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Mathematical Treatment of Phase Transformation and Analytical Calculation Method of Restraint Stress-Strain†

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Abstract

In this paper, in order to develop the model of mathematical treatment of metal during transformation, a series of experiments and theoretical analyses were conducted.

Thermal elastic-plastic analysis was performed using the variously idealized mechanical properties in the region of phase transformation. The validity of the idealization was examined by comparing with the residual stresses produced in RRC-*test and slit weld specimen and clarify the production mechanism of restraint stresses. The main results are as follows.*

(1) When restraint stresses before transformation acts on occurring or developing transformation, the transformation superplasticity phenomenon appears. Thus the formerly produced restraint stresses are relaxed for a time. At the same time, compressive stresses are produced by transformation expansion. Restraint stresses stagnate until welding heat transfers out of the restraint length. Afterwards, restraint stress rapidly increase to be residual stress at room temperature. Therefore, if the detailed information on the production process of restraint stress is necessary, the analysis needs to take into accounts the above-mentioned phenomenon in addition to transformation expansion.

(2) In consideration of the above-mentioned phenomenon, the most accurate model (model M2*) assumes that the material which is cooled to the starting temperature of phase transformation does not possess rigidity for a time while rigidity gradually recovers and transformation expansion occurs in the region of phase transformation. The simplified model (model* M3*) which assumes that the material does not possess rigidity until it is cooled to the starting temperature of phase transformation is also accurate. If only welding residual stress is necessary, the analysis on the assumption that the weld metal and* HAZ *do not possess rigidity until the material is cooled to the terminating temperature of phase transformation is adequate enough that its result roughly coincides with the experimental one (model* M4*).*

*(3) Based on the above outcomes, the already developed analytical calculation theory for estimation of restraint stress-strain perpendicular to the weld line of the weld metal due to slit weld is extended so as to apply to the material (*HT-80*) in which the effect of phase transformation is remarkable.*

KEY WORDS: (Phase Transformation) (RRC-Test) (Slit Weld) (Restraint Stress-Strain) (Analytical Calculation Method) (Inherent Shrinkage) (Thermal Elastic-Plastic Analysis) (Measurement of Mechanical Properties)

1. Introduction

According as large size welded structures have recently been constructed, the thickness of the structural steel plates has been increased. In this tendency, there has occurred an urgent problem that the structural members should be lighter and economized. To meet this demand, various kinds of high strength steel of relatively high strength have been used for both marine and land structures. Therefore, it is required to accurately estimate welding residual stresses produced in welded joints of high strength steel plates.

In such kinds as high strength steel or 9%-Ni steel, phase transformation is produced at relatively low temperature in the cooling stage, and the transformation expansion strains are large. Accordingly, welding residual stresses are greatly reduced by phase transformation. This was clarified from the results of RRC-test, a typical test for one-dimensional restraint condition, and importance was discussed to the consideration of the effect of phase transformation[1].

Henceforth, this subject has continuously been studied. Using the finite element method, a theoretical analysis of transient and residual stresses produced by multi-layered

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butt welding of a very thick plate was performed[2]. In the analysis, idealizing the behavior of the material in the phase transformation region at the cooling stage, it was assumed that rigidity is not resumed until the weld metal and HAZ (heat affected zone) would be cooled to a phase transformation temperature. In addition, a theoretical analysis was performed for a butt welded joint of two plates in consideration of the effect of phase transformation[3]. In this analysis, transformation expansion was assumed to occur at a moment when the material would be cooled to a phase transformation temperature in the cooling stage from high temperature to room temperature. In both of these theoretical analyses, the effect of phase transformation was idealized. However, details of mechanical properties in the phase transformation region and the production mechanism of restraint stresses are still unknown in many points.

In this paper, a series of experiments and thermal elastic-plastic analyses by the finite element method are carried out for restraint stresses produced in welded joints of steel plates in which the effect of phase transformation is remarkable. The results are synthetically investigated, so that the mechanical properties in the phase transformation region is idealized for theoretical analysis and the production mechanism of restraint stresses is clarified. Moreover, in order to apply the analytical calculation method of restraint stresses-strains (in case of mild steel in which phase transformation is produced at relatively high temperature in the cooling stage, or other kinds of steel such as Al-alloy or austenitic stainless steel in which phase transformation is not produced) produced in the weld metal of a slit welded joint[4, 5] to steel plates in whcih the effect of phase transformation is remarkable, the theory is extended based on the results of the above mentioned research on the phase transformation region. Applicability of the extended theory is confirmed by comparing the experimental and the thermal elastic-plastic analysis results.

2. Idealization of Mechanical Properties in Phase Transformation Region and Production Mechanism of Restraint Stresses

Using high strength steel (HT-80, the chemical compositions are shown in **Table 1**), in which transformation expansion due to phase transformation is relatively remarkable, various experiments and thermal elastic-plastic analyses are performed. The results are synthetically investigated. Reasonable idealization of the mechanical properties for the theoretical analysis in consideration of the effect of phase transformation is made. Moreover, the production mechanism of restraint stresses in the wholly cooling stage including the phase transformation region is clarified.

Table 1 Chemical compositions of base metal and weld metal

	C	Si	Mn	P	S	Cu	Cr	Ni	Mo	V	B
Base Metal	0.11	0.30	0.81	0.010	0.004	0.19	0.51	1.10	0.47	0.03	0.0015
Weld Metal	0.06	0.58	1.18	—	—	—	1.38	0.38	0.49	—	—

2.1 Determination of phase transformation region, and measurement and idealization of mechanical properties

Distribution of residual stresses in a welded joint is under the influence of material properties of the base plate and the filler wire. It is reported that welding residual stresses of a welded joint in general are influenced more remarkably by its base plate than its filler wire[6]. In this paper, only the characteristic of a base plate is considered, and weld metal is treated the same as HAZ of base plate.

Using a thermorestor (simulation apparatus of welding thermal cycle with high frequency induction heating), heating and cooling rates are variously changed to measure the thermal expansion history of the specimen. From the results of measurement, starting and finishing temperatures of phase transformation are determined. At the same time, magnitude of phase transformation expansion strain and coefficient of instantaneous linear expansion are determined. In addition, utilizing the heating-cooling control apparatus of the thermorestor, a tension test is performed to the specimen, after heated to a certain temperature, variously changing the cooling rate. As a result, the Young's modulus and the yield stress are measured.

2.1.1 Determination of starting and finishing temperatures of phase transformation, and measurement of phase transformation expansion strain

Starting and finishing points of phase transformation in both heating and cooling stages are determined as indicated in **Fig. 1** in which the thermal expansion history is schematically illustrated. The starting and finishing points of phase transformation in the heating stage are respectively indicated by S_h and F_h, and those in the cooling stage S_c and F_c. Temperatures measured at these points are shown in **Fig. 2**. In the heating stage, the starting temperature T_{hs} and the finishing temperature T_{hf} of phase transformation are approximately constnat little depending on the heating rate. While, in the cooling stage, the starting temperature T_{cs} and the finishing temperature T_{cf} monotonously fall according as the cooling rate increases and each converges to a certain value (cooling rate is measured from *800*°C to *300*°C).

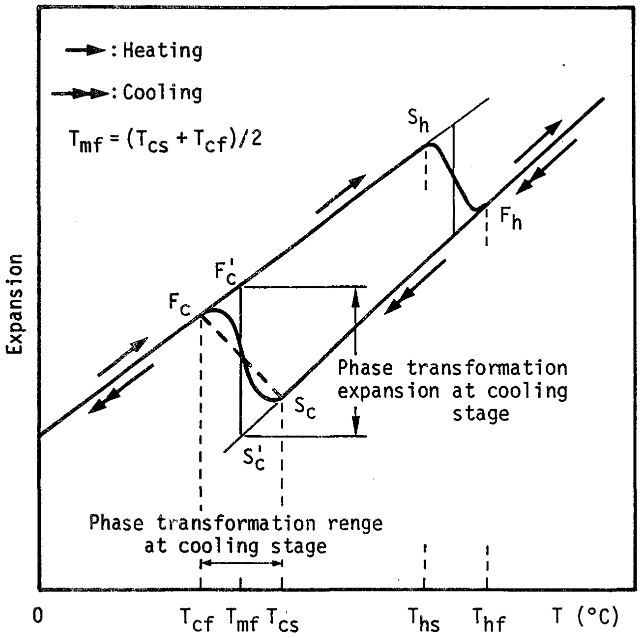


Fig. 1 Schematic representation of temperature expansion relation including phase transformation

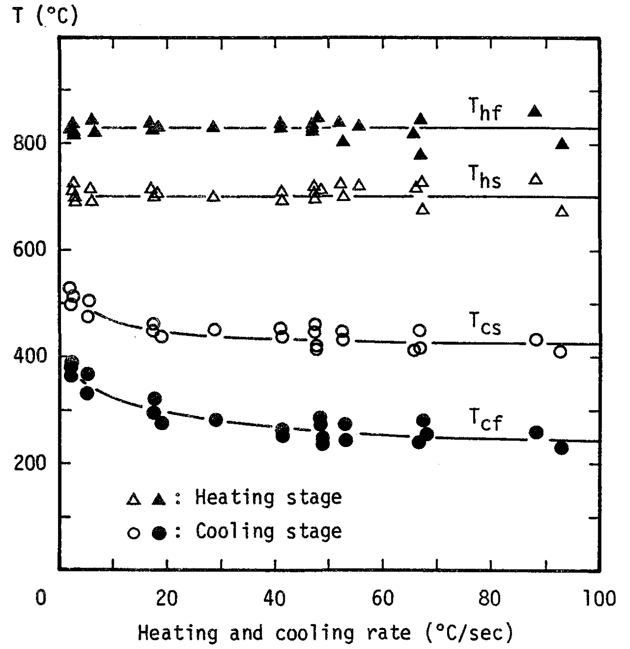


Fig. 2 Relations between heating (or cooling) rate and phase transformation temperature

Variously changing the heating rate and the cooling rate, phase transformation expansion strains in heating and cooling stages are measured. The results are shown in **Fig. 3**. They show constant values not depending on the heating rate nor the cooling rate.

2.1.2 *Measurement of mechanical properties*

The linear expansion coefficient (hereinafter called instantaneous linear expansion coefficient) α, the Young's modulus E and the yield stress σ_Y at a temperature T in both heating and cooling stages are measured. The results are shown in **Fig. 4.** Concerning the yield stress in the heating stage, the measured value at *700*°C is smaller than that at room temperature. In this paper, the mechanical rigidity recovery temperature T_m of the material is determined as *700*°C. Therefore, the Young's modulus and the yield stress will be treated as zero at and higher than *700*°C.

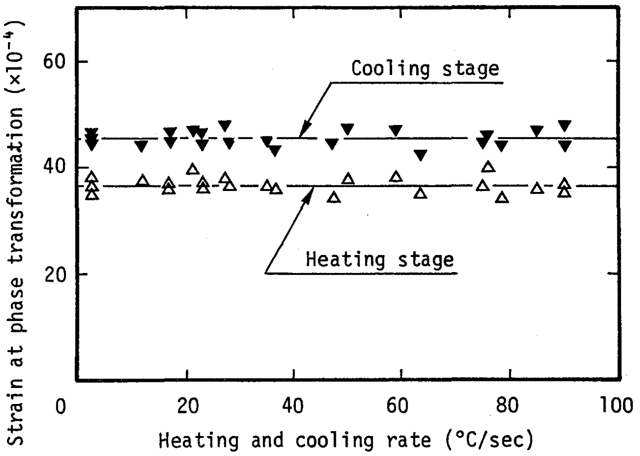


Fig. 3 Relations between heating (or cooling) rate and phase transformation strain

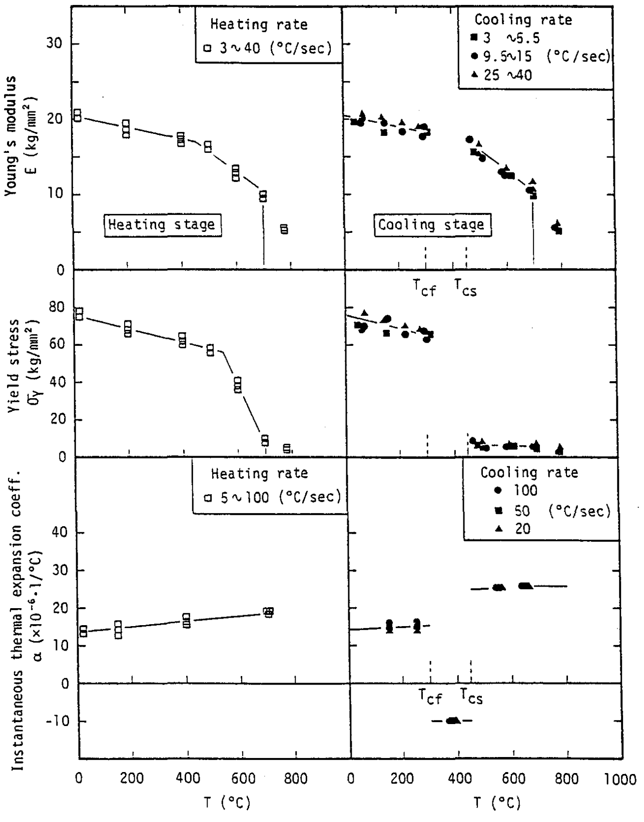


Fig. 4 Temperature dependency of mechanical properties (E, σ_Y and α)

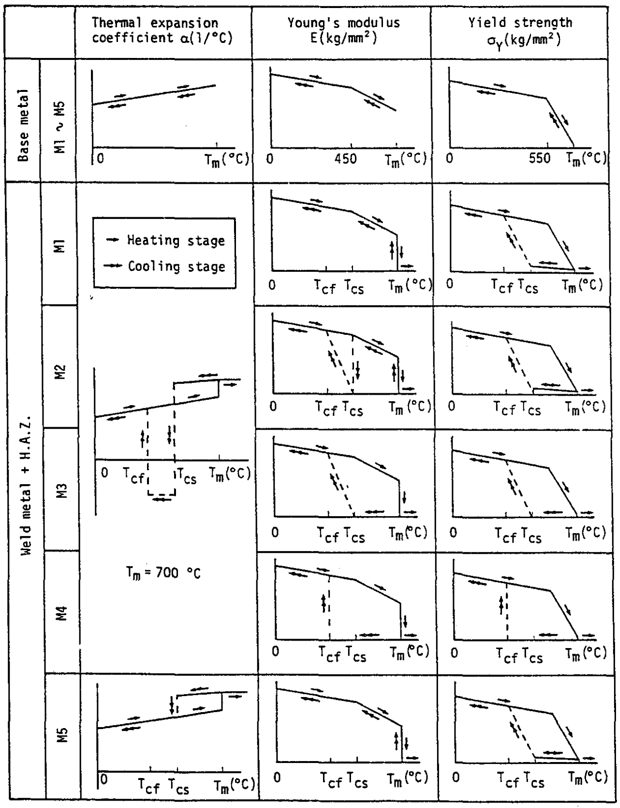
As for the mechanical properties in the heating stage, measured values are idealized by straight lines as shown in Fig. 4.

In the cooling stage, E is measured the same as that in the heating stage above the transformation starting temperature T_{cs}, but σ_Y and α differ from those in the heating stage (Fig. 4). E, σ_Y and α were also measured in the transformation region, but all the results were unreliable. Between the transformation finishing temperature T_{cf} and room temperature, measured values of E, σ_Y and α are idealized by straight lines just the same as those in the heating stage (Fig. 4). It is also known from measurement that α does not depend on the cooling rate from high temperature to T_{cs} but slightly depends on it from T_{cf} to room temperature.

2.1.3 Idealization of mechanical properties for phase transformation region in cooling stage

It has been difficult to directly measure mechanical properties in the phase transformation region. In order to idealize the mechanical properties in the phase transformation region, they are variously idealized as schematically shown in **Table 2**.

Table 2 Idealization of mechanical properties of HT-80 and models for theoretical analysis



(1) Idealization of temperaure dependent Young's modulus E in cooling stage

Young's modulus which changes with the temperature history are classified into five models M1 ~ M5 (Table 2). Idealization of E in the range from the rigidity recovery temperature T_m to T_{cf} is as follows, while measured value of E is used alike in all M1 ~ M5 from T_{cf} to room temperature T_i (Fig. 4).

Model M1: measured values of E from T_m to T_{cs} are idealized by a straight line which is the same as that in the heating stage. It is also assumed that the idealized values from T_{cs} to T_{cf} are the same as those in the heating stage.

Model M2: the measured value of E at the cooling stage which traces the same line as that in the heating stage from T_m to T_{cs} falls to zero at T_{cs} and linearly recovers to the measured value of E at T_{cf} (this is an idealized model for transformation superplasticity phenomenon which will be mentioned later).

Model M3: E is assumed to be zero from T_m to T_{cs} and linearly recovers to the measured value of E from T_{cs} to T_{cf}.

Model M4: E is assumed to be zero from T_m to T_{cf} and instantaneously recovers to the measured value of E at T_{cf}.

Model M5: the same as Model M1.

Hereinafter, the names of models M1 ~ M5 idealized for Young's modulus will be used also for the various combinations of idealized mechanical properties.

(2) Idealization of temperature dependent yield stress σ_Y in cooling stage

From T_{cf} to room temperature, measured values of σ_Y are idealized by a straight line in every model.

Models M1, M5: measured values of σ_Y are idealized by a straight line from T_m to T_{cs}. They are assumed to linearly recover from T_{cs} to T_{cf}, that is, the phase transformation region.

Model M2: σ_Y which is the same as in Model M1 and M5 from T_m to T_{cs}, and falls to zero at T_{cs} and linearly recovers to be the measured value of σ_Y at T_{cf}.

Model M3: it is assumed that σ_Y is zero at higher temperature than T_{cs} and linearly recovers from T_{cs} to T_{cf}.

Model M4: assuming σ_Y to be zero from T_m to T_{cf}, σ_Y is instantaneously recovered at T_{cf}.

(3) Idealization of instantaneous linear expansion coefficient α in cooling stage

Based on the measured results of temperature-expansion curves schematically represented in Fig. 1, the temperature-expansion curve is idealized to coincide with that in the heating stage at and lower than T_{cf}. Thus determined α is idealized by a solid line and used in models M1 ~ M5 at and lower than T_{cf}.

Models M1 ~ M4: from T_m (*700*°C) to the transformation starting temperature T_{cs}, measured values are idealized by a straight line, and the value at *700*°C is used at and higher than *700*°C. As for the phase transformation region, T_{cs} (S_c in Fig. 1) and T_{cf} (F_c) are connected by a solid line for idealization (idealized α is indicated in the phase transformation region in Fig. 4), and α is determined. This α is applied to the transformation region as constant.

Model M5: from the high temperature to T_{cs}, α is the same as those of models M1 ~ M4, but from T_{cs} to the lower temperature, it agrees to that in the heating stage, since transformation expansion is neglected in this model.

2.2 Simulation of production mechanism of restraint stresses by experiment and thermal elastic-plastic analysis

The RRC-test is conducted first. Secondly, it is simulated by thermal elastic-plastic analysis using variously idealized mechanical properties. In addition, using a slit weld specimen which is a typical example of the two dimensional restraint state, welding residual stresses are analyzed and measured. Judging from these results, validity of the mechanical properties idealized for the phase transformation region is investigated.

2.2.1 Experiment and thermal elastic-plastic analysis

(1) RRC-test (rigid restraint cracking test)

SMAW is applied to the RRC-test. It is confirmed that restraint by small weld cracks does not relax.

In this test, reaction force is measured and divided by throat thickness (measured value), so that the average restraint stress of the weld metal is estimated. Transient and residual average restraint stresses are shown in **Fig. 5** by using several symbols. Measured results of temperature in the weld metal are also shown in Fig. 5.

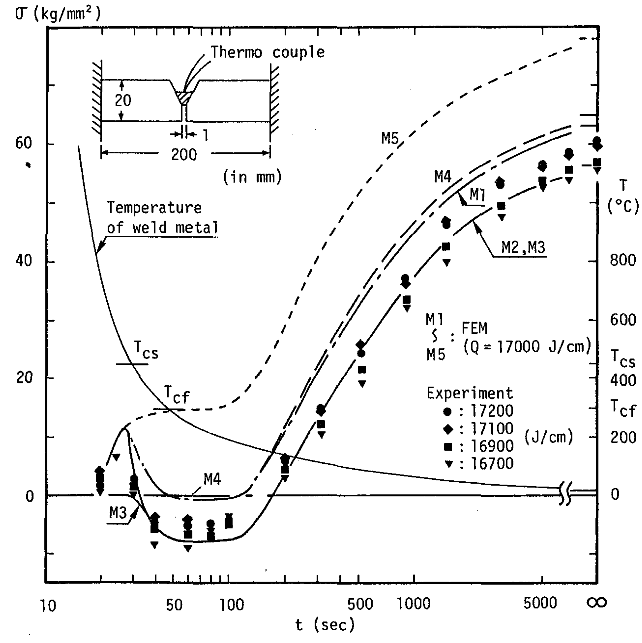


Fig. 5 Transient stresses and residual stresses of RRC-test (HT-80)

For various combinations of idealized mechanical properties, thermal elastic-plastic analyses are performed by the finite element method. Calculation results of temperature by FDM (finite difference method) are shown in **Fig. 6** together with measured results. Both results are in good agreement. Using the calculation results of temperature, thermal stress analysis are carried out. Transient and residual stresses are shown by curves in Fig. 5.

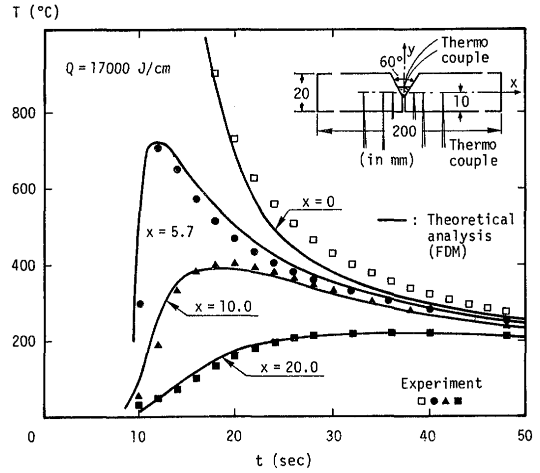


Fig. 6 Temperature histories of RRC-test

By Models M1 ~ M4 in which transformation expansion is considered, the analysis reproduce fairly well the experimental results. Above all, using model M2 and its simplified version, model M3, the results of analysis are in good agreement with the experimental ones. It is seen from the comparison with model M5 in which transformation expansion is neglected that the phenomenon in the preliminary stage of the production of restraint stresses is under a great influence of transformation expansion which accompanies phase transformation.

(2) Slit weld test

For slit weld test, the material is the same as that used in the RRC-test. The size ratios, shape and coordinate system of the specimen are shown in **Fig. 7**. MIGW is applied with heat input *Q=17000J/cm*.

When welding is completed, contact balls are attached

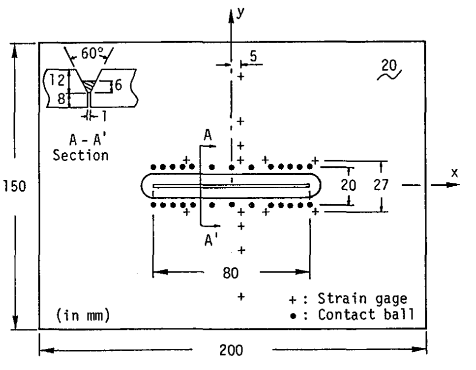


Fig. 7 Slit weld specimen

on both sides along the weld line at the gage length of *d=20mm* on the top and bottom surfaces of the specimen as indicated by 「●」 in Fig. 7. Restraint stresses were released by cutting the weld metal along the weld line, and dislocation produced along the weld line was measured. The average values measured on both surfaces are indicated in half by 「●」 in **Fig.** 8. Moreover, two SR-4 gages are attached at right angle on the top and bottom surfaces of the base plate as indicated by 「+」 in Fig. 7, so that residual stresses are measured as average values on the two surfaces by the stress relaxation method. Measured residual stresses along the line (*y=13.5mm*) parallel to the weld line, σ_x, and those perpendicular to the weld line (*y =0mm*), σ_y, are indicated by 「●」 in **Fig. 9**. Similarly, residual stresses along the *y* axis at *x=5mm*, σ_x and σ_y, are indicated by 「●」 in **Fig. 10.**

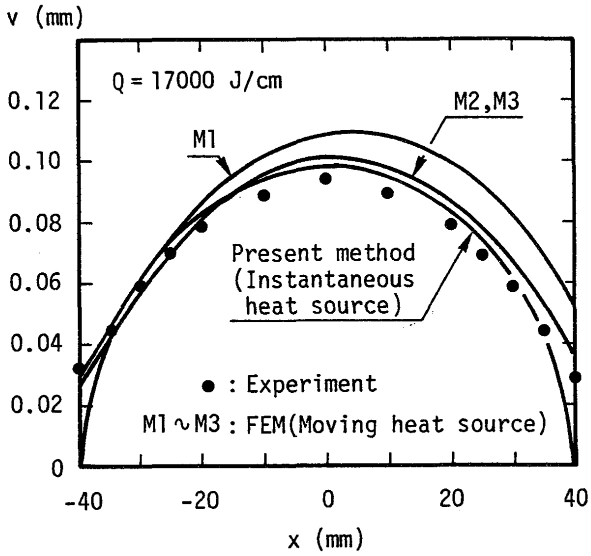


Fig. 8 Inherent displacement along slit (HT-80)

On the other hand, thermal elastic-plastic analyses were performed using on models M1, M2 and M3, and considering the effect of the movement of heat source. Calculated of displacements produced at *y=10mm* are indicated by solid lines in Fig. 8. Calculated residual stress distributions along *y=13.5mm* are indicated by solid lines in Fig. 9 and those along the *y* axis at *x=5mm* in Fig. 10.

Like the case of RRC-test, the analyses by using model M1, M2 and M3 well reproduce the experimental results. Above all, model M2 and its simplified version: model M3, are in good agreement with the experimental results.

2.2.2 Production mechanism of restraint stresses and idealization of mechanical properties

Not only the results of the RRC-test but also those of the thermal elastic-plastic analysis for the RRC-test are examined in detail in order to investigate idealization of mechanical properties and the production mechanism of restraint stresses.

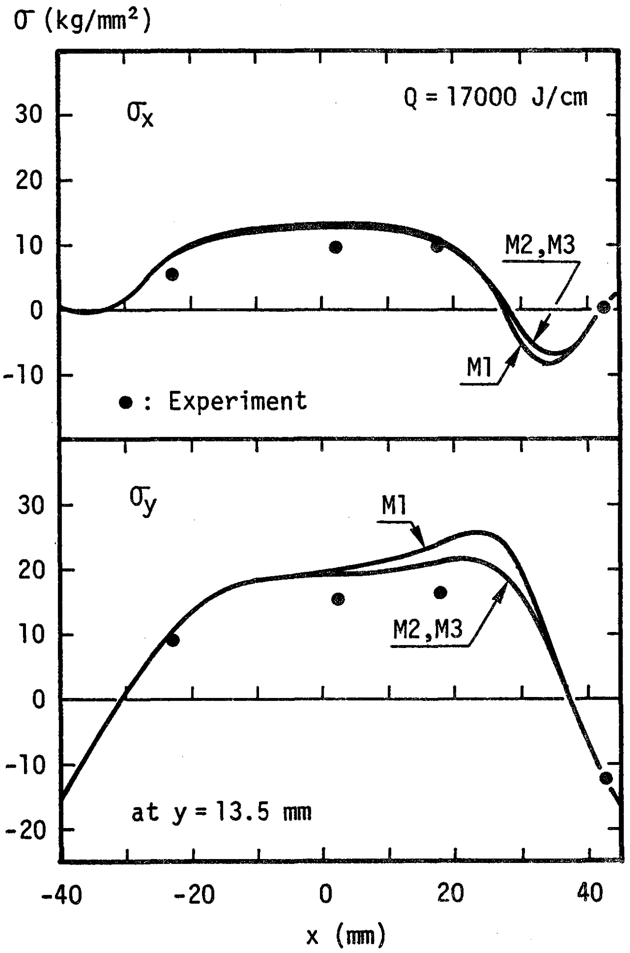


Fig. 9 Welding residual stresses, σ_x and σ_y along x axis of slit specimen (HT-80)

According to the results of the RRC-test (Fig. 5), the production mechanism of restraint stresses can be classified into the following four stages.

1) The first stage: small tensile stresses are produced. This is because when the groove expanded locally by welding heat tries to restore its original shape according as heat conducts, the weld metal which has already recovered rigidity resists against this shrinkage.
2) The second stage: average restraint stresses are converted from tension to compression (as will be mentioned later, this is the effect of transformation superplasticity and transformation expansion).
3) The third stage: stresses do not change. This is because while welding heat conducts within the restraint length of the base plate, heat stored in the specimen is constant and expansion and shrinkage roughly offset each other within the restraint length of the specimen.
4) The fourth stage: average restraint stresses increase rapidly and become residual stresses. According as welding heat conducts out of the restraint length of the specimen, shrinkage occurs and the weld metal resists

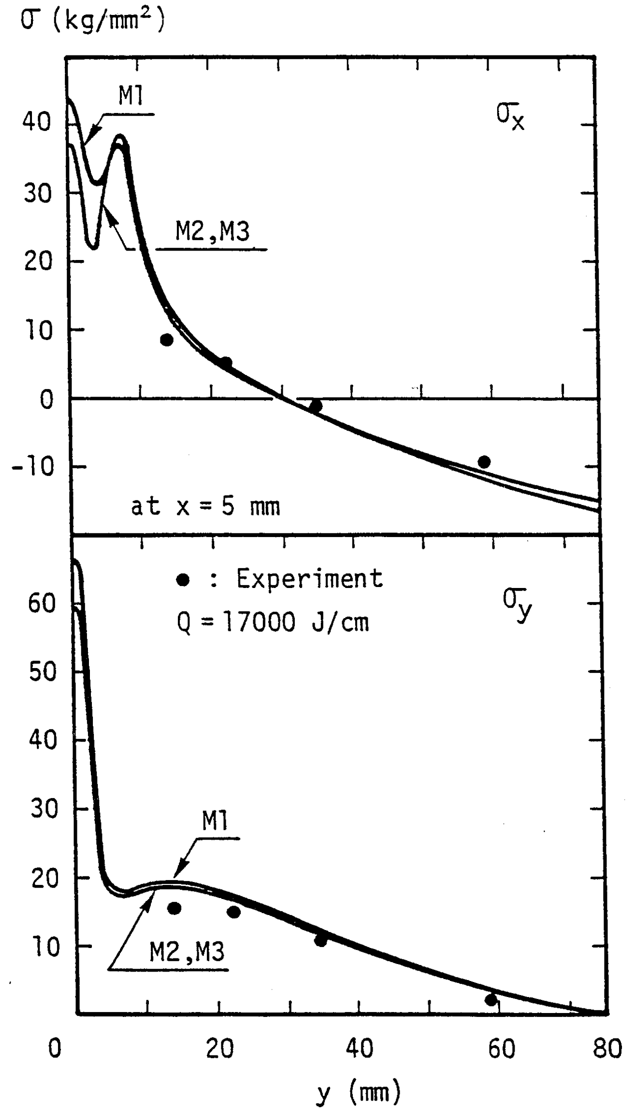


Fig. 10 Welding residual stresses, σ_x and σ_y along y axis of slit specimen (HT-80)

against it. As a result, stresses increase rapidly and become residual stresses at room temperature T_i.

Among these behaviors, the second stage appears at the phase transformation starting temperature T_{cs} and the third stage at the phase transformation finishing temperature T_{cf}, when HT-80 is used (Fig. 5).

In model M1 which was assumed in the formerly mentioned thermal elastic-plastic analysis to recover its rigidity in the phase transformation region, restraint stresses greatly decrease under the direct influence of transformation expansion but not to the degree of producing compression stresses. Therefore, it is hard to claim that actual behaviors are accurately simulated by this model.

It is known from the study on transformation superplasticity that, when transformation occurs and develops in addition to transformation expansion in the phase transformation region, small tension stresses lower strength and produce extraordinary ductility$^{7)}$. This phenomenon should be taken into account for the modelling. Therefore, idealizing the lowering of strength, the Young's modulus E and the yield stress σ_Y are set as zero at the transformation starting temperature T_{cs}, so that restraint stresses produced by cooling until T_{cs} are assumed to entirely relax due to transformation superplasticity. It is model M2 which is on the assumption that rigidity recovers linearly according as transformation expansion develops in the phase transformation region. Model M2 reproduces best the experimental results for the whole process of restraint stress production. Model M3, the simplified version of model M2, in which the weld metal and HAZ are assumed to have no rigidity until cooled to T_{cs} shows the same history of restraint stresses as that of model M2 below T_{cs}. As for model M4, it is assumed that the specimen which does not have rigidity until the transformation finishing temperature T_{cf} instantaneously recovers rigidity at T_{cf}. Therefore, transformation expansion is not accompanied with compression stresses and residual stresses are larger than those of models M2 and M3. Yet model M4 is very similar to model M1 in the result.

Consequently, the production mechanism of restraint stresses is estimated. In the first stage, small restraint stresses produced before transformation affect as acting stresses when transformation occurs and develops. As a result, strength is deteriorated and ductility becomes extraordinary. In the second stage, this transformation superplasticity phenomenon relaxes the previously produced restraint stresses. At the same time, compression stresses are produced by transformation expansion. In the third stage, stresses stagnate until welding heat conducts out of the restraint length of the specimen and in the fourth stage, stresses become residual stresses.

Strictly speaking, the phenomenon in the second stage can be observed even in mild steel. However, general kinds of mild steel seem to take steps of 1 → 3 → 4 processes$^{8)}$. This is because phase transformation in the cooling stage occurs near by or higher than the mechanical rigidity recovery temperature with small transformation expansion, so that the phenomenon in the second stage does not clearly appear.

Judging from the above mentioned outcomes, the production mechanism of restraint stresses in welded joints of steel plates including those in which the effect of phase transformation is remarkable is considered as follows (schematic representation of the mechanism is shown in **Fig. 11**).

If the welded joint is further cooled from the mechanical rigidity recovery temperature T_m, tension restraint stresses (*ma* in Fig. 11) are produced. In the steel plate which either produces no phase transformation at T_m or

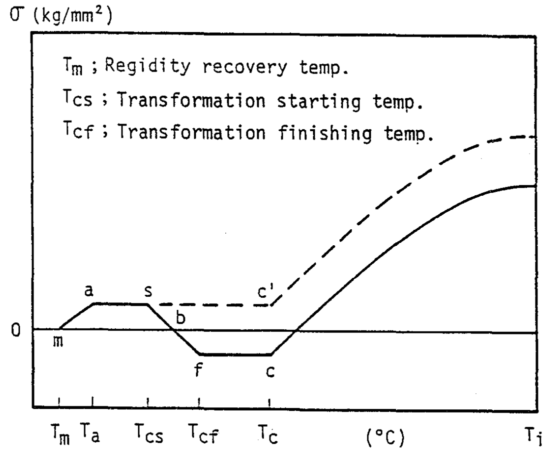


Fig. 11 Schematic representation of mechanism of production of residual stress

produces it higher than T_m, restraint stresses stagnate (*asc'*) until welding heat conducts out of the restraint length at T_c. Then, restraint stresses start to increase rapidly near by T_c and become residual stresses at room temperature T_i (e.g. a mild steel plate).

On the other hand, when phase transformation starts to develop at temperature T_{cs}, strength of the steel plate is lowered by superplasticity, so that restraint stresses relax (*sb* in Fig. 11). At the same time, compression restraint stresses (*bf*) are produced by transformation expansion. From temperature T_{cf} to T_c, stresses stagnate (*fc*) the same as mentioned above, and restraint stresses start to increase rapidly near by T_c and become residual stresses at T_i. In this case, if temperature T_{cs} nears T_a, stresses are considered to hardly stagnate (*as*). Similarly, if T_{cf} nears T_c, stresses scarcely stagnate (*fc*). Therefore, when transformation occurs lower than T_m, stresses stagnate (*asc'*) depending on the restraint length of the specimen. Moreover, the (*sbf*) line shifts either toward the higher temperature side or the lower temperature side depending on the transformation starting temperature T_{cs}. As a result, the production mechanism of restraint stresses varies from case to case.

It became clear that idealization of mechanical properties in the transformation region should be based on the understanding that restraint stresses produced before transformation are relaxed in a short time by deterioration of strength and extraordinary ductility which are observed in the transformation superplasticity phenomenon, and that transformation expansion afterwards develops. This process is represented in model M2 in which remarkable deterioration of strength due to the transformation superplasticity phenomenon is idealized and model M3 which is the simplified version of model M2. When only welding residual stresses of a welded joint are necessary, the analysis may be based on the assumption that, as represented in model M4, the weld metal and HAZ do not recover rigidity until cooled to the phase transformation finishing temperature T_{cf}, because the results roughly reproduce the experimental ones at all times. This idea is considered to be the theoretical background of Ref. 2) in showing a good agreement between the calculation results on the assumption that the weld metal does not recover rigidity until cooled to phase transformation temperature and the experimental results.

3. Development of Analytical Calculation Method of Restraint Stresses-Strains Based on Inherent Shrinkage

Based on the above mentioned mechanical behavior including phase transformation, the analytical calculation$^{4,5)}$ method of restraint stresses-strains developed for slit welds, a typical example of the two dimensional restraint state, is extended to steel plates in which the effect of phase transformation is remarkable. The results by this extended calculation method are compared with experimental and thermal elastic-plastic analyses results. As a result, it is confirmed that the extended method is valid.

3.1 Application of extended theory for analytical calculation method

In case of steel plates in which either phase transformation does not occur in the weld metal and HAZ in the cooling stage or occurs at relatively high temperature and consequently little influences residual stresses, thermal deformation or dislocation produced in the base plate along the slit when the welded joint is cooled to the rigidity recovery temperature T_m is regarded as inherent shrinkage i.e. the source of restraint stresses-strains due to slit weld$^{4)}$.

On the other hand, it was clarified that in the case of steel plate in which phase transformation occurs at relatively low temperature in the cooling stage with large transformation expansion, tensile restraint stresses produced in the cooling stage lower than the rigidity recovery temperature are relaxed in a short time by the transformation superplasticity phenomenon and at the same time converted to compressive restraint stresses with transformation expansion.

Among the simulations of the RRC-test by thermal elastic-plastic analyses, it is known that model M3 is one of the good models which show well temperature dependent mechanical properties. Idealization of this model is based on the consideration that the plate does not recover rigidity until the transformation starting temperature T_{cs} (both the Young's modulus and yield stresses are zero) but linearly recovers the original mechanical properties from T_{cs} to the transformation finishing temperature T_{cf}. It is also assumed that transformation expansion fully develops from T_{cs} to T_{cf}.

Followingly, in order to take these effects into account in the analytical calculation method, the idealization is further simplified as follows.

The rigidity recovery temperature of the weld metal, T_m, is set as the intermediate temperature between T_{cs} and T_{cf}. This intermediate temperature, $(T_{cs} + T_{cf})/2$, is newly set as T_{mf}. T_{mf} is called the virtual mechanical rigidity recovery temperature in this paper. Total expansion accompanying phase transformation is assumed to instantaneously occur at T_{mf}. In this case, the expansion accompanying phase transformation is not concerned in the analysis since it develops when rigidity is zero. In another words, restraint stresses and strains produced in the weld metal and HAZ higher than virtual mechanical rigidity recoverly temperature T_{mf} are disregarded. In this point, this method greatly differs from that of Ref. 3) in which transformation expansion is considered to instantaneously occur when weld metal is cooled to the phase transformation temperature in the process of a series of elastic-plastic behaviors from high temperaure to room temperature.

This idealization makes it possible to calculate restraint stresses-strains by the already introduced analytical calculation method[4, 5] by treating T_m as T_{mf} and others as they are.

3.2 Validity of extended analytical calculation method

In order to investigate the validity of the extended analytical calculation method, an experiment was conducted using a same slit weld specimen (HT-80) as used in Section 2.2.1 (Fig. 7).

Observed displacement (*1/2* of dislocation) produced by releasing restraint stresses of the weld metal along the slit are indicated by 「●」 in Fig. 8. Also shown in Fig. 8 is the half of inherent shrinkage or the direct source of restraint stresses-strains calculated by substituting T_{mf} for T_m into the analytical calculation equation which was presented in Ref. 4). When elastic restraint stresses (residual stresses) are produced in the weld metal, the above mentioned dislocation and inherent shrinkage should agree[9]. As these agree well in this case, restraint stresses-strains which can be calculated by the analytical calculation method using the inherent shrinkage may be considered to be reliable. In addition, the thermal elastic-plastic analyses were performed and restraint stresses perpendicular to the weld line produced in the weld metal (analysis result of M3) are shown in **Fig. 12**. It is seen that the analytical calculation results correspond well with the thermal elastic-plastic analysis result. As a result, it is confirmed that restraint stresses-strains perpendicular to the weld line can be accurately estimated even for the steel plates in which the effect of phase transformation is remarkable.

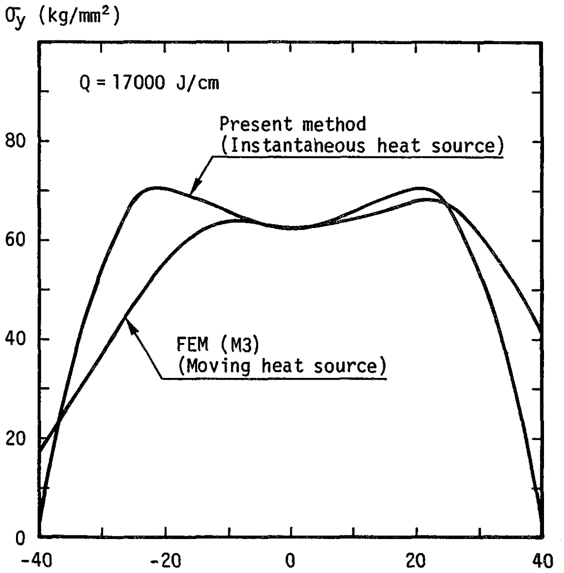


Fig. 12 Welding residual stress σ_y along slit (HT-80)

4. Conclusion

In this paper, an extensive experiment was performed in order to investigate the mechanical properties of high strength steel (HT-80) for a wide range of temperature. On the other hand, in addition to the RRC-test and the slit weld test, thermal elastic-plastic analyses were performed variously idealizing the mechanical properties in the phase transformation region. These results were synthetically investigated in order to idealize for theoretical analysis the mechanical properties in the phase transformation region and to clarify the production mechanism of restraint stresses. The results are summarized as follows.

1) The production mechanism of restraint stresses in the steel plate in which phase transformation is remarkable was clarified using the model shown in Fig. 11.

   Restraint stresses produced before transformation at the cooling stage affect as acting stresses in the production and development processes of transformation, so that the phenomenon of transformation superplasticity, i.e. remarkable lowering of strength and extraordinary ductility, appears and the formerly produced restraint stresses are relaxed in a short time. Simultaneously, compressive stresses are produced by transformation expansion. Restraint stresses stagnate until weld heat starts to conduct out of the restraint length, and increase rapidly afterwards to become residual stresses at room temperature. Therefore, in a case where detailed information on the production mechanism of restraint stresses is necessary, not only transformation expansion but also the above mentioned phenomenon must be taken into account in the analysis.

2) The most accurate model for idealization of the mechanical properties was model M2 in which, considering the lowering of strength and extraordinary ductility observed in the phenomenon of transformation superplasticity, it is assumed that rigidity is relaxed in a short time when the plate is cooled to the phase transformation starting temperature but is gradually recovered in the phase transformation region with the growth of transformation expansion. In addition, model M3, the simplified version of model M2, in which rigidity is assumed not to be recovered until the plate is cooled to the phase transformation starting temperature was proved to be sufficiently accurate. As far as only welding residual stresses are regarded, the analysis on the assumption that the weld metal and HAZ do not recover rigidity until the plate is cooled to the phase transformation finishing temperature may fairly well reproduce the experimental results (model M4).

3) Based on these results, in order to predict residual stresses-strains produced in the weld metal of a slit weld perpendicular to the weld line, the already developed analytical calculation theory was extended to apply to the high strength steel (HT-80) in which phase transformation is remarkable. Usefulness of the analytical calculation method was confirmed by comparison with the experimental and thermal elastic-plastic analysis results. As a result, restraint stresses-strains produced in the weld metal of a slit weld may be simply and accurately estimated by the analytical calculation method.

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