1972-1973 Literature Survey on Welding Stresses and Strains in Japan†

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Abstract

At the 1972 Tronto Assembly of the International Institute of Welding, the working group on "Transient Thermal Stresses and Restraint Evaluation" was organized in Commission X. The group is to present review reports on the concerning subject at the annual assembly of 1973. In connection with this, the present report (IIW Doc. X-699-73) descibes research activities in Japan during 1972 to 1973. The Japanesese literatures which had been published before the Tronto Assembly were summerized in the report entitles "Recent Trend of Researches on Restraint Stresses and Strains for Weld Cracking".

1. Introduction

The working group on "Transient Thermal Stresses and Restraint Evaluation" in Commission X of IIW, which was organized at the 1972 Tronto Assembly, is now undertaking to prepare review reports on the concerning subject. The Japanese literatures which had been published before the Tronto Assembly were summarized in the report entitled "Resent Trend of Researches on 'Restraint Stresses and Strains for Weld Cracking"[1]. The present report describes research activities conducted in Japan during 1972-1973.

In relation to the subject on welding stresses and restraint, there are two study groups in Japan, one of which is the Sub-commission II of the Welding Research Committee in the Society of Naval Architects of Japan and other is the sub-commission of the Welded Structure Research Committee of the Japan Welding Society. The two study groups have joint meetings every two months. At the meeting, the results of individual researches done by the members of the groups are reported and discussed. Usually the results of investigation are published on the relating journals. Accordingly, this report includs the published papers and the documents discussed in the study groups in this period.

A main feature of the research activities in the past one year is that the application of the finite element method has been increased, since the method of thermal elastic-plastic analysis based on the FEM was presented[2]. Consequently, information is now accumulated on not only stresses and deformation of a plate under a moving heat source but also local stresses and strains in the weld metal and its vicinity. Both kinds of information is necessary for studying weld cracking.

2. Transient Stresses and Deformation under a Moving Heat Source

Transient thermal elastic-plastic analysis have been performed so far for a bead-on plate or a plate subjected to a moving heat source along a line, based on the finite element method[1]. In butt weld, however, the molten metal is continuously put into a groove between two plates, and the behavior, in this case, is somewhat different from a bead-on plate. To this ploblem, transient stresses and deformation are separately studied both theoretically and experimentally. For the theoretical thermo-elastoplastic analysis, the finite element method is used[3, 4]. These studies indicate that the FEM analysis predicts the behavior with a reasonable accuracy. A similar analysis is made on the Tekken-type specimen, which will be discussed in Chapter 5.

In relation to end cracking of automatic one-side weld seam, one of important factors is transverse displacement in the weld metal during solidification, where is at a certain distance apart from the end of the plate. A sudy on the ploblem is in progress[5].

3. Transient Stress and Deformation in Multi-pass Weld

There have been in lack of information on the behavior of multi-pass weld due to the existence of difficulties in both theoretical analysis and experiment.

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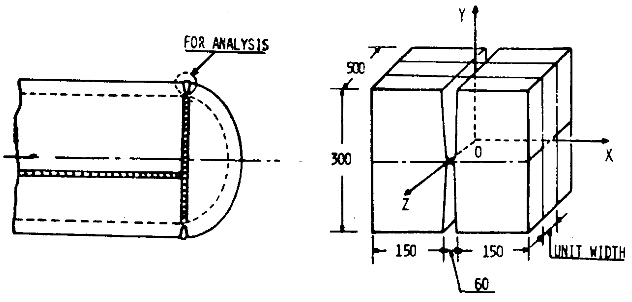
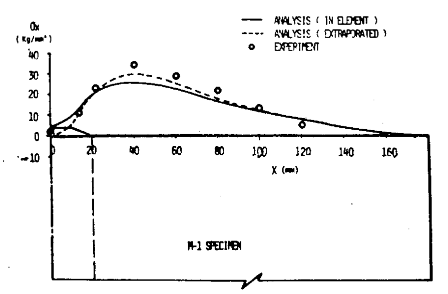
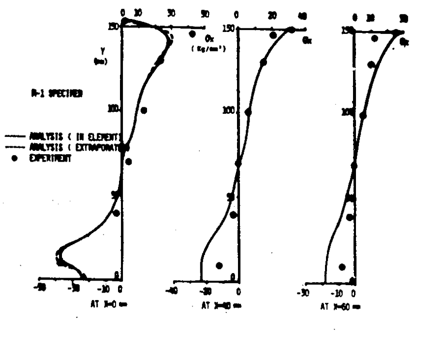
The finite element method is most powerful tool to this kind of ploblem. By this method, the analysis was performed on transient stresses and strains in multi-pass weld (167 passes) during welding and the resulting residual stresses showed very good coincident with the experimental ones[6] (**Fig. 1**). This fact supports the validity of the finite element analysis even on such complicated problem and the information is reliable and useful on the thermoelastoplastic behavior of the weld exhibited during welding. High stress level in tension is always produced slightly below the upper exposed surface of the weld metal just before the following pass is to be laid and this distribution is also seen in the final residual stresses. In contrast with this, the surface of the bead is subjected to compressive or small tensile stress and on the upper surface of the plate, the high tensile stress is reached not at the toe of the weld but 20—30 mm apart from the toe.



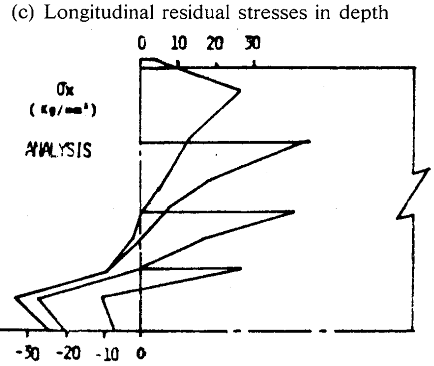
(a) Model for study



(b) Longitudinal residual stresses on the surface



(c) Longitudinal residual stresses in depth

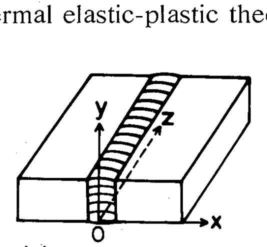


(d) Longitudinal transient stresses in mid-section

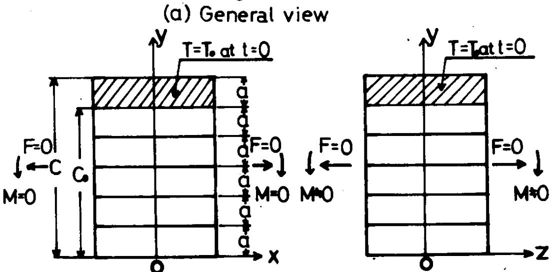
Fig. 1. Residual and transient stresses in multi-pass welding.

To a similar problem, one dimensional analysis[7] was performed on transient stresses and strains of a model (**Fig. 2**). As seen from the results (**Fig. 3**), the distributions of transverse residual stresses are similar to those in the above research. In this example, angular distortion by restraint stresses is allowed and then tensile residual stresses and plastic strains on the lower surface increases as the number of pass increases. In the same way, longitudinal residual stresses and plastic strains were analysed under the assumption that angular distortion is restrained along the weld line. In the study, the effect of welding conditions on residual stress and plastic strain are also discussed.

As an example of multi-thermal cycles, bending deformation of a plate in plane is studied theoretically and experimentally for such a case where the plate is subjected to edge preparation by gas cutting[8]. Theoretical analysis is performed based on one dimensional thermal elastic-plastic theory[9].

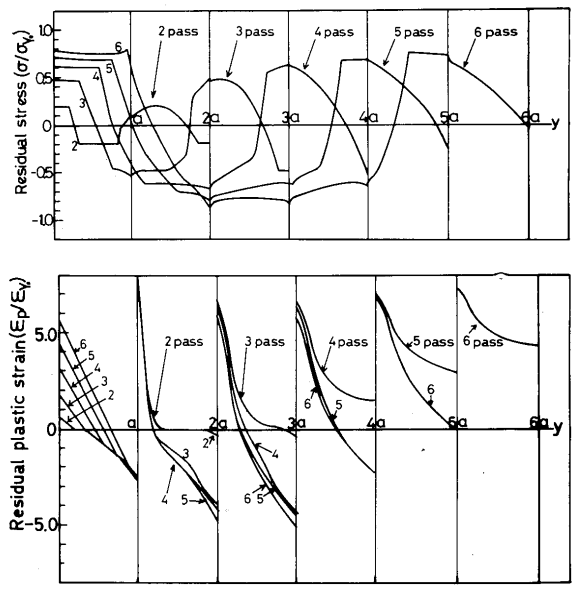


(a) General view

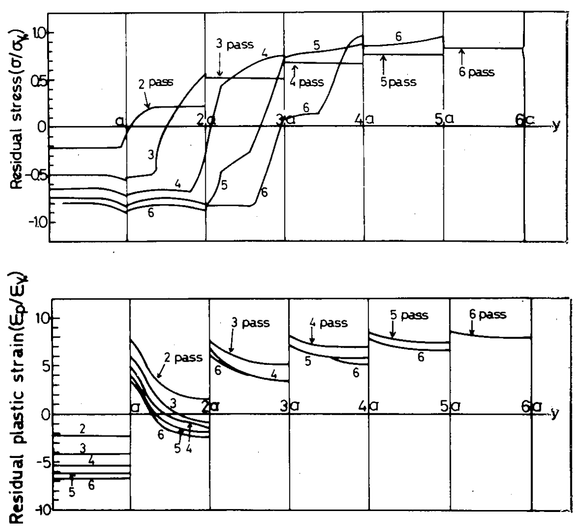


(b) Transverse model (c) Longitudinal model

Fig. 2. Two kinds of model corresponded to the behavior of the transverse and longitudinal direction of multi-pass weld joint.



(a) Transverse section

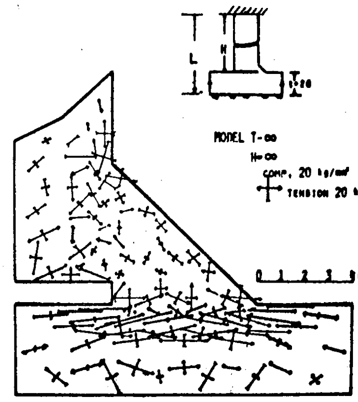


(b) Longitudinal section

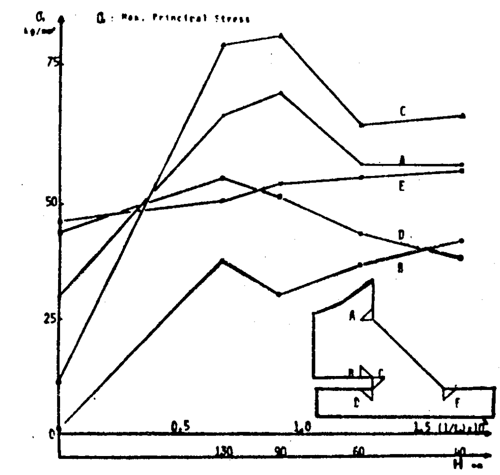
Fig. 3. Residual stress and plastic strain distributions in multi-pass welding.

4. Local Stresses and Strains in Weld

There are two basic types of joints, which are butt and fillet. The behavior of butt joint during welding has been analysed by the FEM and the result was included in the previous report[1]. The thermal elastic-plastic analysis was also applied to fillet weld[10]. In the analysis, the fillet weld was restrained in various ways. In the joint free from any restraint (**Fig. 4 (a)** Model T-F), high stresses were subjected at the root and toe of the weld of the flange. The higher degree of restraint to the vertical movement of the web is imposed, the higher stresses are induced at the root and toe of weld of the web (**Fig. 4 (b)**). In the case where the horizontal movement of the web is constrained (**Fig. 4 (c)**), the toe of the flange and the



(a) Residual principal stress distribution (free from external restraint)



(b) Residual max. principal stress against vertical restraint length, L(=H−t)

Fig. 4. Residual stresses in fillet weld.

root of the web are subjected to very high tensile stresses. In parallel to this, the experimental study was carried out on cold cracking of fillet weld, using newly proposed specimens[11]. The result is sumarized at the relation of the percentage of heel crack and root crack to the intensity of restraint of the web (**Fig. 5**). The higher intensity of restraint is given, the higher percentage of root crack and the lower percentage of heel crack are observed. The result indicates that there is the critical intensity of restraint

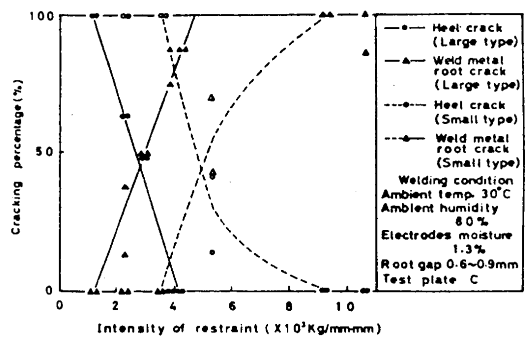


Fig. 5. Relation between cracking percentage and intensity of restraint.

for each type of cracks. In connection with this, a simplified elastic stress analysis was made on residual stresses under the assumption that the shrinkage of the portion above 600℃ to 0℃ is dislocation[11]. This method gives reasonable stress distribution for cases of high degree of restraint, in comparison with the result obtained by the preceeding elaborated method.[10] In one-dimensional members, the intensity of restraint is regarded as a useful parameter to indicate the mechanical condition on weld crack. In addition, the shape of groove has an influence upon the condition of weld cracking. There is a research on this subject.[12] Elastic-plastic analysis by the FEM is carried out on the RRC specimens with different shapes of groove. The result shows that local stress is higher in order of bevel-, K-, oblique y-, Y-, and X-groove for the same intensity of restraint under a certain amount of shrinkage (**Fig. 6**).

Tests on the Tekken-type specimens of high tensile steels with different shapes of groove indicate that higher preheating temperature is required for preventing weld crack on the specimens with bevel- and K- groove which are induced higher local stresses under the same intensity of restraint (**Fig. 7**). The preheating temperature required for preventing weld crack is changed in wide range by the shape of groove.

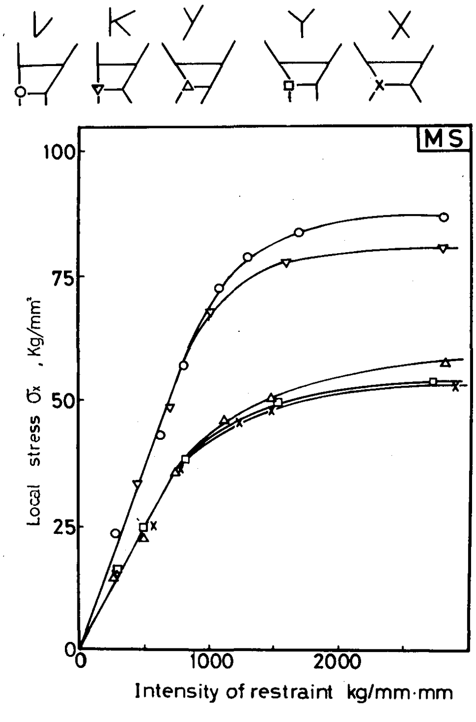
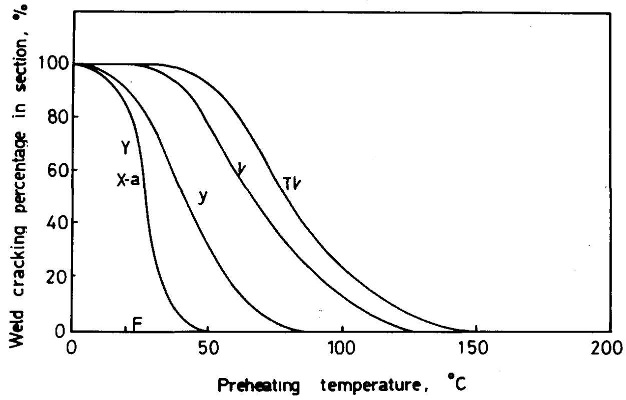
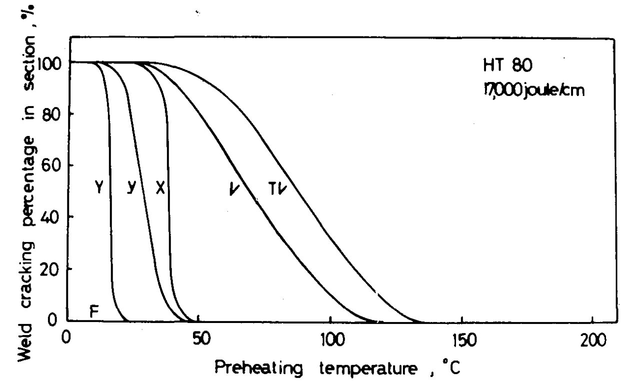


Fig. 6. Effect of groove shape and intensity of restraint of weld joint on local stress at root in weld.



(a) SM58-steel (plate thickness 33mm)



(b) HT80-steel (plate thickness 30mm)

Fig. 7. Effect of groove shape on critical preheating temperature required for preventing weld crack in Tekken type tests.

5. Evaluation of Restraint Intensity

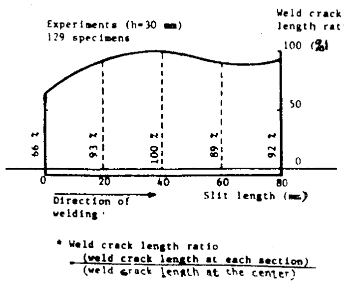
The Tekken weld cracking test is widely used in Japan for assessment of weld crack sensitivity of steels. The intensity of restraint of the specimen is evaluated both theoretically and experimentally, applying the fundamentally same difinition as for one dimensional member. For the specimen, it is common trend that the intensity of restraint is the highest at the ends and the lowest at the center of the slit. In contrast with this tendency, many experimental results indicate that the crack length in cross-section is rather longer in the middle portion and shorter near the ends of slit. There is an investigation[13] into this point. Applying the finite element method, the thermal elastoplastic analysis was performed on the behavior of the specimen of mild steel, simulating the welding condition as precise as possible, such that the groove is open before the deposit metal is laid. According to the result, the residual stresses are tensile and high over the slit length (near the tensile strength) and the plastic strains of the weld metal subjected during welding are 4～5% in the central portion and vanish in the vicinity of the slit ends. (**Fig. 8**) This is due to the thermal deformation which results in larger displacement in the middle. The plastic strain distribution is similar to that of crack length. It is worth paying an attension to not only residual stresses but also plastic strains in connection to weld cracking. For the same specimen, the intensity of restraint of the slit weld was evaluated by the following three ways with the aid of the finite element method:

Relation between the displacement and the reaction stress by

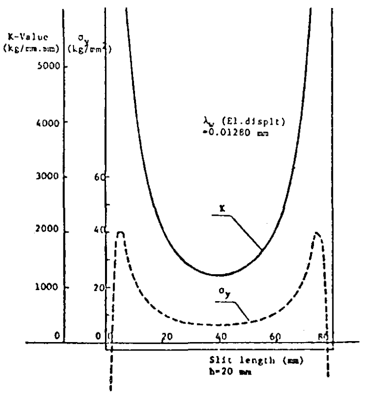
(1) Elastic analysis applying a uniform displacement along the slit length.
(2) Relation between the displacement and the reaction stress by elastic-plastic analysis imposing a uniform displacement along the slit the total reaction force reaches the same amount as the residual stress.
(3) Relation between the residual stress along the slit in the welded specimen and the free displacement there produced by saw cut along the slit, releasing the residual stress.

The distributions of the intensity of restraint evaluated by the above three types of difinition are similar in such way that it is low in the middle and increase rapidly to the slit ends. Therefore, any distribution does not explain directly the tendency in the crack length of the specimen. The fact may require some modification of difinition of the intensity of restraint for the slit weld which would be used as a direct parameter cold cracking.

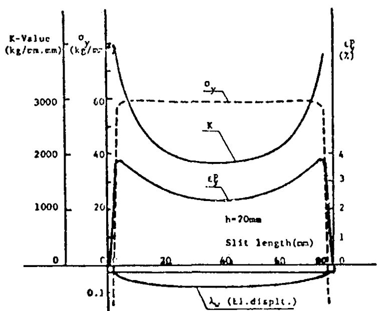
Although there are many points to discuss for the direct application of the intensity of restraint to weld cracking, the average value is still expected to furnish important information of the mechanical condition weld cracking in the slit weld. In relation to this, there is an investigation[14] into the relation between the intensity of restraint and weld crack, using H-type restraint specimen of large size. About the restraint coefficient of the H-type specimen, good coincidence is found between the experiment and the FEM analysis. (**Fig. 9**) It could be apploximately estimated



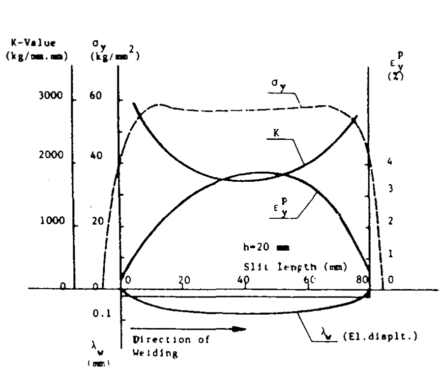
(a) Weld crack length ratio in Tekken-type specimens



(b) Elastic analysis under a uniform displacement along the slit



(c) Elastic-plastic analysis under a uniform displacement



(d) Thermal elastic-plastic analysis under moving welding heat source

Fig. 8. Mechanical characteristics of Tekken-type specimen.

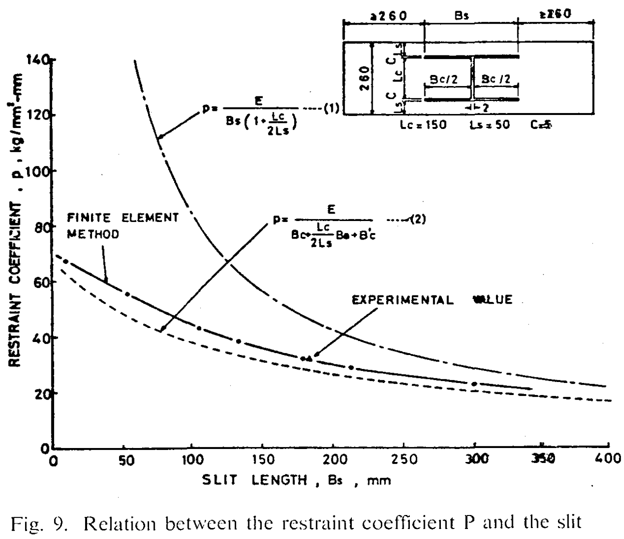


Fig. 9. Relation between the restraint coefficient P and the slit length B_S of H-type restraint specimen.

$$p = \frac{E}{B_c + \frac{L_c}{2L_s} B_s + B_c'}$$

where

$$B_c' = \frac{4L_c}{\pi^3}(\xi+\zeta)^2 \left[\frac{\xi+\zeta}{\xi^2 \zeta} \sum_{m=1}^{\infty} \frac{1}{m^3} \sin^2 \frac{m\pi\zeta}{\xi+\zeta} + \sum_{m=1}^{\infty} \frac{1}{m^3} \sin^2 \frac{m\pi}{\xi+\zeta} + \frac{1}{\xi} \sum_{m=1}^{\infty} \frac{1}{m^3} \sin \frac{m\pi}{\zeta+\xi} \cdot \sin \frac{m\pi\zeta}{\xi+\zeta} \right]$$

$$\xi = \frac{2L_s}{L_c}, \quad \zeta = \frac{L_c+2C}{L_c}$$

by the following equation which was obtained previously from elastic analysis.

It is also suggested from the test results of restraint stress distribution that the weld length L_c should be longer than 150 mm so that the stress is uniform in the midle portion of the slit length (**Fig. 10**).

In butt-welding of heavy plates, the location of the first pass weld in the cross-section of groove is not always at the neutral axis of the plates according to the groove design selected. When the first pass weld is located apart from the neutral axis, the eccentricity induces bending deformation which will influence the local stress in weld metal in connection with the intensity of restraint. Researches have been made to this problem[15), 16)], and the restraint intensity for bending is newly introduced in addition to the restraint intensity under the definition made so far. Calculations[15)] show that the local stress is changed by the factors such as both restraint intensity and the amount of eccentricity (**Fig. 11**). In relation to the fact, it is found from the Tekken-type weld cracking tests[15)] that the preheating temperature required for preventing weld crack varies in a wide range depending upon the location of weld (**Fig. 12**).

In addition to the researches mentioned avobe, evaluation of the restraint intensity has also been made in these twelve months for real structures such as pressure vessel[17)] bulding frame[18)] and turbine casing[19)]. Each of the results is used determining

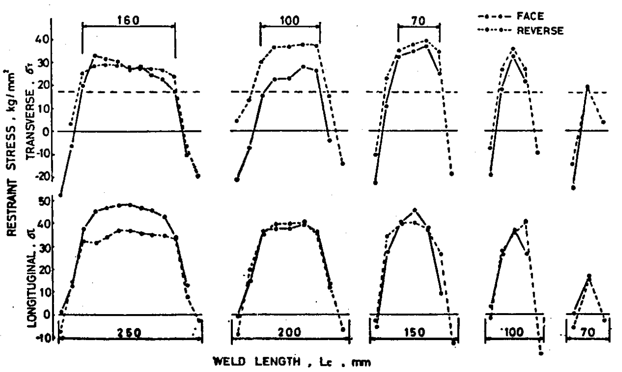


Fig. 10. Measured distribution of restraint stress for various weld length.

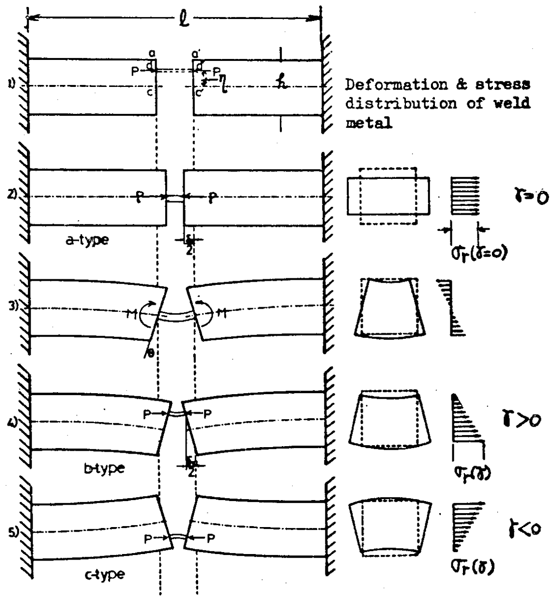


Fig. 11 (a). Illustration of stress and deformation of weld by eccentricity of weld in the direction of plate thickness.

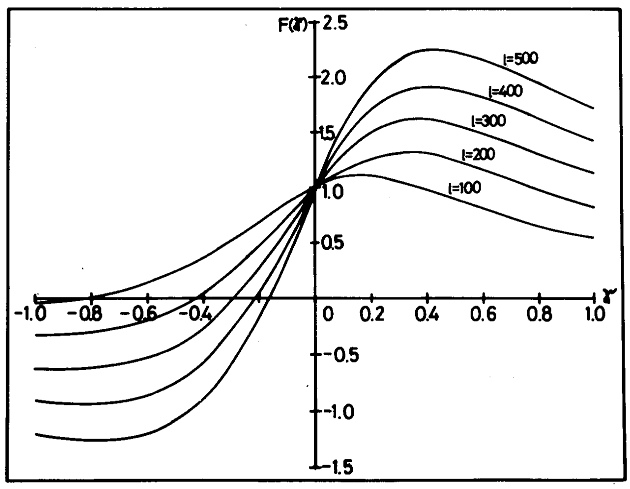


Fig. 11 (b). Effect of eccentricity of weld on ratio of local stress at root of weld, $F(\gamma) = \sigma_r(\gamma)/\sigma_r(\gamma=0)$, γ: Eccentricity of weld $\gamma = 2\eta/h$.

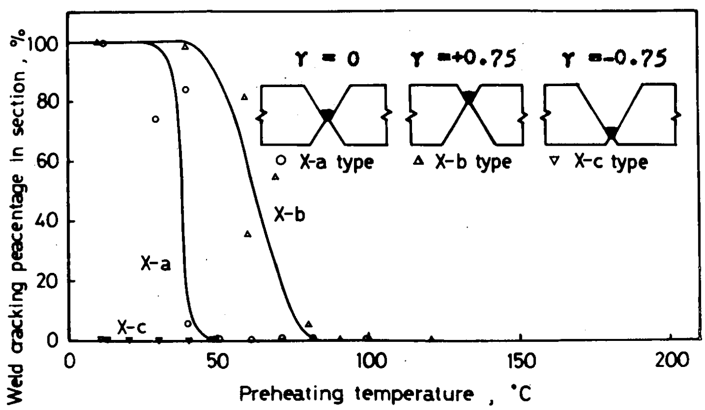


Fig. 12. Effect of eccentricity of weld on critical preheating temperature required for preventing weld crack in Tekken type specimens, (HT80steel, Q=17000 J/cm, plate thickness 30 mm).

welding procedures required for preventing weld crack in construction of real structures.

References

1) Satoh, K., Ueda. Y. and Kihara, H., " Recent Trend of Researches on Restraint Stresses and Strains for Weld Cracking" IIW Doc. IX-788-72, X-659-72 Trans. of JWRI, Vol. 1, No. 1 (1972) (Welding Research Institute of Osaka University, Japan).

2) Ueda, Y., and Yamakawa, T., "Analysis of Thermal Erastic-plastic Stress and Strain during Welding" IIW Doc. X-616-71, Trans. of J.W.S Vol. 2, No. 2 (1971).

3) Fujita, Y., Takeshi, K., Kitamura, M. and Nomoto, T., "Welding Stresses with Special Reference to Cracking" IIW Doc. X-655-72 (1972).

4) Masubuchi, K., Andrews, B. and Urushihara, A., " Finite Element Analysis of Thermoelastoplastic Deformations in Butt Welding" IIW Doc. X-692-73 (1973).

5) Satoh, K., Ueda, Y., Maeda, T., and Kamichika, K., " Study of Preventation of End Cracking in One-side Automatic Welding" Doc. W2-3-73, WD-3-73 Feb. (1973) (in Japanese).

6) Ueda, Y., Takahashi, E., Fukuda, K. and Nakacho, K., "Transient and Residual Stresses in Multi-Layer Weld" IIW Doc. X-698-73 (1973)

7) Satoh, K., Seo, K., Iwai, K., and Takahashi, T., "Thermal Elasto-plastic Analysis on Stress and Strain in Weld Metal during Multi-pass Welding" IIW Doc. X-706-73 (1973).

8) Tsuji, I. and Yamaguchi, K., "Interaction of Thermal Cycles on Longitudinal Bending Deformation of a Strip" Doc. WD-7-73, W2-7-73, April (1973) (in Japanese).

9) Tsuji, I., "Studies on Elastoplastic Thermal Stresses in Rectangular Plates with Uniaxial Temperature Variation" Jl. of Society of Naval Architects of Japan, Vol. 116 (1964). 78-89 (in Japanese).

10) Ueda, Y. Fukuda, K. and Nakcho, K. "Thermal Stresses and Strains in Fillet Weld with Various Restraint" Preprint of Annual Meeting of the Japan Welding Society. Vol. 12 (1973), p-118-119, (in Japanese).

11) Tsuboi, J. and Nishima, S., "Studies of Cold Cracking in Fillet Welds" Preprint of Annual Meeting of the Japan Welding Society, Vol. 12 (1973), p. 128-131 (in Japanese).

12) Satoh, K. Matsui, S., Hasegawa, T., Ono, T., Hozumi, S and Tamaoki, M., "Effect of Groove Shape of Weld on Weld Cracking" Doc. WD-9-73, April (1973) (in Japanese).

13) Ueda, Y., Fukuda, K. and Low. J. K. "Study on the Mechanical Characteristics of the Tekken-type Specimen" Preprint of Annual Meeting of the Japan Welding Society, Vol. 11 (1972) p. 382-383 (in Japanese).

14) Akashi, S. and Natsume, M. " Study Weld Cracking under Various Restraint Conditions" Jl. of the Japan Welding Society, Vol. 41 (1972) No. 6 p. 675-686 (in Japanese).

15) Satoh, K., Matsui, S., Ito, Y. and Hasegawa, T. "Effect of Eccentricity of Weld in the direction of Plate Thickness on Local Stress and Weld Cracking" Preprint of Annual Meeting of the Japan Welding Society, Vol. 11 (1972) p. 348-349, Doc. WD-9-73, W2-9-73 (1973), (in Japanese).

16) Akashi, S. and Natsume, M. "Study on Restraint Intensity for Bending of Weld Joint" Doc. WD-6-72 (1972), (in Japanese).

17) Kuriyama, R., Kohno, T., Yamazaki, Y. and Murayama, T. "Intensity of Restraint of Weld Joints in Pressure Vessel" Preprint of Annual Meeting of the Japan Welding Society, Vol. 10 (1972) p. 89-90 (in Japanese).

18) Matsumoto, M., Iezawa, T. and Inagaki, M. "Intensity of Restraint of Weld Joints in Building Frame" Preprint of Annual Meeting of the Japan Welding Society, Vol. 11 (1972) p. 350-351, (in Japanese).

19) Sasaki, H., Watanabe, K., Kirihara, S., Sejima, I. and Rokutani, T. "Effects of Restraint Intensity on Delayed Cracks in the Welds of High-Strength Steel" IIW Doc. IX- -73, X-700-73 (1973).

** Doc.-W2 and WD: Document to the Subcommission II of the Welding Research Committee in the Society of Naval Architects of Japan and to Subcommission of the Welded Structure Research Committee of the Japan Welding Society.