Development and Manufacturing of the High-Pressure Low-Pressure Trial Rotor Forgings with High-Strength and Superior-Toughness

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—Synopsis—

In order to develop the HP-LP rotor material with superior strength and toughness balance, fundamental studies, which were concerned to the effects of chemistry on mechanical properties and extensive segregation, were performed on modified CrMoV steel. Based on these test results, 2.5%NiCrMoV steel was developed by EPRI/GE/Toshiba/JSW, 2.25%CrNiMoVWNb steel was developed by Toshiba/JSW, 0.2%Mn1.8%NiCrMoV steel was developed by Hitachi/JSW. Then, trial rotor forgings were produced and evaluated for these modified CrMoV steels, the superior strength and toughness as well as good creep strength was confirmed. And then, superclean 9%CrMoVNiNbN steel was developed for advanced HP-LP rotor material with superior strength and toughness balance than that of modified CrMoV steels. A trial HP-LP rotor forging, which was made from superclean 9%CrMoVNiNbN steel, was produced and superior mechanical properties were confirmed.

1. Introduction

With the recent global environmental problem taken into account, a vigorous movement has been seen to increase the power generation efficiency at a fossil fuel power plant for the purpose of reducing both quantity of CO_2 emissions and consumption of fossil fuels[1]. Under such circumstances, the combined cycle (C/C) type power generation which permits the waste heat of a gas turbine to be applied as the power of driving a steam turbine is highlighted as a form of power generation, which allows for an improvement of power generating efficiency. In the C/C type power generation, a steam turbine often applies a monoblock high- and low- pressure (HLP) combined type rotor. According to operating steam temperature of this rotor, it is required a high-temperature creep strength at the high-pressure (HP) portion and both room and high-temperature strength, especially an excellent toughness around the center at the low-pressure (LP) portion. Conventionally, a small-sized HLP rotor has been made of NiMoV steel, CrMoV steel, 1%CrMoVNiNb steel[2,3], or the like. In our manufacturing process of HLP rotor shaft, we have performed a differential heat treatment method, in which the HP portion is heated to higher temperature and afterwards forced air cooled and the LP portion is heated to lower temperature afterwards water spray cooled, so that the HP portion will be given a creep strength and the LP portion will be given a excellent toughness.

However, according to the increase of both power plant output and start/stop frequency on the backgrounds, the HLP rotor has been being more and more required to enlarge its drum diameter and to increase its toughness to a far higher level than ever. In the case of enlarging the drum diameter, cooling rate will decrease, and then the ferrite will precipitate at the center of the rotor, leading to a decrease in both strength and toughness. Consequently, the development of a new material with high hardenability has been required. In order to develop the material which has a sufficient level of hardenability, high toughness and high creep strength all to be suited for the HLP rotor with a large drum diameter, investigations in the world have been being made concentratedly on the modified CrMoV steels which were compensated the hardenability and toughness of the CrMoV steel, and which were kept a creep strength at a level comparable with that of CrMoV

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steel[4-6], were investigated and developed.

Since the initial stages or the midcourse of developing the modified CrMoV steels, we at Japan Steel Works have started the joint researches with various partners while manufacturing and evaluating the large-sized HLP trial rotors, applying a composition of those developed materials which have both superior toughness and high creep strength. Moreover from a future point of view, it is supposed that a material for an HLP rotor with a large drum diameter will be desired in the future to satisfy the required creep strength while having a superior toughness even with a high tensile strength. We have developed the superclean 9%CrMoVNiNbN steel, and using this material, we have manufactured and evaluated a large-sized HLP trial rotor[7].

This report describes an alloying design method, considering the mechanical properties and solidification characteristic of the modified CrMoV steel. And then describes, manufacturing, and evaluated test results of three types of developed low alloy steels. The first is the superclean 2.5%NiCrMoV steel[4], which was developed through the joint research with Electric Power Research Institute (EPRI), General Electric Company (GE), and Toshiba Corporation (Toshiba), based on the results successfully achieved by EPRI and BethForge. The second is the 2.25% CrNiMoVWNb steel[5], which was developed through the joint research with Toshiba. And the third is the 0.2%Mn1.8%NiCrMoV steel[6], which was developed through the joint research with Hitachi Ltd (Hitachi). Furthermore, the present paper is to report the results of our investigation and evaluation on another large-sized HLP trial rotor which was made on a manufacture basis of the superclean 9%CrMoVNiNbN steel[7] developed as the material capable of applying with the case where far higher strength and superior toughness are likely to be desired in the future.

2. Development of the Materials for an Advanced HLP Rotor Made of Low-alloy Steel:

In order to develop the material which would improve hardenability and toughness in a great measure while maintaining creep strength equivalent to that of CrMoV steel, we investigated the fundamentals to the effects of alloying elements and impurity elements on the mechanical properties of the modified CrMoV steel. Furthermore, large-sized trial rotors were manufactured and evaluated. These test results are outlined hereunder.

2.1 Improvement of the Toughness by Adding Alloying Elements:

In order to investigate the effects of alloying elements on the mechanical properties of the modified CrMoV steel, we made 50 kg of the laboratory ingots whose compositions are shown in **Table 1.** As a material for comparison, the conventional CrMoV steel was also made, too. These ingots were forged into a 35mm thick plate and then normalized by heating at 1050℃ and performed the tempering at 650℃. After preliminary heat treatments, quality heat treatment was performed. Tempering curves were taken with changing the tempering temperature in the quality heat treatment. From these tempering curves, each tempering temperature was decided, at which tensile strength equaled 820MPa. Furthermore at the decided tempering temperature, the each material was tempered after quenching in the quality heat treatment. These materials were used to conduct a tensile test, a Sharpy impact test and a creep test so as to investigate the effects of alloying elements on mechanical properties[9].

Table 1 Chemical composition of modified CrMoV steel 50kg laboratory heats (mass%)

	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Nb	As	Sn	Sb	N
SC1	0.25	0.02	0.03	<0.003	0.002	1.24	2.39	—	1.26	0.27	—	<0.003	<0.003	0.0003	0.0083
SC2	0.25	0.02	0.03	<0.003	0.001	1.24	2.39	—	1.25	0.27	—	<0.003	<0.003	<.0003	0.0080
SC3	0.25	0.03	0.03	<0.003	0.002	1.24	2.01	—	1.25	0.27	—	<0.003	<0.003	0.0004	0.0078
SC4	0.25	0.02	0.02	<0.003	0.002	1.25	1.60	—	1.26	0.27	—	<0.003	<0.003	0.0005	0.0081
SC5	0.25	0.02	0.02	<0.003	0.002	0.59	2.00	—	1.25	0.27	—	<0.003	<0.003	0.0003	0.0084
SC6	0.25	0.03	0.02	<0.003	0.002	2.00	2.00	—	1.24	0.27	—	<0.003	<0.003	0.0003	0.0075
SC7	0.25	0.03	0.70	<0.003	0.002	1.26	2.04	—	1.23	0.27	—	<0.003	<0.003	0.0003	0.0075
SC8	0.24	0.02	0.03	<0.003	0.001	1.22	2.01	0.01	1.26	0.27	0.030	<0.003	<0.003	0.0009	0.0065
SC9	0.25	0.03	0.04	<0.003	0.002	2.54	2.07	0.01	1.25	0.27	—	<0.003	<0.003	0.0005	0.0071
HC	0.31	0.02	0.02	<0.003	0.001	2.48	1.54	0.02	1.38	0.25	0.035	<0.003	<0.003	0.0007	0.0062
HO	0.31	0.01	0.02	<0.003	0.001	2.53	1.54	0.02	1.40	0.25	—	<0.003	<0.003	0.0007	0.0066
CM	0.27	0.02	0.72	<0.003	0.001	0.39	1.19	0.02	1.19	0.26	—	<0.003	<0.003	0.0006	0.0070
VC	0.28	0.25	0.66	0.008	0.007	0.15	1.25	0.10	1.20	0.27	—	—	0.006	—	0.0074

As an example of the effects of an alloying element on mechanical properties, **Figs. 1** and **2** show the effects of a Cr content on temper resistance, toughness and creep strength. From these results, an increase of Cr content reduces the temper resistance more effectively while improving toughness, to the contrary. Moreover, an increase of Cr content reduces the creep strength.

Similar tests were performed on those materials whose Mn, Ni and Nb contents varied. Test results are summarized in **Table 2**. In other words, a decrease of Mn improves the temper resistance but decreases the toughness while improving the creep strength. Addition of Ni has about an effect similar to that with Cr addition. In other words, it decreases the temper resistance but improved the toughness while decreasing the creep strength. Furthermore, addition of Nb increases both temper resistance and toughness without affecting the creep strength. Thus, an addition of alloying elements often affect contradictory to each other onto toughness and creep strength[10,11]. Consequently, we knew that it would be very difficult to improve both properties toughness and creep strength at a same time by optimizing the alloying elements.

As already referred to above, the effects of alloying elements on toughness and creep strength in the modified CrMoV steel could be summarized as shown in **Table 2**. There are many alloying elements which are effective contradictorily on toughness and creep strength, and then we have recognized that a simultaneous improvement of both properties involved a great deal of difficulties. From a microstructural point of view, those factors effective on the toughness

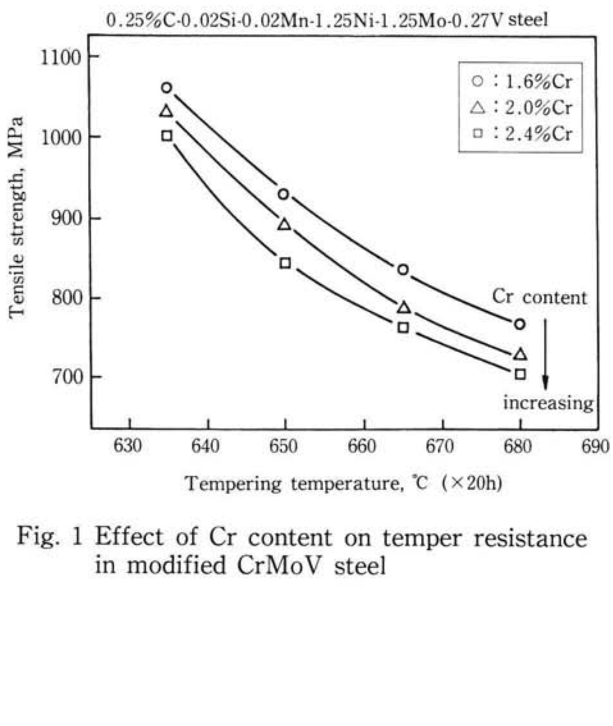

Fig. 1 Effect of Cr content on temper resistance in modified CrMoV steel

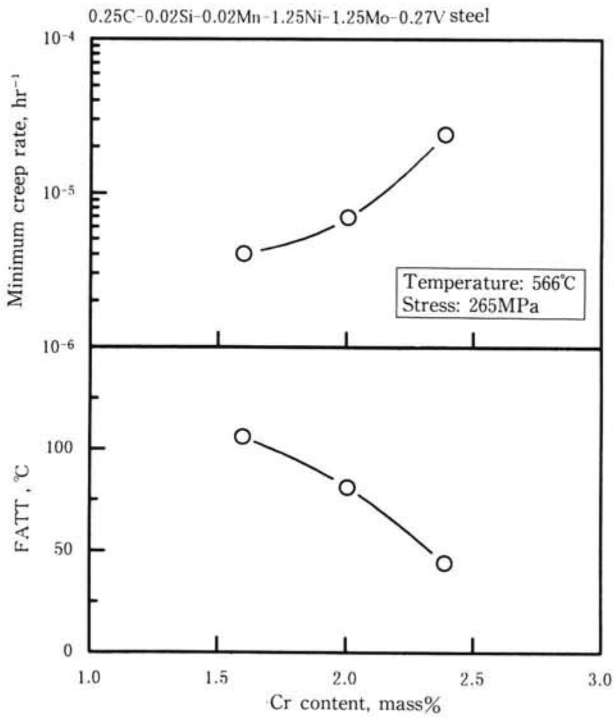

Fig. 2 Effects of Cr content on toughness and creep strength in modified CrMoV steel

Table 2 Effects of alloying elements on hardenability, toughness and creep strength in modified CrMoV steel

Mechanical Property	Superclean		Alloying element compensated		
	Decrease of impurity element	Decrease of Mn content	Cr added	Ni added	Nb added
Hardenability	——	Decrease	Improve	Improve	——
Toughness	Improve				Improve
Creep strength	Improve	Improve	Decrease	Decrease	——

and creep strength of the modified CrMoV steel might well be summarized as shown in **Fig. 3** by way of the bainite transformation start (Bs) temperature. A decrease of the Bs temperature would make the bainite lath structure finer. With reducing the bainite lath size, toughness increases, and creep strength decreases to the contrary.

2.2 Effects of High Purification on Mechanical Properties

Several types of the modified CrMoV steel have been developed for an HLP rotor material. Since they have a higher content of Ni than that of the conventional CrMoV steel, the developed steels may be expected to differ in the effects of their impurity elements on toughness, temper embrittlement susceptibility and creep strength. In order to investigate the effects of impurity elements on toughness, temper embrittlement susceptibility and creep strength, we tested the 50kg labolatory heats[12] which were varied

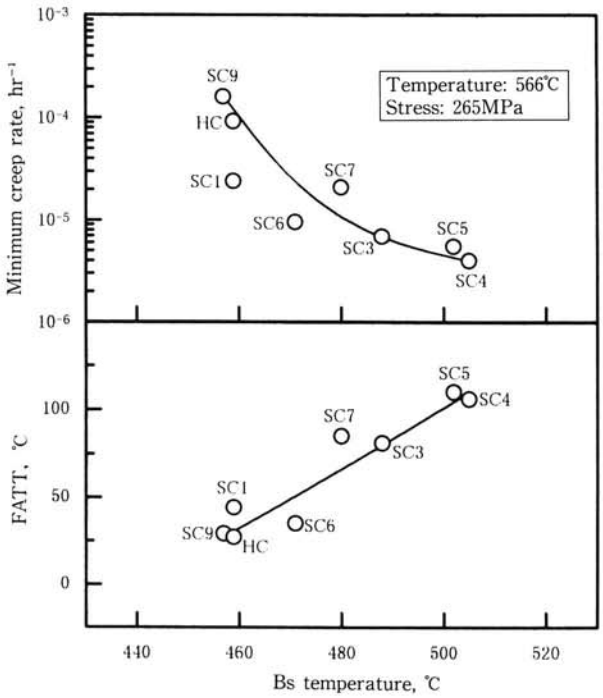

Fig. 3 Relationship between toughness, creep strength and Bs temperature in modified CrMoV steel

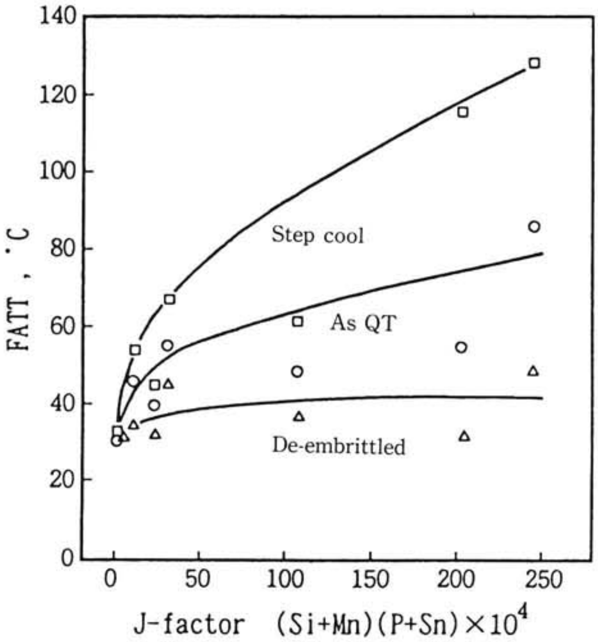

Fig. 4 Relationship between FATT and impurity element

Si, Mn, P and Sn contents, using the superclean 2.5% NiCrMoVNb steel[8] developed by EPRI and Beth-Forge. J-factor (=(Si+Mn)(P+Sn)$\times10^4$), one of the temper-embrittlement parameters, was made to vary within a range of 0.9 thru 245. **Table 3** shows the chemical compositions of the test steel ingots. Each test was performed, with the tensile strength standardized to 790MPa by changing the tempering temperature in the quality heat treatment.

Fig. 4 shows the relationship between temper embrittlement susceptibility and impurity element in this type of steel. The obtained relationship between FATT and J-factor of three types of materials ; the first was as quality heat treated, the second was de-embrittled after quality heat treatment and the third was embrittled after quality heat treatment, were plotted in this figure. FATT of the as quality heat treated material increases with increasing the J-factor value. This tendency continued within a J-factor range of 0 thru 40, in which FATT rose remarkably. Over a J-factor of 40, the tendency of increasing FATT became small. This phenomenon could be observed as a more remarkable change in the embrittled material.

Furthermore, **Fig. 5** shows the comparison of the temper embrittlement susceptibility with the embrittled test data[13] obtained by Watanabe et. al. on the 3.5%NiCrMoV steel and 2 1/4CrlMo steel. In this figure, the vertical axis shows Δ FATT which means the difference of FATT measuring after the embrittled treatment and de-embrittled treatment. The 3.5%NiCrMoV steel used as a material for LP rotors is known for its very high temper-embrittlement susceptibility. The steel type reported herein, however, showed a considerably high level of temper-embrittlement susceptibility although it

Table 3 Chemical composition of modified CrMoV steel 50kg laboratory heats (mass%)

	C	Si	Mn	P	S	Ni	Cr	Mo	V	Nb	Sn	N	J-factor
A1	0.31	0.02	0.01	<0.003	0.0010	2.51	1.50	1.42	0.25	0.029	<0.003	0.0062	0.9
A2	0.34	0.02	0.02	0.011	0.0011	2.58	1.50	1.42	0.25	0.028	0.017	0.0065	11.2
A3	0.32	0.01	0.75	<0.003	0.0010	2.59	1.50	1.38	0.25	0.030	<0.003	0.0098	22.8
A4	0.33	0.02	0.73	0.011	0.0012	2.61	1.51	1.39	0.25	0.030	0.016	0.0082	202.5
A5	0.32	0.26	0.71	<0.003	0.0010	2.64	1.52	1.36	0.25	0.030	<0.003	0.0081	29.1
A6	0.31	0.25	0.73	0.011	0.0011	2.52	1.57	1.46	0.25	0.030	0.014	0.0063	245.0
A7	0.30	0.02	0.41	0.009	0.0010	2.50	1.52	1.46	0.25	0.030	0.016	0.0098	107.5

J-factor= (Si+Mn) (P+Sn) $\times10^4$

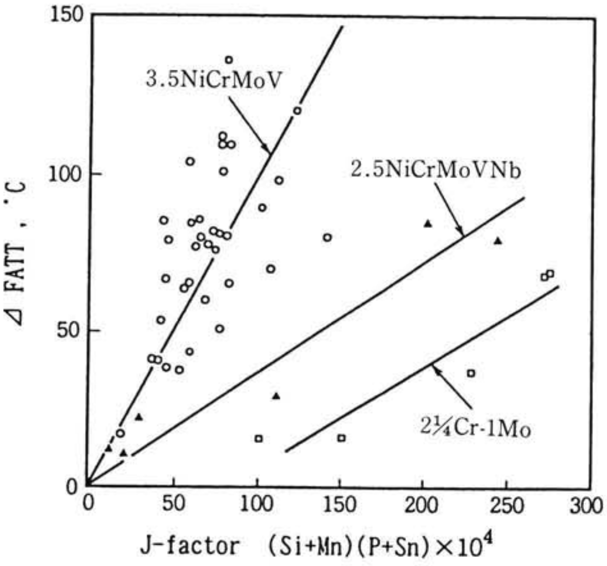

Fig. 5 Comparison of temper embrittlement susceptibility in 2.5NiCrMoVNb, 3.5NiCrMoV and 2-1/4Cr-1Mo steel

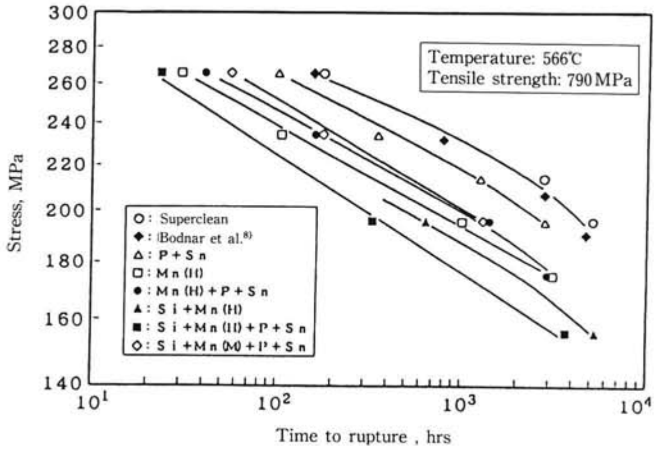

Fig. 6 Effects of impurity elements on creep strength

compared a little unfavorably with the 3.5%NiCrMoV steel. Thus, it was proven that suppressing the J-factor at a lower level would contribute greatly to a reduction of the temper-embrittlement susceptibility.

Fig. 6 shows the effects of impurity element on the creep strength in 2.5NiCrMoVNb steel. The creep test was conducted at a temperature of 566℃. Moreover, the data which was collected by Bodnar et. al.[8] are plotted in the figure. A chemical composition tested by Bodnar nearly identical with steel A1. These superclean steel were reduced Si, Mn and impurity elements to the minimum level as possible. As compared with steel A2-A7 which contains one or several of Si, Mn and impurity elements, steel Al shows the highest level of creep strength, showing the tendency to decrease the creep rupture strength with increasing Si, Mn and impurity elements.

From the test results referred to above, we could obtain a conviction that the toughness might be improved while maintaining the creep strength level of the conventional CrMoV steel by compensating and optimizing the alloying element contents as well as jointly using a superclean material to reduce the impurity elements.

3. Alloying Elements and Solidification Properties

The 3.5%NiCrMoV steel already developed completely as a material for LP rotors could not be observed remarkably segregated even if it was a large ingot[14,15]. However modified superclean CrMoV steel was observed a remarkable carbon segregation at the center portion and a macro segregation. These segregation mechanisms were analyzed, accordingly.

In order to simulate carbon segregation at the center of a large ingot, we made 8 tons sand mold ingot (ϕ840mm×1,015mm) which was designed so as to attain a solidification rate nearly identical with that of 100 tons VCD ingot. **Table 4** shows the composition of the 8 tons sand mold ingots. **Fig. 7** shows the segregation index of carbon (Is) at the center from the bottom to the top of the ingot. Both conventional CrMoV and 3.5%NiCrMoV steel ingots showed a slightly increase of Is. However any other steel were observed remarkable increase in Is. This segregating phenomenon is promoted by increasing density differ-

Table 4 Chemical composition of 8 tons sand mold ingot (mass%)

	C	Si	Mn	P	S	Ni	Cr	Mo	V	Nb
0.4Ni-1.3Mo	0.29	0.24	0.76	0.004	0.0007	0.40	1.09	1.29	0.26	—
1.7Ni-1.7Mo	0.21	0.04	0.14	0.005	0.0011	1.68	1.44	1.68	0.26	—
1.7Ni-1.7Mo-Mn	0.22	0.05	0.47	0.005	0.0010	1.69	1.43	1.63	0.25	0.010
1.7Ni-1.7Mo-Nb	0.22	0.03	0.15	0.005	0.0011	1.72	1.49	1.70	0.26	0.019
1.7Ni-1.0Mo	0.22	0.03	0.15	0.006	0.0014	1.72	1.48	1.01	0.27	0.017
2.6Ni-1.4Mo	0.31	0.03	0.04	0.004	0.0013	2.55	1.48	1.41	0.25	0.021
3.6Ni-0.4Mo	0.26	0.03	0.02	0.004	0.0008	3.60	1.72	0.43	0.13	—
0.2Ni-0.1Mo	0.21	0.27	0.33	0.007	0.0080	0.18	0.07	0.07	—	—

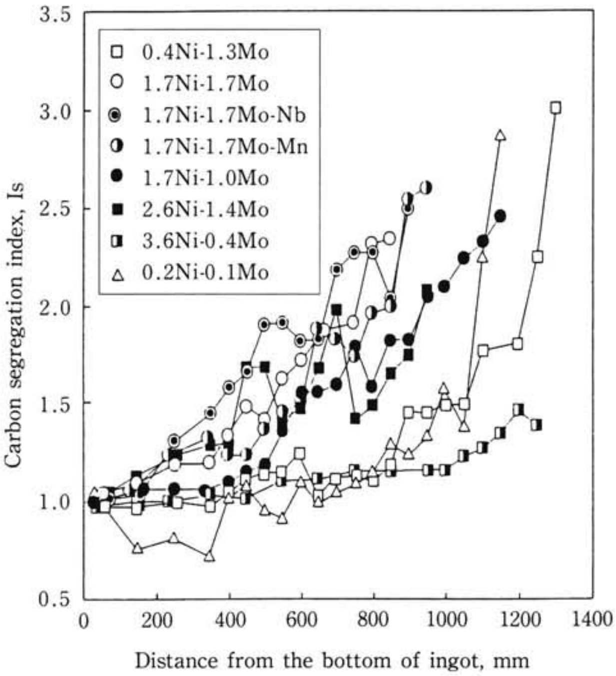

Fig. 7 Distribution of carbon at the center of 8 tons sand mold ingot

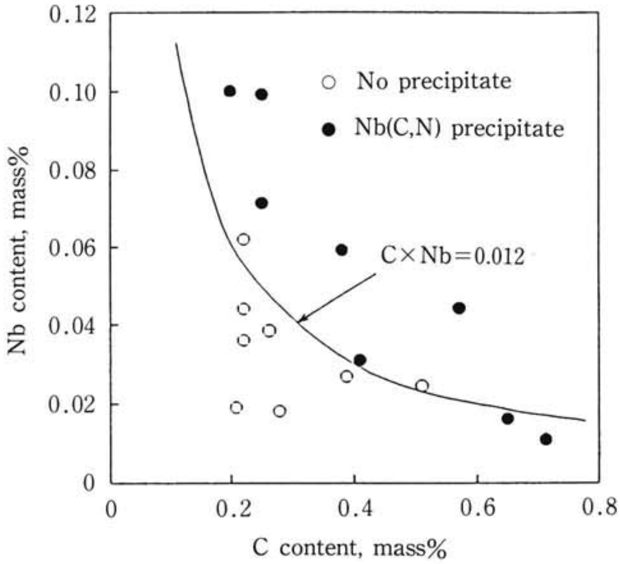

Fig. 8 Effect of C and Nb contents on the formation of eutectic Nb(C,N)

ence ($\Delta\rho$) between bulk and segregated liquids, decreasing the peritectic reaction temperature and increasing the solidification time[17].

In order to investigate the formation behavior of the eutectic Nb(C,N) inclusion which would reduce the ductility and toughness, 180 g of the test piece molten at 1550°C was cooled down at a solidification cooling rate of 180°C/h. This cooling rate was a simulation of a large ingot at the center[18]. **Fig. 8** shows the effect of carbon and Nb contents on the formation of the eutectic Nb(C,N). From the figure, it can be seen that the critical condition for the formation of the eutectic Nb(C,N) is $C \times Nb = 0.012$ at the center of a 100 tons class VCD ingot in the modified CrMoV steel. In the case of a large sized ingot, carbon content at the center of this ingot could be projected to be remarkably high even if a composition design and a ingot design for reducing a segregation should apply. Even if the ladle composition should satisfy a relation of $C \times Nb \leqq 0.012$, it should be noted that there are possibilities that the eutectic Nb(C,N) may be formed in carbon concentrated area at the center of the ingot.

4. Manufacturing the Trial Rotor Made of Modified CrMoV Steel, and Results of Evaluation

Based on the investigation concerning alloying composition design concepts and segregation tendencies referred to above, a large sized trial HLP rotors were manufactured and evaluated the

Table 5 Chemical composition of trial rotors (mass%)

			C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Al	Nb	As	Sn	Sb
A	2.5NiCrMoV	Aim	0.24	max. 0.05	max. 0.05	max. 0.004	max. 0.0020	2.50	1.60		1.20	0.25			max. 0.008	max. 0.010	max. 0.0050
		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	max. 0.03	0.50	max. 0.003	max. 0.0015	1.70	2.25	max. 0.05	1.10	0.20	max. 0.005	0.015	max. 0.006	max. 0.005	max. 0.0015
		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	max. 0.05	0.15 ~ 0.25	max. 0.010	max. 0.0100	1.70 ~ 1.90	1.90 ~ 2.10	max. 0.10	1.10 ~ 1.30	0.23 ~ 0.30	max. 0.008		max. 0.008	max. 0.010	max. 0.0050
		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

producibility and mechanical properties of the material which we had developed as a material for HLP rotors through the joint research[4-6]. Described below are the keys of the composition design and of the production process, segregation behaviors and obtained mechanical properties, with their representative values taken up as examples.

4.1 Aim for HLP Rotors Made of Modified CrMoV Steel

Table 5 shows the chemical compositions of those trial rotors which we manufactured and evaluated through the joint research. Steel A[4] was the super-clean 2.5%NiCrMoV steel, which contained 2.5%Ni, with Mn extremely reduced to decrease the temper embrittlement susceptibility and to increase the creep strength. And Nb was not added to Steel A. Steel B[5] had 0.5%Mn added, for a reduction of carbon segregation. In order to suppress the temper embrittlement susceptibility at a lower level, care was used to minimize the impurity elements. Furthermore in order to attain the fine grain, an extremely small amount of Nb was added without forming eutectic Nb(C,N). In addition, steel B was the 2.25% CrNiMoVWNb steel with 0.2%W. Steel C[6] was 0.2% Mn1.8%CrMoV with Mn content of 0.2% without adding Nb. These three types of steel manufactured the large sized trial HLP rotor which had an LP diameter: ϕ1,720 - 1,850mm and an HP diameter: ϕ1,000-1,200mm. Aim of mechanical property were 760-870MPa in tensile strength at both LP and HP portions, less than the room temperature in FATT at the LP center and the creep strength at the HP portion was equal to that of the conventional CrMoV steel.

4.2 Manufacturing Process of the Trial HLP Rotor Made of Modified CrMoV Steel

As an example of the trial HLP rotor manufacturing process, **Fig. 9** shows a manufacturing sequence of Rotor A. The melting and refining were performed in an electric furnace and a ladle refining furnace (LRF). After the refining, the molten steels were poured under vacuum. Vacuum carbon deoxidation (VCD) occurred during the pouring. These VCD ingots weighed 75-90 tons. The height to diameter (H/D) ratio was set to 1.6 in order to increase the solidification rate at the center of the ingot for reducing the segregation at the center. The hot forging operation were performed by using 10,000 and 8,000 ton hydraulic presses. Upsetting were performed several times, in order to get a satisfactory effect of forging to the core of the ingot. A preliminary heat treatment was performed after the forging operation.

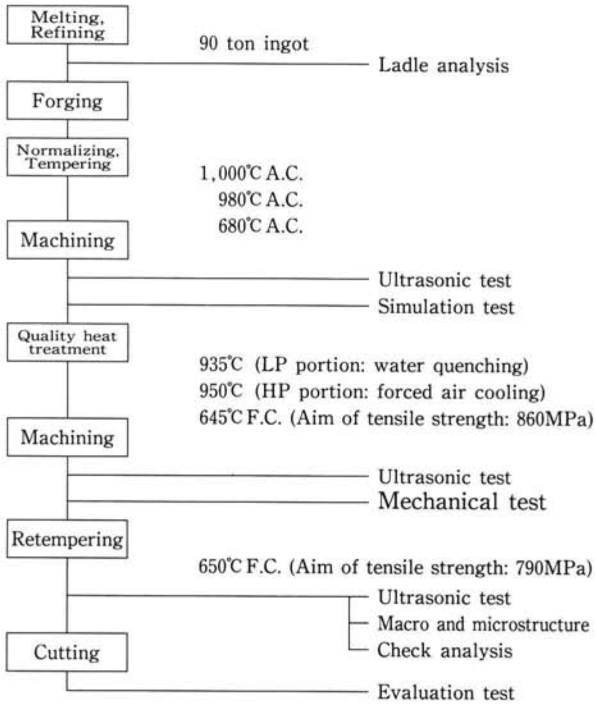

Fig. 9 Manufacturing sequence of the trial rotor A

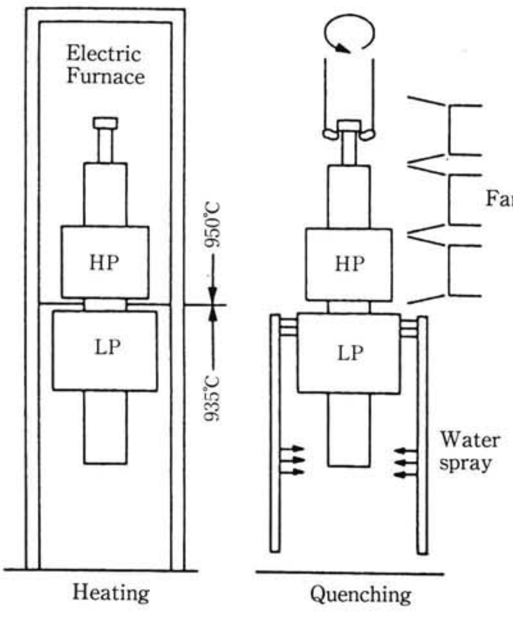

Fig. 10 Schematic of differential heat treatment

And then, for quality heat treatment, Rotors A and B were performed a differential heat treatment. **Fig. 10** shows a schematic of the differential heat treatment. In order to attain a good toughness, austenitizing temperature of LP portion were decreased, and cooling rate of LP portion were increases by using water spray quenching. In order to attain a high creep strength, HP portion was quenched from a higher temperature by using forced air. With the differential heat treatment applied, the temper resistance differed between LP and HP portions. Therefore in the quality heat treatment the second tempering temperature was different LP with HP portion. **Table 6** shows the quality heat treatment condition on rotor B by way of example. In the case of rotor C, the same quality heat treatment conditions were applied to both LP and HP portions. After the heat treatment, an ultrasonic examination was performed. These trial rotor were entirely free from any defects. **Fig. 11** shows an appearance of rotor C after machining.

4.3 Evaluation of Mechanical Properties for HLP Trial Rotors Made of Modified CrMoV Steel

(1) Solidification Characteristic of Trial Rotor

To investigate the solidification characteristic of the modified CrMoV steel, each manufactured trial HLP rotor was examined for the distribution of compositions from the top to the bottom at center core of the ingot. **Fig. 12** shows a distribution of the chemical compositions in rotor B. A little inverse segregation could be seen on the bottom of the ingot and a little normal segregation on the top side of the ingot. Nevertheless, these segregations were similar to that of the conventional CrMoV steel[19]. On rotor A, the sulfur print and the macrostructure were observed at the body cross section of the LP portion. No sulfur indication were appeared in sulfur print, the segregation spots observed in the macrostructure were observed at a same level with the conventional CrMoV steel.

Table 6 Quality heat treatment conditions of rotor B

Quenching	: 900℃ ×48h→Water spray (LP portion)
	: 970℃ ×48h→Forced air cooling (HP portion)
First tempering	: 580℃ ×46h
Second tempering	: 625℃ ×59h (LP portion)
	: 640℃ ×59h (HP portion)

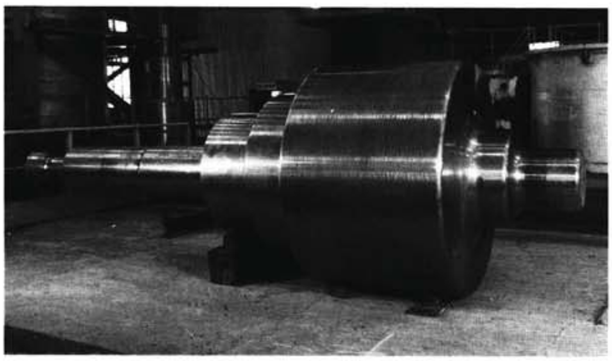

Fig. 11 Appearance of rotor C after machining

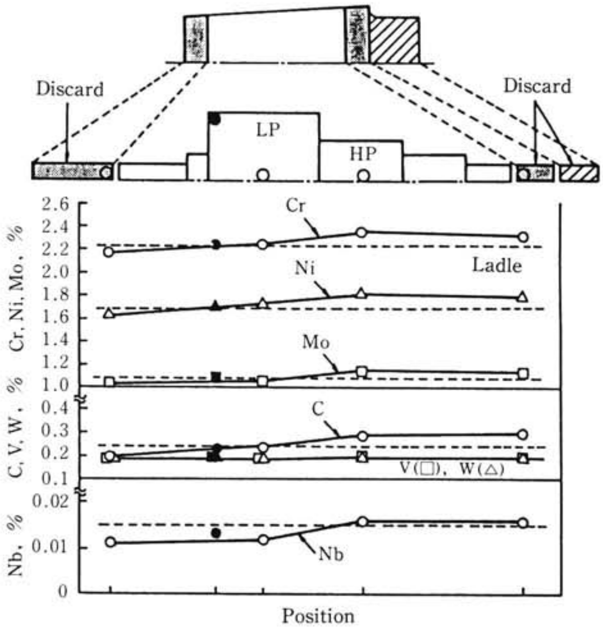

Fig. 12 Distribution of chemical compositions in rotor B

(2) Toughness

HLP rotor is required high strength and good toughness, especially at the LP portion. **Fig. 13** shows the mechanical properties at each location of rotor A. As shown in Fig. 9, rotor A was performed tempering to a level of tensile strength 860MPa. Then, half of the LP portion on the journal side was cut off in order to evaluate the high strength material. And then, the HP portion and half of the LP portion were performed retempering to a level of tensile strength=790MPa. In a result of the mechanical test, FATT=15°C with tensile strength=805MPa, was obtained at

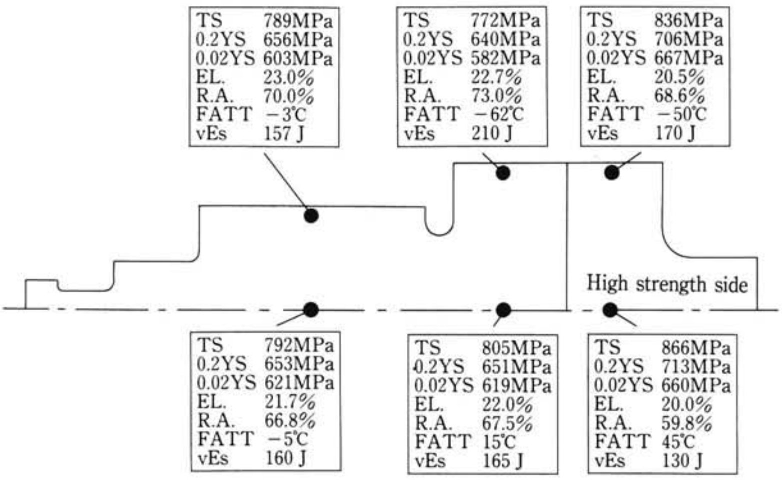

Fig. 13 Distribution of tensile and impact properties in rotor A

the center of the LP portion. It was confirmed that a aim of toughness could be fully achieved. At the center of the LP portion on the high strength side, FATT of 45°C with tensile strength of 866 MPa was obtained. FATT also increased with increasing the tensile strength. This strength/toughness balance was nearly equal to the data of the laboratory heats **(Fig. 14)**

Because an operating temperature range of HLP rotor could not avoid the temper embrittlement temperature, it is necessary to suppress the temper embrittlement susceptibility as possible as low level. **Table 7** shows the results of evaluating the temper embrittlement susceptibility of rotor A by using a step-cooling heat treatment. This table summarized that no temper embrittlement was observed by applying the superclean steel.

(3) Creep Strength

The HP portion is exposed to the same steam conditions as those of the CrMoV steel which has applied as HP and intermediate pressure (IP) rotors. Therefore the aim of the creep strength was equal or superior to that of the conventional CrMoV steel. **Fig. 15** shows the creep test results by using the HP material of rotor C, with the mean creep strength curve[19] of the conventional CrMoV steel. And it was confirmed that the creep strength of the trial HLP rotor was higher than the creep strength of the conventional CrMoV steel.

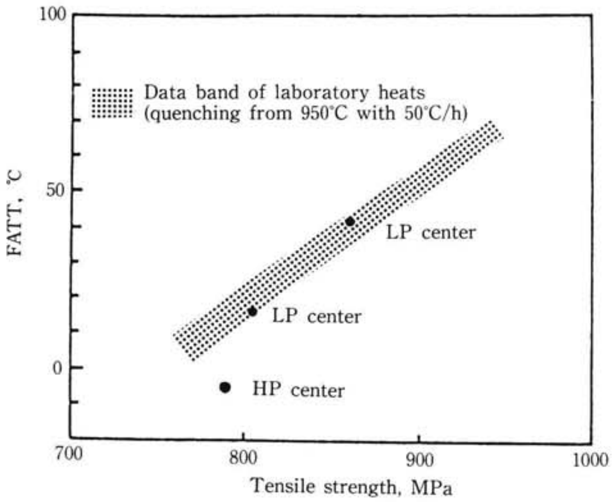

Fig. 14 Strength/toughness balance of rotor A

Table 7 Results of step cooling test for rotor A

	ΔFATT(℃)	ΔvEs(Joule)
LP-H(Surface)	+5	+15
LP-L(Surface)	−5	+6
HP(Surface)	+3	+2

Step Cool 593℃ × 1h − 538℃ × 15h − 524℃ × 24h − 496℃ × 48h − 468℃ × 72h (cooling rate : 5.6℃/h)

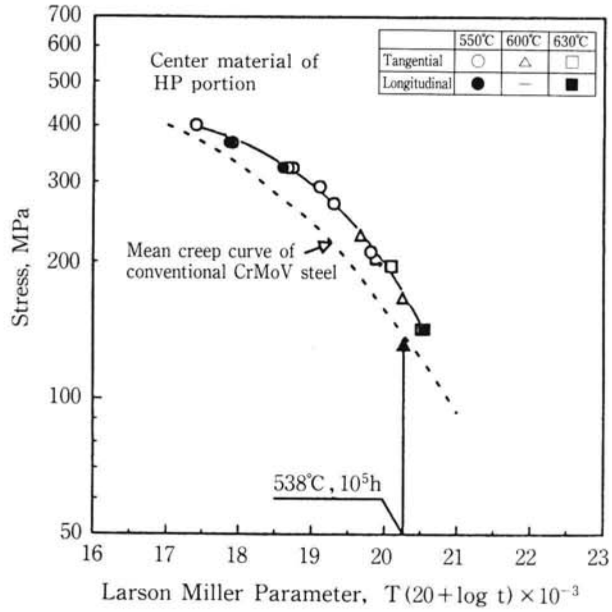

Fig. 15 Creep strength of rotor C

(4) Strength/Toughness Balance

As referred to above, the trial HLP rotor made of the modified CrMoV steel to which alloying element compensating, optimization and high purification had been applied, was manufactured and evaluated mechanical properties. As a result, it was confirmed that the trial rotor had a superior strength/toughness balance while maintaining good producibility and the creep strength equal to the conventional CrMoV steel.

These low-alloy steel rotors have been already produced for applications in several C/C power plants.

5. Development of the Superclean 9%CrMoVNiNbN Steel, Manufacturing a Trial Rotor, and Evaluation Test Results:

In the future, request of increasing drum diameter is expected for HLP rotor. And it is predicted that a material will be required to show excellent toughness with high tensile strength, and to satisfy the creep requirement, too. **Fig. 16** shows the strength/toughness balance in the conventional CrMoV steel and in the modified CrMoV steels which have been developed so far. From this figure, it may be indicated that the typical FATT of the modified CrMoV steel is approximately 50°C, with tensile strength of

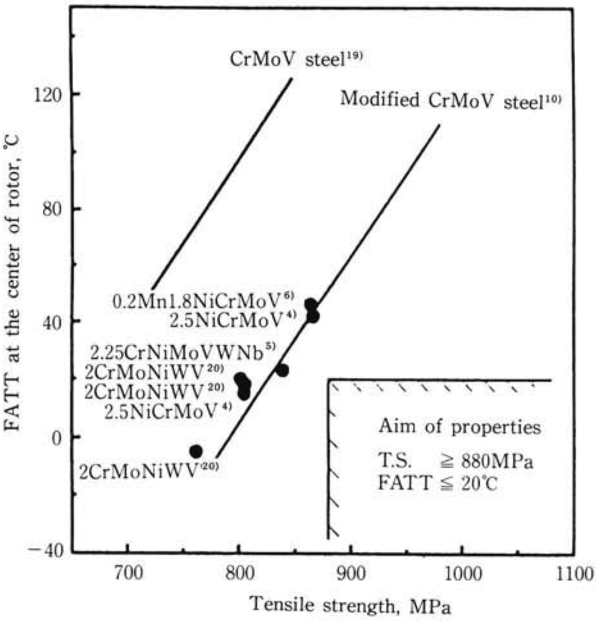

Fig. 16 Tensile strength and toughness balance in low alloy steels

900MPa. Therefore we investigated the development of the material, which provided the superior strength and toughness balance. The aim of mechanical properties was the superior strength/toughness balance than that of the modified CrMoV steel and the creep strength of conventional CrMoV steel level. Fundamental research and optimization of composition were performed with the 9%CrMoV steel as the base material. And then, a trial rotor was manufactured and tested for evaluation. Described below are the development process, manufacturing process of the trial rotor and evaluation test results.

5.1 Development of the Superclean 9%CrMoVNiNbN Steel

With the 9%CrMoV steel as the base material, the contents of C, Si, Mn, Ni, Cr, Mo, V, Nb and N were varied to investigated the effects of impurity elements and alloying elements on temper resistance, toughness and creep strength. 50kg ingots were cast, forged, and performed the simulated heat treatment of larger diameter rotor. The second tempering was performed to obtain the tensile strength of 880MPa by controlling the tempering temperature at quality heat treatment. The effects of alloying elements on the mechanical properties as shown in **Table 8** were obtained. Based on these test results, the superclean 9%CrMoVNiNbN steel was selected to be the best composition for the trial HLP rotor material as showed in **Table 9**.

Table 8 Effects of alloying elements on mechanical properties of 9%CrMoV steel

Element	Temper resistance	Toughness	Creep strength
C	Increase	Improve	Decrease
Si	Increase	Decrease	Decrease
Mn	Increase	No effect	Decrease
Ni	Decrease	Improve	Decrease
Cr	Increase	9.5%	10.0%
Mo	Increase	1.3~1.4%	Improve
V	0.21%	0.21%	No effect
Nb	Increase	No effect	Improve
N	Increase	Decrease	Improve

Table 9 Chemical composition of the trial HLP rotor

C	Si	Mn	Ni	Cr	Mo	V	Nb	N	P,S,Al,As,Sn,Sb
0.16	<0.1	<0.1	1.3	9.8	1.4	0.21	0.05	0.04	superclean

5.2 Manufacturing and Evaluating Test Results of the Trial HLP Rotor:

(1) Aim of Mechanical Properties and Manufacturing of the Trial Rotor

This developed material was characterized as following point:

○ Applying the superclean steel, which was reduced Si, Mn and other impurity elements.
○ Addition of 1.3%Ni in order to obtain excellent hardenability and toughness.
○ Optimization of other alloying element.

The aim of FATT was less than 20℃ with tensile strength of more than 880 MPa as shown in **Fig. 16**. The aim of creep strength was equal or superior to that of the conventional CrMoV steel. A dimension of the trial rotor was followed. The diameter of LP portion was ϕ1,750 mm and the diameter of HP portion was ϕ1,200 mm.

The basic electric furnace and the LRF were used for melting and refining. An ingot was cast through vacuum carbon deoxidation (VCD) process. Then electro-slag remelting (ESR) process was performed and an ingot with 1800 mm diameter with the weight of 65 ton was made. After forged by 10,000 and 8,000 ton presses, preliminary heat treatment and quality heat treatment was performed. This developed material indicated the superior hardenability and was able to obtain a uniform martensite structure over a wide cooling rate range as shown in **Fig. 17** so that it can obtain a uniform structure from the HP portion to the LP portion and from the surface to the center. After the quality heat treatment, ultrasonic inspection was performed and no indications were detected.

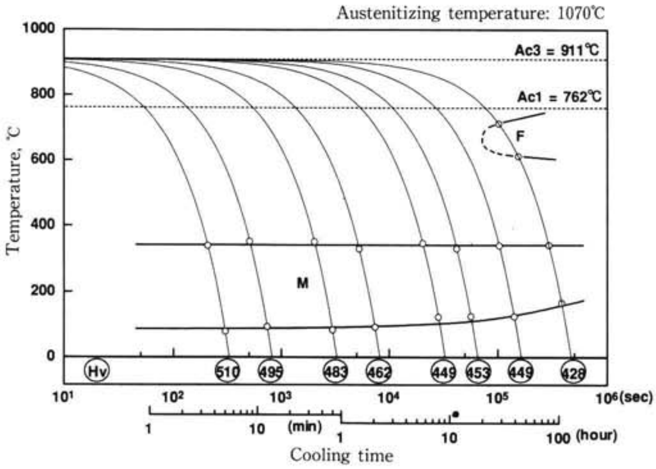

Fig. 17 Continuous cooling transformation diagram of the superclean 9%CrMoVNiNbN steel

(2) Mechanical Properties of the Trial HLP Rotor Forging

From a result of chemical analysis at various portion in the trial rotor, the homogeneous distribution of chemical composition was confirmed from bottom to top of the trial rotor and from center to surface. At the center of the LP portion, no indications appeared in the sulfur prints and the macrostructure test on the cross section. Homogeneous tempered martensite structure was observed from the surface to the center.

At the LP center where good toughness was specially required, a vary good strength/toughness balance was obtained i.e. FATT of -3°C with tensile strength of 870MPa. **Fig. 18** shows the strength/toughness balances at the LP center of the conventional CrMoV steel[19], of the modified CrMoV steels[4-6,10,20] and of the superclean 9%CrMoVNiNbN steel. The superclean 9%CrMoVNiNbN steel shows a superior strength/toughness balance than that of low alloy steel. In the case of increasing tensile strength, it may be predicated that this developed material will indicate a small decrease in toughness compared with low alloy steel. The creep rupture strength of superclean 9%CrMoVNiNbN steel exceeds that of conventional CrMoV steel.

Fig. 19 shows the creep rupture strength at the HP portion of the trial rotor and that of the conventional CrMoV rotor.

As described above, it was confirmed that the superclean 9%CrMoVNiNbN steel provides the superior strength/toughness balance and creep strength than the modified CrMoV steel and the conventional

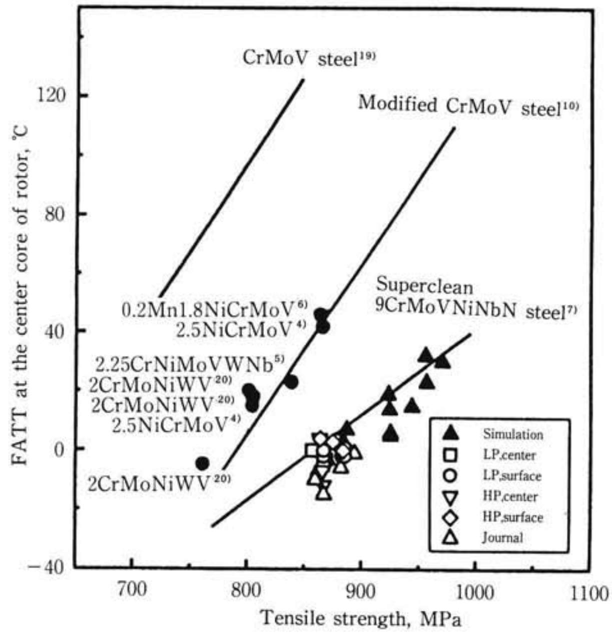

Fig. 18 Strength/toughness balance of the trial rotor and the low alloy rotor

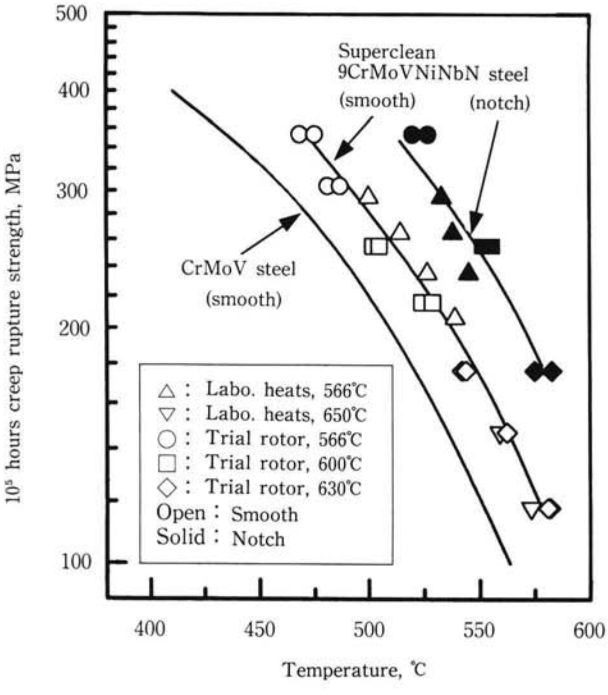

Fig. 19 Creep rupture strength of the superclean 9%CrMoVNiNbN Steel

CrMoV steel. Therefore the superclean 9%CrMoVNiNbN steel is particular suitable material to the HLP rotor which has a large drum diameter and requires high strength and high toughness.

6. Summary

In order to develop a material for the large-sized HLP rotor which has high strength and high toughness, effects of chemistry, impurity elements and ingot design on the mechanical properties and segregation tendencies were investigated. Based on the test results, we developed a modified CrMoV steel through a joint research with various partners. And manufacturing and evaluation of large sized trial HLP rotors were performed. And then, the basic investigation and development of the superclean 9% CrMoVNiNbN steel was performed, in order to provide more superior toughness material. The trial rotor was manufactured and evaluated. Obtained results are summarized below.

(1) The effects of alloying elements and impurity elements on the mechanical properties of modified CrMoV steel were investigated and an alloying design data was obtained. In addition, a basic concept was established for the alloying design and ingot design, with considering the solidification characteristic in manufacturing a large sized VCD ingot.

(2) The modified CrMoV steel which was compensated hardenability, was optimized alloying element, and was reduced impurity elements indicates a good hardenability and toughness while keeping the creep strength of the conventional CrMoV steel.

(3) These modified CrMoV steels which were developed through joint researches with EPRI/GE/Toshiba, with Toshiba and with Hitachi, were used to make large sized HLP rotors. Good producibility of these modified CrMoV steels were confirmed.

(4) From various test result of the trial HLP rotors, it was confirmed that they indicated a good strength/toughness balance as aimed and small embrittlement susceptibility with keeping the creep strength equal to that of the conventional CrMoV steel.

(5) In order to provide the material which indicate superior strength/toughness balance than the modified CrMoV steels for requiring enlargement of the drum diameter in the future, the superclean 9% CrMoVNiNbN steel was developed. Then the trial rotor was manufactured and evaluated. From evaluation tests, it was confirmed that good mechanical properties were obtained.

Thus, we have developed the modified CrMoV steel which has good toughness as a material for large HLP rotors, and the superclean 9%CrMoVNiNbN steel applicable to more larger-sized HLP rotor. In addition, trial rotors were made of each developed material and evaluated. As the results, it was confirmed that the excellent properties were obtained for large sized HLP rotor.

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