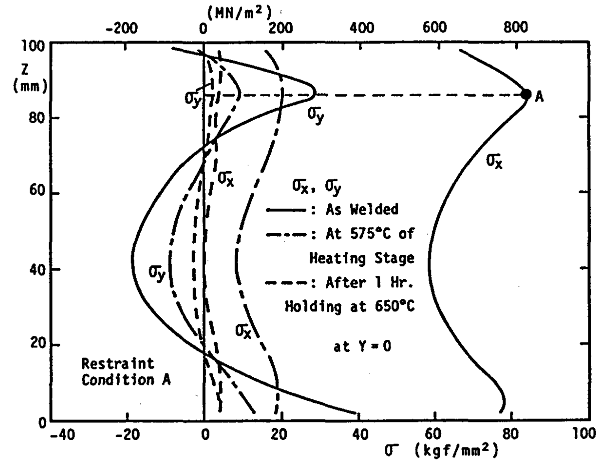
6. Analytical Results and Discussion

The results obtained by the thermal elastic-plastic-creep analyses are shown in **Figs. 6 and 7**, which are the transient and residual distributions of longitudinal (in the direction of welding) stress σ_x and transverse (in the direction of plate width) stress σ_y during welding and SR treatment. Figure 6 is in the case of the restraint condition A. Figure 7 is in the case B. Figure (a) represents the distributions at the middle cross section (Y=0) and Fig. (b) represents those on the top surface (Z=100 mm), respectively.

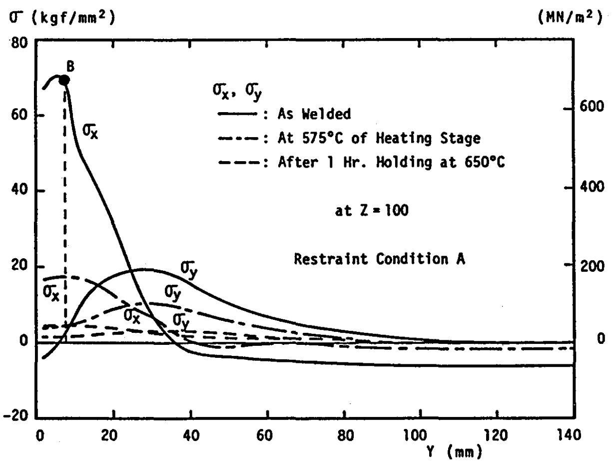
The maximum tensile stress is the most important related to the various cracks, so attention is focused on the value and the position of the maximum stress.

6.1 Welding residual stresses

The welding residual stresses are indicated by solid lines in Figs. 6 and 7. Near the few finishing beads, they show almost the same distributions without distinction of the restraint condition. The magnitudes of the stresses are somewhat larger in the severe restraint

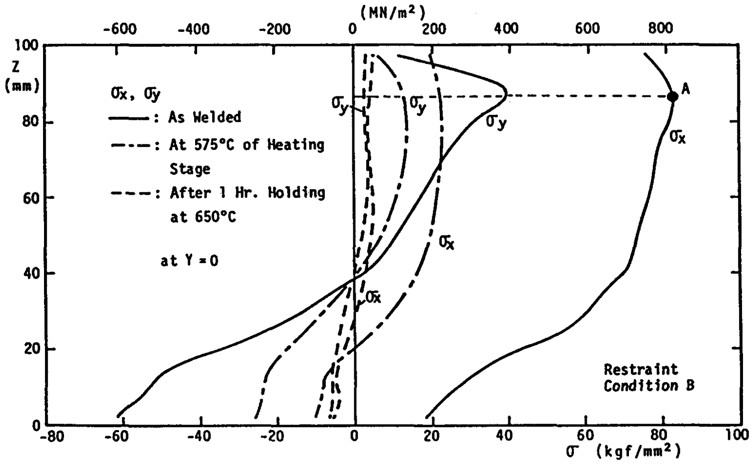


(a) At the middle cross-section (Y=0)

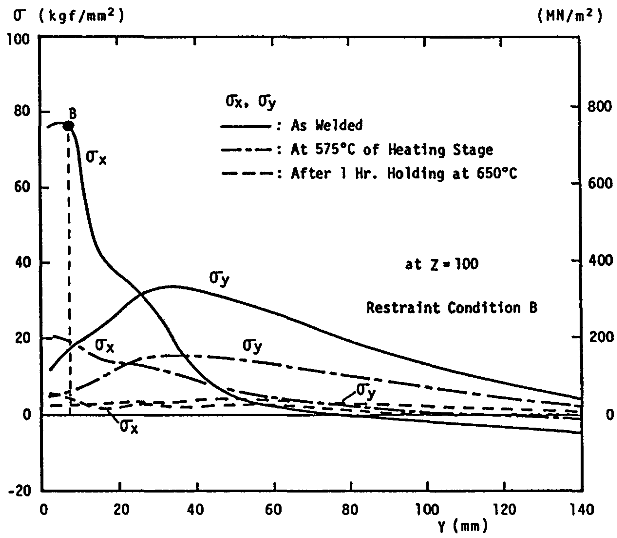


(b) On the top surface (Z=100 mm)

Fig. 6 Longitudinal and transverse stresses of thick welded joint after welding and during SR (In the case of restraint condition A)



(a) At the middle cross-section (Y=0)

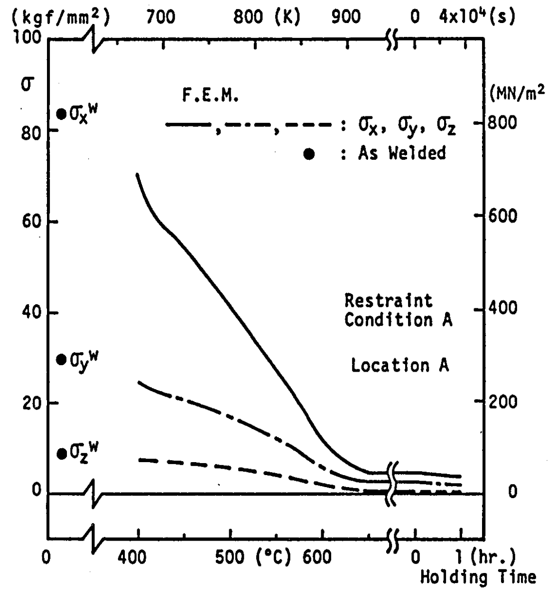


(b) On the top surface (Z=100 mm)

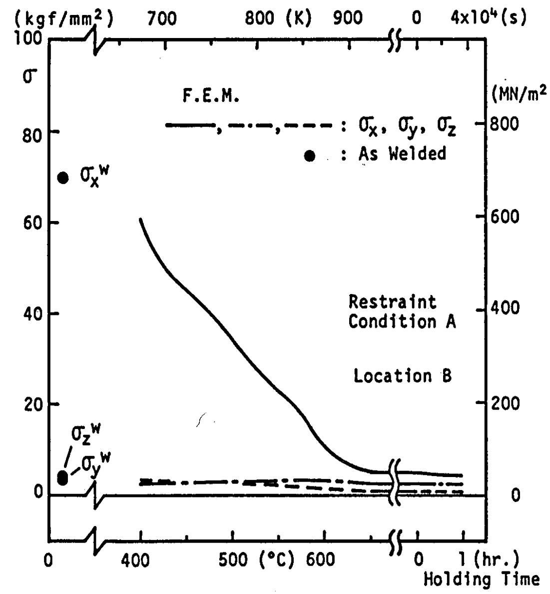
Fig. 7 Longitudinal and transverse stresses of thick welded joint after welding and during SR (In the case of restraint condition B) condition B than in the flexible condition A. The maximum stress of σ_x appears a little inside of the top surface at the middle cross-section. The value and the position are the same in the two restraint conditions.

Near the bottom surface, the stress distributions are largely different dependent on the restraint condition.

These characteristics of the welding residual stress distributions are the same as the thick welded joint of high tensile steel (SM50), and the production mechanism is explained in Reference 4.



(a) At the location A



(b) At the location B

Fig. 8 Changes of welding residual stresses during SR (In the case of restraint condition A)

6.2 Transient and residual stresses during stress-relief annealing

The changes of welding residual stresses during SR treatment are described next. The shapes of the distributions are fundamentally similar to the welding residual stress distributions. Where the magnitude (absolute value) of the stress is large, the reduction of the stress is large too. So the shapes of the distributions become smoother curves than before SR treatment. The position of maximum stress does not change. These tendencies are the same as the behaviors shown in Reference 2.

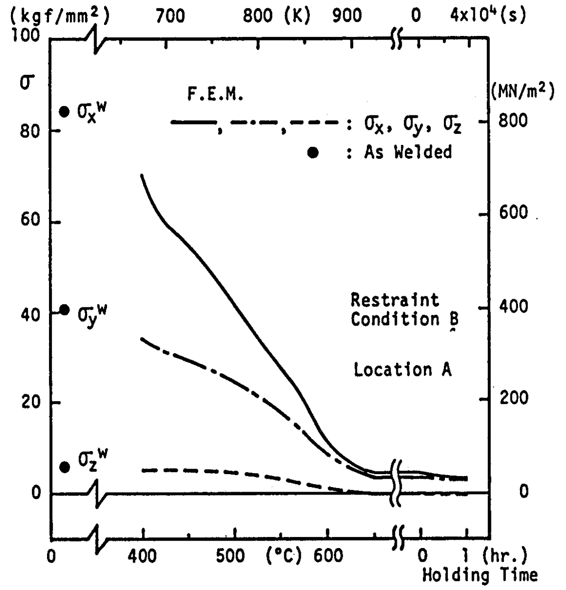
In Figs. 6 and 7, the changes of the stresses are represented until the end of the holding stage. The stresses at the end of the SR treatment can be calculated as follows : As the stresses are reduced enough in the holding stage, it may be assumed that the creep strain hardly increases in the cooling stage. Then the stresses at the end of cooling stage, that is at the end of SR treatment, can be obtained by multiplying the stress value at the end of the holding stage by the ratio of Young's moduluses at the end of cooling stage and at the end of the holding stage. The value is estimated on the safety side, that is a little larger than the exact value.

As seen clearly in Figs. 6 and 7, the maximum tensile welding residual stress is the x-component, and the maximum σ_x appears at 10 and a few mm under the top surface in the middle cross-section (at the location A in Figs. 6 and 7). The y-component, σ_y, has a large value at the same location too. On the top surface, the maximum σ_x is produced at the toe in 7-8 mm from the center (at the location B in Figs. 6 and 7).

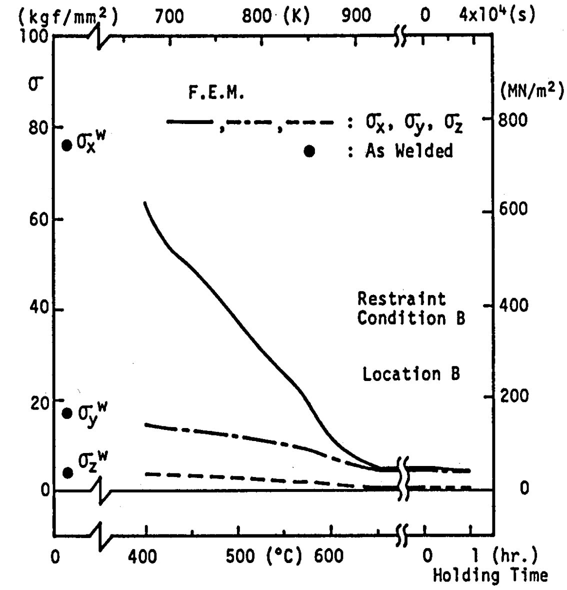
Figures 8 and 9 represent the transitions of normal stress components, σ_x, σ_y and σ_z, at the above-mentioned locations A and B during SR treatment. Figure 8 is for the restraint condition A, and Fig. 9 is for the condition B. A little σ_z exists in the finite element of the top surface, which does not exist on the top surface actually. At the location A where σ_x has maximum value and σ_y has a large value, three normal stresses decrease, keeping their ratio of magnitudes almost constant. This characteristic of the reduction of stresses is very important and will play an important role in developing the estimating equations of the stresses relaxed by SR treatment in the thick welded joint.

7. Conclusion

This study aims to develop a simple analytical method which facilitates the calculation of transient and residual stresses of the thick welded joint during SR treatment. For this purpose, in the first report, the estimating equations in an uni-axial stress state were



(a) At the location A



(b) At the location B

Fig. 9 Changes of welding residual stresses during SR (In the case of restraint condition B)

formulated for relaxation tests at changing and constant temperatures, which present a phenomenon similar to the stress relaxation phenomenon during SR treatment. In this second report, for expansion of this method to the SR treatment of the thick welded joint in three-axial stress state, the thermal elastic-plastic-creep analyses by the finite element method were performed to obtain the stresses produced by welding and relaxed by SR treatment in the thick joint. The results were examined in detail, and the characteristics of the transient stresses in multi-axial stress state were studied.

As a result, an important characteristic was determined : At the location where the stresses have maximum values, the stresses decrease, keeping their ratio of magnitudes almost constant.

This characteristic will be utilized to extend the simple method developed in the first report to the estimating equations of the stresses relaxed by SR treatment in the thick welded joint in the next report.

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