

# Effects of Post Weld Heat Treatment (PWHT) Temperature on Mechanical Properties of Weld Metals for High-Cr Ferritic Heat-Resistant Steel

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*Welded joints of high-Cr ferritic heat-resistant steel, ASTM A335 Gr. P91, were subjected to post weld heat treatment (PWHT) to improve mechanical properties and to reduce residual stress. We have measured the  $A_{c1}$  of weld metals for Gr. P91 steel, containing varying amounts of Mn+Ni, and have examined the effects of PWHT temperatures on the mechanical properties of each weld metal. The upper limits of the PWHT temperature for the respective weld metals are considered.*

## Introduction

High-Cr ferritic heat-resistant steel is a material that, along with austenitic heat-resistant steel, has long been studied and utilized. This ferritic steel has a smaller coefficient of thermal expansion compared with the austenitic heat-resistant steel and exhibits excellent creep rupture strength thanks to, among other things, the addition of Nb, V and N. Therefore, this steel is widely used in thermal power plants that run and stop repeatedly, in accordance with the power demand, in an environment of steam at high temperature and pressure. The steel ASTM A335 Gr. P91 is a typical high-Cr ferritic heat-resistant steel and is applied particularly to large diameter thick-walled pipes such as the main steam pipes in thermal power plants.

The welded joints of Gr. P91 steel are generally subjected to post weld heat treatment (hereinafter referred to as "PWHT") to reduce residual stress and to improve the performance of the weld. If the PWHT is conducted at an appropriate temperature and time, the welded joint exhibits favorable mechanical properties. However, if the PWHT temperature is too low, the weld metal exhibits inadequate toughness due to insufficient tempering effect. On the other hand, if the PWHT temperature is too high, the tensile strength at ambient and elevated temperatures becomes insufficient due to excessive tempering effect. Especially in cases where the PWHT temperature exceeds the  $A_{c1}$  transformation point of the weld metal, the weld metal undergoes reverse transformation, which results in a microstructure containing fresh martensite with high strength and low toughness. This microstructure deteriorates the performance of the welded joint. To avoid these problems, the PWHT temperature is controlled

in the actual implementation.<sup>1), 2)</sup> In connection with selecting welding consumables, chemical constituents, such as Mn and Ni, that lower the  $A_{c1}$  transformation point are regulated.<sup>3)</sup> However, not much has been done to validate the applicability of this control and regulation to the weld metals from the aspect of mechanical properties.

In this study, two types of weld metals for Gr. P91 steel, containing different amounts of Mn+Ni, were mainly used to study the change of their mechanical properties during PWHTs performed at temperatures exceeding their  $A_{c1}$  transformation points. The upper limit of the PWHT temperature allowable for each weld metal is considered.

## 1. Experimental method

### 1.1 Tested materials

The materials tested were the weld metals TRUSTARC<sup>TM, note)</sup> CM-9Cb (hereinafter "CM-9Cb") and TRUSTARC CM-95B9 (hereinafter "CM-95B9"). Both are Kobe Steel's covered electrodes for Gr. P91 steel. The CM-9Cb has been used for over 20 years, mainly in thermal power plants in Japan. On the other hand, CM-95B9 is a covered electrode that meets the American Welding Society (AWS) standard, A5.5 E9015-B9: 2006, and features a lower content of Mn and Ni in the weld metal, compared with CM-9Cb. In the following description, the weld metal of CM-9Cb is referred to as "A", and that of CM-95B9 is referred to as "B".

Fig. 1 shows the shape of the welding groove configuration. Plates of JIS G3106 SM490A were used for the test. Prior to the test, each groove surface

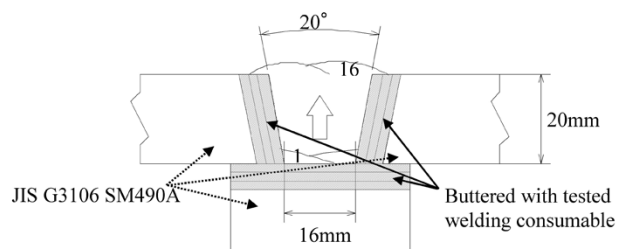


Fig. 1 Groove configuration and pass sequences

note) TRUSTARC (TRUSTARC<sup>TM</sup>) is a trademark of Kobe Steel.

Table 1 Welding conditions

Diameter of core rod	$\phi$ 4.0mm
Welding current (Polarity)	150 A (DCEP)
Welding voltage	26~29 V
Welding speed	14~20 cm/min.
Pass sequences	8Layers 16Passes
Preheat and interpass temperature	235~255 °C
Heat input	Avg.16 kJ/cm
Welding position	Flat

was provided with three layers of buttering welding using respective welding consumables tested and machined smoothly so as to prevent the fluctuation of the chemical composition due to dilution by the base material. **Table 1** shows the welding conditions inside the groove.

## 1.2 PWHT conditions

Each specimen for mechanical properties evaluation was subjected to PWHTs. For weld metal A, the PWHTs were conducted at five temperatures: i.e., 670, 730, 760, 790 and 820°C. For weld metal B, PWHTs were conducted at four temperatures; i.e., 720, 760, 800 and 850°C. The holding time for each PWHT was 4 hrs. The lower control limit for the PWHT temperature was 300°C, while the heating rate and cooling rate above the lower control limit temperature were 55°C/h or lower.

## 1.3 Measurement of $A_{c1}$ transformation points of weld metals

In order to measure the  $A_{c1}$  transformation point, a solid cylindrical specimen of  $\phi 8 \times 66$ mm was taken from each weld metal, as-welded. Each specimen was taken in the direction parallel to the welding direction and from a location at the center of the bead width and of the plate thickness. The  $A_{c1}$  transformation point is defined as the temperature at which the austenitic phase starts to form during the heating process. A general method for measuring the  $A_{c1}$  transformation point involves detecting the expansion and contraction of the specimen during the phase transformation.<sup>4)</sup> This type of measurement technique, however, often yields measurement values that vary significantly, because its accuracy depends on the method of the expansion/contraction measurement and the measurement conditions. Therefore, a preliminary study was conducted to verify the validity of the method adopted in this study for measuring the  $A_{c1}$  transformation point.<sup>5)</sup> The measurement method adopted involves heating a specimen by induction in a high vacuum atmosphere of approximately  $10^{-3}$  Pa, and detecting the diameter change of the specimen during the heating, using a non-contact high-precision measuring system

equipped with an LED device. The heating rate of the specimen was 10°C/min up to 600°C and was 5°C/min in the temperature range from 650 to 1,050°C, the range in which reverse transformation is expected to occur. On the other hand, a carbon steel containing 0.19mass%C was used as a standard sample to verify the validity of the measurement result. For this verification, comparisons were made between the  $A_{c1}$  transformation point measured and the  $A_1$  point that is roughly derived from the Fe-C phase diagram.

## 1.4 Mechanical properties evaluation of weld metal

The mechanical properties evaluated were tensile strength at room temperature, Charpy impact absorbed energy at 20°C and the creep rupture time at 600°C (applied stress : 108MPa and 147MPa). The specimens, in accordance with AWS A5.5, were prepared from each weld metal after the PWHT for the room temperature tensile test and Charpy impact test. Each creep rupture specimen had a diameter of  $\phi 6.0$ mm with extensometer limb and was taken in the direction parallel to the welding direction and from a location at the center of the bead width and of the plate thickness.

## 1.5 Observation on the state of carbonitride precipitation and the extracted residue analysis

A transmission electron microscopy (TEM) study was conducted on the precipitation state of carbonitride after the PWHT. Each TEM observation sample was taken from a cross-section vertical to the welding direction at the center of the bead width and of the plate thickness. The observation was conducted by an extraction replica technique. Extracted residue analysis was conducted to identify the amount and composition of carbonitride, using a solid cylindrical specimen of  $\phi 8 \times 20$ mm. Each specimen was taken from the same location as the TEM observation sample, but in the direction parallel to the welding direction.

## 2. Experimental results and discussion

### 2.1 The chemical compositions of weld metals

**Table 2** shows the chemical compositions of weld metals A and B, as well as that of the carbon steel used as the standard sample for the measurement of  $A_{c1}$  transformation point. The amounts of Mn+Ni in the weld metals were 2.49 mass% for A and 1.38 mass% for B.

### 2.2 $A_{c1}$ transformation point of weld metals

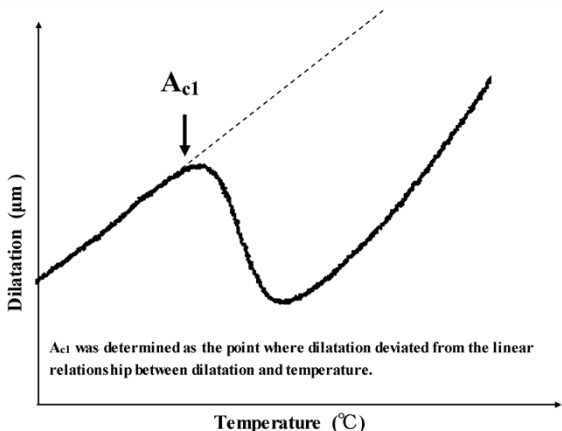
**Table 3** shows the  $A_{c1}$  transformation points

Table 2 Chemical compositions of testing materials

Testing materials	Chemical compositions (mass%)									
	C	Si	Mn	Ni	Cr	Mo	V	Nb	N	Mn+Ni
Weld metal A	0.07	0.35	1.57	0.92	8.86	1.02	0.24	0.025	0.028	2.49
Weld metal B	0.11	0.23	0.85	0.53	9.01	1.01	0.25	0.034	0.027	1.38
Carbon steel	0.19	0.10	0.03	-	-	-	-	-	-	0.03

Table 3 Measurement results for A<sub>c1</sub>

Weld metal A	733 °C
Weld metal B	785 °C
Carbon steel with 0.19mass%C	732 °C



measured. The A<sub>c1</sub> transformation point of the 0.19 mass%C carbon steel, used as the standard sample, was found to be 732°C. This temperature agrees well with the A<sub>1</sub> transformation point of approximately 727°C derived from the Fe-C system phase diagram. This result verifies the reliability of the method used to measure the A<sub>c1</sub> transformation point in the present study; i.e., the method involving heating a specimen by induction in a high vacuum atmosphere, and detecting the change in the diameter of the specimen using a non-contact high-precision measuring system with an LED device.

The A<sub>c1</sub> transformation points of weld metals A and B, measured in accordance with this method, were 733°C and 785°C, respectively. These measurement results are hereinafter used as the A<sub>c1</sub> transformation points of the respective weld metals.

### 2.3 Effect of PWHT temperature on mechanical properties of weld metals

Fig. 2 and Fig. 3 show the relationships between the PWHT temperature and mechanical properties at room temperature of the weld metals A and B, respectively. Also included in each figure is the strength of Gr. P91 steel specified by ASTM.

The room-temperature tensile strength of weld metal A decreases with rising PWHT temperature until the PWHT temperature reaches 760°C, but increases when the PWHT temperature exceeds 760°C. The room-temperature tensile strength of weld metal B, on the other hand, decreases monotonically with rising PWHT temperature and becomes almost

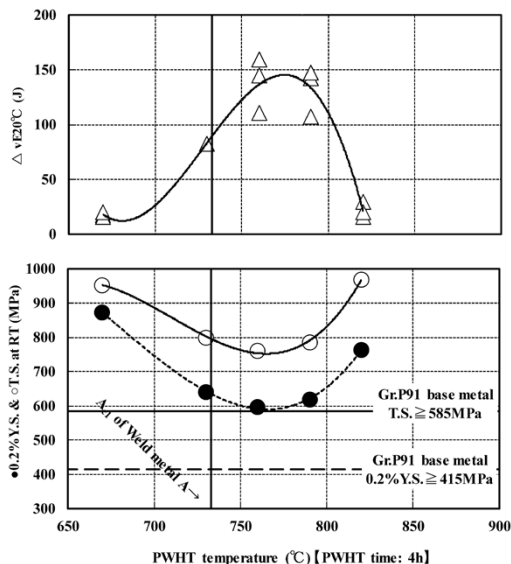


Fig. 2 Relationship between PWHT temperature and mechanical properties of weld metal A at RT

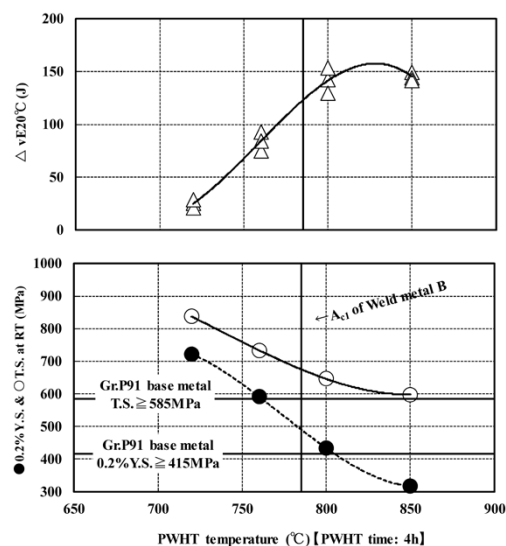


Fig. 3 Relationship between PWHT temperature and mechanical properties of weld metal B at RT

equal to the lower-limit strength value specified for the steel at the PWHT temperature of 800°C. At 850°C, 0.2% proof strength at room temperature drops below the lower-limit strength value specified for the steel.

The absorbed energy of weld metal A increases with rising PWHT temperature until the temperature reaches 760°C, but decreases when the PWHT temperature exceeds 760°C. The absorbed energy of weld metal B, on the other hand, increases with rising PWHT temperature and appears to reach a maximum at a PWHT temperature between 800°C and 850°C.

Fig. 4 shows the relationship between the PWHT temperature and creep rupture time of weld metals A and B. When the applied stress is low (108MPa), the creep rupture times of both weld metals A and B become shorter with rising PWHT temperature. The

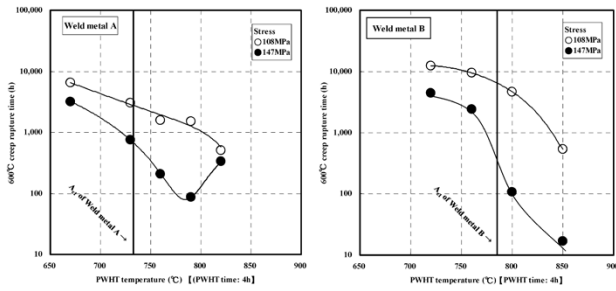


Fig. 4 Relationship between PWHT temperature and 600°C creep rupture time of weld metals A and B

creep rupture time of weld metal B decreases abruptly at PWHT temperatures exceeding 800°C. When the applied stress is high (147MPa), the creep rupture time of weld metal A shortens with rising PWHT temperature until the temperature reaches 790°C, but, in contrast to this, above 790°C, it lengthens. The creep rupture time of weld metal B, on the other hand, shortens with rising PWHT temperature and decreases abruptly at PWHT temperatures exceeding 760°C.

In the case of weld metal A, a reversal phenomenon was observed, at a boundary of the PWHT temperature, in each mechanical property, i.e., the room-temperature tensile strength, absorbed energy and creep rupture time under high applied stress. This phenomenon is considered to be caused by fresh martensite precipitated at PWHT temperatures exceeding the  $A_{c1}$  transformation point. Fresh martensite is formed from the austenitic phase that is formed at temperatures exceeding the  $A_{c1}$  transformation point, undergoing martensitic transformation in the cooling process. The primary objective of PWHT is tempering; however, the fresh martensite is not tempered and exhibits high strength and low toughness. This is considered to have caused the reversal phenomena in the mechanical properties.

There are two facts that should be noted. The first fact is that the reversal of the mechanical properties of weld metal A occurs at temperatures higher than its  $A_{c1}$  transformation point. This fact is roughly explained by the reverse transformation ratio. Fig. 5

shows the reverse transformation ratios of weld metals A and B. Each reverse transformation ratio was determined from the temperature vs. expansion/contraction curve obtained by the  $A_{c1}$  transformation point measurement. For each of weld metals A and B, the ratio of the reverse transformation to the austenitic phase is rather small in the temperature range immediately above the  $A_{c1}$  transformation point, which makes the amount of fresh martensite precipitated in the cooling process small and not enough to cause the reversal of the mechanical properties. On the other hand, as the PWHT temperature rises, the reverse transformation ratio increases, increasing the amount of fresh martensite with high strength and low toughness. This is considered to have caused the reversal phenomena described above. Meanwhile, unlike weld metal A, weld metal B did not show any reversal of mechanical properties even when the PWHT temperature greatly exceeded its  $A_{c1}$  transformation point and the reverse transformation ratio became sufficiently large. This phenomenon cannot simply be explained by the reverse transformation ratio alone. For an explanation, two assumptions were considered; i.e., the precipitation of low C fresh martensite and the precipitation of ferrite phase<sup>6)</sup>. The former, in particular, was considered on the basis of the fact that weld metal B has a smaller amount of Mn + Ni compared with weld metal A. When the amount of Mn + Ni is small, only a small amount of solid solute C is generated in the austenitic phase by the reverse transformation. As a result, low C fresh martensite that is relatively soft is considered to precipitate in the cooling process.

The following experiment was conducted to verify these assumptions. The specimens for the  $A_{c1}$  transformation point measurement were prepared from weld metals A and B, both as-welded. Each specimen was held for 1h at a temperature approximately 30°C higher than its respective  $A_{c1}$  transformation point and was subjected to the cooling process at a cooling rate of 2°C/min. The temperature

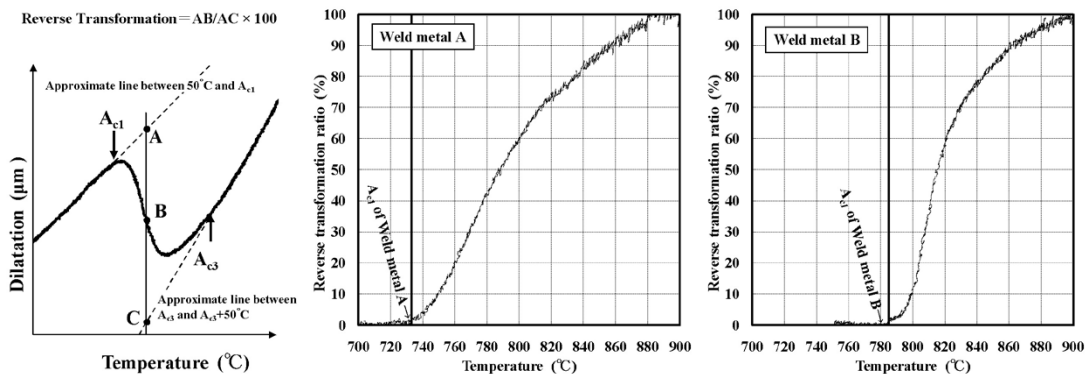


Fig. 5 Relationship between temperature and reverse transformation ratio of weld metals A and B



vs. expansion/contraction curve was measured during the cooling process to confirm the precipitated phase. Fig. 6 shows the results. Weld metal A exhibits a linear expansion behavior, an indication of fresh martensite formation, at around 400°C. Weld metal B, on the other hand, exhibits another linear expansion behavior, an indication of third phase precipitation, at around 750°C. Fig. 7 shows the microstructures of weld metals A and B after this test, and Fig. 8 shows the Kernel Average Misorientation (KAM) images of the respective fields. The KAM images are obtained by electron backscatter diffraction (EBSD) analysis and provide measures of crystal misorientation and lattice strain. A KAM image represents the average crystal misorientations between a pixel and the nearest neighboring pixels in the image, and displays the crystal misorientation distribution in the observed field. Martensite has a large lattice strain in its crystal lattice, enabling the KAM image to discriminate between ferrite and martensite in the microstructure. Comparing weld metals A and B in Fig. 7, it can be seen that the microstructure of weld metal B has a coarse white texture in the perpendicular direction in

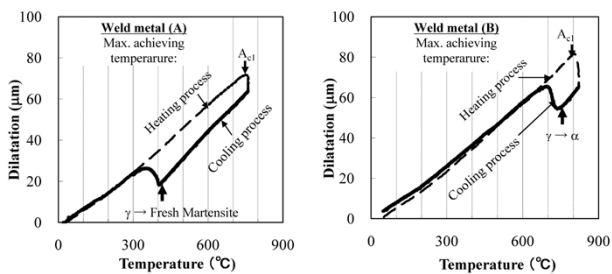


Fig. 6 Phase transformation temperature of weld metals A and B during cooling process

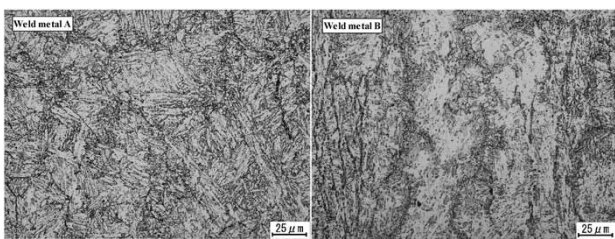


Fig. 7 Microstructures of weld metals A and B after phase transformation temperature analysis

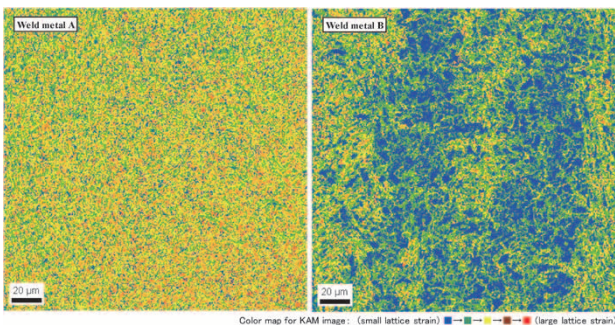


Fig. 8 KAM images of weld metals A and B after phase transformation temperature analysis

the middle of the photograph. This white structure corresponds to the area of concentrated blue in the KAM image of weld metal B shown in Fig. 8, which indicates that the lattice strain of this area is significantly smaller than that of the structure in the surrounding area. This implies that the white structure observed in weld metal B may possibly be ferrite. The identification of this precipitate phase will be pursued further.

The second fact that should be noted is that weld metal A shows a reversal in the relationship between PWHT temperature and creep rupture time under high applied stress, which, however, is not the case for the low applied stress. This is considered to have been caused by the difference between the deformation behavior of the creep rupture test specimens under high stress and that under low stress.<sup>7)</sup> In other words, when a high stress is applied, deformation occurs throughout the entire specimen. Fresh martensite, with highly dense dislocations in its crystal grain, contributes to the prolonged creep rupture time. On the other hand, under a low applied stress, deformation preferentially occurs in the vicinity of prior austenitic grain boundaries. Hence, the fresh martensite is considered not to have contributed to the prolonged creep rupture time.

The above results confirm that the upper limit of allowable PWHT temperature is governed by the mechanical properties, rather than by the  $A_{c1}$  transformation point.

## 2.4 Effect of PWHT temperature on the precipitation state and composition of carbonitride precipitation in weld metals

An investigation was made regarding the effect of PWHT temperature on the precipitation state and precipitate amount/composition of carbonitride in weld metal A. Fig. 9 shows the TEM images of weld metal A after PWHT at each temperature. No

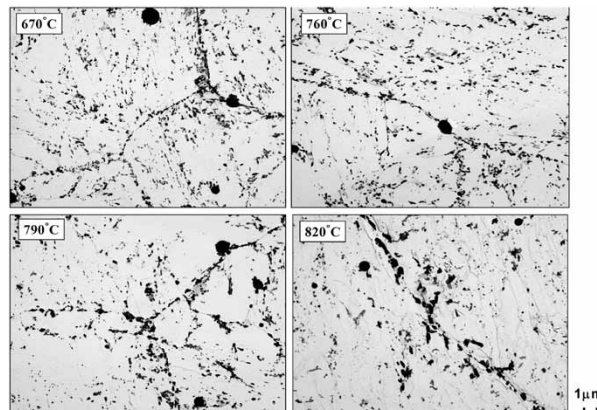


Fig. 9 TEM images of weld metal A after PWHT at different temperatures

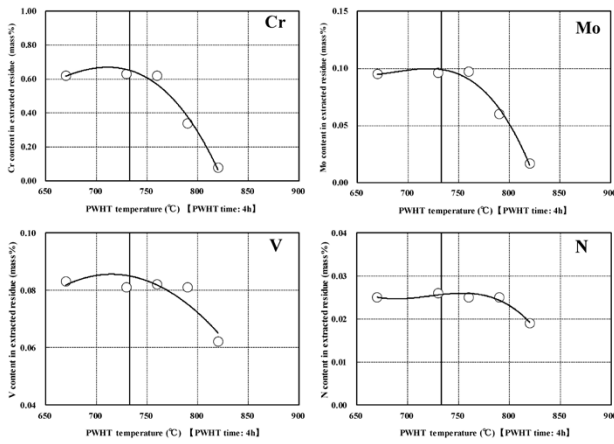


Fig.10 Analysis of extracted residues of weld metal A after PWHT at different temperatures

significant difference was found in the precipitation amount and distribution of carbonitride between the PWHT temperatures of 670°C and 760°C. However, it was clearly observed that the precipitates of intragranular carbonitride are more thinly distributed at 790°C, and the lath carbide on grain boundaries has been coarsened at 820°C.

Extracted residue analysis was conducted to quantitatively compare the precipitation amount of carbonitride at the respective PWHT temperatures. Fig.10 shows the analysis results. It is confirmed that the elements Cr, Mo, V and N all decrease abruptly when the PWHT temperature exceeds 760°C. This is considered to have been caused by the increased PWHT temperature promoting the dissolution of carbonitride into the matrix to form a solid solution.

### 3. The upper limit PWHT temperature allowable for each weld metal

The  $A_{c1}$  transformation points of weld metals A and B were measured and found to be 730°C and 780°C, respectively. If the construction standard that stipulates that the PWHT temperature must be lower than the  $A_{c1}$  transformation point is followed, the upper limits of the PWHT temperature for weld metals A and B should be approximately 730°C and 780°C, respectively. However, the PWHT temperature of 730°C provides weld metal A with tempering insufficient to achieve the desired mechanical properties. In the case of weld metal B, on the other hand, the PWHT temperature of 780°C makes the room-temperature tensile strength almost equal to the lower limit value of the standard for Gr. P91 steel, which raises a concern that the margin against the specification becomes too small. Thus, a PWHT temperature selected merely on the basis of the  $A_{c1}$  transformation point may not be practical. Comprehensive contemplation of

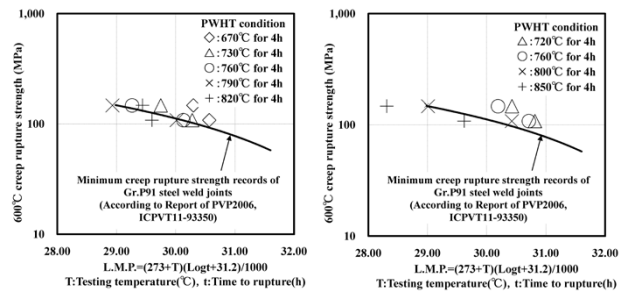


Fig.11 Creep rupture strengths of weld metals A and B after PWHT at different temperatures

mechanical properties is considered to be important in determining the PWHT temperature.

Fig.11 shows the creep rupture strengths of weld metals A and B. The creep master curve for the Gr. P91 steel welded joint is also included. From the results, and now assuming that the weld metal is required to have a creep rupture strength that is equal to or greater than that of the welded joint, the upper limits of the PWHT temperatures for weld metals A and B become 760°C and 800°C respectively.

If the PWHT temperature of 760°C is used for weld metal A, the weld metal exhibits a favorable toughness with its tensile strength at room temperature fully satisfying the specification for Gr. P91 steel. In the case where the PWHT temperature of 800°C is used for weld metal B, the weld metal exhibits a favorable toughness; however, its room-temperature tensile strength has only a small margin against the Gr. P91 steel specification, as described above.

After the comprehensive consideration of mechanical properties based on the above results, the upper limits of the PWHT temperatures for weld metals A and B are concluded to be 760°C and 800°C, respectively.

### Conclusions

Two types of weld metals were prepared using CM-9Cb and CM-95B9, Kobe Steel's covered electrodes designed for ASTM A335 Gr. P91 steel. The weld metals are mainly characterized by their different Mn + Ni content. Each of them was subjected to post weld heat treatment (PWHT) at temperatures above its  $A_{c1}$  transformation point to study its mechanical properties after the heat treatment. There was discussion concerning the upper limit of the PWHT temperature allowable for each of the weld metals. The results show that the amount of Mn+Ni for the CM-9Cb weld metal was 2.49mass%, and the  $A_{c1}$  transformation point was 733°C. In accordance with the construction standard stipulating that the PWHT temperature must be lower than the  $A_{c1}$  transformation point, the upper limit of the PWHT temperature should be 730°C; however, on the basis

of the evaluation results for mechanical properties, a PWHT temperature of up to 760°C is judged to be allowable.

The amount of Mn + Ni for the CM-95B9 weld metal was 1.38mass% and  $A_{c1}$  transformation point was 785°C. If the standard described above is followed, the upper limit of the PWHT temperature should be 780°C; however, on the basis of the evaluation results for mechanical properties, a PWHT temperature of up to 800°C is judged to be allowable.

The above findings indicate that the PWHT temperature for a weld metal of high Cr ferritic heat-resistant steel should not be determined merely on the basis of the Mn + Ni content and/or the  $A_{c1}$  transformation point, but rather should take into consideration the mechanical properties, including creep rupture performance.

The present paper studying the upper limit of the PWHT temperature focuses only on the weld metals. However, more comprehensive research should be done to evaluate the actual welded joints, and this would include a study of the base material and the heat-affected zone of the base material.

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