Development of High Strength 2% Cr Steel Tubes (HCM2S) for Boilers

by

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Synopsis

A new high strength 0.06C-2,25Cr-1.6W-V-Nb steel(HCM2S) has been developed for boiler applications. The new steel has extremely high creep rupture strength, approximately 1.8 times that of conventional 2.25Cr-1Mo steel(STBA24). The weldability of this steel is much improved, making it superior to conventional Cr-Mo steels, and the steel needs no pre-weld or post-weld heat treatment. This steel has already been approved for ASME SA-213 as Code Case 2199. Furthermore, the new steel has been installed in the superheater of a utility power boiler and field tested since April, 1993.

1. Introduction

T22 (2.25Cr-1Mo) steel has the highest allowable tensile stress of conventional Cr-Mo steels. Therefore, a large quantity of T22 has been used for the high temperature portions, such as steam generators and pressure vessels, of fossil fuel power plants. However, this steel usually contains 0.1% or more carbon, which leads to considerable hardening during weld heat cycles, and requires pre-weld and post-weld heat treatment in order to prevent weld induced cracks.

Furthermore, the creep rupture strength of T22 is not always sufficient compared with 9 to 12% Cr steels containing V and Nb such as T91[1].

Considering these circumstances, a new low C-2.25Cr-1.6W-V-Nb steel (HCM2S) has been developed for fossil fuel fired boiler materials. The 10^5h extrapolated creep rupture strength at 600°C of HCM2S is approximately 1.8 times higher than that of T22 and almost same as that of T91.

The weldability of this steel is made superior to that of conventional Cr-Mo steels by reducing the carbon content. The lowering of carbon eliminated the requirement for pre-weld and post-weld heat treatment.

This steel tube has been installed in the superheater of a utility power boiler and field tested since April, 1993. Furthermore, this steel has already been approved in ASME SA-213 as Code Case 2199.

This paper describes the properties and the results of 1 year and 2.5 years power boiler service for the developed steel tube.

2. Development Philosophy

Figure 1 shows the philosophy for the development of low C-2.25Cr-1.6W-V-Nb steel (HCM2S). The carbon content was lowered to less than 0.1% in order to improve the weldability and apply under the as welded condition without pre-weld and post-weld heat treatment. The maximum quenched hardness should be controlled below Hv 350. The excellent creep rupture strength of this steel was accomplished by substituting W for a part of Mo and the addition of a slight amount of boron. The optimum amounts of solution strengthening elements (W, Mo) and precipitation strengthening elements (V, Nb) were considered to be 1.6W-0.1Mo-0.25V-0.05Nb (mass%). The microstructure in normalized and

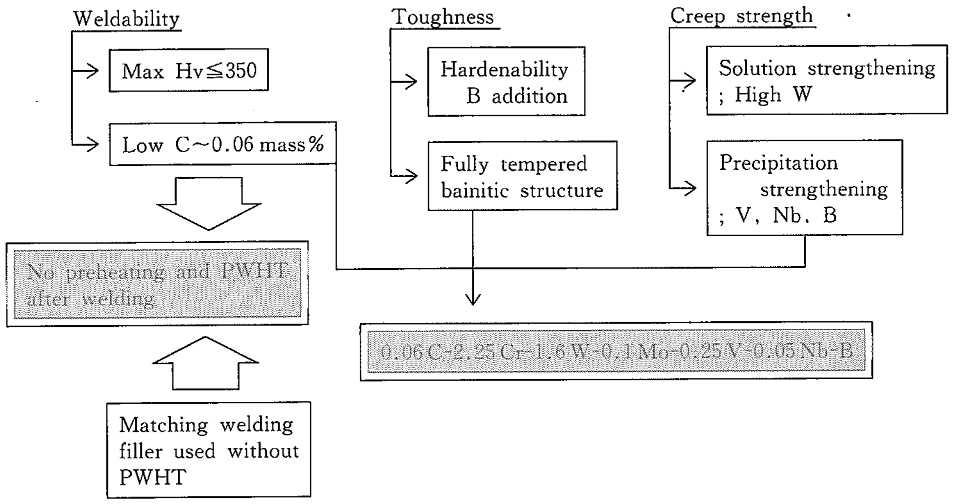


Fig. 1 Development philosophy of HCM2S steel tube

tempered condition consists of fully tempered bainitic structure, which ensures sufficient toughness.

Based on the above considerations, the optimum chemical compositions of the developed steel were determined.

3. Specification

The specification of chemical compositions and tensile properties at room temperature for HCM2S steel tube is shown in **Table 1**.

4. Properties of HCM2S Steel

4.1 Materials Tested

Table 2 shows the chemical compositions of materials tested for HCM2S steel tubes. These were melted, rolled, hot extruded, cold drawn and heat treated as shown in **Fig. 2**. These tubes were normalized at 1 050°C and then tempered at 780°C.

The properties of these tubes thus fabricated were evaluated in terms of microstructure, elevated temperature strength (tensile test, creep and creep rupture), toughness, corrosion resistance and weldability.

Table 1 Specification of HCM2S steel tube

1. Chemical composition (mass%)

	C	Si	Mn	P	S	Cr	Mo	W	V	Nb	sol. Al	B	N
HCM2S	0.04 -0.10	≦ 0.50	0.30 -0.60	≦ 0.030	≦ 0.010	1.90 -2.60	≦ 0.30	1.45 -1.75	0.20 -0.30	0.02 -0.08	≦ 0.030	≦ 0.0060	≦ 0.030

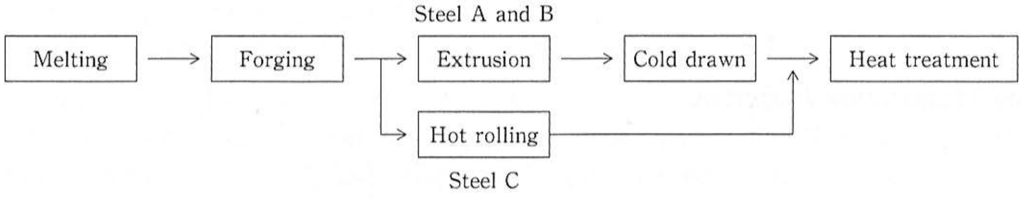
2. Room temperature tensile properties

	Tensile strength (MPa)	0.2% proof stress (MPa)	*Elongation (%)
			Longitudinal
HCM2S	≧510	≧400	≧20

Note) Tubular specimen (JIS No.11) or
strip specimen (JIS No.12)

Table 2 Chemical composition of materials tested

Steels	Size (mm)	Chemical composition(mass%)												
		C	Si	Mn	P	S	Cr	Mo	W	V	Nb	sol.Al	B	N
A	ϕ54.0×112	0.06	0.20	0.46	0.014	0.001	2.18	0.09	1.54	0.25	0.05	0.001	0.0023	0.002
B	ϕ54.0×112	0.06	0.20	0.47	0.006	0.002	2.27	0.09	1.50	0.23	0.05	0.009	0.0039	0.008
C	ϕ50.8×16	0.06	0.22	0.48	0.006	0.002	2.25	0.09	1.55	0.23	0.05	0.005	0.0032	0.008
Specification		0.04~ 0.10	≦ 0.50	0.30~ 0.60	≦ 0.030	≦ 0.010	1.90~ 2.60	≦ 0.30	1.45~ 1.75	0.20~ 0.30	0.02~ 0.08	≦ 0.030	≦ 0.0060	≦ 0.030



Heat treatment : Normalizing and tempering

Fig. 2 Procedure for HCM2S steel tube production

4.2 Microstructure

Photo 1 shows the optical microstructure of HCM2S steel tube. This steel consists of fully tempered bainite without ferrite. It is generally said that M_2C carbides such as Mo_2C form in T22 (2.25Cr-1Mo) conventional steel[2]. While in the developed steel (0.1Mo-1.6W), the main precipitates are V(C, N), $M_{23}C_6$ and M_7C_3, and M_2C carbides such as W_2C were not observed as shown in **Photo 2**.

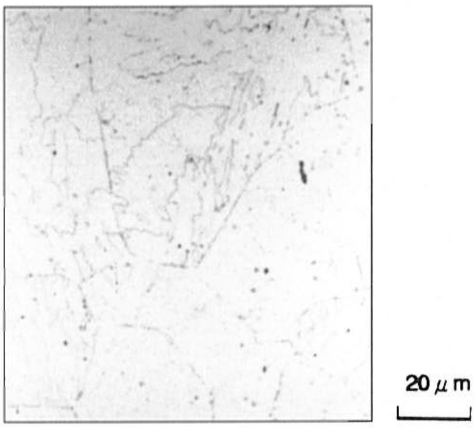


Photo 1 Optical microstructure of HCM2S steel

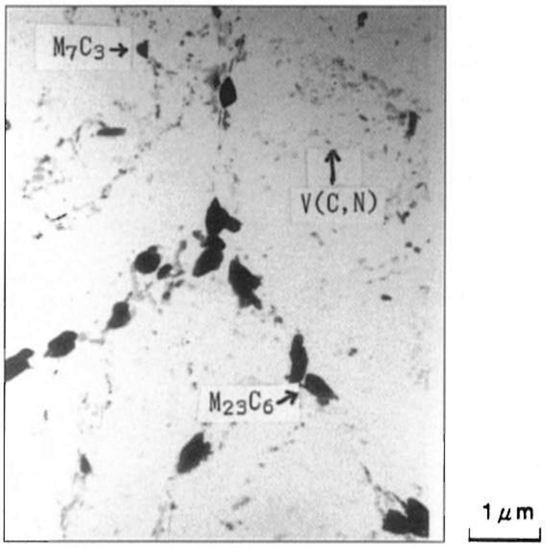


Photo 2 Transmission electron micrograph of extracted replica for HCM2S steel

4.3 Mechanical Properties at Room Temperature

The tensile, Charpy impact properties and hardness at room temperature of HCM2S steel tubes is shown in **Table 3**. The tensile properties satisfy the specification and the impact properties are also

Table 3 Mechanical properties at room temperature for HCM2S steel tubes

Steel	Size (mm)	Tensile properties⁽¹⁾			Charpy impact value⁽²⁾		Hardness (HRB)
		Tensile strength (MPa)	0.2% proof stress (MPa)	Elongation (%)	Impact value at 0°C(J)	Brittle fracture (%)	
A	φ54×t12	596	504	24	429 436 411	0 0 0	91.2
B	φ54×t12	559	461	30	372 376 378	0 0 0	88.2
C	φ50.8×t6	552	421	26	265 277 282	0 0 0	87.8
Specification		≧510	≧400	≧20	—	—	—

(1) Tensile test specimen : φ6×GL 30mm (JIS No.14A)
W10×GL 45mm (JIS No.14B)
(2) Charpy impact test specimen : 10×10, 2mm V-notched

good for all tubes.

4.4 Elevated Temperature Properties

The tensile properties of HCM2S steel are shown in **Fig. 3**. The tensile strengths and the yield strengths at room temperature of this steel are laid at around 600Mpa and 500MPa, respectively. The strength level at each temperature of the developed steel is higher than those of T22 3). The tensile ductilities are high enough for boiler tubing.

The creep rupture strength and the allowable tensile stress of HCM2S steel are shown in **Fig. 4** and **Fig. 5**, respectively. The longest term data were obtained up to around 2×10^4h. The HCM2S steel has the 10^5h extrapolated creep rupture strength apporoximately 1.8 times greater than that of T22 at 600°C. The excellent creep rupture strength of this steel is accomplished by substituting W for a part of Mo and the addition of a slight amount of B as shown as **Fig. 6**.

Figure 7 shows the comparison of the change in the amount of extracted residues after aging for the

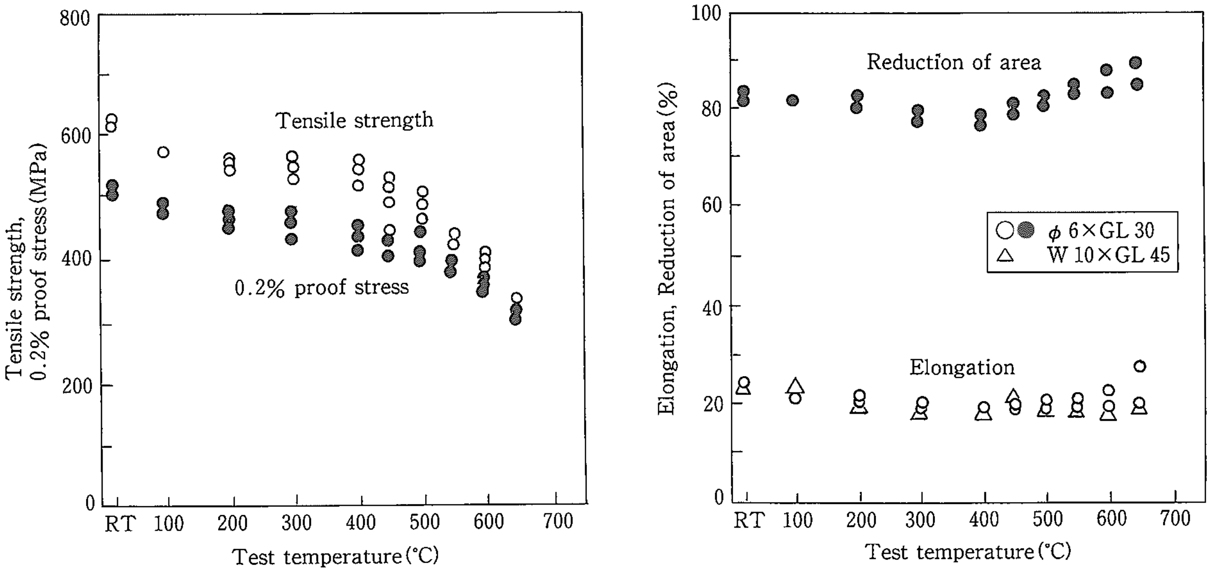


Fig. 3 Elevated temperature tensile properties for HCM2S steel tubes

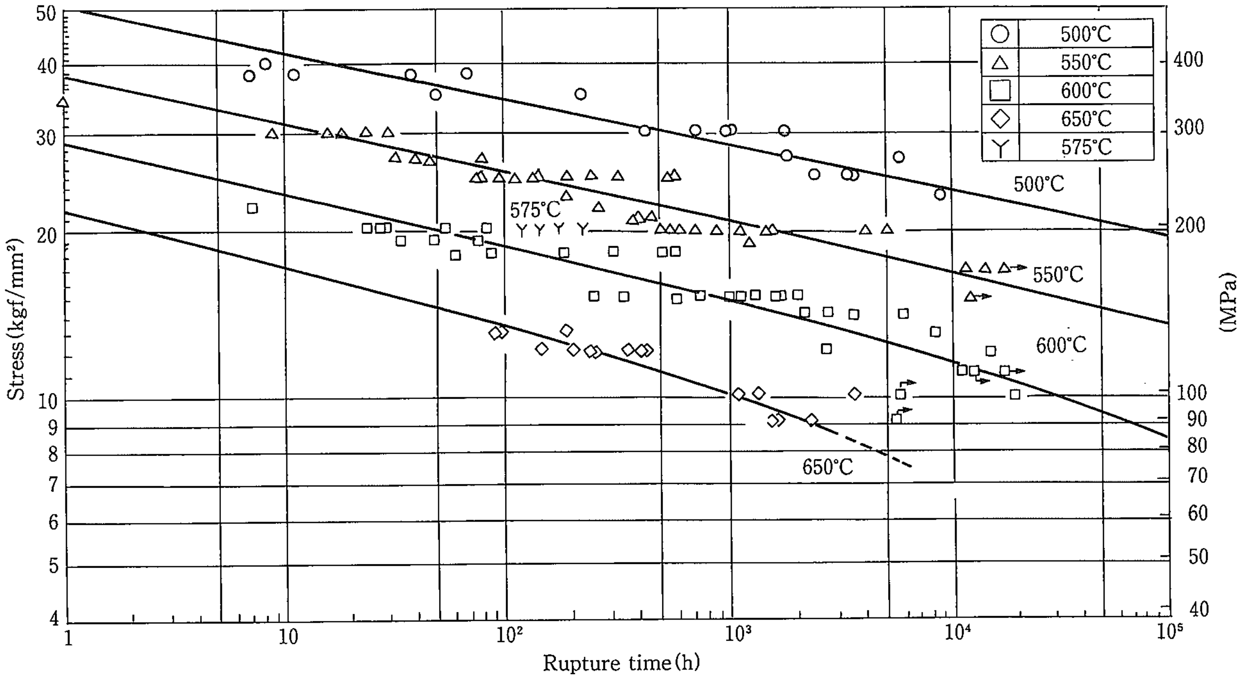


Fig. 4 Creep rupture strength properties for HCM2S steel tubes

developed steel (0.1%Mo-1.6%W) and the reference steel (1%Mo) steel. In the 1%Mo steel, the amount of Mo as carbides tends to increase rapidly by short term and/or low temperature aging, which resulted in the deterioration of the creep rupture strength due to the decrease of solid solution strengthening effect by Mo[2].

While in the developed steel (0.1Mo-1.6W), the amount of W as carbides is ralatively small even after aging for 10^4h at 600°C.

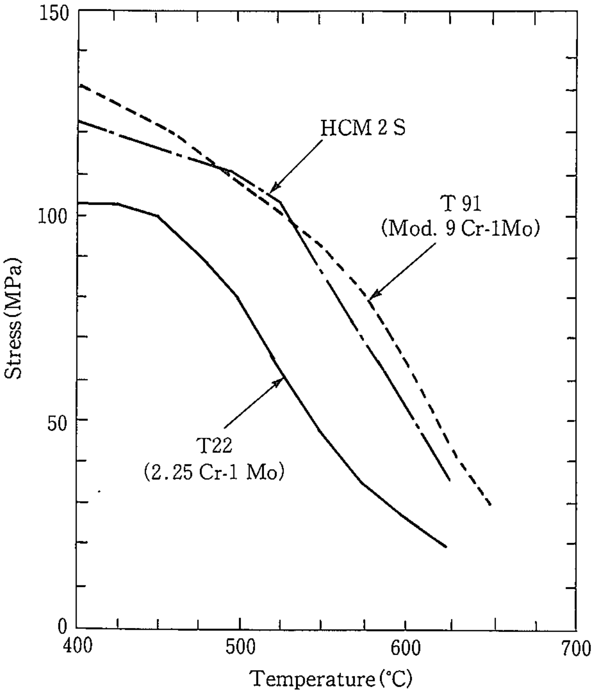


Fig. 5 Comparison of allowable tensile stress between HCM2S steel and conventional steels

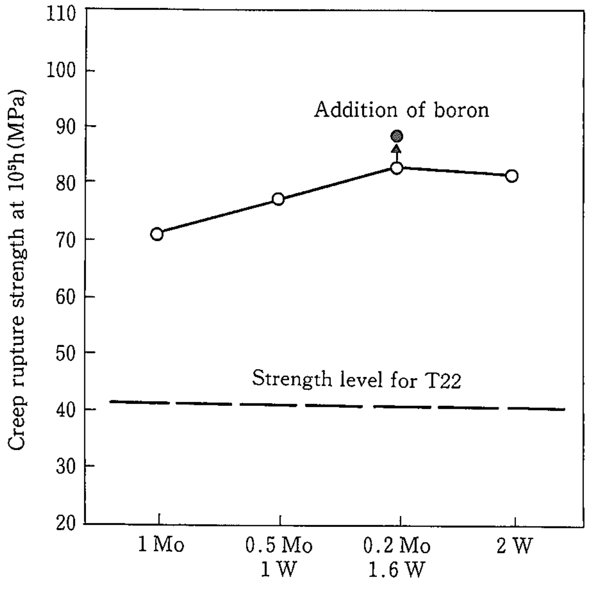


Fig. 6 Effect of Mo and W on the 10^5h extrapolated creep rupture strength at 600°C (Moeq.=Mo+0.5W is kept to 1%)

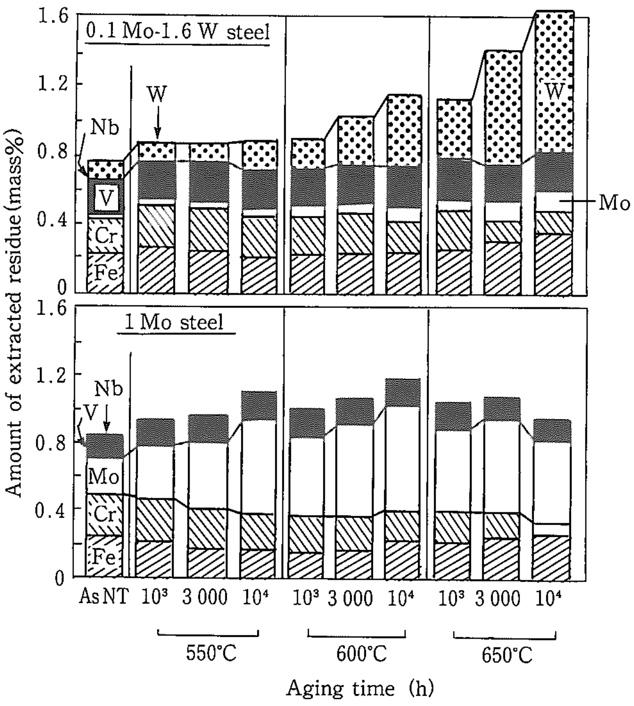


Fig. 7 Change in the amount of extracted residues after aging for HCM2S (0.1%Mo−1.6%W) and 1%Mo steel

Based on these consideration, it may be concluded that the solid solution strengthening effect of W in the developed steel is larger than that of Mo in the 1%Mo steel in the longer term and/or higher temperature range, which resulted in higher creep rupture strength in the developed steel.

Figure 8 shows the effect of cold work on the creep rupture strength for HCM2S steel. There is no deterioration in creep rupture strength by cold work, when the cold work ratio is less than 20%.

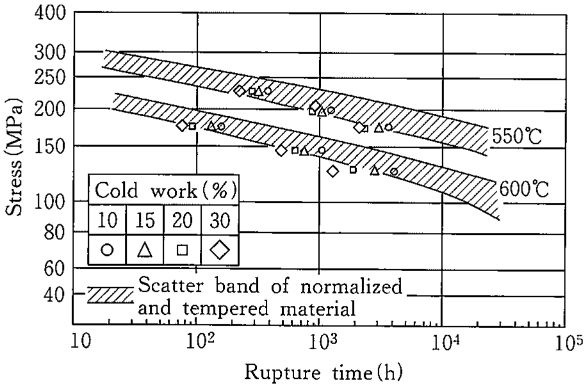


Fig. 8 Effect of cold working on the creep rupture strength for HCM2S steel

4.5 Long Term Aging Properties

The Charpy impact tests at 0°C were conducted on the materials aged at 550~650°C for a maximum of 10^4h. **Figure 9** summarizes the result. The impact value tends to decrease according to the increase of aging duration when the aging temperature is 550°C. However, this steel is found to have high enough values even after long term exposure.

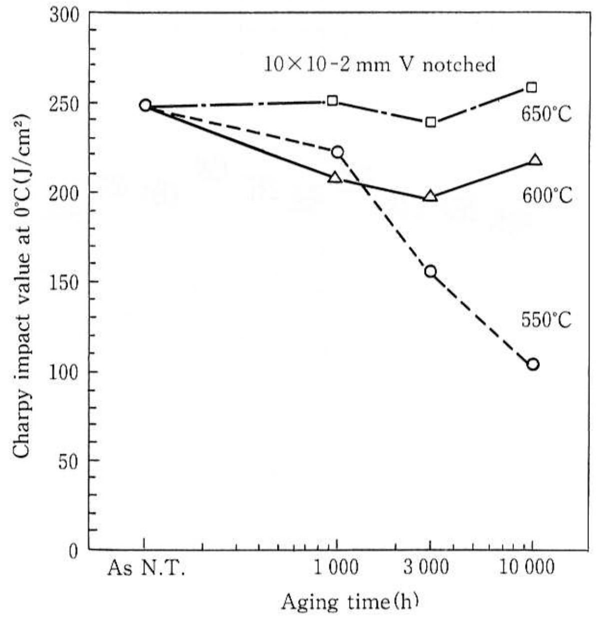


Fig. 9 Charpy impact properties at 0°C after aging for HCM2S steel tube

4.6 High Temperature Corrosion Resistance

The high temperature corrosion resistance of HCM2S steel was evaluated by the hot corrosion test in synthetic coal ash and the steam oxidation test. The hot corrosion resistance and the steam oxidation resistance of HCM2S steel are almost the same as T22 conventional steel as shown in **Fig. 10**.

4.7 Weldability and Properties of Welded Joints

The hardenability of HCM2S steel was reduced by lowering the carbon content, and the weldability was remarkably improved. **Figure 11** compares the cold cracking susceptibility by Y-groove restrain weld cracking test between HCM2S steel and the conventional steels such as T22 and T91. It was demonstrated that no cracks occurred in HCM2S steel even at room temperature or under any preheating condition. This suggests that HCM2S steel has excellent weldability.

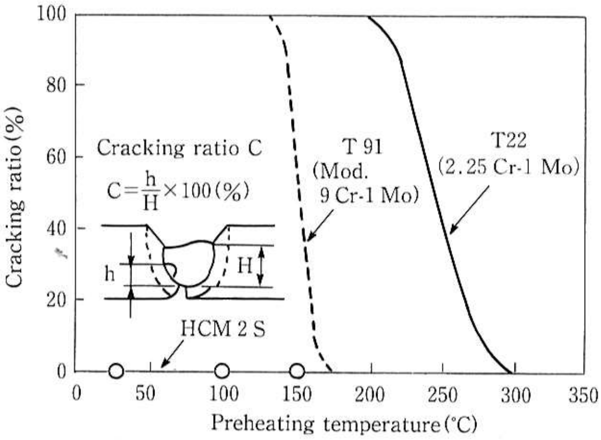
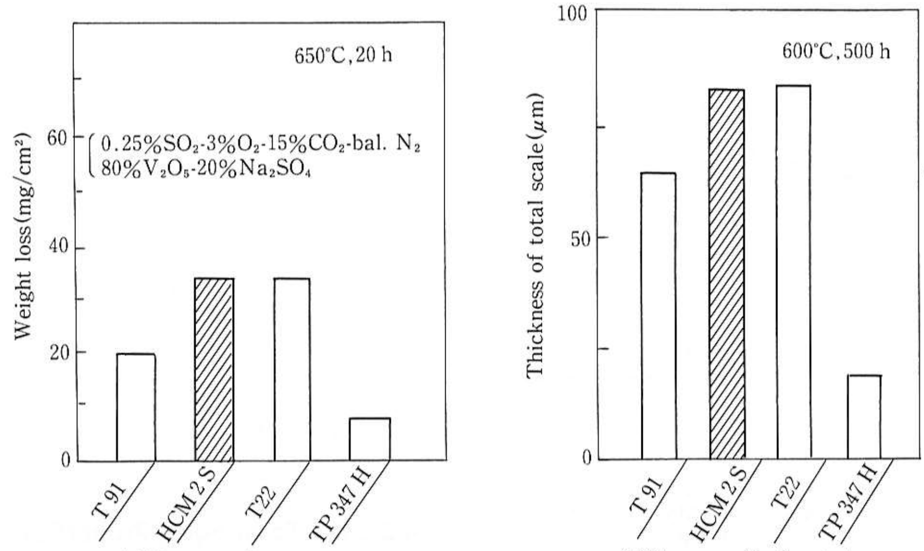


Fig. 11 Comparison of Y-groove weld cracking ratio between HCM2S and conventional steels

Matching welding consumables for HCM2S steel have been developed for gas tungsten arc (GTA) welding and shielded metal arc (SMA) welding. The chemical compositions of base metal and welding consumables applied for welded joints tests are shown in **Table 4**. The welding condition for welded



(a) Hot corrosion test (b) Steam oxidation test

Fig. 10 Comparison of steam oxidation and hot corrosion resistance between HCM2S and conventional steels joints is shown in **Table 5**. The Charpy impact values of weldments and the hardness distribution of welded joints are shown in **Table 6** and **Fig. 12**. The average Charpy impact values at 20°C under the as welded condition are around 200J/cm^2 and 40J/cm^2 respectively. It is noticed that hardness remains as low as approximately Hv300～350 even without PWHT. This suggests that the pre-weld and post-weld heat treatment would not be required for welding of HCM2S steel. As for tensile properties at room temperature, all of the specimens of welded joints ruptured in the base metal as shown in **Table 7**. The side bend test also showed satisfactory results. As for creep rupture strength of welded joints, it is generally said that the deterioration in the creep rupture strength for T22 steel become larger according to the increase of testing temperature and/or duration$^{4)}$. In contrast, for HCM2S

Table 4 Chemical compositions of GTAW and SMAW filler metals

(mass%)

	C	Si	Mn	P	S	Ni	Cr
Base metal	0.06	0.20	0.52	0.013	0.002	0.10	2.26
GTAW	0.04	0.50	0.49	0.004	0.005	0.49	2.19
SMAW	0.06	0.32	0.79	0.004	0.002	1.00	2.24

	Mo	W	V	Nb	B	Al	N
Base metal	0.11	1.58	0.27	0.05	0.003	0.026	0.0074
GTAW	0.10	1.59	0.24	0.03	—	—	—
SMAW	0.10	1.56	0.30	0.04	—	—	—

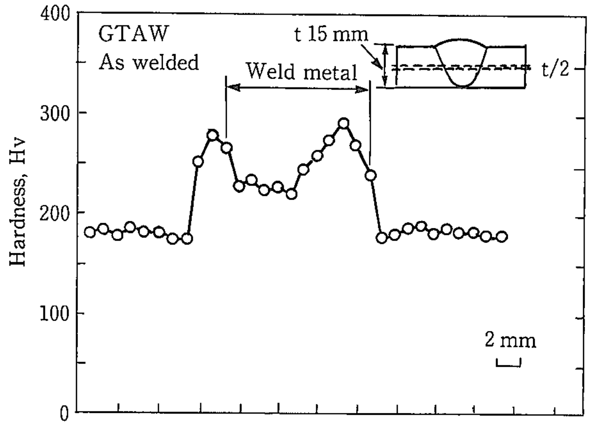
Base metal : t15mm plate
PWHT : As welded, (715°C×30min A.C)

Table 6 Charpy impact properties at 20°C for GTAW and SMAW welded joints

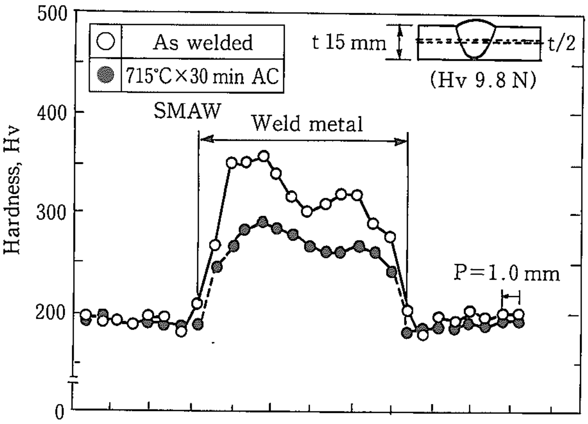
Welding method	PWHT	Impact value (J/cm^2)		
		0°C	20°C	40°C
GTAW	No (As-welded)	67, 120, 71 Ave. 86	125, 224, 299 Ave. 216	343, 244, 174 Ave. 254

Welding method	PWHT	Impact value (J/cm^2)	
		0°C	20°C
SMAW	No (As-welded)	34, 32, 40 Ave. 35	53, 32, 34 Ave. 40
	715°C×30min	62, 107, 110 Ave. 93	142, 213, 227 Ave. 194

Test specimen : 10×10-2mm V-notched



(a) GTAW



(b) SMAW

Fig. 12 Hardness distribution of welded joints for HCM2S steel tube

Table 5 Welding condition for GTAW and SMAW welded joints

Process	Filler (mm)	Pass	Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/cm)	Preheating (°C)	Shielding gas
GTAW	ϕ2.4	1st	120	15	8	13.5	No (RT)	100%Ar
		2nd -16th	180	17	10	18.4	No (RT)	100%Ar

Process	Pass	Current (A)	Voltage (V)	Speed (cm/min)	Preheating (°C)
SMAW	1st	70	23	5-8	No (RT)
	2nd -12th	90	24	7-11	No (RT)

steel, it was demonstrated that the creep rupture strengths of GTA and SMA welded joints were well within the scattering band for the base metal at 550°C, 600°C and 650°C as shown in **Fig. 13**.

Table 7 Elevated temperature properties for GTAW and SMAW welded joints

Welding method	PWHT	Room temperature T.S. (MPa)	Room temperature Rupture portion	600°C T.S. (MPa)	600°C Rupture portion
GTAW	As welded	577 570	B.M. B.M.	350 375	B.M. B.M.
SMAW	As welded	584	B.M.	362	B.W.
	715°C×1h	550	B.M.	324	B.M.

B.M. : Base Metal

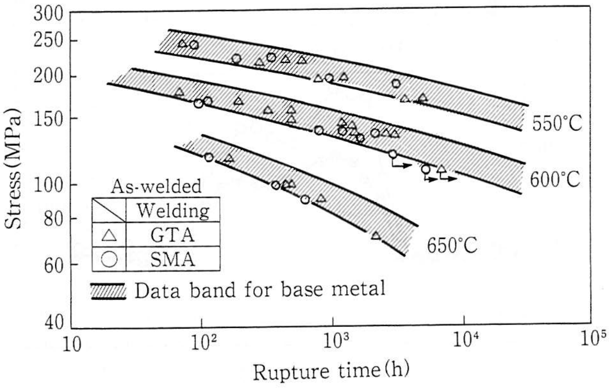


Fig. 13 Creep rupture strength properties of welded joints for HCM2S steel tubes

5. Service Experience of HCM2S Steel Tube

The developed HCM2S steel tube and the conventional T22 steel tube have been installed in the superheater of a utility power boiler and field tested since April, 1993. The operating condition of the boiler is shown in **Table 8**. The test tubes were installed into the superheater sections, as shown in **Fig. 14**. The dimensions of these tubes were 38.1 mm O.D ×6.0 mm thick.

Table 8 Operation condition of the boiler

· Type	Forced circular type (156MW)
· Fuel	Mixture of blast furnace gas and oil
· Pressure	19MPa(S.H.), 4MPa(R.H.)
· Sream temperature	571 °C (S.H.outlet), 543 °C (R.H.outlet)

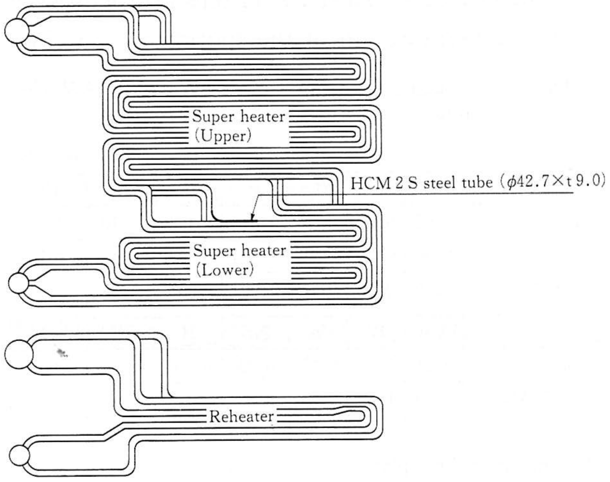


Fig. 14 Position of HCM2S steel tubes in the boiler

After 1 year and 2.5 years service exposure, the test tubes were removed from the boiler. The net service exposed times are 9 200h and 20 509h, respectively. For the removed tubes, dimensional measurements and evaluation of mechanical properties, corrosion resistance, and micro struture were performed.

5.1 Chemical Composition

The results of chemical composition analysis for the removed tubes are shown in **Table 9**. Each element satisfies the specification.

Table 9 Chemical compositions of removed tubes

(mass %)

Service duration	C	Si	Mn	P	S	Cr	Mo	V	Nb	W	N
1 year	0.05	0.19	0.48	0.016	0.001	2.23	0.13	0.24	0.057	1.67	0.006
2.5 years	0.06	0.19	0.48	0.021	0.001	2.25	0.13	0.26	0.05	1.66	0.006
Spec.	0.04 /0.10	≦ 0.50	0.10 /0.60	≦ 0.030	≦ 0.010	1.90 /2.60	0.05 /0.30	0.20 /0.30	0.02 /0.08	1.45 /1.75	≦ 0.030

5.2 Tube Dimension

There is little difference in outer diameter and wall thickness between a new tube and removed ones for HCM2S steel tube, as shown in **Fig. 15**.

5.3 Mechanical Properties

The tensile properties at room temperature and 600°C for removed tubes are shown in **Fig. 16**. It was demonstrated that the tensile strength and 0.2% proof stress after service for HCM2S steel are higher than those for T22 steel.

The Charpy impact properties at 0°C for removed HCM2S tubes are shown in **Fig. 17**. The Charpy impact value deteriorated after 1 year service exposure, however the values tend to saturate and are higher than 70 J/cm² even after 2.5 years service.

The creep rupture properties of removed HCM2S

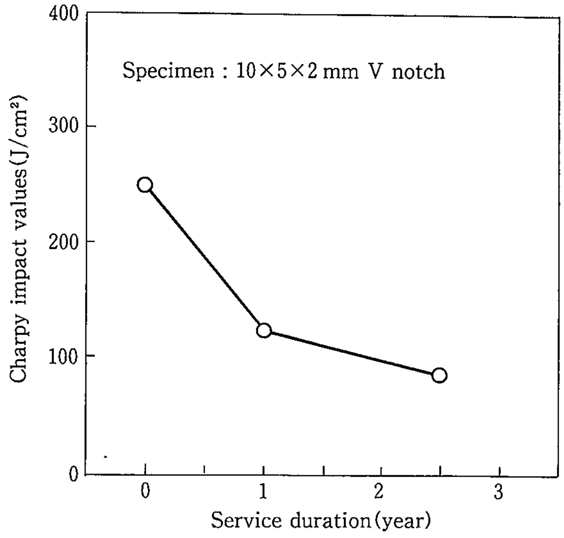


Fig. 17 Charpy impact properties at 0°C for removed HCM2S steel tubes

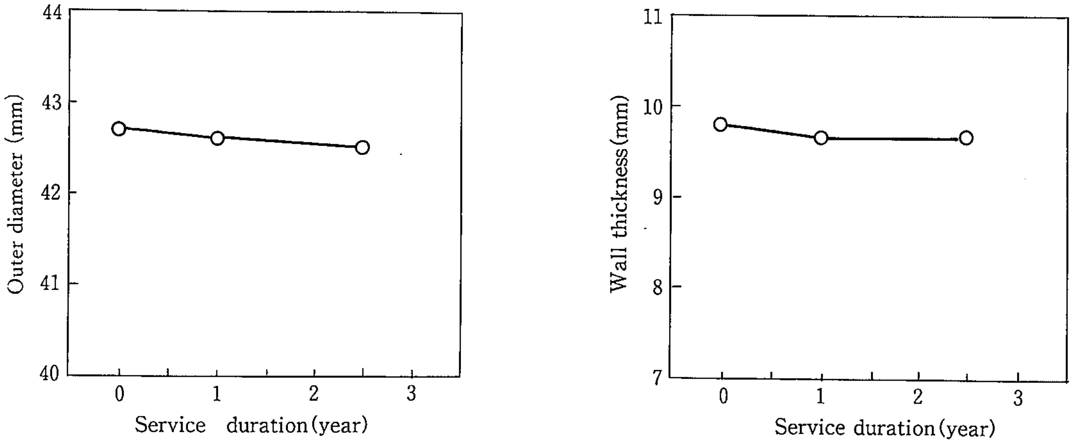
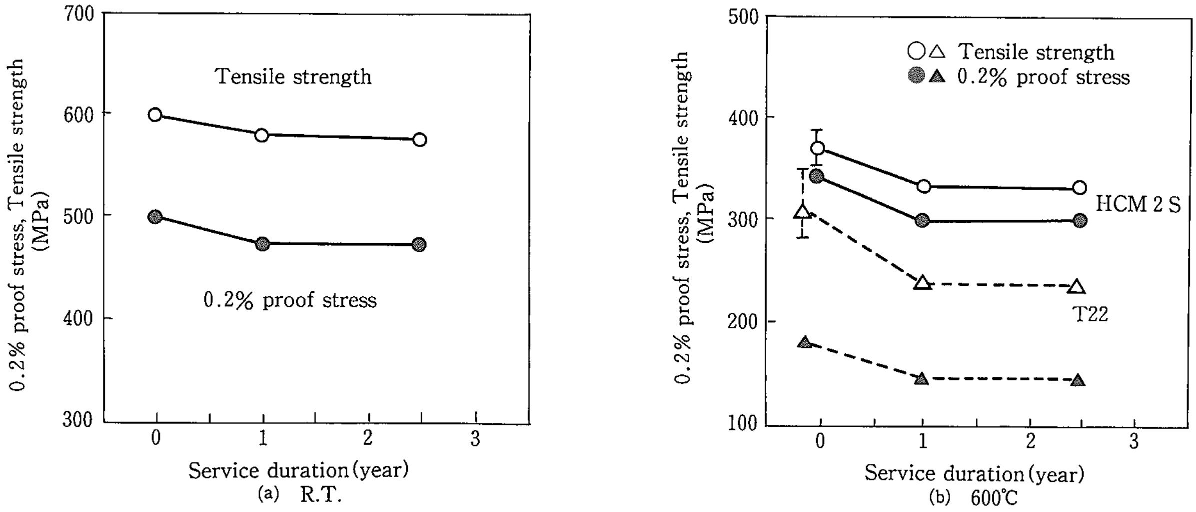


Fig. 15 Results of outer diameter and wall thickness for removed HCM2S steel tubes



(a) R.T.

(b) 600°C

Fig. 16 Tensile properties at room temperature and 600°C for removed tubes steel tube is shown in **Fig. 18**. There is no difference in the creep rupture strength between virgin materials and those with 1 year and 2.5 years of service.

5.4 Steam Oxidation Resistance

The rerationship between the steam oxidation scale thickness and the service duration in a boiler is shown in **Fig. 19**. **Photo 3** shows the comparison of steam oxidation behavior for tubes used for 2.5 years. It was demonstrated that the steam oxidation resistance of HCM2S steel was almost the same as T22, because the Cr contents in both steels are the same.

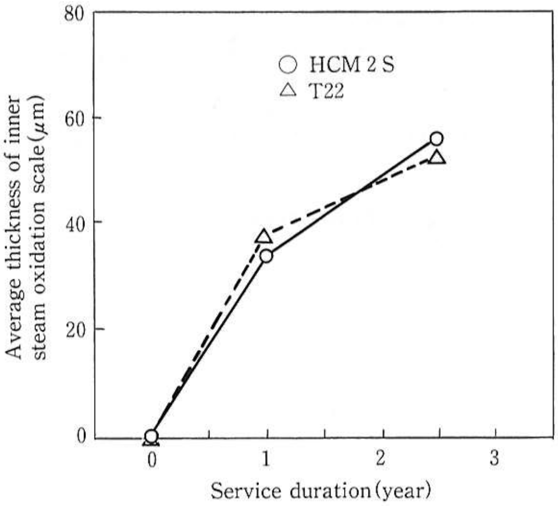
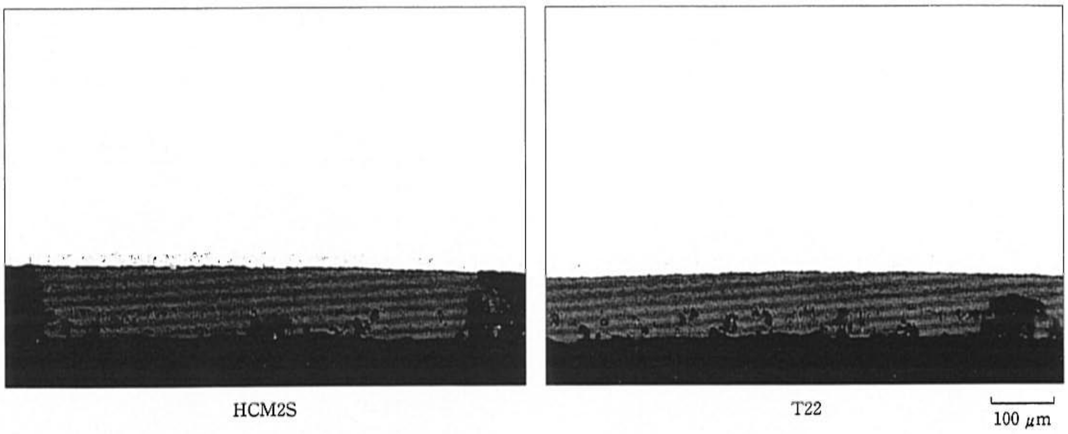


Fig. 19 Thickness of steam oxidation scale for removed tubes


HCM2S

T22

Photo 3 Steam oxidation scale of 2.5 years service exposed HCM2S and T22 steel tubes

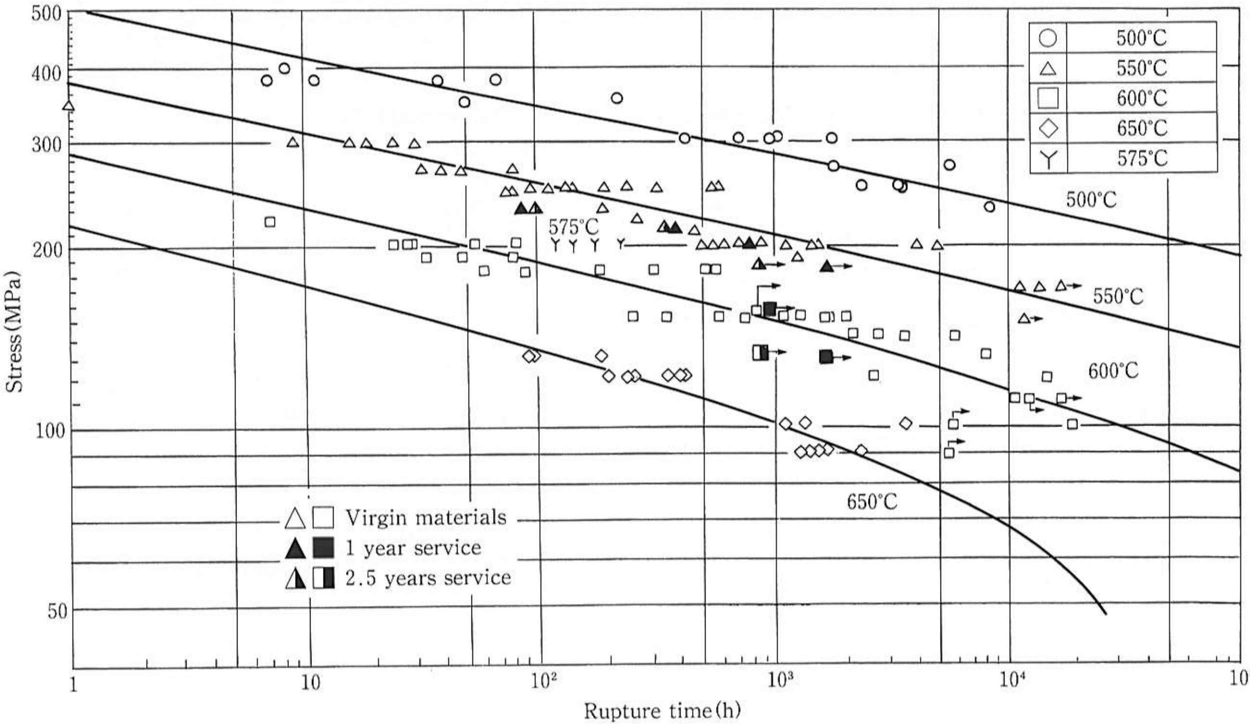


Fig. 18 Creep rupture strength properties for removed HCM2S steel tubes

6. Conclusions

The developed HCM2S (lowC-2.25Cr-1.6W-V-Nb) steel has enhanced creep rupture strength approximately 1.8 times greater than that of T22 conventional steel and comparable to that of T91 at 600°C. In addition, the toughness after long term exposure, the high temperature corrosion resistance and the weldability of HCM2S steel are also sufficient. This steel can be applicable under the as welded condition without pre-weld and post-weld heat treatment, because of the carbon content lowering.

These good properties of this steel were demonstrated by 1 year and 2.5 years field service tests in a fossil fuel fired boiler.

As a result, HCM2S steel can be widely used for superheater, reheater and water wall tubings, replacing conventional low alloy Cr-Mo steels such as T22.

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