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G115 STEEL AND ITS APPLICATION FOR 600+℃ A-USC-PP

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Abstract: G115 is a novel ferritic heat resistant steels developed by CISRI in the past decade, which is an impressive candidate material to make tubes, pipes and forgings of advanced ultra super critical (A-USC) fossil fired power plants used for the temperature scope from 600℃ to 650℃. The successful development of G115 extends the upper application temperature limitation of martensitic steel from 600℃ to about 650℃. This breakthrough is imperative for the design and construction of 610℃ to 650℃ A-USC fossil fired power plants, from the viewpoint of the material availability and economics of designed coal fired power plants. This paper systematically introduced the developing history and achieved progress of G115 steel. The strengthening mechanism of the novel martensitic steel was briefly discussed and the optimized chemical composition, mechanical properties of G115 steel were described. The details of four-round industrial trials of G115 tube and pipe at BaoSteel in the past years were introduced, with the emphasis on the microstructure evolution during aging and creep testing, through which it can be clearly shown that the microstructure of G115 steel is very stable up to the temperature of 650℃. Correspondingly, the comprehensive mechanical properties of G115 steel are very good. The creep rupture time is longer than 17000 hours at the stress of 120MPa and at the temperature of 650℃ and 25000+ hours at the stress of 100MPa and at the temperature of 650℃, which is about 1.5 times higher than that of P92 steel. A the same time, the oxidation resistance of G115 steel is a little bit better than that of P92 steel. If G115 steel is selected to replace P92 pipes at the temperature scope from 600℃ to 650℃, the total weight of the pipe can be reduced up to more than 50% and the wall thickness of the pipe can be reduced up to about 55%. In addition, the upper application temperature limitation of G115 steel is about 30℃ higher than that of P92 steel. Thus, G115 steel is an imposing candidate material for the manufacturing of 600+℃ advanced ultra-super-critical (A-USC) fossil fuel power plants in china and overseas.
Keywords: 600+℃ advanced ultra-super-critical (A-USC); G115 steel; Tubes and pipes

1. Introduction

In recent years, the construction of advanced ultra-supercritical (A-USC) fossil-fired power generation plant with higher efficiency has been accelerated by the demand of reducing CO2 emission for the protection of global environment. Since the first 600℃ USC power plant was successfully launched in the November of 2006, more than 200GW electric capacity of 600℃ USC units has been commercially installed in china mainland by the end of 2015, which accounts for more than 90% of available 600℃ USC units worldwide, and more 600℃ USC units will be constructed in China in the near future. The steam parameter evolution of Chinese USC power plants was schematically plotted in Figure 1[1].

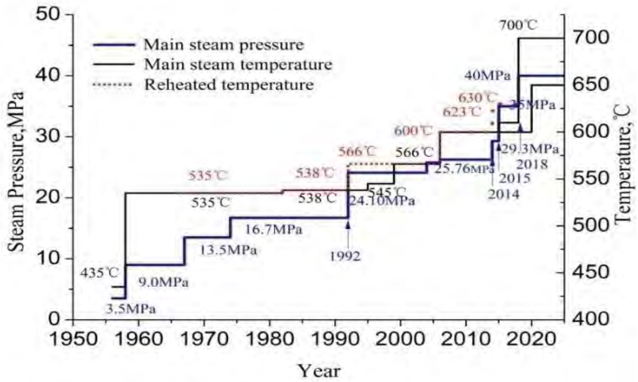

Figure 1 Steam parameter evolution of Chinese USC power plants

On July 23, 2010, Chinese government officially announced a national program to build a demo 700℃ A-USC power plant in the near future, probably starting from the year of 2025, depending the availability and maturity of heat resistant steels and alloys. To fulfill such a goal, a national consortium has been directly organized by the National Energy Administration (NEA) of China, including seventeen research facilities, manufacturers and power plant operators, which all are the leading player in their own sectors. Well known, the critical challenge of 700℃ A-USC technology lies in the R&D of high-temperature materials, not only for boiler system but also for turbine system. It is worth to mention that 610℃ and 623℃ A-USC fossil power plants had been successfully built in China by the year of 2014. And the first 700℃ A-USC testing rig had also been put into operation by the end of 2015.

2. Boiler materials spectra for 630-700℃ A-USC PP

Basically, those mature materials successfully used in 600℃ USC power plant will still be applied in 630-700℃ A-USC power plant, in where the working temperature is below 600℃. When the steam temperature increases from 600℃ to 700℃, different novel materials are necessarily required for various temperature scopes. According to published literature and our knowledge, the materials R&D sub-committee of Chinese consortium for 700℃ A-USC power plant has discussed, evaluated and summarized the candidate materials spectra used for 630-700℃ boiler of A-USC power plant in China, as schematically shown in Figure 2[2].

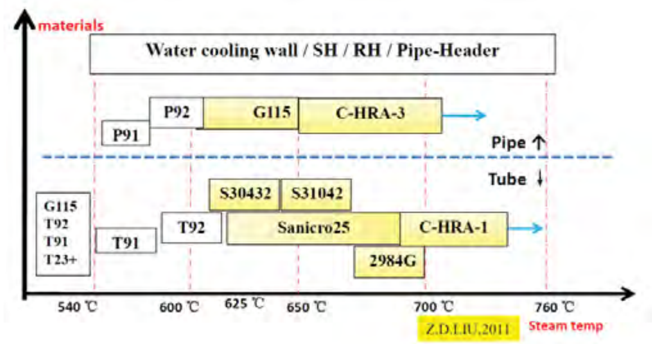

Figure 2 Candidate materials spectra used for 700℃ boiler of A-USC PP in china

Among these candidate materials, G115 martensitic steel is specially designed and innovated to manufacture boiler piping system for the steam temperature scope of 630-650℃ by the Central Iron and Steel research Institute (CISRI) and has been patented in the year of 2012[3]. The industrial importance of G115 steel lies in the fact that it makes possible to build 630-650℃ A-USC fossil fired power plants with economic competitiveness. The upper steam temperature limitation for P92 steel is 623℃. C-HRA-3 or Inconel617B alloy is of much higher heat resistance. However, they are much more expensive than G115 steel. From such a viewpoint, G115 martensitic steel laid a solid basis for the design and construction of 630-650℃ A-USC fossil fired power plants.

3. Strengthening mechanism of G115 martensitic steel

The typical chemistry of P91 and G115 steels is listed in Table 1. For P92 steel, the solid solution strengthening and precipitation strengthening are the major strengthening mechanisms, along with the dislocation and substructure strengthening. P92 had been the best available commercial martensitic heat resistant steel before the development of G115 steel.

Table 1 Typical chemistry of T/P92 and G115P steels

Steel	C	Cr	Mo	W	Co	Nb	V	B	N	Cu	Ce	Others
T/P92	0.10	9	0.45	1.8		0.05	0.20	0.0035	0.050			
G115P	0.08	9		2.8	3.0	0.05	0.20	0.0150	0.008	1.0	0.10	Others

To break through the upper temperature limitation of martensitic heat resistant steel, a stronger matrix and better harmonious strengthening are necessary, which must be carefully analyzed and selected. It had been experimentally proved that 8.8-9.0%Cr is the best balance point for 9-12%Cr martensitic steel to achieve acceptable creep strength and oxidation resistance at the same time. To obtain a stronger matrix, G115 is of 2.8%W-3%Co for piping and 3%W-3%Co for tubing. Impact energy is a sensitive indicator for piping system design. The superabundant addition of tungsten contributes to more Laves phase precipitation, which heavily undermines the toughness of the steel pipe. The addition of 1.0%Cu to G115 steel is supposed to further improve the strength and oxidation resistance with the help of small scale Cu-rich precipitation [4]. It has been experimentally verified that the addition of 1.0%Cu is of no negative effect on the thermal deformation and toughness/ductility of the steel. The collaborative addition of B-N was explored by Abe et al [5]. The effectiveness of collaborative addition of B-N was experimentally investigated by Liu et al [4].

4. Industrial manufacturing of G115 tube and pipe

G115 tubes and pipes have been industrially made at BaoSteel of China since 2008 by various processing routines, as shown in Table 2.

Table 2 Industrial manufacturing of G115 tube and pipe

Trial	Time	Dimension	Steel maker	Processing routine
1	2008	Φ38×9 mm	BaoSteel	Piercing + cold rolling
2	2010	Φ254×25 mm	BaoSteel	Hot pressing
3	2014	Φ51×10 mm	BaoSteel	Continuous hot piercing
4	2015	Φ610×90 mm	BaoSteel	Hot pressing

Currently, BaoSteel can commercially provide G115 tube and pipe with the dimension from Φ38×9 mm to Φ900×90 mm. The normal metallurgical routine could be 40-100 ton EAF+LF+VD. The thermo-mechanical deformation routine is hot piercing for G115 tube and hot-extrusion for G115 pipe. The delivery price of G115T/P at the plant is estimated to be about 12,700 US$/ton, or 80,000 RMB/ton.

5. Microstructure and comprehensive properties of G115 pipe

The specimens investigated in the current paper were from hot-extruded G115 pipe, with the dimension of Φ254×25×3500 mm in the year of 2010.

Table 3 Mechanical properties of G115 steel pipe

Temp	Rm, MPa	Rp0.2, MPa	A,%	Z,%	Akv2,J		HB
R.T.	763	623	23	72.3	115	112	210
650℃	380	338	26.5	85			

The mechanical properties at room temperature and 650℃ of the G115 pipe were listed in Table 3. Obviously, the steel is of reasonable impact energy, implying that the steel is of potential to make heavy thickness pipes or forgings. The impact energy is higher than 112J at room temperature. The photo-graphics of G115 pipe after aging at 650℃ up to 8000 hours were shown in Figure 3, in which, it is clearly that the martensitic lath width keeps very stable, thinner than 425nm. However, when the aging temperature is 700℃, the martensitic lath width grows much faster, as indicated in Figure 3, 650℃ should be the upper application limitation of the steel.

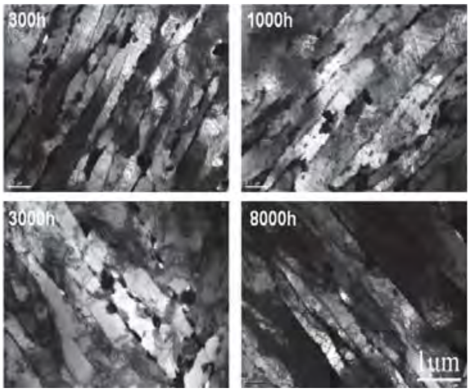

Figure 3 TEM photos of G115 steel after aging at 650℃

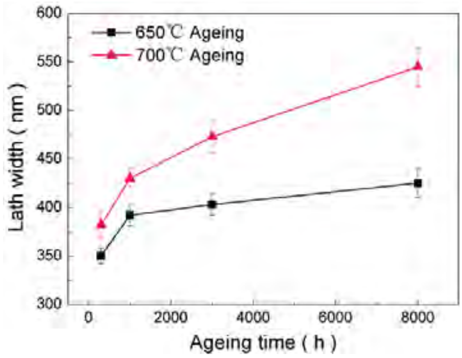

Figure 4 Evolution of G115 martensitic lath width during aging

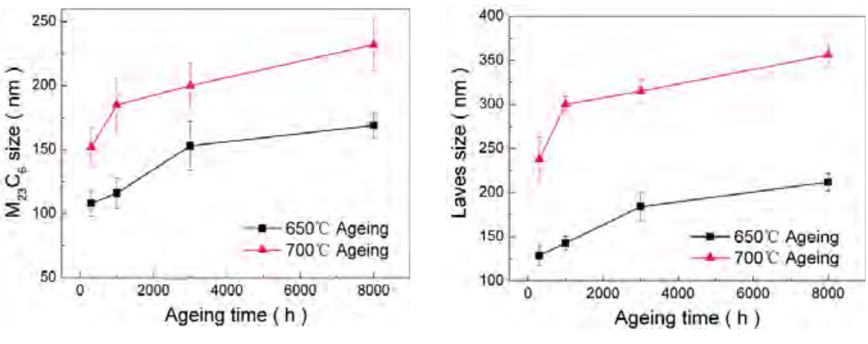

Figure 5 Evolution of $M_{23}C_6$ and Laves phases of G115 steel during aging

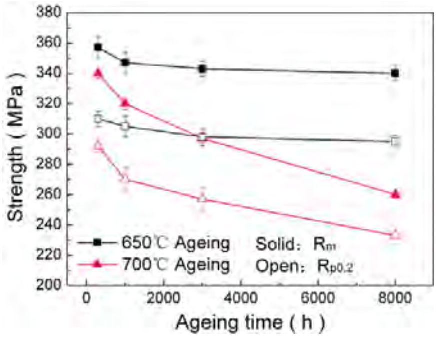

Figure 6 High temperature strength of G115 steel during aging

The major precipitation of G115 steel during 650-700℃ aging includes MX, Cu-rich precipitate, $M_{23}C_6$ and Laves phase. Among them, MX and Cu-rich particles are very fine, basically in nanometer-scale, and very stable during aging. From the viewpoint of precipitation hardening, the deterioration of creep strength of the steel results from the coarsening and aggregation of $M_{23}C_6$ and Laves phase particles. The evolution of $M_{23}C_6$ and Laves phase during aging was shown in Figure 5. The velocity of coarsening of $M_{23}C_6$ and Laves phase under 650℃ aging are much lower than that of 700℃ aging. The size of $M_{23}C_6$ is less than 170 nm and Laves phase is about 200 nm under 650℃ aging up to 8000 hours. Correspondingly, the yield strength and tensile strength of G115 at 650℃ and 700℃ after 650℃ aging were drawn in Figure 6. The mechanical properties of G115 at 650℃ aging are very stable.

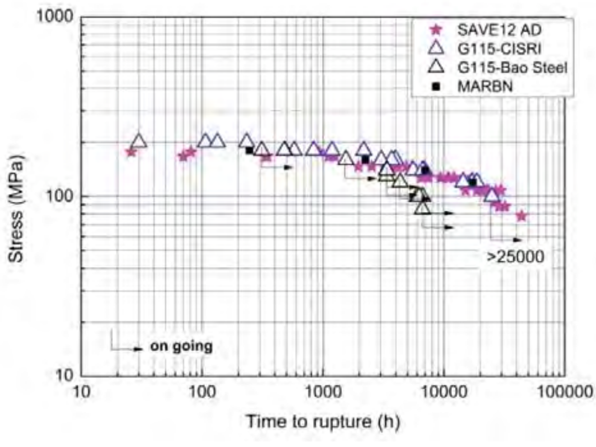

Figure 7 Creep rupture strength of G115 steel pipe

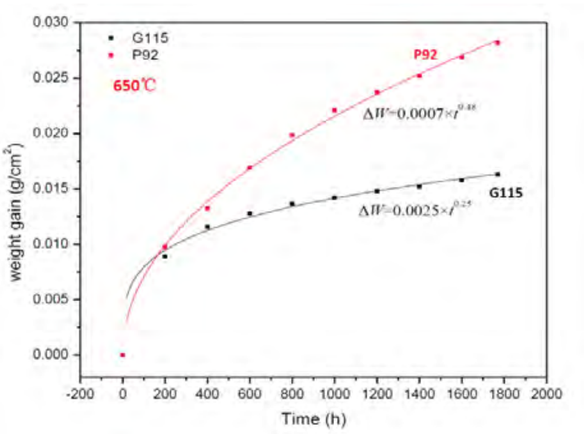

Figure 8 Oxide resistance of G115 and P92 steel pipes

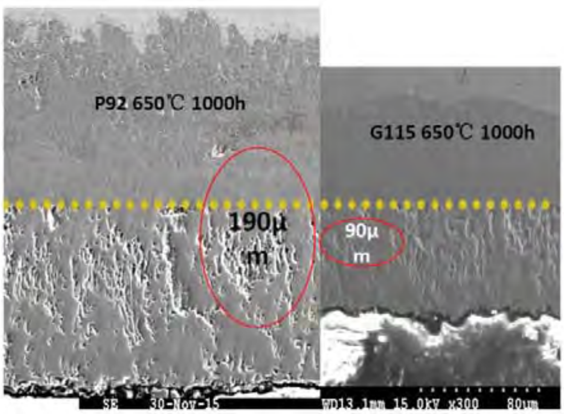

Figure 9 Oxide scales of G115 and P92 steel pipes

The curves of current available creep test results of the G115 steel pipe and other G115 trial samples under 650℃ were plotted in Figure 7. Longer time creep tests of G115 are undergoing at CISRI and BaoSteel. In fact, the G115 is of excellent creep strength among all commercially available ferritic heat resistant steels worldwide so far, much higher than that of P92 steel. Meanwhile, G115 steel has a reasonable oxidation resistance as shown in Figure 8 and Figure 9, comparing to P92 steel. The industrial welding verification of G115 tubes and pipes had been carried out at Shanghai Boiler Maker in the past years, and the welded joints showed excellent properties during creep testing as expected.

6. The application and prospect of G115 steel

After ten years industrial exploration at CISRI and BaoSteel, G115 steel is gradually mature and will enter market in the near future. It will be selected to manufacture the pipes and forgings in the temperature scope from 630℃ to 650℃ in A-USC fossil boiler. Likely, G115 pipe may replace some P92 pipe in the temperature scope from 610℃ to 630℃, due to the much higher creep strength of G115 steel. For the same situation, if replacing P92 pipe with G115 pipe, the wall thickness and the weight of the designed pipes can reduce about 50%, as shown in Figure 10. Considering the delivery price of G115 pipe aforementioned, G115 steel pipes and forgings are of very strong market competitiveness.

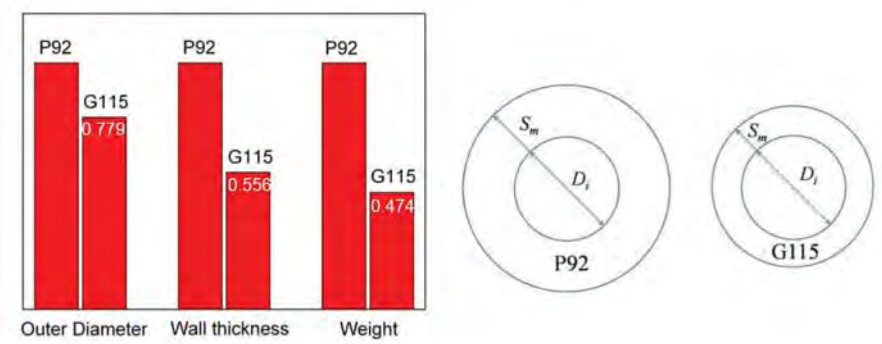

Figure 10 Effectiveness of replacement of P92 pipe with G115 pipe

7. Conclusive summary

G115 has been successfully developed by CISRI and BaoSteel and it is an imposing material for the making of boiler pipes and forgings at the temperature scope from 600℃ to 650℃ and the water wall tubing of 700℃ A-USC power plants, due to its excellent creep rupture strength and reasonable oxide resistance as well as its economic competitiveness.

Acknowledgments

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