Dynamical Characteristics of TRC Test and RRC Test†

Yukio UEDA* and Yoshiki MURAMATSU**

Abstract

TRC and RRC tests are basic testing methods for studying cold cracking sensitivity of materials. The restraint condition of RRC test is clearly defined but that of TRC test is not. In contrast with this, the testing method of TRC test is much easier than that of RRC test, and an arbitrary loading diagram after welding can be applied in the test.

Therefore, it is very important and useful to clarify the dynamical characteristics of both tests and their correlation.

For this purpose, a series of thermal elastic-plastic analysis by the finite element method was carried out.

The results are summarized as follows.

(1) There is no essential difference between dynamical characteristics of TRC test and of RRC test if the loading process in TRC test is chosen as similar as the process of development of restraint stress in RRC test.

(2) In TRC test, stress distribution in the throat section may be determined only by the final restraint load, but plastic strain distribution is affected very much by the loading process.

(3) In order to obtain stress and plastic strain distribution in the throat section, which are very similar to those of RRC test, it is necessary to impose in TRC test a loading process as indicated below,

(a) the load may be applied when heat begins to be transmitted out of the restraint length.

(b) the load may reach at the final value at a temperature which the corresponding RRC test ends.

(c) the final load may be equal to that of RRC test.

(4) The correlation between the two tests is obtained as follows,

(a) the free contraction S is measured.

(b) a tensile test is conducted for a weld joint of 2l length.

(c) the elongation of the specimen should be the same as S.

KEY WORDS: (TRC Test) (RRC Test) (Thermal El-Pl Analysis) (Restraint Stress) (Restraint Strain) (Thermal Cycle) (Loading History)

1. Introduction

TRC (Tensile Restraint Cracking) test and RRC (Rigid Restraint Weld Cracking) test are typical testing methods to study sensitivity of cold cracking of welded joints. The essential difference between these two methods is in the process of loading or development of restraint stresses. In TRC test, specified load is applied after an arbitrary time passes after welding. In RRC test, a specified gage length (restraint length) is kept constant during and after welding, so that shrinkage of specimen caused by cooling is restrained and restraint stresses are produced. Although the restraint length of an actual welded joint is not necessarily kept so constant as in RRC test, its restraint condition is considered comparatively similar to that of RRC test. RRC test has both a merit and a demerit, that is, restraint condition of a joint can be clearly defined by restraint intensity, but a special device is necessary for experiments. So does TRC test, that is, experimental method is so simple that load can be variously applied at the cooling stage, but its relation with restraint condition remains unclear. In order to make the best use of these testing methods, it is important to clarify their respective dynamical characteristics and deduce their correlation. For these testing methods, many experiments and analyses[1),2)] have been performed. Especially, a couple of detailed analytical calculations[3),4)] have already been tried for RRC test. In this research[5)], thermal elastic-plastic behaviors appear in the specimens of these testing methods are newly analyzed by the finite element method, and their respective dynamical characteristics are clarified.

2. Method of Calculation

A *20mm* thick mild steel plate with Y-groove was

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* Professor

** Researcher, National Research Institute for Metals

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analyzed under the assumption that stresses are in plane stress state along the weld line. In RRC test, the restraint length was set as *2l=200*, *300* and *400mm*, and in TRC test, the length between chucks or the restraint length *300mm* mostly. Mesh division by finite elements used in common for both analyses of heat conduction and thermal elastic-plastic behavior are shown in **Fig. 1**. Temperature dependencies of physical and mechanical properties are shown in **Figs. 2 and 3**, respectively. The mechanical rigidity recovery temperature was set at *750*°C.

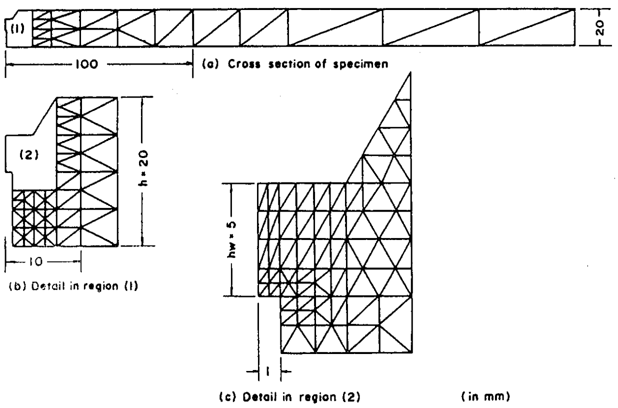

Fig. 1 Mesh division for analysis by F.E.M.

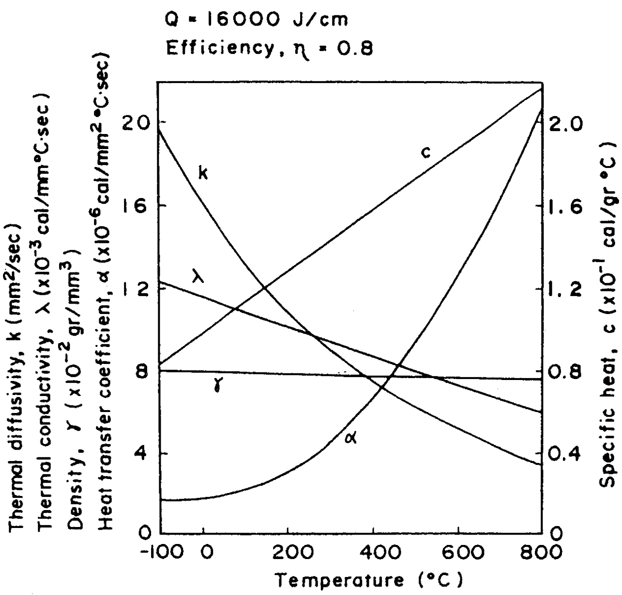

Fig. 2 Temperature dependencies of physical properties (Mild steel)

Using the condition of heat input shown in Fig. 2 (heat input: $Q=16,000J/cm$, heat efficiency: $\eta=0.8$), heat conduction was calculated by the two dimensional finite difference method. In this calculation, the thermal diffusivity shown in Fig. 2 was used considering the effect of thermal diffusion. Thermal cycle of the root was obtained as shown in **Fig. 4**. Using the calculated transient temperature distribution at the cooling stage to room temperature (*15*°C), thermal elastic-plastic analyses were conducted by

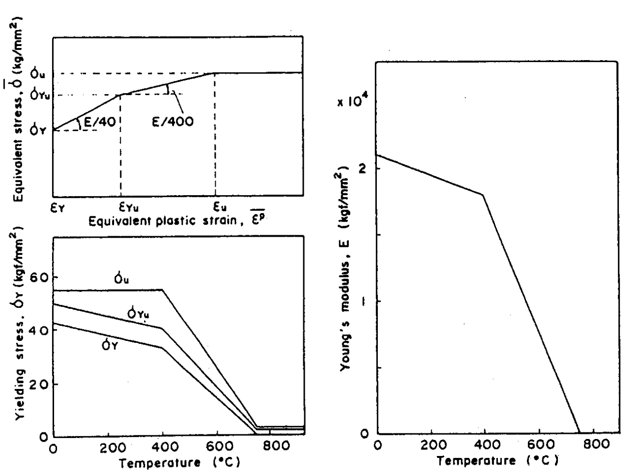

Fig. 3 Temperature dependencies of mechanical properties (Mild steel)

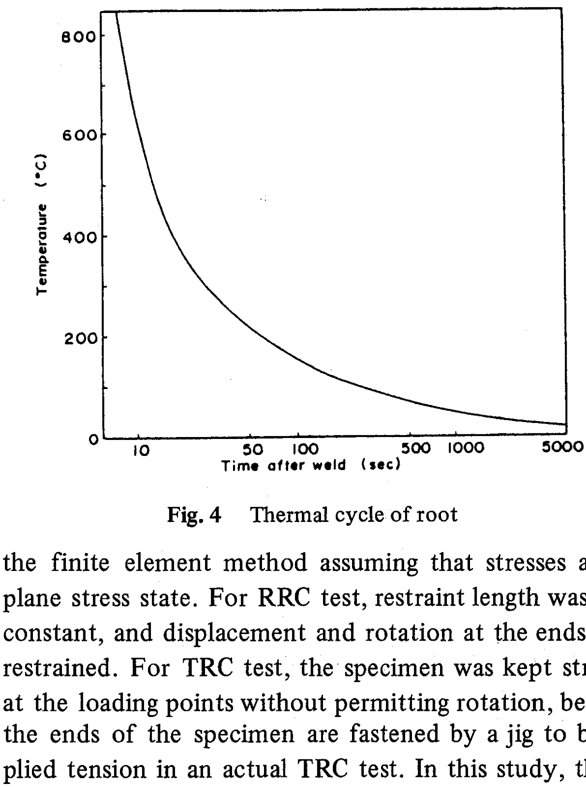

Fig. 4 Thermal cycle of root

the finite element method assuming that stresses are in plane stress state. For RRC test, restraint length was kept constant, and displacement and rotation at the ends were restrained. For TRC test, the specimen was kept straight at the loading points without permitting rotation, because the ends of the specimen are fastened by a jig to be applied tension in an actual TRC test. In this study, the effect of transformation expansion was not considered.

3. Thermal Elastic-plastic Analysis for RRC Test

3.1 Restraint stresses and their developing process

Results of calculations for RRC test will be described in the following. The relation between the developing history of average restraint stress produced in the longitudinal direction (mean longitudinal restraint stress for the entire cross section of the specimen) and temperature of the root are shown in **Fig. 5** by solid lines. As was clarified by Satoh, Matsui, et al.[2)], in RRC test, a small amount of tensile average restraint stress is produced at the early stage, because local thermal expansion in pro-

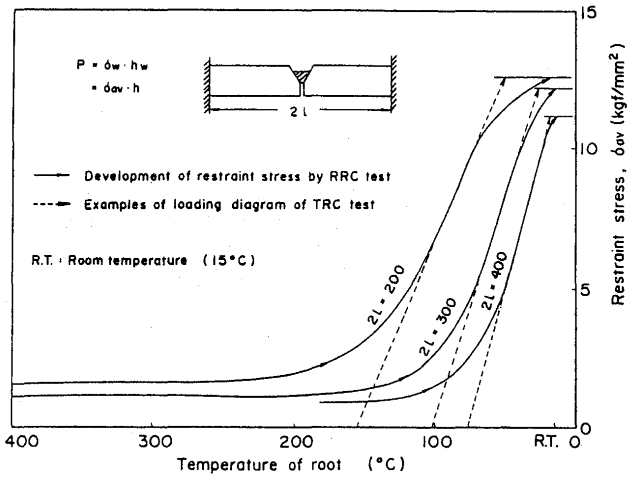

Fig. 5 Development of restraint stress by RRC test

duced by concentrated heat input immediately after welding. And this shrinks by averaging the temperature distribution at the throat section. After temperature distribution is averaged and before heat conducts to out of the restraint length, overall heat quantity stored in the specimen is constant except thermal diffusion, so that thermal contraction does not occur and average restraint stress roughly stagnates. As heat conducts and dissipates out of the ends, the specimen begins to shrink and restraint stress starts to increase rapidly until the specimen is cooled to room temperature. Accordingly, as shown in Fig. 5, the shorter the restraint length is, the earlier restraint stresses start to increase. The time when average restraint stress starts to increase can be estimated by a simple calculation of one-dimensional thermal conduction. Broken lines in Fig. 5 indicate simplified histories of stress development in RRC test, which will be used as one of loading histories in the calculation of TRC test. The relation between restraint length and final restraint stress is shown in **Fig. 6**.

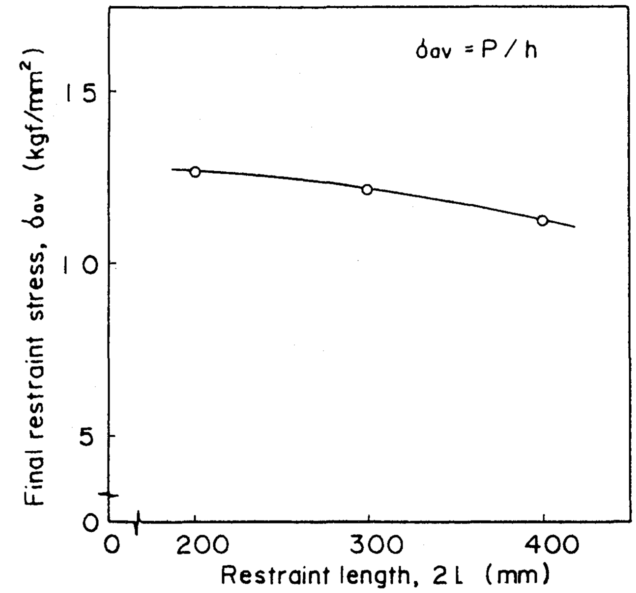

Fig. 6 Relation between restraint length and final restraint stress

3.2 Distributions of stresses and strains

Shown in **Fig. 7** are the distributions of restraint stress σ_x and plastic strain ϵ_x^p (both are in the tensile di-

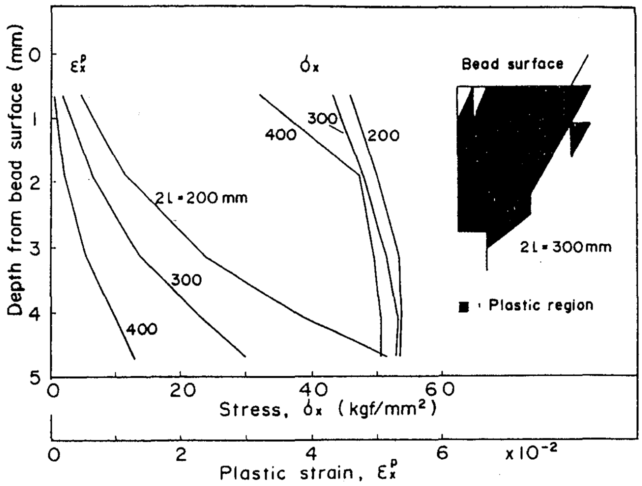

Fig. 7 Distributions of stress and plastic strain in throat section at RRC test

rection) produced in the throat section along the thickness direction. As restraint length is shortened and restraint condition becomes severe, plastic strains increase rapidly but stresses do not increase so much. The reason is that in yielded elements, stresses are increased only by work hardening due to increase of shrinkage by cooling, while most of shrinkage becomes plastic strains (refer to Fig. 3). Illustrated in Fig. 7 is the plastic region in the vicinity of welded portion when restraint length is *2l=300mm*.

4. Thermal Elastic-plastic Analysis for TRC Test

4.1 Example of basic calculation for TRC test

As mentioned previously, loading history may be freely chosen in TRC test. As a basic example, the simplified history of average restraint stress development obtained by RRC test with *2l=300mm*, which is shown in Fig. 5, was assumed as a loading history as shown in **Fig. 8**. Calculated results are shown in Fig. 8 in the same manner as in Fig. 7, for distributions of stress and strain respectively, and for plastic region of the throat section. Comparison of these results with those of RRC test (*2l=300mm*) indicated in Fig. 7 shows similarity in both magnitude and inclination.

4.2 Comparison of distributions of stress and strain in the throat section of TRC test under variously loaded conditions with those of RRC test

Various loading histories used in analyses of restraint stress and strain produced in TRC test are shown in **Fig. 9** and **Table 1**.

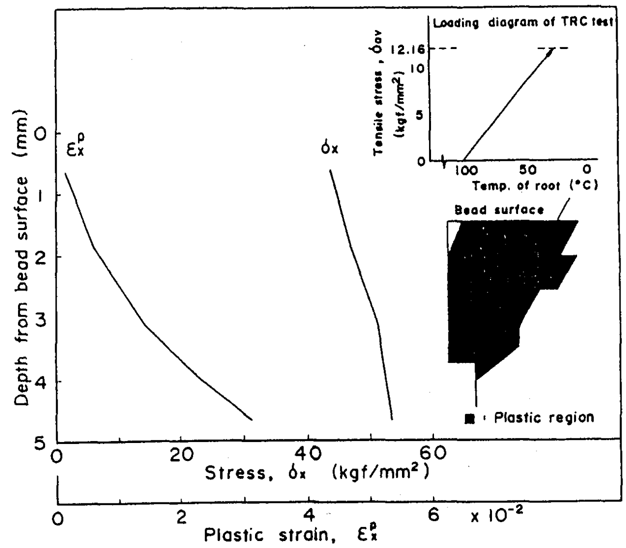

Fig. 8 Distributions of stress and plastic strain in throat section at TRC test

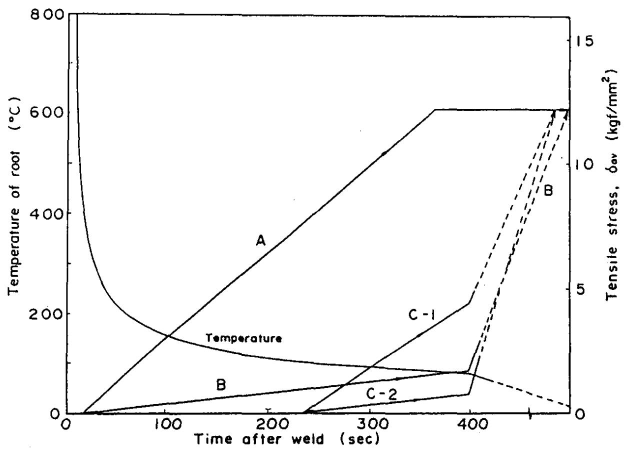

Fig. 9 Loading diagrams of TRC test

Table 1 Conditions of loading diagrams at TRC test

Mark		Final load	Temp. range for loading	Loading rate	2l to obtain the final load at RRC test
A		12.16	400 → 80	0.695 kg/sec	300
B		12.16	400 → 15	0.083 kg/sec (400 → 27.5°C) 1.856 kg/°C (27.5 → 15°C)	300
(1)	C-1	12.65	154 → 50	2.43 kg/°C	200
	C-2			0.308 kg/sec	
(2)	C-1	12.16	102 → 26	3.2 kg/°C	300
	C-2			0.099 kg/sec	
(3)	C-1	11.22	76 → 17	3.8 kg/°C	400
	C-2			0.081 kg/sec (76 → 27.5°C) 3.232 kg/°C (27.5 → 17°C)	
		(kgf/mm²)	(°C)		(mm)

Loading history A: while temperature of the root is cooled from *400*°C to *80*°C, load is increased proportionally to time elapsed after welding until the final restraint force is attained. From *80*°C to room temperature, load is unchanged.

Loading history B: while the root is cooled from *400*°C to *15*°C, load is increased proportionally to time elapsed after welding until the final restraint is attained.

Loading history C: two kinds of simplified histories of stress development in RRC test are applied, which correspond to the broken lines in Fig. 5 (in Fig. 9, corresponding to the broken line of *2l=300mm* in Fig. 5). One is to load proportionally to the decrease of temperature (C-1), and the other is to set the starting and finishing loading points at the same ones as of (C-1), and increase load proportionally to time elapsed between the two points (C-2).

The starting and finishing loading points are shown in Table 1 for A, B and C. The final loads in loading histories A and B are the same as that of RRC test with *2l=300mm.* The final loads in loading history C are those of RRC test with *2l=200, 300,* and *400mm.*

Distributions of stresses and plastic strains in the throat section along the throat thickness direction are shown in **Figs. 10-1** to **10-3**. Calculated results for loading histories

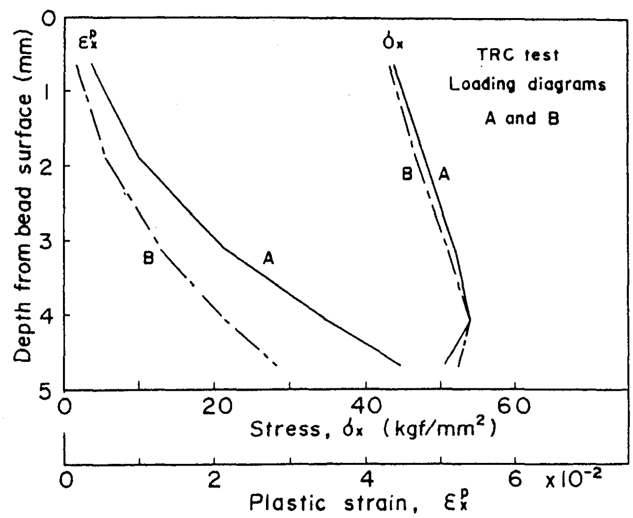

Fig. 10-1 Distributions of stress and plastic strain in throat section at TRC test

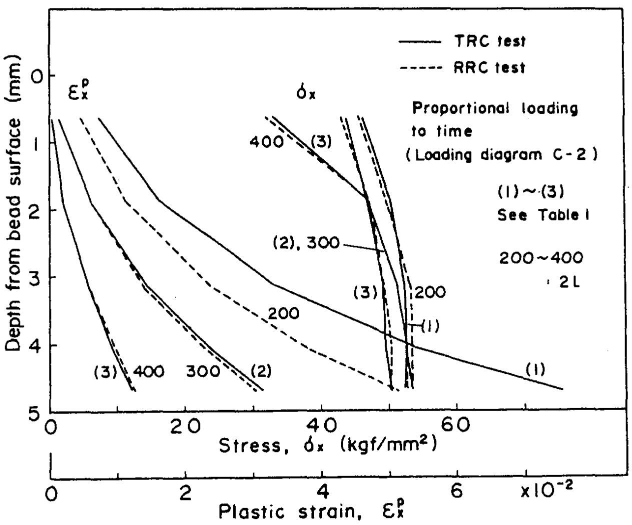

Fig. 10-2 Distributions of stress and plastic strain in throat section at TRC and RRC test

A and B are shown in Fig. 10-1. Distributions of stresses are similar, but distributions of plastic strains is much

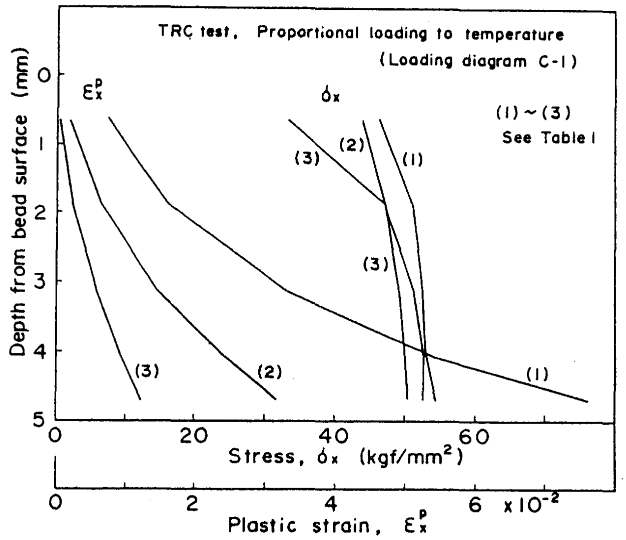

Fig. 10-3 Distributions of stress and plastic strain in throat section at TRC test

larger with loading history A than with loading history B. This is because history A and history B differ in temperature at which the same final restraint force is attained (the finishing point of loading). Such temperature is higher in history A than in history B; *80*°C in history A and *15*°C in history B. Accordingly, their yield surfaces (**Fig. 11**)

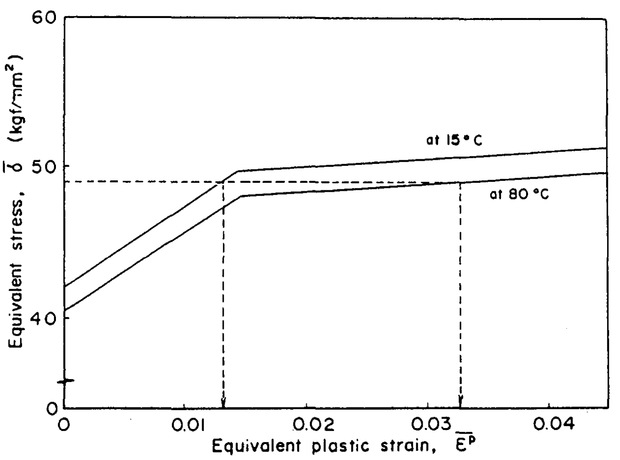

Fig. 11 Temperature dependent relation between equivalent stress and equivalent plastic strain

which show temperature dependency differ. As is seen from Fig. 11, even with a slightly smaller yield surface, plastic strains increase largely under the same stresses.

The calculated results for loading history C are shown in Figs. 10-2 and 10-3, for respective cases when loading is proportional to time elapsed and to decrease of temperature at the root. The broken lines in **Fig. 10-2** indicate the calculated results for RRC test. As for the calculated results for TRC test with loading history C, stresses and plastic strains are almost the same in both cases where loading is applied proportionally to time elapsed and to decrease of temperature. The reason may be that with loading history C, loads are applied when the root is at such a low temperature range as *150-20*°C (Table 1), and yield stresses are high and change only little. In addition, such a loading method as by imposing displacement, in which strains are compulsorily imposed until a certain magnitude of displacement is obtained and plastic strains in yielded region may be largely increased, was not applied. Instead loads were simply applied at the ends of the specimen, so that the load increment can be sustained in the elastic region. Accordingly, plastic strains in yielded region do not extremely increase.

For the same final restraint force, RRC test and TRC test are compared. In the throat section, stresses distribute almost the same, and so do plastic strains except for those under some kind of loading history. However, it is seen from the comparisons between RRC test (*2l=200mm*) and TRC test (loading history C), and RRC test (*2l=300mm*, Fig. 10-2) and TRC test (loading history A, Fig. 10-1) that plastic strains are much larger in TRC test. The reason is the same as afore-mentioned that the same loads are imposed at a higher temperature in TRC test.

Correlation between TRC test and RRC test will be detailed in 4.3. If stresses and strains produced by TRC test should be the same as those by RRC test, it is necessary to set the temperatures of the root at the initial and final loadings (especially, temperature at the final loading) by TRC test the same as those by RRC test (the final loading is applied at room temperature). Actually, the temperature at which the initial loading is applied coincides with the time when heat starts conducting and dissipating out of the restraint length, and restraint stresses start increasing rapidly. Such temperature need not be very accurate. As for the temperature at the final loading, it is important that loading has been completed at the time when the whole specimen is cooled to room temperature (that is, the final state of RRC test), because yield stress depends on temperature. If yield stress changes little between *30*°C and *0*°C (the case of the material used for calculations), the temperature at the final loading should fall in this temperature range. Accordingly, it is generally desired that the temperature at the final loading be selected as close to room temperature as possible in experiments.

In the calculations done for TRC test, the length between chucks was set as *300mm*. Usually, the first layer of welding is laid off-centered, so that bending moment is produced as well as tension by restraint. This bending moment may be influenced by the length between chucks. Chucks clamp the specimen and do not allow bending rotation. Changing this length between chucks to *200* and *400mm*, calculation was conducted for TRC test. The calculated results of distributions of stresses and strains are shown in **Fig. 12**. Results are almost agreeable in both cases with *200* and *400mm*. Therefore, the effect of difference of length between chucks seems to be negligible.

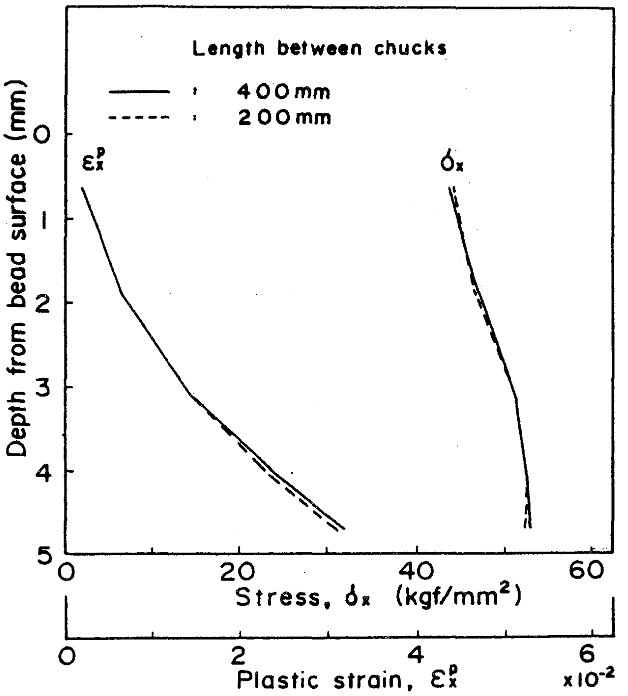

Fig. 12 Distributions of stress and plastic strain in throat section at TRC test for various lengths between chucks

4.3 Correlation between TRC test and RRC test

It has been proved in the above sections that stresses and strains distribute almost the same in TRC test as in RRC test if loading condition is properly chosen. In this case, it is very important not only to control temperature of the specimen but also to estimate the final restraint force without conducting RRC test. This final restraint should be used in TRC test. As a result, the correlation between TRC test and RRC test may be clarified.

Shrinkage S by TRC test was obtained by thermal elastic-plastic analysis. Transverse deformation due to free expansion and contraction produced in free TRC test specimen (angular deformation is restricted, the end surface is kept perpendicular to the horizontal plane, and length between chucks is set as *300mm*) was calculated. As the result, the relation between temperature at the root and displacement at the end was obtained as shown in **Fig. 13**. In the calculation, shrinkage below the mechanical rigidity recovery temperature (*750*°C) was assumed as free contraction S. In case of RRC test, if restraint length $2l$ is changed, restraint intensity R_f changes. That is,

$$R_f = Eh \,/\, 2l$$

where E: Young's modulus, h: thickness of base plate

In RRC test, this free contraction S is restricted under various restraint intensity R_f, so that restraint stresses are produced in response to respective restraint intensity as shown by "o" in **Fig. 14**.

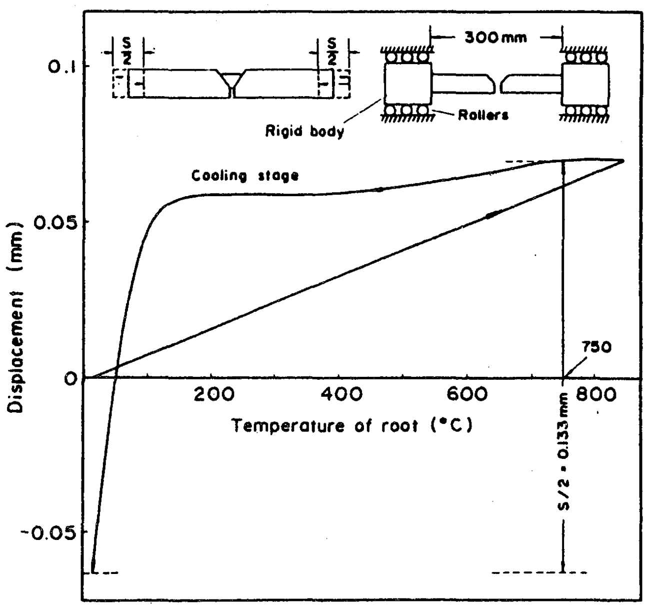

Fig. 13 Free expansion and contraction of butt welding joint

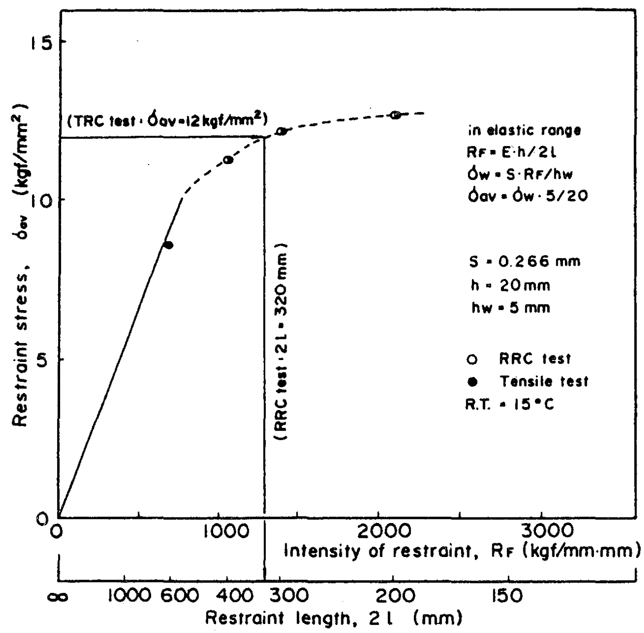

Fig. 14 Relation between restraint stress and intensity of restraint or restraint length

It was assumed that temperature history in the loading process and its effect on the mechanical properties of material can be neglected. In this case, if a tensile force is applied to make free contraction S zero using various length between chucks, the relation between load and $2l$ when S is zero should coincide with the relation in Fig. 14. Assuming that the average temperature of the specimen at the test is *15*°C, an elastic-plastic analysis was performed. The analytical results on this tension test almost coincide with the results of RRC test as shown by "●" in Fig. 14. This implies that basic behavior can be reproduced highly accurately even by an elastic-plastic analysis. In this calculation, such material as mild steel was assumed, and the effect of phase transformation expansion was not considered. If material in which the effect of phase transformation expansion is significant is used, it is necessary to consider such effect.[6),7)] Otherwise, the calculation should be inaccurate for actual RRC test.

The afore-mentioned calculating method of the final restraint force can be transformed into the following experimental method. After applying the first layer weld to a butt welded joint, free contraction S is observed keeping angular distortion zero. Then, variously changing restraint length, the specimen is loaded so as to make free contraction S zero. As the result, the relation between the final load (the final restraint force) and the restraint intensity (or restraint length) can be obtained. In this way, using several specimens with different restraint length, the relation between the restraint intensity and final restraint force can be directly obtained.

It is also possible to draw up the same relation from a single specimen, if the following steps are taken. After conducting a tension test (stretching) on a specimen with an arbitrary gage length $2l$, the relation between load P and elongation u is found out as in **Fig. 15**. When the gage

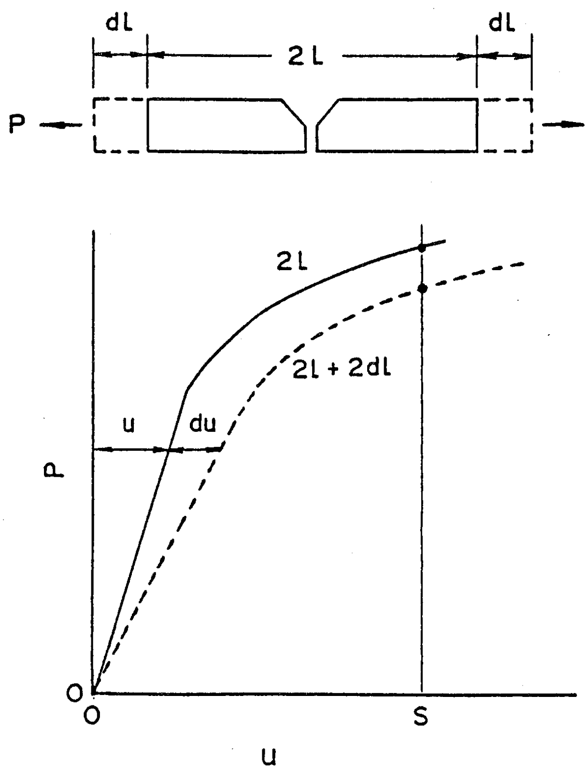

Fig. 15 Relation between load and displacement in tensile test

length of the specimen increases from $2l$ to $2l + 2dl$, the additional portion $2dl$, which is always in elastic region, elongates additionally by $du=P{\cdot}2dl/E{\cdot}A$ under load P based on this relation (A: cross sectional area of base plate). That is, the total elongation of the specimen under the same load P is $u + du = u + P{\cdot}2dl/E{\cdot}A$ as indicated by the broken line in Fig. 15. The final restraint force P_r in the specimen of length $2l + 2dl$ can be calculated referring to the condition, $u + du = u + P{\cdot}2dl/E{\cdot}A=S$. And the restraint intensity R_l can be given as $R_l = Eh/(2l + 2dl)$. With thus calculated P_r and R_l, changing dl variously, the P_r and R_l relation can be easily obtained from the P-u curve which was obtained experimentally with one specimen.

As having pointed out previously, setting of temperature at the initial loading is also very important in TRC test. If this temperature is assumed to correspond to the time when the restraint force in RRC test starts to rise after stagnation (stresses at the end of specimen), it can be easily obtained by an experiment as well as by a simple one-dimensional heat conduction calculation.

After temperatures at the initial and final loadings, and the restraint force are determined as described above, TRC test is conducted using these determined values. Distributions of stresses and strains produced in the welded portion of TRC test are almost the same as those of RRC test in which temperature history is considered. On the contrary, when an arbitrary load is applied in TRC test and stresses and strains are obtained, it is easy to tell from the restraint stress-intensity relation shown in Fig. 14 that which restraint intensity (restraint length) in RRC test the restraint condition of this TRC test corresponds to. In this case, if temperature at loading is higher than the temperature range corresponding to the obtained restraint length, strains of TRC test do not agree to those of RRC test.

So far, detail study has been made on the correlation between TRC test and RRC test based on the results of theoretical analyses. There may be a small amount of scatter in the experimental results of TRC and RRC tests, and they indicate small difference. From the nature of the tests, both TRC and RRC tests are not highly reproduceable. One of the main purpose of these testing methods is to select appropriate critical restraint intensity, critical restraint stresses, or preheating temperature for prevention of welding cold cracks. Judging from the above mentioned facts, the study and discussion made in this paper are accurate enough for this purpose.

5. Conclusion

The dynamical characteristics of TRC test and RRC test, and their correlation were investigated based on the results of thermal elastic-plastic analysis by the finite element method. The results can be summarized as follows:

(1) If a loading history similar to the stress development history in RRC test is given in TRC test, almost the same stress and strain distributions at the weld as of RRC test can be obtained in TRC test. From the dynamical point of view, there is not essential differ-

ence between these testing methods.

(2) In TRC test almost the same final stress-strain distribution at the weld as of RRC test can be obtained even though the loading history is propotional either to time or temperature, if (a) the initial load is applied at the same temperature as of the weld when heat conducts out of the restraint length, (b) the temperature at the final loading is the same as of RRC test, and (c) the value of the final load (final restraint force) is the same as of RRC test. In TRC test, if the initial load is applied when the temperature of the wled is high and so at the final load, plastic strain in the weld is much larger than the case in which loads are applied at low temperature, even though the final load are the same. This may cause a big difference in accumulation of hydrogen.[8] It is obvious that timing of loading plays an important role.

(3) One of the importance in TRC test is determination of the final load. In order to clarify the correlation with RRC test, the relation between the final load and restraint intensity should be obtained through the following steps.

The first thing is to measure free contraction S. Then an arbitrary length between chucks $2l$ of a specimen is put to a tensile test so as to attain a load-elongation curve. Nextly, finding the condition that free contraction S is zero from this load-elongation curve, the relation between restraint length (restraint intensity) and final restraint force can be obtained. In this result, equivalent results can be obtained in TRC test to those of RRC test.

(4) If the final load is the same, the effect of the restraint length is negligible in TRC test.

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