Effects of Full Annealing Heat Treatment on Long-term Creep Strength of 2.25Cr-1Mo Steel Welded Joint

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Long-term creep strength of Cr-Mo steel with fully annealed ferrite and pearlite microstructure is higher than those of the steels with martensite, tempered martensite and bainite microstructures. In this study, influence of post weld heat treatment at the temperature of austenite single phase region (full annealing PWHT) on long-term creep strength at 550°C has been investigated on 2.25Cr-1Mo steel, in comparison with that of normal post weld heat treatment at the temperature below A_{C1} (standard PWHT). Creep rupture strength of the welded joint subjected to standard PWHT is lower than those of base metal and weld metal in the short-term. However, such differences in creep rupture strength disappear after long-term creep exposure for about 50,000 h at 550°C. On the other hand, creep strength of the welded joint subjected to full annealing PWHT is obviously higher than those of the welded joint subjected to standard PWHT, base metal and weld metal in the long-term condition. It may be also expected to reduce a probability of mechanical damage such as Type IV cracking by the full annealing PWHT, since inhomogeneous microstructures in weld metal and heat affected zone have been essentially extinguished. Full annealing at the temperature of austenite single phase region has been proposed as a new post weld heat treatment condition available to obtain high creep strength and to improve a reliability of welded joint for low alloy Cr-Mo steels.

Key Words: 2.25Cr-1Mo steel, welded joint, long-term creep strength, post weld heat treatment, full annealing, austenite, A_{C1} , microstructure,

1. Introduction

Creep strength of creep resistant steels decreases to a level of the inherent creep strength as a result of microstructural change during long-term exposure at the elevated temperatures^{1), 2)}. Inherent creep strength corresponds to a creep strength of the matrix itself and those of ferritic creep resistant steels are almost the same independent of chemical composition, heat treatment condition and short-term creep strength^{1), 2)}. Recently, it has been reported that creep strength of the 0.5Cr-0.5Mo steel with a fully annealed ferrite and pearlite microstructure is higher than those of the steels with martensite, tempered martensite and bainite microstructures in the long-term³⁾. Higher long-term creep strength of the steel with fully annealed ferrite and pearlite microstructure is attained by its very low mobile dislocation density. Therefore, such improving effect on creep strength is effective under low stress condition where amount of dislocation generated by stress apply is significantly low. It can be suitable for high temperature structural components used under very low stress condition. New approach to improve long-term creep strength of ferritic creep resistant steel has been suggested by the above finding.

On the other hand, in order to maintain good performance and sufficient reliability of high temperature structural com-

ponents, it is important to obtain high creep strength and to control microstructural and mechanical damages in weld zone, such as Type IV cracking⁴⁾⁻⁶⁾. Since occurrence of mechanical damage is promoted by inhomogeneous microstructure in weld zone, such inhomogeneity of microstructure should be extinguished. Full annealing at the temperature of austenite single phase region should dissolve inhomogeneity of microstructure that was formed during welding, as a result of transformation of ferritic microstructure to austenite phase. Therefore, full annealing heat treatment may be useful for suppression of occurrence of mechanical damage in weld zone.

In this paper, the effect of full annealing PWHT at the temperature of austenite single phase region on a long-term creep strength at 550°C has been investigated on 2.25Cr-1Mo steel welded joint, and a possibility of improvement in mechanical property of weldment by full annealing PWHT has been discussed in comparison with standard PWHT condition at the temperature below A_{C1} .

2. Experimental procedure

The material used was a 2.25Cr-1Mo steel plate (JIS SCM440) with a thickness of 50 mm. Chemical compositions of the base metal and the weld metal, heat treatment condition of the base metal are shown in Table 1. There was no significant difference in chemical composition between the base metal and the weld one. The steel plate was normalized for 100 min at 930°C and tempered for 105 min at 730°C. The plates were welded by the narrow gap submerged arc welding method with use of JIS Z 3351 YS-2CM1 wire as a filler metal.

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The welding conditions are shown in Table 2. Macrostructure of the cross sectional area in the welded joint of the plate is shown in Figure 1. No welding defects were observed.

After welding, the plate was subjected to post weld heat treatment. Two type conditions of post weld heat treatment, shown in Table 3, standard condition at the temperature below

Fig.1 Cross sectional view of the welded joint.

A_{C1} (690°C PWHT) and full annealing condition at the temperature of austenite single phase region (930°C PWHT) were employed. Full annealing PWHT was conducted at the same temperature as that of normalizing for the base metal.

Sampling procedure and dimension of the creep test specimens are shown in Table 4 and Figure 2. Creep test specimens of the base metal with 10 mm diameter and 50 mm gauge length were prepared parallel to the rolling direction at locations of $1/4t$ and $3/4t$ (t is a plate thickness) from the plate without post weld heat treatment. Those of the weld metal with 6 mm diameter and 30 mm gauge length were prepared parallel to the weld line at locations of $1/4t$, $2/4t$ and $3/4t$ from the plate subjected to post weld heat treatment at 690°C. Those of the welded joint with 10 mm diameter and 100 mm gauge length were prepared perpendicular to the weld line at locations of $1/4t$ and $3/4t$ from the plates subjected to post weld heat treatment at 690°C and 930°C. Weld line was located at the center of the gauge length in the creep test specimen of the welded joint. Creep tests were conducted at 550°C under constant load condition.

Table 1 Chemical compositions (mass%) of the base metal and the weld metal studied and heat treatment condition of the base metal.

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Al
Base metal	0.12	0.21	0.51	0.004	0.002	0.15	0.19	2.26	0.98	0.007
Weld metal	0.11	0.19	0.75	0.005	0.005	0.13	0.17	2.22	1.02	0.015
Normalizing	930°C / 100min / Fun cooling									
Tempering	730°C / 105min / Air cooling									

Table 2 Conditions of narrow gap submerged arc welding.

Welding current	Arc voltage	Welding speed
480~600 A	28~32 V	25~30 cm/min
Preheating temperature	Interpass temperature	Welding heat input
200~226°C	200~226°C	31.6~37.2 kJ/cm

Table 3 Two type conditions of post weld heat treatment.

Standard condition	690°C / 28h / Air cooling
Full annealing condition	930°C / 30min / Furnace cooling

Table 4 Sampling procedure and dimensions of the creep test specimens.

Material	Creep test specimen			
	Sampling direction	Diameter	Gauge length	Post weld heat treatment
Base metal	Parallel to rolling direction	10mm ϕ	50mm	None
Weld metal	Parallel to weld line Perpendicular to rolling direction	6mm ϕ	30mm	690°C/28h /Air cooling
Welded joint	Perpendicular to weld line	10mm ϕ	100mm	690°C/28h /Air cooling
	Parallel to rolling direction			930°C/30min /Furnace cooling

Fig.2 Sampling procedure of the creep test specimens.

3. Results and discussion

3.1 Effect of initial microstructure

Creep rupture strength at 550°C of the 2.25Cr-1Mo steels with different initial microstructures of ferrite and pearlite (JIS STBA24)⁷⁾, bainite (JIS SCMV4NT)⁸⁾ and tempered martensite (ASTM A542)⁹⁾ are shown in Figure 3. Chemical compositions and heat treatment conditions of these steels are shown in Table 5. Chemical compositions of these three steels are essentially the same. The differences in heat treatment condition resulted in the differences in initial microstructure. Creep rupture strength of the steel with tempered martensite microstructure was higher than those of the other steels in the short-term and large differences in creep rupture strength were observed. Such differences in creep rupture strength, however, decreased with decrease in applied stress. In contrast to the short-term where creep rupture strength of the steel with ferrite and pearlite microstructure was lower than those of the other steels, it showed a slightly higher creep rupture strength than the other steels in the long-term over about 50,000 h¹⁰⁾.

Bright field TEM images of the 2.25Cr-1Mo steels in the as

Fig.3 Stress vs. time to rupture curves of the 2.25Cr-1Mo steels at 550°C.

heat treated condition and the creep ruptured specimens at 550°C-88 MPa are shown in Figure 4. Annealed ferrite and pearlite microstructure with coarse carbide particles and a few fine carbide was observed in the as annealed condition (Fig. 4 (a)). However, no fine carbide particles were observed and dislocation density was very low in the creep ruptured specimen (Fig. 4 (d)). Bainite microstructure in the normalized and tempered condition (Fig. 4 (b)) and tempered martensite one in the quenched and tempered condition (Fig. 4 (c)) have been significantly recovered after creep exposure for 35,924.4 h (Fig. 4 (e)) and 46,816.8h (Fig. 4 (f)), respectively. Coarsening of carbide and decrease in dislocation density were observed in the creep ruptured specimens and the microstructures observed in the creep ruptured specimens were almost the same independent of initial microstructure. Therefore, differences in microstructural features that affect on creep strength of these three steels have disappeared during long-term creep exposure for about 36,000 ~ 63,000 h at 550°C.

Table 5 Chemical compositions (mass%) and heat treatment conditions of three type 2.25Cr-1Mo steels.

Specification	Microstructure	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Al
JIS STBA 24	Ferrite+Pearlite	0.10	0.23	0.43	0.011	0.009	0.07	0.043	2.46	0.94	0.005
JIS SCMV4NT	Bainite	0.12	0.29	0.48	0.015	0.007	0.07	0.05	2.20	0.99	0.017
ASTM A542	Tempered martensite	0.14	0.25	0.55	0.010	0.009	0.13	0.18	2.44	1.03	0.018
JIS STBA24	Ferrite+Pearlite	930°C/20min → 720°C/130min/Air cooling									
JIS SCMV4NT	Bainite	930°C/1h/Air cooling 740°C/2h/Air cooling 700°C/4h/Furnace cooling									
ASTM A542	Tempered martensite	930°C/6h/Water quenching 635°C/6h/Air cooling 600°C/2h/Air cooling

JIS STBA24

JIS SCMV4NT

ASTM A542

a) as annealed

b) as N.T.

c) as Q.T.

d) creep ruptured, $t_r = 63,017.8\text{h}$ e) creep ruptured, $t_r = 35,924.4\text{h}$ f) creep ruptured, $t_r = 46,816.8\text{h}$ **Fig.4** Bright field TEM images of the 2.25Cr-1Mo steels in the as heat treated condition and creep ruptured at 550°C-88 MPa.

From the above results, creep strength is strongly affected by initial microstructure in the short-term, however, such differences in creep strength decrease and disappear after long-term creep exposure of about 50,000 h at 550°C, since recovery of microstructure progress and differences in initial microstructures due to different heat treatment condition disappear. Therefore, long-term creep strength of the 2.25Cr-1Mo steel over about 50,000 h at 550°C is thought to be governed by the inherent creep strength¹¹⁾.

3.2 Effect of welding

Creep rupture strength at 550°C of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joint subjected to PWHT of 690°C/28 h/AC are shown in Figure 5. There are several data points at the same stress condition for one part, since two or three specimens taken from different position in a thickness of the plate have been tested. Effect of sampling position in a thickness of the plate on creep rupture strength was very little for both the weld metal and the welded joint. In the short-term, creep rupture strength of the weld metal and the welded joint were lower than that of the base metal, and creep rupture lives of the weld metal and the welded joint were about 1/3 and 1/5 of that of the base metal, respectively. However, such differences in creep rupture strength decreased with decrease in applied stress. No significant difference in creep rupture strength was observed for these three parts in the long-term over about 50,000 h. Moreover, fracture of the welded joint specimen was observed at fine grain area that was base metal side in a heat affected zone (HAZ), except for one specimen ruptured at 78 MPa where the fracture occurred in a weld metal⁴⁾. Fracture position at fine grain area in HAZ was same as that of large size

creep test specimen with full thickness of 50 mm⁴⁾. Therefore, creep strength of the fine grain area in HAZ is the lowest in the welded joint.

Creep rate vs. time curves at 550°C-157 MPa of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joint subjected to PWHT of 690°C/28 h/AC are shown in Figure 6. There are two curves for both the weld metal and the welded joint corresponding to different sampling position of the specimen in a thickness of the plate. Creep deformation consisted of transient creep stage and accelerating one and no obvious steady state creep stage was observed for all the parts. Creep rate of the weld metal and the welded joint were 3 to 5 times larger than that of the base metal through the creep deformation and creep rupture lives of the former parts were shorter than that of the latter one. Effect of sampling position in a thickness of the plate on the creep rate was very little for both the weld metal and the welded joint. Creep rate vs. time curves at 550°C-69 MPa of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joint subjected to PWHT of 690°C/28 h/AC are shown in Figure 7. In contrast to creep deformation at the higher stress condition of 157 MPa (Fig. 6), differences in creep rate at the low stress condition of 69 MPa were very small, especially in the long-term over about 30,000 h. Almost the same creep rate was observed for the three parts in such long-term and the creep rupture lives were almost the same. Bright field TEM images of (a) the weld metal in the as 690°C PWHT condition, (b) specimen of the weld metal creep ruptured after 77,845 h at 550°C-78 MPa and (c) specimen of the base metal creep ruptured after 54,581 h at 550°C-78 MPa are shown in Figure 8. Rapidly solidified and quenched fine microstructure with high dislocation den-

Fig.5 Stress vs. time to rupture curves at 550°C of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joint subjected to PWHT of 690°C/28 h/AC.

Fig.6 Creep rate vs. time curves at 550°C-157 MPa of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joint subjected to PWHT of 690°C/28 h/AC.

sity was observed in the weld metal even after PWHT at 690°C (Fig. 8 (a)). However, significant progress in recovery, such as coarsening of carbide particles and subgrains and decrease in dislocation density, was observed in the specimen of the weld metal creep ruptured after 77,845 h at 550°C-78 MPa (Fig. 8 (b)). Significantly recovered microstructure observed in the creep ruptured specimen of the weld metal (Fig. 8 (b)) was similar to that of the specimen of the base metal creep ruptured after 54,581 h at 550°C-78 MPa (Fig. 8 (c)), and there was no obvious difference between these two microstructures. Differences in initial microstructure caused by welding and post weld heat treatment has been disappeared during long-term creep exposure of about 50,000 h at 550°C, as a result of recovery of the microstructure such as decrease in dislo-

cation density and coarsening of carbide particles.

Since the base metal has not been subjected to post weld heat treatment, lower creep rupture strength of the weld metal with PWHT of 690°C/28 h/AC and the welded joint with PWHT of 690°C/28 h/AC than that of the base metal in the short-term should be caused by post weld heat treatment. Presence of HAZ resulted in slightly lower creep rupture strength of the welded joint than that of the weld metal, because fracture of the welded joint specimen occurred at fine grain area in a heat affected zone. However, such differences in short-term creep strength disappeared after long-term creep exposure for about 50,000 h at 550°C. Fine microstructure with high dislocation density of the weld metal in the as 690°C PWHT condition has been significantly recovered after long-term creep exposure and there is no obvious difference in microstructure between the weld metal and the base metal, as shown in Fig. 8. Strengthening effects depend on microstructural morphology such as precipitation strengthening has been already disappeared after long-term creep exposure, as a result of microstructural change. It has been considered, consequently, that almost the same long-term creep strength of these three parts is governed by the inherent creep strength that corresponds to strength of the matrix of 2.25Cr-1Mo steel as mentioned above¹¹⁾.

3.3 Effect of full annealing post weld heat treatment

Creep curves at 550°C-78 MPa of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joints subjected to PWHT of 690°C/28 h/AC and 930°C/30 min/FC are shown in Figure 9. There are two creep curves for the base metal. Creep testing time of the welded joint subjected to PWHT of 930°C/30 min/FC is about

Fig. 7 Creep rate vs. time curves at 550°C-69 MPa of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joint subjected to PWHT of 690°C/28 h/AC.

a) Weld metal in the as 690°C PWHT condition. b) Weld metal creep ruptured after 77,845h at 550°C. c) Base metal creep ruptured after 54,581h at 550°C.

Fig.8 Bright field TEM images of the weld metals
(a) in the as 690°C PWHT condition,
(b) creep ruptured after 77,845 h at 550°C-78 MPa and
(c) the base metal creep ruptured after 54,581 h at 550°C-78 MPa.

25,000 h, and the creep test of it is still in progress. Creep rupture strength of the 2.25Cr-1Mo steel under the creep test condition of 550°C-78 MPa is considered to be governed by its inherent creep strength, as mentioned above. Creep strain of about 0.012 at 25,000 h for the welded joint subjected to PWHT of 930°C/30 min/FC was smaller than those of the other parts, it was about 1/3 of that of the welded joint subjected to PWHT of 690°C/28 h/AC and less than 1/2 of those of the base metal and the weld metal with PWHT of 690°C/28 h/AC. Creep strain of the welded joint was clearly reduced by full annealing post weld heat treatment at 930°C in the austenite single phase region, in comparison with the standard PWHT condition at the temperature below A_{C1} . It should be noted that the creep strain of the welded joint subjected to PWHT of 930°C/30 min/FC was smaller than that of the base metal without PWHT. Consequently, creep strength of the welded joint subjected to full annealing post weld heat treatment is higher than that of the base metal in the normalized and tempered condition.

Creep rate vs. time curves at 550°C-69 MPa of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joints subjected to PWHT of 690°C/28 h/AC and 930°C/30 min/FC are shown in Figure 10. Creep testing time of the welded joint subjected to PWHT of 930°C/30 min/FC is about 23,000 h, and the creep test of it is still in progress. Very similar creep deformation behaviour and almost the same creep rupture lives were observed for all the parts except for the welded joint subjected to PWHT of 930°C/30 min/FC. Significant decrease in creep rate by full annealing post weld heat treatment at 930°C was obviously observed. Creep rate vs. time curve of the welded joint subjected to PWHT of 930°C/30 min/FC showed a hump at about 1,000 h, and the creep rate of it was almost the same as those of the other parts at 1,000 h. However, the creep rate of the

welded joint subjected to PWHT of 930°C/30 min/FC decreased with increase in creep testing time after showing hump up to about 10,000 h and the creep rate at 10,000 h was about 1/5 of those of the other parts.

Stress vs. minimum creep rate curves at 550°C of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joints subjected to PWHT of 690°C/28 h/AC and 930°C/30 min/FC are shown in Figure 11.

Fig. 10 Creep rate vs. time curves at 550°C-69 MPa of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joints subjected to PWHT of 690°C/28 h/AC and 930°C/30 min/FC.

Fig. 9 Creep curves at 550°C-78 MPa of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joints subjected to PWHT of 690°C/28 h/AC and 930°C/30 min/FC.

Fig. 11 Stress vs. minimum creep rate curves at 550°C of the base metal without PWHT, the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joints subjected to PWHT of 690°C/28 h/AC and 930°C/30 min/FC.

Minimum creep rate of the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joint subjected to PWHT of 690°C/28 h/AC were larger than that of the base metal in the higher stress condition. However, such differences decreased with decrease in applied stress and minimum creep rate at the stress lower than 80 MPa were almost the same for all the parts except for the welded joint subjected to PWHT of 930°C/30 min/FC. The welded joint subjected to PWHT of 930°C/30 min/FC showed smaller minimum creep rate than those of the other parts even in the low stress condition. Decrease in slope of the curves, which is a stress exponent, with decrease in stress except for the welded joint subjected to PWHT of 930°C/30 min/FC is caused by changes in microstructure during long-term creep exposure. On the other hand, difference in minimum creep rate between the welded joint subjected to PWHT of 930°C/30 min/FC and the other parts increase with decrease in applied stress.

Improving effect of full annealing heat treatment on long-term creep strength is attained by less amount of mobile dislocation. Such strengthening effect is useful only under the condition where creep strength is governed by the inherent creep strength and a magnitude of the strengthening effect increase with decrease in applied stress³⁾. Therefore, it may be expected that improvement in creep strength by full annealing post weld heat treatment is more effective under the low stress service condition of high temperature structural components.

In addition to the strengthening effect, occurrence of mechanical damage in weld zone, such as Type IV cracking, should be suppressed by full annealing post weld heat treatment. Fracture of the welded joint specimen was observed at fine grain area in heat affected zone. However, if chemical compositions of base metal and weld metal are essentially the same, such inhomogeneous microstructure in heat affected zone and weld metal have been essentially extinguished during full annealing post weld heat treatment. Because all the ferritic microstructure is transformed to austenite single phase and homogeneous austenitic microstructure is produced during heat treatment at the temperature of austenite single phase region. Consequently, it may be speculated that mechanical damage such as Type IV cracking can be suppressed by full annealing post weld heat treatment, since such damage is caused by inhomogeneous microstructure produced by welding. It has been concluded that long-term creep strength of low alloy Cr-Mo steel weldment is improved by full annealing post weld heat treatment, and it may be also useful to suppress mechanical damage such as Type IV cracking.

4. Conclusions

Investigation on the effect of full annealing post weld heat

treatment on creep strength of the 2.25Cr-1Mo steel welded joint has shown that :

- (1) Differences in short-term creep strength of the 2.25Cr-1Mo steels caused by variety of initial microstructure decrease with increase in creep exposure time, and disappear after long-term creep exposure for about 50,000 h at 550°C.
- (2) Although the short-term creep strength of the weld metal subjected to PWHT of 690°C/28 h/AC and the welded joint subjected to PWHT of 690°C/28 h/AC are lower than that of the base metal, the creep strength of these parts are almost the same in the long-term over about 50,000 h at 550°C.
- (3) Long-term creep strength of the welded joint subjected to PWHT of 930°C/30 min/FC is higher than those of the other parts. It may be expected that such improving effect of full annealing post weld heat treatment on creep strength of the welded joint is more effective under the lower stress condition, corresponding to service condition of high temperature structural components.
- (4) Occurrence of mechanical damage, such as Type IV cracking, may be suppressed by full annealing post weld heat treatment at the temperature of austenite single phase region, since microstructural defects in weld metal and heat affected zone have been essentially extinguished.
- (5) It has been concluded that long-term creep strength of low alloy Cr-Mo steel weldment is improved by full annealing post weld heat treatment, and it may be also useful to suppress mechanical damage such as Type IV cracking.

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