3rd Workshop on AUSC Power Plant
@ Rome

Next stage of A-USC boiler development – Life evaluation and new material development –

12/13/2017

Keiji Kubushiro

IHI Corporation
Research Laboratory

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Development of A-USC boiler

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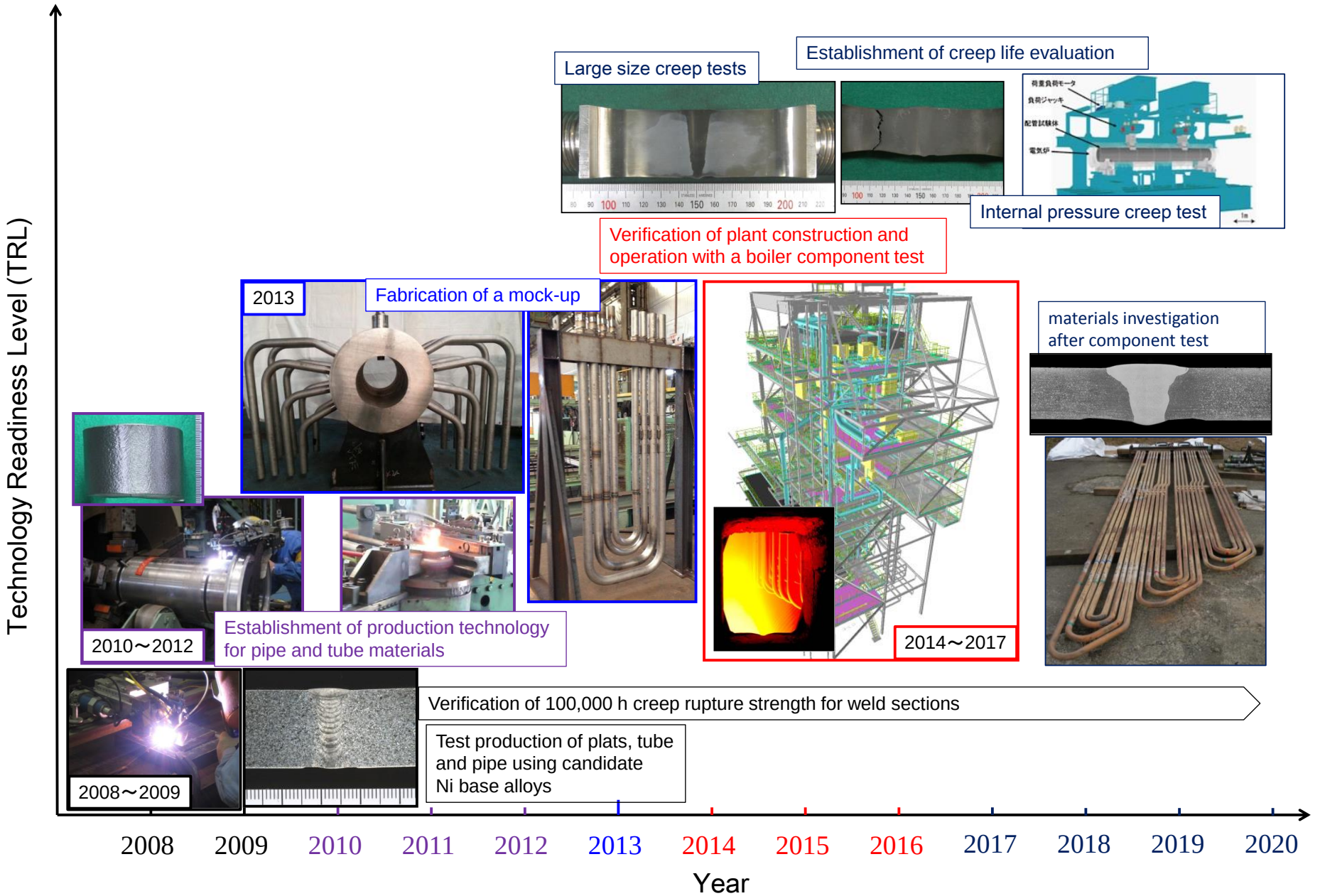

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Summary of A-USC boiler development

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- ✓ Welding and bending technologies for Ni-based alloys had been established.
- ✓ Components made of Ni-based alloy have been installed in an existing commercial coal-fired boiler and component test was conducted on the boiler from 2015 to 2016.
- ✓ The test of nearly 13,000-hour operation under 700 ℃ steam conditions was completed successfully.
- ✓ Integrity evaluation for boiler components after testing was carried out, and few significant defect was detected.

The design and manufacturing technologies for A-USC commercialization boiler are successfully established.

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Ohkuma, MPA seminar (2017)

Move on to the next stage of A-USC technologies

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1. Development of Non Destructive Examination for creep life evaluation

2. Life evaluation of welded components

3. New material development for the cost down

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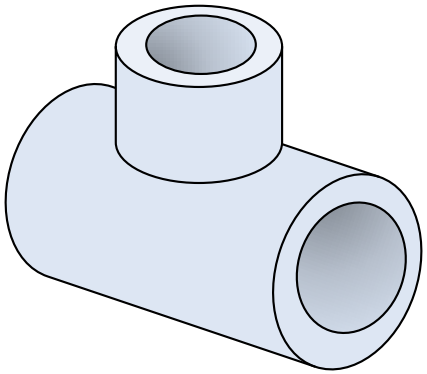
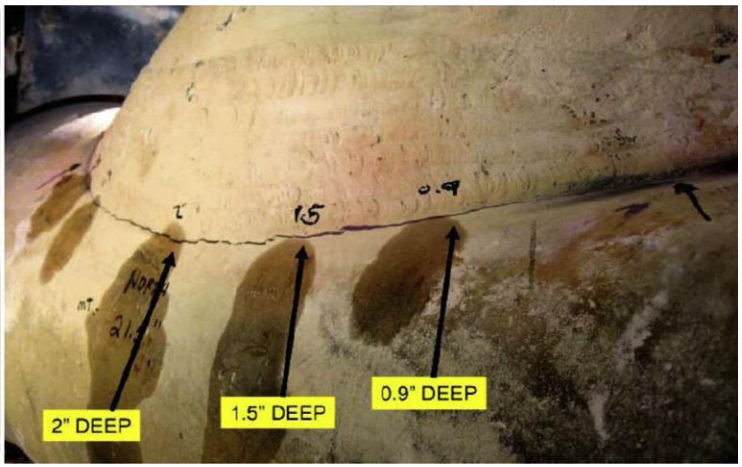
Boiler components failures in USC plants

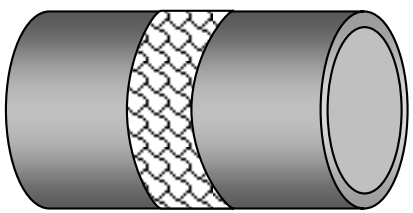
Header welds (branch connection)





Parker: International Journal of Pressure Vessels and Piping (2014)

Dissimilar welds (circumferential welds)



Wei Wang : Procedia Materials Science (2014)

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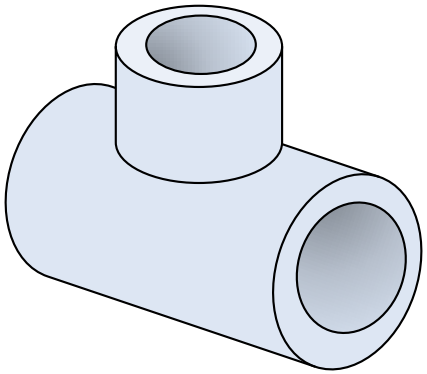
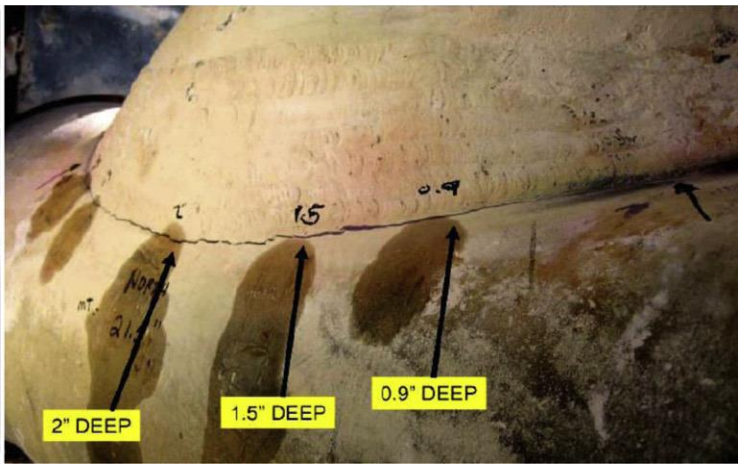
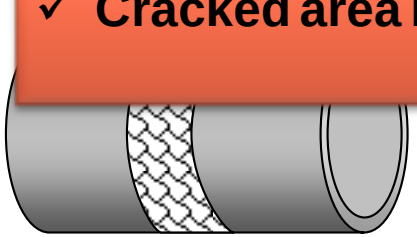
Header welds (branch connection)





Parker: International Journal of Pressure Vessels and Piping (2014)

- ✓ **Creep strength of welds for High Cr steel were lower than base metal.**
- ✓ **Cracked area is under multi-axial stress condition.**



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Boiler components failure in USC plants

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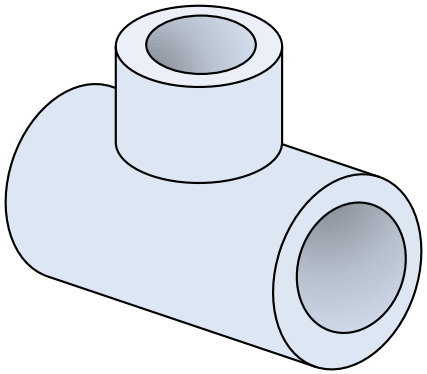
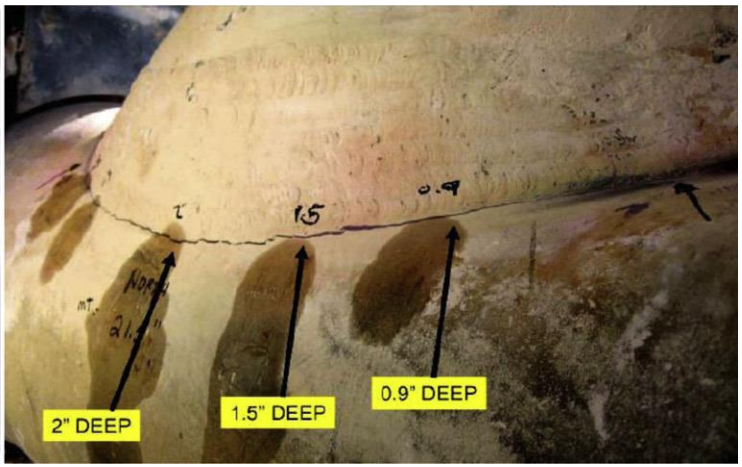
Header welds (branch connection)





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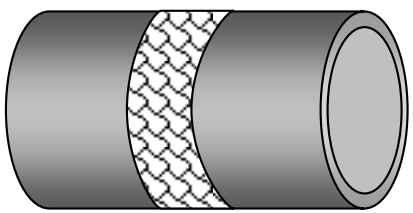
Dissimilar welds (circumferential welds)



- ✓ **Higher thermal stress is initiated because thermal expansions are difference.**
- ✓ **Coarse precipitates on the interface of weld joints.**

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Objective

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In actual plant, Many problems occurred in as follow.

- ✓ Under multi-axial condition
- ✓ Header, stub, seam weld welds
- ✓ Circumferential dissimilar welds

But, most creep rupture tests for HR6W were conducted under uniaxial condition.

To make clear
the application of the current design
the failure mechanisms of the weld sections
the creep damage evaluation method

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Test specimens

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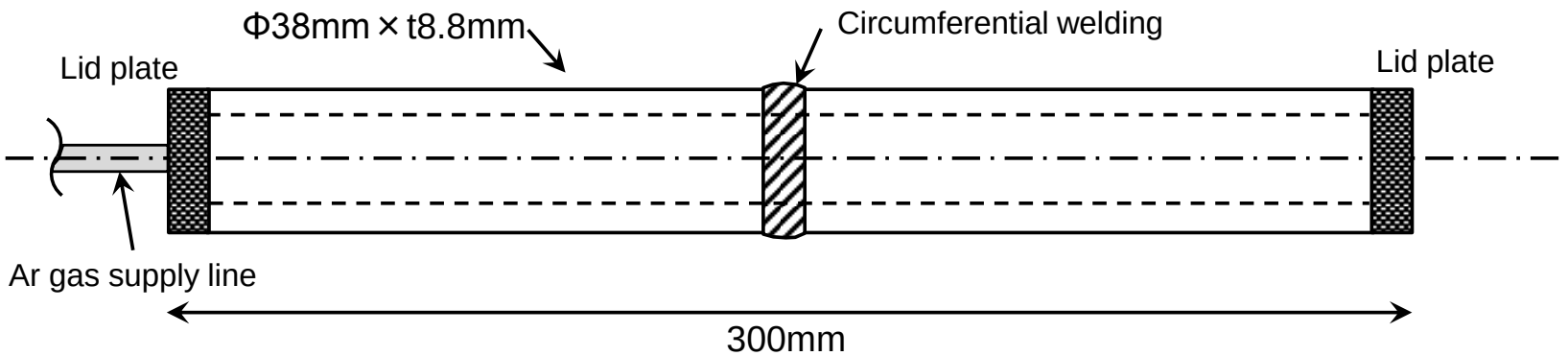
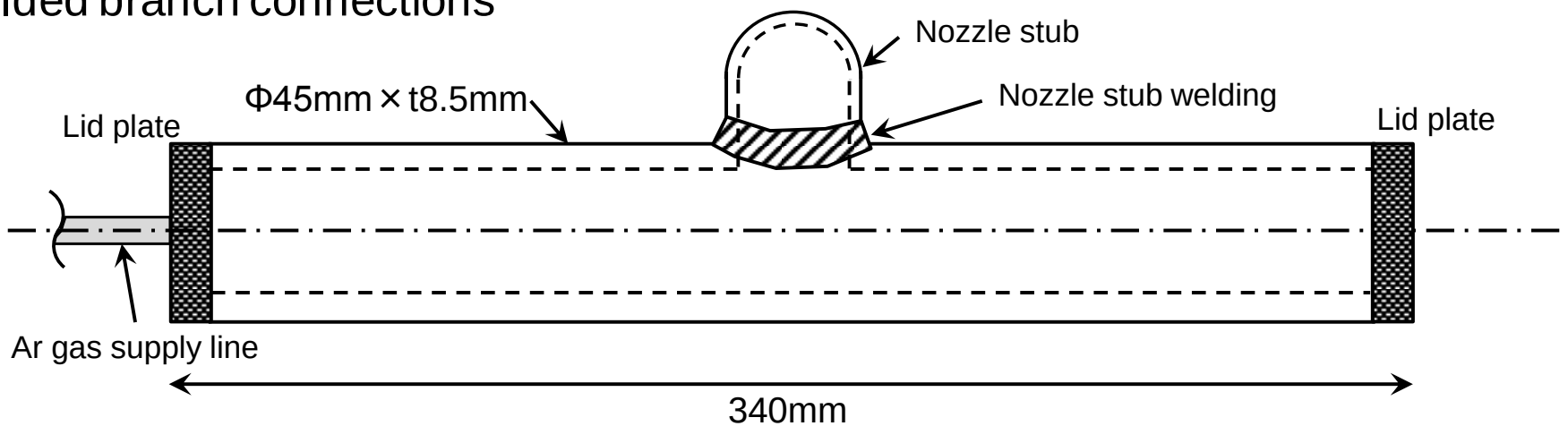
◆ Materials: HR6W tube

➢ Circumferential weld sections



➢ Welded branch connections



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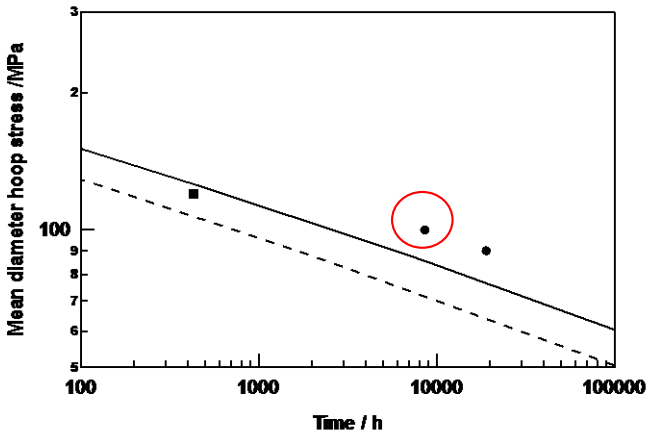
External appearances of the circumferential welds



The leak (rupture) occurred on the base material 50 mm away from the weld section at the center of the test piece.

Kubushiro, EPRI2016

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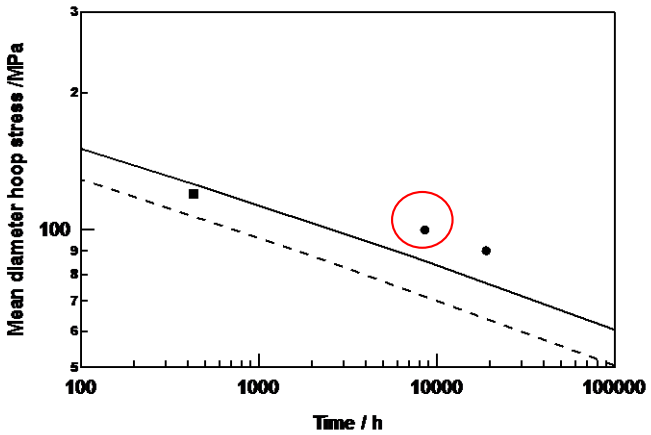
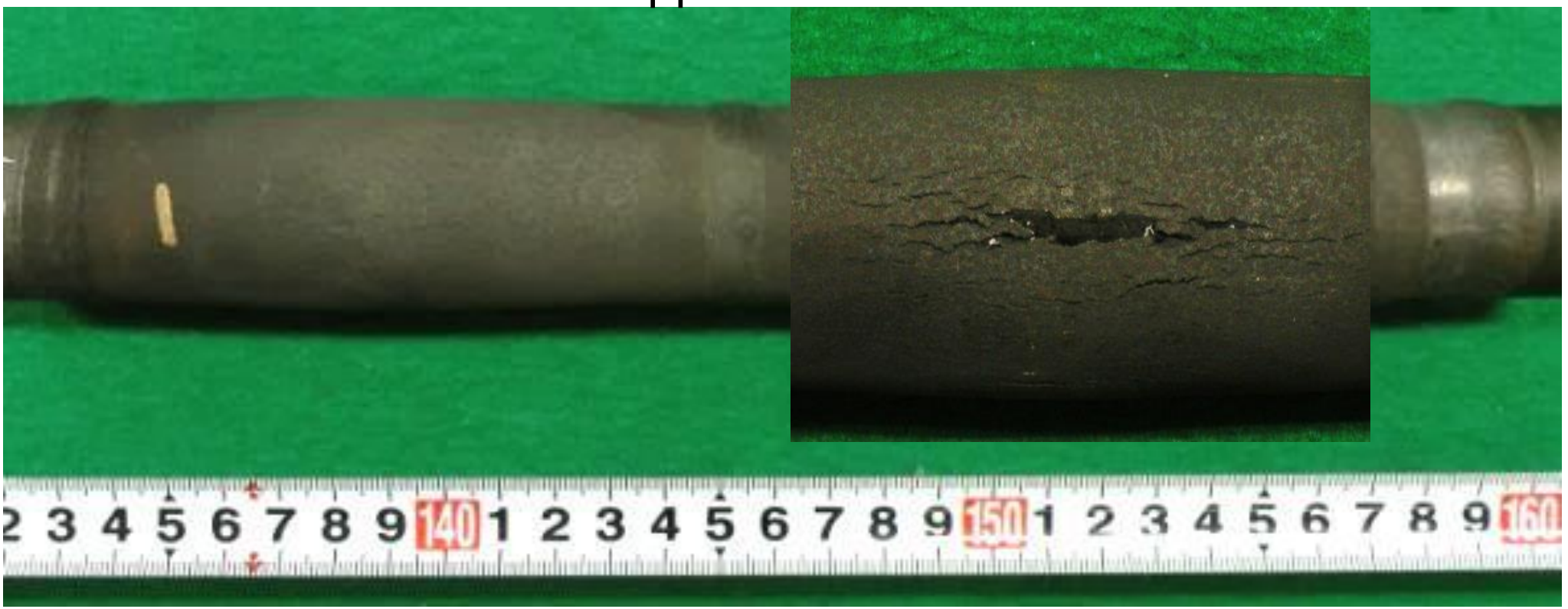
External appearances of the circumferential welds



The leak (rupture) occurred on the base material 50 mm away from the weld section at the center of the test piece.
The test piece also swelled at the base material due to the internal pressure creep at the opposite side of the leak.



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Kubushiro, EPRI2016

Macrostructure of the circumferential welds

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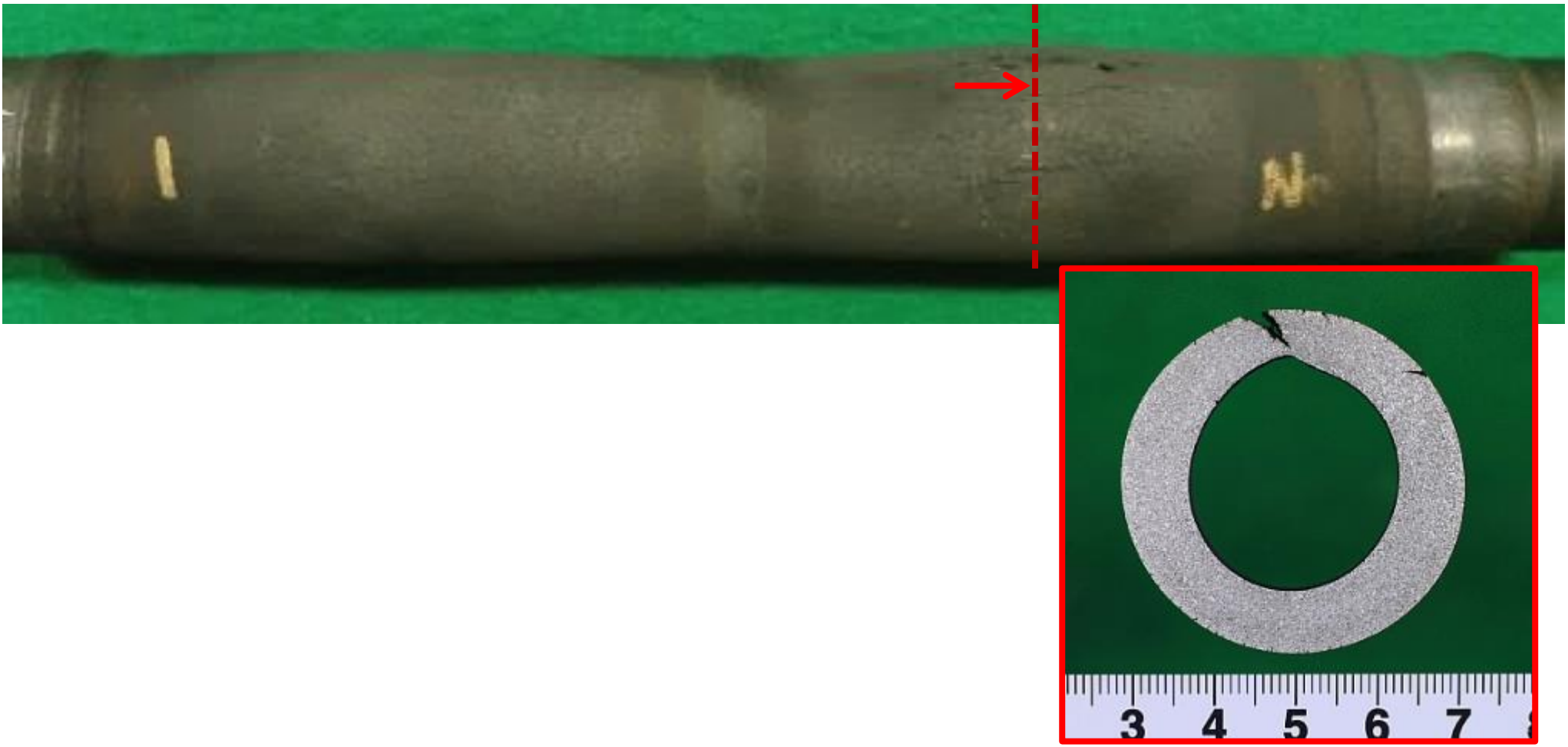
From observation of the cross-section of a leaked region, a crack developed on the external surface, extending toward the internal surface of the test piece.



Kubushiro, EPRI2016

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Macrostructure of the circumferential welds

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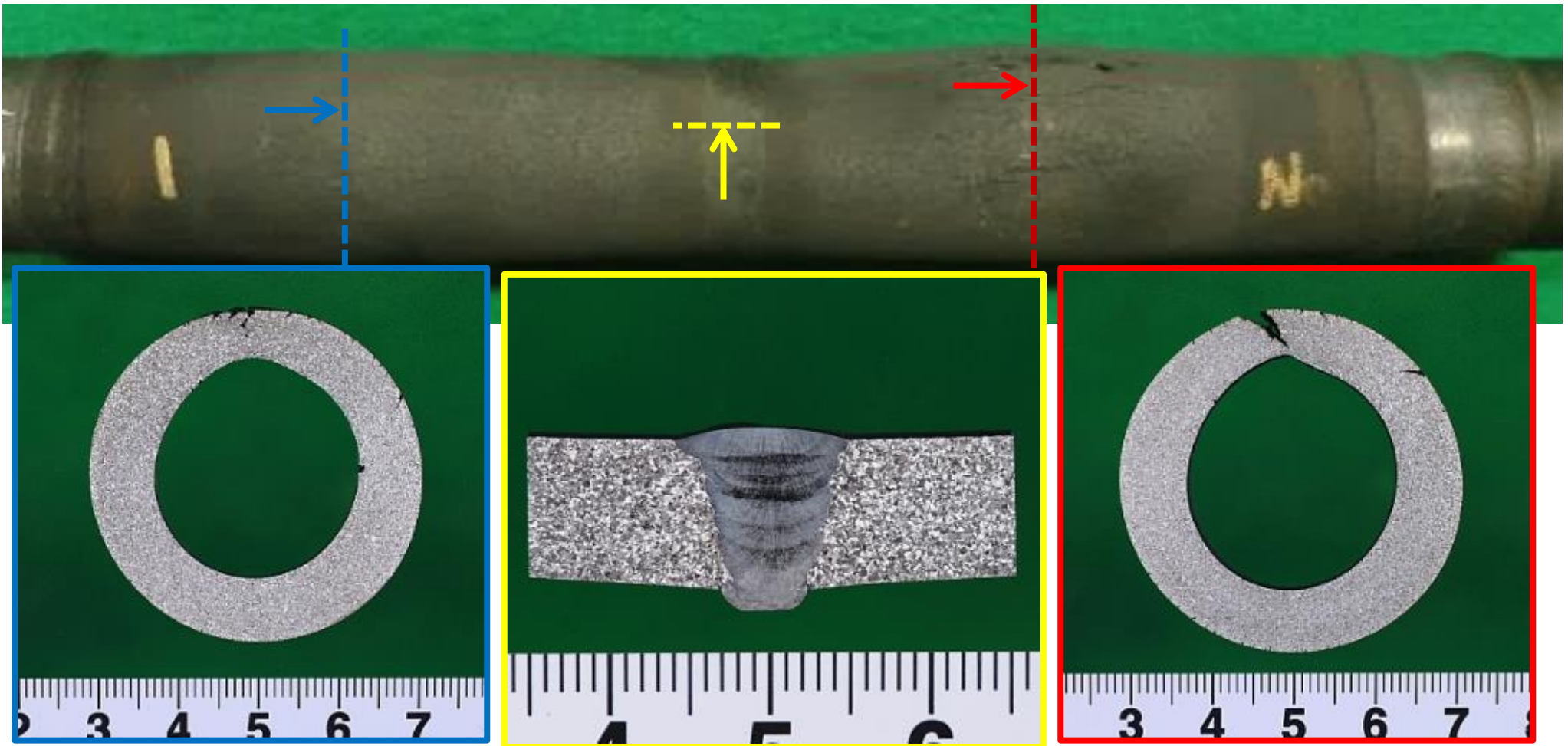
No cracks were found in any region through the cross-sectional macro observation of the weld section, In addition, no creep void was found in the microstructure observation.



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Kubushiro, EPRI2016

FEM analysis of HR6W

FEM analysis code : ABAQUS

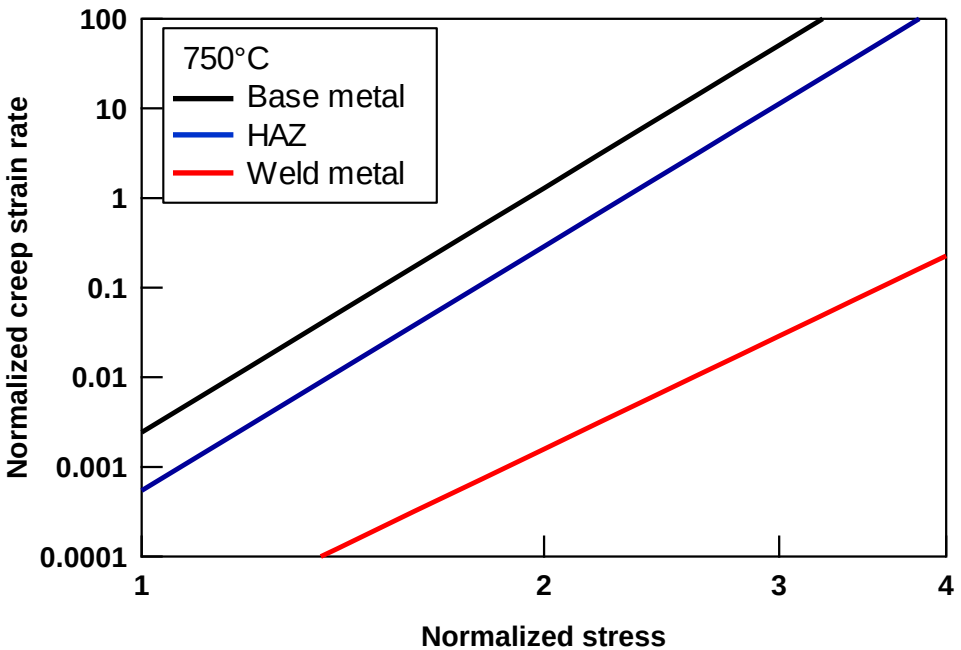
The evolution law of micro damage is formulated.

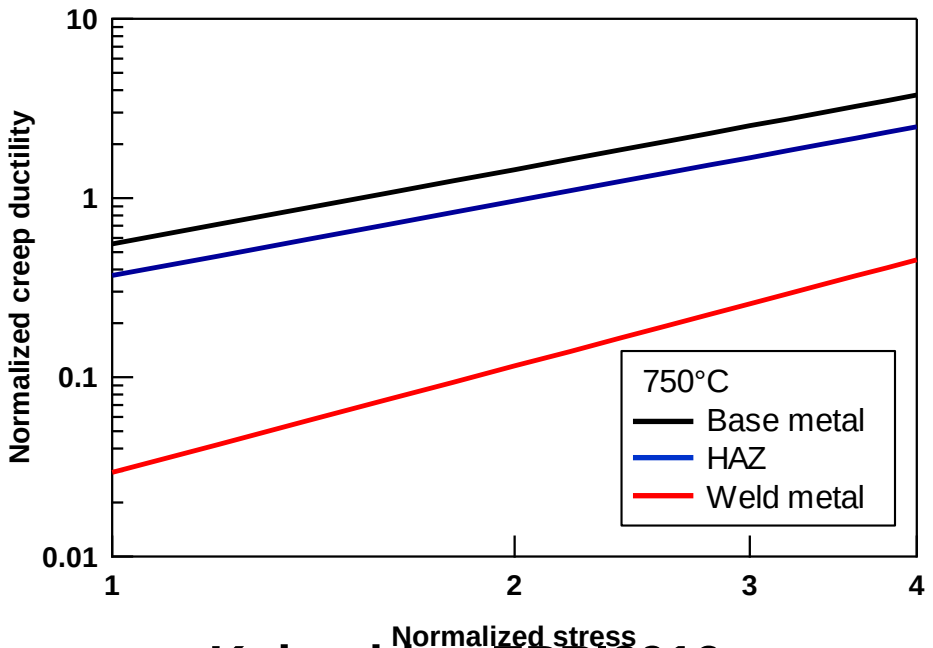
$$\dot{D} = \dot{\varepsilon}_c / \varepsilon_f^*(\sigma)$$

the ductility exhaustion rule

$$\dot{\varepsilon}_c = A\bar{\sigma}^n$$

$$\varepsilon_f^* = \varepsilon_{fu} \exp\left(2.38\left(1 - \frac{\sigma_1}{\bar{\sigma}}\right) + 1.04\left(\frac{1}{2} - \frac{3\sigma_p}{2\bar{\sigma}}\right)\right)$$





Kubushiro, EPRI2016

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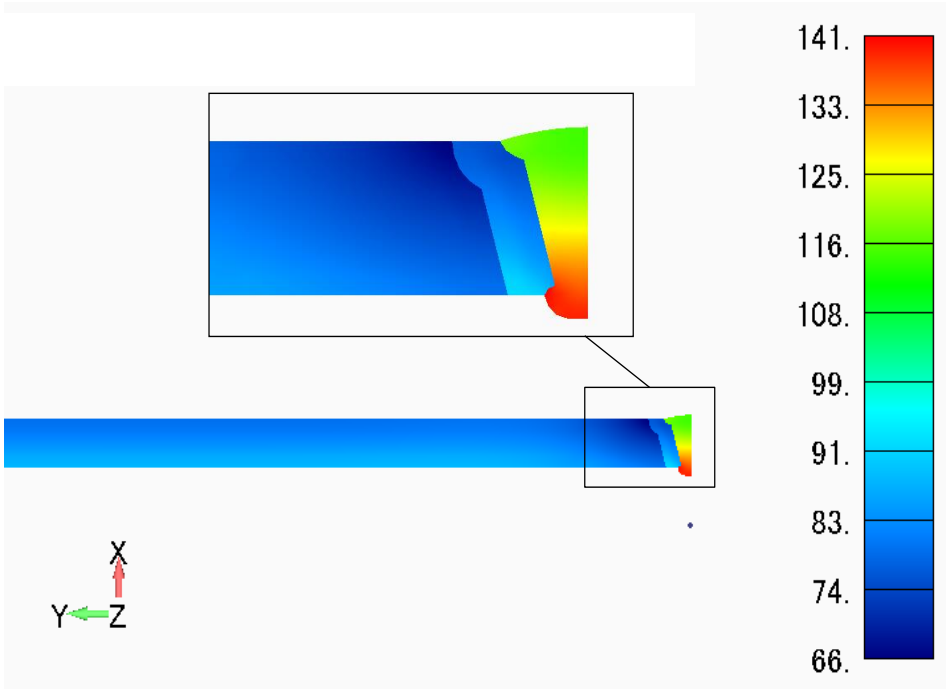
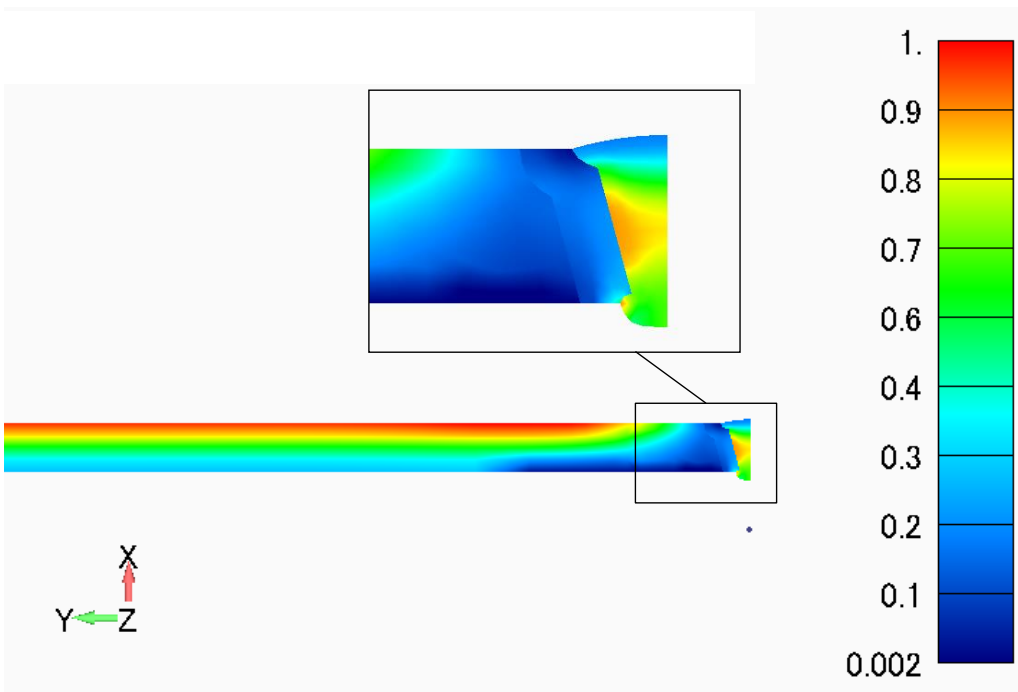
Analysis of the creep damage results by FEM

Different from the distribution of Von Mises stress, the degree of creep damage to the welding metal was smaller than the creep damage to the base material and HAZ. The base material had the largest degree of creep damage. In the distribution of the degree of creep damage to the base material, the external surface had a larger degree of creep damage than the internal surface. These analysis results are well in agreement with the observation results.

The distribution of Von Mises stress



The distribution of creep damage



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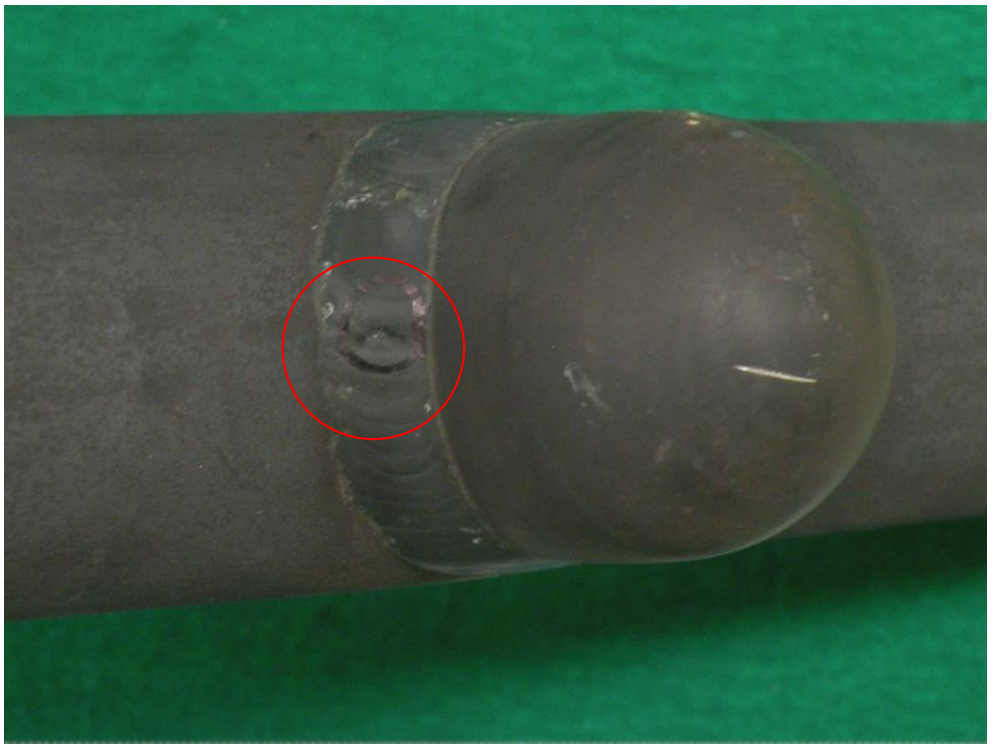
External observation of the test piece

No cracks were found on the side of the weld section.

The leak (rupture) occurred on the welding metal at the shoulder section.



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The cross-sectional observation of the welding metal

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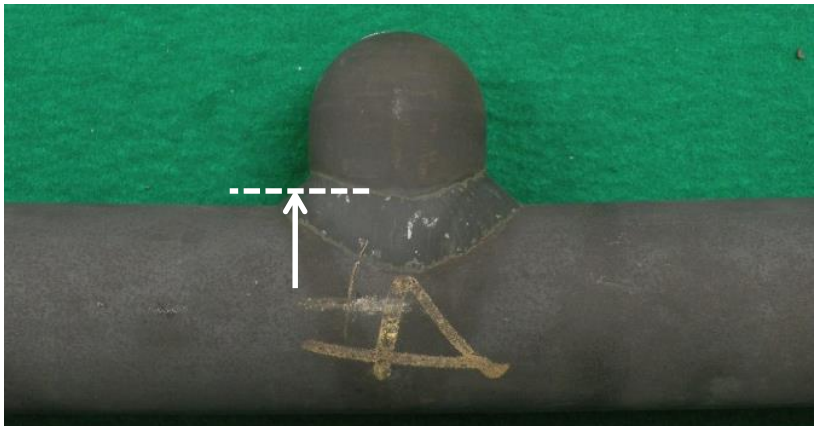
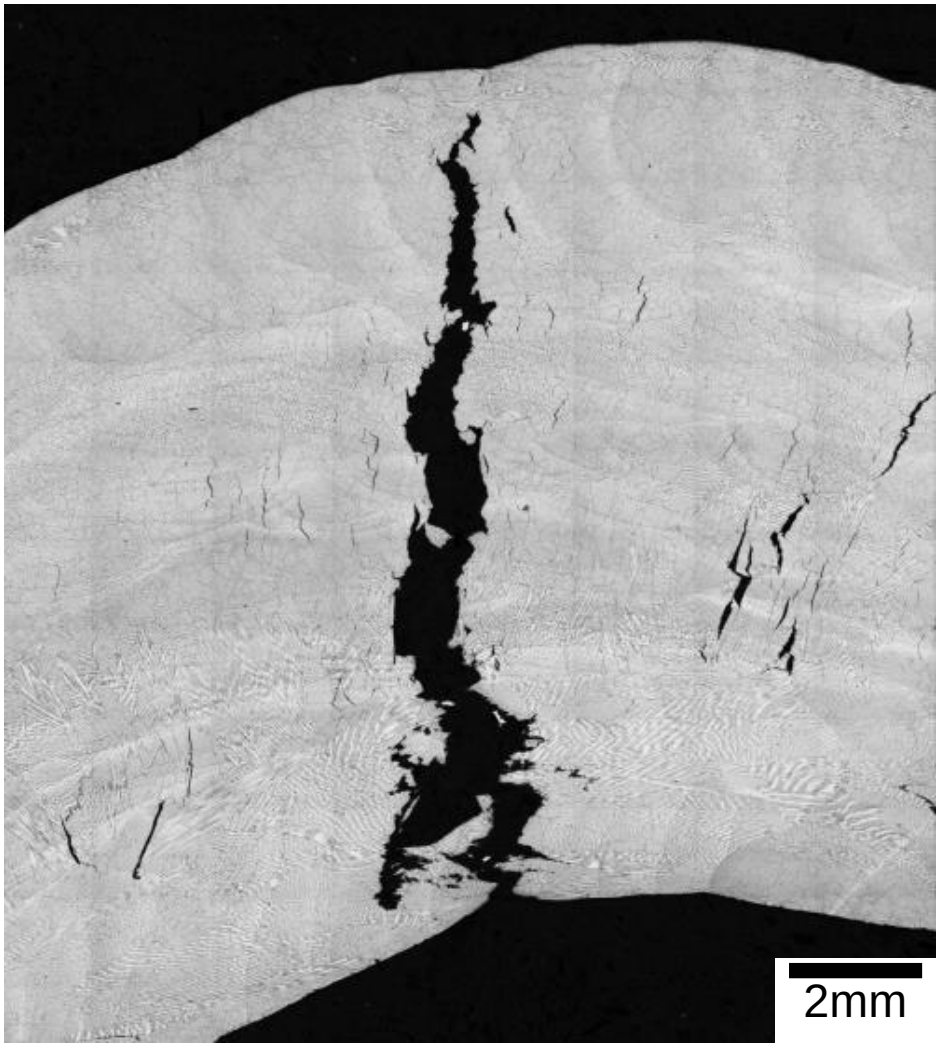
The crack was generated on the internal surface of the test piece and developed toward the external surface. Many creep cracks and voids were found in the area close to the crack.





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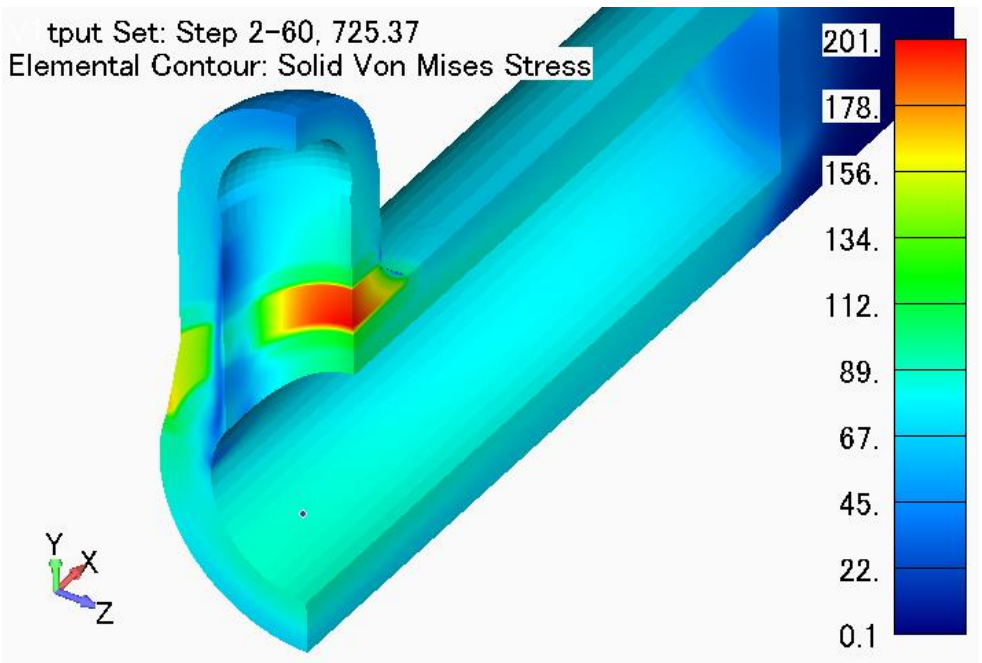
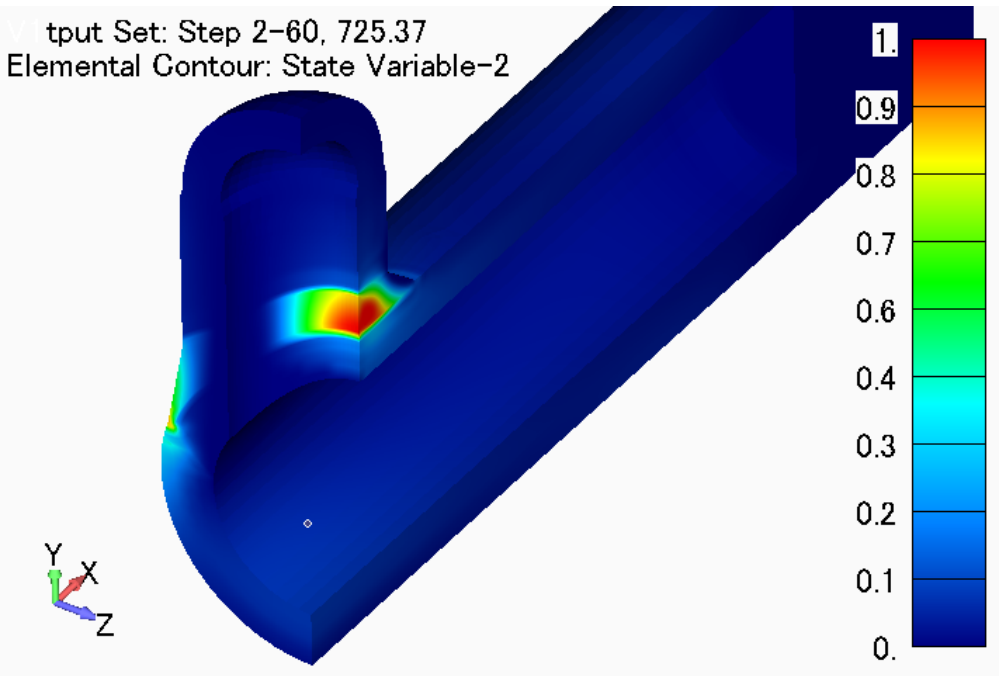
Analysis of the creep damage results by FEM

The location which had the maximum degree of damage was the internal surface of the welding metal at the shoulder section and the location is well in agreement with the location where the crack was generated during the internal pressure creep test. The degree of damage was also higher on the external surface of the HAZ at the weld section, which corresponds to the region with the generation of creep voids in the internal pressure creep test.

The distribution of Von Mises stress



The distribution of creep damage



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Materials for Boiler components

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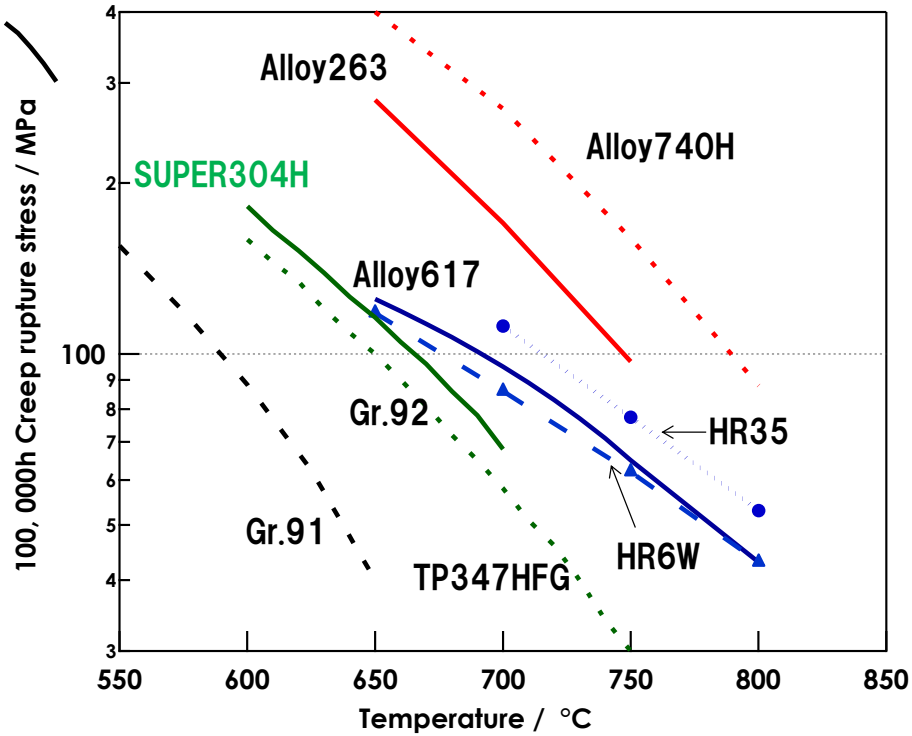
Materials for boilers

Pressure (MPa)	25	25	25	30	30–35
SH Temp (℃)	540	566	600	650	700–720
RH Temp (℃)	560	566	600	650	700–720

Water wall	Low alloy steel		
SH、RH High Temperatre	2.25～9Cr	SUS	Ni-Alloy
Pipe Header	9～12Cr	Ni-Alloy	

100,000h creep rupture strength of candidate Alloys



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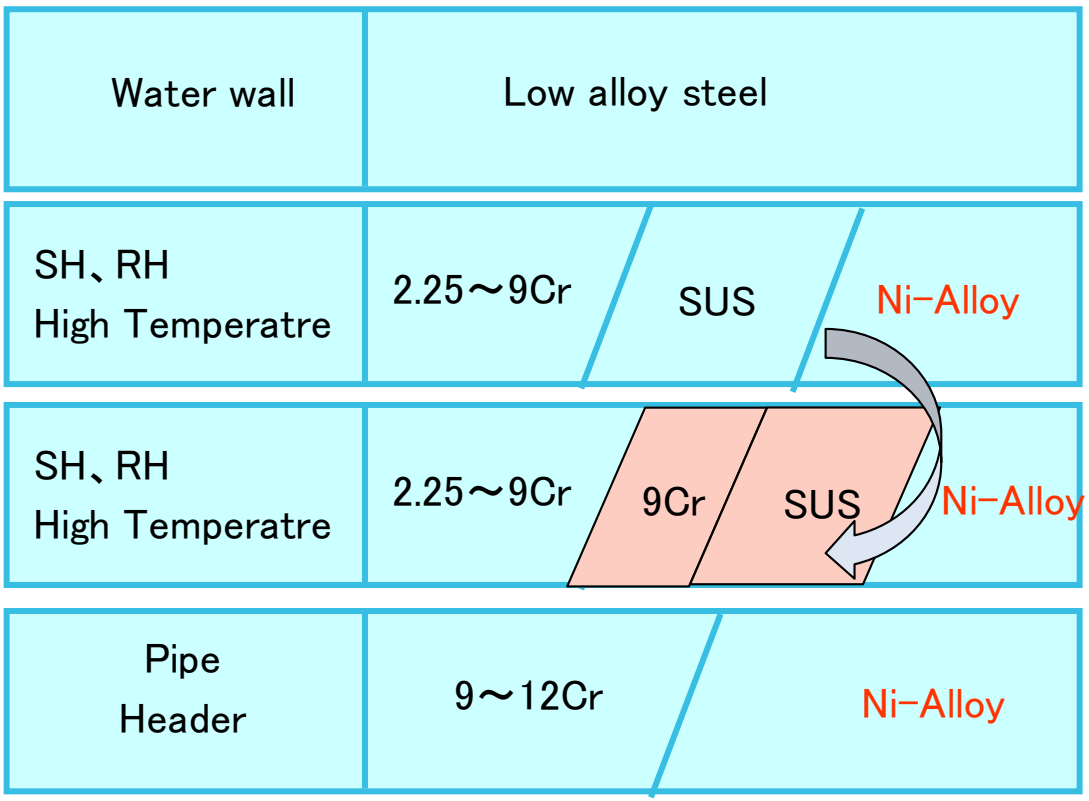

To expand steel application of high temperature parts,

New steels with high strength and good oxidation resistance are required.

Prof. Nakashima in Kyusyu university started to develop new ferritic steel in Japan project

Many research institution participated in this project.

ALCA

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New concept steel development

IHI

High Creep strength | Martensite structure | Oxidation resistance

Fe-Cr-V-Nb-Mo-X-X-X steel

1 1.01 H Hydrogen																	2 4.003 He Helium
3 6.94 Li Lithium	4 9.01 Be Beryllium											5 10.81 B Boron	6 12.01 C Carbon	7 14.01 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Fluorine	10 20.18 Ne Neon
11 22.99 Na Sodium	12 24.31 Mg Magnesium											13 26.98 Al Aluminum	14 28.09 Si Silicon	15 30.97 P Phosphorus	16 32.06 S Sulfur	17 35.45 Cl Chlorine	18 39.95 Ar Argon
19 39.10 K Potassium	20 40.08 Ca Calcium	21 44.96 Sc Scandium	22 47.90 Ti Titanium	23 50.94 V Vanadium	24 51.996 Cr Chromium	25 54.94 Mn Manganese	26 55.85 Fe Iron	27 58.93 Co Cobalt	28 58.70 Ni Nickel	29 63.55 Cu Copper	30 65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.92 As Arsenic	34 78.96 Se Selenium	35 79.90 Br Bromine	36 83.80 Kr Krypton
37 85.47 Rb Rubidium	38 87.62 Sr Strontium	39 88.91 Y Yttrium	40 91.22 Zr Zirconium	41 92.91 Nb Niobium	42 95.94 Mo Molybdenum	43 (98) Tc Technetium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.40 Pd Palladium	47 107.87 Ag Silver	48 112.41 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony	52 127.60 Te Tellurium	53 126.90 I Iodine	54 131.30 Xe Xenon
55 132.91 Cs Cesium	56 137.33 Ba Barium	57 138.91 La▸ Lanthanum	72 178.49 Hf Hafnium	73 180.95 Ta Tantalum	74 183.85 W Tungsten	75 186.21 Re Rhenium	76 190.20 Os Osmium	77 192.22 Ir Iridium	78 195.09 Pt Platinum	79 196.97 Au Gold	80 200.59 Hg Mercury	81 204.37 Tl Thallium	82 207.19 Pb Lead	83 208.98 Bi Bismuth	84 (209) Po Polonium	85 (210) At Astatine	86 (222) Rn Radon
87 (223) Fr Francium	88 226.03 Ra Radium	89 227.03 Ac▸ Actinium	104 (261) Rf Rutherfordium	105 (262) Ha Hahnium	106 (266) Sg Seaborgium	107 (262) Bh Bohrium	108 (265) Hs Hassium	109 (266) Mt Meitnerium	110 (271)	111 (272)	112 (277)	(113)	114 (285)	(115)	116 (289)	(117)	118 (293)

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New concept steel development

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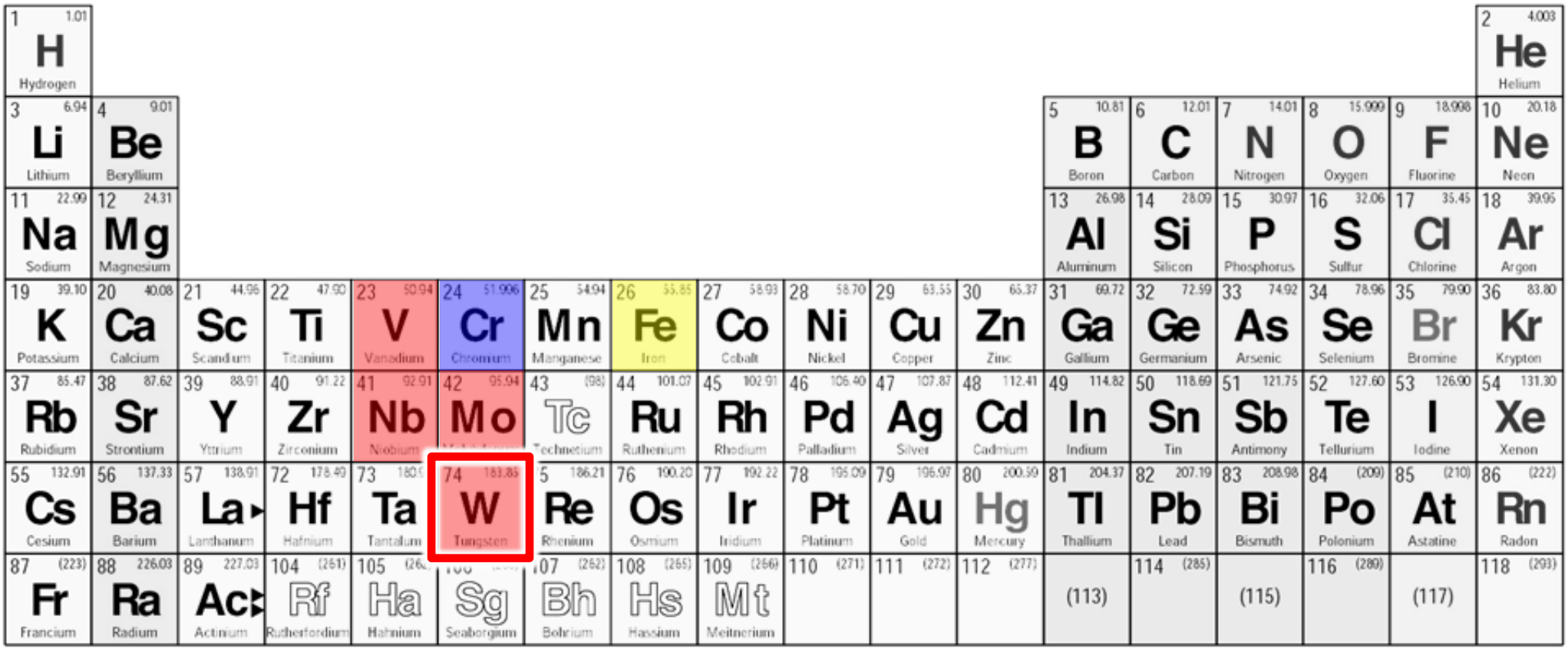
High Creep strength | Martensite structure | Oxidation resistance

Fe-Cr-V-Nb-Mo-**W**-**X**-**X** steel

✓ W: dispersion strengthening by Fe_2W



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New concept steel development

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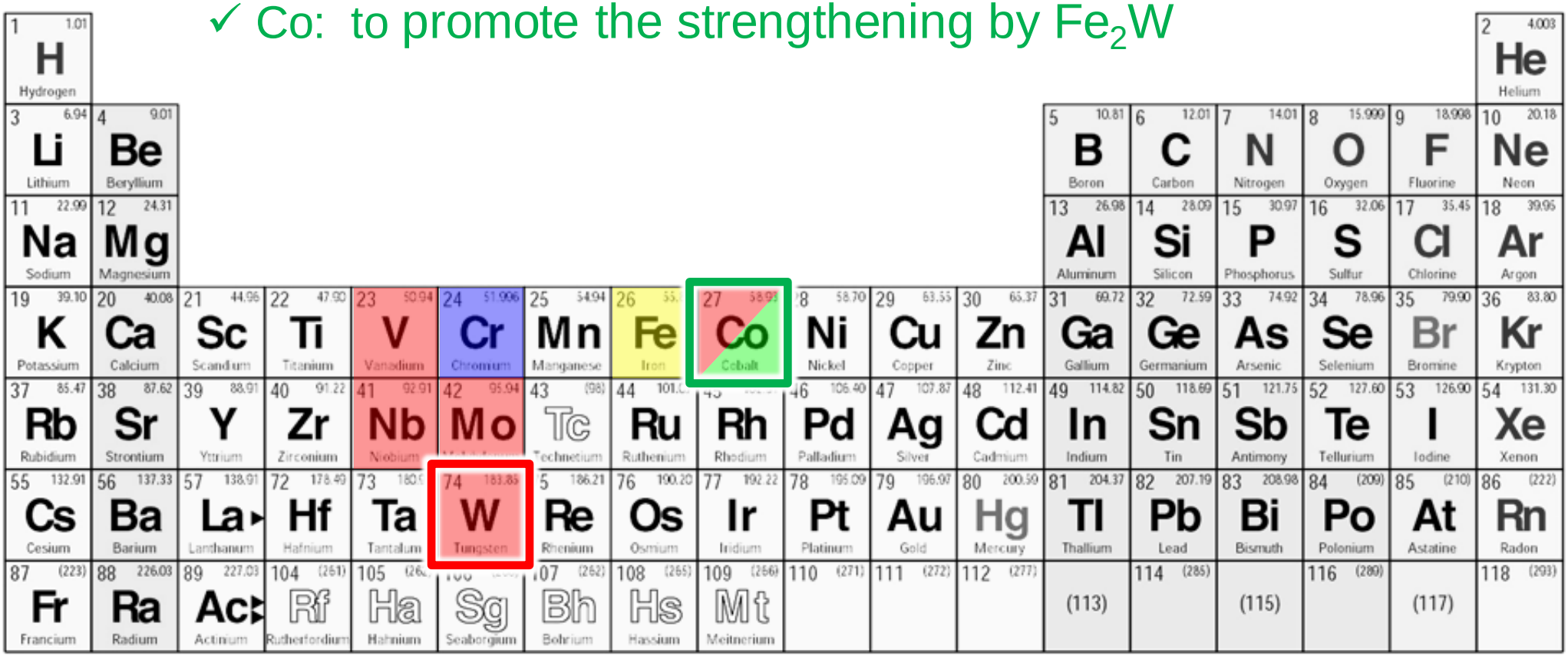
High Creep strength | Martensite structure | Oxidation resistance

Fe-Cr-V-Nb-Mo-**W**-**Co**-**X** steel

- ✓ W: dispersion strengthening by Fe_2W
  - ✓ Co: to promote the strengthening by Fe_2W



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New concept alloy development

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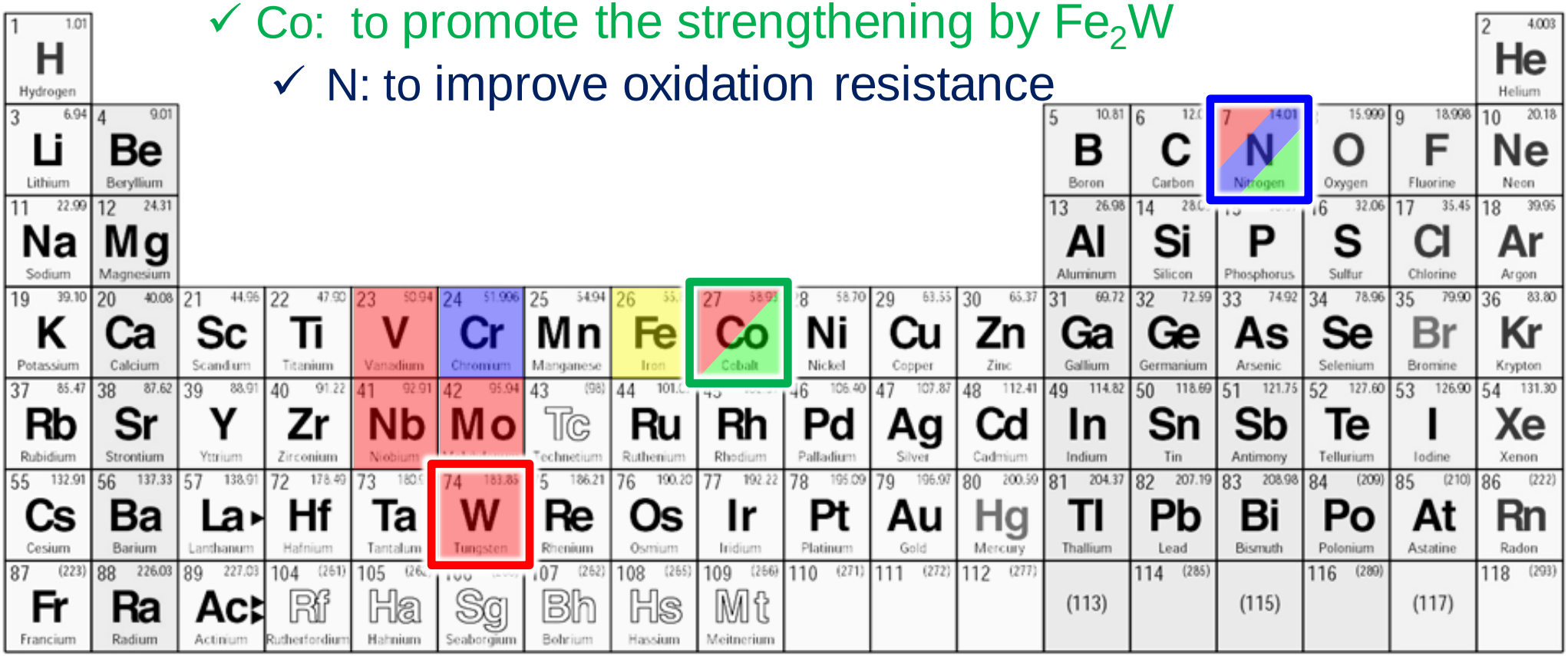
High Creep strength | Martensite structure | Oxidation resistance

Fe-Cr-V-Nb-Mo-**W**-**Co**-**N** alloy

- ✓ W: dispersion strengthening by Fe_2W
  - ✓ Co: to promote the strengthening by Fe_2W
    - ✓ N: to improve oxidation resistance



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New concept alloy development

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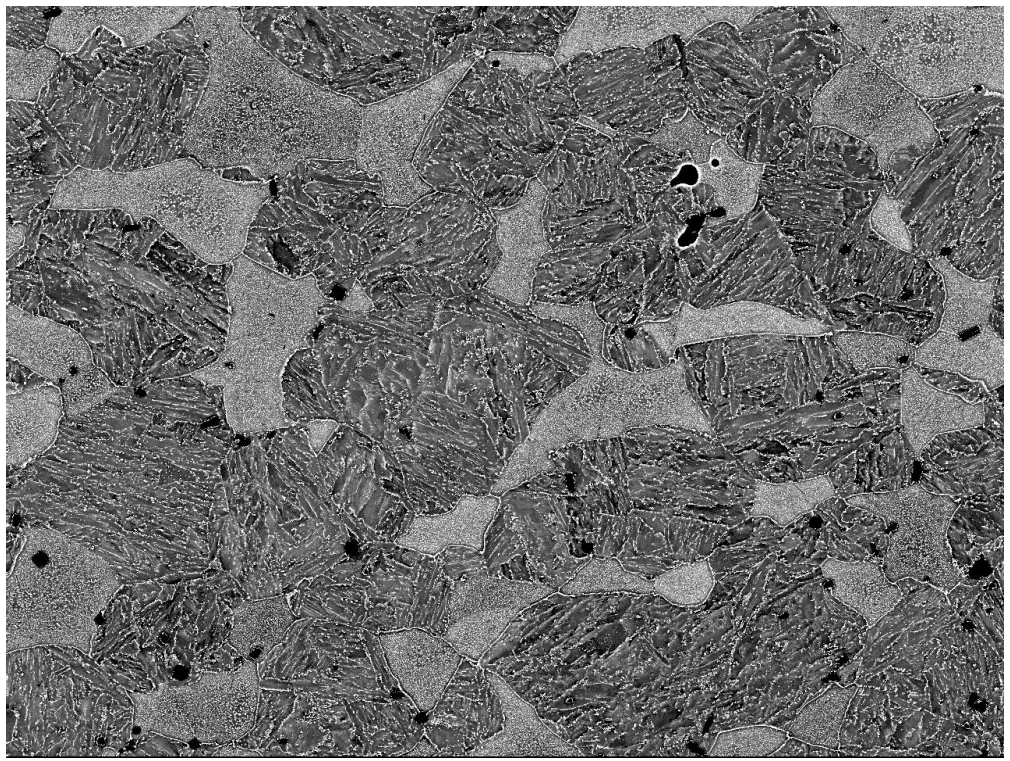
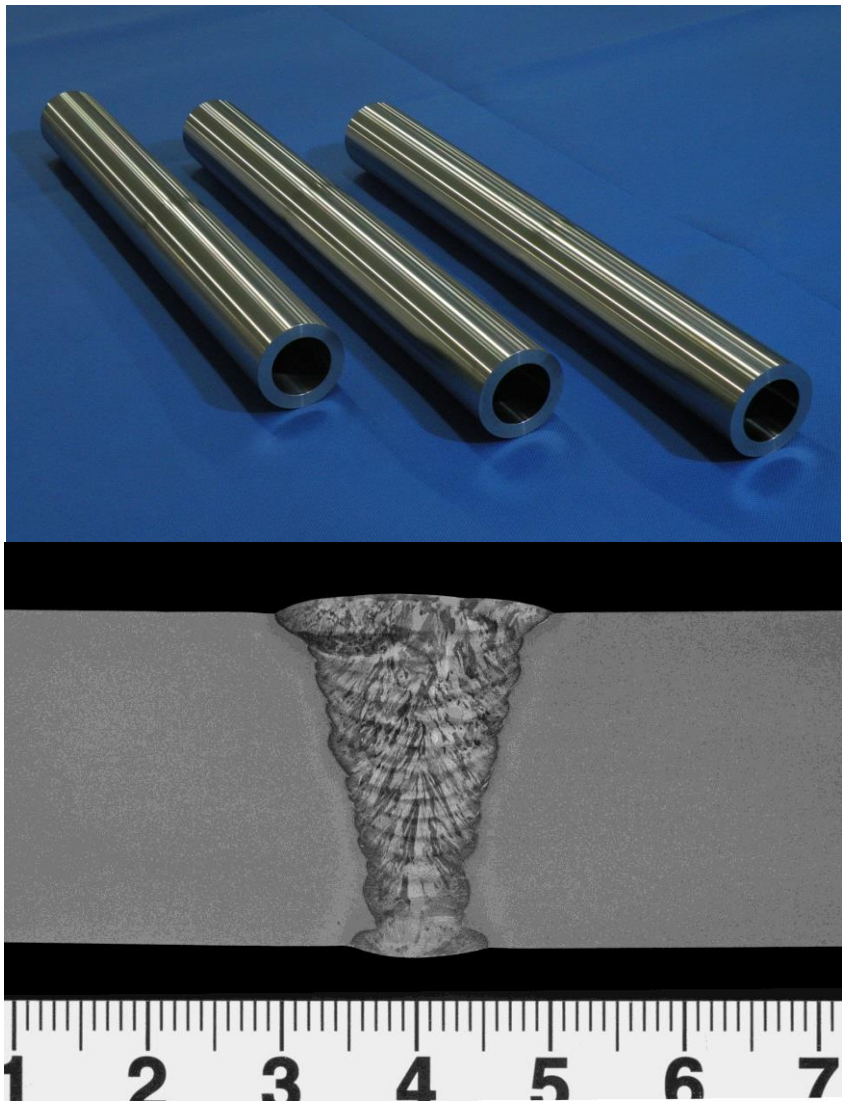
Fe-12Cr-0.6V-0.02Nb-1Mo-6W-4Co-0.35N alloy

- ✓ Ferrite + Martensite strucutre
- ✓ Capable forging
- ✓ Weldable





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Creep rupture strength of New Fe alloy

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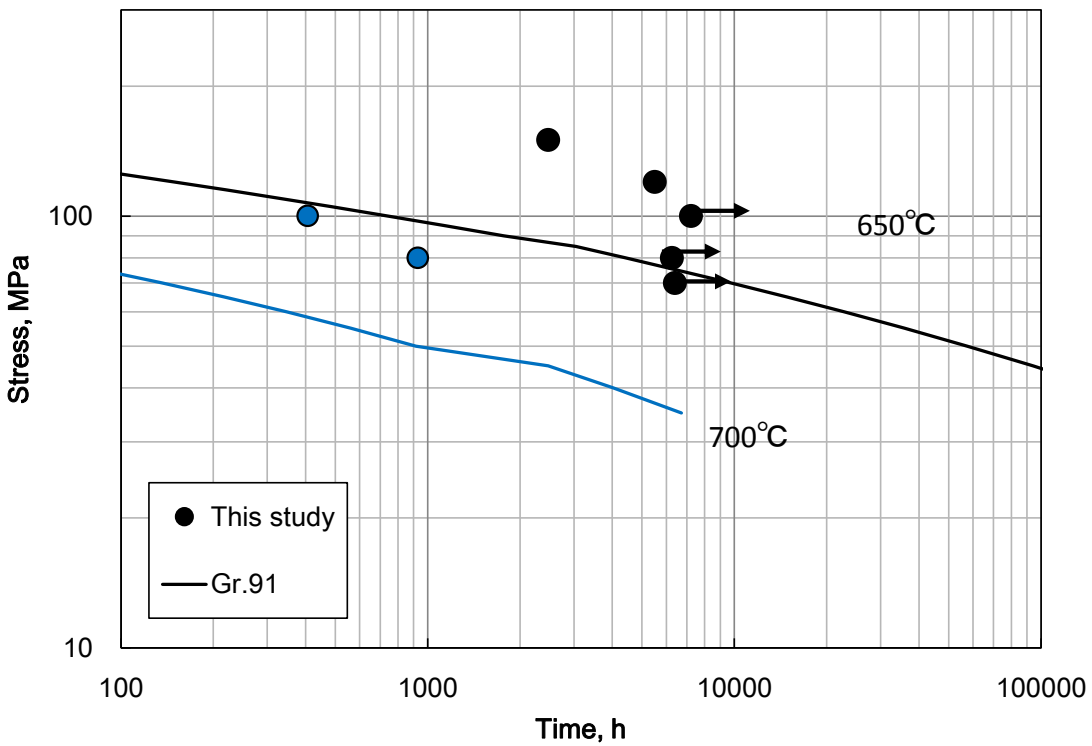
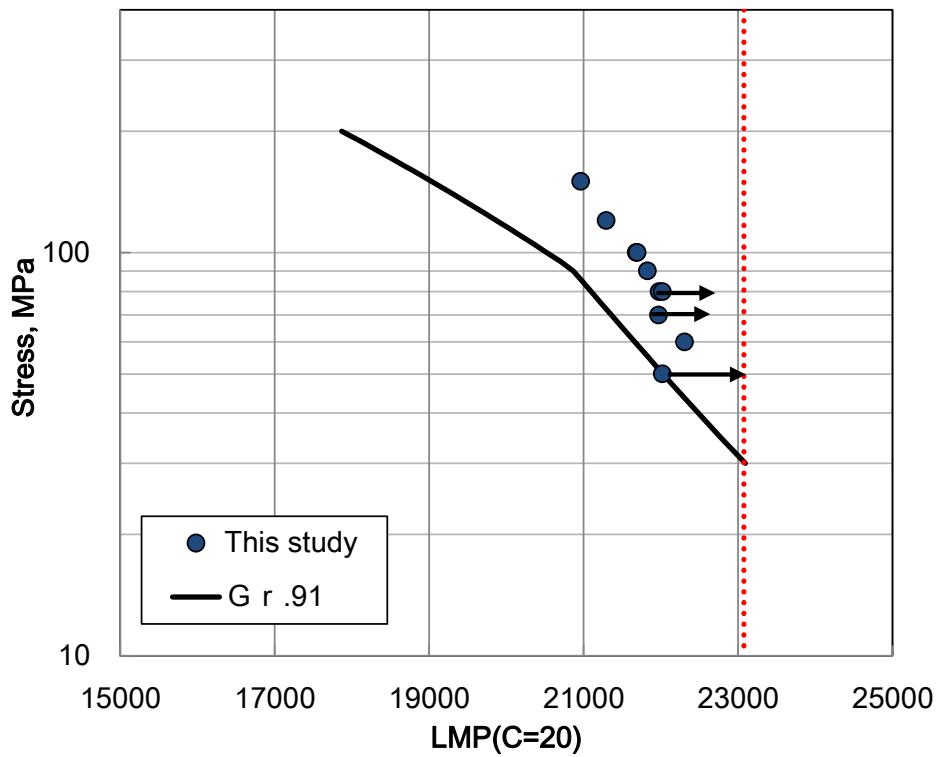
Creep rupture strength of New Fe alloy is much higher than that of Gr.91. In addition, creep rupture strength of New Fe alloy weld is higher too.

Base metal



Weld joint



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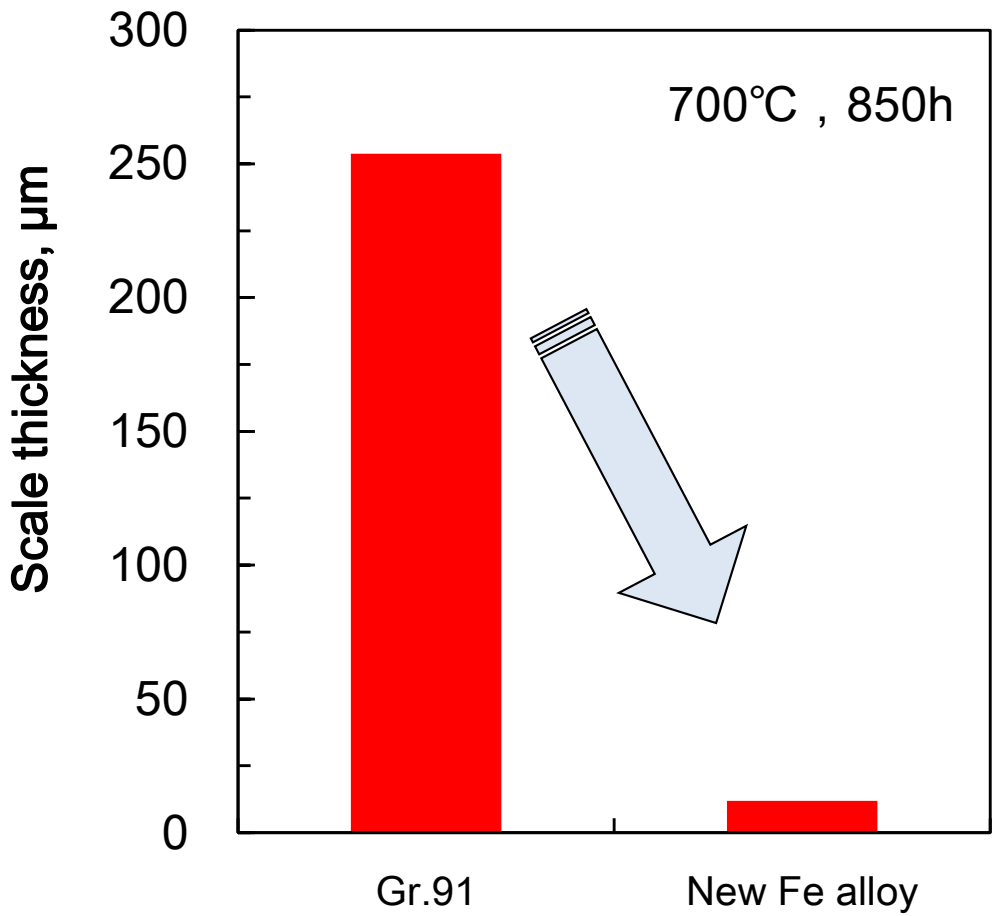
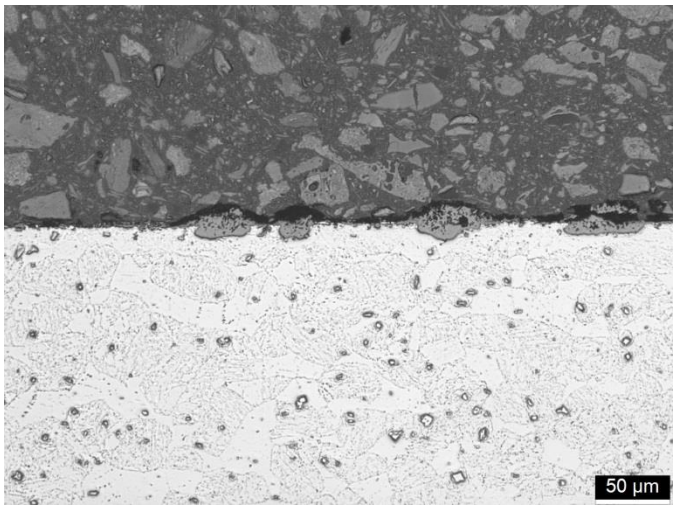
Effect of Nitrogen addition

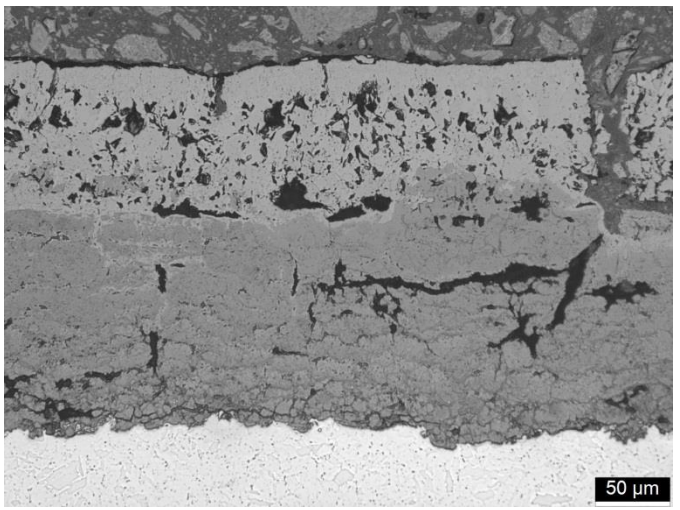
N addition improves high temperature oxidation resistance.



New Fe alloy



Gr.91



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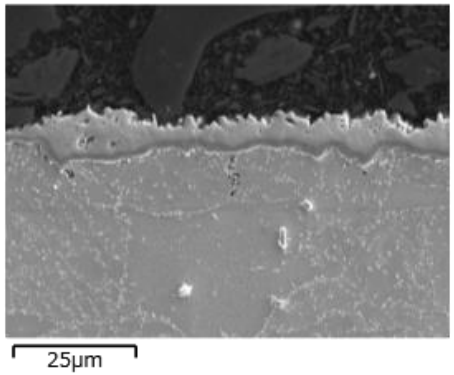
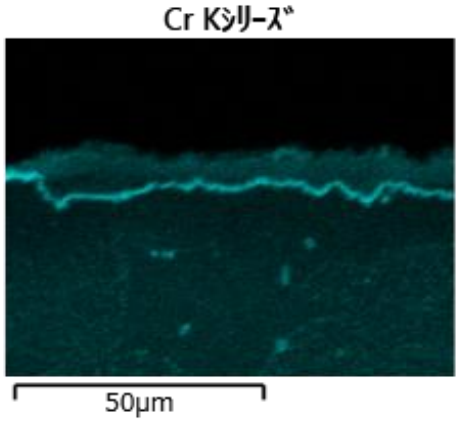
EDX analysis results

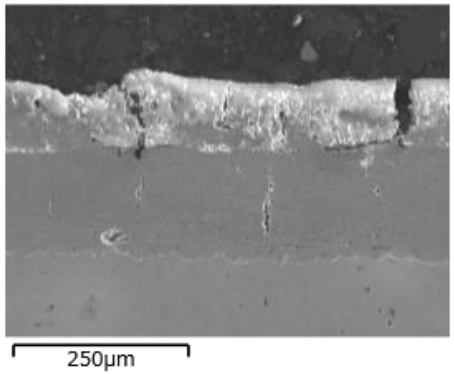
The dense Cr_2O_3 scale was formed in new Fe alloy, but Cr_2O_3 scale was collapsed in Gr.91 .

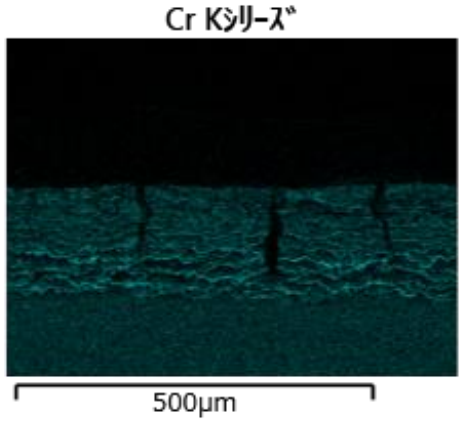
New Fe alloy

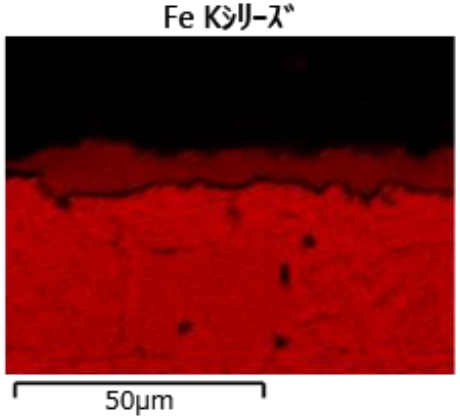
Gr.91

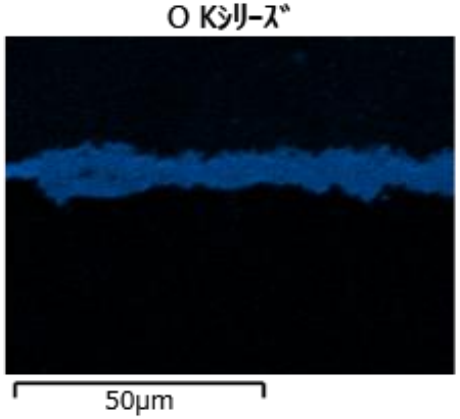


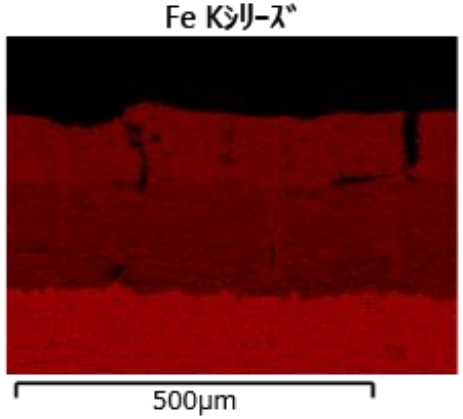


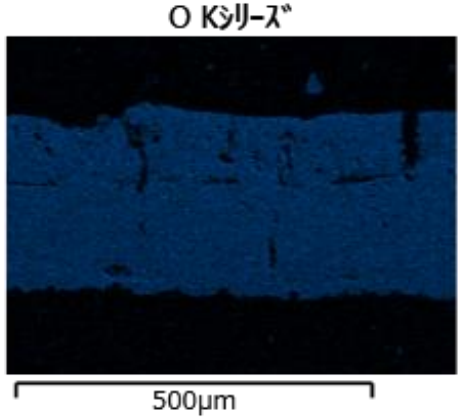












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Summary

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✓ Life evaluation of welded components

The internal pressure creep test was conducted for the circumferential weld section and welded branch connections. Creep analysis using the ductility exhaustion rule is believed to be an effective tool in identifying regions of damage at weld sections in A-USC boilers.

✓ New material development for the cost down

Creep rupture strength of New Fe alloy is much higher than that of Gr.91. N addition effect improve high temperature oxidation resistance.

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Acknowledgement
New material development was carried out as part of the research activities of ALCA (Advanced Low Carbon Technology Research and Development Program). The financial support received from JST (Japan Science and Technology Agency) is greatly acknowledged.