Development of Boiler Technology for 700°C A-USC Plant

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For the purpose of putting 700°C Advanced-Ultra Super Critical (A-USC) power generation technology into practical use, IHI developed fundamental technologies for boilers from 2008 to 2013. In particular, IHI examined the welding technology and bending technology of Ni-based alloy piping of the candidate materials. In the end, IHI established welding methods for every candidate material, even though the welding conditions are different for each material. Regarding bending technologies including cold bending, IHI also established the optimal machining conditions. Based on these conditions, IHI manufactured mockups of header pipes and loop pipes and verified that construction of an actual machine was possible. 100 000 h creep rupture tests are being conducted on welded parts to verify their long-term durability at high temperatures.

1. Introduction

Recently, there is a great need for enhancing coal-fired power generation in view of the need for reducing greenhouse gases emissions such as carbon dioxide (CO_2). Japan has led the world in enhancing the power generation efficiency by increasing steam temperatures. **Figure 1** shows the trend in steam conditions in developing coal-fired power generation technologies. A steam temperature of 593°C was achieved in the 1990's[1] followed by 620°C in 2009 which is the highest temperature used in commercial boilers throughout the world and holds the unbroken record since then.[2] The power generation efficiency of coal-fired power generation has been drastically improved over the last 20 years. However, because its CO_2 emissions are higher than the other power generation technologies, coal-fired power generation still needs further enhancement of power generation efficiency and technological development for CO_2 recovery. Amidst these circumstances, 700°C Class Advanced Ultra-Super Critical (hereinafter referred to as A-USC) pressure has drawn people's attention as one means to achieve coal-fired power generation having enhanced power generation efficiency.[3]-[5] This A-USC technology has been adapted to use steam at a temperature of 700°C which is 100°C higher than the current 600°C USC power-generating technology and therefore expected to lead to applications not only in new power plants but also in the renewal or replacement of existing coal-fired power plants. Because of its expected capability to increase the power generation efficiency by 4% or more compared to the current USC technology, it is believed that A-USC technology will contribute to reducing CO_2 emissions by approximately 10%.

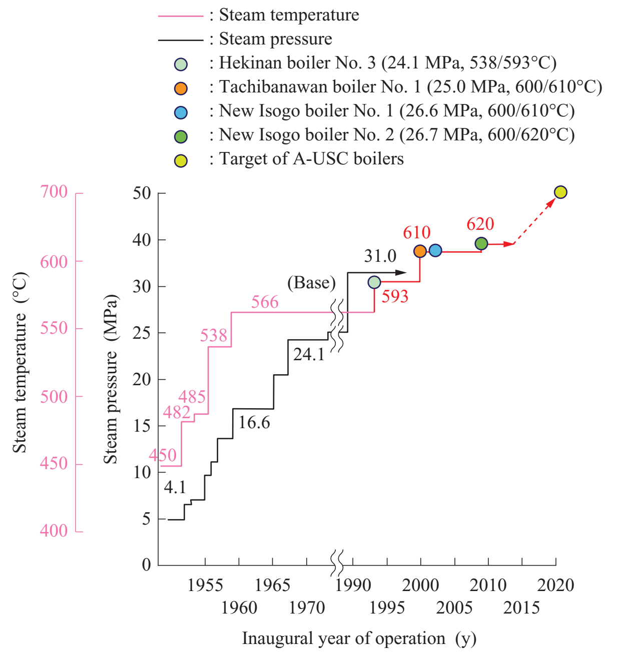


Fig. 1 The trend in the development of steam conditions in Japan

The development of the A-USC technology was initiated in Europe in 1998. Currently, it is being actively developed worldwide including in the USA, India, China and Russia.[6]-[9] Europe and the USA in particular have already conducted boiler component tests and lead the world in this field. India and China are in the fundamental technology development stage. Russia has been developing original materials but it is expected to take more time before these materials can be subjected to boiler component tests. In Japan, the "Development of the fundamental technologies for the commercialization of A-USC thermal power" was started in 2008 as a project subsidized by the Agency for Natural Resources and Energy in the Ministry of Economy, Trade and Industry with the participation of domestic material, turbine, valve and boiler manufacturers. IHI has participated in its development as a boiler manufacturer and contributed to developing boiler fundamental technology. **Figure 2** shows the development plan for A-USC fundamental technologies. Because A-USC technology applies Ni-base alloys to boiler piping, it is necessary to establish production technologies including for the welding and fabrication of such material. Efforts to establish such production technologies were made from 2008 to 2013. The design as well as fabrication and operation planning for boiler component testing have been conducted since 2014. Since it is also important that the boiler material have long-term reliability under high temperatures, material verification tests for long-term creep rupture strength have been conducted continuously since 2010. Trends in design technologies for A-USC boilers have already been introduced in the previous report.(10)

This report focuses on welding and bending technologies of Ni-base alloys which have been developed as part of the fundamental technologies together with interim results of verification tests on creep rupture strength at weld and bent sections. To develop a welding technology, welding conditions were first tested using test pieces of plates and welding technology then was developed by utilizing an actual scale test model and these were finally verified using a mock-up.

2. Characteristics of the candidate materials of A-USC boilers

This section explains the characteristics of candidate materials for A-USC boilers. First, **Fig. 3** shows the 100 000 h creep

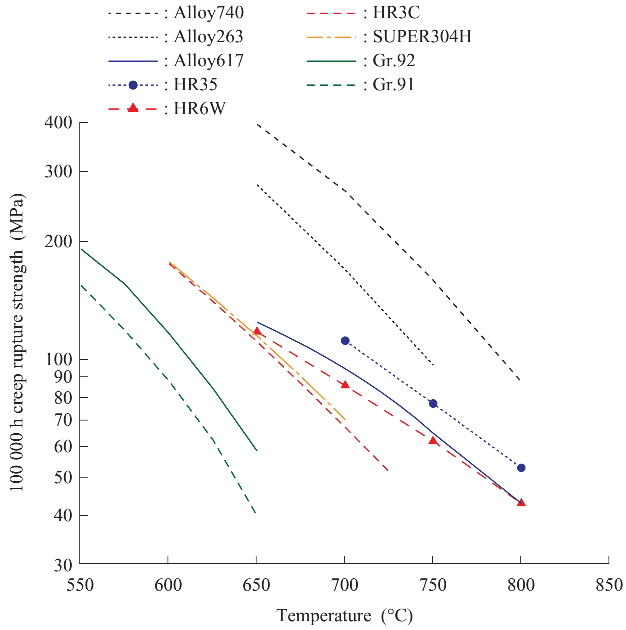


Fig. 3 100 000 h creep rupture strength of boiler materials

rupture strength of several boiler materials together with those used in the USC technologies. In current production of USC power generation, the materials used in high temperature ranges are respectively ferrite steel (Gr. 91 and Gr. 92) for pipes and austenitic stainless steel (SUPER 304H and HR3C) for heat-transfer tubes. The high-temperature strength of these materials is around 100 MPa at a temperature close to 600 to 650°C. The ferrite steel has a tempered martensite structure with precipitation of fine carbide and nitride to increase high-temperature strength and therefore requires adjustment of the precipitation amount by applying thermal treatment prior to usage. Austenitic stainless steel (SUPER 304H, HR3C) is a material subjected to solution heat treatment and delivers high-temperature strength via the

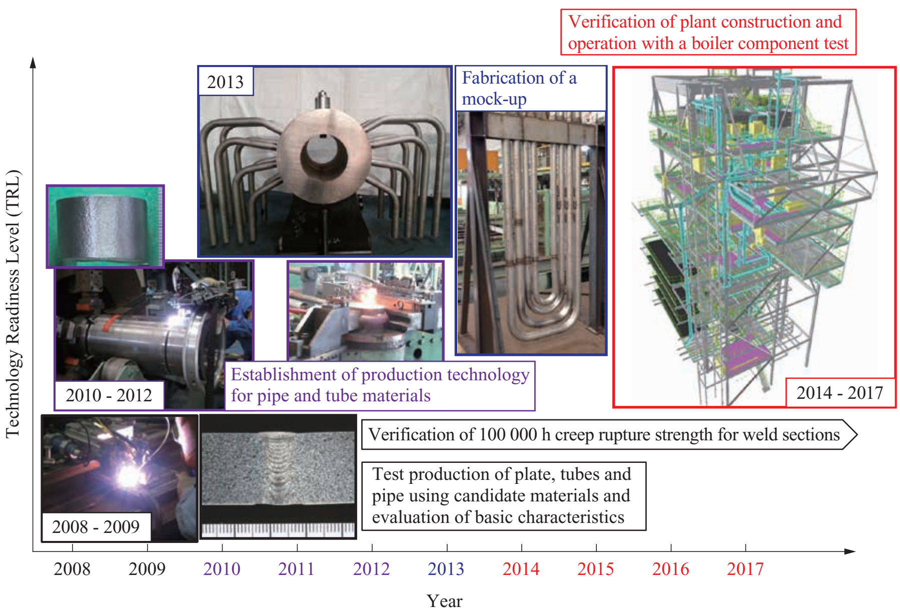


Fig. 2 The development plan of A-USC technology

precipitation of fine carbide and nitride during use. In other words, this material changes its structure while being used and provides strength at high-temperatures.

In contrast, Ni-base alloys (Alloy740, Alloy263, Alloy617, HR35 and HR6W), which are candidate materials for A-USC boilers, have a 100 000 h rupture strength of 100 MPa at temperatures in the vicinity of 650 to 750°C. Thus, Ni-base alloys allow increasing the temperature of boiler materials by 100°C compared to ferrite and austenite stainless steel. These Ni-base alloys achieve high-temperature strength by utilizing intermetallic compound phases for phase strengthening or toughening. The high-temperature strength of the Ni-base alloys increases as the volume percent of their intermetallic compounds are increased. In general, most intermetallic compounds quickly precipitate during thermal treatment to significantly increase the room-temperature strength of the Ni-base alloys. Intermetallic compounds are therefore thought likely to degrade the weldability and workability of the Ni-base alloys. As just described, the candidate materials for A-USC boilers are different from the materials used for current USC not only in terms of strength but also strength development mechanisms and thereby require a full understanding of their characteristics when used. The following sections therefore address results from evaluating the weldability and workability of the candidate materials, HR6W,[11] HR35,[12] Alloy617, Alloy263 and Alloy740H.[13]

3. Establishment of welding technology

3.1 Evaluation of welding technology

In order to confirm weldability and establish welding conditions, welding tests were conducted using plates and forged pipes. **Table 1** shows the test results. As part of the verification tests made on weld joints, bending, tensile and Charpy impact tests were conducted. In order to confirm the creep rupture strength at the weld joints, a creep rupture test with a maximum creep rupture time of 10 000 h was conducted. Photographs of the cross-sectional macrostructure of the weld joint made from HR6W are shown in **Fig. 4** as a typical result of the creep rupture test. These tests confirmed for all Ni-base alloys that: no weld defects were found to be occurred in the bending test; no generation of tiny cracks was found in the weld sections in the microstructure observation; the weld bond lines and Heat Affected Zones (HAZ) showed a high Charpy impact value of 100 J/cm^2; the tensile strength at the welded sections was equal to that of base materials; and the creep rupture strength at the weld

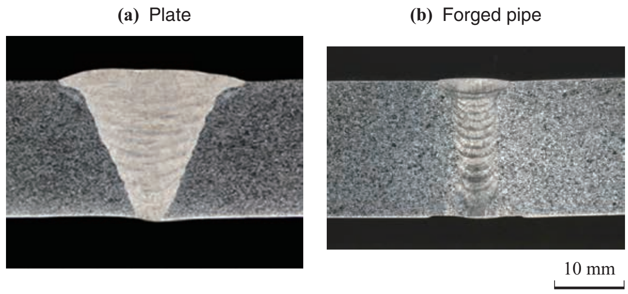


Fig. 4 Cross-section of the macrostructure of HR6W welds

joint was found to be equal to that of base materials in the 10 000 h creep rupture test. The weld conditions established with the plates and forged pipes are therefore considered comparable to tests at the actual boiler size. The weldability was then verified using pipe having the actual dimensions shown in the following section.

3.2 Establishment of pipe welding technologies

To attain the goal of providing adequate creep rupture strength and workability when fabricating pipes, three types of Ni-base alloys, Alloy617, HR6W and HR35, and five types of Ni-base alloys, Alloy617, HR6W, HR35, Alloy263 and Alloy740H were respectively selected as candidate materials for pipes and tubes for A-USC boilers. Welding tests using pipes made from these selected alloys were then conducted. The test results are shown in **Table 2**.

In the welding tests, two types of welding methods called GTAW and SMAW were used. The SMAW method was used only for the welding test of the pipe made from HR6W alloy. In consideration of a previous report saying that pipe made from Alloy617 had different creep rupture strength depending on additive amount of B (boron),[14] the effect of B on the creep rupture strength was also studied. The types of tests conducted for the evaluation of weld joints were Charpy impact, bending, tensile and creep rupture tests. The effect of SR (Stress Relieving) treatment on weld sections of pipes was also studied.[15]

Photographs from observation of the cross-sectional macrostructure of the weld joint made from HR6W are shown in **Fig. 5** as typical test results.

Results from the bending test and microstructure observation show that hot cracks were partially occurred only in pipe made from Alloy617 with high additive amount of B. Therefore, from the viewpoint of weldability of the large-diameter pipe made from Alloy617, it is necessary to select

Table 1 List of welding tests for plates and forged pipes for A-USC boilers

Test piece dimensions (mm)	Material	Filler material	Welding method	Crack at weld Microstructure observation and bending tests	Charpy characteristics at bond line and HAZ (J/cm^2)	Tensile strength (room temperature and high temperature)	Creep rupture strength
- Plate t (thickness) = 25 - Forged and bored pipe ϕ 80 × 20 (t)	HR6W	WEL-AUTO-TIG-617	GTAW	No	100 or more	Equal to base material	Equal to base material
	HR35	WEL-AUTO-TIG-617	GTAW	No	100 or more	Equal to base material	Equal to base material
	Alloy617	WEL-AUTO-TIG-617	GTAW	No	100 or more	Equal to base material	Equal to base material
	Alloy263	NIMONIC Filler Metal 263	GTAW	No	100 or more	Equal to base material	Equal to base material
	Alloy740H	NIMONIC Filler Metal 263	GTAW	No	100 or more	Equal to base material	Equal to base material

(Note) GTAW : Gas Tungsten Arc Welding

Table 2　List of welding tests for A-USC boiler pipes and tubes

Test piece dimensions (mm)	Material	Filler metal	Welding method	Crack at weld	Tensile strength	Creep characteristic evaluation
Pipe ϕ 350 × 40 (t)	HR6W	WEL-AUTO-TIG-617	GTAW	No	Equal to base material	Under test
	HR6W	WEL117	SMAW	No	Equal to base material	Under test
	HR35	WEL-AUTO-TIG-617	GTAW	No	Equal to base material	Under test
	Alloy617 (with high B)	NIMONIC Filler Metal 263	GTAW	Hot crack	Equal to base material	Equal to base material
	Alloy617	WEL-AUTO-TIG-617	GTAW	No	Equal to base material	Under test
Tube ϕ 45 × 8.8 (t)	HR6W	WEL-AUTO-TIG-617	GTAW	No	Equal to base material	Under test
	HR35	WEL-AUTO-TIG-617	GTAW	No	Equal to base material	Under test
	Alloy617	WEL-AUTO-TIG-617	GTAW	No	Equal to base material	Under test
	Alloy263	NIMONIC Filler Metal 740H	GTAW	No	Equal to base material	Under test
	Alloy740H	NIMONIC Filler Metal 740H	GTAW	No	Equal to base material	Under test

(Note)　SMAW : Shielded Metal Arc Welding

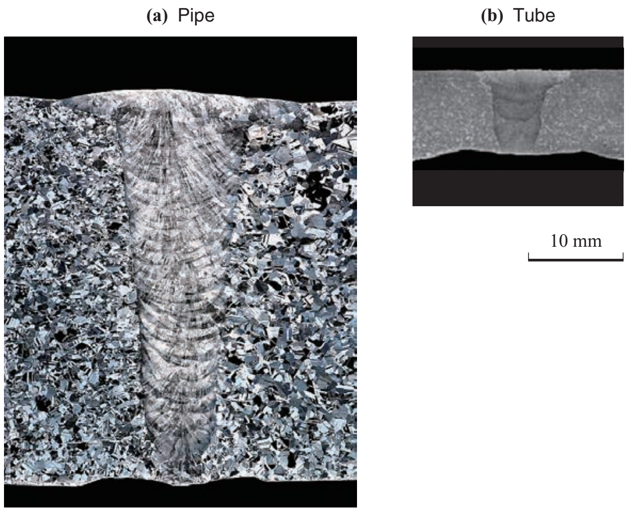


Fig. 5　Cross-section of the macrostructure of HR6W welds

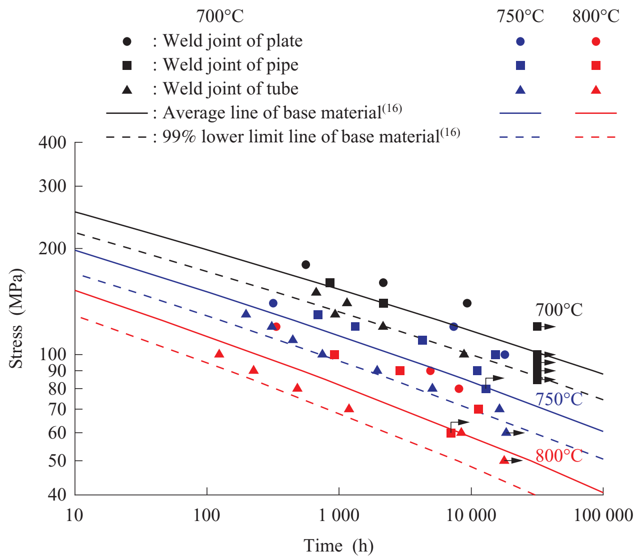


Fig. 6　Creep rupture strength of HR6W welds at 700, 725 and 800°C at stresses from 50 to 180 MPa

Alloy617 content adjusted with microelements including additive amount of B or to reselect applicable welding conditions. Bending tests and microstructure observations made on the other pipes and tubes confirmed that no cracks were occurred.

Figure 6 shows the creep rupture strength test of the weld joint made from HR6W as a typical case. This test results include those for the creep rupture test of the plates explained in **Section 3.1**. In **Fig. 6**, the solid and broken lines respectively show the average and 99% lower limit values of the creep rupture strength of the base materials.[16]

All creep rupture data for the weld joints were plotted within the range of the strength of the base materials. The reason why the strength of the weld joints of tubes with a creep rupture time less than 10 000 h was smaller than the average strength of the base materials is because the base materials of tubes have low short-term creep rupture strength. The creep rupture strength of weld joints of tubes with a creep rupture time not less than 10 000 h was nearly equal to the average strength of the base materials. The creep rupture testing is still being continued to verify the strength with the creep rupture time at 10 000 h.

Figure 7 shows the results from cross-sectional macrostructure observation of the weld joints of plates that ruptured at temperatures between 700 to 800°C with creep rupture times of 300 to 18 000 h. In every test piece, rupture occurred in a region not less than 10 mm away from the weld bond line. In other words, the rupture occurred not in the weld metal or HAZ but in the base material. After detailed microstructure observation of the ruptured test pieces, Nomura[17] confirmed that no micro cracks or creep voids were generated in HAZ. The creep rupture strength of the weld section made from HR6W therefore shows the following relation under all conditions: weld metal > HAZ > base material.

The reason for the higher strength of the weld metal is because Alloy617 which has larger high temperature strength than HR6W was used as the weld metal. The reason for larger strength in HAZ than in the base materials can be explained by the difference in microstructures as illustrated in **Fig. 8**.[17]

No precipitation was found in HAZ close to the weld bond lines or in the area in the base materials 10 mm away from the weld bond lines prior to conducting the creep rupture test. The differences between HAZ and the base material were found only in the hardness and dislocation density.[18] In observations of the structure after creep rupture, it was found that the sizes

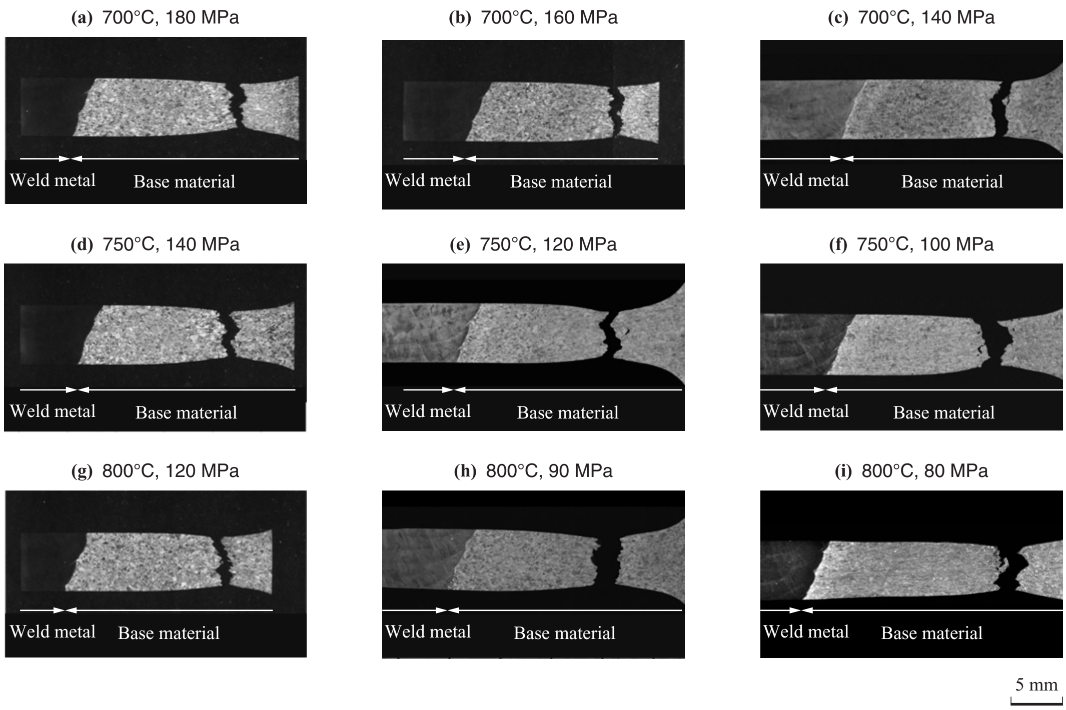


Fig. 7 Cross-sections of the macrostructure of ruptured specimens in HR6W welds

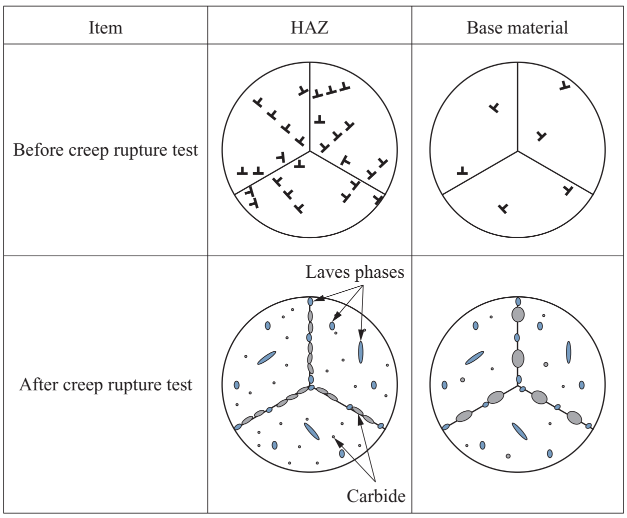


Fig. 8 Schematic illustrations showing the precipitates of HR6W welds before and after creep

of the Laves phases which increase the creep rupture strength of HR6W, were constant in the crystal grains and grain boundaries regardless of the distance from the weld bond lines. In contrast, tiny precipitation of $M_{23}C_6$ carbide which is another strengthening phase in HR6W was found more in the crystal grains and grain boundaries in HAZ than in the base materials. In terms of precipitation of $M_{23}C_6$ carbide within the crystal grains, the sizes were almost equal in regions about 10 mm away from the weld bond lines but became tinier as distances from the weld bond lines became shorter. In HAZ, the precipitation of $M_{23}C_6$ carbide was larger in the crystal grain boundaries than in regions not less than 10 mm away from the weld bond lines. This demonstrates that HAZ and the base materials have different precipitation distribution patterns and also that differences in precipitation of $M_{23}C_6$ carbide in the crystal grains and grain boundaries will appear as a difference in the creep rupture strength between HAZ and the base materials. Therefore, unlike ferrite steel, the creep rupture strength of HR6W will not drop in the weld section[19] and creep rupture will not occur in HAZ.[20]-[23]

4. Establishment of the technology for bending techniques

The fabrication of boilers involves a large number of bending techniques. Either hot bending or cold bending is selected for tubes depending on their degree of bending and hot bending by high-frequency induction heating is selected for pipes. Candidate materials selected for the tubes were HR6W, HR35, Alloy617, Alloy263, and Alloy740H and their hot and cold bending properties were verified. The property of hot bending by high-frequency induction heating was verified on HR6W, Alloy617 and HR35 which are candidate materials for the pipes.

Material sections exposed to heat due to heat and high-frequency bending generally undergo a drop in creep rupture strength. These materials are therefore subjected to a thermal treatment to restore the creep rupture strength after bending process. In contrast, material sections subjected to cold bending to a degree of processing which does not cause a reduction in creep rupture strength can be used without any additional treatment. So it is necessary to verify the creep rupture strength in material sections subjected to hot or high-frequency bending and carried out subsequent thermal treatment. In materials subjected to cold bending, it is also necessary to clarify the relation between the degree of processing and the creep rupture strength. In alloys subjected to high-frequency bending, the creep rupture strength on heat-treated alloy after high-frequency bending was evaluated; and in tubes, the creep rupture strength was evaluated after cold bending.

4.1 Bending test

Figure 9 shows pictures of bent pipes made from HR6W. The bending test results for tubes and pipes are shown in **Table 3**. These pictures show typical bend conditions for HR6W. Conventional manufacturing machines were verified as usable for hot and cold bending of tubes made from all type of alloys. Dimensional measurements and cross-sectional observations confirmed that the ellipticity, flatness and thickness of the test pieces after bend processing were within allowable ranges. The high-frequency bending test made on pipes with currently available facilities confirmed that the ellipticity and flatness after bend processing were within the allowable ranges. Results confirmed that pipes can be manufactured without problems regardless of their size and thickness.

(a) Hot bending tube

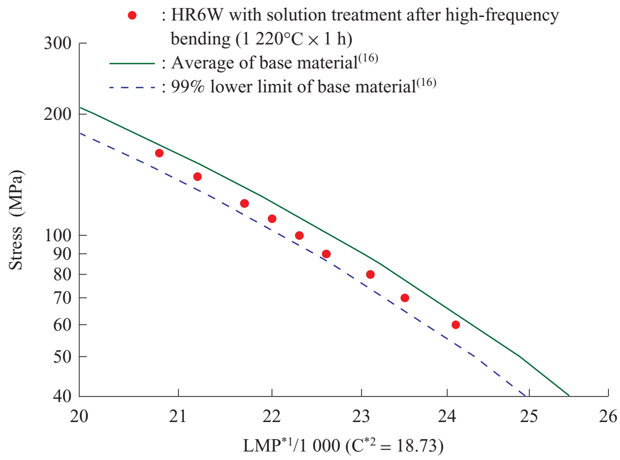
(b) Cold bending tube

(c) Hot bending pipe by high-frequency induction heating

Fig. 9 Appearance of an HR6W bent pipe and tubes

4.2 Creep rupture strength of pipe made from HR6W after bending process

Figure 10 shows the creep rupture strength of HR6W test pieces subjected to solution treatment after high-frequency bending. As shown in **Fig. 10**, the creep rupture strength of HR6W after high-frequency bending remained in the range between the average strength and 99% lower limit strength of HR6W. A 100 000 h verification test is currently underway. The reason why the thermal treatment enabled the creep rupture strength after bending to remain close to the average strength of the base materials was because all of the carbide precipitated during the bend processing was turned into solution through thermal treatment after bending as shown in **Fig. 11**. In other words, the creep rupture strength was restored due to the dispersion of coarse precipitate, which acts to reduce creep rupture strength during the thermal treatment



(Notes) *1 : Larson-Miller parameter value
*2 : Larson-Miller parameter constant

Fig. 10 Creep rupture strength of an HR6W bent pipe following the solution heat treatment

Table 3 List of bending tests for A-USC boiler pipes and tubes

Test piece dimension (mm)	Material	Bending method	Bending angle (degree)	Bending radius (DR)	Bending performance	Evaluation of creep rupture strength
Tube ϕ 45 × 8.8 (t)	HR6W	Hot bending	180	1.7	Good	—
	HR35		180	1.7	Good	—
	Alloy617 (with high B)		180	1.7	Good	—
	Alloy263		180	1.7	Good	—
	HR6W	Cold bending	180	2.8	Good	Improvement of creep strength through cold working
	HR35		180	2.8	Good	Improvement of creep strength through cold working
	Alloy617 (with high B)		180	2.8	Good	Improvement of creep strength through cold working
	Alloy263		180	2.8	Good	No effect from cold working
	Alloy740H		—	—	—	Reduction in creep strength with creep of 7.5% or more
Pipe ϕ 350 × 40 (t)	HR35	Hot bending by high-frequency induction heating	90	4	Good	Same as base material
Pipe ϕ 510 × 40 (t)	HR6W		60	3	Good	Under test
Pipe ϕ 350 × 40 (t)	HR6W		30	4	Good	Under test
Pipe ϕ 350 × 72 (t)	Alloy617		30	4	Good	Under test

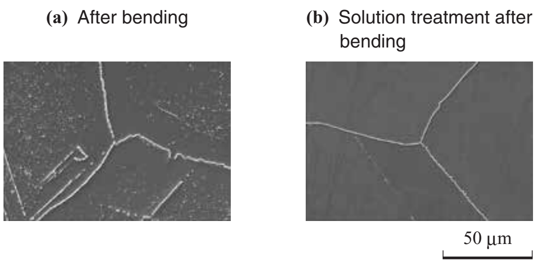


Fig. 11 SEI image of HR6W

and also due to the new precipitation of fine carbide which increases the creep rupture strength during creep.

4.3 Effect of cold working on creep rupture strength

Next, the relation between pre-strain and creep rupture strength was investigated to clarify the effect of cold working on the creep rupture strength. **Figure 12** shows the relation between the pre-strain and creep rupture strength.[24] In **Fig. 12**, life ratios relative to the creep rupture time without pre-strain and pre-strain amounts are respectively plotted on the vertical and horizontal axes. The effects of pre-strain on the creep rupture strength varied largely depending on the type of alloys with HR6W, HR35 and Alloy617 showing increases in creep rupture strength along with an increase in the pre-strain. Alloy263 showed constant creep rupture strength regardless of the pre-strain. In contrast, Alloy740/740H showed constant creep rupture strength up to a pre-strain of 5% and a reduction in creep rupture strength to about one-third that of the creep rupture strength without pre-strain when the pre-strain was at least 7.5%. The effects of cold working on the creep rupture strength vary because of differences in microstructures of the materials.

As reported by Okada,[25] the creep rupture strength of HR6W was increased due to the increased precipitation of fine Cr carbide in grains as the cold work increased. The same mechanism for the increase in creep rupture strength is also assumed for the alloy HR35. The differences in the effects of the cold working on the creep rupture strength among Alloy617, Alloy263 and Alloy740/740H are considered attributable to differences in their microstructures near the grain boundaries. **Figure 13** shows schematic illustrations of the different precipitation patterns in the grain boundaries of several types of alloys. In the case of Alloy617, cold working caused an increase in the precipitation of Mo and Cr carbide in the grain boundary. Creep rupture strength is generally thought to increase along with an increase in precipitation in the grain boundary. The increase in the creep rupture strength was therefore attributable to the increase in the amount of carbide stemming from the increased cold work. In the case of Alloy263, the amount of carbide in the grain boundary was constant regardless of the cold work and therefore the creep rupture strength was also constant. In the case of Alloy740, the amount of carbide in the grain boundary significantly decreased when the cold work was 7.5% or more. The decrease in carbide in the grain boundary was therefore considered the reason for the decline in creep rupture strength.[26]

Evaluation tests for creep rupture strength are currently underway for Alloy617 and Alloy263 with a degree of processing up to 30%.[27], [28] The Alloy263 test piece with cold working showed a slightly higher creep rupture strength than the test piece without cold working. This is because of the fine precipitation of γ', the intra-granular precipitation, due to the dislocation introduced through the cold working. In the future, the reduction in creep rupture strength over an extended time period will be evaluated by way of a long-term

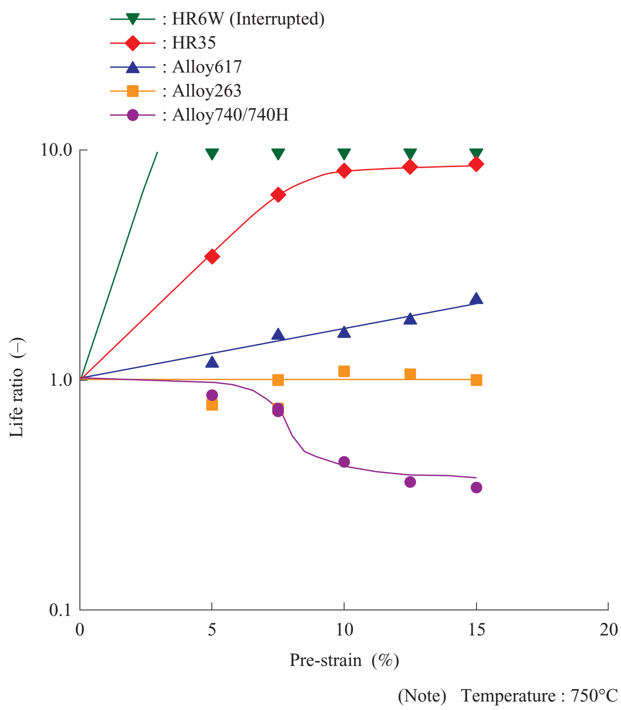


Fig. 12 The effect of cold work on the creep rupture strength of A-USC boiler tubes

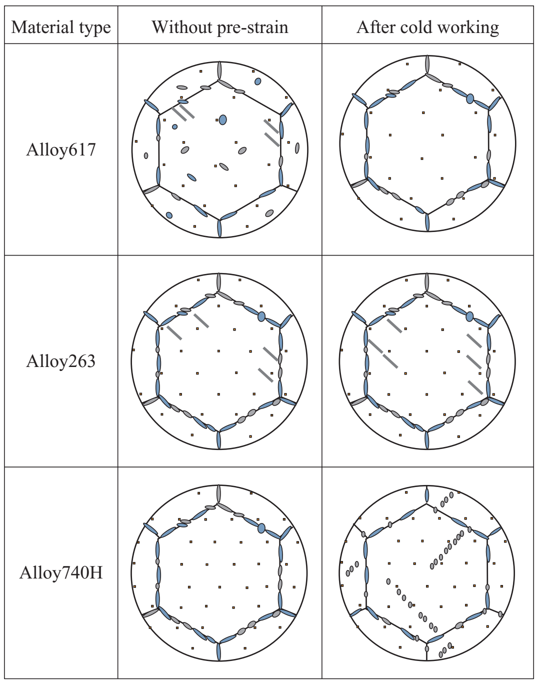


Fig. 13 Schematic illustrations showing the precipitates of cold worked Ni alloys after creep

creep rupture test.

5. Mock-up test

The previous sections addressed the establishment of welding and bending technologies and the verification of the creep rupture strength after bending process. This section focuses on the mock-up test executed to confirm the effectiveness of the established technologies for members expected to be utilized in the actual boiler fabrication. The mock-up comprised looped pipes, a main steam pipe header and a reheater pipe header. **Tables 4** and **5** show the specifications, welding methods and bending conditions for materials used in the mock-up. Also, **Fig. 14** shows the pictures taken in fabricating the mock-up. The material used for the mock-up was HR6W which is one of the candidate materials. **Figure 15** shows pictures of completed parts of the mock-up. Results from the nondestructive inspection showed that no defects were found in the bent and welded sections. **Figure 16** shows cross-sectional macrostructure observations of pipe weld sections. These observations confirmed that welding can be safely executed on the main steam pipe header with a pipe diameter up to 138 mm.

6. Conclusion

Technologies for bending and welding of tubes and pipes made from Ni-base alloys serving as candidate piping materials were established in preparation for developing A-USC boilers.

Welding methods utilizing GTAW and SMAW as well as bending method using high-frequency heating were established for candidate materials in pipes. The effect on weldability from the B (boron) content which is a minor component in materials was also clarified using Alloy617. All candidate Ni-base alloys were verified for their creep rupture strength and creep rupture testing has been underway to verify the 100 000 h creep rupture strength.

In contrast, welding method using GTAW and the bending methods using cold and hot bending were established for

(a) Welding of a seat for a temperature sensor   **(b)** Welding of stub pipes

Fig. 14 Preparing for the mock up trial

(a) Main steam pipe header   **(b)** Hot reheat pipe header   **(c)** Looped pipes

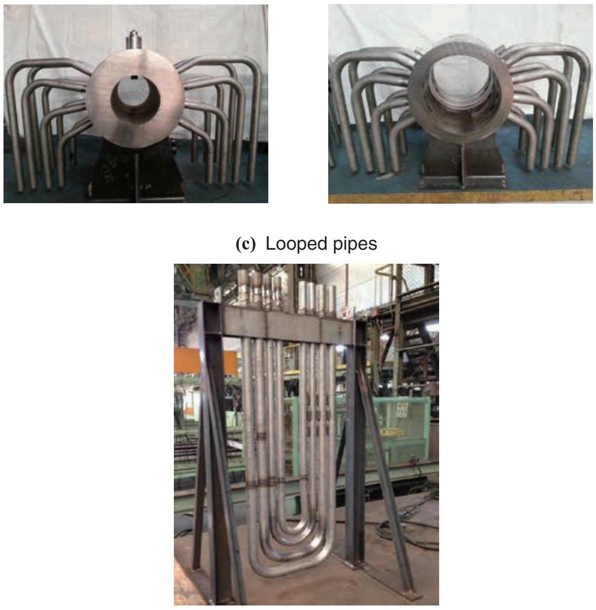


Fig. 15 Appearance of the mockups

candidate materials in tubes. These candidate materials were tested for their creep rupture strength after cold working and the effects of the cold working on the respective candidate materials were clarified.

Based on these established welding and bending technologies,

Table 4 The mock up materials and welding method used for SH and RH header

Material	Pipe (mm)	Filler metal	Welding method	Tube (mm)
HR6W	ϕ 558 × 138 (t)	WEL-AUTO-TIG-617	GTAW	ϕ 50.8 × 11.5 (t)
HR6W	ϕ 635 × 72 (t)	WEL-AUTO-TIG-617	GTAW	ϕ 63.5 × 11.5 (t)

(Note) SH : Superheat
RH : Reheat

Table 5 The mock up materials and bending conditions used for SH and RH header and loop

Material	Mock-up	Dimensions (mm)	Bending method	Bending angle (degree)	Bending radius (DR)
HR6W	Loop	Tube ϕ 50.8 × 11.5 (t)	Hot bending	180	1.7, 2.4, 2.9
HR6W	Main steam pipe header	Tube ϕ 50.8 × 11.5 (t)	Cold bending	30, 60, 80, 90, 100	2.5
HR6W	Hot reheat pipe header	Tube ϕ 63.5 × 11.5 (t)	Cold bending	30, 60, 80, 90, 100	2.4

(Note) SH : Superheat
RH : Reheat

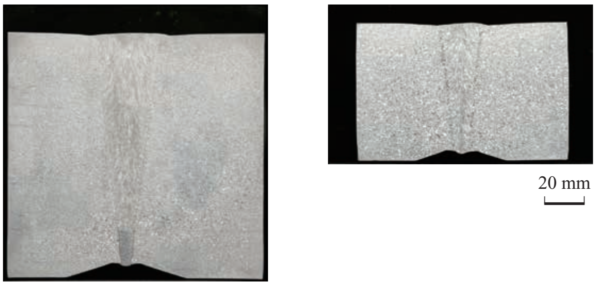


Fig. 16 Cross-section of the macrostructure of HR6W circumferential welds

the boiler component test was started at Mikawa Power Plant (in Fukuoka Prefecture) on April 29, 2015. The test has been executed at a steam temperature of 700°C and sample tests after extubation are expected to be implemented in 2016.

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