Effect of Transformation Expansion on Restraint Stress of Weldment in Relation to Cold Cracking of High Strength Steels†

Fukuhisa MATSUDA* Hiroji NAKAGAWA Kenji SHINOZAKI*** Yasuhiro NISHIO**** Hiroshi KIHARA*******

Abstract

The effects of the transformation expansion on the restraint stress in root pass welded joint of various strength steels of SM41, HT60, HT80, HY130 and HY150 were quantitatively investigated using the RRC test by GTA welding with filler wire.

Consequently, final values of the restraint stress decreased with an increase in strength levels of base steel, namely in the order of SM41, HT60, HT80, HY130 and HY150.For example, the final restraint stresses in SM41, HY130 and HY150 were about 50, 22 and 15kgf/mm^2, respectively, in restraint intensity of 1000kgf/mm·mm. Moreover it was revealed that the final restraint stress decreased approximately linearly as transformation expansion of welded joint obtained by dilatometric technique. Additionally from this investigation, it was suggested that the transformation temperatures of HAZ and weld metals also related to reducing final restraint stress.

KEY WORDS: (Cold Cracking) (High Strength) (GTA Welding) (Transformation) (Restraint)

1. Introduction

Recently HY type steels which have good weldability, high strength and good toughness have been developed. Already HY80, 90 and 110 have been practically used. As regards HY130, however, a serious problem with this material is the high susceptibility to cold cracking in weld metal. Certainly, the value of the lower critical stress (LCS) of HY130 evaluated with the TRC and the LB−TRC test is lower than that of HT80[1),2)] which has been limited to practical use until now due to its high susceptibility to cold cracking.

As well known, hydrogen-induced cold cracking in weldment is generally attributed to three major factors, namely hardened microstructure, diffusible hydrogen content and restraint stress. Since HY130 steel is designed as higher strength and for special purposes, it is difficult to diminish the hardness of heat affected zone (HAZ) and weld metal by modifying the chemical composition. Also it is difficult to expect the increase in the LCS by decreasing the diffusible hydrogen content, because even the LCS with GTA welding which is the lowest hydrogen levels is not sufficient.[2),3)] Moreover welding design to decrease the restraint intensity of welded joint is generally difficult, because HY steel is usually used to heavy thick construction. Thus GTA welding with preheating temperature is the most useful fabricating procedure for the welding of HY130 or higher steel under severe restraint.

On the other hand, it was shown[4)] that the restraint stress of a higher alloy steel like 9%Ni steel is faily lower than usual low alloy high strength steel because of the expansion due to martensitic transformation during cooling after welding. This suggests that, even if a high strength steel has a very low LCS, the steel may be crack−free for welding by the aid of the transformation expansion. Moreover, following HY130 steel for future object, HY150 and HY180 are going to design as higher nickel alloy steel and are also going to expect a sound welding in future.

This study was done for the purpose of development of possibility of a sound welding of higher grade steel in HY type having a low LCS, utilizing the transformation expansion of weldment including weld metal and HAZ of base metal.

2. Materials Used and Experimental Procedures

2.1 Materials used

Base metals used were mild steel SM41*) and

† Received on September 30,1982

* Professor

** Research Instructor

*** Research Associate, Fuculty of Engineering, Osaka University

**** Professor, Fuculty of Engineering, Kinki University

***** Emeritus Professor of Tokyo and Osaka Universities

Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka, Japan

*) SM follows JIS (Japan Industrial Standard), HT is common name for high strength steel in Japan.

Table 1 Designation, type of chemical compositions, yield and tensile strengths of materials used

Base metal (35mm thickness)	Filler wire (1.6mm dia.)	Yield stress of base metal (kgf/mm^2)	Ultimate stress of base metal (kgf/mm^2)
SM41	F41	22	45
HT60(0.1Mo-V)	F60(0.4Mo)	55	65
HT80(1.3Ni-Cr-Mo-V)	F80(2.6Ni-Mo)	78	84
HY130(5.1Ni-Cr-Mo-V)	F(130)(2.5Ni-Cr-Mo)	96	102
	F(130)N(15.0Ni-Cr-Mo)		
	F(180)(10.0Ni-Cr-Mo-Co)		
HY150(8.6Ni-Cr-Mo)	F(150)(8.3Ni-Cr-Mo)	115	120

weldable heat–treated high strength steels HT60*), HT80, HY130 and HY150 whose nominal ultimate strengths were 40, 60, 80, 100 and 120 kgf/mm^2, respectively.

Filler wires used for automatical GTA welding were well matched with base metals in strength levels, and named temporally as F41, F60, F80, F(130), F(130)N, F(150) and F(180) according to its strength level.

Among them F41, F60 and F80 were commercial filler wires and the others were experimental ones. The diameters of them were 1.6mm. Designations, type of chemical compositions, yield strengths and ultimate tensile strengths of materials used were shown in **Table 1**.

2.2 The RRC test used

In this study, the RRC test was used in order to investigate quantitatively the effect of transformation expansion on the restraint stress of weldment.

The RRC (Rigid Restraint Cracking) test has been originally developed by Watanabe et al.[5] in order to evaluate susceptibility to cold cracking of weld zone under rigid restraint condition. In the RRC test, a gauge length across weld line is set and is kept to initial value by applying reaction force against contraction of weldment during and after welding. Generally, the longer the gauge length is, the lower the reaction force is. Moreover the change in the reaction force vs. time or temperature gives information of transformation behavior in weld zone.

By the way, as well known the restraint intensity R_F which indicates the intense of restraint stress of the weldment is defined as the reaction force per unit weld length necessary to return elastic contraction of unit millimeter perpendicular to weld line, and thus expressed by:

$$R_F = Eh/l \quad (1)$$

where: R_F : restraint intensity (kgf/mm·mm)

E : Young's modulus (kgf/mm^2)

h : plate thickness (mm)

l : restraint length, namely the gauge length in this study (mm).

It is revealed by Satoh et al.[4] that final value of restraint stress σ_∞ applied in weld zone theoretically increases in proportion to restraint intensity R_F, when elongation of weld metal is much smaller than that of base metal, and that σ_∞ is given by:

$$\sigma_\infty = (S_\infty / h_W) R_F \quad (2)$$

where: S_∞ : final contraction (mm)

h_W : throat depth of weld zone (mm).

Assuming that the physical constant of material is constant independently of materials used. Then S_∞ is represented by:

$$S_\infty = S_o - \delta_t \quad (3)$$

where: S_o : final contraction without phase transformation (mm)

δ_t : transformation expansion of weldment (mm)

Therefore, the final restraint stress σ_∞ including the effect of phase transformation is obtained by substituting Eq. (3) into Eq.(2)

$$\sigma_\infty = \{(S_o - \delta_t)/h_W\} \cdot R_F \quad (4)$$

This equation indicates that σ_∞ is influenced by δ_t, because S_o and h_W are regarded as nearly constant independently of materials in weldment used.

In this study, two plates with U–groove were put on an universal cracking tester of 25 ton max. in load and butted together with a gap of 1.6mm, and then a test weld bead was deposited as shown in **Fig. 1(a)** and **(b)**. GTA welding with filler wire was used with commercially pure argon shielding gas and constant wire feed system utilizing welding current of 300A, arc voltage of 14V and welding speed of 120mm/min.

By the way, in advance of welding the two plates were arranged with two wedges and two rollers as shown in **Fig.1(c)** and **(d)** to prevent angular and

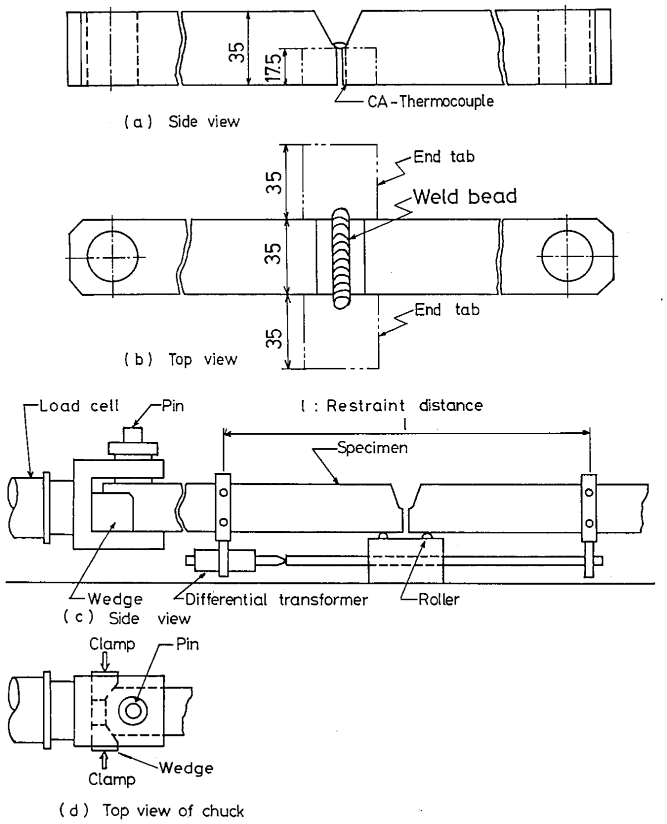


Fig. 1 Dimensions of the RRC test specimen and its setting method

rotational deformation during and after welding. The instantaneous change in the selected gauge length preset was measured using a differential transformer set under the specimen whose measurement accuracy was ± 0.002mm.

The driving motor of the tester automatically keeps the gauge length constant by the indication of the differential transformer. As mentioned later, the reaction force of HY130 and 150 became to zero for a while before the final increment, because the transformation expansion overcame the thermal contraction during cooling after welding. In this case, the gauge length was allowed to expand freely until the gauge length returned to the initial value in order to prevent buckling owing to contractive force.

Two levels of the restraint intensity R_F of 1000 and 3000 kgf/mm·mm were applied, which correspond to gauge length of 735 and 245 mm, respectively. The reaction force showed different mode depending on type of material after welding, and finally reached to a final value at about 100 min after welding, so all the test were stopped after two hours.

The measurement was repeated for 3 or 4 times under the same restraint intensity. The restraint stress was determined by dividing the reaction force by the area of longitudinal cross section, which was

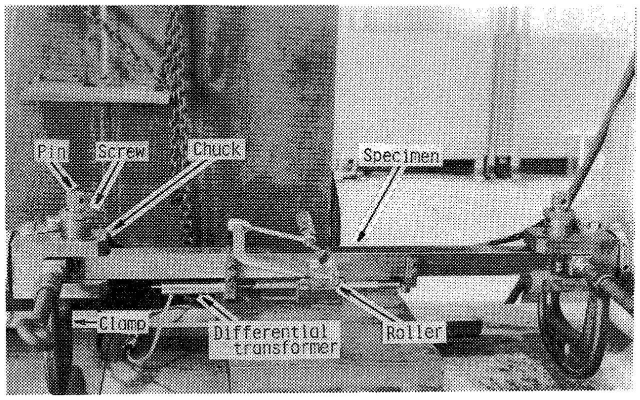


Fig. 2 The RRC test set up

usually obtained as the product of bead length of 35 mm and throat depth of 4 mm. Overall appearance during the RRC testing is shown in **Fig.2.**

2.3. Dilatometric technique

Dilatometric specimens of base metal and weld metal of root pass were directly cut from the RRC tested specimens into 10mm in length and 3mm in diameter. The dilatometric specimens for weld metal were removed along welding direction. Dilatometric specimens were subjected to a simulated welding thermal cycle with high frequency induction heating, in which peak temperature was 1350°C, the time required to reach it was about 5 sec, the holding time

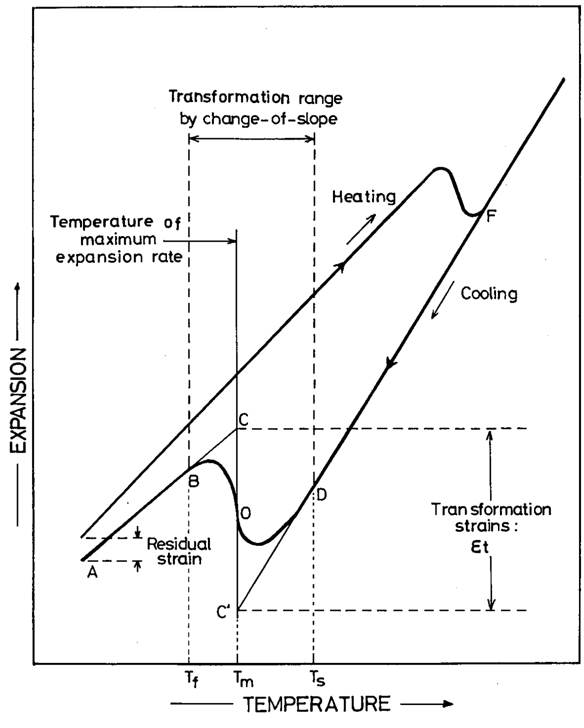


Fig. 3 Definitions of significant features in a high speed dilatometric curve by Stout et al.

was 5 sec and the cooling time from 800 to 500°C was about 5 sec.

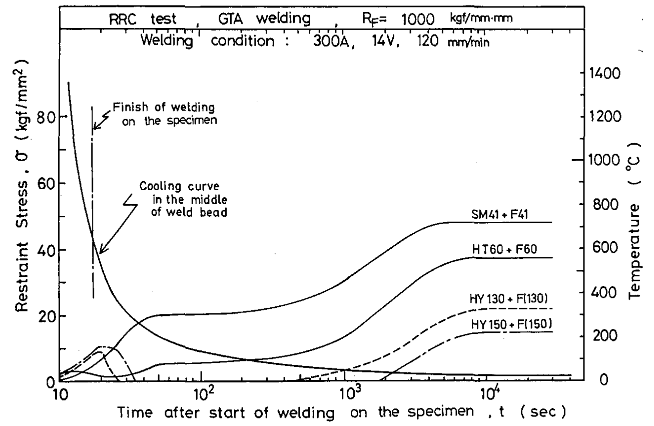
A schematic dilatometric curve obtained by Stout et al.[6] is presented in **Fig. 3** to define the transformation strain ε_t and temperature parameters.

In this study, dilatometric data were measured in accordance with the definition in Fig. 3. Namely, temperatures at the beginning (T_s) and end of transformation (T_f) were taken as the "change-of-slope" points on the dilatometric curves. Transformation strain ε_t was defined by dividing transformation expansion at temperature of maximum expansion rate (T_m) by the length of dilatometric specimen.

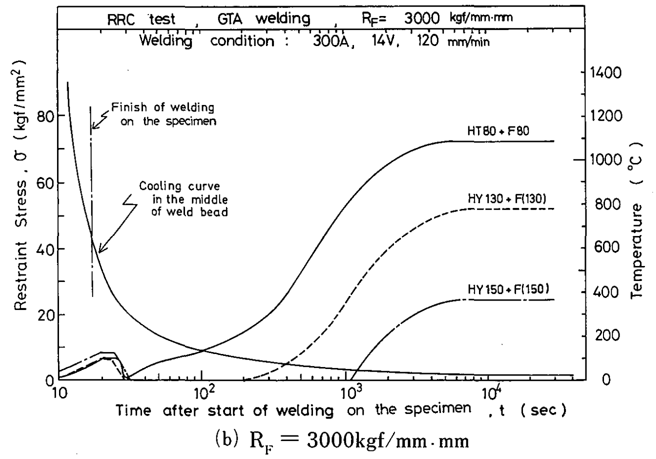
3. Result and Discussion

3.1 Study on restraint stress

Figure 4(a) and **(b)** show continuous developments of the restraint stress for weldments in different combination of base metal and filler wire with a cooling curve in the middle of weld bead in the restraint intensities R_F of 1000 and 3000 kgf/mm·mm. Development of restraint stress in SM41 weldment is roughly classified in three steps as revealed by Satoh.[4] Namely, the restraint stress



(a) R_F = 1000kgf/mm·mm



(b) R_F = 3000kgf/mm·mm

Fig. 4 Change of restraint stress during cooling

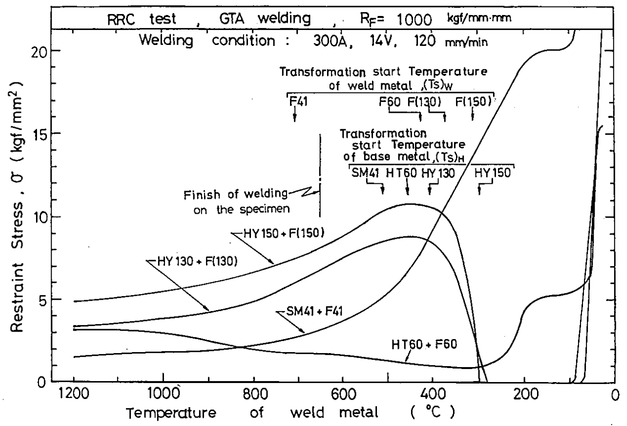
increases rapidly for 50 sec immediately after start of welding (the first step), then is constant for about 200 sec (the second step) and again increases gradually to the final value of about 50 kgf/mm^2 (the third step). The development of the restraint stress in SM41 weldment is similar to the contraction process calculated by Satoh et al.[4] The restraint stress in HT60 weldment increases for about 15 sec, then slightly decreases and hereafter develops similar to SM41. As later shown, the slight decrease is influenced by the transformation expansion in HT60 weldment.

However, the developments of the restraint stress in HY130 and HY150 weldments are different from that in SM41 weldment. Namely, for example, the restraint stress in HY130 increases rapidly for about 20 sec after start of welding, then rapidly decreases to zero and is constant in zero for about 500 sec and again increases gradually to the final value of about 25 kgf/mm^2 in the time period from 500 sec to 100 minutes (6000 sec) after start of welding. The development of the restraint stress in HY150 shows similar mode to that in HY130, though the final restraint stress is lower than that of HY130.

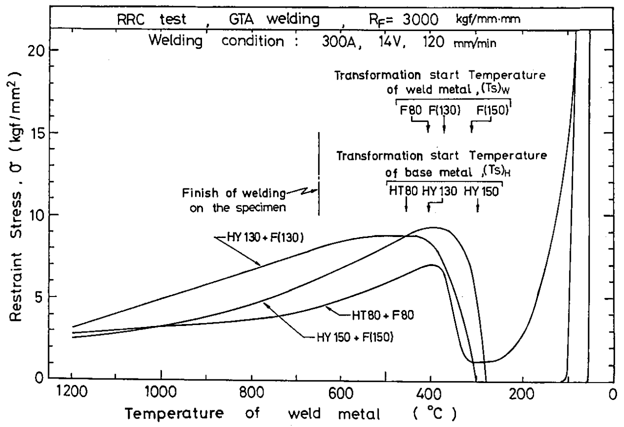
It is noteworthy that the final restraint stress σ_∞ in different weldment decreases in the order of SM41, HT60, HY130 and HY150. In R_F of 3000 kgf/mm·mm in Fig. 4(b), the restraint stresses in HT80, HY130 and HY150 develop like those in Fig. 4(a). However, σ_∞ in R_F of 3000 kgf/mm·mm is higher than that in R_F of 1000 kgf/mm·mm, although the restraint stress in the first step in 3000 kgf/mm·mm approximately equal to that in 1000 kgf/mm·mm.

Then, the relationships between temperature in the middle of weld bead and the restraint stress are shown in **Fig. 5(a)** and **(b)** for the purpose of understanding the reason why the restraint stress in HT80, HY130 and HY150 weldments especially decreases in the first and second steps. The start temperatures (T_s) of transformation in the base and weld metals obtained by dilatometric curves are also shown in same figures, which are tabulated in Table 3 later shown in 3.2.2. The restraint stresses in HT80, HY130 and HY150 weldments decrease in the range 400 to 300°C. This temperature range approximately corresponds to the start temperature in the dilatometric data for these base and weld metals.

Judging from the above mentioned, the decrease in the restraint stress in HT80, HY130 and HY150 weldments except for SM41 and HT60 weldments in the first step is strongly related to the expansion of transformation from phase to phase. It seems that transformation expansion doesn't effectively influence



(a) $R_F = 1000$ kgf/mm·mm



(b) $R_F = 3000$ kgf/mm·mm

Fig. 5 Change of restraint stress during cooling

to SM41 and HT60, because transformation temperature is so high that plastic deformation easily occurs in weld zone.

As mentioned in the above, the transformation expansion of weldment directly and strongly starts to have the effect on the restraint stress at the first step and continues to have the effect even in the second step. On the other hand, as well known cold cracking occurs at temperature below about 200°C. Therefore, it is considered that the restraint stress in the first step is not directly related to cold cracking σ_∞ is the most important for cold crack susceptibility. Hereafter, σ_∞ is mainly discussed.

Satoh et al.[4] experimentally investigated the Eq. (2) in mild steel and HT80, and proved that the values of S_∞/h_W in both materials is approximately equal with each other in both materials in elastic range. However transformation expansion in HT80 is expected to be large in comparison with mild steel, so the final restraint stress in HT80 is guessed to be lower than that in mild steel by the Eq.(3).

By the way, **Fig.6** shows the relationship between the restraint intensity R_F and the final restraint stress σ_∞. In the figure, broken line shows the

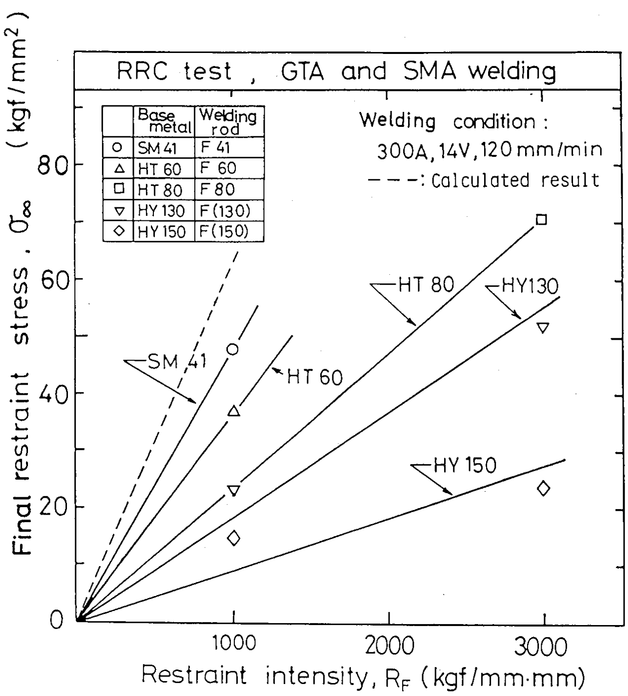


Fig. 6 Relationship between restraint intensity and final restraint stress

Table 2 Physical constants and testing condition for calculating S_∞

Physical constant		testing condition	
Specific heat, c (cal/°C·g)	0.128	Plate thickness, h (cm)	3.5
Density, ρ (g/cm³)	7.79	Throat depth, h_W(cm)	0.4
Thermal diffusivity, k (cm²/sec)	0.146	Heat input, Q (cal/cm)	3250
Coefficient of linear expansion, α (°C⁻¹)	12.3 x 10⁻⁶	Gauge length, l (cm)	73.5

calculated value using the Eq. (2) where h_W is 4mm and S_∞ (=S_0) is 0.25mm. This valus was calculated by the equation obtained by Satoh et al.[8] without consideration of phase transformation. The physical constants used for calculation of S_∞ are shown in **Table 2.** The final restraint stresses in the weldments in this investigation are low in comparison with calculated value and decrease with an increase in strength levels, namely in the order of SM41, HT60, HT80, HY130 and HY150 weldments under the same R_F. Moreover σ_∞ in HT80, HY130 and HY150 weldments is estimated to increase in proportion to R_F in the range 0 to 3000 kgf/mm·mm and especially in high alloyed steel like HY150, σ_∞ is shown only about 20 kgf/mm^2 which is about 1/6 of tensile strength even in a severe restraint intensity of 3000 kgf/mm·mm.

Consequently, the transformation expansion influences not only decrease in the restraint stress in the first and second steps but also that of the final restraint stress σ_∞.

3.2 Study on dilatometric characteristics

As already shown the transformation expansion influences σ_∞. Therefore dilatometric charactristics of base and weld metals were measured in order to investigate quantitatively the effect of transformation charactristics of the weldment on σ_∞.

3.2.1 Transformation strain of heat affected zone and weld metal

Figure 7 shows relationship between transformation start temperature T_S and transformation strain ε_t in different HAZ and weld metal. Transformation strain of HAZ $(\varepsilon_t)_H$ slightly increases as the transformation start temperature decreases.
On the other hand, transformation strains of weld metal $(\varepsilon_t)_w$ are approximately constant in the range 700 to 400°C, then increase rapidly as the transformation start temperature decreases below about 400°C. Besides, $(\varepsilon_t)_w$ are larger than $(\varepsilon_t)_H$ below about

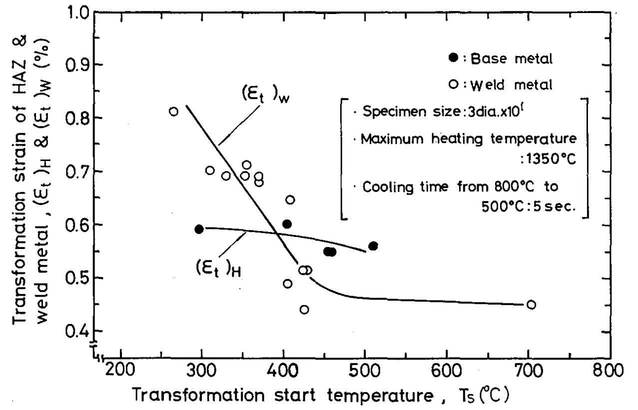
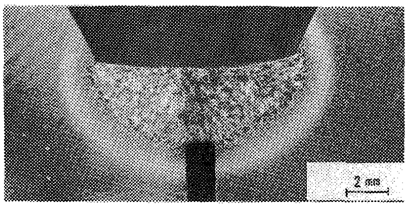
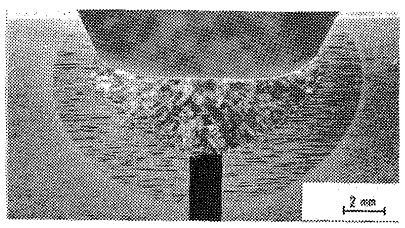


Fig. 7 Relationship between transformation start temperature and transformation strain of HAZ and weld metal



(a) HT60



(b) HY150

Fig. 8 Macrograph of cross section of weld zone

400°C. Although this different behavior is incomprehensible now, difference in minor chemical compositions, anisotropy of columnar crystal, microsegregation during solidification and so on in weld metal are considered to be related to this difference.

3.2.2 Estimation of transformation expansion of weld zone

Figure 8 (a) and **(b)** represent typical cross sections of weld zone in HT60 and HY150. The shape of weld metal of both materials is similar but the size of HAZ is larger in HY150 than in HT60 which is due to lower temperature in the transformation temperature $\alpha \rightarrow \gamma$ in HY150. Now, hardness distributions of HAZ are shown for each weldment in **Fig. 9.** In this figure, the arrow of solid line indicates the boundary between discolored HAZ and base metal, and approximately coincides with the change in hardness. Consequently, the breadths of HAZ increase with an increase in strength levels of materials used. **Figure 10** shows a schematic illustration of weld zone. Then

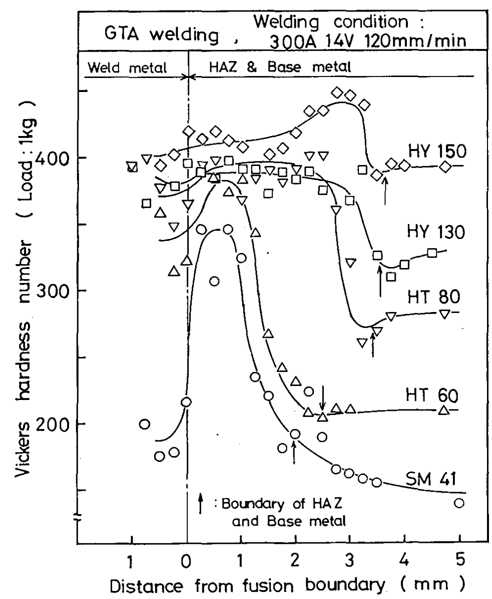


Fig. 9 Hardness distribution of HAZ in materials used

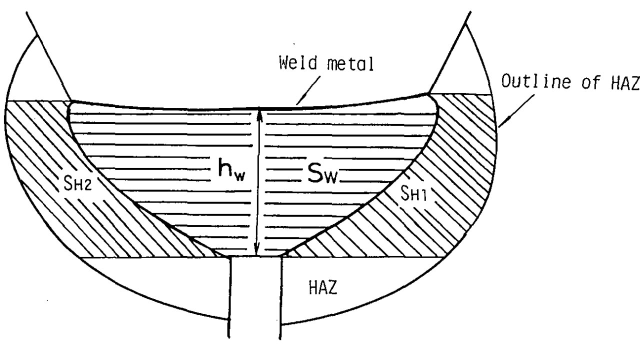


Fig. 10 Schematic illustration of weld zone

Table 3 Summary of dilatometric data

Material		Transformation temperature (°C) Start (Ts)	Finish (T_f)	Transformation strain of HAZ & weld metal, $(\varepsilon_t)_H$, $(\varepsilon_t)_w$ (%)	Transformation expansion of HAZ & weld metal, $(\delta_t)_H$, $(\delta_t)_w$ ($\times 10^{-2}$ mm)	Total transformation expansion of weld joint δ_t ($\times 10^{-2}$ mm)
SM41	B.M.*	510	328	0.55	3.8	—
	F41	703	537	0.45	3.1	6.9
HT60	B.M.	455	226	0.56	3.1	—
	F60	425	322	0.44	3.0	6.1
HT80	B.M.	455	170	0.56	3.8	—
	F60	425	175	0.51	3.5	7.3
	F80	405	150	0.50	3.4	7.2
	F(130)	408	115	0.64	4.4	8.2
	F(150)	355	108	0.72	4.9	8.7
HY130	B.M.	405	136	0.60	4.3	—
	F60	425	295	0.51	3.5	7.8
	F(130)	370	121	0.69	4.7	9.0
	F(130)N	265	20	0.81	5.5	9.8
	F(150)	330	78	0.69	4.7	9.0
	F(180)	353	75	0.69	4.7	9.0
HY150	B.M.	298	62	0.59	5.0	—
	F(130)	370	85	0.69	4.7	9.7
	F(150)	310	63	0.70	4.8	9.8

* : B.M.: Base metal

average breadths of weld metal (l_W) and HAZ (l_H) were defined by:

$$l_W = S_W/h_W \ , \ l_H = (S_{H1}+S_{H2})/h_W \qquad (5)$$

where: S_W : area of weld metal (mm²)
S_{H1}, S_{H2} : area of HAZ (mm²)
h_W : throat depth of weld metal (mm).

If it is assumed that transformation behavior of welded joint is the same as that of dilatometric specimen, the transformation expansions of weld metal $(\delta_t)_w$ and HAZ $(\delta_t)_H$ in welded joint and the total transformation expansion of welded joint δ_t are given by

$$(\delta_t)_w = (\varepsilon_t)_w \cdot l_w \ , \ (\delta_t)_H = (\varepsilon_t)_H \cdot l_H \qquad (6)$$
$$\delta_t = (\delta_t)_w + (\delta_t)_H$$

where $(\varepsilon_t)_w$ and $(\varepsilon_t)_H$ are transformation strains of weld metal and HAZ, respectively. Dilatometric date are summarized in **Table 3**.

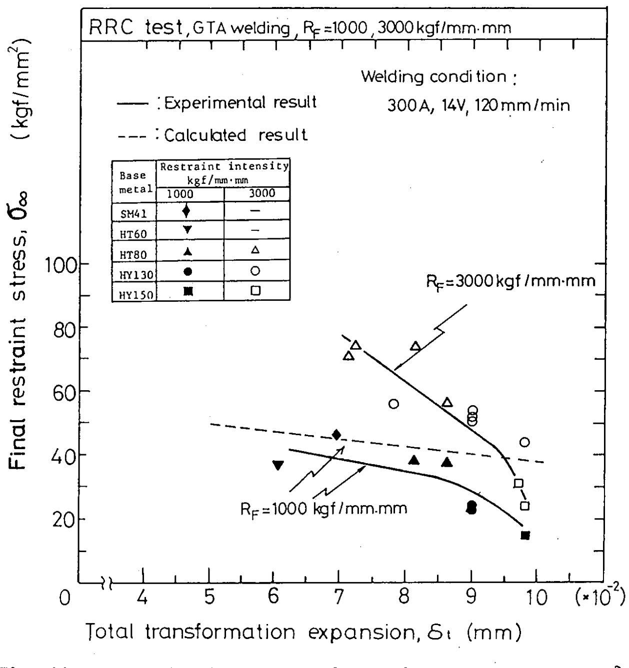


Fig. 11 Relationship between total transformation expansion δ_t and final restraint stress σ_∞. Comparison experimental result with calculated result

3.3 Correlation between transformation expansion and final restraint stress

The relationship between the transformation expansion δ_t and σ_∞ is shown in **Fig 11**. The final restraint stress in solid lines (experimental result) approximately decrease linearly up to HT80 or HY130 weldment and then crookedly with an increase in δ_t independently of restraint intensity. However decreasing gradient against δ_t is higher in high R_F. It means that the weldment which has a high δ_t is much effective for the reducing of σ_∞ in the joint of higher R_F. In HY150 weldment, for example, there is not obviously difference in σ_∞ between 3000 and 1000 kgf/mm·mm of R_F, even though there is three times difference in R_F. Broken line shows calculated results for 1000 kgf/mm·mm of R_F using the Eq. (4) where h_W is 4 mm and S_∞ is 0.25 mm as described in 3.1. The experimental result is lower in comparison with the calculated result. The difference between the experimental and the calculated results increases with an increase in δ_t more than about 0.09mm, namely HY130 and HY150 weldments. This is considered that increasing δ_t is much effective for reducing σ_∞ in HY130 and/or HY150 weldment in comparison with the other weldments. This means that another reason besides δ_t exists for reducing σ_∞ in HY130 and/or HY150 weldment. The authors think that the another reason will correspond to transformation temperature from the result in Table 3. The transformation temperatures of HY130 base and weld metals are lower than those of HT80 base and weld metals, respectively. Furthermore those of HY150 are much lower than those of HY130. The transformation temperature of HY150 is the lowest of all steel weldments used. Therefore not only large δ_t, but also low transformation temperature are very useful to reduce σ_∞ in HY150 weldment.

3.4 Effect of base and weld metals on final restraint stress

Since the expansion coefficients and transformation temperatures of base and weld metal have respective different value, it is important to know the effect of the combination of each base and weld metals on final restraint stress σ_∞.

Figure 12 shows σ_∞ in different combination of HT80,HY130 and HY150 steels with F60, F(130) and F(150) filler wires. Figure 12 shows that the dependence of base metal for σ_∞ is larger than that of filler wire irrespective of R_F. Especially the reducing of σ_∞ is clear in HY150 base metal. However, σ_∞ is considerably reduced using F(150) filler wire in HT80 and HY150 for 3000 kgf/mm·mm of R_F, though there is no evidence in HY130. These results suggest that the decrease in the transformation temperature besides the increase in the transformation expansion strongly effects the reducing in σ_∞. The crack—free weldments of HY130 and HY150 steels may be completed by developing the higher alloy filler wire having high expansion coefficient and low transformation temperature during cooling after welding. However the completion of crack—free weldment may be much easier in HY150 than in HY130.

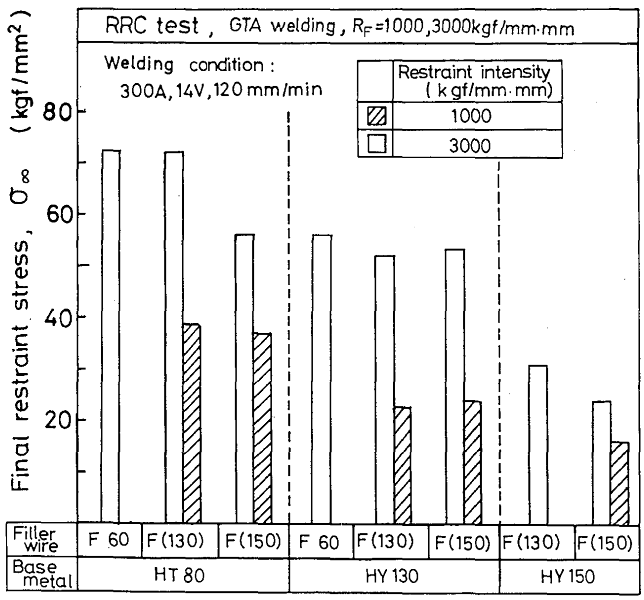


Fig. 12 Final restraint stress of various combinations of base metal and filler wire

4. Conclusion

The effect of transformation expansion on the restraint stress in root pass welding was studied by changing base metal and filler wire using the RRC test.

Main conclusions obtained are as follows;

(1) There is an obvious effect of transformation expansion during cooling on the reduction of the final restraint stress. The effect of transformation expansion on the reduction in the final restraint stress is much obvious in the weldments whose total expansion is larger and restraint intensity is greater. Thus final restraint stress decreases in the order of SM41, HT60, HT80, HY130 and HY150 weldments, namely in the order of strength in this investigation. For example, the final restraint stresses in SM41, HY130 and HY150 were about 50, 22 and 15kgf/mm^2, respectively, in restraint intensity of 1000kgf/mm·mm.

(2) The reduction in the final restraint stress can be also estimated to be attributed to the transformation temperature in addition to the transformation expansion of weldment. The lower the transformation temperature is, the more the reduction in the final restraint stress is. This is cleared in the weldment of HY150 whose transformation temperature is considerably low in comparison with other steels. The combination of the two transformation phenomena reduces obviously the final restraint stress of HY150 weldment. Moreover the final restraint stress in HY150 weldment is not so increased with increase in the restraint intensity.

Acknowledgement

The authors would like to express our gratitude to Mr. Hitoshi Takaguchi, formerly student of fuculty of engineering of Kinki University, for his cooperation of testing and to thank Nippon Steel Cooperation for offering materials used in this investigation.

References

1) F.Matsuda et al.: Trans. JWRI, Vol. 6 (1977) , No.2,pp. 59–73
2) F.Matsuda et al.: Trans. JWRI, Vol.8 (1979), No.1, pp. 113–119
3) F.Matsuda et al.: Trans. JWRI, Vol. 10 (1981), No. 2, pp. 55–63
4) K.Satoh et al.: Tech. Reports of Osaka Univ., Vol. 17 (1967), No. 783, pp. 353–375
5) M.Watanabe et al.: Welding Research Abroad, Vol. 10 (1967), No. 8
6) L.F.Bubba, H.H. Johnson and R.D. Stout: Welding Journal, Vol. 40 (1961), No. 8, pp. 364s–370s
7) C.G. Interrante and R.D.Stout: Welding Journal, Vol. 43 (1964), No. 4, pp. 145s–160s
8) K.Satoh et al.: J. Japan Welding Soc., Vol. 35 (1966), No. 3, pp. 246–256 (in Japanese)