EFFECT OF Ms TEMPERATURE ON RESIDUAL STRESS IN WELDED JOINTS OF HIGH-STRENGTH STEELS




C. Shiga **H.Y. Yasuda** **K. Hiraoka** **H. Suzuki**

ABSTRACT

Thermal stress in the weld joints of high-strength steels after welding receives a great influence of dilatation stress during phase transformation, especially martensitic transformation of the low temperature region in weld metal. In order to quantify the amount of residual stress linked with thermal stress, neutron diffraction analyses were carried out in the welded joints having weld metals with very reduced Ms temperatures. In the butt joint of weld metal with an Ms temperature of about 60 °C, compressive residual stresses of about -400 MPa at the weld centre and of about -75 MPa at the toe were observed. The residual stress distributions were quite different from those of conventional weld metals, which have a tensile residual stress of about 400-500 MPa. The formation mechanism of compressive residual stress and the effect of restraint stress and stress-induced transformation on it are discussed, including previous data. It can be concluded that the reduction amount of residual stress induced by low Ms weld metal is about 11-15 MPa per unit length within about 70 mm weld length.

IIW-Thesaurus keywords: *Austenite; Cold cracking; Cracking; Defects; Diffraction; Fatigue strength; High strength steels; Martensite; Neutron radiation; Radiation; Reference lists; Residual stresses; Steels; Transformation; Weld metal; Welded joints.*

1 INTRODUCTION

Strengthening of steel has the great advantage of making light-weight steel structures, but it also creates many kinds of welding problems, such as weld cracking, stress corrosion cracking and fatigue strength degradation. If these problems are not solved, the application of high-strength steels to steel structures is limited. The relationship of welding problems and their metallurgical factors is shown in Table 1, which summarizes the problems caused by tensile residual stress [1]. This study examines the reduction of residual stress by taking advantage of the dilatation effect of martensitic transformation in weld metal using low transformation temperature welding wire (LTTW) [1-4]. The dual phase microstructure of martensite and austenite in the weld metals obtained by extremely low Ms temperature has been found to be most suitable for improving weld properties, such as fatigue strength [5-7] and cold cracking [8-12], because of the tensile stress reduction effect of phase transformation and the hydrogen trapping effect of retained austenite. But since the dual phase microstructure of martensite and austenite in the weld metals has poor impact-absorbed energy, the oxygen content in weld metals needs to be reduced to below 100 ppm for high impact -absorbed energy [13, 14]. To reduce the oxygen content, we

Prof. Dr. Chiaki SHIGA (shiga@jwri.osaka-u.ac.jp), Prof. Dr. Hiroyuki Y. YASUDA (hyyasuda@mat.eng.osaka-u.ac.jp) and Prof. Dr. Kazuo Hiraoka (hiraoka@jwri.osaka-u.ac.jp) are all with Osaka University, Osaka (Japan). Quantum Beam Science Directorate, Dr.-Eng. Hiroshi Suzuki (suzuki.hiroshi07@jaea.go.jp) is with Japan Atomic Energy Agency, Ibaraki (Japan).

Doc. IIW-2008-09 (ex-doc. IX-2279r1-08), recommended for publication by Commission IX “Behaviour of Metals Subjected to Welding.”

Table 1 – Problems of welded joints and metallurgical analysis

Problems of welded joints		
Item of problem		Metallurgical analysis of problem
1	Weld cracking	
1-1)	HAZ cracking	• Increase in HAZ hardness due to small heat input
1-2)	Weld metal cracking	• Decrease in H_2 trap sites in HAZ • High amount of hydrogen in weld metal • Tensile residual stress • Restraint stress
2	Stress corrosion cracking	• Increase in HAZ hardness • Tensile residual stress
3	HAZ softening	• Ineffective heat inputting • (High heat inputting) • Decrease in Ceq of base steel
4	Toughness degradation	• Coarse grain growth in HAZ • M-A constituents • Tensile residual stress • Restraint stress
5	Fatigue strength reduction	• Stress concentration due to wrong bead dimension • Tensile residual stress
6	Fault existence	• Lack of fusion • Slug fault. Weld crack

have developed high efficiency MIG arc welding, using a coaxial-multilayer hybrid solid wire [15-18].

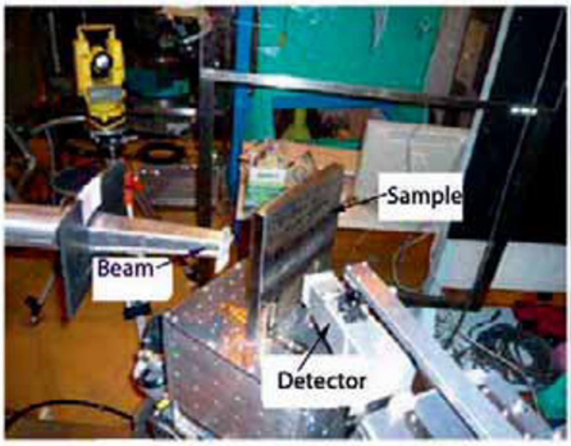
Although we have developed low Ms weld metal from a practical application aspect (such as cold cracking, fatigue and impact energy), we have not yet made an analytical study of the residual stress in newly developed welded joints, which should have the compressive stress due to the dilatation effect of martensitic phase transformation. In order to achieve the formation mechanism of residual stress reduction, which makes it possible to control the residual stress, it is necessary to observe the residual stress in three directions quantitatively at a depth of about 2-5 mm in large-sized welded joints; these are required for high restraint because residual stress may result only from welded structures with high restraint. To meet these requirements on residual stress measurements, a neutron diffraction measurement is more suitable than conventional X-ray measurements.

The first objective of this study is to clarify the residual stress distribution of welded joints with low Ms weld metals using a neutron diffraction measurement. The second objective is to construct the formation mechanism of residual stress reduction resulting from lowering Ms temperature by comparing the residual stresses between weld metals of low and conventional Ms temperatures.

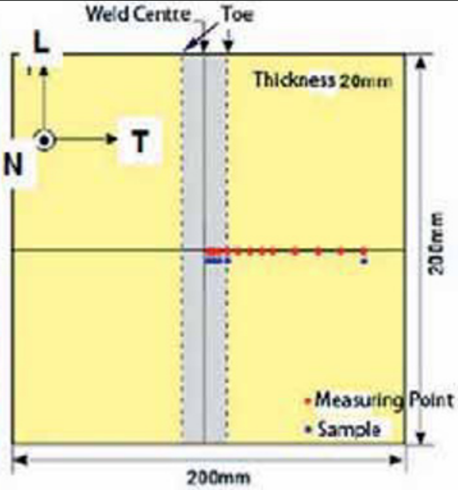
2 METHODOLOGY

To prepare the two kinds of weld metals with low and extremely low Ms, solid PS and PT weld wires of 1.2 mm diameter were used. The PT wire was prepared for the weld metal with full martensite and the PS wire for weld metal with dual-phase martensite and austenite. The welded plates were high-strength steel of 980 MPa in tensile strength and 20 mm in thickness. The MIG butt welding was carried out under the conditions of each side one pass in X-groove. Heat input was in the range of 30-40 kJ/cm. The chemical compositions of both weld metals were examined. The Ni and Cr equivalents (Ni_{eq} and Cr_{eq}) of the PS weld metal were 9.2 % and 12.8 % respectively, while those in the PT weld metal were 7.0 % and 12.0 % respectively. The oxygen content was about 20-30 ppm in the PS weld metal and about 50-60 ppm in the PT weld metal. The PS and PT weld metals are characterised by low Ms temperature and low oxygen content in comparison with conventional weld metal. Since some experiments regarding dilatation measurements and neutron diffraction analysis of conventional weld metals have been finished in the same way as this experiment, only the low Ms weld metals of PS and PT were prepared in this experiment. The dilatation measurements and neutron diffraction measurements were carefully conducted to obtain a good comparison with previous results for conventional weld metals.

Figures 1 a) and 1 b) show a general picture of the test piece during neutron diffraction measurement and the schematic drawing shows the piece dimension with weld length of 200 mm. One piece was used for making standard stress-free samples and for measuring dilatation on cooling. The other piece was used for measuring the residual stress distribution by means of neutron diffraction. The cuboidal standard sample of 6 × 6 × 6 mm^3 for neutron diffraction was made by bonding 8 cubes, with each edge measuring 3 mm in



a) General picture of neutron diffraction apparatus



b) Schematic drawing test piece of welded joint indicating diffraction measurement positions and sampling positions for standard coupons

Figure 1

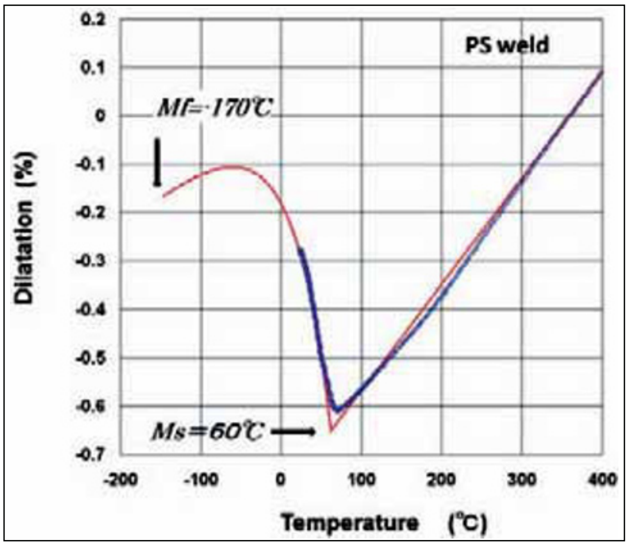
length, which were cut from the six positions in the weld joint indicated by the blue mark in Figure 1 b). The measurement method constructed by H. Suzuki (one of the present authors) was used to measure the elastic constants and lattice parameter of each cuboidal standard sample and the residual stress of welded joints [19, 20].

The neutron diffraction measurements were carried out at a depth of 2 mm from the surface, varying the beam position in the transverse direction [as illustrated by the 14 'T' positions marked in red in Figure 1 b)], using the diffractometer for residual stress analysis (RESA) at the Japan Atomic Energy Agency (JAEA) in Tokai, Japan. At each position, the residual stress components in the longitudinal (L), transverse (T) and normal (N) directions of the welds were measured. The measured residual stress in the welded joints was calibrated by the data obtained from the standard samples.

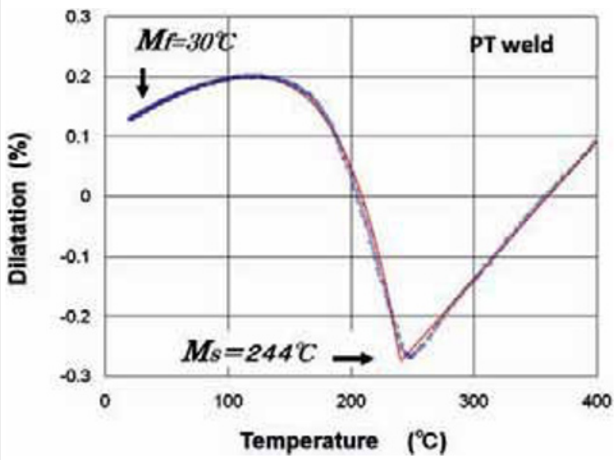
3 EXPERIMENTAL RESULTS

The temperature dependence curves of dilatation of PS and PT weld metals are shown in Figures 2 a) and 2 b), where the blue points represent the experimental values and the red lines are the estimation line. From the estimation equation using the measured values, the Ms and Mf temperatures of weld metals were calculated [21]. The Ms and Mf temperatures of the PS weld metal are 60 °C and -170 °C respectively. The Ms and Mf temperatures of the PT weld metal are 244 °C and 30 °C respectively.

The neutron diffraction peaks of the stress-free standard samples cut from PS and PT weld metals are shown in Figures 3 a) and 3 b). An austenite peak was observed in the PS weld metal [Figure 3 a)], but not in the PT metal [Figure 3 b)]. The volume fraction of the austenite phase is about 20 %, which was estimated

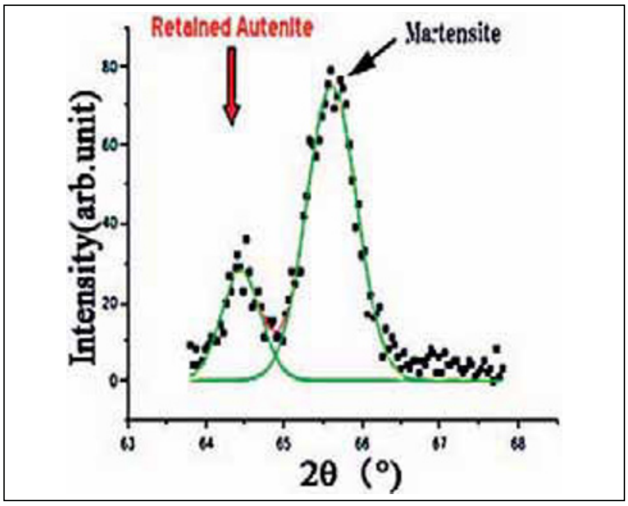


a) PS weld

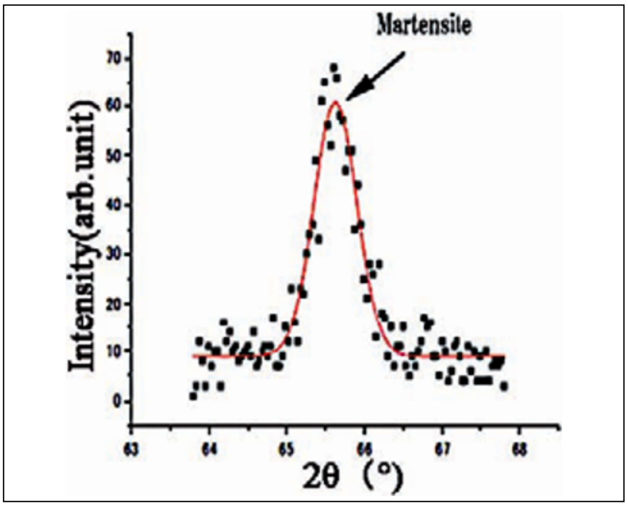


b) PT weld

Figure 2 – Temperature dependence of thermal dilatation of welds



a) in PS weld metal



b) in PT weld metal

Figure 3 – Neutron diffraction profiles of retained austenite and martensite

from the peak intensities corresponding to austenite and martensite.

From the above results, it can be concluded that the PS weld metal has a dual phase microstructure with about 20 % austenite and an Ms temperature of 60 °C, while the PT weld metal has full martensite microstructure and an Ms temperature of 244 °C.

A comparison of residual stress distribution between the PS and PT weld joints is shown in Figures 4, 5 and 6, which correspond to the residual stress in the L, T and N directions respectively. It can be seen that the weld metal region is in the range of ± 13 mm from the centre of the joints, while the HAZ region is from ± 13 mm to about ± 70 mm, and the weld toe is at the position of about ± 13 mm on both sides. The amount of residual stress resulting from welding increases in the following order: L, T and N directions. In both weld metals, the residual stress inside the weld metal is compressive in the L and T directions, i.e. a stress of -400-500 MPa exists around the centre in the L direction and a stress of about -100 MPa in the T direction. The largest tensile residual stress is observed in the HAZ region close to the weld metal, but not at the toe position. The difference in residual stress between the PS and PT weld metals is small; however, strictly speaking, the compressive residual stress in the PS weld metal is somewhat larger than that in the PT weld metal. In other words, the compressive residual stress of weld metal with an Ms of 60 °C and containing about 20 % retained austenite is somewhat larger than that found in weld metal with an Ms of 244 °C and with a full martensite.

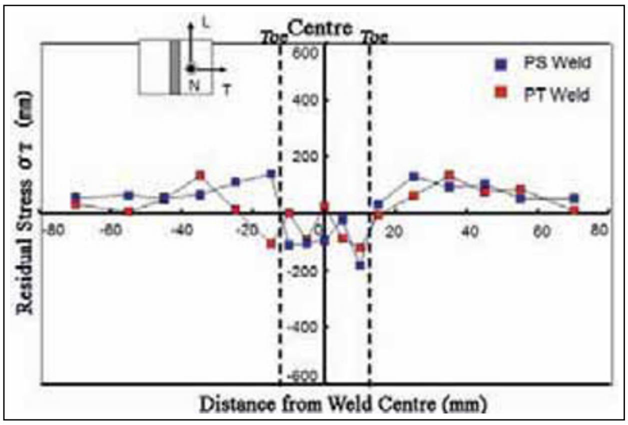


Figure 5 – Comparison of residual stress distribution between PS and PT welds in case of residual stress in T direction (σT)

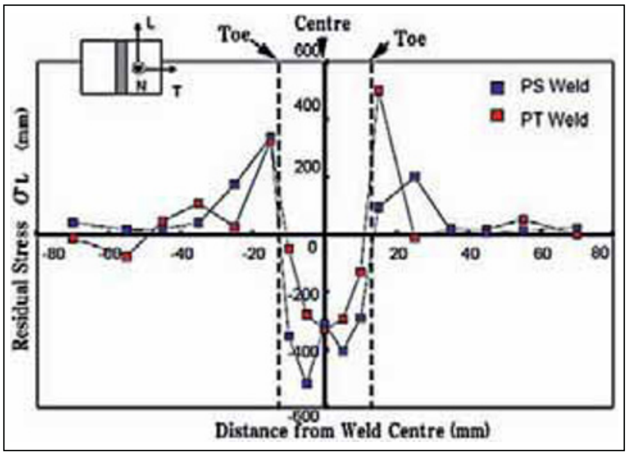


Figure 4 – Comparison of residual stress distribution between PS and PT welds in case of residual stress in L direction (σL)

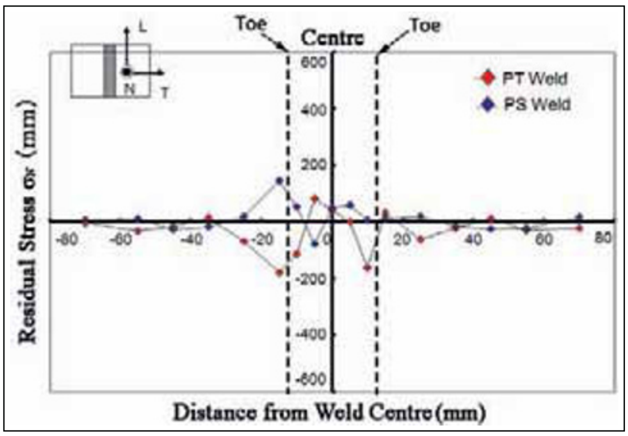


Figure 6 – Comparison of residual stress distribution between PS and PT welds in case of residual stress in N direction (σN)

4 DISCUSSION

4.1 Comparison of residual stress between low Ms and conventional weld metals

Figures 7 and 8 show a comparison of residual stress distributions between low Ms weld metals of 60 °C and 244°C, as demonstrated in this study, and conventional Ms (about 460 °C) weld metal of Terasaki's results, which were observed in weld metal of conventional wire of 800 MPa grade using the stress relaxation method [22-24]. The former corresponds to residual stress of longitudinal direction, while the latter refers to transversal direction. The difference of residual stress distribution between low Ms weld metals and conventional Ms weld metal is remarkable in longitudinal direction – i.e. the low Ms weld metals (60 °C and 244 °C) have a compressive residual stress of about 400 MPa inside weld metals, while the conventional weld metal has a tensile residual stress of 450 MPa. One of the present authors, H. Suzuki, also observed a tensile residual stress of about 400 MPa in conventional Ms weld metal of about 900 MPa grade with neutron diffraction measurement [24]. The residual stress reduction effect due to low Ms weld metal is observed not only in butt weld joints, but also in box weld joints. In the box weld joints as shown in Figure 9 [6, 7], we also observed a reduction of about 170 MPa in tensile residual stress

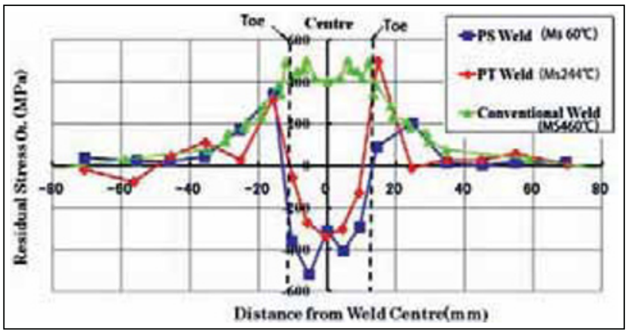


Figure 7 – Comparison of residual stress distribution between conventional weld metal and low weld metal (PT, PS) in case of residual stress in L direction (σL)

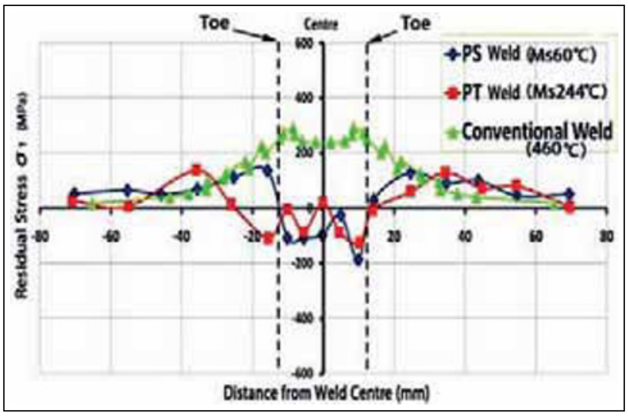


Figure 8 – Comparison of residual stress distribution between conventional weld metal and low Ms weld metal (PT, PS) in case of residual stress in T direction (σT)

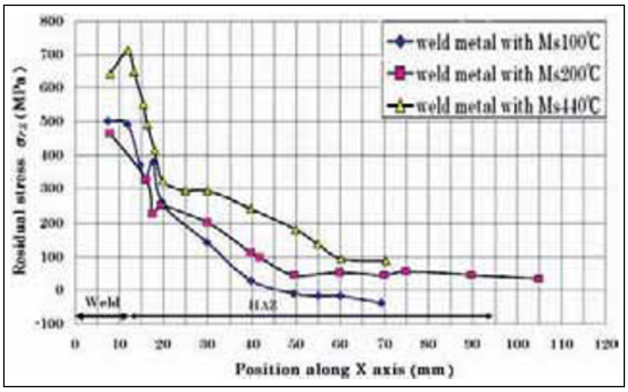


Figure 9 – Effect of Ms temperature on residual stress in T (X) direction observed in box filler weld

in weld metal with an Ms of about 200 °C in comparison with that of conventional weld metal with an Ms of about 440 °C.

Recently, Marinez Diez [25] and Kromm [26] observed the compressive residual stress of about -400 MPa in surface level at weld toe and inside weld metal of LTTA using X-ray measurement. It is difficult to observe the residual compressive stress in L, T and N stress directions in the same time, but the creation of compressive residual stress due to LTTA weld metal has been confirmed.

As shown in Figures 7and 8, the residual stress analysis by means of neutron diffraction measurement shows clearly that lowering Ms is sufficiently effective for residual stress reduction in spite of a decrease in volume fraction of martensite from 100 % to 80 % under the conditions of low oxygen content of 20-60 ppm. By the detailed measurement of residual stress distribution, it is also demonstrated that the dilatation effect induced by martensitic transformation is sufficiently extended up to weld toe, where residual stress is very low or compressive.

As seen in Figure 3, the volume fraction of martensite in the PS weld metal is about 80 % and that in the PT weld metal is 100 %. In addition, Figure 2 shows that the amount of thermal dilatation of the PS weld metal is almost the same with that of the PT weld metal. In spite of these experimental results, the compressive residual stress of the PS weld metal is a little larger than that of the PT weld metal inside the weld metal region. It may be interpreted that the dilatation strain resulting from martensitic transformation in the lower temperature region creates a larger compressive stress because Young's modulus of martensite increases as temperature decreases. Accordingly, concurrent transformation of martensite in the lower temperature region is effective for the creation of a large compressive stress.

Ordinary weld metals have an oxygen content of over 100 ppm. But these weld metals with low Ms need to be reduced below 100 ppm for impact absorbed energy. Before commencing this experiment, we had some fears about the adverse effect of low oxygen content (the reason being that a reduction of oxygen inclusions breaks random orientation of laths and packets, so much that large compressive stress may not be formed because of the decrease in nucleation sites of martensites). However, our fears were unfounded – a high compressive residual stress was observed.

It is known that fractures of welded steel structures have mostly occurred in welded joints because of fatigue crack in the weld toe position, besides other faults such as weld cracking. Compressive residual stress or reduction of tensile residual stress is valuable in preventing fractures of welded joints. The reason is that the dual phase microstructure of the PS weld metal is much more suitable to suppress cold cracking because of both the compressive stress effect of transformation and the hydrogen trapping effect of retained austenite. Generally speaking, fatigue fracture of welded joints occurs mostly at the toe, which has two areas of weakness – high stress intensity due to bad bead dimension and high tensile residual stress. But PS and PT weld metals have a residual stress of zero (0) at the weld toe as shown in Figure 8. We think that tensile residual stress in the HAZ region, apart from the toe position, has little adverse effect on fatigue crack.

4.2 Formation mechanism of compressive residual stress

One of the present authors, K. Hiraoka, examined the relationship of restraint force and residual stress in welded joints of low Ms weld metal (LTTW) [27]. As shown in Figure 10, compressive residual stress may be formed only under strong restraint stress (short length). We think that the large compressive stress of 400-500 MPa observed in this experiment is formed under the strong restraint stress as a result of the struggle of two kinds of operating force – the tensile thermal stress in cooling and the compressive stress in martensitic transformation.

The formation mechanism of compressive residual stress can be more easily understood in relation to Ms and Mf temperatures (*see below*). In the butt welded

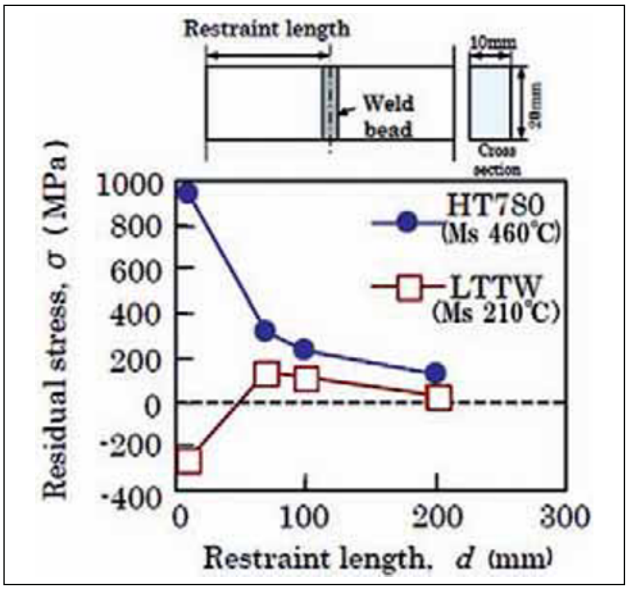


Figure 10 – Relation of residual stress and restraint length in case of both sides fixed

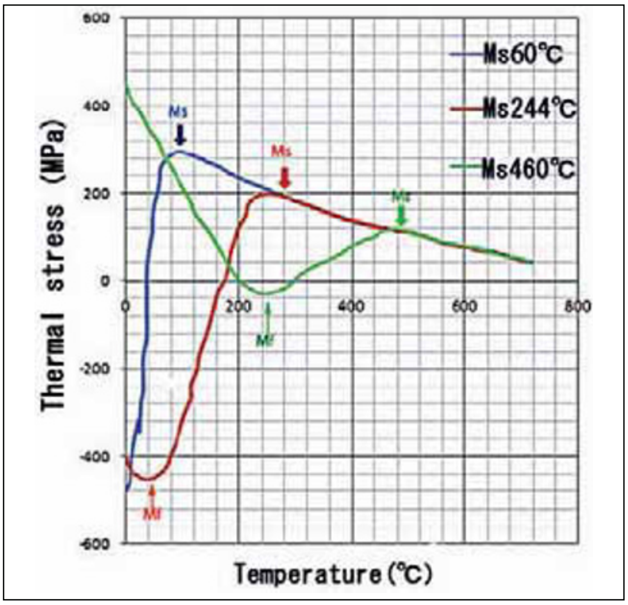


Figure 11 – Schematic drawing representing the formation mechanism of residual stresses which results from different thermal stress behaviour of low Ms weld metals (Ms 60 °C and 244 °C) and conventional one (Ms 460 °C)

joints of 20 mm thickness and 200 mm width used in this experiment, large base plates restrict the weld metal so strongly that residual stress may be formed by thermal stress resulting from the shrinkage of weld metal. The thermal stress is greatly affected by the dilatation of phase transformation in the low temperature region. The schematic drawing in Figure 11 represents the formation mechanism of residual stresses that result from the different thermal stress behaviour of the experiment's low Ms weld metals and conventional Ms weld metals. During cooling after welding, the thermal stress of conventional weld metal with an Ms of about 460 °C begins to decrease to about 220 °C of the martensite finishing temperature (Mf), but it increases again up to about 400-450 MPa in the range from the Mf to room temperature. On the other hand, the thermal stress of weld metal with an Ms of 244 °C continues to decrease down to the bottom in the compressive stress region, but again increases up to about -300 MPa because of the Mf over room temperature. The thermal stress of weld metal with an Ms of 60 °C continues to decrease down to about -400-450 MPa because of the Mf below room temperature.

4.3 Difference in residual stress between L and T directions

Table 2 provides a summary of the estimated values of the amount of residual stress reduction induced by unit length of weld metal with a low Ms temperature, where residual stresses of conventional weld metal and low Ms weld metal is indicated by Rconv and R_{Ms} respectively. In the estimation of the amount of residual stress reduction, Rconv – R_{Ms}, we use the results of Suzuki and Terasaki [19, 22] as Rconv and those of our experiments as R_{Ms}. Furthermore, we assume that

Table 2 – Estimation of the amount of residual stress reduction per unit length induced by low Ms dilatation effect

Welded joint	Stess direction	Residual stress of weld metal (MPa)						Effective weld metal length (mm)	Residual stress reduction per unit length (MPa/mm)
		Conventional wire Rconv			Low Ms wire R_{Ms}		Rconv - R_{Ms}		
		Suzuki	Terazaki	Shiga	Shiga	This experiment			
Butt weld	L direc.	400	450			-400	800 to 850	About 70 mm	11.4 to 12.1
	T direc.	220	240			-100	320 to 340	20 mm [a)] 26 mm [b)]	12 to 13.1
Box weld	T direc			650	480		170	13 mm	13.1

[a)] Terasaki's data.
[b)] This experiment.

the compressive stress in the T direction comes from the dilatation of weld metal width and the compressive stress in the L direction comes from that of the 70 mm within the longitudinal weld metal length. The value of 70 mm is adopted from past results, which show that in the relationship of transverse shrinkage and weld length in welded joints, the shrinkage is almost saturated over 70 mm length [28]. By dividing the amount of Rconv – R_{Ms} by effective weld metal length, the amount of residual stress reduction per unit length in low Ms weld metal can be estimated at about 11.4-12.1 MPa/mm in the L direction and 13.1-14.8 MPa/mm in the T direction, as shown in Table 2. The estimation values do not have a large range. Subsequently, the same estimation with the butt welded joints was carried out for the box welded joints, where the amount of residual stress reduction per unit length was calculated to be 13.1 MPa/mm, which is close to that of the butt weld joints.

It may be said that the amount of residual stress reduction induced by low Ms weld metal is about 11-15 MPa per unit length of weld metal. This estimation is applicable within the 70 mm of both width and length in the weld metal, which was welded under strong restriction. The residual stress reduction induced by martensitic transformation in the low temperature region may be called a “low Ms dilatation effect”.

It is possible to explain the difference of residual stress in L and T directions at weld centre from the following interpretation. Residual stress in the L direction results from the difference between the tensile thermal stress of about 400 MPa and the compressive dilatation stress of 800-850 MPa [(11.4-12.1 MPa/mm) × 70 mm] from martensitic transformation – i.e. the final residual stress in the L direction has a compressive value of about 400-450 MPa. On the other hand, the residual stress in the T direction results from the difference between the tensile thermal stress of 220-240 MPa and the compressive dilatation stress of 320-340 Mpa – i.e. the final residual stress has a compressive value of about 100 MPa. In other words, the difference in residual stress in L and T directions comes from the difference of the effective length of weld metal in L and T directions. It should be emphasized that the amount of residual stress reduction induced by unit length of low Ms weld metal is the same value in L and T directions (about 11-15 MPa per unit length).

4.4 Effect of stress-induced transformation on Ms temperature and residual stress

Weld metal of low Ms temperature has stress-induced transformation phenomena. The influence of the stress-induced transformation on Ms temperature and thermal stress resulting in residual stress is discussed below with reference to the paper by Yamamoto and Hiraoka [29].

The effect of restraint on Ms temperature of weld metal can be clarified by reporting their measurement data. The change in dilatation strain of weld metal without restraint obtained by Formaster measurement is compared with the change in strain in weld metal with restraint by laser speckle measurement in Figure 12 [30]. The Ms temperature of the weld metal with restraint is higher by about 30 °C than that of the weld metal without restraint. The 30 °C rise is caused by stress-induced transformation. The increase in thermal stress under restraint accelerates the starting of the transformation from austenite to martensite.

The effect of stress-induced transformation on residual stress can be understood from the difference of thermal stress in cooling; Figure 13 shows the comparison of

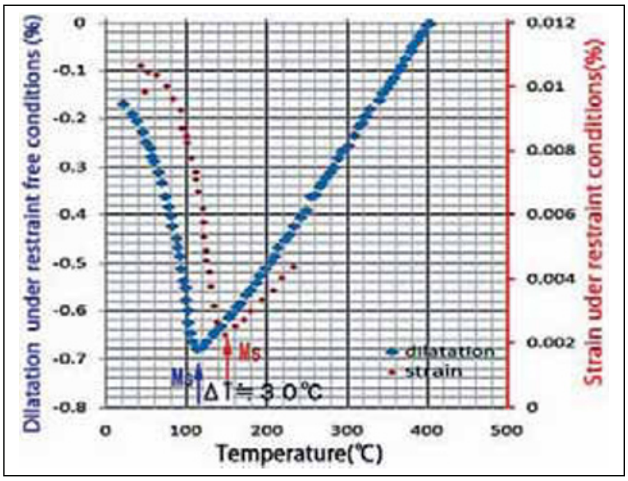


Figure 12 – Comparison of Ms temperature between weld metal with restraint and without it

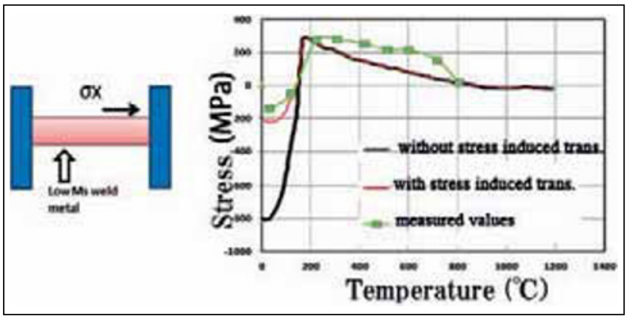


Figure 13 – Comparison of calculated thermal stress curves between the conditions with stress induced transformation and without it

calculated thermal stress curves between the conditions with restraint and without restraint [29]. It can be seen that compressive thermal stress in the low temperature region is weakened by stress-induced transformation and resultant residual stress is also done.

5 CONCLUSIONS

Large sized butt welded joints with two kinds of low Ms weld metals (with Ms temperatures of about 60 °C and about 244 °C) were prepared using 980 MPa grade steels and the residual stress distributions in the region from weld metal to HAZ were measured with neutron diffraction. By comparing the residual stress distributions of the low Ms weld metals with those of conventional weld metals having an Ms temperature of about 460 °C, the following conclusions can be reached:

1) While conventional weld metals have tensile residual stress distributions, low Ms weld metals have compressive residual stress distributions inside the weld metals of butt weld joints.

2) The compressive residual stress in the longitudinal (L) direction of the welding line was about -400 MPa at the weld centre and about -75 MPa at the weld toe in the case of the weld metal with an Ms of about 60 °C. The reduction of tensile residual stress at the toe position may improve the fatigue strength of welded joints.

3) The quantitative analysis of residual stress in the L direction demonstrates that the difference in residual stress between low Ms weld metal and conventional weld metal is about 800 MPa. The reduction of residual stress by about 800 MPa results from the dilatation stress of martensitic transformation.

4) The compressive residual stress of weld metal with an Ms of 60 °C, which contains about 20 %-25 % retained austenite, is somewhat larger than that of weld metal with an Ms of 244 °C, which has full martensite microstructure. Lowering Ms temperature is more effective for the reduction of residual stress in spite of the decrease in volume fraction of martensite. It is caused by the increase of Young‘s modulus coefficiency of martensite accompanying the falling of temperature.

5) It can be estimated that the amount of residual stress reduction induced by low Ms weld metal is about 11-15 MPa per unit length within the 70 mm of both breadth and length in weld metal.

6) Stress-induced transformation only under strong restraint conditions increases Ms temperature and weakens residual stress.

7) The reduction of oxygen content in weld metal down to 50 ppm has no adverse influence on residual stress reduction through martensitic transformation. Weld metals with low oxygen content and low Ms temperature, which creates the dual phase microstructure of martensite and austenite, may thus improve weld cold cracking, fatigue strength and impact absorbed energy in weld joints.

ACKNOWLEGEMENTS

We wish to thank Project leader, Prof. Dr. K. Nogi and Director of JWRI in Osaka University, Dr. Nakata for many helpful suggestions during the course of this work.

This study was carried out as a part of research activities of “Fundamental Studies on Technologies for Steel Materials with Enhanced Strength and Functions” by Consortium of JRCM (The Japan Research and Development Center of Metals). Financial support from NEDO (New Energy and Industrial Technology Development Organization) is gratefully acknowledged.

REFERENCES

[1] Shiga C.: Problems in welded joints and systematic approach to their s solution in STX21 project Science and Technology of Welding and Joining, 2000, vol. 5, no. 6, pp. 356-364.

[2] Ohta A., Watanabe O., Matsuoka K., Shiga C., Nishijima S., Maeda Y., Suzuki N., Kubo T.: Fatigue strength improvement of box welded joints by using Low Transformation Temperature welding material, Quarterly Journal of the Japan Welding Society, 2000, vol. 18, no. 1, pp. 141-145 (in Japanese).

[3] Ohta A., Maeda Y., Suzuki N., Kubo T.: Fatigue strength improvement of box welds by using Low Transformation Temperature welding material, -Tripled fatigue strength by postweld heat treatment-, Quarterly Journal of the Japan Welding Society, 2001, vol. 19, 2, pp. 373-376 (in Japanese).

[4] Ohta A., Watanabe O., Matsuoka K., Maeda Y., Nguyen N.T., Suzuki N.: Fatigue strength improvement of box section member by using Low Transformation Temperature welding material, Quarterly Journal of the Japan Welding Society, 2000, vol. 18, 4, pp. 628-633 (in Japanese).

[5] Nakamura T., Hiraoka K.: Development of Low Transformation-Temperature of welding materials, Materia Japan, 2006, vol. 45, no. 6, pp. 429-437 (in Japanese).

[6] Shiga C., Mraz L., Bernasovsky P., Hiraoka K.: Improvement of welded joints with low martensite transformation temperature weld consumables, IIW Doc. IX-2149-05, Prague, July 2005.

[7] Shiga C., Mraz L., Bernasovsky P., Hiraoka K., Mikula P., Vrana M.: Residual stress distribution of steel welded joints with weld metal of Low Transformation Temperature, Doc. IIW-1824-07 (ex-doc. IX-2149r1-05), Welding in the World, 2007, vol. 51, no. 11/12, pp. 11-19.

[8] Zenitani S., Hayakawa N., Yamamoto J., Hiraoka K., Morikage Y., Kubo T., Yasuda K., Amano T.: Development of new Low Transformation-Temperature welding consumable to prevent cold cracking in high strength steel welds, Proceedings of 2002 Symposium for Welded Structures of the Japan Welding Society, Osaka, 2002, pp. 346-353 (in Japanese).

[9] Zenitani S., Hayakawa N., Yamamoto J., Hiraoka K., Morikage Y.: Relationship between cold cracking and restraint intensity in welds formed by Low Transformation-Temperature welding consumables, Pre-Prints of the National Meeting of the Japan Welding Society, 2002, vol. 71, pp. 120-121 (in Japanese).

[10] Hayakawa N.: Characteristics of Low Transformation-Temperature welding consumables, Pre-Prints of the National Meeting of the Japan Welding Society, 2003, vol. 72, pp. F9-F12 (in Japanese).

[11] Hayakawa N., Zenitani S., Yamamoto J., Hiraoka K., Morikage Y., Kubo T., Yasuda K.: Characteristics of Low Transformation-Temperature weld metals with retained austenite, Pre-Prints of the National Meeting of the Japan Welding Society, 2003, vol. 72, pp. 240-241 (in Japanese).

[12] Zenitani S., Hayakawa N., Yamamoto J., Hiraoka K., Morikage Y., Kubo T., Yasuda K., Amano T.: Development of new Low Transformation-Temperature welding consumable to prevent cold cracking in high strength steel welds, Science and Technology of Welding and Joining, 2007, vol. 12, no. 6, pp. 516-522.

[13] Gunic F., Hayakawa N., Katabami M., Terashima H., Hiraoka K. : Improvement of mechanical properties of LTT weld metal, Pre-Prints of the Japan Welding Society, 2005, vol. 76, pp. 104-105.

[14] Gunic F., Nakamura T. , Hayakawa N., Hiraoka K., Terashima H., Katabami M.: Improvement in toughness of LTT weld metal by oxygen reduction, Proceedings of the 9th Ultra-Steel Workshop, NIMS, Ibaraki, 2005, pp. 180-181.

[15] Nakamura T., Hiraoka K., Hayakawa N., Gunic F.: Improvement of welded joint property by new welding technology, Proceedings of International ATS steelmaking conference, ATS, Paris, 2005, pp. 226-227.

[16] Nakamura T., Hiraoka K.: Development of Low Transformation-Temperature welding wire, Proceedings of 8th Ultra-Steel Workshop, NIMS, Ibaraki, 2004, pp. 248-249.

[17] Nakamura T., Hiraoka K.: Development of stable MIG welding in pure Ar gas using new hybrid wire, Proceedings of the 9th Ultra-Steel Workshop, NIMS, Ibaraki, 2005, pp. 178-179.

[18] Nakamura T., Hiraoka K.: Development of stable MIG welding in pure Ar gas by new-hybrid wire, IIW Doc. SG-212-1080-05, Prague, 2005, July.

[19] Suzuki H., Holden M., Moriai A., Minakawa N., Morii Y.: Residual stress evaluation of butt weld sample of high tensile strength steel using neutron diffraction, Zairyo, Society of Materials Science, Japan, 2005, vol. 54, no. 7, pp. 685-691 (in Japanese).

[20] Suzuki H., Holden T.M.: Neutron diffraction measurements of stress in an austenitic butt weld, The Journal of Strain Analysis for Engineering Design, 2006, vol. 41, no. 8, pp. 575-582.

[21] Hai Qiu, Ingang Qi, Fuxin Yin, Hiraoka K.: Determination of parameters for fitting the dilatation curve of austenite-martensite transformation in Cr-Ni Steels, ISIJ International, 2009, vol. 49, no. 1, pp. 146-148.

[22] Satou K., Terasaki T.: Effect of welding conditions on residual stresses distributions and welding deformation in welded structures materials, Journal of the Japan Welding Society, 1976, vol. 45, no. 1, pp. 42-53 (in Japanese).

[23] Satou K., Terasaki T.: Effect of welding conditions on welding deformations in multi pass welded butt joint, Journal of the Japan Welding Society, 1976, vol. 45, no. 4, pp. 464-470 (in Japanese).

[24] Satou K., Terasaki T., Tanaka T.: Numerical analysis for residual stress distribution in welded joint , Journal of the Japan Welding Society, 1979, vol. 48, no. 8, pp. 616-620 (in Japanese).

[25] Martinez Diez F.: Development of a compressive residual stress field around a weld toe by means of phase transformation, Doc. IIW-1891-08 (ex-doc. IX-2231r1-07), Welding in the World, 2008, vol. 52, no. 7/8, pp. 63-78.

[26] Kromm A., Kannengiesser T.: Characterizing phase transformations of different LTT alloys and their effect on residual stress and cold cracking, IIW Doc. IX-2311-09, Singapore, July 2009.

[27] Yamamoto J., Hayakawa N., Zenitani S., Muramatu Y., Hiraoka K.: Effect of transformation expansion of weld metal and restraint intensity of weld joint on residual stress distribution, Pre-Prints of the National Meeting of the JWS, 2003, vol. 72, pp. 238-239 (in Japanese).

[28] Satou K., Terasaki T.: Effect of welding conditions on welding deformations in welded structural materials, Journal of the Japan Welding Society, 1976, vol. 45, no. 4, pp. 302-308 (in Japanese).

[29] Yamamoto J., Meguro S., Muramatsu Y., Hayakawa N., Hiraoka K.: Analysis of martensite transformation behavior in welded joint of low transformation-temperature materials, Quarterly Journal of the Japan Welding Society, 2007, vol. 25, no. 4, pp. 560-568 (in Japanese).

[30] Muramatsu Y., Kuroda S., Yamamoto J.: Application of laser speckle strain measurement on welding with several kinds of filler materials, Pre-Prints of the National Meeting of the Japan Welding Society, 2003, vol. 73, pp. 338-339 (in Japanese).