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Development of 9CrW Tube, Pipe and Forging for Ultra Supercritical Power Plant Boilers

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Abstract:

Highly pressured steam with an elevated temperature has been studied worldwide in recent years to improve the efficiency of boilers for thermal power generation and also from a standpoint of an energy conservation and a global environmental conservation. The final target of the steam conditions for the boilers is such an ultra supercritical pressure as 352 atmospheric pressures and 649°C, but the present one is 316 atmospheric pressures and 593°C[1]. Studies on a material which can stand such severe steam conditions were carried out, and a 9CrW steel (NF616) for boiler use has been developed. This steel has been standardized in ASME as a tube and pipe, which has a creep rupture strength of about 1.3 times higher than the existing Mod. 9Cr-1Mo steel and is expected as the material for realizing a future ultra supercritical pressure steam power plant.

1. Introduction

With the current trend toward energy conservation, in recent years, high-pressure steam with an elevated temperature has become commonly used to improve the efficiency of thermal power-plant boilers. In addition to the primary objective of decreasing fuel consumption, resulting from the improvement of the efficiency of power generation, this type of steam is also employed in an effort to protect the environment by suppressing the discharge of carbon dioxide (CO_2). Because high-pressure steam with an elevated temperature is indispensable in increasing power-generating efficiency, steel with superior performance, as opposed to conventional heat-resistant steel is required.

Austenitic stainless steel such as SUS304HTB, SUS321HTB, and SUS347HTB is normally employed for superheaters and reheaters in supercritical power plants, as austenitic stainless steel is stronger than the ferritic steel at high temperatures. However, it has disadvantages such as lower thermal conductivity and a larger thermal expansion coefficient which cause scale peel-off due to expansion and contraction during startup and shutdown of the boilers. This effect increases along with the thickness of the steel in use. Therefore, there is a great need for high-chromium ferritic steel as the thick-wall piping for a supercritical boiler and an ultra-supercritical boiler in which the steam temperature is 600°C or more[2].

The development of steel that can resist high temperatures and high pressure is indispensable in realizing an ultra-supercritical boiler. The authors have been involved in research on ferritic steel that can withstand the above harsh conditions, and have

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developed 9CrW (NF616) steel[3-6]. Its creep rupture strength at 600°C significantly exceeds the strength of the ferritic Mod.9Cr-1Mo steel (T91, P91, F91) developed by ORNL of the US.

Here, we will discuss the development and properties of the steel, tube, pipe and forging for an ultra-supercritical boiler.

2. Features of NF616

With respect to chemical composition, the remarkable feature of NF616 is that it contains tungsten, which is not added to conventional heat-resistant steel. Tungsten contributes to solid-solution hardening and precipitation hardening, and increases creep rupture strength. The development target of NF616 is to achieve high creep rupture strength by distributing and precipitating fine carbide and nitride in matrix, and by hardening solid solution using substitutional or interstitial element. Basically, the microstructure of NF616 is the tempered martensitic single-phase to improve creep rupture strength and toughness.

3. Properties of Tube, Pipe and Forging

3.1 Trial production of tube, pipe and forging

An analysis of the chemical composition standard of NF616 and the chemical composition and dimensions of the prototype are shown in **Tables 1** and **2**, respectively. **Fig. 1** shows the manufacturing process. Melting and refining were carried out by means of vacuum induction melting (VIM), electric arc furnace melting (EAF) - electro slag remelting (ESR), use of the basic oxygen process (BOP) , etc. Casting was done by means of the ingot - casting method and continuous-casting method in the manufacture of ingots and slabs, respectively. The melted amount ranged from 300 kg to 120 ton.

The manufacturing methods of the individual products are as follows:

Hot extrusion for the piping for the superheater;

Seamless rolling for the piping for the main steam pipe and header;

Hot forging for the large-diameter forged pipe and forging.

The small-size tube has an outer diameter of 38.1 mm to 70 mm and a thickness of 6.6 mm to 12 mm, the medium size pipe has an outer diameter of 300 mm to 352 mm and a thickness of 40 mm to 56 mm, the large-size forged pipe has a diameter of 318 mm to 584 mm and a thickness of 50 mm to 134 mm, and 50 mm to 200 mm in thickness. With respect to heat treatment, normalizing or oil quenching at 1,050°C to 1,100°C and tempering at 760°C to 780°C are applied depending on the product size, taking creep rupture strength, tensile strength, and toughness into consideration. **Photo 1** shows a manufactured forging tee.

3.2 Application properties of thick wall material

It was reported that sufficient application properties of thin wall material was ensured[7,8]. For thick steel, however, care should be taken during the manufacture of said thick wall material to ensure the same usage performance as thin wall material. As the wall becomes thicker, the cooling speed of the central section slows. Then, based on the microstructure problems, it is suspected that δ ferrite may precipitate, that grain size may be coarse, and that precipitation conditions may change.

As a result of radiation heat, the cooling speed of the inner surface is slower than that of the outer surface. This effects the microstructure of the steel. Since these changes in microstructure effect mechanical properties, measures must be taken to ensure the properties.

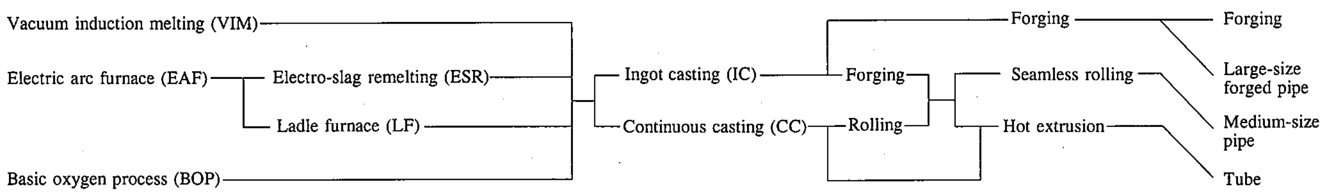

Fig. 1 Manufacturing process of the prototype

Table 1 Standard chemical analysis (mass %)

Specification		C	Si	Mn	P	S	Cr	Mo	W	Ni	V	Nb	N	Al	B
Chemical composition	min.	0.07	–	0.30	–	–	8.50	0.30	1.50	–	0.15	0.04	0.030	–	0.001
	max.	0.13	0.50	0.60	0.020	0.010	9.50	0.60	2.00	0.40	0.25	0.09	0.070	0.040	0.006

Table 2 Chemical analysis and dimensions of tested steel samples (mass %)

Heat	Size	C	Si	Mn	P	S	Cr	Mo	W	Ni	V	Nb	N	Al	B
EPT	54 OD×12t	0.106	0.04	0.46	0.008	0.001	8.96	0.47	1.84	0.06	0.20	0.069	0.051	0.007	0.003
YAT	54 OD×12t	0.124	0.02	0.47	0.011	0.006	9.07	0.46	1.78	0.06	0.19	0.063	0.043	0.002	0.003
EPP	350 OD×50t	0.106	0.04	0.46	0.008	0.001	8.96	0.47	1.84	0.06	0.20	0.069	0.051	0.007	0.001
YBP	300 OD×40t	0.101	0.04	0.47	0.011	0.001	8.96	0.48	1.94	0.06	0.20	0.065	0.045	0.005	0.004
JAP5	318.5 OD×50t	0.100	0.12	0.43	0.005	0.001	9.00	0.50	1.80	0.16	0.20	0.060	0.044	0.012	0.001
JCP	508 OD×83t	0.100	0.26	0.47	0.009	0.003	8.84	0.34	1.88	0.29	0.19	0.065	0.042	0.003	0.001
DBF1	300 OD×100t	0.110	0.26	0.49	0.009	0.003	8.98	0.38	1.91	0.19	0.19	0.067	0.045	0.002	0.002
DDF	400 OD×150t	0.120	0.29	0.33	0.008	0.001	8.89	0.36	1.72	0.13	0.16	0.060	0.037	0.002	0.001

In this steel with a thickness of 400 mm, the cooling speed of the central section 1/2 t when air-cooled is shown in **Fig. 2**, the microstructure is martensitic single-phase, without δ ferrite, and the hardness is equivalent to steel with a thickness of 50 mm. The thick steel is slightly softer than thin steel assumedly because of the different precipitation state, but the difference is not significant. **Photo 2** shows the microstructure of a pipe with a thicknes of 125 mm. Equalizing the cooling speeds of the inner surface and outer surface results in the same grain sizes in a thickness range from 1/4 t of outer surface to 3/4 of inner surface. No difference in the microstructure of the pipe is recognized among the above three positions of each thickness.

Photo 3 shows a photograph of the pipe taken using a transmission electron microscope following heat treatment. This photograph of the sampled replica shows that many fine precipitates are distributed homogeneously in and between martensitic lathes. Differences in the type, size, and distribution of the precipitates are small, and no significant differences are observed.

3.3 Mechanical properties of tube, pipe and forging

Fig. 3 shows the high-temperature tensile test results for individual products of the tube, pipe and forging. The directions of samples are longitudinal for thin-wall tube, and longitudinal and circumferential for thick and medium-size pipe, large-size forged pipe, and forging. For forged tees, the test pieces were sampled in the thickness direction and from the center of the corner. The minimum values of tensile properties at the room temperature specified in the standard are 620 MPa in tensile strength, 440 MPa in 0.2 % proof stress, and 20 % in elongation. The above results meet these values sufficiently. The thick wall forging and large-size forged pipe show nearly equivalent tensile properties to the thin-wall tube. Small differences in tensile strength are shown, regardless of the individual products. With respect to thick wall material, no differences in tensile properties are recognized, regardless of the sampling positions of the test pieces in the thick-

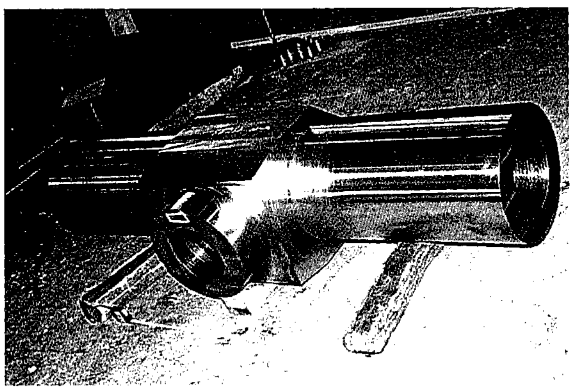

Photo 1 Appearance photograph of a forged tee

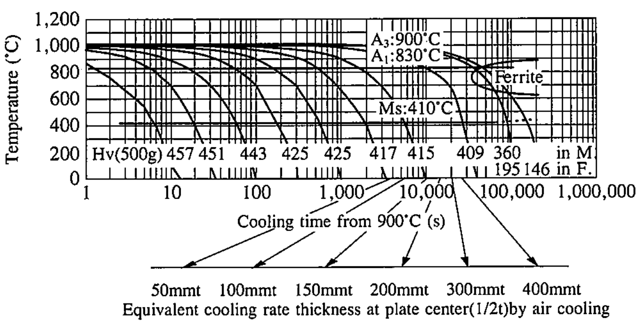

Fig. 2 Continuous cooling curves of NF616 forging

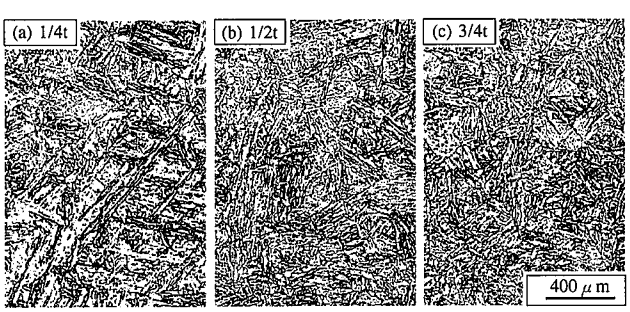

Photo 2 Microstructure of a large-size forged pipe

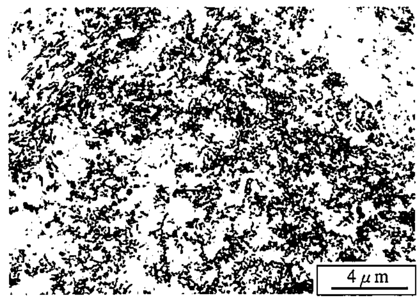

Photo 3 Microstructure of a medium-size pipe

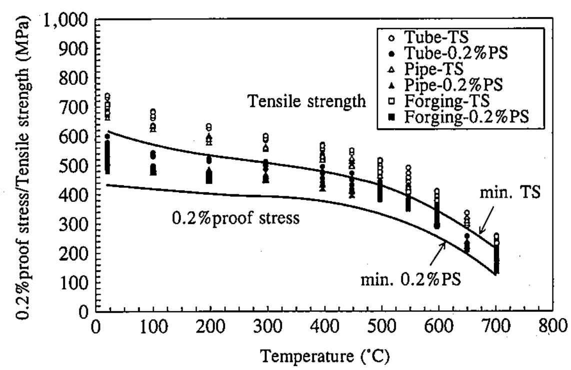

Fig. 3 High-temperature tensile strength test results

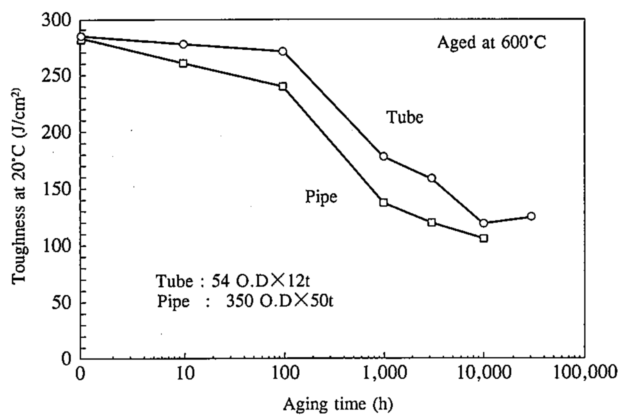

Fig. 4 Transition of toughness following aging

ness direction or sampling direction. No anisotropy is considered.

Fig. 4 shows the transition of the Charpy impact value of the tube and medium-size pipe at 20°C following long-term aging at 600°C. For the first 1000 hours, the toughness decreased largely as a result of aging, but stabilized 10,000 hours later. Following long-term aging, a toughness of more than 100 J/cm^2 at 20°C is obtained and considered sufficient for the boiler steel. This tendency of a decrease in toughness is also seen with Mod.9Cr-1Mo steel. With respect to large-size forged pipe and forging, a toughness of approx. 200 J/cm^2 at 20°C is obtained following heat treatment. For thick wall material, sufficient toughness is ensured.

Fig. 5 shows the transition of the stress - the creep rupture time of tube, pipe and forging with respect to the individual products. Data now over 50,000 hours is now available, and the creep rupture strength at 600°C after 10^5 hours of aging is estimated by the Larson-Miller method to be as high as approx. 1.3 times that of the existing Mod.9Cr-1Mo steel (ASME SA213-T91/SA335-P91). Thick medium-size pipe, large-size forged pipe, and forging are slightly lower rupture strength than thin tubing during the short period, but as tough as the tube over an extended period. Small differences in the rupture properties are recognized regardless of the sampling locations and directions. No anisotropy is considered.

4. Activities to Put Tube, Pipe and Forging into Use

4.1 Standardization

In Feb. 1993, an application was made for the registration of tube and pipe as an ASME standard to the ASME Boiler and Pressure Container Standard Committee. As a result, in August 1994, heat-exchanger tube and pipe for piping were registered as ASME Section 1 Code Case 2179 in the steel name of ASME SA-213 T92 and ASME SA-335 P92, respectively. Another application was made to ASME in May 1996 for the forging. Simultaneously, an application for tube and pipe were also made to ASTM, and standardization will occur in the near future.

In Japan, applications have also been made for three kinds of product, i.e., tube, pipe, and forging for registration as a technical standard of the material for power-generating boilers, and are scheduled to be registered in 1997.

4.2 Advantages of the use of high-strength steel

Research on ultra-supercritical boilers is carried out primarily by the Electric Power Research Institute (EPRI: USA) and COST (Europe). One of the principal technical problems with ultra-supercritical boilers is that the thicker tube and pipe tend to break due to creep fatigue rupture caused by repeated stress during adjustment of the boiler load. High-strength ferritic steel, such as NF616, with little thermal expansion coefficient and good thermal conductivity, is required.

Fig. 6 shows the allowable stress of the standardized material in ASME in comparison with Mod.9Cr-1Mo steel. At 600°C, NF616 shows 1.3 times the allowable stress of Mod.9Cr-1Mo steel. Higher temperatures increase this ratio, and thinner wall tubing is more advantageous. **Fig. 7** shows a comparison of tube-wall thickness assuming a temperature of 610°C, with a pressure of 280 kg/cm^2 (27.5 MPa) and a diameter of 400 mm. NF616 requires only 98.4 mm, while Mod.9Cr-1Mo steel requires 141.2 mm. The thickness reduction of thick-wall steel contributes to the reduction of cost for steel and load for processing, welding, and working, as well as a reduction in thermal stress in case of the shutdown of boilers. Furthermore, this results in a decrease in the creep rupture damage to steel.

4.3 Formability

Since 1990, the international joint research project (EPRI

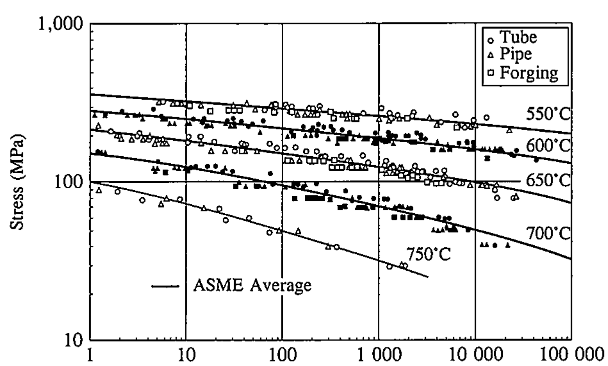

Fig. 5 Creep rupture strength

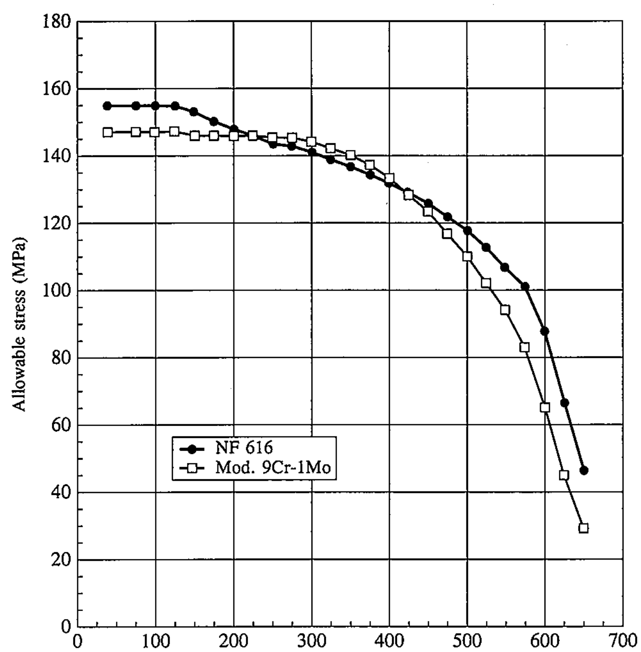

Fig. 6 Comparison of allowed tensile stresses

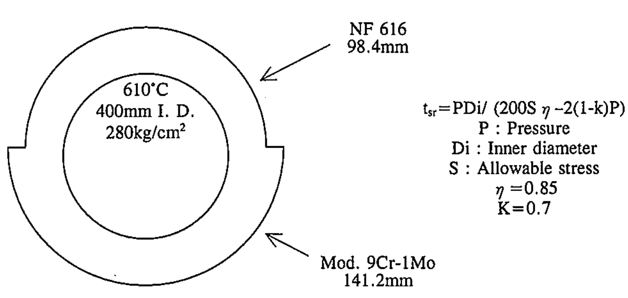

Fig. 7 Comparison of tubing wall thickness

RP1403-50) has been promoted by material manufacturers, boiler fabricators, and electric-power companies in the United States, the United Kingdom, Denmark, and Japan in an effort to develop thick-wall pipe for ultra-supercritical boilers. The research program consists of the Phase-1 Material Evaluation and Phase-2 Field Test. In Phase-1, the properties, bending formability, and weldability of base metal and the welded portion were evaluated by the boiler fabricators and electric-power companies. NF616 was evaluated highly.

The development of welding material NF616 has been completed. It obtained a good evaluation result in the EPRI RP1403-50 project, as well as from boiler fabricators and electric-power companies in Japan and overseas. Its weldability is superior to 2.25-Cr steel, even though it is high-Cr steel.

5. Field Test

A field test on superheater tube and main steam pipe is being carried out in Japan and overseas.

5.1 Field test on tube

The field test on tube has been carried out since 1987 at the Tobata Co-Operative Thermal Power Plant No. 4 boiler of Tobata Co-Operative Thermal Power Co., Inc. under a grant from MITI[10-12]. The maximum working pressure in the boiler is 19.3 MPa, the maximum steam temperature is 569°C, and the metal temperature is 600°C. The tube was inserted at the high-temperature section of the tertiary superheater by replacing part of the conventional SUS321HTB tube. 13,763 hours, 21,212 hours, and 44,567 hours after installation, samples were taken and evaluated. In comparison with the material when inserted, although precipitates agglomerated at the grain boundary and lath boundary, their coarsening is not significant. As **Photo 4** shows, the precipitate type and precipitation condition remained unchanged from 13,763 hours after installation, and were the same as those of the aged steel at 650°C after 10,000 hours (equivalent to 600°C for 2,000,000 hours). Therefore, future change is anticipated to be small. The Charpy impact properties and hardness of the welded portion remained stable from 13,763 hours after installation. Consequently, it was confirmed that the tube is stable for long-term use. A field test exceeding 65,000 hours is now under way, with no problems.

The tube was inserted at the same time as Mod.9Cr-1Mo and X20CrMoV121 into the superheater of the Wilhelmshaven boiler

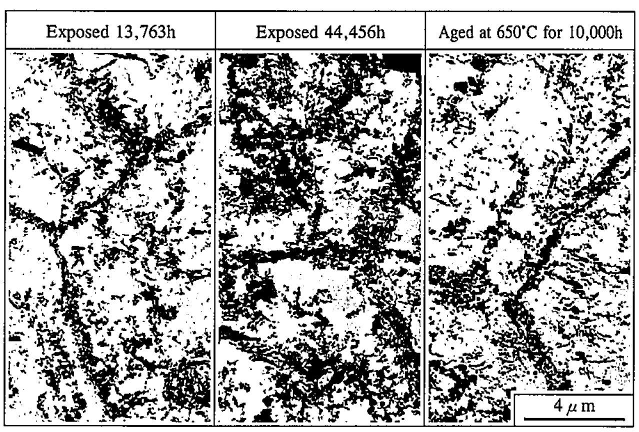

Photo 4 Precipitation conditions of the field-tested tubes

Table 3 Comparison of the steam oxidizing scale thickness of the field-tested tubes

Steel		NF616	Mod.9Cr-1Mo
Temperature (°C)		608	609
Exposure time (h)		8,458	8,458
Scale thickness (μm)	min.	180	185
	max.	315	325
	average	247	247

manufactured by Preussen Electra in 1992[13]. **Table 3** shows the steam oxidizing scale thickness after the field test was conducted at a metal temperature of 608°C, together with Mod.9Cr-1Mo. Its steam oxidizing scale thickness after the 8458 hours of operation is as high as that of Mod.9Cr-1Mo.

5.2 Application of pipe and forged pipe

Since 1992, the pipe has been under a field test in the No. 3 boiler, Vestkraft, ELSAM, in Denmark[14]. The maximum working temperature and steam pressure are 25.4 MPa and 560°C, respectively. The pipe was inserted into the main steam pipe, and partly replaced the existing X20CrMoV121 pipe. In order to keep its inner diameter identical to the existing pipe, the outer surface was planed, taking the allowable stress into account. The field test is now being carried out with no any problems.

The EPRI RP1403-50 project field test moved to Phase-2 in 1995. To insert the pipe into the most advanced ultra-supercritical boiler as a part of the header, the construction of the header was completed, and it is now being installed in an actual boiler.

5.3 Application of forging in actual boilers

In 1996, in the EPRI RP1403-50 project, the property evaluation of forged tee was begun by the boiler manufacturers in the same manner as with the pipe.

6. Conclusion

NF616 (9CrW) was developed as new 9Cr steel, which is superior in strength at elevated temperatures to conventional 9Cr steel. Because this steel is hardened by tungsten, to which 1.8 % tungsten was added, it has approx. 1.3 times higher creep rupture strength than the Mod. 9Cr-1Mo (T91, P91, F91) steel currently in use, and was registered as an ASME standard. This steel will soon be put into actual use as tube for superheaters and reheaters, a header and a main steam pipe, and forging for tees and reducers.

Because the thermal-power plants that will be constructed in the future will tend to use high-temperature and high-pressure steam, the application of the high-strength steel, NF616, will be a major advantage from the viewpoint of the accomplishment of high temperature and high pressure resistance, cost minimization, higher reliability, and economy.

Acknowledgment

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