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Mechanism of Production of Residual Stress due to Slit Weld†

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Abstract

In actual structures, slit weld connections are used frequently. In this case, large portion of weld cracks is detected in the first weld. In order to avoid weld cracks, it is important to investigate the mechanical behavior of slit type connection. It has been reported that the conventional concept of restraint intensity cannot predict the resulting residual stress due to slit weld on small size of specimen.

A series of thermal elastic-plastic analysis was performed on plates different in size and slit length. It may be concluded that there are three kinds of deformation which cause thermal stress; (1) the shrinkage of the weld metal, (2) locally confined thermal deformation of the base plate, and (3) over-all deformation of the base plate. In case of short slit, the over-all deformation is the main cause of thermal stress. In case of long slit, this does not play an important role and then the conventional concept of restraint intensity is applicable to estimate the residual stress.

1. Introduction

When structures are constructed by welding, they contain, consequently, residual stress and deformation. These may cause weld cracks and influence performance of the structures. In order to avoid weld cracks, it is always necessary to estimate mechanical behavior of welded joints, especially, thermal stress by welding. When connection is simple such as of one dimensional members or of members in one dimensional stress state, the magnitude of residual stress can be fairly accurately estimated by the concept of restraint intensity.[1] However, actual structures contain many types of weld joint in which slit weld joints are used frequently. In the case of slit weld, large portion of weld crack is detected in the first weld. Consequently, study on the mechanical behavior of the slit weld at the first weld is important. In connection with this point, the authors had reported that welding residual stresses in a short slit weld do not follow the conventional concept of restraint intensity, which is usually applied to one dimensional members.[2] In this paper, an investigation is carried out into the mechanism of production of thermal stress and deformation, and applicability of the concept of restraint intensity for slit welds, based on the thermal elastic-plastic analysis by the finite element method.[3), 4)]

2. Theoretical Analysis by Finite Element Method

2.1 Specimens including a slit joint for analysis

Usually, a slit weld is completed by an electrode moving from one end of the slit to the other, and filling up weld metal in the groove. The prototype of specimens used in the analysis is shown in **Fig. 1.** The cross section of the slit is idealized so that the analysis is reduced to two dimensional stress, neglecting effect of the type of groove on local stresses. If necessary, the effect is taken into account approximately by introducing the stress concentration factor. Thicknesses of the base plate and the weld metal of each specimen are 20 mm and 5 mm respectively, while varying the length, breadth, and slit length. The notations and dimentions of the specimens are shown in **Table 1.** The base metal of the specimens is mild

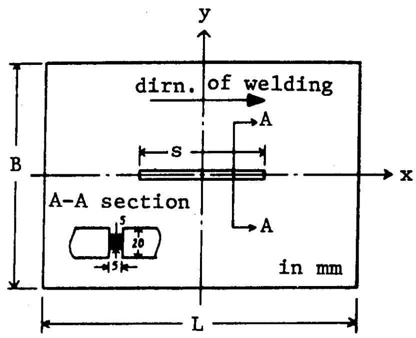

Fig. 1. Slit weld specimen

Table 1. Dimensions of specimens.

NAME OF SPECIMEN	LENGTH L(mm)	WIDTH B(mm)	SLIT LENGTH s(mm)
1X1Y	200	150	80
1X2Y	200	300	80
2X1Y	400	150	160
2X2Y	400	300	160
INF80	2000	1500	80
INF400	2000	1500	400
INF800	2000	1500	800

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steel and the corresponding electrodes is furnished for welding.

In this study, the first weld is performed by manual arc welding. The condition of welding is as follows; welding heat input=3000 cal/cm, and welding velocity =15 cm/min.

2.2 Theoretical analysis

The method of analysis used in this paper is the "thermal elastic-plastic analysis" developed by one of the present authors.[3), 4)] The analysis can be divided into two separate parts; heat-conduction analysis and stress analysis from temperature distributions calculated in the preceding heat conduction analysis. For both analyses, the dependency of physical and mechanical properties of both base and weld metals on temperature is taken into consideration, as shown in **Figs. 2** and **3.** These properties are quoted from those obtained previously.[2)]

2.2.A Heat conduction analysis

For the heat conduction analysis, the finite difference method is applied, dividing each specimen into small triangular meshes. These meshes are also used for the following stress analysis by the finite element method. The condition of welding is realized in the analysis by assuming that weld metal is deposited into a small finite length of the slit successively. This is regarded as "moving heat source".

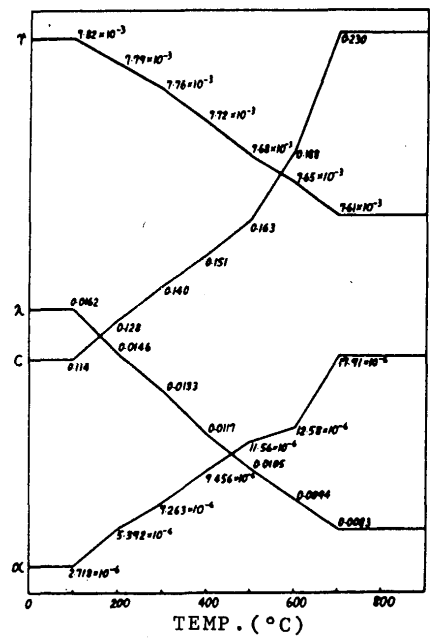
2.2.B Thermal elastic-plastic analysis

With the whole history of transient temperature distributions, the stress analysis is performed by the method of thermal elastic-plastic analysis. In actual welding, the weld metal is deposited into the slit continuously. The portion of slit where the weld metal not yet supplied possesses no stiffness, and its boundary with the base plate is still mechanically "free". This is taken into consideration in the analysis, since welding sequence influences the distribution of thermal stresses.

2.3 Results of Analysis

2.3.A Results of heat conduction analysis

The results of heat conduction analysis for specimens 1X1Y, INF400 and INF800 are shown in **Fig. 4.** They are transient isothermal contours at the instant when their peak temperature have dropped to 700 °C after the welding is finished. From the results, it can be seen that the isothermal contours of specimens 1X1Y, 1X2Y and INF80, containing a short slit, are "short ellipses", approximately circles; on the other hand, those of specimen INF800, containing a long slit, are "long ellipses". These long ellipses excluding both ends, are nearly strainght lines parallel to the slit. Summarizing the results in **Fig. 5,** the isothermal contours of 100°C are represented in non-dimensional scale, normalized by their slit lengths. It is a general



γ: specific weight
λ: heat conductivity (cal/mm/°C/sec)
c: specific heat (cal/g/°C)
α: heat transfer coef. (cal/mm^2/°C)

Fig. 2. Dependency of physical properties on temperature.

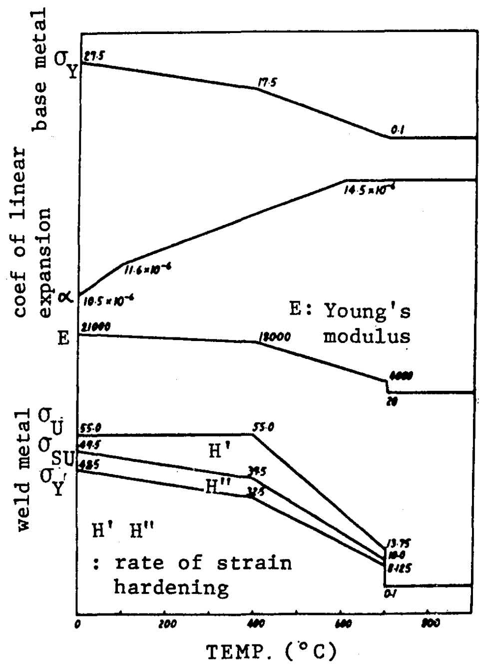


Fig. 3. Dependency of mechanical properties on tempe ·ture.

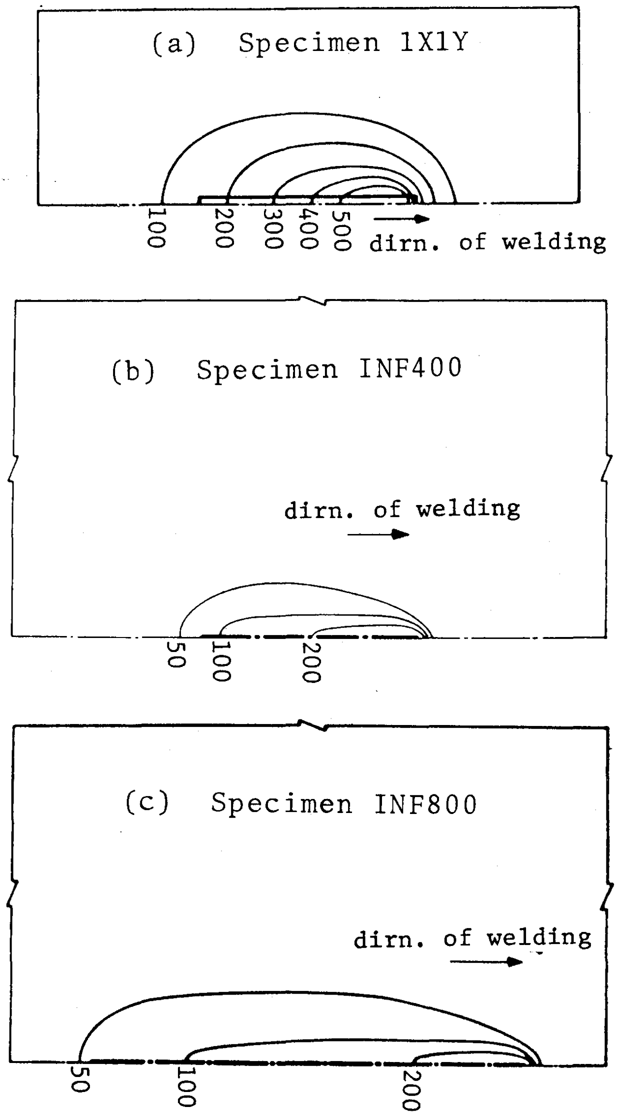


Fig. 4. Isothermal contours when the maximum temperature has dropped to 700°C.

trend that isothermal contours are close to circles for a short slit and changing to ellipses when the slit becomes longer; and for a much longer slit, the ellipses are approximately straight lines parallel to the slit, except the vicinity of both ends.

2.3.B Results of stress analysis

According to results of the stress analysis, the distributions of residual stresses are influenced by the slit length, the size of the specimen etc. Paying a particular attention to this point, the results of the stress analysis will be presented in the following.

(1) Specimen 1X1Y

In the first place, specimen 1X1Y is analysed whose size is the same as the Tekken weld cracking test specimen. Residual transverse stresses, σ_y, and plastic strains, ε_y^p, along the slit are illustrated by the solid lines in **Fig. 6** and the residual longitudinal stresses, σ_x, are in **Fig. 7.** Regarding the residual transverse stress, any remarkable variation is not observed even in the vicinity of the slit ends. In contrast

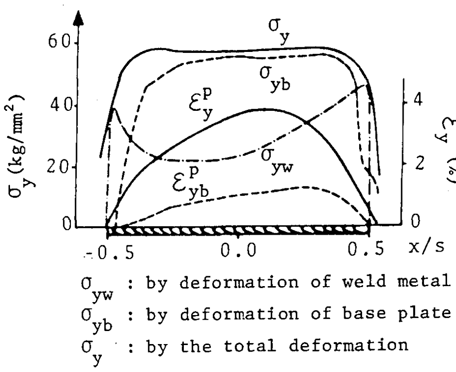


Fig. 6. Transverse stresses and plastic strain along the slit (specimen 1X1Y).

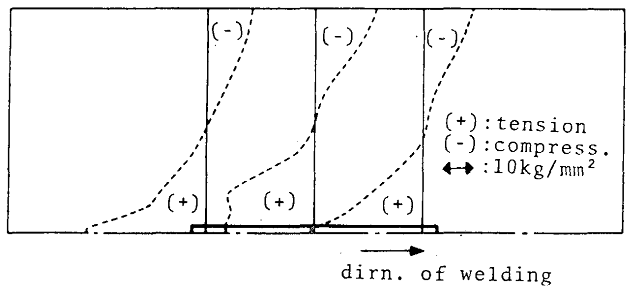


Fig. 7. Residual longitudinal stress distribution (specimen 1X1Y).

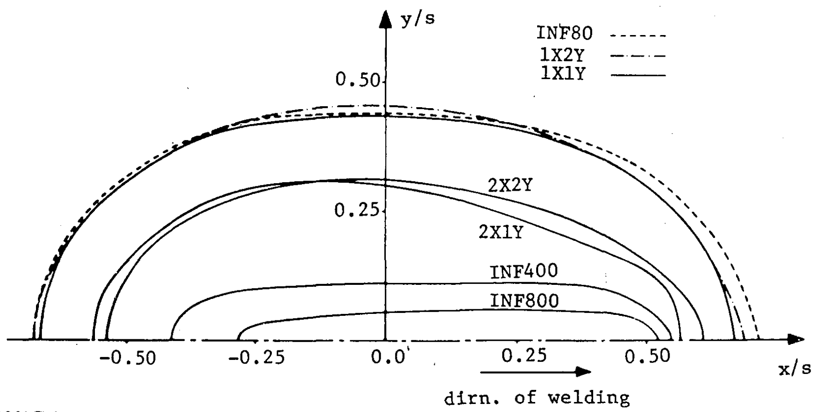


Fig. 5. 100°C isothermal contours of each specimen when their max. temperature have dropped to 700°C.

with this, the transverse plastic strain is high in the central portion of the slit and decreases to zero toward both ends. These tendencies are somewhat different from those estimated by the conventional concept of restraint intensity. On the other hand, the residual longitudinal stress distribution indicates that the base plate is subjected to bending as a beam. In order to study the mechanism of production of these stresses, the following detailed information will be supplied with the aid of the stress analysis.

Fig. 8 shows the transient deformations of line BB′ of specimen 1X1Y. It is seen from the figure that line BB′ tends to move towards the slit in the course of welding; and tends to return back to its original position at the cooling stage of the specimen. Displacement of line BB′ differs at the location of a point under consideration. On the other hand, the weld metal starts to shrink immediately after it has been laid. The magnitude of free shrinkage is almost constant along the slit. Residual stresses are produced by a combination of these deformations, and their effects on the stress distribution are different. Although it is impossible to separate these effects in experiment, it can be realized in the theoretical analysis used here in the following way.

For this purpose, the stress analysis is carried out on the same temperature distributions obtained previously, assuming that the weld metal does not expand nor shrink, though still possesses its original mechanical properties. The resulting residual transverse stress, σ_{yb}, and plastic strain, ε^p_{yb}, along the slit are shown by the dotted lines in Fig. 6. The transverse stresses at the central part of the slit are higher than those in the vicinity of the ends.

The same stress analysis is performed in a similar way, but with an assumption that the base metal does not expand nor shrink, though has the original mechanical properties. Residual transverse stress, σ_{yw}, along the slit is indicated by the chain line in the same figure. In this case, the transverse stresses are high near the slit ends, whereas those at the middle portion are low; and their average magnitude is much lower than those produced by the deformation of the base plate.

(2) Specimens 1X2Y, 2X1Y, 2X2Y

Residual transverse stresses and plastic strains of the specimens of XY series (1X2Y, 2X1Y, 2X2Y, including 1X1Y) are represented in **Fig. 9.** For specimen 1X2Y, larger in width, the deformation of the base plate is hindered by its higher rigidity in its plane; on the other hand, this higher rigidity produces higher stress in the weld metal for the same amount of shrinkage of the weld metal. As specimen 2X1Y has a longer slit and its in-plane rigidity is lower, the resulting stresses are not high in the first half span of the slit due to the effect of the welding sequence. Specimen 2X2Y, similar to specimen 1X1Y, indicates smaller in residual plastic strain but stress, in comparison with specimen 1X1Y.

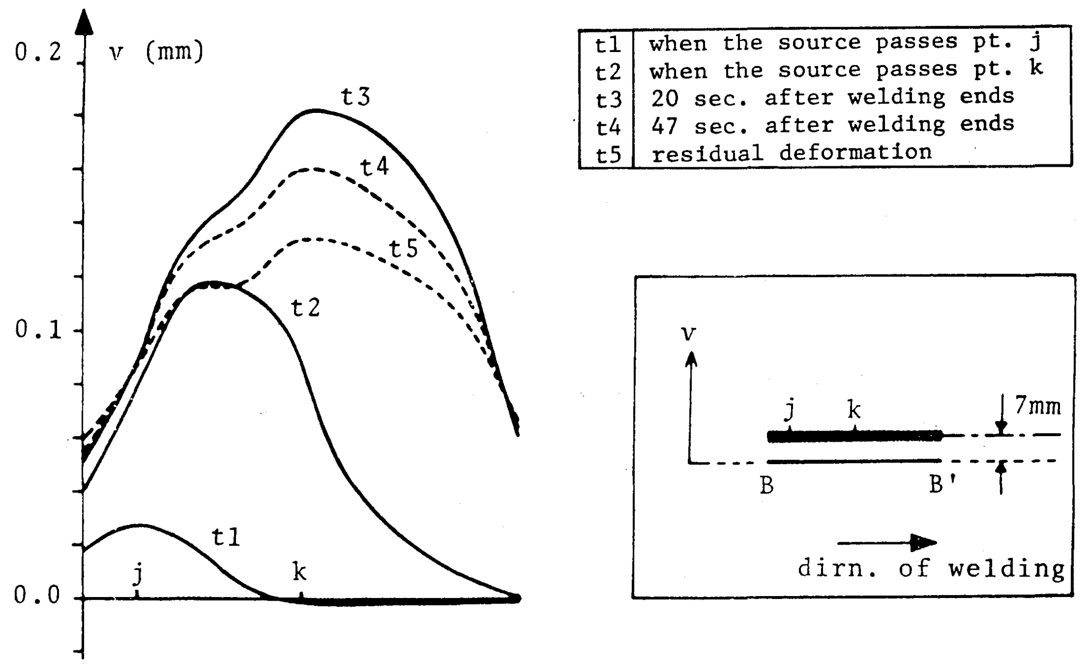


Fig. 8. Transient transverse deformation of BB′.

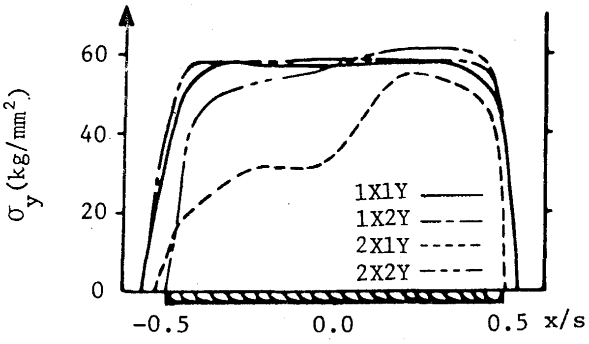


Fig. 9 (a). Residual transverse stress along the slit of XY specimens.

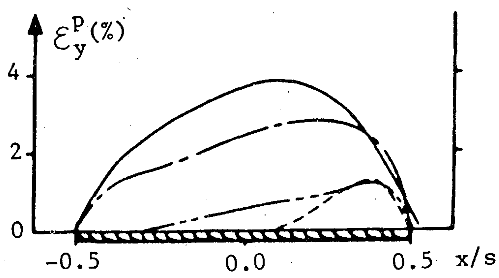


Fig. 9 (b). Residual transverse plastic strain along the slit of XY specimens.

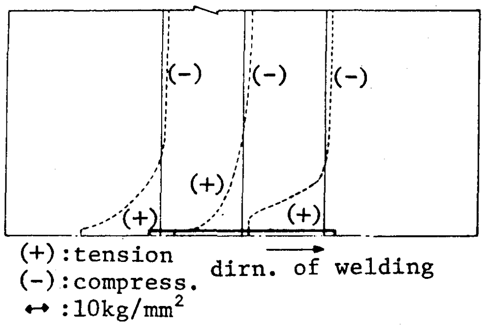


Fig. 10. Residual longitudinal stress distribution (specimen 1X2Y).

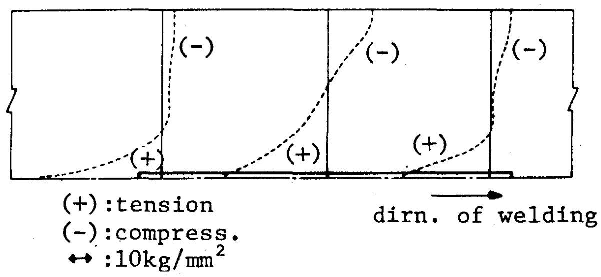


Fig. 11. Residual longitudinal stress distribution (specimen 2X1Y).

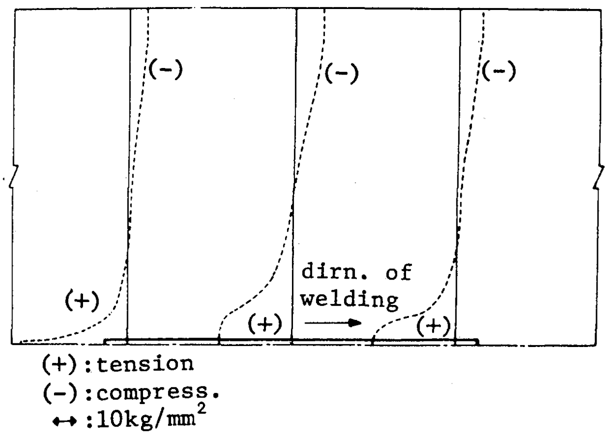


Fig. 12. Residual longitudinal stress distribution (specimen 2X2Y).

(3) Specimens of INF series

Members of real structures, such as ships, bridges, etc., containing long slit weld joints can be considered as infinitely large plates, comparing with specimens of XY series under the same welding condition. In this case, thermal deformation of the base plate should be confined in narrow area along the slit, and cannot be expected as a whole. This implies that the distribution of residual stress may be different from those of the small specimens. In order to clarify these points, the thermal stress analysis is conducted on a different group of specimens, that is INF series.

As mentioned before, description about the specimens is given in Table 1. The results of the heat conduction analysis and that of the stress analysis are represented in Fig. 4, and **Figs. 13** to **16** respectively.

For specimen INF80, having the same slit length of 80 mm as specimens 1X1Y and 1X2Y, resulting plastic strain along the slit falls slightly below that of specimen 1X2Y, showing clearly that higher in-plane rigidity of the base plate prevents its thermal deformation as a whole. Comparing these three specimens 1X1Y, 1X2Y and INF80, containing a short slit length

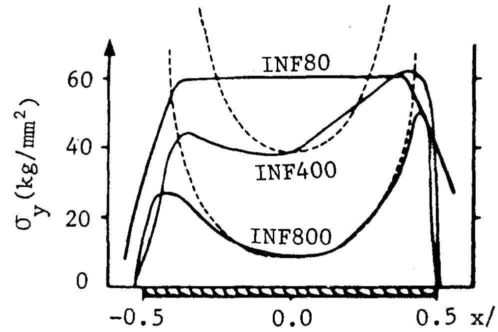


Fig. 13 (a). Residual transverse stress and elastic transverse stress by restraint intensity along the slit of INF specimens.

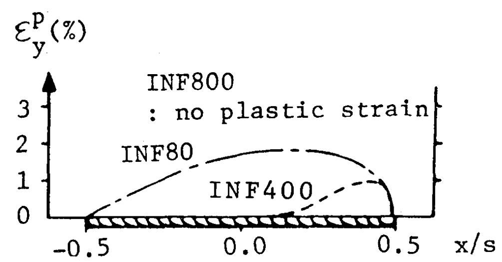


Fig. 13 (b). Residual transverse plastic strain along the slit of INF specimens.

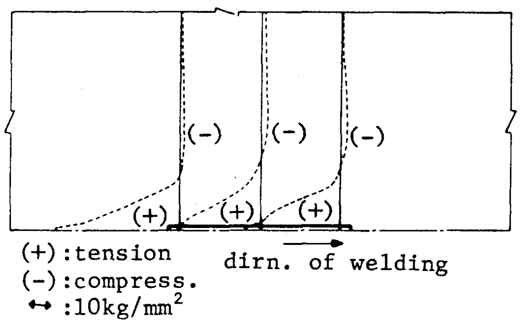


Fig. 14. Residual longitudinal stress distribution (specimen INF80).

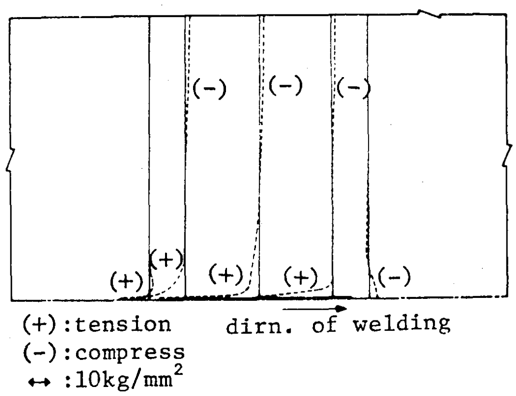


Fig. 15. Residual longitudinal stress distribution (specimen INF400).

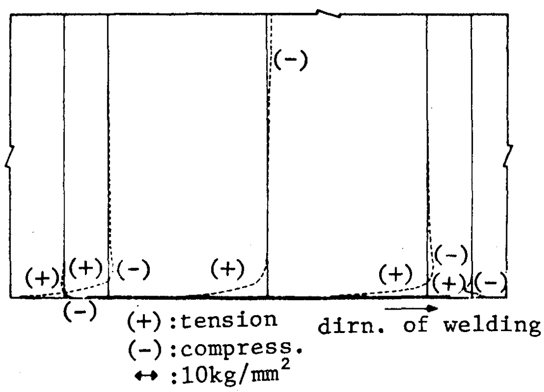
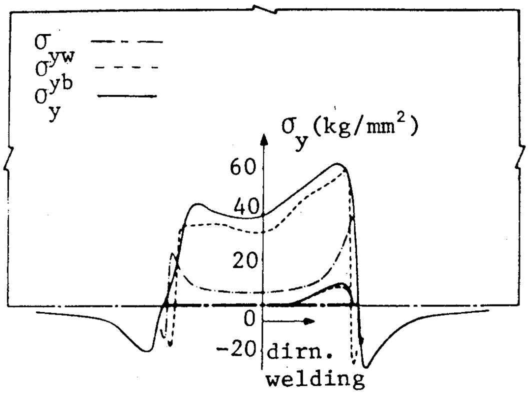


Fig. 16. Residual longitudinal stress distribution (specimen INF800).

of 80 mm, it can be deduced about the effect of the size of specimen that an increase in width, from 1Y to 2Y, reduced the residual plastic strain significantly; and further increase above 2Y reduces slightly. In other words, for a constant slit length of 80 mm, specimen 1X1Y indicates the severest mechanical condition for cracking.

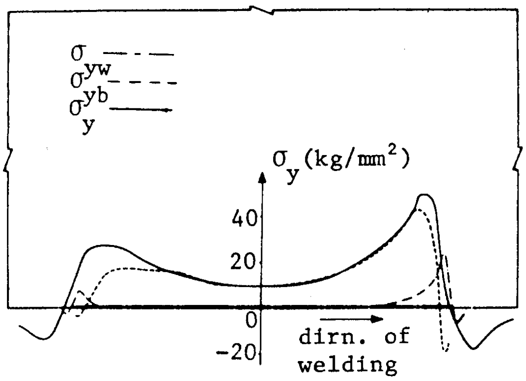
Specimen INF400 shows a totally different distribution of residual transverse stress along the slit from those of the specimens having a slit length of 80 mm; the stress in the middle portion of the slit is lower than that at both ends. In specimen INF800, this phenomenon becomes clearer, and the average stress becomes smaller and falls well below its yield stress.

This transverse stress distribution resembles to that of specimen 1X1Y, which is produced only by the shrinkage of the weld metal. Therefore, it is expected that deformation of the base plate is similar to the shrinkage of the weld metal. The same way of the thermal stress analysis is applied to specimen INF800, as done for specimen 1X1Y, considering separately the deformation of the base plate and the shrinkage of the weld metal. Results are shown in **Fig. 18.** Residual transverse stresses in both cases,



σ_{yw}: by deformation of weld metal
σ_{yb}: by deformation of base plate
σ_y : by the total deformation

Fig. 17. Transverse stresses and plastic strain along the slit (specimen INF400).



σ_{yw}: by deformation of weld metal
σ_{yb}: by deformation of base plate
σ_y : by the total deformation

Fig. 18. Transverse stresses and plastic strain along the slit (specimen INF800).

σ_{yb} and σ_{yw}, are similar and distribute in such a way that the stress is high near the ends of the slit and low at the central portion. It is seen that thermal deformation of the base plate may be divided into two parts; one is locally confined deformation along the slit and the other is deformation as a whole of plate. The latter is very small in this case. This fact indicates that the shrinkage of the weld metal and the local deformation of the base plate have a similar effect upon the resulting residual stress distribution.

The same analysis is conducted for specimen INF400, and results are given in **Fig. 17.** These results represent the transitional stage of specimen 1X1Y and specimen INF800.

(4) Correlation with the intensity of restraint

When the conventional concept of restraint intensity for one dimensional members is extended to slit welds, either of the following two loading conditions is assumed to evaluate the intensity of restraint;

(i) residual transverse stress is uniform along the slit,
(ii) the shrinkage of the weld metal is uniform over its entire length.

Basic understanding to this concept seems to be that residual stress is caused mainly by the shrinkage of the weld metal in which locally confined uniform thermal deformation of the base metal along the slit may be included. Therefore, contribution of other thermal deformation of the base plate than the local uniform one upon residual stress is not accounted.[1]

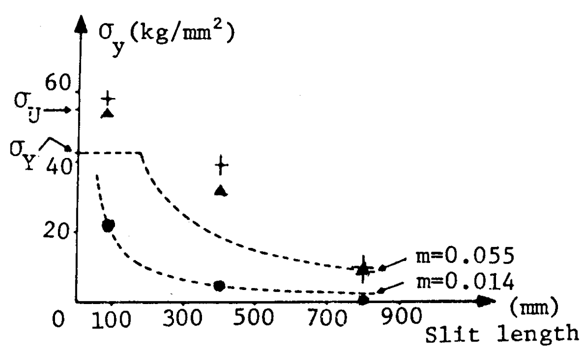
In the case of specimen INF800, transverse stress computed by the concept of restraint intensity (under a uniform contraction) has almost the same distribution as that obtained by the thermal elastic-plastic analysis. This is shown in Fig. 13 (a). In this case, the deformation of the base plate produces most portion of residual stresses, which is well related with the intensity of restraint. On the contrary, in the case of specimen 1X1Y, the deformation of the base plate produces a different pattern of distribution, whereas the shrinkage of the weld metal does produce a similar pattern. Furthermore, specimen INF400 is identified to lie between these two cases. These relation is represented in **Fig. 19,** where residual stresses at the mid span of the slit are shown against the slit length. In the figure, restraint stress predicted by the intensity of restraint is shown by the dashed line. This is calculated in the following way:

For a slit weld provided in an infinitively large plate, the restraint stress in the weld, σ_w, is computed by the expression[5), 6)]

$$\sigma_w = mK = \frac{mEh}{2\pi}\left(\frac{1}{s+2X} + \frac{1}{s-2X}\right)$$

where

$$m = \alpha\sqrt{\frac{\theta_s H \tan\beta}{C}}$$



+: by total deformation
▲: by deformation of base plate
●: by deformation of weld metal

Fig. 19. Correlation of analysed results and restraint intensity.

where

K : intensity of restraint (kg/mm.mm)
E : Young's modulus (kg/mm^2)
h : thickness of base plate (mm)
s : slit length (mm)
α: coefficient of thermal expansion ($°C^{-1}$)
θ_s: melting temperature of weld metal (°C)
2β: bevel angle of weld groove
C : specific heat of the material (cal/g/°C)
H : specific deposited heat (cal/g)

The numerical value of m in the above expression lies between 0.038 and 0.055 for manual arc weld of steel. As an acceptable upper value, 0.055 is used in this case.

The difference between this predicted value and the computed final residual stress, indicated by +, is caused by the over-all deformation of the base plate. Accordingly, the conventional concept of restraint intensity is applicable to longer slit length than 800mm with a good accuracy, where the above mentioned difference is small. In the same figure, another dashed line for m=0.014 is also drawn. This curve coincided with the computed residual stresses, σ_{yw}, at the mid span. Therefore, the residual stress produced by only the shrinkage of the weld metal can be predicted by the intensity of restraint, if the stress is within the elastic limit.

3. Concluding Remarks

A series of the thermal elastic-plastic analysis is conducted and, based on the results of the analysis, the mechanism of production of thermal stress due to slit weld is investigated. In the analysis, the thermal deformation in the base plate and weld metal is imposed to the specimen separately and the contribution of each deformation upon the final restraint stress is studied.

The deformation of the weld metal consists solely of its thermal shrinkage, of which magnitude is dependent on only its welding condition. When the size of the base plate is kept constant, a specimen containing a longer slit has lower in-plane stiffness, in which the magnitude of the residual stress is reduced.

The deformation of the base plate is composed of not only locally confined thermal deformation, but also the resulting over-all deformation of the plate. The shrinkage of the weld metal and the locally confined deformation of the base plate are equivalent to the over-all contraction of the specimen of RRC tests. The deformation of the base plate contributes more to the residual stress than the shrinkage of the weld metal. This tendency is also observed in the case of RRC tests. For a constant slit length and under the same welding condition, higher in-plane stiffness of the base plate hinders the over-all deformation; however more stress is produced by the same amount of deformation. In specimens of XY series, specimen 1X1Y indicates the highest residual stress and plastic strain. Generally, when the slit becomes longer, the effect of the over-all deformation decreases and the residual stress is mainly produced by uniformly distributed contraction along the slit, which consists of the remaining two deformations.

The concept of restraint intensity for slit welds does not take into account the over-all deformation of the base plate.. For short slits where the effect of this deformation is large, the restraint intensity is no more valid for evaluation of restraint stress. When the slit is long, this effect decreases, the restraint intensity well predicts the residual stress, by using the contraction of the locally confined deformation of the base plate and the shrinkage of the weld metal.

Acknowledgement

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