Analysis of Stress Intensity Factor due to Surface Crack Propagation in Residual Stress Fields Caused by Welding* (Comparison of Influence Function Method and Inherent Strain Analysis)

Katsumasa MIYAZAKI**, Masahito MOCHIZUKI***,
Satoshi KANNO**, Makoto HAYASHI†,
Masaki SHIRATORI†† and Qiang YU††

Stress intensity factors due to surface crack propagation were analyzed by using the influence function method and inherent strain analysis of the residual stress fields caused by welding. The initial residual stress in a plate welded-butt joint was calculated by using inherent strain analysis, and the redistribution of residual stress and the stress intensity factor due to crack propagation were analyzed as changes in the structure's shape. Stress intensity factor was also calculated by using an influence function database. The stress intensity factor in the residual stress fields due to crack propagation obtained by using inherent strain analysis completely agreed with that obtained by using the influence function method. The results of the crack propagation analysis were compared with the experimental results of a fatigue test. It was validated that both the inherent strain analysis and the influence function method were efficient for analyzing stress intensity factors in residual stress fields caused by welding.

Key Words: Welded Joint, Residual Stress, Stress Intensity Factor, Crack Propagation, Influence Function Method, Inherent Strain Analysis, Stress Redistribution, Surface Crack

1. Introduction

It is important for evaluating the integrity of welded structures to understand the effect of factors

on the strength of welded joints and the rate of crack propagation. The factors are residual stress, stress concentration, mechanical properties, and the micro-structure of the material. Residual stress is well known to have a much greater effect on fatigue strength and stress-corrosion cracking than the other factors^{(1),(2)}.

The method of evaluating crack propagation under the small scale yielding condition in residual stress fields is, in general, to use the superposition technique as the basis for analyzing the stress intensity factor imposed by the initial residual stress and the effect of residual stress is considered as a change of stress ratio⁽³⁾⁻⁽¹⁷⁾. Residual stress in a welded joint is usually redistributed by crack propagation. This is because crack propagation changes the topology of the welded joint. There are two typical methods for evaluating crack propagation: one is based on a consideration of the redistribution of residual stress by crack propagation^{(5),(6)}; in the other, residual stress

* Received 19th October, 2001. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 65, No. 636, A (1999), pp. 1709-1715 (Received 1st October 1998).

** Mechanical Engineering Research Laboratory, Hitachi, Ltd., 3-1-1 Saiwai, Hitachi, Ibaraki 317-8511, Japan

*** Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan. Formerly, Mechanical Engineering Research Laboratory, Hitachi, Ltd. E-mail: mmochi@mapse.eng.osaka-u.ac.jp

† Mechanical Engineering Research Laboratory, Hitachi, Ltd., 502 Kandatsu, Tsuchiura, Ibaraki 300-0013, Japan

†† Faculty of Engineering, Yokohama National University, 156 Tokiwa-dai, Hodogaya, Yokohama 240-0067, Japan

is evaluated in terms of the effect of changes of crack opening and closing^{(6),(8),(10),(15),(17)}. The effectiveness of both methods has been verified by experiments with simple specimens such as base-metal plates or compact-tension specimens.

Most actual cracks in structures are surface cracks, which have a three-dimensional configuration. The influence function method is effective in the analysis of surface crack propagation^{(18)–(26)}. This is because the influence-functional databases make using the influence function method to evaluate stress intensity factors under arbitrary distributions of stress easy. Influence-functional databases have already been constructed for surface cracks in homogeneous plates and round bars^{(21)–(24)}. This makes it easy to solve the stress intensity factors for a variety of surface cracks in structures. Application of the influence function method to the crack propagation analysis in the presence of residual stress fields is yet to be investigated. There is a particular need to carry out such a study for welded structures.

The finite element method has recently become a common way of analyzing stress intensity factors⁽²⁷⁾. It is effective for each object to analyze the stress intensity factor by a large-scale computation, but it is difficult to obtain the factors as quickly as with the influence function method. Evaluating the stress intensity factor is difficult to use for the finite element method for the analysis of a surface crack in the presence of the elastic-plastic residual stress fields caused by welding processes.

The propagation behavior of surface cracks in the residual stress fields induced by welding is investigated in this paper. Initial residual stress in a butt-welded joint between a pair of plates is evaluated by using the inherent strain analysis⁽²⁸⁾, which is a hybrid method between strain measurement and elastic computation. The redistribution of residual stress and the stress intensity factors are then elastically calculated. The influence function method is also applied to calculate the stress intensity factors in the residual stress field, and the result is compared with that obtained by inherent strain analysis. Fatigue crack propagation is then tested to verify the effectiveness of the inherent strain analysis and the influence function method for evaluating stress intensity factors in the residual stress field.

2. Using Influence Function Method to Evaluate Stress Intensity Factors

The influence function method is used to evaluate stress intensity factors of a surface crack under a small scale yielding condition⁽²¹⁾. Stress intensity factor is analyzed by applying the superposition prin-

ciple when an object receives an external loading⁽²⁹⁾. The distributed force $\bar{T}_0$ is defined as the force on the hypothetical crack face when an elastic body without a crack is under an external load. The stress intensity factor of an elastic object with a crack that is subjected to an arbitrary external force $\bar{T}_0$ is equal to that of the same elastic body with force $-\bar{T}_0$ on the crack face without external load. In the influence function method, the stress intensity factor for an arbitrary unit force applied to the crack's surface is must be calculated by using the theoretical equation or the elastic finite element method, and the database of stress intensity factors can be constructed by performing the calculation for all the unit forces.

Figure 1 shows a schematic illustration of how the principle of superposition applies to a structure under a residual stress field⁽¹²⁾. The condition of residual stress relaxation by crack propagation is equivalent to that on the crack's faces being loaded with forces in the opposite directions to those of the initial residual stress distributions. When the superposition principle is applied to the residual stress field, it is possible to obtain the stress intensity factor after crack propagation in the redistributed residual stress field by loading the stress distribution corresponding

Fig. 1 Principles of the superposition technique for calculating stress intensity factor in residual stress fields

to the initial residual stress on a propagated crack face.

In the influence function method, the influence functional database is used to calculate the stress intensity factor under the condition of initial distribution of residual stress. The influence functional database is prepared by constructing the results of calculating the stress intensity factor for each of a number of arbitrary positions on the crack's face is loaded with a unit force. The stress intensity factor in the residual stress field then becomes equal to the superposition of those for the arbitrary unit forces.

Influence function method can calculate stress intensity factor in residual stress field by using the influence functional database. That means the distribution of initial residual stress on the crack's face is thus important for the evaluation of the stress intensity factor in residual stress field.

3. Evaluation of Residual Stress Redistribution and Stress Intensity Factor by Inherent Strain Analysis

Inherent strain analysis elastically evaluates the distribution of residual stress by using the inherent strain distribution which is generated in an elastic body as a result of thermal elastic-plastic behavior during the welding process⁽²⁸⁾. The inherent strain distribution in a welded structure is analyzed by solving an inverse problem from the elastic strain measured by using strain gauges, X-ray diffraction, and the like.

Residual stress in a structure is redistributed by the relaxation of the residual stress around the crack's tip when a crack is propagated in the residual stress field. The stress intensity factor of the propagated crack is determined by the redistributed residual stress. The distribution behavior of residual stress by crack propagation has been analyzed by the finite-element method with an inherent strain field. Residual stress was assumed to have been elastically relaxed from the initial conditions of stress distribution when the plastic region near crack tip becomes much smaller than the crack's size under the condition of the small scale yielding^{(12),(30)-(34)}. The distribution of inherent strain that is induced by the welding process is not changed by crack propagation, except in a small part of the plastic region near the crack tip. Residual stress redistribution is induced by the geometrical changes that are caused by crack propagation. The stress intensity factor due to residual stress is calculated by the assumed crack propagation method in the residual stress field applying to the finite-element method⁽²⁷⁾.

4. Analysis of Propagation of Surface Crack in a Plate Butt-Welded Joint

4.1 Configuration of welded joint and distribution of initial residual stress

The configuration of a butt-welded joint between two plates that is used to evaluate the redistribution of residual stress and the stress intensity factor due to crack propagation in a residual stress field is shown in Fig. 2(a). The plate butt-joint was welded in an X-shaped pair of grooves, in a sequence such that the V-shaped grooves on each side were welded in turn. The base material was a mild steel and the weld material is even-matched with shielded metal arc welding.

The distribution of residual stress in the plate butt-welded joint was calculated by using the conventional inherent strain method⁽²⁸⁾. The elastic strain which was released by the cutting specimen was measured and inherent strain was used to calculate from the measured strain as an inverse problem. Residual stress can be elastically calculated from the distribution of inherent strain by using the three-dimensional finite-element analysis.

Figure 3 shows the distribution of residual stress through thickness direction shown in (a) and on the surface shown in (b) of the center of the weld metal in a plate butt-welded joint. Tensile longitudinal

(a) Shape and dimensions of specimen

(b) Cross-section and assumed surface crack

Fig. 2 Butt-welded plate joint for evaluation of residual stress redistribution and stress intensity factor due to crack propagation in residual stress field

Fig. 3 Initial residual stress distribution by welding in the thickness direction in a butt-welded plate joint

Fig. 4 Initial residual stress distribution by welding along the weld line center on the surface in a butt-welded plate joint

stress is distributed through the weld metal in the direction of its thickness. Transverse stress is compressive at middle distances from the surface in the same direction and tensile near the surface. Both longitudinal and transverse stresses on the surface are tensile. These calculated distributions were confirmed to be in good agreement with the values measured by the stress relieving method with strain-gauges on the specimen's surface, and the precision of the inherent strain analysis was validated by comparison with the results of the application of other methods of evaluation by one of the authors^{(28),(35),(36)}.

Initial surface crack for the crack growth evaluation was assumed to appear on the first side of the weld to have been deposited, as shown in Fig. 2(b). The redistribution behavior of residual stress by the crack propagation and the stress intensity factor were analyzed by using the finite-element method in an inherent strain field.

A surface crack was assumed to propagate in the direction of thickness on the center of the weld line.

The aspect ratio of the crack, a/c , was set at 1.0 and 0.25 and these values were fixed during crack propagation in the calculation of stress redistribution, as shown in Fig. 2(b). The behavior of the residual stress redistribution due to crack propagation was analyzed as a change of topology by using the inherent strain distribution which corresponds to the initial residual stress field. The stress intensity factor was also calculated by using the assumed crack propagation method⁽²⁷⁾.

The influence function method was also used to analyze stress intensity factors due to propagation of the surface crack under the condition of the aspect ratio being constant throughout the crack's growth by using the initial residual stress distribution obtained from the inherent strain analysis.

4.2 Analysis of redistribution behavior of residual stress and stress intensity factor

History of residual stress redistribution due to crack propagation in a plate welded butt-joint is shown in Figs. 5 and 6 at the aspect ratio $a/c=1.0$. Redistribution of stress in the direction of thickness and on the surface at the weld line's center gradually changes as the crack propagation. The rate of change of the residual stress distribution at the aspect ratio $a/c=0.25$ was lower than at $a/c=1.0$. The size of the surface crack is much narrower than that of the cross-section of weld metal in the specimen. There is thus little relaxation and redistribution of residual stress by topological change, even after the surface crack has been enlarged through crack propagation.

Figures 7 and 8 show the history of the stress intensity factor as the crack at the respective aspect ratios $a/c=1.0$ and 0.25 propagates, both for the directions of crack depth and length. These results are for the inherent strain analysis and the influence function method, and the results are plotted in the same figure. The results of the inherent strain analysis and the influence function method agree well with each other.

It is well known that there are a lot of useful methods and references to do with calculating stress intensity factors of the simple-shaped cracks in the presence of residual stress fields, and both the inherent strain analysis and the influence function method were validated their effectiveness to the calculation of stress intensity factor for an arbitrary crack.

4.3 Verification by testing fatigue crack propagation

The stress intensity factor due to residual stress, for an arbitrary crack shape, can be obtained by either the inherent strain analysis or the influence function method. The accuracy of these analyses of crack propagation in the presence of a residual stress

Fig. 5 Redistribution of residual stress in the thickness direction due to crack propagation in a butt-welded plate joint

Fig. 6 Redistribution of residual stress along the weld line center on the surface due to crack propagation in a butt-welded plate joint

field has been verified by fatigue testing in a plate butt-welded joint.

Fatigue test was performed by using the plate butt-welded joint shown in Fig. 2(a) and crack propagation behavior was measured from the beach-mark tracks. The material was processed by the electric discharge machining, in order to obtain a crack with a semi-elliptical shape and an initial depth and length of $a=5$ mm and $2c=20$ mm. The crack was notched at the side on which the weld metal was first deposited, as is shown in Fig. 2(b). Crack propagation test was done under conditions of a frequency of loading $f=5$ Hz, stress ratio $R=0.1$, and a maximum stress $\sigma_{\max}=118$ MPa.

Crack propagation was analyzed by using the influence function method. The range of the stress intensity factor, ΔK_r , in the residual stress field during fatigue test was calculated with consideration of the maximum and minimum stress intensity factors due to the external loads $K_{\max}$ and $K_{\min}$ on the surface crack and the stress intensity factor due to residual

Fig. 7 Changes in stress intensity factor with crack propagation as calculated by influence function method and inherent strain analysis (aspect ratio $a/c=1.0$)

Fig. 8 Changes in stress intensity factor with crack propagation as calculated by influence function method and inherent strain analysis (aspect ratio $a/c=0.25$)

stress, K_R .

$$\Delta K_r = (K_{\max} + K_R) - (K_{\min} + K_R) \quad (1)$$

Equation (1) shows that the stress intensity factor K_R for residual stress is added to both extremes of the external load. The effects of residual stress at the two extremes offset when the total loading superposed the external load and residual stress is always tensile ($K_R > 0$, $K_{\min} + K_R > 0$), and the range of the stress intensity factor $\Delta K_{r,t}$ in a tensile residual stress field is then expressed by the following equation.

$$\Delta K_{r,t} = K_{\max} - K_{\min} \quad (2)$$

The stress intensity factor for the minimum external load is regarded as $K_{\min} + K_R = 0$ when the sum of the minimum external loading and residual stress is compressive ($K_R < 0$, $K_{\min} + K_R < 0$). The range of the stress intensity factor $\Delta K_{r,c}$ in a compressive residual stress field is as follows.

$$\Delta K_{r,c} = K_{\max} + K_R \quad (3)$$

Fatigue crack growth rate da/dN was obtained by referring to a databook⁽³⁸⁾ for the following equation represented by the Paris law.

Fig. 9 Fracture surface of a butt-welded plate joint specimen

$$da/dN = 3.23 \times 10^{-9} (\Delta K)^{3.3} \quad (4)$$

The unit for the fatigue crack growth rate da/dN is mm/cycle, and the stress intensity factor range ΔK is $\text{MPa} \sqrt{\text{m}}$. The stress ratio R generally affects the characteristics of the fatigue crack's propagation. The stress ratio gradually changes with the crack propagation when residual stress is precisely considered in the evaluation of crack growth. The effect of the stress ratio is regarded as negligible when the stress intensity factor contains within its higher ranges, and the characteristics of the fatigue crack propagation at $R=0.05$ were used in the analysis of the fatigue crack propagation, to provide a conservative evaluation.

The results of the crack propagation analysis and fatigue crack propagation testing under the same conditions were compared. The propagation of the surface crack was analyzed with and without consideration of the residual stress distribution in the welded joint, in order to evaluate the effect of residual stress on the surface crack's propagation.

Figure 9 shows a cross-section through the plate butt-joint specimen after fatigue crack propagation test. The relation between numbers of loading cycles and crack length as estimated from the beach mark was recorded. A specimen without initial residual stress was reported to have a semi-circular trace ($a/c=0.75$) in the cross-section and then penetrated through thickness direction⁽³⁹⁾. A semi-elliptical trace was, in contrast, observed for the as-welded specimen with residual stress. This is because the compressive stress is distributed in the mid-thickness region of the welded joint so that the crack propagation through thickness direction is restricted.

A comparison of the history of fatigue crack propagation in a plate butt-welded joint by experiment and by numerical calculation is shown in Fig. 10. The analytical result for the influence function method agrees very well with the results of experiment, as long as residual stress distribution is considered in the crack propagation analysis. On the other hand, analysis in which the residual stress is not considered has the crack propagating rapidly because

Fig. 10 Comparison of fatigue crack propagation behaviors in a butt-welded plate joint as determined by experiment and by calculation

there is no compressive stress in the middle thickness region of the specimen. It is found that the importance of the consideration of residual stress distribution in evaluating crack propagation in a welded joint has thus been demonstrated.

5. Discussion

Both the influence function method and inherent strain analysis are able to precisely evaluate the changes in the stress intensity factor that are due to crack growth in a residual stress field. Crack propagation analysis should be performed by using the influence function method when an influence functional database has already been constructed for the object under evaluation. The influence function method is efficient and so provides a short calculation time for normal usage. The inherent strain analysis is superior when the configuration of the object to be evaluated or the condition of constraints is complicated. It also calculates the redistribution behavior of residual stress by crack propagation and the time taken in computation for an elastic analysis is not too long, even when a complicated three-dimensional object is evaluated⁽⁴⁰⁾.

The crack faces are sometimes brought into contact by a compressive residual stress. When the effect of crack contact on the stress intensity factor K_r in the residual stress field is not negligible, the stress intensity factor in the residual stress field must be obtained by stress analysis using the inherent strain analysis with consideration of the contact condition⁽¹³⁾. The effect of the crack's opening and closing should be considered in the analysis of crack propagation when crack faces are in contact. The effect of the crack opening and closing on the stress ratio may be negligible in the evaluation described in the previous section, because only the high region of the stress

intensity factor range was examined.

The crack growth rate is considered to be conservative in the previous section, as obtained by using the fatigue crack growth characteristics without applying to the threshold of the stress intensity factor range ΔK_{th} in the Paris law. When evaluation near the threshold of the stress intensity factor range ΔK_{th} is required, it should be considered.

Both the influence function method and the inherent strain analysis can precisely evaluate the changes in the stress intensity factor and in crack propagation behavior that take place in the presence of a residual stress field. It is important and, in fact, essential for the precise analysis of crack propagation to predict the accurate distribution of the initial residual stress in a welded structure.

6. Summary

The redistribution behavior residual stress and the stress intensity factor due to propagation of a surface crack in the presence of a residual stress field caused by welding was examined by using the inherent strain analysis and the influence function method. The behavior of the stress intensity factor was calculated by inherent strain analysis in which the redistribution behavior of residual stress was taken into account. It is also analyzed by the influence function method, and the results of both are in good agreement with each other. Fatigue crack propagation test in a plate butt-welded joint was performed to clarify the validity of the evaluating method. It was found that both the inherent strain analysis and the influence function method are effective in calculating stress intensity factors in the presence of residual stress fields.

References

- (1) Mochizuki, M., Hattori, T. and Nakakado, K., Residual Stress Reduction and Fatigue Strength Improvement by Controlling Welding Pass Sequences, Transactions of the American Society of Mechanical Engineers, Journal of Engineering Materials and Technology, Vol. 122, No. 1 (2000), pp. 108-112.
- (2) Mochizuki, M., Hayashi, M. and Hattori, T., Residual Stress Distribution Depending on Welding Sequence in Multi-Pass Welded Joints with X- Shaped Groove, Transactions of the American Society of Mechanical Engineers, Journal of Pressure Vessel Technology, Vol. 122, No. 1 (2000), pp. 27-32.
- (3) Glinka, G., Effect of Residual Stress on Fatigue Crack Growth in Steel Weldments under Constant and Variable Amplitude Loads, Fracture Mechanics, ASTM STP, Vol. 677 (1979), pp. 198-214.
- (4) Parker, A.P., Stress Intensity Factors, Crack Profiles, and Fatigue Crack Growth Rates in Residual Stress Fields, Residual Stress Effects in Fatigue, ASTM STP, Vol. 776 (1982), pp. 13-31.
- (5) Nelson, D.V., Effects of Residual Stress on Fatigue Crack Propagation, Residual Stress Effects in Fatigue, ASTM STP, Vol. 776 (1982), pp. 172-194.
- (6) Honda, K., Torii, T., Toi, N. and Motoki, K., Effect of Residual Stress Field on Fatigue Crack Growth in Cracked Plates, Journal of the Society of Materials Science, Japan, (in Japanese), Vol. 31, No. 348 (1982), pp. 908-914.
- (7) Kobayashi, H. and Todoroki, A., Effect of Weld-Induced Residual Stress on Fatigue Crack Growth in Compact Specimen, Journal of the Society of Materials Science, Japan, (in Japanese), Vol. 35, No. 391 (1986), pp. 401-406.
- (8) Ohji, K., Kubo, S., Tsuji, M., Ogawa, H. and Sakurada, K., Methods of Predicting Fatigue Crack Growth Lives in Residual Stress Fields, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 53, No. 492, A (1987), pp. 1516-1524.
- (9) Mukai, Y., Murata, M. and Kim, E.J., A Proposal for Stress Intensity Factor Range Calculation Method by Partial Opening Model of Fatigue Crack under Weld Residual Stress Field and Prediction of the Crack Propagation Behavior, Quarterly Journal of the Japan Welding Society, (in Japanese), Vol. 5 (1987), pp. 269-272.
- (10) Jono, M. and Sugeta, A., Effect of Residual Stress on Fatigue Crack Growth Rate and Crack Closure under Varying Loadings, Journal of the Society of Materials Science, Japan, (in Japanese), Vol. 36, No. 409 (1987), pp. 1071-1076.
- (11) Kitsunai, Y., Kobayashi, H., Narumoto, A., Ishizuka, T., Iida, K. and Yoshihisa, E., Effect of Residual Stress on Fatigue Crack Growth Behavior of STS42 Steel Weldments, Journal of the Society of Materials Science, Japan, (in Japanese), Vol. 36, No. 409 (1987), pp. 1077-1083.
- (12) Todoroki, A. and Kobayashi, H., Prediction of Fatigue Crack Growth Rate in Residual Stress Field (Application of Superposition Technique), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 54, No. 497, A (1988), pp. 30-37.
- (13) Todoroki, A., Kobayashi, H. and Nakamura, H., Prediction of Fatigue Crack Growth Rate in Residual Stress Field (Consideration of Partial Crack Surface Contact), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 54, No. 498, A (1988), pp. 205-211.
- (14) Stacey, A. and Webster, G.A., Influence of Residual Stress on Fatigue Crack Growth in Thick-Walled Cylinders, Analytical and Experimental Methods for Residual Stress Effects in Fatigue, ASTM STP, Vol. 1004 (1988), pp. 107-121.
- (15) Torii, T., Honda, K. and Hisakawa, I., Surface Fatigue Crack Propagation Behavior in Residual Stress Fields Distributed along the Thickness of

- Plates (On Fatigue Crack Propagation Rate toward the Depth of Surface Precracks), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 56, No. 524, A (1990), pp. 745-751.
- (16) Beghini, M., Bertini, L. and Vitale, E., Fatigue Crack Growth in Residual Stress Fields, Experimental Results and Modeling, *Fatigue and Fracture Engineering of Materials and Structures*, Vol. 17 (1994), pp. 1433-1444.
 - (17) Toyosada, M. and Niwa, T., Fatigue Crack Propagation Behavior in the Field of Residual Stress Distribution — Study of Fatigue Crack Propagation Behavior based upon RPG Load (7th Report), *Journal of the Society of Naval Architects of Japan*, (in Japanese), Vol. 178 (1995), pp. 505-511.
 - (18) Buchalet, C.B. and Bamford, W.H., Stress Intensity Factor Solutions for Continuous Surface Flaws in Reactor Pressure Vessels, *Mechanics of Crack Growth*, ASTM STP, Vol. 590 (1976), pp. 385-402.
 - (19) Yagawa, G., Ichinomiya, M. and Ando, Y., Theory and Experiment of Thermal Impact Fracture from Crack (Application of Stress Intensity Factor Analysis Based on Discrete Error), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 45, No. 395, A (1979), pp. 734-742.
 - (20) McGowan, J.J. and Raymund, M., Stress Intensity Factor Solutions for Internal Longitudinal Semi-Elliptical Surface Flaws in a Cylinder under Arbitrary Loadings, *Fracture Mechanics*, ASTM STP, Vol. 677 (1979), pp. 365-380.
 - (21) Shiratori, M., Miyoshi, T. and Tanigawa, K., Analysis of Stress Intensity Factors for Surface Cracks Subjected to Arbitrarily Distributed Surface Stresses, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 51, No. 467, A (1985), pp. 1828-1835.
 - (22) Shiratori, M., Miyoshi, T. and Tanigawa, K., Analysis of Stress Intensity Factors for Surface Cracks Subjected to Arbitrarily Distributed Surface Stresses (2nd Report, Analysis and Application of Influence Coefficients for Flat Plates with a Semielliptical Surface Crack), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 52, No. 474, A (1986), pp. 390-398.
 - (23) Shiratori, M., Miyoshi, T., Sakai, Y. and Zhang, G., Analysis of Stress Intensity Factors for Surface Cracks Subjected to Arbitrarily Distributed Surface Stresses (3rd Report, Analysis and Application of Influence Coefficients for Round Bars with a Semielliptical Surface Crack), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 53, No. 488, A (1987), pp. 779-785.
 - (24) Shiratori, M., Miyoshi, T. and Sakai, Y., Analysis of Stress Intensity Factors for Surface Cracks Subjected to Arbitrarily Distributed Surface Stresses (4th Report, Application of Influence Coefficients for the Cracks Originating at the Notches and Welding Joints), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 53, No. 492, A (1987), pp. 1651-1657.
 - (25) Shiratori, M., Yu, Q. and Nishijima, A., Analysis of Stress Intensity Factors for Cracked Members under Displacement Constraint, *Proceedings of the National Meeting of the Japan Society of Mechanical Engineers*, (in Japanese), Vol. 4, No. 930-9 (1993-3), pp. 56-58.
 - (26) Shiratori, M., Yu, Q., Nishijima, A. and Watanabe, K., Analysis of Stress Intensity Factors for Surface Cracks in Thermal Stress Field, *Proceedings of the 6th Computational Mechanics Conference of the Japan Society of Mechanical Engineers*, (in Japanese), No. 930-71 (1993-11), pp. 227-228.
 - (27) Watanabe, T., *Fracture Mechanics — From Theory and Analysis to Engineering Application*, (in Japanese), Yagawa, G. Edited, (1988), pp. 229-254, Baifu-kan.
 - (28) Mochizuki, M., Hayashi, M. and Hattori, T., Numerical Analysis of Welding Residual Stress and Its Verification Using Neutron Diffraction Measurement, *Transactions of the American Society of Mechanical Engineers, Journal of Engineering Materials and Technology*, Vol. 122, No. 1 (2000), pp. 98-103.
 - (29) Okamura, H., *Introduction to Linear Fracture Mechanics* (in Japanese), (1976), pp. 36-43, Baifu-kan.
 - (30) Mukai, Y., Nishimura, A. and Kim, E.J., Redistribution of Residual Stress Caused by Crack Propagation Initially through Residual Tensile Stress Field, *Quarterly Journal of the Japan Welding Society*, (in Japanese), Vol. 4 (1986), pp. 154-159.
 - (31) Mukai, Y., Nishimura, A. and Kim, E.J., Redistribution of Residual Stress Caused by Crack Propagation Initially through Residual Compressive Stress Field, *Quarterly Journal of the Japan Welding Society*, (in Japanese), Vol. 4 (1986), pp. 634-639.
 - (32) Honda, K., Torii, T. and Fei, Z., Analysis and Measurements of Residual-Stress Redistribution due to Material Removal in a Plate, *Journal of the Society of Materials Science, Japan* (in Japanese), Vol. 37, No. 415 (1988), pp. 391-397.
 - (33) Honda, K., Torii, T. and Fei, Z., Residual-Stress Redistribution and Deformation due to Material Removal during the Formation of a Full-Depth Hole in a Plate, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 55, No. 512, A (1989), pp. 879-886.
 - (34) Sato, T., Kobayashi, H. and Arai, Y., Finite Element Analysis of Residual Stresses of Ceramics/Metal Joints (Effect of Cutting on Redistribution of Residual Stresses), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 57, No. 540, A (1991), pp. 1801-1807.
 - (35) Mochizuki, M., Hayashi, M. and Hattori, T., Residual Stress Analysis by Simplified Inherent Strain at Welded Pipe Junctures in a Pressure Vessel, *Transactions of the American Society of*

- Mechanical Engineers, Journal of Pressure Vessel Technology, Vol. 121, No. 4 (1999), pp. 353-357.
- (36) Mochizuki, M., Hayashi, M. and Hattori, T., Comparison of Five Evaluation Methods of Residual Stress in a Welded Pipe Joint, JSME Int. J., Ser. A, Vol. 42, No. 1 (1999), pp. 104-110.
- (37) Miyazaki, K., Enomoto, K., Hayashi, M. and Kanno, S., Evaluation of Surface Fatigue Crack Growth Using Stress Intensity Factor with a Plastic Zone Correction, Proceedings of the 72nd Spring Annual Meeting of the Japan Society of Mechanical Engineers, (in Japanese), Vol. 2, No. 95-1 (1995-3), pp. 344-345.
- (38) The Society of Materials Science, Japan, Edited, Databook of Fatigue Crack Growth Rates of Metallic Materials, The Society of Materials Science, Japan, Vol. 1 (1983), pp. 22-23.
- (39) Iida, K. and Kho, Y., Empirical Expressions of Surface Fatigue Crack Shape, Journal of the Society of Naval Architects of Japan, (in Japanese), Vol. 147 (1980), pp. 211-218.
- (40) Mochizuki, M., Hayashi, M., Nakagawa, M., Tada, N. and Shimizu, S., A Simplified Analysis of Residual Stress at Welded Joints between Plate and Penetrating Pipe, JSME Int. J., Ser. A, Vol. 40, No. 1 (1997), pp. 8-14.
-