Niobium Bearing Structural Steels
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INVESTIGATION AND APPLICATION OF FERRITIC BOILER STEELS IN ULTRA-SUPER-CRITICAL (USC) POWER PLANTS

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Abstract

This paper briefly introduces the significant importance of the enhancement of plant boiler steel parameters to worldwide energy resource savings and emissions reduction, and the strategic research projects to the R&D of ferritic boiler steels in China, Europe, Japan, Korea and USA. A summary of the historic evolution of ferritic boiler steels in the last fifty years and the critical significance and importance of niobium (Nb) addition is given.

The emphasis of the paper is on chemistry design and optimization of such steels, the effect of heat treatment on properties, experimental simulation of hot deformation process, testing to determine the creep rupture strength as well as data accumulation. Finally, the application prospect of ferritic boiler steels in USC power plants for today and tomorrow is also discussed.

Importance of ultra-super critical (USC) fossil power plant technology

With the fast development of the Chinese economy in the past decades, the shortage of resource and energy has becoming the critical issue to concern. Since 2002, the shortage of electrical power became a serious problem across the whole nation, which negatively influences peoples' daily life and economical development. To meet the ever-increasing requirement, the Chinese government has to modify national planning on the development of electrical power. The proposed number was recently increased from 960 million KW to 1340 million KW. The total amount and percentage distribution of Chinese electrical resource from the year of 2000 to 2020 are listed in Table 1. Obviously, fossil fuel power plants are dominant, because of the relatively rich coal resources in China.

Table 1. Total amount and percentage distribution of Chinese electrical resource.

Year	Amount，M KW	Fossil fuel	Hydro	Nuclear	New energy
2000	319	72.10%	24.87%	0.66%	-
2005	470	74.80%	23.20%	1.90%	0.14%
2007	713	77.73%			
2020	1340			4.00%	

However, more than half of annual coal production was used by fossil fuel power plants as seen in Table 2.

Table 2. Chinese annual coal production and used by fossil fuel power plants (100 million tons).

Year	2002	2003	2004	2007	2020
Coal production	12.5	16.6	17.5	25.23	?
Used for fossil power plants	7.0	8.5	9.3		
Ratio of above	56%	51.20%	53.14%		

Coal is a limited and non-renewable fossil resource. The combustion of coal in power plants generates huge amount of CO_2, SO_2 and NO_x, heavily polluting the environment. Technically, an increase of the steam parameter of fossil fuel power plants is the most important approach to save coal resources and reduce harmful gas pollution. As shown in Table 3, the higher steam parameter is then the higher thermal efficiency of power plants and the less coal consumption. Currently, the steam parameter of most Chinese fossil fuel power plants is sub-critical or below. The average coal consumption of Chinese fossil power plants in 2007 was 357 g/KWh, which reduced by 10 g/KWh compared with that in 2006. The first ultra super-critical fossil fuel power plant, YuHuan power plants in Zhejiang Province of China, was commissioned in the late 2006. The average coal consumption of the plant in 2007 was 283.2 g/KWh.

Table 3. Steam parameters of power plants and average coal consumption.

Type of power plant	Steam pressure, MPa	Steam temp，°C	Coal consumption g/KWh
Medium pressure	3.5	435	455
High pressure	9	510	372
Ultra-high pressure	13	535/535	351
Sub-critical	17	535/535	323
Super-critical	25.5	566/566	300
Ultra super-critical	27	600/600	273
Ultra super-critical	30	600/600/600	256
Ultra super-critical	35	700/720	223

It was reported that the total electrical power amount was 2698 billion KWh in 2007. If all fossil fuel power plants of China had been replaced by ultra super-critical power plants, the nation would have saved 200 million tons standard coal annually, reducing by 540 million tons CO_2

emissions yearly. In addition, it would have also consumed cherished resources and energy to dig the extra 200 million tons standard coal and transport the coal to power plants which generally are far away. More importantly, the burning of the extra 200 million tons standard coal pollutes the environment even worse.

After seven years of hard work, the Kyoto Protocol was finally approved by more than 100 countries worldwide. The green house gas emission of these countries accounts for about 55% of total emission in the year of 1990. Kyoto Protocol proposed that the emission of green house gases in developed countries decreases 5.2% during the period of 2008 to 2012, compared to the year of 1990. Therefore, Kyoto Protocol is not only an environmental problem but also an economical and political issue. Today, the emission of CO_2 in China already ranks second worldwide and it is predicted that China will exceed the USA in 2025. Thus, the effective development of ultra super-critical fossil fuel power plants in China is one of the most important approaches to ensure national energy securities, save resources and reduce environmental pollution.

National strategic research plans of USC steels

Heat resistant steels used for ultra super-critical fossil power plants take a long development time and require a large budget. Therefore, it is necessary and imperative to have national strategic research plans in place to develop advanced boiler steels. European countries launched COST501 plan from 1983 to 1997 to investigate heat resistant steels used for 30MPa/ 600/620°C power plants, and launched COST522 plan from 1998 to 2003 to investigate heat resistant steels used for >30MPa/ 650°C power plants, and is now running COST536 plan. Since 1998, European Commission launched Thermie Plan (also called 700 plan) for 17 years to investigate heat resistant steels used for 37.5MPa/7000 power plants. The American government launched the CCT plan to support material technology development used for high efficient power plants from 1986 to 1992, and since 1992, the American government launched Combustion 200 plan, which was merged into Vision 21 plan later.

Japan imported technologies of ultra super-critical power plants from European countries and the USA in the 1960s. Japanese government settled its national research plan from 1982 to 2001 to emphasis on the development of heat resistant steels used for fossil power plants. The first stage of the plan was to develop steels used for 31MPa/566/566/566°C steam parameters and the second stage of the plan was to develop steels used for 34MPa/593/593/593°C steam parameters. In addition, Japanese government had funded the National Institute for Material Sciences (NIMS) since 1997 to develop ferritic boiler steels used for 650°C steam parameters. Through importing, absorbing, imitation, and innovation, Japan has overtaken the European countries and the USA in the field of heat resistant steels used for fossil power plants in recent decades. Since 2003, the Korean government also launched a national research plan to support ferritic heat resistant steel development used for 650°C steam parameters.

The Chinese government started to support boiler steel investigation since 2003, and settled two research projects in a laboratory study of T122 and S30432 steels as well as ferritic boiler steel used for 650 steam parameters in 2003 and 2006 respectively. Recently, the Ministry of Sciences and Technology of China launched a national strategic plan to realize the commercialization of advanced boiler steels used for ultra super-critical fossil power plants in China from 2007 to 2011. In addition, the Central Iron and Steel Research Institute and BaoSteel Co. Ltd. already signed a long-term strategic contract to jointly develop advanced heat resistant steels used for fossil power plants to gradually meet market requirement inside China.

Requirement to advanced boiler steels of development of Chinese USC plants

The first 600MW super-critical fossil power plant in China, with a steam parameter of 24.2MPa/566°C/566°C, was commissioned in November 2004. The first 1000 MW ultra super-critical fossil power plant in China, with a steam parameter of 26.25MPa/600°C/600°C, was commissioned in December 2006. Near the end of 2007, Chinese boiler manufacturers already got 220 orders of 600MW super-critical fossil power plants, 76 orders of 600MW ultra super-critical fossil power plants, and 94 orders of 1000MW ultra super-critical fossil power plants, which clearly indicate a rapid growth of ultra super-critical fossil power plant in China. The dimension and amount required tubes and pipes for boiler construction are listed in Table 4. The critical steel grades required for boiler construction are including T/P91, T/P92, T/P122 (HCM12A), S30432 (Super 304H) and S31042 (HR3C). Besides T91 steel, all of the aforementioned steels are imported from overseas today in China.

Table 4. Dimension and amount requirement of boiler tubes and pipes.

Dimension , mm	Amount, Ton per 10^4 KW
φ (31-146) X (3-20)	60
φ (159-245) X (10-30)	4
φ (273-711) X (20-130)	18
φ (720-1066) X (20-100)	3
Other special tubes and pipes	5
Total requirement of 90 tons per 10^4 KW, 70% of them are alloy steels	

Based on Table 4, it requires about 2.45 million tons advanced boiler steel tubes and pipes to build 390 fossil power plants in China. Among them, about 1.70 million tons are alloyed steel tubes and pipes. In addition, it was estimated that it requires 1100 tons of T/P91 steel and 600 tons TP347H steel tubes to build a 1000 MW super-critical fossil power plant. It requires 1500 tons of T/P91 and T/P92 steel and 860 tons S30432 and S31042 steel tubes to build a 1000 MW ultra super-critical fossil power plant. Assuming that it increases 400 to 500 million KW in China from 2008 to 2012, and 150 million KW of the power is produced by super-critical fossil power plants and 300 million KW of them is ultra super-critical fossil power plants, it will need about 630 thousand tons of T/P91 and T/P92, about 90 thousand tons of TP347H, and 250 thousand tons of S30432 and S31042. The sub-total of the above steel requirements is about 970 thousand tons. If considering the requirement of maintenance in power plants, it needs an extra 300 to 500 thousand tons steel tubes and pipes. Thus, the total requirement of boiler steel tubes and pipes in

China from 2008 to 2012 ranges from 1.30 to 1.50 million tons. Undoubtedly, China is the biggest market worldwide for heat resistant steels used for ultra super-critical fossil power plants.

Evolution of ferritic boiler steels

Compared to austenitic boiler steels, ferritic boiler steels are of better heat transfer efficiency, lower thermal expansion, higher cost savings and better weldablility. So far, the evolution of ferritic boiler steels could be divided into four generations or four stages (see Table 5). In the past half century, the application temperature of ferritic boiler steel grades available are SAVE12, NF12, 9Cr-3W-3Co(NIMS) and 15Cr-6W-3Co as well as maraging steels, used for 650°C steam temperature. However, it is still too early to assert the aforementioned steels grades can be successfully applied in the construction of fossil power plants, because the properties and their stability of the steel grades are required to be inspected from a viewpoint of longer time duration. In fact, G102 steel, developed by Professor Rongzao Liu of Central Iron and Steel Research Institute (CISRI) of China in 1960s, should be included in Table 5 as well. This feature of the steel will be introduced in the following part of the paper and the highest application temperature of the steel is about 600°C. The steel has more than 40-year service history in many power plants around the world. The mechanism of multi-element strengthening was perfectly applied in this low alloy boiler steel, which opened a novel door to develop higher creep rupture strength ferritic boiler steels.

Table 5. Evolution of typical 9-12% Cr ferritic boiler steels

Gen.	Year	Major alloying elements	Typical steel grades	Highest Temp °C
1^{st}.	1960-70	Adding Mo or Nb、V	EM12, HCM9M, HT9, F9, HT91	565
2^{nd}	1970-85	Optimizing C、Nb and V	T91, HCM12, HCM2S	593
3^{rd}	1985-95	Replacing Mo with W	HCM12A(T/P122), NF616（T/P92）, E911(T/P911)	620
4^{th}	1995-	Optimizing C、N，increasing W and adding Co	NF12, SAVE12, 9Cr-3W-3Co	650

Chemistry design and optimization of ferritic boiler steels

Boiler steels work in an environment of elevated temperature, high pressure and corrosion. The key technical properties of boiler steels are creep rupture strength and corrosion-resistance. Thus, the chemistry design and optimization of boiler steels are critical to achieve these requirements. Long time testing data is imperative not only for creep rupture strength, but for corrosion-resistance, implying that a big budget and very long time is required. To save money and time, it is significant for the chemistry design and optimization of boiler steels to do fundamental research in order to accumulate and analyze experiences. The chrome content of the present ferritic boiler steels ranges from 9% to 12%. Table 6 shows the typical chemical compositions of major ferritic boiler steels.

Table 6. Chemical compositons of typical 9-12%Cr ferritic boiler steels（wt%).

Steel grade	C	Si	Mn	Cr	Ni	Mo	W	Nb	V	N	B	Cu	Co	Fe
G102	0.08-0.15	0.45-0.75	0.45-0.65	1.6-2.1	-	0.5-0.65	0.3-0.55	-	0.18-0.28		< 0.008	Ti: 0.08-0.18		
T/P91	0.08-0.12	0.20-0.50	0.30-0.60	8.0-9.5	≤ 0.40	0.85-1.50	-	0.06-0.10	0.18-0.25	0.03-0.07	-	-	-	Bal
T/P92	0.07	≤ 0.50	0.30-0.60	8.5-9.0	≤ 0.40	0.30-0.60	1.50-2.00	0.04-0.09	0.15-0.25	0.03-0.07	0.001-0.006	-	-	Bal
T/P122	0.07-0.14	≤ 0.50	≤ 0.70	10.0-12.5	≤ 0.50	0.25-0.60	1.50-2.50	0.04-0.10	0.15-0.30	0.04-0.10	0.0005-0.005	0.30-1.70	-	Bal
T/P911	0.09-0.13	0.10-0.50	0.30-0.60	8.5-9.5	0.10-0.40	0.90-1.10	0.90-1.10	0.06-0.10	0.18-0.25	0.05-0.09	-	-	-	Bal
NF12	0.08	0.2	0.5	11	-	0.2	2.6	0.07	0.2	0.05	0.004	-	2.5	Bal
SAVE12	0.10	0.3	0.2	11	-	-	3.0	0.07	0.2	0.04	0.07Ta 0.04Nd	-	3.0	Bal
9Cr-3W-3Co	0.08	0.3	0.5	9.0	-	-	3.0	0.05	0.19	0.004	0.014	-	3.0	Bal

W-Mo solid solution strengthening and V-Ti precipitation hardening were used when designing G102 steel in 1960s. In addition, B element was added to further increase creep rupture strength. Because of the low content of alloying elements of G102 steel, its highest application temperature is about 600°C. The idea to develop G102 steel was of importance to the following investigation. The successful development of T91 steel in 1978 determined the major chemistries of ferritic boiler steels. Since then, the novel steel grades developed added and optimized alloying elements, based on the major chemistries, to continuously increase creep rupture strength. The creep rupture strength of typical ferritic boiler steels was shown in Figure 1. Carbon content of steels was 0.10% or less to ensure lower carbon equivalent. Higher chrome content enhances corrosion-resistance. However, it also increases chrome equivalent at the same time. As seen in Figure 2 (Schaeffler Chart), the higher chrome equivalent may lead to the occurrence of δ-ferrite, resulting in the decrease of the creep rupture strength.

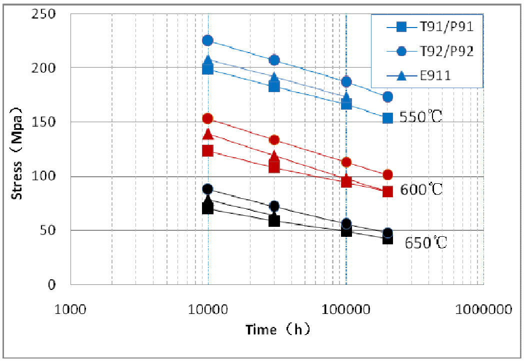


Figure 1. Creep rupture strength of typical ferritic boiler steels.

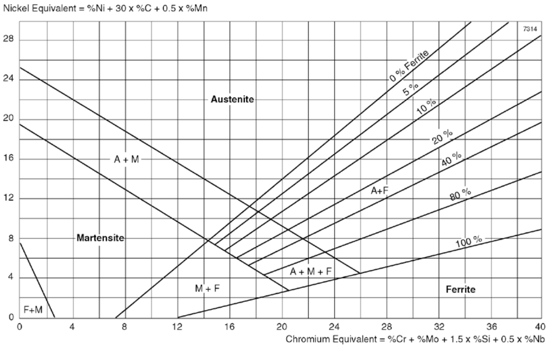


Figure 2. Typical Schaeffler chart of heat resistant and stainless steels.

Experimental results showed that when chrome content exceeds 11%, the occurrence of δ-ferrite is basically unavoidable. When the chrome content reaches 15%, the amount of δ-ferrite can be about 30% or more. Such a high δ-ferrite amount undermines the application possibility of 15% chrome steels in the construction of fossil power plants. Presently, T/P92 has a higher creep rupture strength among the available ferritic boiler steels used for 600°C steam temperature, and 9Cr-3W-3Co steel is higher creep rupture strength among the available ferritic boiler steels used for 650°C steam temperature. T/P92 steel has been successfully used in the construction of ultra super-critical fossil power plants. Industrial pipes of 9Cr-3W-3Co steel have been made in Japan and properties' requirements of the steel pipes require further inspection. T/P92 steel and 9Cr-3W-3Co steel are of 9% chrome. Their corrosion resistance to water steam does not meet the application requirement. Instead, the interior surface of steel pipes needs to be specially treated. T/P122 steel is at 12%Cr. Even within the chemistry scope of ASME CC2180, the amount of δ-ferrite of the steel can be 30% or more. It may be the reason that ASME reduced the allowable stress of T/P122 steel up to 27% recently. This issue is a real problem with T/P122 steel. But, this should not lead to a negation of the steel grade. CISRI and BaoSteel, in China, are exploring the steel in depth and will attempt to develop a novel steel in between T/P92 and 9Cr-3W-3Co steel for 600-620°C steam temperature boilers.

Hot deformation investigation of ferritic boiler steels

The investigation of hot deformation is of significance to help to forge, pierce and extrude boiler steel tubes and pipes. The constitute equation of 9-12% Cr steels during hot compressing was experimentally investigated. The specimens were taken from tempered T122 bar and its chemical compositions were as follows (wt%): 0.12C, 0.38Si, 0.58Mn, 0.007P, 0.007S, 11.37Cr, 0.37Ni, 0.38Mo, 1.93W, 0.05Nb, 0.20V, 0.058Ti, 0.0028B, 0.86Cu, 0.067N, 0.037Al. The trial was conducted by Gleeble3500. The dimension of specimen was 10×15mm. According to the study of equilibrium phases and microstructure evolution of T122 steel during heating, hot deformation temperature was chosen at 900, 950, 1000, 1050, 1100, 1150 and 1200°C respectively. Strain rate was set at 0.01, 0.1, 1.0 and $10s^{-1}$ respectively, as shown in Figure 3. During test, the specimens were first heated to 1200°C at the rate of 10°C/s, holding for 5 minutes, followed by cooling to hot deformation temperature at the rate of 2.5°C/s and holding for 30 seconds, before the hot deformation test. Friction heat and deformation heat were taken into consideration during experimental data treatment,

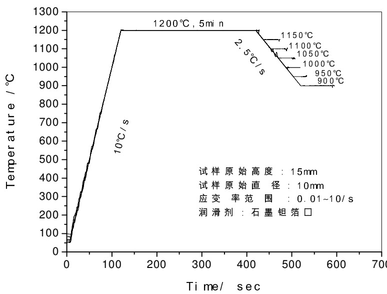


Figure 3. Hot deformation test design of T122 steel.

In order to obtain the constitute equation of T122 steel, stress-strain curves obtained under the aforementioned seven deformation temperatures and four strain rates were firstly fitted to determine material contents. The average value of the material contents was treated as the initial value to do nonlinear least squares fitting. MATLAB programmer was used to do the fitting and optimization. The two-stage constitute equation of T122 steel could be expressed as follows:

When ε : ε_c :

$$\sigma_{(e)} = \sigma_0 + (\sigma_{ss(e)} - 15)[1 - \exp(-\frac{\varepsilon}{\varepsilon_r})]^{1/2}$$

When $\varepsilon > \varepsilon_c$:

$$\sigma = \sigma_{(e)} - (\sigma_{ss(e)} - \sigma_{ss})\{1 - \exp[-(\frac{\varepsilon - \varepsilon_c}{\varepsilon_{xr} - \varepsilon_c})^2]\}$$

where : $\sigma_{ss(e)} = 252.525 \cdot \sinh^{-1}(\frac{Z}{8.031 \times 10^{18}})^{0.1457}$

$$\sigma_{ss} = 291.7238 \cdot \sinh^{-1}(\frac{Z}{6.408 \times 10^{18}})^{0.1845}$$

$$\sigma_0 = 11.933 \cdot \sinh^{-1}(\frac{Z}{30289})^{0.148}$$

$$\varepsilon_r = 0.011582 + 0.080272 \cdot \dot{\varepsilon}^{-0.01141}$$

$$\varepsilon_C = 1.6264 \times 10^{-6} \cdot (\frac{Z}{\sigma_{ss(e)}^2})^{0.42062}$$

$$\varepsilon_{xr} = 18.252 \cdot (\frac{Z}{\sigma_{ss(e)}^2})^{-0.13635} + \varepsilon_c$$

$$Z = \dot{\varepsilon} \exp(\frac{Q}{RT})$$

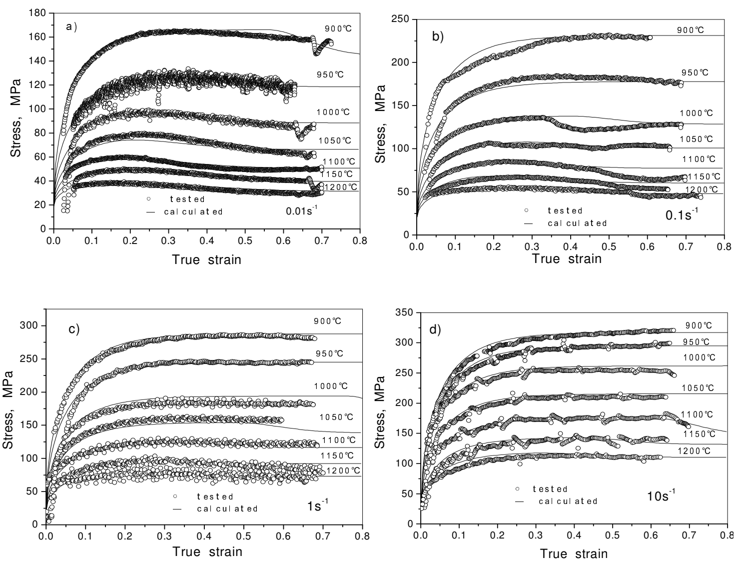


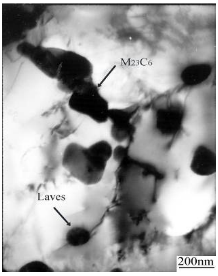
Figure 4. Calculated and measured true stress-strain curves of T122 steel.
(a) $0.01s^{-1}$,(b)$0.1s^{-1}$,(c)$1.0s^{-1}$ (d)$10.0s^{-1}$

Calculated and measured true stress-strain curves of T122 steel are shown in Figure 4. The flow stress of T122 steel increases with an increase of strain when the steel was deformed within the temperature of 900°C to 1050°C at the strain rate of $10s^{-1}$. The increase in strain may be attributed to the increase of dislocation density of the steel. With the continuous increase of strain, softening gradually increases till the dynamic balance of dislocation increment and annihilation, in which the flow stress tends to be saturated. Namely, the flow stress is independent of the change of strain. On the other hand, when T122 steel was hot deformed within the temperature of 1100°C to 1200°C and at the strain rate of $0.01s^{-1}$ and within the temperature of 1100°C to 1200°C and at the strain rate of 0.1 s^{-1}, then dislocation density increases with the increase of strain. Correspondingly, the flow stress reaches its peak value. However, when strain reaches a critical value, dynamic recrystallization may occur, which leads to a rapid decrease of dislocation density until complete recrystallization occur when the flow stress decreases to a stable value.

It is clear that the results of calculated and measured flow stress curves are of good agreement with each other under different deformation situations, as shown in Figure 4, although there are a few deviations found in the curves, i.e., in the strain scope of 0.1 to 0.35 at 900°C and $0.1s^{-1}$ and at 1000°C and 1150°C under $0.1s^{-1}$. The deviations may result from the fact that recycled recrystallization is not taken in to consideration into the models.

Effect of Niobium in the boiler steels

The boiler steels used for ultra super-critical fossil power plants can be mainly divided into two categories: ferritic and austenitic boiler steels. The niobium element is the major alloying element of the two kinds of boiler steels. The chemical compositions of typical ferritic boiler steels were listed in Table 6. The niobium content in the steels is basically controlled to be about 0.05% and the vanadium content is generally added in about 0.20%. So far, the major precipitates found in ferritic boiler steels after long term service are MX, $M_{23}C_6$ laves phase and the Z phase. The morphologies of the former three phases were shown in Figure 5. In general, $M_{23}C_6$ and laves phase are coarse and distributed along the grain boundaries. MX is finer, basically in nanometer scale, and distributed inside grains and along the grain boundaries. Experimental investigation showed that nanometer fine MX precipitates existed in typical ferritic boiler steels, such as NbC, VC, Nb(CN), and V(CN). Especially, the wing-shaped MX in T91 enhances creep rupture strength greatly. In addition, the precipitates are of good stability which ensures the high and stable creep rupture strength of the steel. In the course of boiler steel service, it is the key issue to keep the stability of the microstructure and to control the growth of precipitates. The MX phase is one of critical factors to ensure the stability of the microstructure of ferritic boiler steels after long term service at elevated temperature and high pressure. The chemical phase analysis showed that niobium element is fundamental and the important part of the MX phase. Thus, the niobium element is one of most important chemical elements to ensure microstructure stability of boiler steels after long term service.



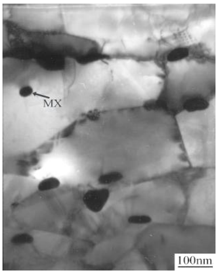


Figure 5. Morphologies of precipitates of T122 after long-term aging.

After long time testing or service, the Z phase may occur in ferritic boiler steels. Generally, the size of the Z phase is very coarse. Some researchers thought that the formation of the Z phase is at the expense of annihilation of the MX phase. Therefore, this transition may obviously undermine the creep rupture strength of boiler steels. However, the mechanism of niobium in the transition was far from understood, which should be a challenge worldwide, and needs to be further explored.

Table 7. Chemical compositions of typical austenitic boiler steels (wt%).

Steel grade	C	Si	Mn	Cr	Ni	Mo	W	Nb	N	B	Cu	Fe
TP347H	0.04-0.10	≤ 1.00	≤ 2.0	17.0-20.0	9.0-13.0	-	-	0.32-1.00	-	-	-	Bal
TP347HFG	0.04-0.10	≤ 1.00	≤ 2.0	17.0-20.0	9.0-13.0	-	-	0.32-1.00	-	-	-	Bal
S30432	0.07-0.13	≤ 0.30	≤ 1.00	17.0-20.0	7.5-10.50	-	-	0.30-0.60	0.05-0.12	0.001-0.010	2.50-3.5	Bal
NF709	0.15	0.5	1.0	20	25	1.5	-	0.2	-	-	0.1Ti	Bal
S31042	0.04-0.10	≤ 0.75	≤ 2.0	24-26	17-23	-	-	0.2-0.6	0.15-0.35	-	-	Bal
SAVE25	0.10	0.1	1.0	23	18	-	2.5	0.45	0.2	-	3.0	Bal

The chemical compositions of typical austenitic boiler steels were listed in Table 7. Niobium is the major alloying element in the steels. The average niobium content in TP347H and TP347HFG is 0.65% and the average niobium content in S30432 and S31042 is about 0.45%. Niobium plays a key role in keeping the stability of microstructure and properties of austenitic boiler steels.

The development of TP347HFG steel was based on TP347H steel. TP347H steel has an acceptable elevated temperature corrosion-resistance. However, its corrosion resistance at elevated temperature steam requires further improvement. Compared to the heat treatment of TP347H, an increase soft-treatment temperature to 1250-1300°C is necessary to make complete solid solution of the MX carbides, (i.e., NbC, followed by reasonable precipitation during subsequent cooling). Meanwhile, the solid solution temperature of the steel is similar to the TP347H steel grade.. Under such processing, precipitated NbC not only prohibits grain growth but also enhances creep rupture strength. Obtained grain can be as fine as ASTM grade No.8 or higher, ensuring a much better corrosion resistance at elevated temperature steam of the steel. Apparently, niobium plays a critical role in the course of the development of TP347HFG steel.

According to the requirement of Japanese designers, Chinese boiler makers recently added inter-granular corrosion into their ordering document of S30432 steel as an additional technical requirement. In fact, the additional technical requirement greatly increases the technical challenges to produce the boiler steel and consequently results in an increase in production cost. To meet this challenge, the authors of the current paper experimentally investigated the major influential factors of the problem and found the content of carbon and niobium has a direct effect on inter-granular corrosion of the steel. Experimental results were described in Figure 6 and the solid solution temperature should be higher than 1100°C. As seen, the left and upper region of ABCD line in Figure 6 stands for non-inter-granular corrosion region. The region below the dotted line AD stands for inter-granular corrosion region. As for the triangle region of ACD, it requires further investigation to determine whether an inter-granular corrosion region or not. Clearly, when carbon ranges in 0.081% to 0.110%, niobium must be higher than 0.69% to ensure non-inter-granular corrosion. However, the niobium content has exceeded the upper limitation (0.30-0.60%) of the element in ASME specification (2004 version), although the niobium ranged from 0.20% to 0.80% in ASME specification (2002 version). According to ASME Code Case 2328-1 and related specification, the technical solution is to make carbon content in the scope of 0.07% to 0.08% to ensure non-inter-granular corrosion of S30432 steel.

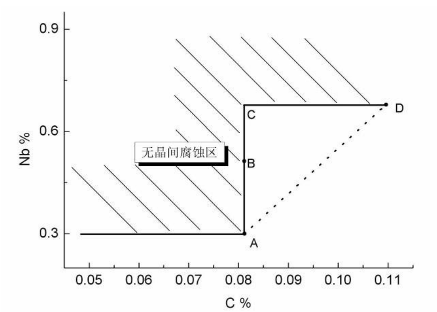


Figure 6. Effect of Carbon and Niobium of S30432steel on inter-granular corrosion.
(solid solution temperature ≥ 1100°C)

According to expected requirements of advanced boiler steels used for ultra super-critical fossil power plants during 2008 to 2012 in China in the Part 3 of the paper, the estimated requirement of pure niobium is about 2900 tons. Considering other Nb-bearing steels and maintenance, the total required pure niobium will exceed 3500 tons in the construction of ultra super-critical fossil power plants in China in the coming five years.

CISRI Creep Data-Base (CCDB) of steels of power plants

Creep data of boiler steels is a very important reference to designers. The European Creep Collaborative Committee (ECCC) and NIMS of Japan had built creep data sheets of heat resistant steels independently in the past years. Some creep rupture testing has been lasting for more than 100 thousand hours, and the longest test reached to 200 thousand hours, or even to 300 thousand hours. In China, CISRI started to establish a creep data-base in 2007 to accumulate various data. The data-base developed at CISRI was named as CISRI Creep Data-Base, which has been issued a patent from the Chinese Bureau of Copyright in May of 2008 (2008SRBJ2578). Based on C/S internet structure, Visual Basic 6.0 and SQL Server 2000 commercial package were used to develop the data-base. The source code of the data base software was 11089 rows. The data base software enables the function of query, tabulation, mapping and data analysis. The CISRI Creep Data-Base is made up of various properties of boiler steels, rotor steels and blade steels used for ultra super-critical fossil power plants. Standards of different countries and published historic literature were also included in the Data-Base.

The current creep data of the Data-Base was from the published literatures worldwide and accumulated data from research institutes, steel makers and boiler makers of China in the past years. Meanwhile, new data will be added to the Data Base yearly or monthly. CISRI is investigating the consistency and unanimity of creep testing machines and associated standards, so as to enable effectively using limited creep testing machines of China to enrich creep data as fast as possible. The major purpose of the data base is to serve technical professionals from metallurgical, mechanical and electric industries.

Summary – Development and expectation

The research and application of ferritic boiler steels is one of most important bases to build ultra super-critical fossil power plants in China and overseas. The major energy-expense countries (or developed countries) had launched national strategic research plan to develop boiler steels to support the continuous improvement and advancement of steam parameters of power plants in the past decades. Presently, Japan, European countries and the USA lead boiler steel technologies. Ferritic boiler steels developed by the above countries can basically meet the requirement of construction of 600°C steam parameter power plants. The Japanese scientists are investigating ferritic boiler steels used to 650 Based on C/S internet structure, Visual Basic 6.0 and SQL Server 2000 commercial package were used to develop the data-base. The source code of the data base software was 11089 rows. The data base software enables the function of query, tabulation, mapping and data analysis. The CISRI Creep Data-Base is made up of various properties of boiler steels, rotor steels and blade steels used for ultra super-critical fossil power plants. Standards of different countries and published historic literature were also included in the Data-Base.

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The technology of boiler steels directly relates to national safety of energy and economy. Unfortunately, China is a late-comer in this important technical field. In fact, China is the largest advanced boiler steel requirement opportunity for future decades. Within the coming five years (2008-2012), the amount of advanced boiler steel tubes and pipes required to build planned ultra super critical fossil power plants in China ranges from 1.30 to 1.50 million tons. Correspondingly, the production of the steels will require 3500 tons of pure niobium. In order to fulfill a historic task to develop and make advanced boiler steels domestically, the Chinese government has launched a strategic research project on the research and development of advanced boiler steels. CISRI is leading a big research group, from institutes, universities, and major steel and boiler makers of China, to complete the great mission. We are confident that there will be a big progress in the research and production of advanced boiler steels used for ultra super-critical fossil power plants in China in the near future.

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