Study on properties of 18MND5 steel forgings for PWR steam generator

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Abstract. In the pressurized water reactor (PWR) nuclear power plant, the shell material of steam generator is required to have good strength-toughness matching, anti-fatigue performance, and neutron radiation resistance to ensure the long-term safe and reliable service. The manufacturing requirements of Manganese-Nickel-Molybdenum alloy steel forgings of steam generator channel head for Hua-long Pressurized Reactor (HPR1000) and Advanced Passive PWR(AP1000) nuclear power plant were compared. The heat treatment process, chemical composition, mechanical properties, metallographic structure of 18MND5 steel forging and SA 508-III steel forging were analysed and studied. The results show that the performance heat treatment temperature of HPR1000 forging has more stringent controls and with lower element content of C, Mo, P, Si, V, Co than the AP1000 forging. By reducing the C content, HPR1000 forging got better toughness while the strength was ensured.

1 Introduction

Nuclear power is a safe, economical, efficient and clean energy, which is an important choice fighting with climate change. The total number of nuclear power plants in the United States, France, Japan and other developed countries accounts for more than half of the total number of the world, especially in France, where the total power generation of nuclear power accounts for about 70% of its total power generation. China is a major developing country in the utilization of nuclear energy and nuclear technology. At present, there are 47 nuclear power units in commercial operation, with a total installed capacity of 48,751 MWe, generating 348.1 billion kilowatt-hours of electricity annually. Another 15 nuclear power units are under construction. Active and orderly development of nuclear power is an important way to fulfill China's commitment to emission reduction and achieve the strategic goals of "carbon peak" and "carbon neutrality".

Nuclear power plant equipments such as pressure vessels, steam generator service under extreme conditions with high temperature, high pressure and irradiation environment. Therefore, the shell material has high requirements such as good strength matching, fatigue resistance, neutron irradiation resistance, good machinability and weldability. Manganese-Nickel-Molybdenum alloy steel with high strength, good toughness has been widely used in shell materials of nuclear island equipment[1].

HPR1000 is the third generation of million-kilowatt advanced pressurized water reactor (PWR) nuclear power plant technology independently researched and developed by China with complete intellectual property rights, which has highly requirements on equipment safety. In this paper, Manganese-Nickel-Molybdenum alloy steel forgings of steam generator channel head of HPR1000 and AP1000 is taken as an example, and the manufacturing requirements in the standards and
Procurement specifications were compared. The properties of 18MND5 steel forgings for HPR1000 and SA 508-III steel forgings for AP1000 were analysed and studied.

2 Manufacturing process
Select pig iron, high quality scrap steel and iron alloy smelting, using alkaline arc furnace crude steelmaking water, through the refining furnace using vacuum degassing and aluminum kill and deoxidize, before and during casting ingot, in order to get rid of harmful gas especially hydrogen, vacuum treatment of molten steel, effectively remove P, S, H, O and other impurities, to ensure the quality of ingot and thermal processing. To remove most of shrinkage and segregation, casting ingot shall ensure that adequate excision quantity, and total forging ratio should be greater than 3. The specific manufacturing process is shown in Fig. 1. The channel head forging of steam generator is shown in Fig. 2.

![Fig. 1 The manufacturing process flow of steel forging](image1)

![Fig. 2 The channel head forging of steam generator](image2)

3 Heat treatment
In order to improve the composition uniformity of the forgings, reduce segregation, adjust and refine the grain and microstructure, and further reduce the hydrogen content in the steel to prevent the crack induced by the residual segregation zone, the channel head forgings need to carry out a preliminary heat treatment after forging, to ensure that the hydrogen content is not more than 0.8ppm after the treatment[2-4]. The preliminary heat treatment process requirements for HPR1000 and AP1000 forgings are shown in Table 1.
Table 1. The preliminary heat treatment process

| Heat treatment | Normalizing | Tempering |
|---------------|-------------|-----------|
| Requirement of HPR1000 | 895/985°C, ≥12Hrs, ≤150°C/Hr, Air Cooling | 605/695°C, ≥14Hrs, Air Cooling or Furnace Cooling |
| Requirement of AP1000 | 895/985°C, ≥3Hrs, ≤150°C/Hr, Air Cooling | 605/695°C, ≥6Hrs, Air Cooling or Furnace Cooling |

The performance heat treatment of channel head forging is quenching and high temperature tempering. In the process of heat treatment, austenitizing temperature, tempering temperature and holding time, especially the cooling rate after the austenitizing temperature have major impact on the microstructure and mechanical properties of steel forging. In order to get the best mechanical strength and toughness at low temperature, quenching must rapid cooling (the time interval from opening the furnace to completion of immersing the whole forging should be no more than a few minutes), to ensure that the entire cross section of the forging with bainite structure and uniform distribution of tempered bainite after tempering. The heat treatment conditions of HPR1000 and AP1000 forgings are shown in Table 2.

Table 2. The performance heat treatment process

| Heat treatment | Quenching | Tempering |
|---------------|-----------|-----------|
| Requirement of HPR1000 | 890±15°C, ≥8Hrs, ≤160°C/Hr, water quenching | 650±15°C, ≥10Hrs, Air Cooling |
| Requirement of AP1000 | 870/920°C, ≥6Hrs, ≤160°C/Hr, water quenching | ≥638°C, ≥8Hrs, Air Cooling |

The comparison of Table 1 and Table 2 shows that there is no difference in the normalizing temperature, tempering temperature and heating rate of HPR1000 and AP1000 forgings in the preliminary heat treatment, while HPR1000 has longer holding time and tempering time. In terms of performance heat treatment, The quenching temperature and tempering temperature of HPR1000 forging are higher than the AP1000 forging, and the time is also required to be longer.

4 Material analysis

4.1 Chemical composition

The chemical composition requirements of HPR1000 and AP1000 forgings are shown in Table 3. As can be seen from Table 4, HPR1000 has relatively strict control over the contents of C, Mo, P, Si, V, Co, while AP1000 has more strict control over Ni, S, Cu, Al. According to test methods such as RCC-M MC1211 and ASTM A370-03, photoelectric emission spectrum analyzer and oxygen-nitrogen-hydrogen analyzer were used to analyze the chemical composition of forging samples, as shown in Table 3. Reducing C content can ensure the strength requirement, improve toughness, and enhance the weldability of steel. Ni content can improve the activity of C atoms, strengthen the segregation of C atoms around the dislocation, and hinder the dislocation movement, so as to play an indirect solution strengthening role, and at the same time improve the low temperature toughness[5]. The control of Ni
content in the upper limit of the composition range is beneficial to improve the performance of the HPR1000 forgings.

**Table 3. The chemical composition requirements and results of steel forging**

| Element | Cr | Mo | V | Cu | Al | Co |
|---------|----|----|---|----|----|----|
| Requirement of HPR1000 | ≤0.25 | ≤0.43~0.57 | ≤0.01 | ≤0.20 | ≤0.04 | ≤0.05 |
| Requirement of AP1000 | ≤0.25 | ≤0.43~0.57 | ≤0.01 | ≤0.20 | ≤0.04 | ≤0.05 |
| HPR1000 Tsc1 | 0.21 | 0.51 | 0.004 | 0.034 | 0.01 | 0.01 |
| Requirement of HPR1000 | ≤0.00 2 | Info. | Info. | Info. | ≤0.8p pm | - |
| Requirement of AP1000 | ≤0.00 2 | Info. | Info. | Info. | ≤0.8p pm | - |
| HPR1000 Tsc1 | ≤0.00 2 | 0.004 | ≤0.00 3 | 0.001 | 0.65 | - |

4.2 Mechanical property

The requirements of room temperature and high temperature mechanical properties of HPR1000 and AP1000 forgings are shown in **Table 4**. The yield strength and tensile strength requirements of HPR1000 forgings are lower than the AP1000 forgings, nearly 30~40 MPa at room temperature and 20~36 MPa at 350℃. By using computer-controlled electronic universal testing machine, and according to the test methods such as RCC-M MC1211 and ASTM A370-03, the tensile strength ($R_m$), yield strength ($R_{p0.2}$), elongation, and reduction of area of the forging are obtained. The test results meet the requirements of the HPR1000 forgings specification.

**Table 4. The tensile property requirements and results of steel forging**

| Test Temperature | Requirement of HPR1000 | Requirement of AP1000 | HPR1000 Tmc1 | HPR1000 Tmc2 | Requirement of HPR1000 | Requirement of AP1000 |
|------------------|------------------------|-----------------------|--------------|--------------|------------------------|-----------------------|
| Room             | Room                  | 20℃                  | 20℃          | 350℃        | 350℃                  | 350℃                  |
| $R_{p0.2}$ /MPa   | ≥420                  | ≥450                 | 470          | 475          | ≥350                  | ≥370                  |
| $R_m$ /MPa        | 580~700               | 620~795              | 615          | 599          | ≥522                  | ≥558                  |
| A (%)            | ≥20                   | ≥16                  | 23.5         | 26.0         | -                     | -                     |
| Z (%)            | ≥35                   | ≥35                  | 75.0         | 74.0         | -                     | -                     |
Table 5 shows the impact test requirements of HPR1000 and AP1000 forgings. HPR1000 forgings require that three specimens should be broken for each set of tests at test temperatures including 20°C, 0°C and -20°C, and the shear section rate and lateral expansion are provided for information. The pendulum impact tester is used to conduct Charpy V-Notch impact test according to RCC-MC1220 and ASTM A370-03. The comparison shows that at approximate temperatures of -20°C and -21°C, the average minimum value of the absorbed energy of HPR1000 forgings is 56J, which is higher than the 48J required by AP1000 forgings. It also shows that the C content has a significant effect on the performance of steel forgings, the lower C content results in lower strength but better toughness and lower ductile-brittle transition temperature, the higher C content results in higher strength but reduced toughness.

### Table 5. The impact toughness requirements and results of steel forging

| Requirement of HPR1000 | Test Temperature | Absorbed energy (J) (longitudinal) | Absorbed energy (J) (transverse) |
|-----------------------|------------------|------------------------------------|----------------------------------|
|                       | +20°C            | individual value≥88               | individual value≥72              |
|                       | 0°C              | average value≥72, individual value≥56 | average value≥56, individual value≥40 |
|                       | -20°C            | average value≥56, individual value≥40 | average value≥40, individual value≥28 |
| Requirement of AP1000 | 12°C             | average value≥68, individual value≥68 | /                                |
|                       | -21°C            | average value≥48, individual value≥41 | /                                |
| HPR1000 Tsk01~Tsk03    | +20°C            | 198, 211, 207, average value 205    | /                                |
| HPR1000 Tsk04~Tsk06    | 0°C              | 182, 212, 165, average value 186    | /                                |
| HPR1000 Tsk07~Tsk09    | -20°C            | 169, 105, 160, average value 144    | /                                |

### 4.3 Microstructure

The requirements for grain size and non-metallic inclusions of HPR1000 and AP1000 forgings are shown in Table 6. After rough grinding, fine grinding and mechanical polishing, the forging sample is corroded with 3%-4% nitric acid alcohol solution, and then the structure is observed under the optical metallurgical microscope. Fig.3 shows the metallographic structure of HPR1000 steel forgings which is typical tempered bainit. Because the bainite structure has high strength and good toughness, it plays a very critical role in the stability of the final mechanical properties of the forging[6-7]. The grain size of the forging is grade 7, and the grain size is finer, which meets the HPR1000 requirements of grade 5.
Metal inclusions are evaluated according to ASTM E45-02 Method A, and the evaluation results are shown in Table 6, which also meets the requirements.

![Microstructure of Steel forging](image)

**Table 6.** The grain size and non-metallic inclusion grading requirements and results of steel forging

| Requirement of HPR1000 | Grain size | Type A | Type B | Type C | Type D |
|------------------------|------------|--------|--------|--------|--------|
| ≥5                     | ≤1.5       | ≤1.5   | ≤1.5   | ≤1.5   |

| Requirement of AP1000  | Grain size | Type A | Type B | Type C | Type D |
|------------------------|------------|--------|--------|--------|--------|
| ≥5                     | ≤2.0       | ≤2.0   | ≤1.5   | ≤1.5   |

| HPR1000 Tsg1           | 7          | 1      | 0.5    | 0      | 1      |

### 5 Conclusion

The preliminary heat treatment of HPR1000 steam generator channel head forgings is normalizing and tempering and the performance heat treatment is quenching and high temperature tempering. Both of these heat treatments are more stringent controls on the temperature and longer holding time than the AP100 forgings.

Compared with AP100, HPR1000 steam generator channel head forgings has more stringent composition requirements of C, Mo, P, Si, V, Co, etc. The C content has a significant effect on the performance properties of HPR1000 steel forgings, and the lower C content results in better combination of low temperature impact toughness and tensile strength.

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