Development of High-Quality Large Scale Forgings for Energy Service

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—Abstract—

Growing energy demand promotes the construction of high performance energy plants with large scale. A dramatic increase of plant performance has been achieved by the enlargement of their major components such as turbine rotor shafts and pressure vessels. The Japan Steel Works, Ltd., has been continuing the efforts for improvements of production technology, material technology, reliability assessments and so on. The efforts gave birth to several epoch-making large and high quality forged components for energy plants. Recently, on the viewpoint of environmental problem such as global climate change or in order to meet the advanced process, further development of new production technology and improvement of material are needed and will be made in the near future. This paper gives an overview of the development of large high-quality forgings for energy service in the Japan Steel Works, Ltd.

1. Introduction

Since the steam turbines in fossil fuel power plants and nuclear power plants, pressure vessels for nuclear power plants, and pressure vessels for petroleum refineries are critical equipments operated at core parts of energy plant and are required of high degree of reliability, most of their main components like rotor shafts, pressure vessel shells, flanges, and heads are made of large scale forgings. In post war period of high rate of economic growth, while domestic demands for energy increased very appreciably and high efficiency and large scale energy plants were built, it was no discussion that there have been progress in infrastructures such as enlargement of equipment, manufacturing technology, material technology, quality assurance, and evaluation technology for reliability with regard to forgings. In recent years, compliance with global environmental issue associated with exhaust of carbon dioxide, development and application of new processes are pushing the trend of operating conditions toward higher temperature and pressure. Then the technology to produce large scale forgings of integrity as well as material development to cope with higher degree of required quality has become important.

The Japan Steel Works, Ltd. (JSW hereinafter) has been consistently involved with larger scale and higher quality of forgings for energy industry plants since after the last war, and has manufactured many components to the world. While the progress of large scale forgings, that have been supported by wide range of technology developments and material developments, is difficult to be described in a short note, here limiting to forgings for power plant and petroleum refinery, a review was made with regard to outline of progress after the war and some technology and material developments of recent times.

2. History of Manufacturing Technology

Not to mention, larger scale and higher reliability of energy equipment have been supported by development of manufacturing technology for high quality forged components. While manufacturing process for components of rotor shaft, pressure vessel and others differs for each, each process has been applied with the most advanced manufacturing technology, that has been developed at JSW Muroran Plant. Here, its history will be reviewed with regard to steel making, forging, and heat treatment technology.

2.1 Steel making technology

Formation of segregation and cavities in ingot gets prominent with increase of solidification time in larger ingot. Therefore, in order to produce high quality large scale forging, it is important to establish manufacturing technology of high quality ingot with suppressed formation of segregation and cavity as well as to reduce impurity elements and nonmetallic inclusions. It is also without discussion that

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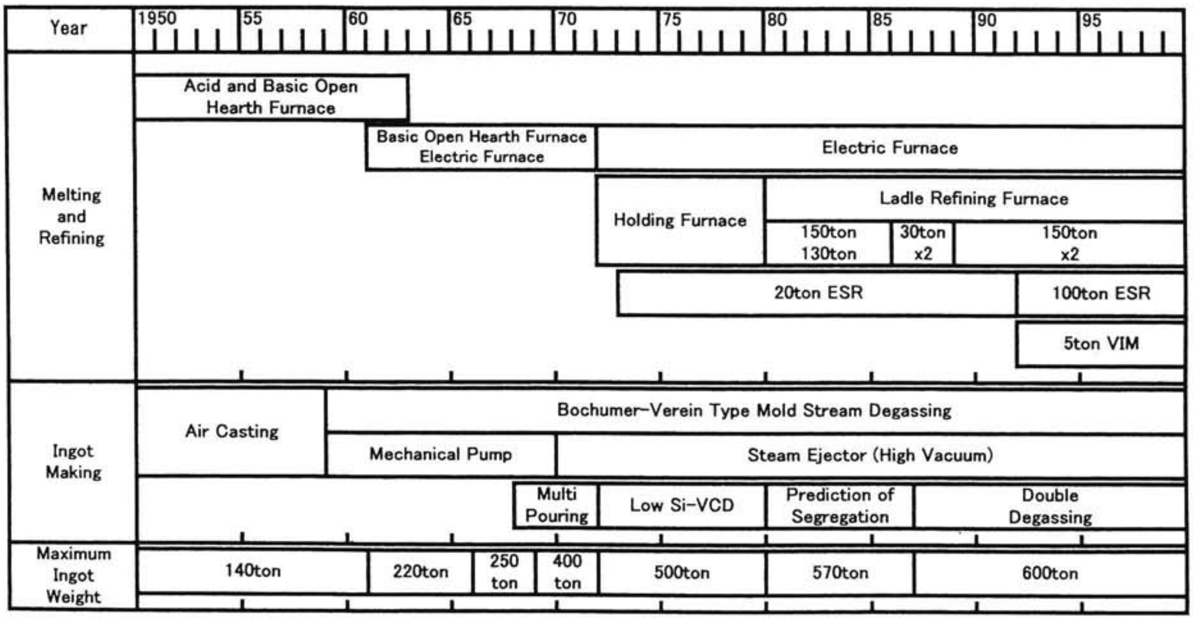
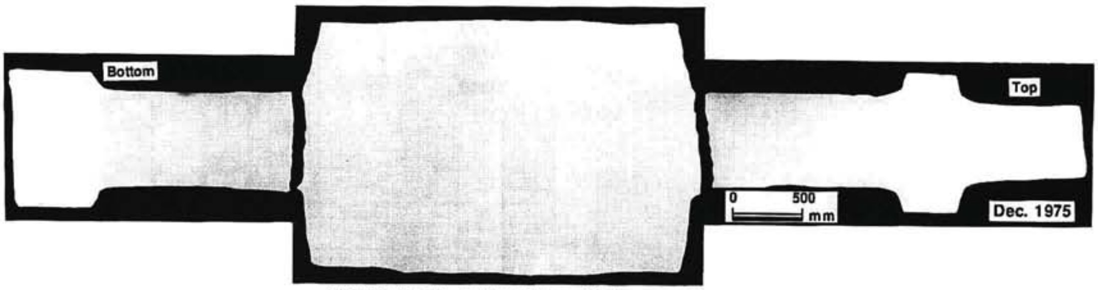


Fig. 1 A history of steel making technology and equipment since 1950 in JSW

minimization of gas elements like H, and O, and impurity elements like P, Sn, and Cu, which are cause for defect and damage during manufacturing and service, is important.

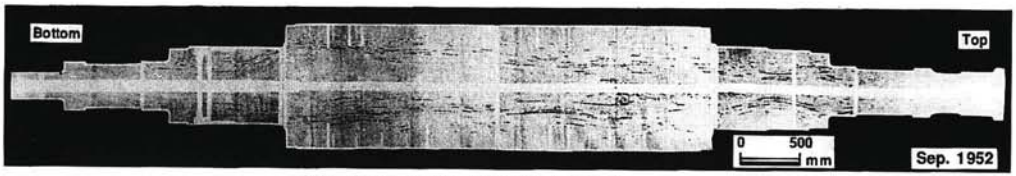
Fig. 1 shows a history of steel making technology at Muroran Plant after world war two[1,2]. In 1960 was introduced a Bochumer-Verein type degassing equipment, though it was a mechanical type. At the time, it was well known that decrease of hydrogen content in the steel is important to avoid defects like white spot. However, though the hydrogen absorption is likely to happen by casting in air, the method that had been taken was to use basic open-hearth furnace that is good at refining ability for dephosphorization and desulfurization at the first stage and to again refine in acid open-hearth furnace to reduce hydrogen at the second stage before casting. After introduction of Bochumer-Verein type degassing equipment, dehydrogenation by vacuum casting became possible, and then refining became to be done with basic electric furnace and basic open-hearth furnace. In 1969, the introduction of steam ejector improved degree of vacuum at time of degassing and the hydrogen content in the steel could be reduced further[3].

On the other hand, with introduction of vacuum casting equipment, vacuum carbon deoxidation (VCD) technology became commercially successful in 1970[4]. In the VCD process, a molten steel with low silicon conent is cast in high vacuum, Carbon and O in the steel react to be exhausted as CO. With application of VCD, the minimization of silicon content in the steel became possible. Decrease of Si content not only gives fine solidification structure and controlls formation of macro segregation in large scale ingot but also decreases the susceptibility to temper embrittlement in NiCrMoV steel which is widely used for low pressure steam turbine and 2.25Cr1Mo steel for pressure vessel [1,7,8]. **Photo. 1** shows sulfur prints in sections of 3.5NiCrMoV steel rotor forgings manufactured with Si deoxidation method or VCD method, and it is seen that segregation streak, clearly observed in Si deoxidized steel, is little observed in VCD steel. In 1969, multiple pouring(MP) process was industrialized. In this process, molten steels from multiple number of furnaces, each of which is adjusted with composition separately, are combined to make a large ingot[5,9]. With increase in ingot size, positive segregation of carbon at the side of hot top of ingot becomes remarkable, and in MP process, the enrichment of C is controlled by successive pouring of several heats with composition adjusted separately. By this technology, an ingot of 400 tons, the world largest, of minimal segregation was manufactured to make four poles generator shaft and monoblock low pressure rotor, the world largest at the time[9]. In 1972, still larger ingot of 500 tons was manufactured. Also, simulation technology for solidification and estimation technology for composition segregation were developed. These technologies contributes very much to manufacturing of



Ni-Cr-Mo-V LP Turbine Rotor Shaft
from 140 Ton V.C.D. Ingot
Chemical Compositions (mass%)

C	Si	Mn	P	S	Ni	Cr	Mo	V
0.22	0.02	0.31	0.006	0.008	3.47	1.79	0.41	0.12



Acid Open Hearth Furnace Air Cast
75 Ton Ingot
Chemical Compositions (mass%)

C	Si	Mn	P	S	Ni	Cr	Mo	V
0.34	0.38	0.51	0.021	0.008	3.60	0.19	0.43	0.15

Photo. 1 Sulfur prints in section of 3.5NiCrMoV steel rotor shafts manufactured by application of Si deoxidation or VCD

large ingot of superior quality[10-12]. In 1972, a holding furnace was installed to keep molten steel after refining by electric furnace, and open-hearth furnace was put into idle. Then in 1980, the holding furnace was equipped with vacuum equipment and ladle furnace was installed, making further decrease in impurity element content possible. In 1986, two units of ladle furnace with capacity of 30 tons were installed and, in 1987, two units with capacity of 150 tons were installed. By using these six ladle furnaces, manufacturing of 600 tons ingot by fully ladle refined melt became to be possible. Present manufacturing process for 600 tons ingot is shown in **Fig. 2**, and an appearance of 600 tons ingot is shown in **Photo. 2**. **Fig. 3** shows manufacturing process of ingot through ladle refining. Steel is subjected to oxidation refining by electric furnace. After pouring to ladle furnace by way of complete slag cut, then the steel is subjected to reduction refining. Then in the ladle, degassing is done by agitation with argon and by vacuum treatment. Subsequently the melt goes through mold stream degassing in vacuum. This process was named

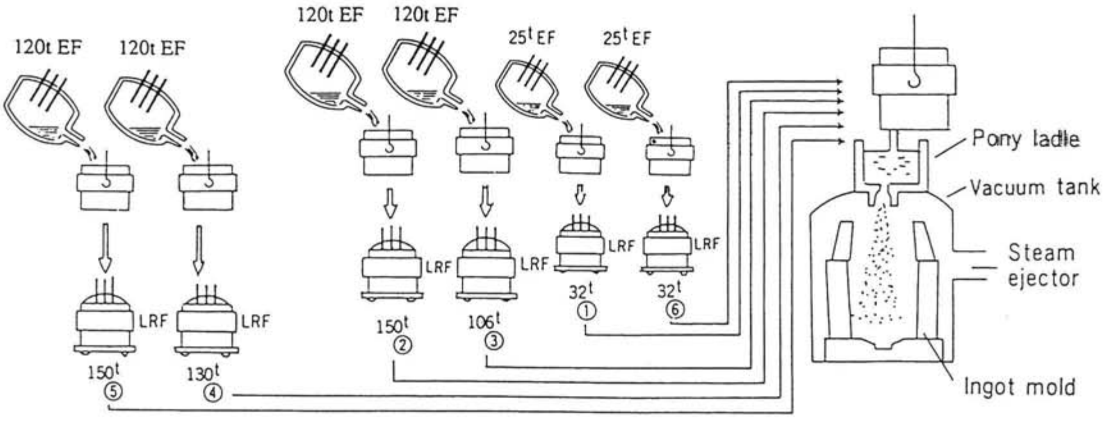


Fig. 2 Manufacturing process for 600 tons ingot

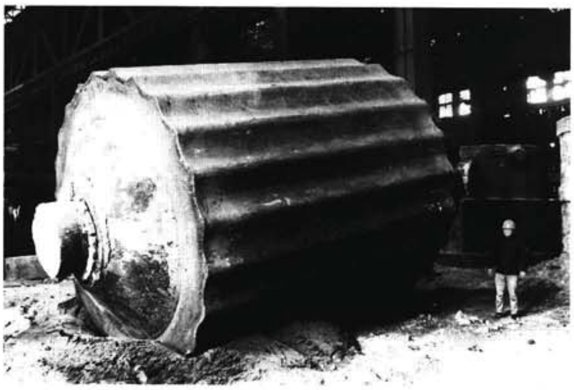


Photo. 2 Appearance of 600 tons ingot

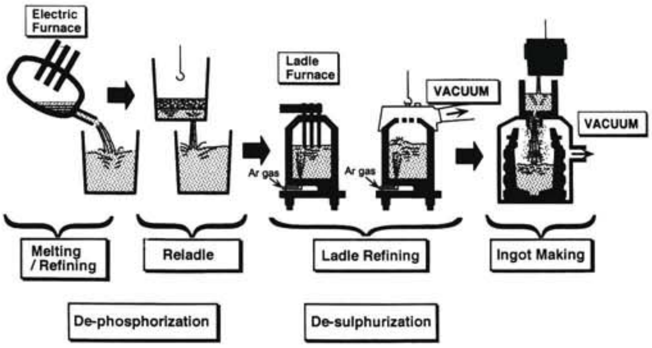


Fig. 3 Melting, refining and ingot making process of high purity steel

double degassing. With application of ladle refining technology, impurity elements contents in the steel were decreased remarkably. As described later, superclean steel is also manufactured by application of this process.

As a secondary refining equipment by remelting, an ESR with capacity of 20 tons was installed in 1963, and has been applied to manufacturing of 18Mn18Cr retaining ring and others. In 1992, an ESR equipment with maximum melting weight of 100 tons and maximum mold diameter of 1.8m was installed and started the operation. This domestically largest ESR equipment is being used for manufacturing of large scale integrated high pressure-low pressure (HLP) combination rotor and latest heat resistant 12Cr rotor. Also, a 5 tons vacuum induction melting furnace(VIM) was installed in 1992, and is utilized for manufacturing of heat resistant alloys.

Fig. 4 and **Fig. 5** show, as examples of progress of refining technology, a history of contents of impurity elements (P, S) in rotor material, and history of values of elongation and reduction in area in tensile test, respectively$^{13)}$. Decrease in S content as shown in **Fig. 4** evidently contributes to increase in elongation and reduction in area, and elimination of anisotropy as shown in **Fig. 5**.

As described above, currently a manufacturing technology for sound and high purity large steel ingot is established.

2.2 Forging technology

In forging process, it is necessary to eliminate the solidification structure of ingot by use of high temperature diffusion and by plastic deformation as well as to attain an integrity in inner property by consolidation of cavities formed in the ingot. At the Muroran Plant, in addition to 10,000 tons hydraulic press,

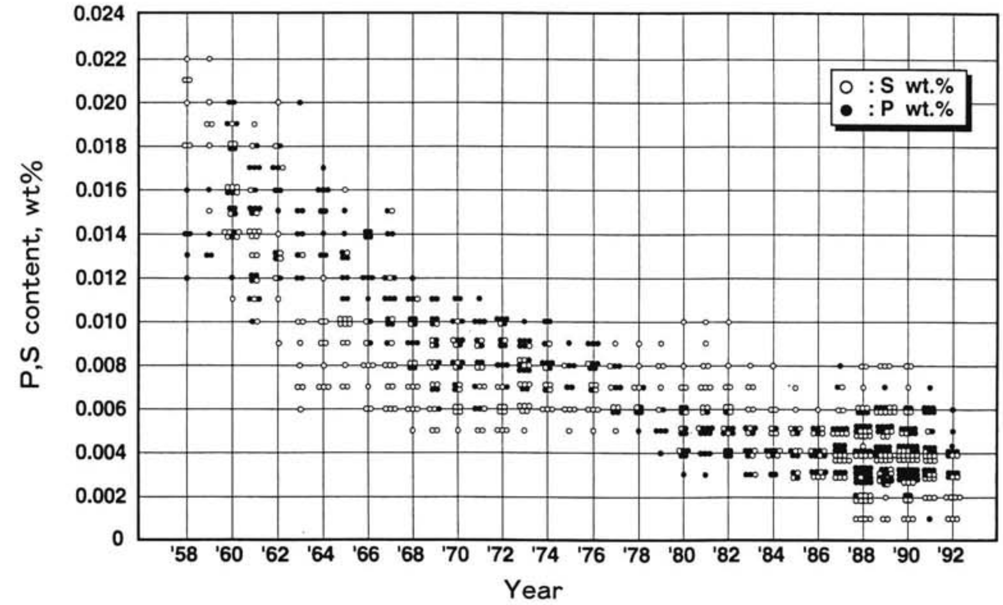


Fig.4 A history of contents of impurity elements P and S in rotor material

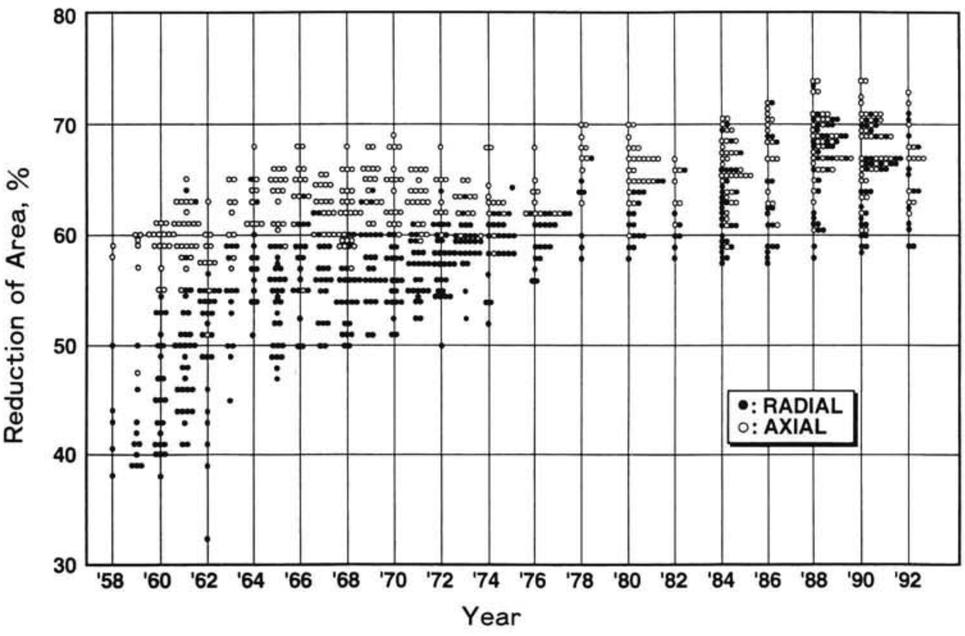


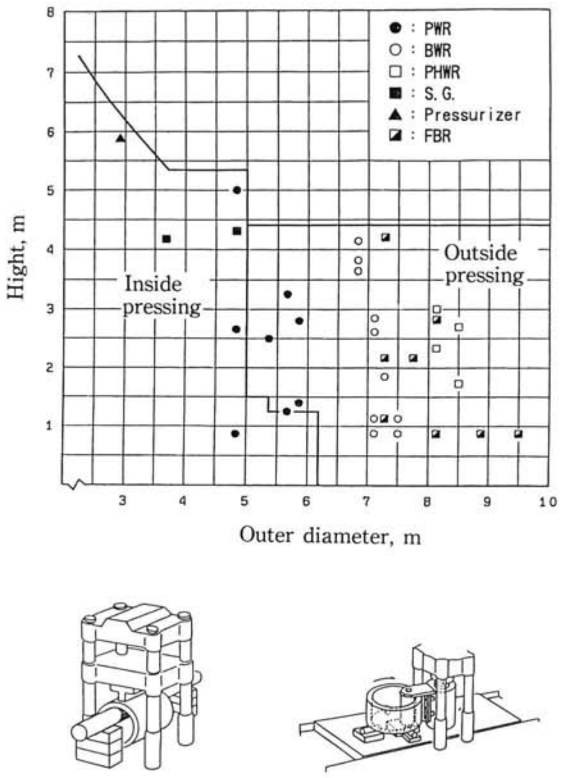
Fig. 5 A history of reduction in area and its anisotropy in tensile test of rotor material

which started operation in 1940, and 8,000 tons press, installed in 1970, an oil hydraulic press of 3,000 tons, capable of automatic operation with computer control was installed in 1988. With increase in ingot size, cavities are susceptible to arise in ingot. At the same time, the stress and strain, that are needed for consolidation of cavities are difficult to reach at the center of the material. Therefore special forging technology needs to be applied to large ingot. In 1959, a kind of warm forging process (JTS Process) was developed as a method to consolidate cavities in large ingot[14]. The JTS process, by cooling a uniformly heated material to surface temperature of about 800℃, develops temperature difference between interior portion and surface portion of the material, and with utilization of the resultant difference in flow stress between interior and outer portion, gives larger forging effects to interior portion. Later, as a forging method for ultra large ingot for monoblock low pressure rotor, upseting forging technology was improved. Recently, application of finite element method (FEM) analysis to problems in plastic deformation has become general, and it has become possible to analyze and quantify the conditions for consolidation of cavities in accordance with product shapes[15,16].

On the other hand, some components for large scale pressure vessel has become too large to be forged inside of press machine, and then equipment has been developed to perform forging outside the press with use of 10,000 tons press[17]. **Fig. 6** shows, with regard to forming of pressure vessel ring, its forming method, possible size of forging, and actual record. **Photo. 3** shows appearances of inside and outside press machine forging.

2.3 Heat treatment technology

In heat treatment process, optimum heat treatment conditions to cope with increasing size of forgings and higher degree of quality were examined and applied. In monoblock low pressure rotor which has body diameter as large as about 3 m, the issue is an inspectability of the forging by ultrasonic examination. In order to attain good inspectability, it is important to obtain fine grain structure so that ultrasonic wave has good penetration. Refining of grain in NiCrMoV steel is done with reverse transformation and recrystallization due to austenitization. In case of large shaft component, several times of austenitization is done to attain fine grain microstructure. In rotating body like steam turbine rotor shaft, it is necessary to have uniform microstructure in order to prevent vibration during service. In order to obtain homogeneous microstructure, heat treatment in vertical furnace and rotation heat treatment are conducted. Since in integrated high pressure-low pressure rotor used in combined cycle power generation and indivisual power generation plants, high temperature strength is required at high pressure portion and high strength together with high toughness is required at low pressure portion, differential heat treatment as shown in **Fig. 7** was developed. High pressure portion is cooled in air after heating to high temperature, and

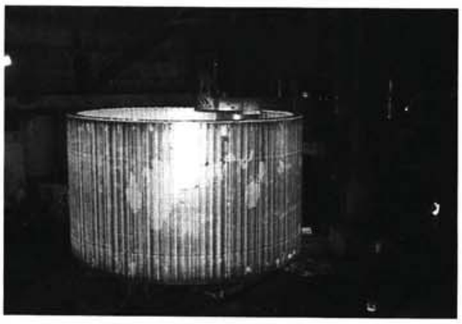


Inside pressing

Outside pressing

Fig. 6 Manufacturing capacity for rings and representative manufacturing records

a) Inside pressing



b) Outside pressing

Photo. 3 Forging of large ring components

Photo. 4 Quenching of high pressure-low pressure combination rotor

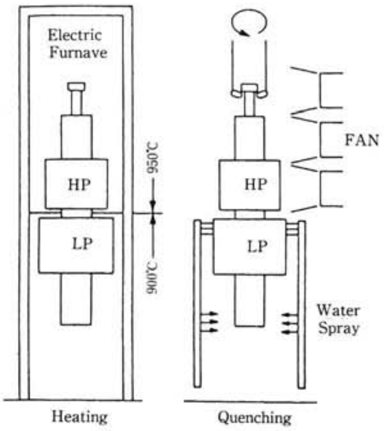


Fig. 7 Schematic diagram of differential heating and differential quenching

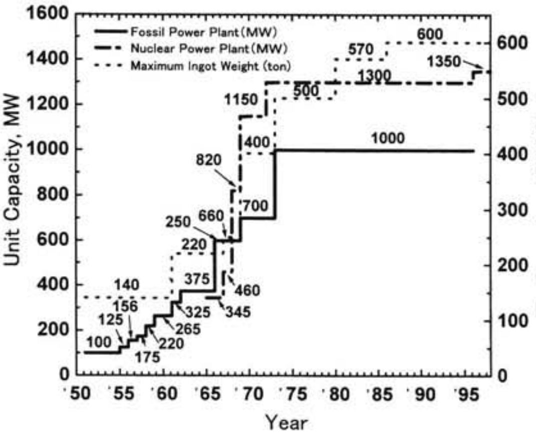


Fig. 8 A history of unit power generation capacity in power plants of Japan

low pressure portion is water cooled from relatively low temperature. **Photo.4** shows a high-pressure and low-pressure combination rotor immediately before differential quenching. In recent years, it has become possible to predict the characteristics after heat treatment like quenching and tempering in large steel forgings by FEM simulation.

3. Progress in Components for Energy Service

3.1 Turbine rotor shaft components

At the Muroran Plant, though shaft materials for generator have been manufactured since before world war two, remarkable enlargement of power plant components progressed with support from increase in energy demands in high economic growth

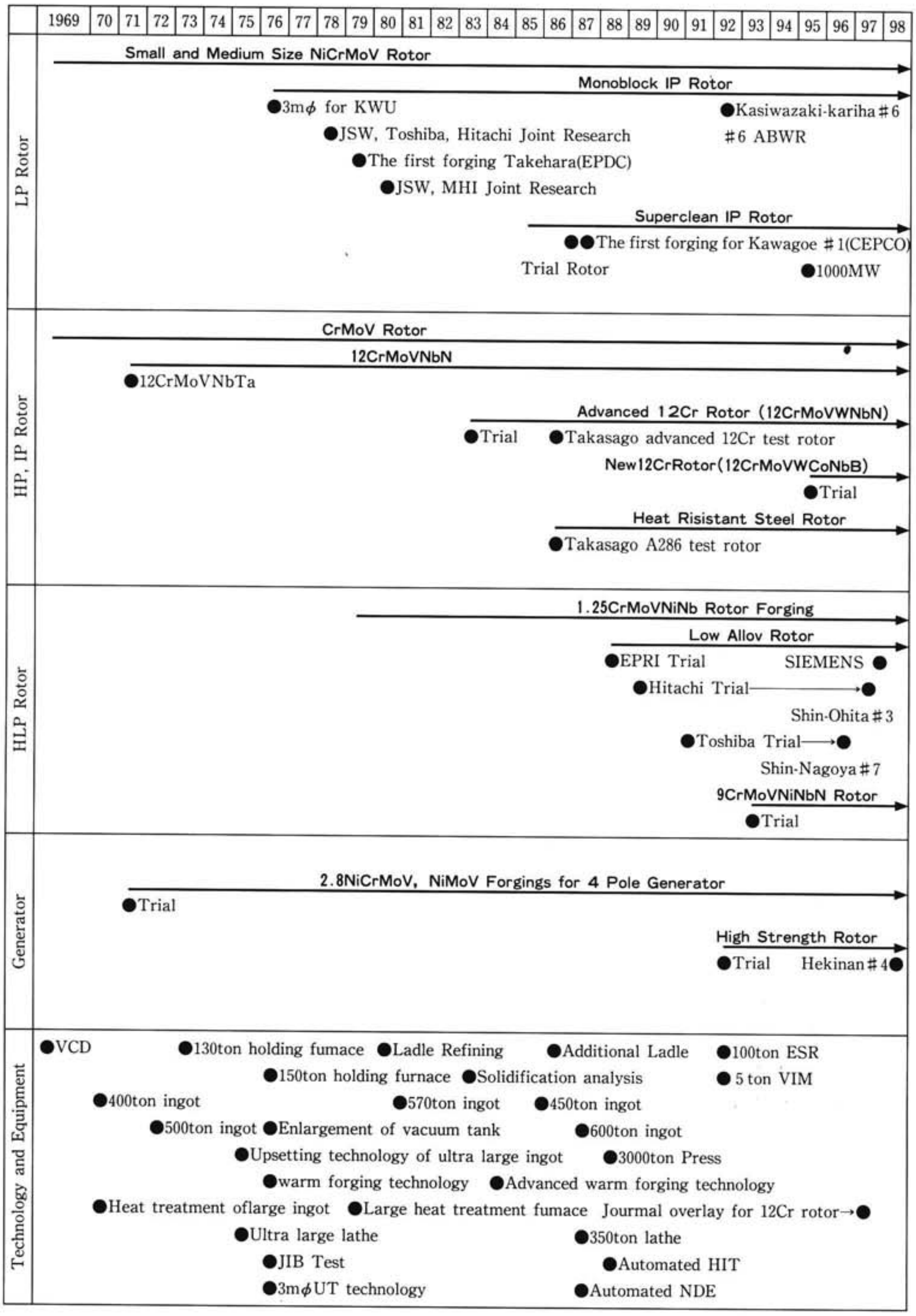


Fig. 9 Progress of steam turbine rotor and manufacturing technology

period after the war. **Fig.**8 shows a history of maximum unit capacity of power plants in Japan[12]. Drastic increase in capacity of fossil power plant began in late 1960s, and the capacity reached 1,000MW in early period of 1970s. On the other hand, capacity of nuclear power plant also increased remarkably from late 1960s to early 1970s, and in early period of 1970s were already built plants of class of 1,300MW. More recently ABWR plant with output of 1,350MW, the largest one in the country, has started operation. In order to realize these large capacity plant, it was necessary to have larger rotor and generator with higher reliability. **Fig. 9** shows developments of power plant components together with history of equipment. In 1970, when a high vacuum equipment according to steam ejector was introduced, VCD technology was established, and low Si NiCrMoV steel low pressure rotor, that had less susceptibility to temper embrittlement and lower degree of segregation, was manufactured. In the year was established a manufacturing technology for 400 tons ingots[19], and large body diameter four poles generator shaft for half speed machine in nuclear power plant was manufactured[9]. Also in case of low pressure rotor, a design to change the disc from shrunk fit type to monoblock one was started. With establishment of 400 tons ingot manufacturing technology, an integration of large scale low pressure rotor became possible[20-22]. For a practical use, a monoblock low pressure rotor for West Germany was manufactured in 1976[20], and became a forerun for later gigantic monoblock rotor forgings. Entering 1980s, in order to cope with fuel cost issue and global environmental problems, higher efficiency in power plant was directed, and materials development toward steam temperature beyond 593 ℃ was initiated[23]. With regard to low pressure rotor, in order to decrease susceptibility to temper embrittlement, a development of superclean steel in which impurity elements like Si, Mn, P, and Sn were reduced to an extreme was conducted. In 1985, a superclean 3.5NiCrMoV steel trial rotor was manufactured as a joint program with turbine manufacturer[23-25]. As for high temperature rotor, manufacturing technology for an advanced 12Cr rotor with W alloying and A286 alloy high pressure rotor to cope with main steam temperature of 650℃ was established[26]. On the other hand, in 1990s, a development of integrated high-pressure low-pressure rotor by using alloy steel for steam turbine of large capacity combined cycle plant was conducted together with turbine manufacturers[27-36], and practical machine was manufactured in 1995[30]. More recently, a development of ferritic materials for high and intermediate pressure rotors that can stand operation at main steam and reheated steam temperature of 630 to 650℃ are being conducted since ferritic steel is superior in respects of operation and manufacturing characteristics[37-39]. Also in aspect of reliability evaluation technology, assessment technologies including thermal stability test for rotating shaft component[40-45], and internal pressure burst test (JIB Test) with use of center core have been established[46-50], contributing to stability of quality and to higher reliability.

Followings are four major developments of recent times.

(1) Development of manufacturing technology for integrated low pressure turbine rotor.

Since late 1960s, nuclear and fossil fuel power plant increased the capacity remarkably. Nuclear power plant, where increase of capacity progressed very rapidly, required four poles generator rotor having a very much larger shape than two poles one as a half speed machine (body diameter for two poles machine is about 1m, and the one for four poles is about 1.8m), and further required larger low pressure turbine rotor. At the time, for manufacturing of large low pressure turbine, a structure of spindle and shrink fit discs as shown in **Fig. 10(a)** or welded type (mainly used in Europe) which was constructed by combining components manufactured from medium and small ingots as shown in **Fig. 10 (b)** had been adopted[51]. At the Muroran Plant, manufacturing technology for 400 tons ingot, the world largest at the period, for large scale component such as four poles generator had been established in 1969[19]. In 1970, there was a proposal from Kraftwerk Union (KWU) of West Germany to change the shrink fit type rotor which was likely to subject to high stress by reason

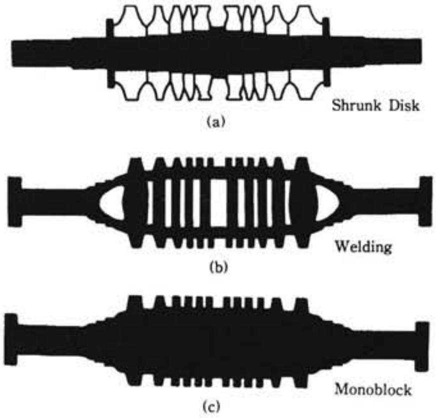


Fig. 10 Typical structure of large rotor forging

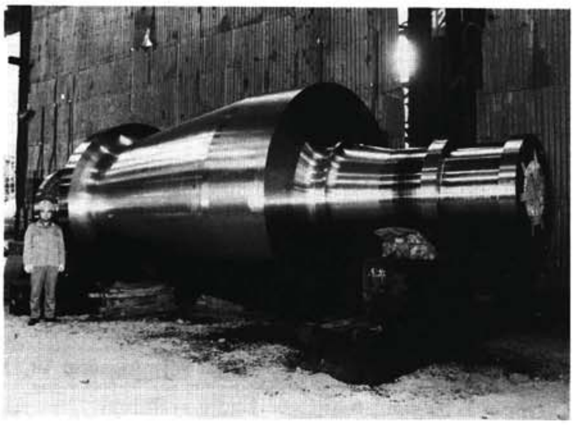


Photo. 5 The first large monoblock LP rotor forging for FRG

of the structure and to vibration, to monoblock type. Thus started a project toward realization of ultra large monoblock low pressure rotor as shown in **Fig. 10(c)**. A monoblock type low pressure rotor with maximum body diameter of 2,950mm was produced in 1971, and results of various evaluation tests proved its superior characteristics⁹⁾. **Photo. 5** is the monoblock type low pressure rotor of 2.8NiCrMoV steel completed and shipped to West Germany. For domestic plant, the first monoblock rotor forging was delivered to Takehara Plant of Electric Power Development Corporation in 1979. Later, entering 1980s, nuclear plants in United States and Europe have suffered, in many occasions, from stress corrosion cracking in discs subjected to shrunk fitting. The damage was considered to be caused by that because shrunk fitting portion is subjected to high stress, disc material have high strength, and it have by structural feature, stress concentration portion such as key way. Accordingly, the monoblock type low pressure rotor, that can be made to be of lower strength material and eliminate high stress concentration portion, became adopted as replacement rotor for existing plant or low pressure rotor for newly built nuclear power plant(19,22). Essential points in manufacturing are to produce sound large ingot with uniform properties, to give sufficient forging effect into center of large shaft of body diameter as large as 3 m, to achieve uniform strength and ductility, and high toughness in shaft material, to attain good inspection characteristics into inside of large body shaft material, to decrease residual stress and others, and ultimate level of technology for ultra large forging has been applied. In 1992, largest diameter integrated type low pressure rotor forging was manufactured with body diameter at time of completion of 2,800mm for 1,350 MW ABWR plant at No. 6 and No. 7 of Kasiwazaki-Kariha of Tokyo Electric Power Co. and cumulative number of shipment of the rotor as of April 1998 amounts to 145 pieces. With application of superclean technology to 600 tons ingot, to be described later, a monoblock type low pressure steam turbine rotor forging was also manufactured(52,53). Its appearance is shown in **Photo. 6.**

(2) Superclean low pressure rotor forging

NiCrMoV steel, which is widely used for low pressure steam turbine rotor was highly susceptible to temper embrittlement depending on contents of impurities like P and Sn. Prominent embrittlement occurs when the steel is used between 350 and 550℃ (54-56). Therefore until recent time, service tem-

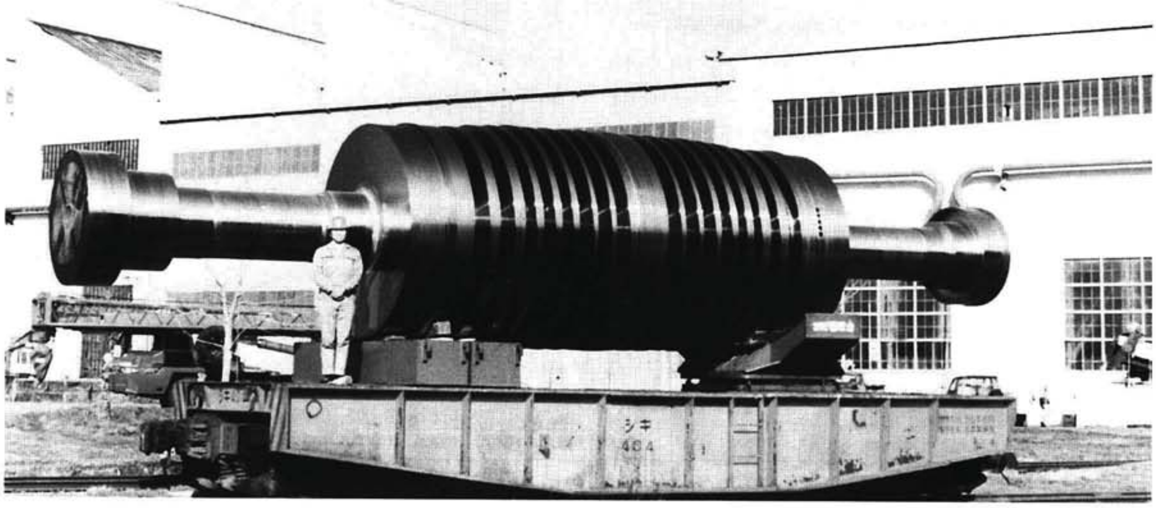


Photo. 6 Superclean monoblock LP rotor shaft

perature of low pressure turbine was limited to below 343℃ at which no significant temper embrittlement progressed[57]. On the other hand, from 1980s at fossil fuel power plant, ultra super critical power plant with higher efficiency by increase in main steam and/or reheat steam temperature and pressure was programmed as measures for decrease in fuel cost and for global environmental issue accompanying the carbon dioxide exhaust. In low pressure rotor, the minimization of susceptibility of base material to temper embrittlement became an important issue to cope with higher operating temperature.

In order to decrease susceptibility to temper embrittlement, it is essential to use high purity steel, and especially to decrease impurity elements like P and Sn that affect temper embrittlement. At that time, a joint research was progressing with Electric Power Research Institute (EPRI) of United States with respect to elimination of temper embrittlement susceptibility of various steels[58]. With a viewpoint that it is necessary to decrease the parameter J factor[59] :$J=(Si+Mn)(P+Sn)10^4$ to below 10 in order to prevent temper embrittlement of 3.5NiCrMoV steel, lower Si was applied by using VCD technology that had been industrialized already in manufacturing of low pressure rotor forging and further reduction of impurity elements such as P, Sn, As and Sb was made. Furthermore, Mn, that was added with aim of S scavenging and deoxidation, was also reduced[60]. As the result, J-factor yields around 4. This high purity steel is of extremely lowered content of impurity elements like Si, Mn, P, Sn, As, Sb, Cu, and Al, and gas contents like O and H, and was named superclean steel[60]. **Table 1** shows methods to achieve reduction of impurity elements **Table 2** shows a guideline of superclean 3.5NiCrMoV steel composition set by EPRI[60]. With regard to large rotor, trial forging of low pressure rotor with diameter of actual machine was made in 1985 as a joint program with turbine manufacturer. Thereafter its superior characteristics was clarified by evaluation in turbine manufacturers, forgemasters and EPRI[24,25,57,61]. The special features of manufacturing of superclean steel consisted of reduction of impurity elements like As, Sn, Sb, and Cu by very tight selection of raw materials, and of reduction of Mn by high degree of oxidation refining in electric furnace in addition to application of latest refining technology by ladle furnace[25]. **Fig. 11** shows a change of Charpy fracture appearance transition temperature (FATT) according to isothermal aging at temperature range of 343 to 454℃ in superclean 3.5 NiCrMoV steel. As compared to isothermal aging test up to 100,000 hours in conventional shaft steel which was manufactured in early period of 1970s[55], it has been proved that the superclean steel did not cause temper embrittlement, and high degree of reliability is held even the steam temperature is increased. In addition to the above, superior characteristics of superclean steel is confirmed in areas including low cycle fatigue[61], corrosion resistance[62] and high temperature strength[61]. Therefore, superclean steel has became to be applied not only for measures against temper embrittlement, but also for measures to protect corrosion fatigue and so on. The steel has also applied to other high temperature component like gas turbine disc. In 1988, superclean rotor forging was manufactured for the first ultra super critical

Table 1 Attainable impurity content (wt%)

	Attainable range	Technology and process to be applied
Mn	0.03max.	Oxidizing refinig in EF → reladle
Si	0.03max.	Oxidizing refinig and VCD
P	0.003max.	Oxidizing refinig in EF → reladle
S	0.002max.	Ladle refining
Sn	0.005max.	Selection of raw material
As	0.006max.	ditto
Sb	0.0015max.	ditto
Al	0.005max.	VCD
H	1.0 ppm max.	Duoble vacuum treatment
O	30 ppm max.	Ladle refining and VCD
N	50 ppm max.	Ladle refining

Table 2 Target and specified composition for superclean 3.5NiCrMoV steel by EPRI

	wt% (ppm for H, O and N)															
	C	Si	Mn	P	S	Ni	Cr	Mo	V	Al	As	Sm	Sb	H	O	N
EPRI Aim	0.25	0.02	0.02	0.002	0.001	3.50	1.65	0.45	0.10	0.002	0.002	0.002	0.001			
EPRI Spec.	0.30 max.	0.03 max.	0.05 max.	0.005 max.	0.002 max.	3.75 max.	2.00 max.	0.50 max.	0.15 max.	0.005 max.	0.005 max.	0.005 max.	0.002 max.	1.5 max.	35 max.	80 max.
ASTM A470 Cl.7	0.28 max.	0.10 max.	0.20 ~0.60	0.015 max.	0.018 max.	3.25 ~4.00	1.25 ~2.00	0.25 ~0.60	0.05 ~0.15	—	—	—	—	—	—	—

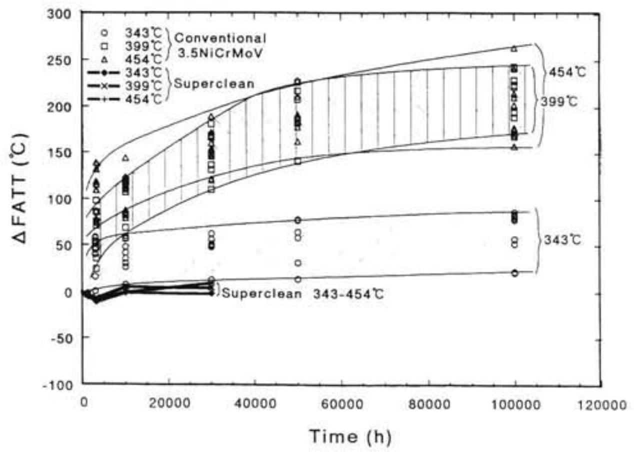


Fig. 11 Change in FATT by isothermal aging in conventional steel and superclean steel

power plant of No. 1 unit of Kawagoe Power Plant of Chubu Electric Power Co. (**Photo. 7**), and later 30 pieces of superclean rotor forging have been manufactured[52,53] as of April of 1998 including the monoblock type low pressure rotors from 600 tons ingots (**Photo. 5**).

(3) High pressure-low pressure (HLP) combination rotor

While high pressure-low pressure combination rotor (HLP rotor) was utilized mainly in small scale independent power generating plant, recently it has been much more utilized as steam turbine in large capacity combined cycle plant, and as for larger output independent power generating plant. The merit of integrating high pressure turbine and low pressure turbine could be cited to be saving of construction space and construction cost, and ease of maintenance. However, as characteristics of the material, it is required to possess superior high temperature strength at high pressure side where the steam temperature is higher, and high strength and high toughness, at low pressure side with large body diameter in order to bear increased centrifugal force due to longer blades and larger body diameter. Generally, creep strength and toughness are conflicting properties, and alloy design of the material to fulfill both properties in superiority was the important point in the development of high pressure-low pressure combination rotor. For recent advanced type combined cycle power plant (ACC Power Plant), several low alloy steels with addition of Cr and Ni more or less than 2% has been developed. JSW conducted a development of low alloy steel rotor and manufacturing of trial rotor forging as a joint program with turbine manufacturers[27-29], and evaluated the characteristics. Representative chemical compositions of trial rotors that was manufactured by JSW are shown in **Table 3**. The trial rotor was investigated in details and a good balance of strength and toughness, which is sufficient to cope with larger body diameter, was revealed at center of low pressure portion. At high pressure portion, a creep rupture strength exceeding that of CrMoV steel was also revealed[27-30]. As of April 1998, eleven pieces of high pressure-low pressure combination rotor that was developed have been delivered for ACC power plants. Essential points in achieving the required quality include the application of differential heating and quenching, as shown in **Fig. 7**, due to requirement of different characteristics as of creep strength and low temperature toughness at high pressure portion and low pressure portion respectively. Additionally, with regard to alloy composition, a deliberate consideration for ingot making was needed to cope with easy enrichment and segregation of C in center portion[2]. **Photo. 8** shows appearance of high pressure-low pressure integrated rotor for Shin-Nagoya ACC of Chubu Electric Power Co. **Fig. 12** shows a relationship between tensile strength and fracture appearance transition temperature (FATT) at center of the low pressure portion in the developed low alloy steel rotor[34,35], the balance of strength and toughness is remarkably superior to that of CrMoV steel. In the near future, larger scale in high pressure-low pressure combination rotor could be needed and in order to realize it, it is required to improve the balance of strength and toughness further still with the creep strength of the present high pressure-low pressure

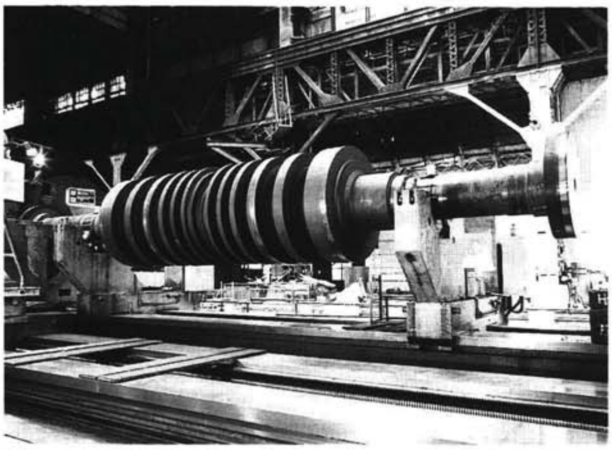


Photo. 7 Superclean low pressure rotor forging for Kawagoe #1 of Chubu Electric Power Co.

Table 3 Chemical composition of the trial HLP rotors (wt%)

			C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Al	Nb	As	Sn	Sb
A	2.5NiCrMoV	Aim	0.24	0.05 max.	0.05 max.	0.004 max.	0.0020 max.	2.50	1.60		1.20	0.25			0.008 max.	0.010 max.	0.0050 max.
		Ladle	0.23	0.03	0.03	0.003	0.0010	2.50	1.60	—	1.20	0.24	—	—	0.002	0.003	0.0010
B	2.25CrNiMoVWNb	Aim	0.24	0.03 max.	0.50	0.003 max.	0.0015 max.	1.70	2.25	0.05 max.	1.10	0.20	0.005 max.	0.015	0.006 max.	0.005 max.	0.0015 max.
		Ladle	0.24	0.02	0.45	0.004	0.0009	1.69	2.22	0.04	1.08	0.19	0.005	0.015	0.004	0.004	0.0010
C	0.2Mn1.8NiCrMoV	Aim	0.20 ~ 0.26	0.05 max.	0.15 ~ 0.25	0.010 max.	0.0100 max.	1.70 ~ 1.90	1.90 ~ 2.10	0.10 max.	1.10 ~ 1.30	0.23 ~ 0.30	0.008 max.		0.008 max.	0.010 max.	0.0050 max.
		Ladle	0.23	0.01	0.20	0.004	0.0020	1.74	2.03	0.03	1.17	0.26	0.003	—	0.003	0.003	0.0010

combination rotor material for ACC . JSW has developed a high purity 9 % CrMoVNiNbN steel as a next generation steel based on 9 % CrMoV steel having good hardenability[34,35]. As a result of evaluation of trial rotor with scale of actual machine, as shown in **Fig. 12**, it has been verified to have much better balance of strength and toughness at low pressure portion than the low alloy steel rotor[34,35]. Using this steel, it has become possible to have the FATT of around 0℃ at center of low-pressure portion of body diameter 2,000mm and at tensile strength of 900 MPa. Then larger scale in high pressure-low pressure integrated rotor of future is considered to be feasible.

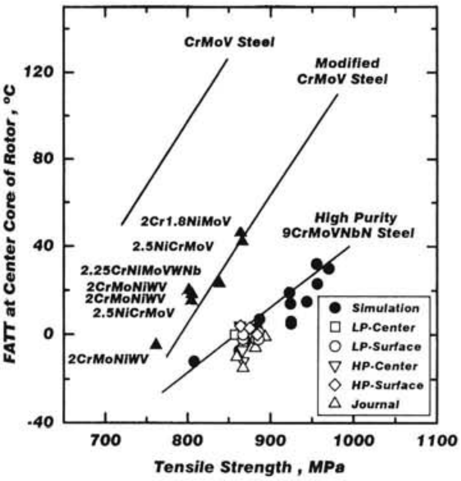


Fig. 12 Balance of strength and toughness in various HLP rotor material

(4) 12Cr, advanced 12Cr and new 12Cr rotor

In accordance with increase of efficiency of fossil power plant, steam temperature in high and/or intermediate pressure rotor has increased. However the CrMoV steel, that had been conventionally used as high or intermediate pressure rotor, was approaching to a limit in terms of high temperature strength. The situation had been recognized since 1960s[64], and GE was soon to begin to use 12CrMoV steel for these high temperature rotors. JSW also has manufactured 12Cr steel rotor forging for domestic power plants since the first 12CrMoVTaN steel rotor in 1971. In 1985, turbine manufacturers conducted development of advanced 12Cr steel rotor that possessed superior high temperature strength than conventional 12Cr steel rotor, as a intermediate pressure rotor material for ultra super critical power plant with steam temperature of 593℃ [65]. As a joint program of electric power companies and turbine manufacturer, an evaluation of three steel grades was conducted. JSW manufactured trial rotors of actual scale in two grades of steel in the joint program. On the other hand, another joint program for ultra super critical power plant (Phase 1) was conducted with Electric Power Development Co., Ltd. as its chief member. In its Phase 2, a steam condition of main steam temperature of 650℃ and of reheat temperature of 593℃ was investigated[66]. At the time, the high pressure rotor to comply with 650℃ was set to be austenitic heat resistant alloy of iron base, A286 , and use of

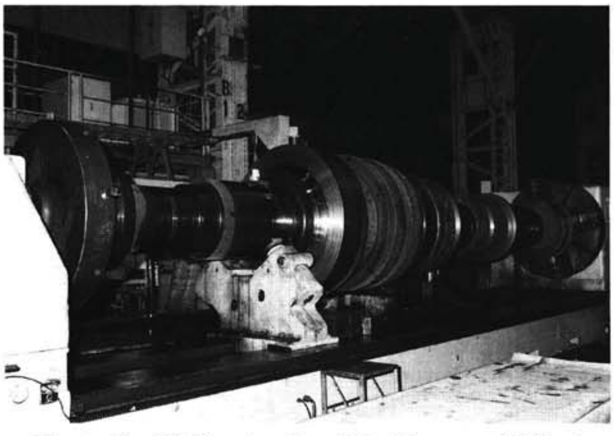


Photo. 8 HLP rotor for Shin-Nagoya ACC of Chubu Electric Power Co.

advanced 12Cr steel was considered for intermediate pressure rotor to meet 593℃ steam condition. JSW manufactured A286 rotor as high pressure rotor to be used for rotating test at Takasago Power Plant to be conducted by joint program with Electric Power Development Co., Ltd. and an advanced 12Cr steel rotor as intermediate pressure rotor. From 1985 to 1993, rotation test and evaluation were conducted at Takasago Power Plant and Matsuura Power Plant of Eiectric Power Development Co., Ltd. As the results, the advanced 12Cr steel in compliance with 593℃ was evaluated to be able to be used with no problem. On the other hand, with regard to A286 alloy, creep fatigue damage accompanying start and stop of operation was found to be large due to low thermal conductivity inherent with austenitic steel and due to large thermal expansion. In addition to this, due to higher manufacturing cost, the application of A286 rotor was judged to be too early[67]. With this development of events, for realization of ultra super critical pressure plant with steam temperature of 650℃, it has become essential to develop ferritic steel rotor capable of coping with operation at 650℃. Currently JSW is also conducting a joint program with turbine manufacturers. Alloy design of new 12Cr rotor is based on fore running research by Professor Emeritus Fujita of University of Tokyo[68,69], and improvement of high temperature strength has been sought by alloying with W, Co, B, and others. Together with a domestic turbine manufacturer, a intermediate pressure trial rotor for class of 1,000MW was manufactured from ESR ingot weighing about 80 tons, and its characteristics are being investigated. The results suggested that creep strength for 100,000 hours at 100 MPa, a base for operating temperature in intermediate pressure rotor, was 630 to 650℃ (advanced 12Cr Steel has about 600℃), proving that operation is possible at this steam temperature. In the future, a conduction of a rotation test at 650℃ by test rotor is scheduled as Joint Program Phase 2 of Electric Power Development Co., Ltd.[70]. Though these materials should continue to have evaluation including long period stability, it is considered to largely contribute to realization of next stage ultra super critical power plant.

Recently, for prevention of adhesion in bearing portion of 12Cr steel rotor, a technology of overlaying low alloy steel as a substitute of conventional shrunk fitting of low alloy steel sleeve was established, contributing very much to higher reliability of earing portion[71].

3.2 Nuclear power plant

Upon construction of Japan's first commercial nuclear reactor, Tokai No. 1 Calder Hall type reactor of The Japan Atomic Power Company, the most important component steel plates for pressure vessel were imported from England, but as the results of inspection, many defects were found. To substitute this, JSW delivered steel plates for the nuclear reactor pressure vessel with no problem at all in the quality, and the case became a beginning to delivery of nuclear plant component[72]. As the material for nuclear reactor pressure vessel of superior toughness, low susceptibility to neutron irradiation embrittlement and superior weldability is required. Continuing efforts for improvement of component quality as well as material quality have been made by application of the most advanced manufacturing technology such as attainment of higher purity. JSW has been involved with enlargement of RPV and integration in order to improve reliability and safety of vessel by minimization of weld seams in the whole vessel[73-80]. **Fig. 13** shows a history of nuclear pressure vessel components with their integration. In 1966, forged ring with plate thickness of 270 mm of ASME SA336 steel was manufactured and evaluated[73]. As commercial nuclear reactor pressure vessel component, a forged flange for Tsuruga No.1 unit of The Japan Atomic Power Company was manufactured in 1969. Further, in 1972, in order to produce large component of size too big to be forged within the press, an outside machine forging process (**Fig. 6**) was industrialized, and was applied to manufacturing of a ring with outer diameter of 5,780 mm and height of 2,500 mm for Biblis-B PWR of West Germany from 400 tons ingot (**Photo. 9**)[82]. In the year were installed ladle furnaces of 150 tons and 130 tons, and ladle refining and double degassing process were applied also to manufacturing of nuclear reactor pressure vessel material. In 1980, pressure vessel shell ring material with outer diameter of 4,890 mm and height of 2,900 mm for core region of Tsuruga No. 2 PWR of The Japan Atomic Power Company was integrated[81], and the similar design was applied to later plants. With regard to BWR, similarly, reactor core region shells for such as 1,100 MW plants of Kashiwazaki-Kariha No. 3 and 4 of Tokyo Electric Power Co. became integrated forgings. Since the pressure vessel rings at reactor core region subject to neutron irradiation, it is desirable to reduce impurity elements like P and Cu that cause irradiation embrittlement. Therefore the higher purity was sought by severe selection of raw materials and application of ladle refining,

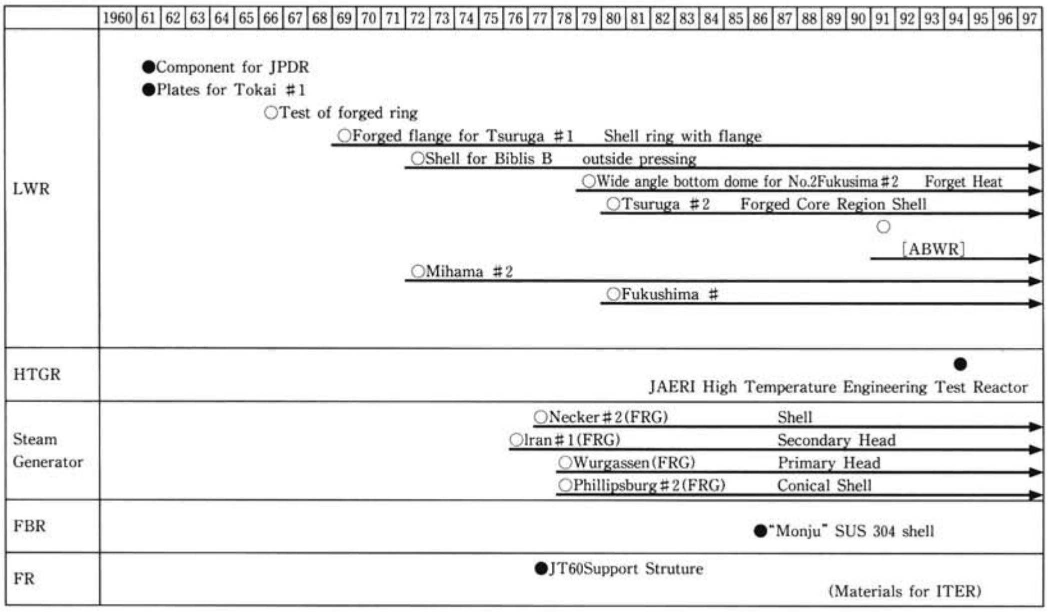


Fig. 13 A history of various components of nuclear pressure vessel

Photo. 9 Shell for Biblis-B PWR

resulting to realization of superior toughness and lower susceptibility to neutron irradiation embrittlement[83]. With regard to austenitic stainless steel to be used as structural material for nuclear reactor, development of manufacturing technology to cope with larger scale and integration was also progressed[84,85]. From 1985 a large scale stainless steel forging was manufactured for fast breeder reactor prototype, "Monju"[86].

In 1991, for the first advanced type BWR (ABWR) in Japan, Kashiwazaki-Kariha No. 6 and No. 7 unit of Tokyo Electric Power Co. was delivered a bottom petal made of ingot weighing 600 tons and various other components[79].

While the forged heads are manufactured by hot working on a large diameter circular plate by press, with establishment of outside machine forging technology for large diameter forged plate and of hot bend forming technology, a bottom dome for Second Fukushima Plant No. 2 (1,100MW) BWR of Tokyo Electric Power Co. was manufactured in 1979, and later the method has been applied to forged heads of many plants in the country and abroad[78]. With regard to steam generator for PWR plants, integration of components have progressed, and change to forgings has been achieved over for cases in which forming was difficult because of shape, like conical shell, secondary head and primary head[78]. **Photo. 10** shows an appearance of integrated steam generator primary head forging.

Other instances include manufacturing of high temperature engineering test reactor component using 2.25CrlMo steel for Japan Atomic Energy Research lnstutute as a new type of pressure vessel[87,88] and a development of nuclear fusion reactor material[89].

Nuclear reactor pressure vessel component requires high degree of reliability, and then research on evaluation technology for materials is also an important development theme. JSW continues efforts to evaluate reliability for extremely thick nuclear-reactor pressure vessel materials by such measures as domestically first development of dynamic elastic-plastic fracture toughness(J_{Id}) testing machine[90,91] examination of drop weight test method[92,93], develop-

Photo. 10 Integrated forging of primary head for PWR steam generator

ment of elastic-plastic fracture toughness test method in transition temperature range[94-97], establishment of prediction method of fracture toughness value[98-100], irradiation embrittlement test[83], and thermal shock test[101].

In the following will be described an outline of development of pressure vessel components for ABWR and large scale stainless steel forgimg as topics of recent developments.

(1) Advanced BWR (ABWR) nuclear power plant components[79]

While domestically the first advanced type BWR (ABWR) plant, Kashiwazaki-Kariha No. 6 and 7 of Tokyo Electric Power Co., has already been operating, JSW has progressed a examination of manufacturing of large scale forgings from the stage of concept design for pressure vessel, and has been involved with the layout of the components. In ABWR, the re-circulating pump, which had been placed outside of pressure vessel up to that time, became inner containing type, and diameter of the vessel became larger than the conventional one. The layout of pressure vessel components is shown in **Fig. 14**. Every part became very much larger. Bottom petal and other components with larger diameter and more complicated shape were manufactured from gigantic ingots. The bottom petal was manufactured from a large diameter forged ring with thickness of 1,300mm, height of 1,770mm and outer diameter of 7,750mm, which was made from 600 tons ingot (**Photo. 11**). These components are confirmed to have superior strength and toughness, and also to be superior in low temperature toughness such as RT_{NTD}. Construction of ABWR plant is planned also for future, and a technology to sufficiently cope with manufacturing of large scale forgings for the plant has been established.

2) Large scale stainless steel components for fast breeder reactor (FBR)[84-86]

For more efficient use of uranium, a development of fast breeder reactor has been conducted Power Reactor and Nuclear Fuel Development Corporation, and constructed prototype reactor "Monju" successive to experimental reactor "Joyo". JSW manufactured forged stainless steel components for its pressure vessel. Since the operation temperature of "Monju" is as very much high as about 530℃ in comparison to conventional nuclear reactor, its structural material was set to be 304 type stainless steel by taking account of high temperature strength. The pressure vessel, with dimension of inner diameter of about 7,000mm, and height of 17,780mm, is made of a world largest stainless steel forgings. While the layout of pressure vessel is shown in **Fig. 15**, the components such as rings with large diameter, large length, and small thickness, very thick flange with outer diameter of about 8,800mm and thickness of 550mm, and very thick disc, are largely exceeding the records of conventional stainless steel forgings for core internal of light water reactor. JSW organized a project team to develop its manufacturing technology. Ingot of maximum weight of 260 tons was used for pressure vessels components, and manufacturing

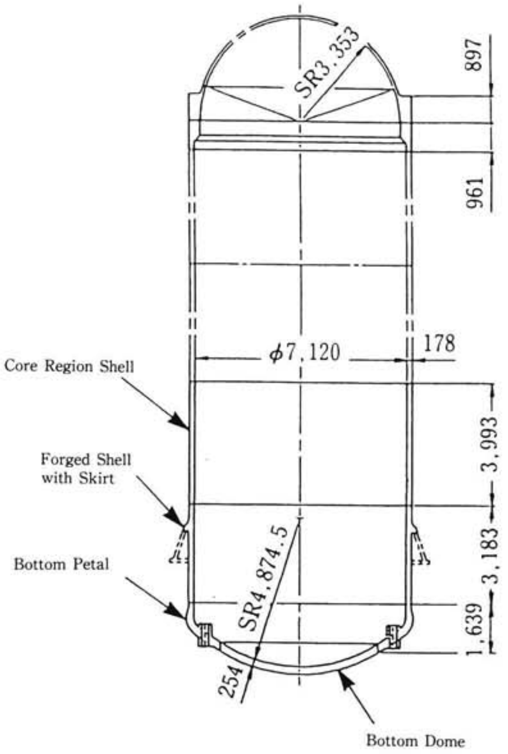


Fig. 14 Layout of ABWR pressure vessel

Photo. 11 Bottom petal for ABWR pressure vessel

Photo. 12 Final machining for intermediate shell ring for "Monju"

was done by outside machine forging process with use of 10,000 tons press. **Photo. 12** shows the appearance of intermediate shell body. In the manufacturing, in order to achieve high quality and superior inspectability, various technologies including a setting of optimum composition, large scale ladle refining furnace, higher purity and cleanliness by use of double degassing process, measures for grain refining, and prevention of heat treatment distortion were developed and applied[86].

3.3 Petroleum refinery

As the pressure vessel for petroleum refining takes various designs and materials depending on the process, here a case of large scale hydrogenation reactor which has severe operational environment of high temperature and high pressure hydrogen, will be described on its progress.

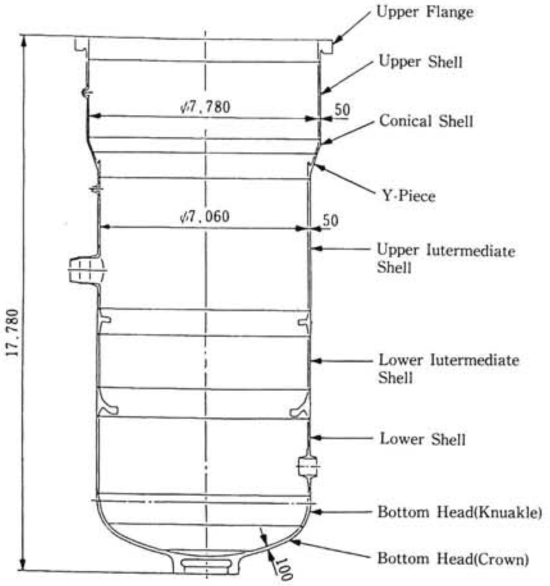


Fig. 15 Layout of components in "Monju" of prototype fast breeder reactor

It was since JSW received an order of H-Oil reactor's large scale pressure vessel for Kuwait Shaba Refinery in 1963 when the company began with much emphasis the manufacturing of large scale petroleum refining pressure vessel. The history of design and manufacturing technology to the present is summarized in **Fig. 16**[102]. Introductory period of petroleum refining process was positioned to be the first generation in the company. Though the pressure vessel at the time was manufactured by welding of formed steel plates, in 1968 the world first pressure vessel with welded structure by 3CrlMo steel forged shell ring was manufactured for NIOC Company. In that period, as a stainless steel overlay method for inner surface of pressure vessel, an overlay technology with use of stainless steel hoop was also established[103]. The 1970s is located to be second generation, investigation and improvement were done. Those are development of detection technology of damage during service[112] like temper embrittlement occurred in aged vessel[104-106], disbonding of overlay[107-108], hydrogen embrittlement[106,108-111], and hydrogen attack[107]. From the second generation, specification according to J-factor was begun for prevention of temper embrittlement[59]. During the period, VCD technology was established, and J-factor was remarkably reduced due to lower Si in base material. In the area of manufacturing technology, a manufacturing technology of partially enlarged shell and integral bottom head was developed. Structural improvement in gasket groove and internal supporting structure was made. The third generation starting from 1981 was a period when higher reliability in

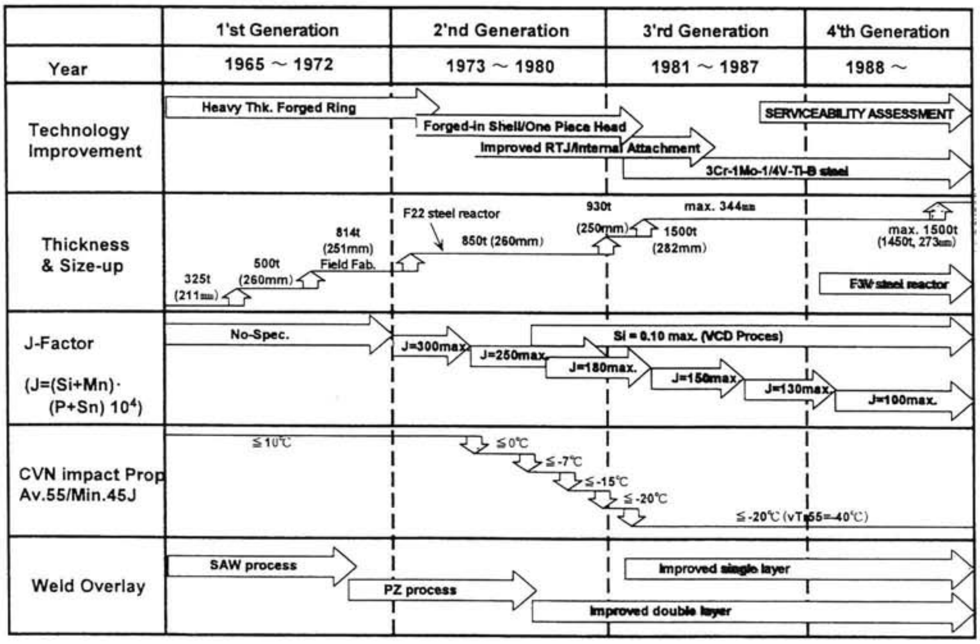


Fig. 16 History of manufacturing technology for hydrotreating reactor made of 2.25Cr1Mo steel

pressure vessel was aimed, and further reduction of susceptibility to temper embrittlement of vessel materials and improvement of toughness were achieved. During the period, development of 3Cr1Mo1/4VTiB steel, which currently has many business records as high strength pressure vessel material, was started[113-115]. Also, research on safety evaluation of aging pressure vessels, and on evaluation technology of remaining life were conducted[116-122], contributing to improvement in safety and reliability. The fourth generation is a period of replacing the equipment which subjected to damages due to long term service, and of introduction of new equipment. Knowledge on various damages of pressure vessel was further deepened, and reliability improved greatly. **Fig. 17** shows a yearly change of J-factor specification values and distribution of frequency for 2.25Cr-1Mo steel. By the application of VCD technology and ladle refining, the value has recently become below 100. This is a level at which

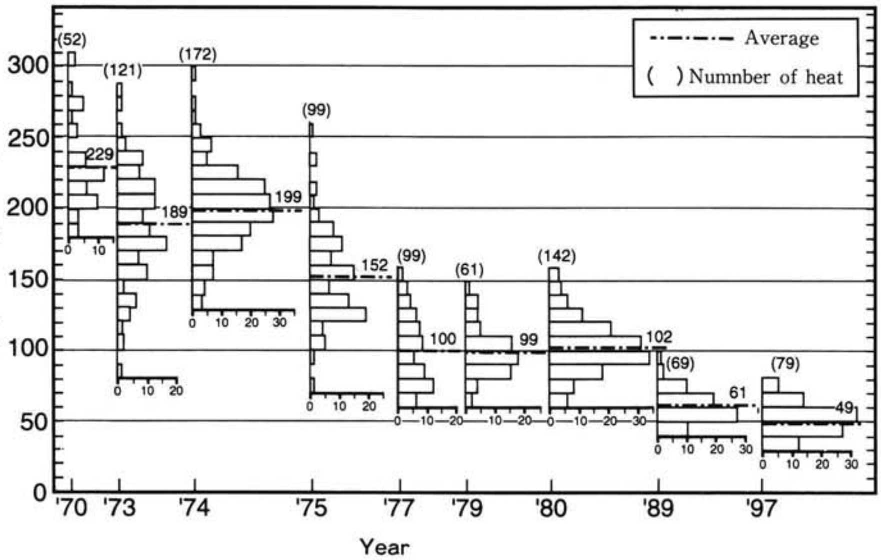
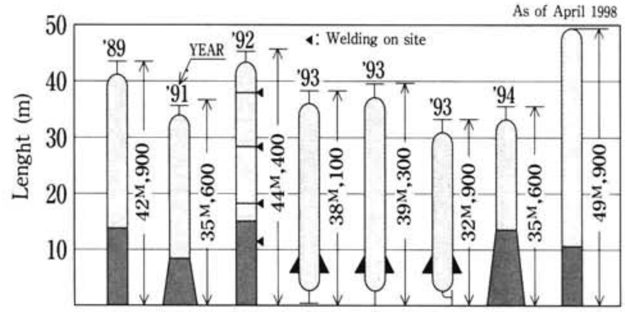


Fig. 17 Change in J-factor in 2.25Cr1Mo steel pressure vessel components

temper embrittlement nearly disappear in 2.25 Cr1Mo steel. In the fourth generation, a high strength CrMo steel pressure vessel was introduced in accordance with new processes, and production of 3Cr1Mo1/4VTiB steel for commercial plant was realized[102,123,124]. **Fig. 18** shows examples of latest large scale pressure vessels, enlargement of pressure vessel is remarkable from the third to the fourth generation, and in 1993 the largest pressure vessel weighing 1,450 tons was delivered. One of the recent important developmental issue, high strength CrMo Steel, will be described in the following.



Shell I.D.	(mm)	3,400	4,110	4,520	4,500	4,500	4,500	4,522	3,658
Shell Thickness	(mm)	229	271	296	271	273	293	285	243
Weight	(Ton)	@755	@1,080	@1,280	1,330	1,450	@1,160	@1,065	@1,080
Number		2	4	4	1	1	4	2	3

Fig. 18 Large pressure vessels recently manufactured

When the operation temperature of pressure vessel has become higher and exceeds 450℃ due to application of new processes, conventional 2.25Cr1Mo steel has a risk of hydrogen attack. Then a material equivalent to 3Cr1Mo steel is needed. On the other hand, since creep deformation occurs in this temperature range, conventional CrMo steel has its allowable stress value decreased sharply. In such a case, vessels with extremely thick wall will be required. In order to solve this problem, a development of pressure vessel material, that has superior high temperature strength and hydrogen attack resistance, was progressed since 1980[114]. **Fig. 19** shows a history of development of high strength CrMo steel reactor material in JSW. In the development project of direct liquefaction of coal in Sunshine Program of Ministry of International Trade and Industries for 5 years from 1980, manufacturing technology of pressure vessel for design condition of 200 to 300 atmospheric pressures and temperature of 480℃ including welding were established. After preliminary manufacturing and evaluation, a pressure vessel material of 3Cr1Mo1/4VTiB was developed[113-115]. The material was given a material certification and accepted for designation as ASME Code Case 1971 by ASME in 1985, and in 1989 was specified in ASME Code Sec. II and Sec. VIII as pressure vessel material (forgings as SA336F3V). The developed steel was given certification also in Germany, England, and Holland. Since F3V steel allows high design stress at high temperature, it has many advantages including enabling reduction of weight of pressure vessel. The material

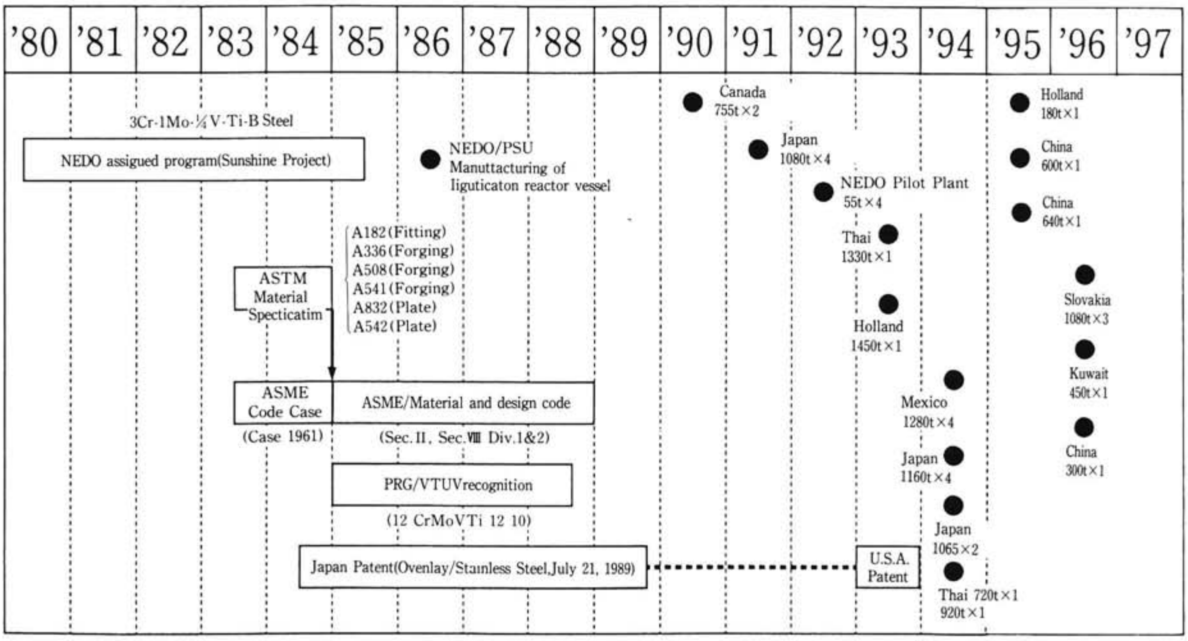


Fig. 19 A history of development of high strength CrMo steel (F3V steel)

has higher resistance to damages like hydrogen attack and hydrogen embrittlement, lower susceptibility to temper embrittlement, and better resistance to disbonding[123,124]. **Fig. 20** shows recommended limit service temperature for various CrMo steels, and it is seen that F3V steel has especially high environmental strength. The first pressure vessel made is that for coal liquefaction pilot plant of Japan which started operation in 1987, and for commercial use is for Husky Oil Company of Canada which started operation in 1992. Thereafter 38 units have been manufactured. **Photo. 13** shows a reactor made of F3V steel (weight 1,450 tons) shipped for SNR Company of Holland.

As a high strength steel for pressure vessel, there is 2.25CrMoV steel of ASME Code Case 2098. This material has environmental strength equivalent to F3V steel and allows high stress, as shown in **Fig. 20**. Project has progressed with development of welding material and is now at stage of realization. Other than these, there is 9CrMoV steel for high temperature cracking process above 510℃ which is under development.

4. Conclusion

Supported by rapid increase in energy demands after the war, forged steel components for fossil fuel power and nuclear power plants, and petroleum refineries have become large in scale. Requirement of quality for component materials to be used in these components has also become high level. JSW has carried out the technology developments for high purity material, manufacturing technology of ultra large ingot, forging technology, heat treatment technology, development of new materials as well as installation of latest secondary melting equipment and forging press in order to cope with demands of industries.

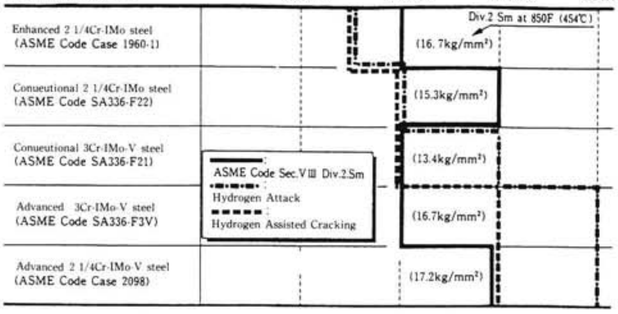


Photo. 13 World large weight reactor for Pernis Refinery of SNR Company (Holland)
(material: 12CrMoVTi1210, thickness; 273mm, total weight; 1450ton)

The paper outlined the history of these technologies and manufacturing equipment as "Progress of Large Scale Forgings for Energy Industries". Details of each technology and product could not be reached here, but referencing to the cited literatures would hopefully be a help.

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