

Development of High- and Intermediate-Pressure Steam Turbine Rotors for Efficient Fossil Power Generation Technology

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—Synopsis—

This article summarizes the history of the development of large turbine rotors for fossil power generation in the world, including recent topics of research and development at JSW. The first half of the article describes the engineering current of thermal condition of the fossil power plant and the progress of high chromium ferritic heat resistant steels for ultra super critical (USC) power generation. The second half introduces the present status of the development of turbine rotors for advanced-ultra super critical (A-USC) power generation in Japan, followed by our recent manufacturing experience, in which we successfully manufactured 10-ton class A-USC turbine rotors of a Ni-Fe base superalloy with a fine grain structure and sufficient permeability of ultrasonic waves. These superalloy rotors are expected to contribute to further developments of fossil power generation as the high chromium steel rotors have greatly helped fossil power plants become more and more efficient and reduce the emission of greenhouse effect gases.

1. Introduction

The World Energy Agency predicts global energy demand will increase by about 30%⁽¹⁾ and global power demand by about 70%⁽²⁾ between 2011 and 2035. In addition, it predicts global CO₂ emissions will increase by about 20% from 30 billion tons in 2011 to 35.7 billion tons in 2035, with remarkable increases in China and India⁽¹⁾. In Japan, the shutting down of all domestic nuclear power plants after the March 2011 accident at the Fukushima Daiichi Nuclear Power Plant resulted in dependence on fossil power generation, causing an increase of 112 million tons in CO₂ emissions from power generation in fiscal 2012. Although there is an urgent need to reduce greenhouse gas emissions significantly, renewable energy sources are not sufficient to meet global power demand. Accordingly, fossil fuels remain the mainstream fuels for power generation worldwide. Among them, consumption of coal is expected to continue for a long time into the foreseeable future due to large reserves and low costs. However, the CO₂ emissions intensity of coal-fired thermal power generation is the highest among fossil fuels (LNG, oil, and coal). Therefore, there are demands to

raise the efficiency of coal-fired thermal power generation plants. Because generating efficiency can be enhanced by increasing the temperature and pressure of steam when it enters a steam turbine, development of heat-resistant materials to achieve that has been promoted for a number of years. At present, the maximum steam temperature reached to 620 °C, and ferritic heat-resistant steel with a 9-12% Cr content is used as the material exposed to such high-temperature steam. To attain greater efficiency, development of a Ni-based superalloy as a material that is resistant to 700 °C or higher temperatures is currently underway worldwide.

JSW has manufactured various kinds of components for power generation facilities; e.g. high- and intermediate-pressure turbine rotor⁽³⁻⁵⁾, low-pressure turbine rotor⁽⁶⁻⁷⁾, monoblock-type high- and low-pressure turbine rotor⁽⁸⁻¹¹⁾, generator rotor, retaining rings⁽¹²⁻¹³⁾, turbine casing⁽¹⁴⁻¹⁶⁾, boiler pipes⁽¹⁷⁻¹⁸⁾, and gas turbine disks⁽¹⁹⁻²⁰⁾. This article focuses on materials for high- and intermediate-pressure turbine rotors, and outlines technological trends as steam temperatures rise at fossil power plants.

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2. Changes in Thermal Conditions of a Fossil Power Plant

Figure 1 shows changes in thermal steam conditions at the inlets of steam turbines for fossil power plants in Japan. Steam conditions have changed from sub-critical, which is below the critical point of water (374 °C, 22.1 MPa) through super critical (Pressure \geq 22.1 MPa, Temperature \leq 566 °C), to ultra super critical (“USC”: Pressure \geq 22.1 MPa, Temperature \geq 593°C). Pressure and temperature of 4.1 MPa and 450 °C in 1950 rose to 16.6 MPa and 566 °C in 1959. In 1967, Super critical steam, of which pressure was 24.1 MPa and the temperatures of main and reheat steam were 538 and 566 °C, respectively, was adopted for the first time at Anegasaki power station, unit 1 (output: 600 MW). Subsequent efforts were made to increase power plant capacity, reaching 1000 MW capacity for a single unit at Kashima thermal power station unit 5 in 1974. However, high temperatures were not addressed for more than 30 years. Although oil-fired power generation plants were constructed one after another in the 1960s, after the oil crises in the 1970s, coal-fired power plants were introduced from the perspectives of energy saving, energy security, and economy, and higher efficiency has been pursued. Consequently, the first plant employing USC power generation with a 593 °C reheat steam temperature was realized at Hekinan No. 3 unit (700 MW) in 1993, followed by further improvements in temperature resistance capabilities: thermal conditions were achieved of 600 °C/600 °C at Misumi unit 1 and Haramachi unit 2 (both 1000 MW) in 1998, and in 2000 of 600/610 °C at Tachibanawan thermal

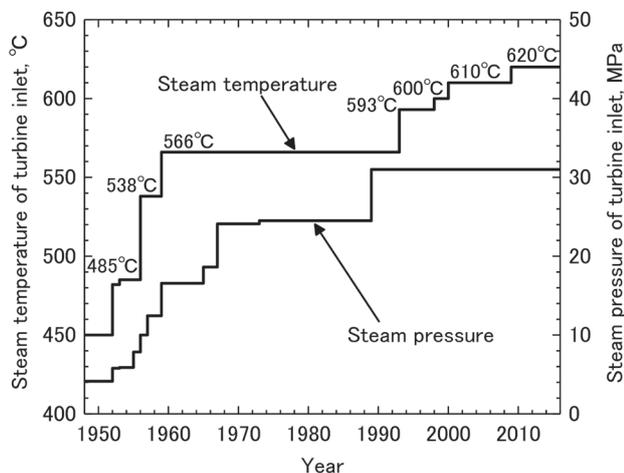


Figure 1 Changes in thermal conditions at the inlets of steam turbines for fossil power generation in Japan.

power station units 1 and 2 (1050 MW) in 2000. Currently, the highest steam temperature is 600/620 °C at Isogo thermal power station unit 2 (600 MW), of which commercial operation started in 2009.

Meanwhile, in the United States, the first USC plant was established in 1957, adopting thermal conditions of 31 MPa, 621 °C at Philo 6 (125 MW). In 1960, the world’s highest thermal conditions of 34.5 MPa, 649 °C were adopted at Eddystone station unit 1 (325 MW). However, because Eddystone unit 1 experienced high costs for austenitic steel and Ni-base alloy which were used to address elevated temperatures, and other problems such as damage to boilers, thermal conditions of 27 MPa, 538 °C became the mainstream for newer plants⁽²¹⁾.

3. Development of Rotor Materials for USC Power Generation

To improve thermal conditions, heat-resistant materials that can be used at high temperatures and under high pressures are indispensable. To this end, many heat-resistance materials have been developed for turbine rotors, turbine blades, casings and boiler pipes/tubes, and valves. This chapter reviews the development history of materials focusing mainly on high chromium (Cr) ferritic heat resistant steels, which are used for high- and intermediate-pressure steam turbine rotors—important components of USC power generation plants.

Concerning metal materials used at high temperatures, creep phenomena, which cause deformation over time, are needed to be taken into account even the loaded stress is below their yield strength. Because steels present remarkable creep deformation at approximately 500 °C or higher, it is crucial to develop materials with high creep strength to address increasingly high temperatures at plants. For high- and intermediate-pressure turbine rotors, a 100,000-hour creep rupture strength is required to be 100 MPa or greater. The 100,000-hour creep rupture strength of each material is shown in Figure 2⁽²²⁾. The creep strengths of Advanced and new 12Cr steel and their derivatives are shown by the band in the figure. 1Cr-1Mo-0.25V steel (referred to “1CrMoV” below) has been widely used at 566 °C or below. Both 10CrMoVNbN steel developed in the United States and 10CrMoVTaN steel developed in

Japan⁽²³⁾, which have higher creep strengths than 1CrMoV steel, were used mainly for 566 °C intermediate-pressure turbine rotors. However, because a 100,000-hour creep rupture strength of 100 MPa can be sustained at approximately 570 °C, a new high-strength ferritic heat-resistant steel for USC that can address 593 °C had to be developed.

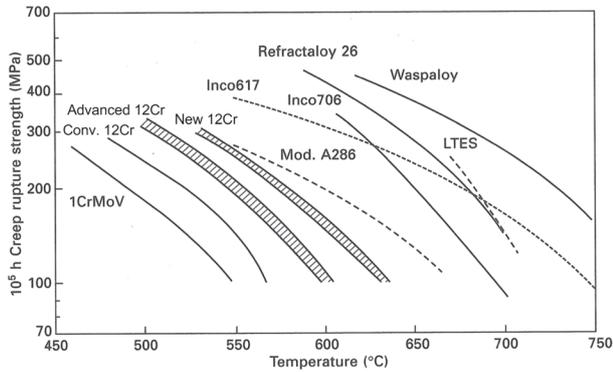


Figure 2 100,000-hour creep rupture strength of materials for turbine rotors⁽²²⁾.

Figure 3 shows the trends of USC technological development. In Japan, technological development of USC fossil power plants was conducted by Electric Power Development Co., Ltd (EPDC), and heavy electrical equipment manufacturers during the period 1980-2001. Compared to conventional thermal conditions of 24.1 MPa, 538/566 °C, the goals of Phase 1 in 1980-1994, were 31.4 MPa, 593/593/593 °C (Step 1), which were possible by extending conventional technologies (ferritic steel), and 34.3 MPa, 649/593/593 °C (Step 2), which requires new materials and technologies (austenitic steel). The goal of Phase II in 1994-2001 was set to

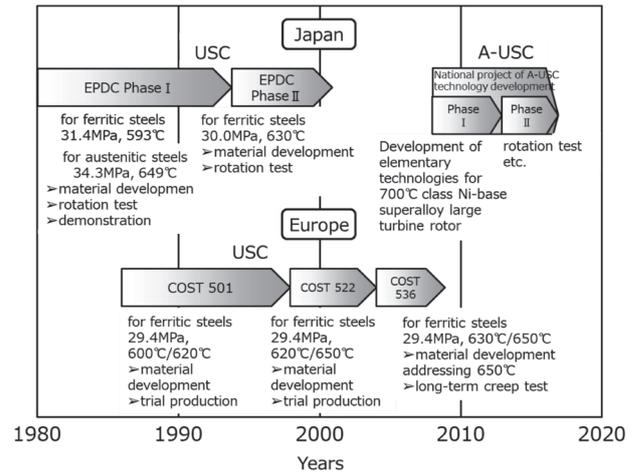


Figure 3 USC/A-USC technological development projects.

30.0 MPa, 630/630 °C using ferritic steel. The power generation efficiency of the 1000 MW model was estimated to be 44.2%, 44.9%, 44.16%, each, against the conventional 42.1%⁽²⁴⁾.

Based on intensive research by Fujita and others on 9-12Cr steel, some kinds of 600 °C-class Advanced 12Cr steels including TOS107⁽²⁵⁾, HR1100⁽²⁶⁾, TMK1⁽²⁷⁾, and TMK2⁽²⁸⁾ have been developed in the 1980s. As shown in Table 1, the feature of these steels is the compositions with different Mo/W balances and similar Mo equivalent (defined as [mass%Mo] + 0.5[mass%W]) of 1.5⁽²⁹⁾. Compared to conventional 12Cr steel, toughness and microstructural stability have been improved by reducing C and increasing Ni. Through the trial production of an Advanced 12Cr steel rotor supposed to be used as an intermediate-pressure rotor of a 1000 MW model, its manufacturability, soundness of internal properties, and physical and

Table 1 Chemical compositions of high Cr ferritic steel for USC turbine rotor.

		(mass%)												
		C	Si	Mn	Ni	Cr	Mo	W	V	Nb	Ta	N	Co	B
Conventional 12Cr	10CrMoVNbN	0.19	0.30	0.65	0.6	10.5	1.0	-	0.20	0.085	-	0.060	-	-
	10CrMoVTaN ⁽²³⁾	0.18	0.27	0.62	0.30	10.3	0.94	-	0.25	-	0.089	0.0412	-	-
Advanced 12Cr	TOS107 ⁽²⁵⁾	0.14	0.03	0.52	0.73	10.36	1.05	1.06	0.21	0.07	-	0.0414	-	-
	HR1100 ⁽²⁶⁾	0.15	0.04	0.54	0.64	10.2	1.2	0.34	0.15	0.05	-	0.05	-	-
	TMK1 ⁽²⁷⁾	0.14	0.08	0.51	0.60	10.23	1.48	-	0.17	0.056	-	0.045	-	-
	TMK2 ⁽²⁸⁾	0.12	0.07	0.47	0.51	10.59	0.37	1.84	0.17	0.045	-	0.052	-	-
	COST E ⁽³⁶⁾	0.11	0.08	0.42	0.78	10.79	1.10	1.02	0.19	0.040	-	0.050	-	-
	COST F ⁽³⁶⁾	0.14	0.08	0.55	0.56	9.99	1.40	-	0.17	0.059	-	0.041	-	-
New 12Cr	TOS110 ⁽³³⁾	0.11	0.08	0.1	0.2	10.0	0.65	1.8	0.2	0.05	-	0.02	3.0	0.01
	HR1200 ⁽³⁴⁾	0.10	0.06	0.46	0.25	10.2	0.14	2.51	0.21	0.07	-	0.017	2.44	0.013
	MTR10A ⁽³⁵⁾	0.12	0.05	0.05	<0.05	10.2	0.65	1.75	0.2	0.06	-	0.02	3.3	0.002
	COST FB2 ⁽³⁷⁾	0.13	0.07	0.32	0.15	9.29	1.50	-	0.19	0.050	-	0.025	1.30	0.0075

mechanical properties were verified⁽³⁰⁾. Furthermore, at the aforementioned Step 1, a rotating test was conducted using an Advanced 12Cr steel rotor at 593 °C and a 50 MW demo test was conducted at EPDC Wakamatsu work⁽³¹⁾, followed by a series of onsite applications at 600 °C-class plants.

Because ferritic steel is not strong enough at 649 °C, A286 alloy (Fe-15Cr-26Ni-1.5MoVAITiB), austenitic iron-base superalloy, became a candidate material. To make the alloy suitable for large forged components, chemical components were modified; for example, C content was lowered to suppress the precipitation of coarse carbides and Ti content was also reduced to improve segregation without degrading creep strength, notch sensitivity and ductility⁽³²⁾. An approximately 1.6 tons turbine rotor of Discaloy (Fe-13Cr-25Ni-3MoAlTi) was used at Eddystone in the United States on the premise of base load operation. In Step 2, a 5000-hours rotating test with 151 times of start-and-stop operation, which simulates daily start and stop (DSS) at power stations, was conducted using an A286 rotor of approximately 12.5 tons at 649 °C⁽²⁴⁾. Some issues concerning austenitic steel such as an operational limitations owing to thermal fatigue caused by low thermal conductivity and large thermal expansion coefficient were clarified. There also found an economic issues due to high material costs. Figure 4 shows an A286 turbine rotor manufactured by JSW using a 20-ton steel ingot prepared by electroslag remelting process (ESR). The maximum diameter of the turbine rotor was 892 mm, and its weight was 7.54 tons.

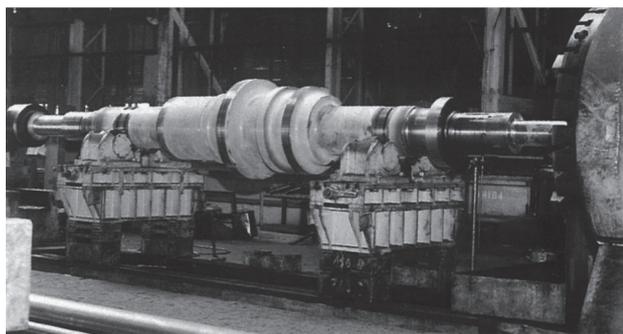


Figure 4 A286 turbine rotor.
(Body diameter: 892 mm, Total length: 6,044 mm, 7.54t)

In Phase II, with emphasis on economic efficiency and operability compared to Phase I, Step 2, which used austenitic steel, research was conducted aiming for the early realization of a 30 MPa, 630 °C USC plant that uses high-strength ferritic steel.

TOS110⁽³³⁾, HR1200⁽³⁴⁾, and MTR10A⁽³⁵⁾ are kinds of New 12Cr steels for 630 °C. Performances of TOS110 and HR1200 toward practical application were evaluated in Phase II through an approximately 500-hours rotating test at 650 °C, as well as JSW's in-company test about manufacturability. Containing Co and B for suppressing the generation of δ -ferrite, and improving creep strength, respectively, is the noteworthy feature of these steels. They also contain more W compared to the Advanced 12Cr steel and reduced amounts of Ni and Mn. Figure 5 is an exterior view of the HR1200 trial turbine rotor made from a ESR ingot of approximately 80 tons. Figure 6 is an exterior view of a TOS110 turbine rotor with an overlay welding on journals. Overlay welding on journals of a high Cr steel turbine rotor is necessary to prevent the adhesive wearing with bearings, even the B containing steels with poor weldability⁽³³⁾.



Figure 5 HR1200 trial turbine rotor.
(Body diameter: 1,215 mm, Body length: 3,366 mm, Total length: 8,064 mm)

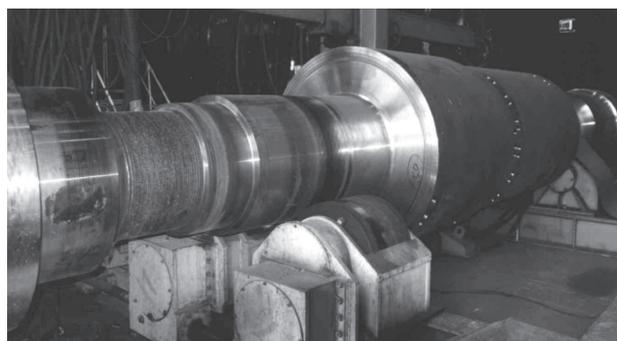


Figure 6 TOS110 trial turbine rotor.
(Body diameter: 1,296 mm, Body length: 3,040 mm, Total length: 7,734 mm, 47.1t)

In Europe, with the goal of 29.4 MPa, 600 °C/620 °C, “COST501”—a COST program (COST: Cooperation in the field of Science and Technology) was implemented in 1986-1997, resulting in the development of 600 °C-class steel rotor E⁽³⁶⁾ containing 1%Mo and 1%W, and rotor F⁽³⁶⁾ containing 1.5%Mo. These compositions are equivalent to those of TOS107 and TMK1. Moreover, FB2⁽³⁷⁾ containing Co and B was

developed to address 620 °C. In the project of COST522 which was held in 1998-2003, the target was 29.4 MPa, 620 °C/650 °C. In COST536 which was held in 2004-2009, materials development and long-term creep tests were conducted aiming for the goal of 29.4 MPa, 630-650 °C. As a result of these developments, it became possible to raise the steam temperature range at European plants from 530-565 °C to 580-620 °C⁽³⁸⁾. Pursuing further improvements in heat resistance capability, development of high Cr steels is continuing in Japan and overseas⁽³⁹⁾. Figure 7 is an exterior view of a COST E intermediate-pressure rotor (1,210 mm in diameter) made from vacuum carbon deoxidation process (VCD) and Figure 8 shows a COST FB2 intermediate-pressure rotor (1,365 mm in diameter) made from ESR. Both products were the first models we manufactured. The COST E rotor was made from a 113-ton VCD steel ingot and the COST FB2 rotor was made from a 102-ton ESR steel ingot. Although the heating time of these rotors during heat treatments was inevitably long due to the large body diameters, and then, grains

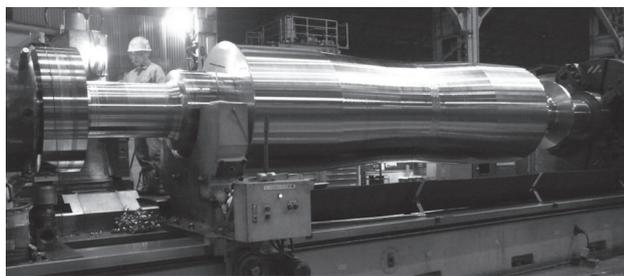


Figure 7 COST E turbine rotor (first model).
(Body diameter: 1,210 mm, Body length: 3,895 mm, Total length: 6,242 mm, 37.9t)

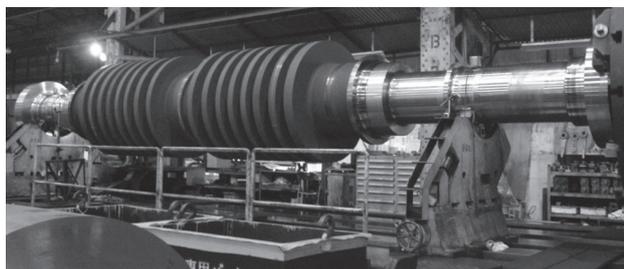


Figure 8 COST FB2 turbine rotor.
(Body diameter: 1,365 mm, Body length: 3,981 mm, Total length: 9,301 mm, 45.95t)

Table 2 Number of 12Cr rotors shipped.

Rotors	Steels	Shipped
Conventional 12Cr	10CrMoVNbN, 10CrMoVTaN	43
Advanced 12Cr	TOS107, HR1100, TMK1, COST E	220
New 12Cr	TOS110, MTR10A, COST FB2	46
Total	-	309

are easy to coarsen by high quenching temperatures of 1090-1100 °C, controlling the grain growth at the time of manufacturing made the permeability of ultrasonic waves sufficiently good. Table 2 shows the number of 12Cr rotors we have shipped. The first shipments of a conventional 12Cr steel rotor, an Advanced 12Cr steel rotor, and a New 12Cr steel rotor were in 1971, 1989, and 1998, respectively.

The total number of such rotors shipped by the end of January 2018 was 309 excluding trial turbine rotors. All of them were for actual plants.

4. Development of turbine rotor forgings for A-USC in JSW

4.1 Trend of A-USC in Japan

A-USC power generation has been paid much attention as a promising technology of efficient power generation. In Japan, the national project of the study of element technologies for the development of A-USC power plant has launched in 2008 at the initiative of Agency for National Resources and Energy⁽⁴⁰⁾. JSW have joined the project and developed the nickel-base superalloy turbine rotor, collaborating with heavy electric machinery companies in Japan⁽⁴¹⁻⁴²⁾. One of our example of the manufacturing A-USC turbine rotor is shown as below.

4.2 Manufacturing the A-USC turbine rotor of FENIX-700

FENIX-700 (Ni-36Fe-16Cr-1.3Al-2Nb, in mass%) is a modified alloy of Alloy706 that is widely used as a material for high temperature components such as gas turbine disks. Compared to Alloy706, FENIX-700 contains less niobium and a large amount of aluminum, and the stability of the microstructure at high temperatures and manufacturability of large forgings are ameliorated⁽⁴³⁾. So far, we have succeeded in producing a FENIX-700 large ESR ingot of 1,050 mm in diameter without macrosegregation for the first time in the world, and examined the properties concerning the manufacturability of large forgings in detail⁽⁴⁴⁾. For example, the lower limit of the forging temperature of FENIX-700 is lower than that of Alloy617, which is the candidate alloy mainly studied in Europe, indicating that FENIX-700 is advantageous to forge. Moreover, the behavior of grain growth and the effects of the mass effect, which is the large difference in the cooling rate between the surface and center of the

turbine rotor, are clarified⁽⁴⁵⁾.

The ingots were prepared using the double-melting process consisting of vacuum induction melting (VIM) and ESR. The ingots were forged using a 14,000-ton free hydraulic press to destroy the solidification structure and homogenize the microstructure of the forgings. Then, the forgings were annealed at 980 °C, followed by aging at 840 °C and 730 °C. The forgings after heat treatment were underwent machining and ultrasonic inspection. Two trial rotors were produced in the present work. The ingots for the first and second trial rotors were 1,050 mm in diameter, 2,750 mm in length, and 19 tons in weight, and 1,050 mm in diameter, 2,380 mm in length, and 17 tons in weight, respectively. The melting process was completed normally. To assess the effects of the forging conditions on the microstructure and mechanical properties, we set the temperature of the final forging process for the second trial rotor 50 °C lower than that of the first one, and increased the forging ratio by approximately 60%. In addition, we increased the forging ratio by approximately 50% at the center of the second trial rotor compared to the first one. As shown in Figure 9, the 10-ton class turbine rotor forgings of FENIX-700 was successfully manufactured.

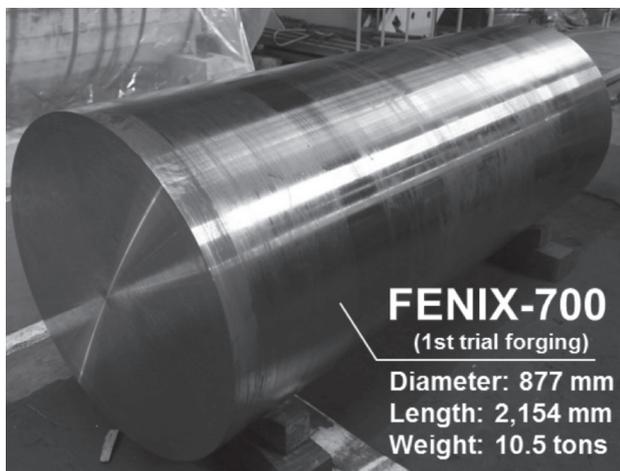


Figure 9 FENIX-700 1st trial forging.

Figure 10 shows the distribution of grain size number of two trial rotors. Because the lengths of the trial rotors are not equal, the specimen positions are described by X_n , which is the distance from the bottom side normalized by the rotor length. The values of X_n of the bottom, middle, and top parts of the first and second trial rotors are almost equal, meaning that the relative position of the specimen can be regarded as the same. The grains of the second trial rotor are finer than that

of the first one, especially, the grains in center at the position of $X_n = 0.5$ were remarkably refined. As mentioned above, the temperature of the final forging process was lowered and the forging ratio was increased, especially at the center, in the second trial. In the manufacturing process of the nickel or nickel-iron base superalloy, the strain energy accumulated during the final process drives the grain growth in the following solution heat treatment. Therefore, the downstream grain size and strain of the forgings play very important roles in controlling the final grain size of the rotor. The grain refinement of the second trial rotor is attributed to the large strain and suppression of the grain growth during the final process. Because the surface is more prone to strain than the center, the grain at the surface is considered to be more refined.

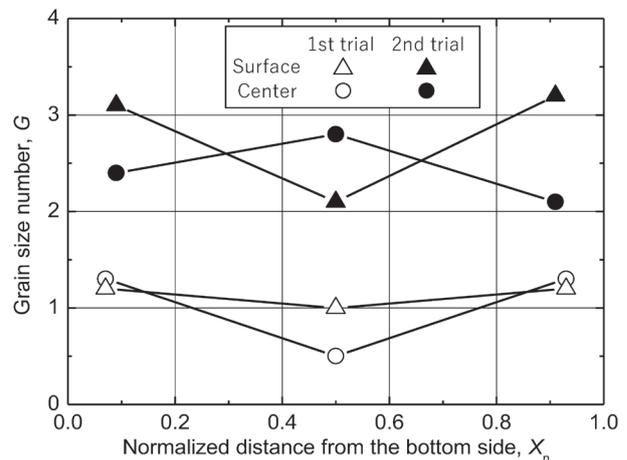


Figure 10 Distribution of grain size number of FENIX-700 turbine rotors.

The effect of grain refinement was also recognized in the difference of permeability of ultrasonic wave at the ultrasonic examination. Minimum detectable flaw size (MDFS) of the second trial forgings was 1.6 to 1.9 mm, which was obviously smaller than those of the first one 3.7 to 4.8 mm, indicating that the permeability of the ultrasonic wave in the second trial rotor was better than that of the first one. In general, the ultrasonic wave is strongly attenuated by the large particles. Thus, the excellent permeability of the second trial rotor is realized by the grain refinement, improving the reliability of the ultrasonic inspection.

Furthermore, toughness and ductility are also confirmed to be improved by grain refinement, and estimated creep strength at 700 °C, 10⁵ hours exceeds 100 MPa regardless of fine grain⁽⁴¹⁾. This result is highly appreciated by domestic and overseas customers who are interested in the

efficient power generation technologies, and the knowledges obtained in this trial production has stimulated us to develop the nickel-base superalloy large turbine rotors with higher quality for the commercialization of A-USC in the future.

5. Conclusions

JSW has been engaged in the practical application of new materials mainly through the development of materials and manufacturing technologies and the trials of prototype turbine rotor productions. Consequently, since our first shipment of a high Cr steel rotor in 1971, we have delivered more than 300 turbine rotors to actual power plants. JSW also successfully developed a Ni-Fe base superalloy FENIX-700 turbine rotor, which is compatible with 700 °C-class A-USC. As high Cr ferritic heat resistant steel rotors have contributed significantly to the higher efficiency of fossil power plants and reduction of emissions of greenhouse effect gases, superalloy rotors currently under development are also expected to contribute to the further progress of high-efficiency fossil power plants.

Acknowledgement

A part of the present work was sponsored by Ministry of Economy, Trade and Industry of Japan.

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