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Review

Current Progress in Advanced High Cr Ferritic Steels for High-temperature Applications

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The article presents recent developments and future trends in high Cr ferritic heat resistant steels. Research programs are underway worldwide to improve the performance of 8 to 13% Cr ferritic steels for high temperature applications of up to 650°C. We developed the super 12% Cr heat resistant steel called TAF steel in 1956. The creep rupture strength of TAF steel is two or three times higher than those of H46 and AISI422 at 600 and 650°C. Our research in this area was well ahead of work being conducted in other countries.

Recently the author succeeded in developing TR1100, TR1200, TB9 and TB12 with excellent high temperature properties and room temperature toughness through the improvement of TAF steel. In the near future, these new steels will be applied to turbine rotors, blades, and boiler tubes for advanced supercritical power plants, to fuel cladding, wrapper and steam generater tubing for fast breeder reactors, and to first wall materials for conceptual fusion reactors. These steels are a key to making these plants and reactors practical.

KEY WORDS: high Cr ferritic heat resistant steel; creep rupture strength; turbine rotor; boiler tube; advanced supercritical power plant; fast breeder reactor; nuclear fusion reactor.

1. Introduction

Development activity of 12% Cr heat-resistant steels increased significantly in the early 1940's in England in response to the need for gas turbine disks and steam turbine blades. These activities continued through the 1950's, resulting in the development of H46,[1] FV 448[2] and other steels which provide higher creep rupture strength.

In the United States at that time, AISI-422,[3] Allegheny Ludlum Type 419,[3] Lapelloy[3] and other super 12% Cr steels were introduced and have been used for steam turbine blades and bolting materials for turbine cylinders.

In Europe, HT-9[3] and EM-12[4] have had wide applications to boiler tubing materials which require better formability, fabricability and weldability.

Table 1 shows the nominal compositions, heat treatment conditions and 10^4 h creep rupture strength for these steels. H46 and AISI-422 which have considerably higher creep rupture strength find their great application in steam and gas turbines, while HT-9 is widely used as boiler tubes.

The author and co-researchers began in 1953 the research program of this sort of ferritic heat resistant steels and succeeded in developing the new ferritic steel TAF,[5] two or three times as strong as H46 in creep rupture strength, in 1956. Modified versions of TAF steels are TB9[6] and TB12[7] (see Table 4) with superior formability and weldability, and TR1100, TR1150 and

Table 1. High Cr ferritic heat-resistant steels. (mass%)

	C	Mn	Si	Ni	Cr	Mo	W	V	Nb	Other element	Heat treatment	10^4 h creep rupture strength (MPa)		
												550°C	600°C	650°C
H46	0.16	0.6	0.4	—	11.5	0.65	—	0.3	0.3	0.05N	1 150°C O.Q. 650°C A.C.	308	118	61
FV448	0.13	1.0	0.5	—	10.5	0.75	—	0.15	0.45	0.05N	1 150°C O.Q. 650°C A.C.	293	139	60
AISI422	0.23	0.6	0.4	0.7	12.5	1.0	1.0	0.25	—	—	1 060°C O.Q. 650°C A.C.	257	130	64
A.L. Type 419	0.25	1.0	0.3	0.5	11.5	0.5	2.5	0.4	—	0.10N	1 100°C O.Q. 650°C A.C.	—	—	—
Lapelloy	0.30	1.0	0.25	0.3	12.0	2.75	—	0.25	—	—	1 100°C O.Q. 650°C A.C.	258	127	—
HT-9	0.20	0.6	0.4	0.5	11.5	1.0	0.5	0.3	—	—	1 050°C O.Q. 760°C A.C.	200	100	—
EM-12	0.10	1.0	0.4	—	9.5	2.0	—	0.3	0.4	—	1 080°C O.Q. 785°C A.C.	210	120	60
TAF	0.18	0.5	0.3	—	10.5	1.5	—	0.2	0.15	0.03B	1 150°C O.Q. 700°C A.C.	373	216	137

TR1200 (see Table 2) with promising creep rupture strength and toughness for large steam turbine rotor materials.

These newly developed steels are expected to find application beyond the original steam turbine, gas turbine and boiler tubing materials. Other applications include fuel cladding, wrapper and steam generator tubings for fast breeder reactors and the first wall materials for the conceptual fusion reactor. Many development programs for 8–14% Cr steels are now underway worldwide as well as in Japan.

2. Steels for Advanced Supercritical Power Plant

In the United States, due to the prices and availability of oil and the marked slowdown in the construction of nuclear power plants, attention is still focused on the coal-fired power plants with high availability and efficiency as new generating capacity addition. EPRI's studies have concluded that, on the economic basis, the coal-fired plant should be designed with advanced supercritical steam conditions and a plant using 315 kg/cm^2 and 593°C steam is a technically sound choice. Based on the studies, EPRI has a plan to operate a 600–800 MW coal-fired unit with the above steam condition in 1995. Development of 9–12% Cr ferritic heat-resistant materials would be the key to the plant operation.

In Japan, Electric Power Development Co. (EPDC), who coordinates the development program of all Japanese utilities and manufacturers, started in 1981 the development of technologies on advanced steam condition (Ultra Super Critical: U.S.C.) EPDC now has a plan to put into operation a demonstration power plant; simulated to 1 000 MW coal-fired unit, with 102 kg/cm^2 and 650°C steam condition in 1990 (step-2). The EPDC's development program is considered to be of great importance and would place an impact on the trend of power plant technologies.

2.1. Steels for Steam Turbine Rotor

In the early 1960's a new rotor forging steel was developed by General Electric, the composition shown as "G.E." in **Table 2**. The G.E. steel, which has been used successfully in the super critical power plant for 20 years provides a substantial improvement in creep rupture strength up to 570°C. However, today there has emerged a strong need to develop a new rotor steel for the applications at higher temperature of 593 to 650°C for advanced power plants.

The steam condition of 593°C (1 100°F) to be targeted in EPRI's development program would be presumably due to the doubt that a large uncooled 11% Cr rotor could be successfully operated at over 593°C.

Development program of new ferritic rotor steels was begun in 1982 by the author with Kobe Steel and Mitsubishi Heavy Industry and the key to develop the new rotor steels for the operation at 620°C has been found through the improvement of TAF steel. Table 2 shows the newly developed rotor steels with typical chemical compositions, heat treatment conditions and 10^5 h creep rupture strength at 600 and 650°C. These new rotor steels, TR1100/1150/1200, provide a substantial improvement in creep rupture strength over G.E. rotor steel. **Figure 1** shows the comparison between

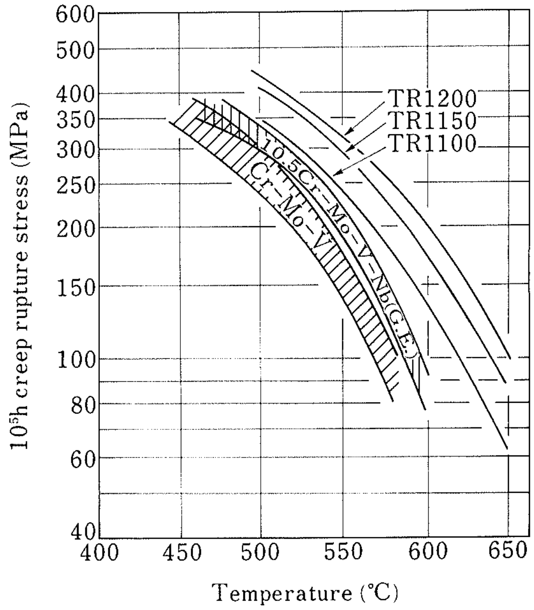

Fig. 1. High temperature strength of typical turbine rotor and developed steels.

Table 2. Advanced 10–12% Cr steels for steam turbine rotor. (mass%)

	C	Si	Mn	Ni	Cr	Mo	W	V	Nb	N	Al	Remarks
G.E.	0.19	0.30	0.65	0.6	10.5	1.0	—	0.20	0.085	0.060		1)
TR1100	0.14	0.05	0.50	0.6	10.2	1.5	—	0.17	0.055	0.040	0.002	593°C 2)
TR1150	0.13	0.05	0.50	0.7	10.7	0.4	1.8	0.17	0.060	0.045	<0.005	621°C
TR1200	0.13	0.05	0.50	0.8	11.0	0.15	2.5	0.20	0.080	0.050	<0.005	650°C

	Heat treatment	10^5 h creep rupture strength (MPa)	
		600°C	650°C
G.E.	1 050°C O.Q. 570°C A.C. 620°C A.C.	(68)	—
TR1100	1 050°C O.Q. 570°C A.C. 680°C A.C.	118	64
TR1150	1 050°C O.Q. 570°C A.C. 680°C A.C.	157	83
TR1200	1 050°C O.Q. 570°C A.C. 710°C A.C.	(176)	(98)

1) Over 20 years experience at 566°C 2) Applied to the EPDC's demonstration plant.

the mean values of the predicted 10^5 h creep rupture strength of TR1100, TR1150 and TR1200.

Taking into account the maximum metal temperature of the rotor which drops by 10–15°C from the steam inlet temperature and the design stress for the rotor being 120–130 MPa, the author consider that the new rotor steels could be applied to the targeted steam condition as TR1100 for 593°C and TR1150 for 620°C. In the case of TR1150 which differ from the conventional G.E. rotor material in containing a considerable amount of W, mechanical property testings should be performed on the coupon taken from the actual size rotor forgings. In addition a long time aging program should be done to determine the extent of embrittlement tendencies. TR1200[18)] is still in development stage for the purpose of introducing the rotor steel to be used at 650°C. The author is convinced that a 12–15 ton rotor forging to be used in the steam condition with 350 kg/cm^2 and 650°C could be introduced through the pursuit of the optimum compositions and heat treatment condition.

Below, the outline of the development concept will be discussed.

As the stress rupture curve of G.E. rotor steel which contains higher carbon and nitrogen indicates a marked decrease of creep rupture strength at extended times, 0.19% carbon content should be lowered to 0.13% coupled with 0.04% nitrogen. In addition TR1100 steel contains 1.5% Mo for solid-solution strengthening and stabilization of $M_{23}C_6$ and M_6C carbides and 0.05% Si for reducing the segregation of ingot. The TR1100 of these modified compositions gives better creep rupture strength over G.E. steel, 20–30°C higher in terms of temperature. Based on the result which shows the effectiveness of W at an elevated temperature over Mo, development studies have been performed on steels with increased W content under the condition of 1.2–1.5% Mo equivalence (Mo% + 1/2W%). **Figure 2** shows the high-temperature strength and toughness at room temperature of these materials. A 3% content of W can remarkably improve the creep rupture strength though the toughness at room temperature decreases. Being intended for use at temperatures about 80°C higher than for G.E. steel, TR1200 steel is tempered at 710°C.

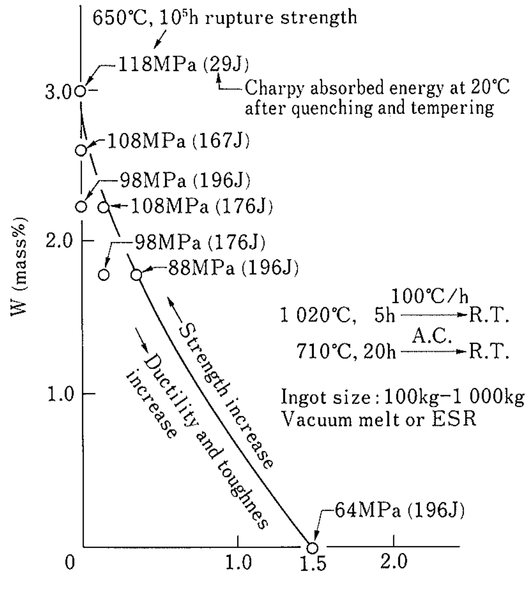

Fig. 2. Effects of Mo and W on 650°C, 10^5 h rupture strength and Charpy absorbed energy of super 11 Cr steels for rotor.

Although the austentic steels like A286 (15Cr–26Ni–1.3Mo–2.15Ti–0.2Al–0.3V) and Discaloy (13.5Cr–25Ni–3Mo–1.75Ti) are the candidate rotor materials for EPDC's step-2 steam turbine to be operated at 650°C, there would be a significant disadvantage of higher thermal expansion and lower thermal conductivity. That disadvantage gives rise to a higher thermal stress which, coupled with a lower yield strength, might reduce the low-cycle fatigue life in the case of the cyclic operation of a power plant. Therefore, the steam condition of the advanced power plant would be determined on the basis of the high temperature strength of 10–12% Cr ferritic steels.

2.2. Steels for Boiler Tube

The author started the research and development of high Cr ferritic steels for use in boiler tubes with Nippon Steel Corp. in 1975, considering that steels of this type had excellent strength at 550 to 650°C, good corrosion resistance and formability, and had been expected to be extensively used later.

At that time the author had already developed TAF steel whose high temperature strength was the highest of all high Cr ferritic steels, and had the long term data (10^4 to 10^5 h) at high temperature.[5)] However, this steel with high B content did not have good weldability and formability which are required for boiler tubes. For this reason, new high Cr ferritic heat resistant steels for boiler was designed, whose chemical compositions and heat treatment conditions are shown in **Table 3**, on the basis of TAF steel.

Optimum C content is considered to be 0.05 to 0.10% in order to satisfy high temperature strength, good weldability and formability which are required for boiler steels. C content less than 0.05% gives good weldability, but reduces high temperature strength. On the other hand, C content more than 0.10% works reversely. Therefore, two kinds of steel, T-1 and T-2, whose C contents are set at 0.05 and 0.10% respectively, and other compositions are the same as those of TAF steel, were adopted.

Though optimum Cr[9)] content had been found to be 9 to 10% by previous investigations, Cr content of 10% was selected in consideration of corrosion resistance at high temperature of about 600°C. Addition of other

Table 3. Design of chemical composition and heat treatment condition of 10% Cr boiler tube steels. (mass%)

Steel	C	Si	Mn	Cr	Mo	V	Nb	N
T-1	0.05	0.3	0.5	10	2.0	0.10	0.05	0.02
T-2	0.10	0.3	0.5	10	2.0	0.10	0.05	0.02

1 050°C for 0.5 h, air cooled, 700°C for 1 h, air cooled.

alloying elements to 0.05 to 0.10%C–10%Cr steel produces delta ferrite of 20 to 30%, which is beneficial for weldability.

Mo is the most important element that determines the high temperature strength of this type of heat resistant steel. Mo content was fixed at 2% in consideration of corrosion resistance, formability, toughness, and delta ferrite content, though Mo enhances solution hardening and precipitation hardening by carbides ($M_{23}C_6$, M_6C and so on) and intermetallic compounds (Fe_2Mo) with its increase in content.

Addition of even small amount of V remarkably changes the high temperature strength of this steel. Optimum content of V is 0.20% for C content of about 0.2%.⁵⁾ Addition of 0.25% V to 0.05% C steel causes precipitation of only V_4C_3. Therefore, V content of 0.25% is excessive and should be less than 0.10 or 0.15% in order to raise high temperature strength by gradual precipitation of many kinds of carbides such as $M_{23}C_6$, M_6C and NbC. V content was eventually fixed at 0.10% in consideration of weldability and so on.

Addition of small amount of Nb also raises high temperature strength. Because NbC is hard to dissolve even at high temperature, Nb content must be 0.03 to 0.05% for the 0.05% C steel and 0.02 to 0.03% for the 0.1% C steel respectively, in order that NbC can dissolve into the matrix by normalizing at 1 050°C. But if all Nb-carbides dissolve into the matrix at the normalizing temperature of 1 050°C, grain growth occurs and causes reduction of notch toughness. Therefore, Nb content was fixed at 0.05%, so that small amount of NbC remains even after subjection to normalizing.

This heat resistant steel thus designed is strengthened by very fine precipitation of V_4C_3 and NbC in tempering and in the early stage of creep, followed by precipitation of $M_{23}C_6$, M_6C and so on. The carbon of 0.05% contained in this steel is shared to form carbides as follows:

0.020% for V_4C_3, 0.005% for NbC, and 0.025% for $M_{23}C_6$ and M_6C.

Moreover, following equation must be satisfied in order that $M_{23}C_6$ and M_6C besides V_4C_3 and NbC can precipitate:

$$V/51 + Nb/93 < C/12$$

Stress *vs.* rupture time curve of T-1 steel is shown in **Fig. 3**¹⁰⁾ with those of other representative heat resistant steels. It is clear that T-1 steel has higher 10 h⁴⁾ creep rupture strength at 600°C than those of ever developed 9% Cr ferritic steels and even that of austenitic stainless steel (type 304). Low strength of EM-12 (9Cr–2Mo–V–Nb) is deduced owing to that most of C atoms are consumed to form V_4C_3 and NbC, and the amounts of $M_{23}C_6$ and M_6C precipitates are scarce.

In addition, the effects of V and Nb on creep rupture strength at 600 and 650°C of 0.05C–10Cr–2Mo steels are shown in **Figs. 4** and **5**.¹¹⁾ The alloy compositions of T-1 steel seem to be fairly well designed, however these figures indicate also the difficulty of steel design which gives high strength at higher temperature for longer term, because the higher strength at 650°C is obtained not at 0.1% V but at high V content of 0.18%.¹¹⁾ Addition of large amount of V is necessary, for V carbide is more stable than the other carbides at 650°C.

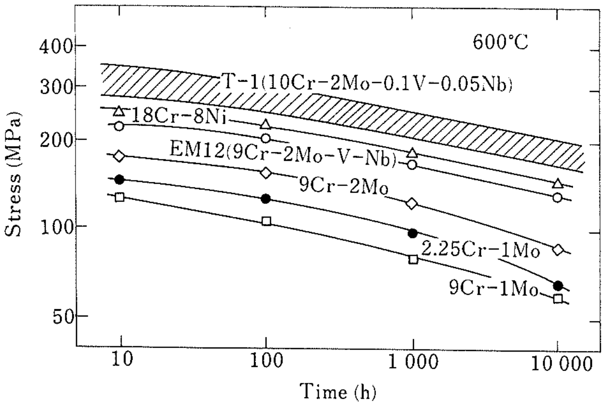

Fig. 3. Creep rupture strength of T-1 steel and other representative heat resistant steels at 600°C.

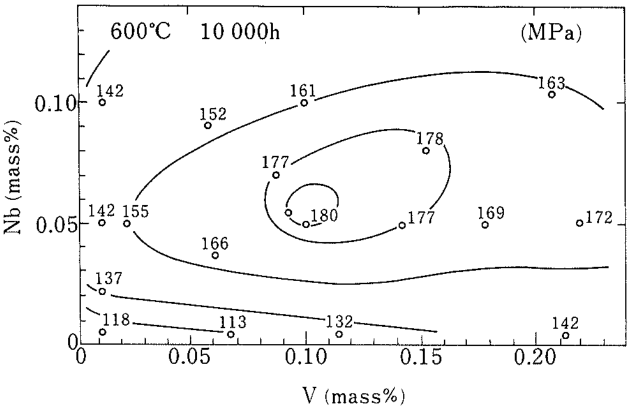

Fig. 4. Effects of V and Nb on 10^4 h creep rupture strength at 600°C, equi-strength diagram.

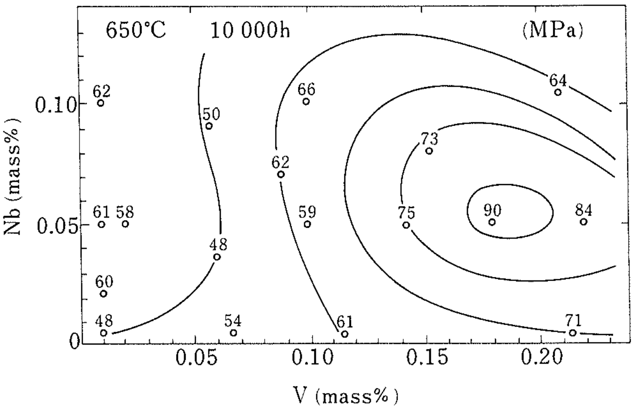

Fig. 5. Effects of V and Nb on 10^4 h creep rupture strength at 650°C, equi-strength diagram.

Creep rupture strengths for T-1 and T-2 steels are shown in **Fig. 6**. It is clear that creep rupture strength increases by 20 to 30% with increase in C content. This is because sufficient amount and distribution of $M_{23}C_6$, V_4C_3 and NbC precipitates are formed at higher C content.

Subsequently, investigations of the effects of alloying elements such as Mo,¹⁰⁾ V+Nb,¹⁰,¹¹⁾ Cr,¹²⁾ Ni¹³⁾ and

W[14] have been continued, and resulted in the development of TB9 and TB12 (9 or 12%Cr–0.5Mo–1.8W–V–Nb) steels for boiler tubes of excellent high temperature strength. 10^5 h creep rupture strengths of these steels at 600 to 650°C are about twice as high as that of the modified 9Cr–1Mo steel[15] which was recently developed by ORNL (Oak Ridge National Lab.) in cooperation with C.E., Inc. (Combustion Engineering, Inc.).

Chemical compositions and creep rupture strengths of these steels are shown in **Table 4** and **Fig. 7** in comparison with other representative steels. This table shows that TB12 steel has more excellent strength at about 650°C than austenitic stainless steels. In Fig. 7, it is clear that TB12 has about five times as high strength at 600°C as those of conventional ferritic steels, and this increase in strength means increase in allowable temperature by 120 to 130°C. Therefore these TB9 and TB12 steels are epochal heat resistant steels and indeed promising as excellent steels for boiler tubes in place of 2 1/4Mo steel, type 316, 321 and 347 steels.

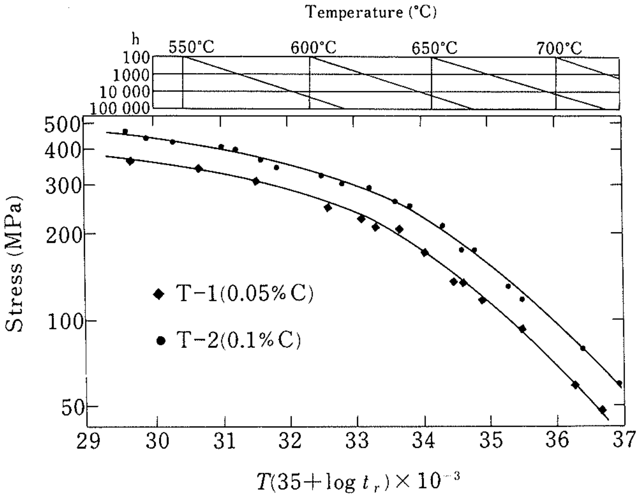

Fig. 6. Creep rupture strength of T-1 and T-2 steels.

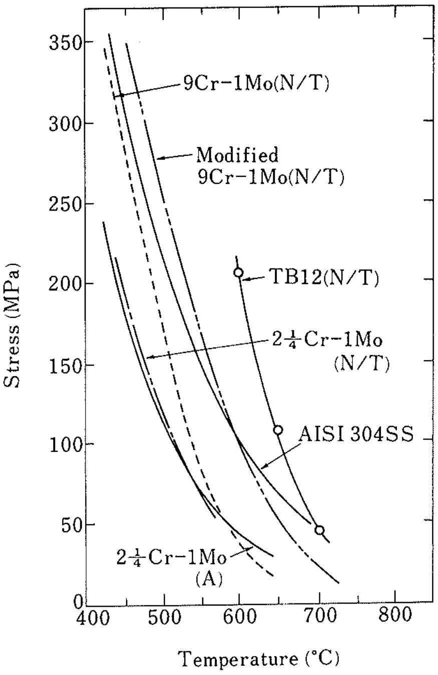

Fig. 7. 10^5 h creep rupture strength of heat resistant steels.

Table 4. Boiler tubing materials. (mass%)

	C	Si	Mn	Ni	Cr	Mo	W	V	Nb	N	B	10^5 h creep rupture strength (MPa)	
												600°C	650°C
9Cr–1Mo	0.10	0.5	0.4	—	9	1.0	—	—	—	0.02	—	39	20
Mod.9Cr–1Mo	0.10	0.35	0.45	<0.2	8.75	0.95	—	0.21	0.08	0.05	—	98	49
Mod.NSCR 9	0.08	0.05	0.5	0.1	9	1.6	—	0.16	0.05	0.03	0.003	128	69
TB9	0.08	0.05	0.5	0.1	9	0.5	1.80	0.20	0.05	0.05	—	196	98
TB12	0.08	0.05	0.5	0.1	12	0.5	1.80	0.20	0.05	0.05	0.003	206	108
AISI304	0.08	0.6	1.5	10	18.5	—	—	—	—	0.05	—	118	69
AISI347	0.06	0.5	1.7	12	17.5	—	—	—	0.8	0.02	—	128	78

Table 5. Alloy designed high-Cr ferritic heat resistant steels. (mass%)

	C	Mn	Si	Ni	Cr	Mo	W	V	Nb	N	B
TF1	0.12	0.5	0.20	0.8	9.0	0.60	1.6	0.2	0.06	0.050	0.003
TF2	0.18	0.5	0.05	0.1	11.0	0.20	2.4	0.2	0.08	0.025	0.015
TF3	0.18	0.5	0.05	0.1	10.5	0.20	2.4	0.2	0.08	0.025	0.015

	Heat treatment	10^5 h rupture strength (MPa)			Remarks
		550°C	600°C	650°C	
TF1	1 050°C A.C., 730°C A.C.	274	147	78	Casing, Valve
TF2	1 100°C A.C., 750°C A.C.	343	196	108	Turbine blade
TF3	1 100°C A.C., 750°C A.C.	343	196	108	Bolt

2.3. Steels for Turbine Blade, Casing and Bolt

It is expected that turbine blades, casings and bolts in future advanced super critical power plants will have to be resistant to temperature 50–100°C higher compared to those made of conventional materials. Thus studies on various types of ferritic steel and austenitic stainless steel are currently under way. Anyway, the use of a high-Cr ferritic steel turbine rotor will require the adoption of a high-Cr ferritic steel casing, or the use of an austenitic heat-resistant alloy turbine rotor will require the adoption of an austenitic steel casing.

When the latter, *i.e.* austenitic heat-resistance alloy, is used, night time shutdown will be difficult as stated above. Therefore, from the economic point of view, high-Cr ferritic steel is likely to be adopted in power plants, even if the steam conditions have to be reduced from the optimum ones. The research by the author currently does not include a study on the characteristics of high-Cr ferritic steel as material for casings, valves, blades or bolts. **Table 5**[12)] shows creep rupture strength for alloys designed.

3. Steels for Fast Breeder Reactor

Type 316 steel is presently used for fuel and wrapper tubings of fast breeder reactors, and mod. type 316 (with Ti and Nb addition), D-9 (0.05C–14.5Ni–14.5Cr–2Mo–0.25Ti–0.05Zr) and so on are under further investigation for that purpose. Besides studies are recently being made on 9 to 12% Cr ferritic steels. This is because ferritic steels have relatively high strength at high temperature, good corrosion resistance to liquid sodium, and excellent characteristics against neutron irradiation, namely good resistance to swelling. Therefore, 9 to 12% Cr steels, whose 4 to 6×10^4 h creep rupture strengths at 650°C are equivalent to or higher than those of 316 steels which are less in resistance to swelling, are urgently required, and at present, TB9 steel seems the most suitable material for these purposes. On the other hand, Power Reactor and Nuclear Fuel Development Corporation is making effort to develop a high Cr ferritic steel that has 10^4 h creep rupture strength at 650°C of 15 kgf/mm^2. Creep rupture strength of TB12 steel tempered at 760°C is expected to reach this value, but the problem is to form thin and narrow tubing such as fuel cladding tubing of this steel.

The use of high Cr ferritic steel in steam generator in place of 2 1/4 Cr–1Mo steel or type 321 steel is also investigated, because it has good corrosion resistance to liquid sodium and water. 9Cr–1Mo steel, EM-12 steel and so on have already been in use in the U.K. and France. Therefore, the use of TB9 and TB12 steels also in steam generator is required.

4. Steels for Nuclear Fusion Reactor

Though it is planned to use type 316 steel for the first wall materials of the nuclear fusion reactor, improvement of its resistance to swelling and the embrittlement is remained as the problem. On the other hand, HT-9 steel, a high Cr ferritic steel, is actively being investigated to take the place of this type 316 steel in the U.S.A. HT-9 steel is very much superior to type 316 steel. Though this HT-9 steel has been applied for boiler in Europe for a long time, further improvement is necessary to apply this steel to the first wall material in the future. In the U.S.A., mod. 9Cr–1Mo steel has already been developed and investigated as a material in place of HT-9 steel. The author thinks that TB9 steel is more excellent as the material with low induced radioactivity than mod. 9Cr–1Mo steel, as mentioned below.

Recently the materials with low induced radioactivity are under investigation in the U.S.A. The author has proposed the following ferritic and austenitic steels for it. As allowable contents of alloying elements for the induced radioactivity are <0.0030% Mo, <0.00029% Nb, <0.91% Ni, <0.12% Cu and <0.33% N,[16)] the optimum ferritic steel is deduced to be the 0.12C–0.05Si–0.4Mn–9Cr–2.5W–0.2V–0.12Ta–0.03N steel which is high Cr ferritic TB9 steel without Nb and Mo. On the other hand, of the austenitic steel, nickel less Mn–Cr steel or 0.2C–0.05Si–18Mn–12Cr–2W–0.5V–0.2Ta–0.2N is recommended. In the U.S.A., Fe–30Mn–(0 to 10Cr) and Fe–15Mn–(5 to 15Cr) steels are investigated. Though the former has good resistance to swelling, the latter is thought to be suitable for the use at 400 to 600°C.

5. Heat Treatments of Steels

When high-Cr ferritic steel is used as material for a large-sized turbine rotor, the diameter of the drum will be 1 000–1 200 mm, leading to a hardening cooling rate of about 100°C/h at the central part. This causes the precipitation of a rather large amount of carbides during the hardening cooling process. Thus the C content should be maintained at 0.12–0.13% while increasing the N content to 0.04–0.06% to improve the high-temperature strength. Accordingly, the low C content requires a low hardening temperature of 1 050°C compared to conventional 1 050–1 100°C and in addition, the tempering temperature should be increased from conventional 620–650 to 700–720°C in order to achieve a stable high-temperature strength.

For relatively small components such as turbine blades, on the other hand, the high-temperature strength may be improved by increasing the C content. However, 0.2% C content or greater leads to coagulation of carbides during operation. Thus the optimum conditions are (C+1.5N) content of about 0.18–0.22%, or 0.18%C+0.025%N, and hardening and tempering temperatures of 1 100 and 750°C, respectively.

For such components as boiler tube which require improved long-term creep rupture strength and formability at room temperature, it is desirable to perform tempering at a temperature 130–150°C higher than the service temperature. **Figure 8** shows the stress–creep rupture time curve of a 9Cr–Mo–W–V–Nb steel. This steel was heat treated to 1 050°C for 30 min and air cooled, and then to 775°C for 1 h and air cooled. This gives a stable creep rupture strength at 600–650°C, as seen from Fig. 8.

	C	Si	Mn	P	S	Cr	Mo	W	V	Nb	B	N
A	0.070	0.06	0.42	0.002	0.005	8.98	0.52	1.65	0.16	0.049	0.004	0.038
B	0.054	0.05	0.45	0.005	0.004	9.04	0.50	1.82	0.20	0.050	-	0.037
C	0.085	0.06	0.45	0.004	0.002	9.00	0.50	1.80	0.20	0.054	0.004	0.048

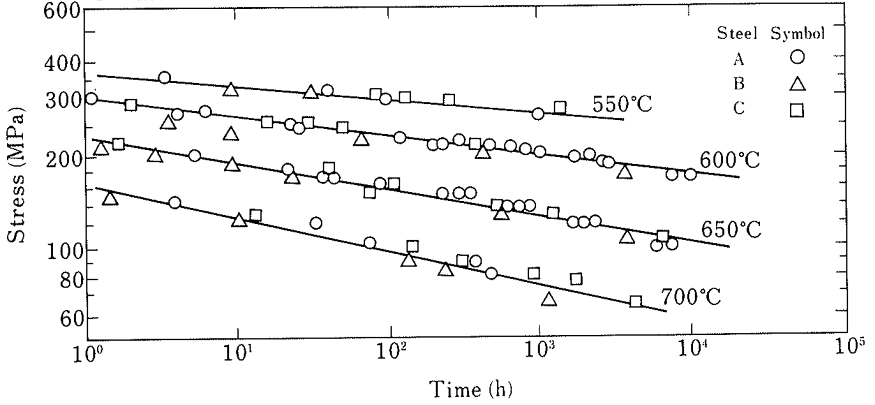

Fig. 8. Stress–creep rupture time diagram of 9Cr–Mo–W–V–Nb steels.

In general, the optimum heat treatment to provide high-Cr ferritic steel with improved toughness and ductility in addition to long-term creep rupture strength are as follows: heating is performed at 1 050–1 100°C (depending on heating time) so as to allow a several-percent carbide to remain after the hardening treatment, the diameter of grain size being kept as small as possible to improve the toughness and ductility, and tempering being carried out for 1–2 h at temperature 130–150°C higher than the service temperature, which corresponds to 10^5 h at a service temperature calculated through the Larson–Miller parameter $T(30+\log t)$.

6. Conclusion

Recent developments and future trends of high Cr ferritic heat resistant steels are summarized. These steels are lately paid attention and being applied to advanced supercritical power plants, fast breeder reactors, nuclear fusion reactors, and so on. High Cr ferritic heat resistant steels have been hitherto thought to be applicable only below 550 to 600°C. However, studies performed in recent years made this steel applicable up to 650°C. Thus it is not too much to say that the time, when the future power plants (including nuclear fusion reactor) are put to practical use, depends on the development of high Cr ferritic resistant steels.

Our works are now ahead of foreign researches in the field of high Cr ferritic heat resistant steels, and these steels are expected to be further in vestigated and increasingly improved. The author also desires to promote more actively the investigations on these steels and to serve the high technology in the world.

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