Analysis on the Properties of NC30Fe alloy for U-bend tubes of Steam generator

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Abstract: The Nickel-Chromium-Iron Alloy (NC30Fe), which is an austenitic nickel-based alloy as the ideal material for U-bend tubes of steam generator in PWR nuclear power plant because of its good strength and corrosion-resistant and used widely in domestic and abroad. The manufacturing requirements of NC30Fe alloy of steam generator U-bend tubes for Hua-long Pressurized Reactor (HPR1000) and Advanced Passive PWR (AP1000) were compared and the heat treatment process, chemical composition, mechanical properties, metallographic structure were analyzed and studied.

1 Introduction
The steam generator is a key equipment connecting the primary loop and secondary loop of PWR nuclear power plant. Its main function is to transfer the heat generated by the reactor to the secondary loop through thousands of heat transfer tubes inside and generate steam, thereby promoting the steam turbine unit generates electricity. The Nickel-Chromium-Iron Alloy (NC30Fe and UNS UN06690) not only has excellent resistance to stress corrosion cracking, but also has high strength, good metallurgical stability and excellent processing performance[1-3]. It has become an ideal nuclear power steam generator for heat transfer tube material, which is widely used in second-generation improved pressurized water reactor (CPR1000), third-generation advanced pressurized water reactor (HPR1000) of china, American passive safety advanced pressurized water reactor (AP 1000), and European advanced pressurized water reactor (EPR) as shown in Table 1.

Table 1. The tubes of steam generator

| Grade  | Dimension (mm) | Tubes (set) |
|--------|----------------|-------------|
| CPR1000 | φ19.15×1.04     | 4474        |
| HPR1000 | φ17.48×1.04     | 6156        |
| AP1000  | φ19.05×1.09     | 5980        |
| EPR     | φ19.05×1.09     | 5980        |

In this paper, the Nickel-Chromium-Iron Alloy (NC30Fe) U-bend tubes of steam generator for HPR1000 and AP1000 is taken as an example and the manufacturing requirements in the standards...
and procurement specifications were compared. The properties of NC30Fe U-bend tubes for HPR1000 were analysed and studied.

2 Manufacturing process
Primary melt is performed either in vacuum induction furnace or in arc electric furnace. Each electrode is vacuum remelted to ingot by electroslag remelting (ESR) to optimize its cleanliness as regard inclusions and its chemical homogeneity. Tubes are produced from tube hollows by a sequence of cold working (pilgering and drawing) and annealing processes. Following the final cold working process, the tubes shall be processed generally as final mill annealed (bright annealed), straightened, belt ground, mechanical performance sampling tests, NDE inspected with ultrasonic examination and eddy current examination, Thermal Treated, bent into U-bend with the smaller radius U-bends Stress-Relieved and inspected with eddy current examination[4]. The specific manufacturing process is shown in Fig.1. The U-bend tubes of steam generator is shown in Fig.2.

![Fig.1 The manufacturing process flow of U-bend tubes](image-url)
The tubes shall undergo a final mill annealing heat treatment after cold worked (pilgering and drawing). After straightening, outside surface grinding, ultrasonic and eddy current testing, the tubes shall be complementary thermal treated. The small U-bend radius tubes shall also be subjected to stress relieving heat treatment[5-7].

During the final mill annealing heat treatment on the tubes after the last cold pilgering or drawing operation, the furnace atmosphere shall not produce surface carburization, decarburization or nitriding on the final tubes. The heat treatment process requirements for HPR1000 and AP1000 tubes are shown in Table 2.

**Table 2. The Final Mill Annealing heat treatment**

| Requirement of HPR1000 | Final Mill Annealing heat treatment                                                                 |
|------------------------|-----------------------------------------------------------------------------------------------------|
|                        | 1. It shall be performed in a continuous furnace under protective atmosphere;                        |
|                        | 2. The minimum temperature measured on the coldest tube is 1065℃ with a holding time of 1 minute minimum; |
|                        | 3. The cooling time from 900℃ to 500℃ is lower than 3 minutes.                                       |

| Requirement of AP1000  | Final Mill Annealing heat treatment                                                                 |
|------------------------|-----------------------------------------------------------------------------------------------------|
|                        | 1. It shall be performed in a dry protective atmosphere.                                              |
|                        | 2. The furnace shall be specially controlled and a minimum measured tube temperature of 1090℃.      |
|                        | 3. The tubes shall be held above minimum annealing temperature for a period of at least 2 minutes and cooled from the final mill anneal temperature to below 500℃ within 6 minutes. |
The Thermal treatment (TT) shall be performed after final mill anneal, straightening and grinding activities. The heat treatment process requirements for HPR1000 and AP1000 tubes are shown in Table 3. Studies show that TT treatment increases the chromium concentration of grade boundary chromium depletion caused by the formation of grain boundary carbides, and improves the distribution and morphology of grain boundary carbides, which can significantly increase stress corrosion cracking resistance of the tubes.

### Table 3. The Thermal Treatment

| Requirement of HPR1000 | Thermal Treatment                                                                 |
|------------------------|----------------------------------------------------------------------------------|
|                        | 1. It shall be performed at the temperature of 716±15°C and hold for at least 6 hours; |
|                        | 2. It shall be performed in vacuum with protective atmosphere;                   |
|                        | 3. The cumulative time at the temperature 705-735°C corresponding to the TT heat treatment on straight tubes and stress relief heat treatment of the small U bent radius shall not exceed 24 hours. |

| Requirement of AP1000 | Thermal Treatment                                                                 |
|------------------------|----------------------------------------------------------------------------------|
|                        | 1. It shall be performed in a vacuum to 715-735°C and holding for a minimum of 12 hours; |
|                        | 2. It shall be performed in vacuum with Argon or Helium gas of protective atmosphere; |
|                        | 3. The cumulative holding time for Thermal Treatment, including re-Thermal Treatment and Stress Relief shall not exceed 28 hours. |

The short radius bends shall also be subjected to stress-relieving heat treatment. The Stress Relief cycle and other requirements shall be the same as the Thermal Treatment except holding time for a minimum of 2 hours.

The comparison of Table 2 and Table 3 shows that the HPR1000 tubes have lower temperature and shorter holding time than AP1000 tubes in the final mill annealing heat treatment and Thermal treatment.

### 4 Material analysis

#### 4.1 Chemical composition

The chemical composition requirements of HPR1000 and AP1000 tubes are shown in Table 4. As can be seen from Table 4, AP1000 has relatively strict control over the contents of Cr, Fe, Al, Ti, C. Sulphur-carbon analyser, nitrogen-oxygen analyser and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) were used to analyze the chemical composition of tubes samples, as shown in Table 4. The test results meet the requirements of the HPR1000 tubes specification.
Table 4. The chemical composition requirements and results of tubes (wt%)

| Element | Requirement of HPR1000 | Requirement of AP1000 | HPR1000 Ts-c1 | AP1000 Ts-c2 |
|---------|------------------------|-----------------------|---------------|-------------|
| Ni      | ≥58.00                 | ≥58.00                | 59.6          | 59.4        |
| Cr      | 28.00~31.00            | 28.50~31.00           | 29.4          | 29.3        |
| Fe      | 8.00~11.00             | 9.00~11.00            | 10.11         | 9.9         |
| Mn      | ≤0.50                  | ≤0.50                 | 0.30          | 0.28        |
| Si      | ≤0.50                  | ≤0.50                 | 0.16          | 0.31        |
| Al      | ≤0.50                  | ≤0.40                 | 0.16          | 0.02        |
| Ti      | ≤0.50                  | ≤0.35                 | 0.20          | 0.31        |
| C       | 0.010~0.030            | 0.015~0.025           | 0.019         | 0.020       |
| P       | ≤0.015                 | ≤0.015                | <0.008        | <0.008      |
| S       | ≤0.003                 | ≤0.003                | <0.0004       | <0.002      |
| Cu      | ≤0.05                  | ≤0.05                 | <0.0002       | 0.010       |
| Co      | ≤0.016                 | ≤0.016                | 0.006         | 0.010       |
| B       | ≤0.003                 | ≤0.002                | <0.002        | 0.0003      |
| Nb      | ≤0.10                  | ≤0.10                 | <0.001        | 0.01        |
| N       | ≤0.05                  | ≤0.05                 | 0.03          | 0.020       |
| As      | Info.                  | -                     | <0.04         | -           |
| Sn      | Info.                  | -                     | <0.04         | -           |
| Sb      | Info.                  | -                     | <0.04         | -           |

4.2 Mechanical property

The requirements of room temperature and high temperature mechanical properties of HPR1000 and AP1000 tubes are shown in Table 5. The room temperature tensile strength requirements of HPR1000 tubes is higher than the AP1000 tubes. The yield strength and tensile strength requirements of HPR1000 tubes are lower than the AP1000 tubes in 350°C. By using computer-controlled electronic universal testing machine, and according to the test methods such as RCC-M MC1212, ASTM E8 and ASTM E12, the tensile strength, yield strength, elongation of the tubes are obtained. The test results meet the requirements of the HPR1000 tubes.

Table 5. The tensile property requirements and results

| Requirement          | Test Temperature | \(R_{p0.2}\)/MPa | \(R_m\)/MPa | A%(5d) |
|----------------------|-----------------|-----------------|-------------|--------|
| Requirement of HPR1000 | Room            | 275~375         | 630~800     | ≥35    |
| Requirements of AP1000 | Room            | 276~380         | ≥586        | ≥30    |
The sample from one end of tube in the Thermally Treated condition shall be flare tested. The test specimen shall consist of a tube section 40 mm in length, and the flare test shall be performed in accordance with MC 1000 using a frustrum-shaped mandrel with an apex angle of 60°. The requirements of HPR1000 and AP1000 tubes are shown in Table 6. The flare test results meet the requirements of the HPR1000 tubes specification.

**Table 6. The flare test requirements and results**

| Requirement of HPR1000 | Angle of mandrel | Expanded size | Criteria |
|------------------------|------------------|---------------|----------|
| Ts-f1                  | 60°              | 30%           | No cracks or tears |
| Requirements of AP1000 | 60°              | 30%           | Shall not exhibit cracking, breaks, linear defects of other injurious defects |
| HPR1000 Ts-f2          | 60°              | 30%           | No cracks |

**4.3 Microstructure**

Metallographic specimens shall be prepared in accordance with ASTM E3. After mounting and polishing, the specimen shall be etched in a 2% bromine-methanol solution at room temperature and rinsed with methanol or ethanol for evaluating microstructure. If necessary to achieve a good etch, the polished surface may be activated in concentrated hydrochloric acid and rinsed in methanol prior to etching. **Fig.3** is the metallographic structures of HPR1000 tubes which show continuous grain boundary carbides precipitation with little intragranular precipitates [8-9]. The grain size of the forging is grade 7, and the grain size is finer, which meets the HPR1000 tubes requirements of grade 5 to 7. The requirements for inclusions of HPR1000 and AP1000 tubes are shown in **Table 7**. Inclusion are evaluated according to ASTM E45-02 Method A, and the evaluation results are shown in **Table 7**, which also meets the requirements.
Fig.3 The Microstructure of tubes(500×)

Table 7. The inclusion grading requirements and results

| Type         | Type A | Type B | Type C | Type D |
|--------------|--------|--------|--------|--------|
|              | T      | H      | T      | H      | T      | H      |
| HPR1000      | Oxide and sulfide | 1 | 0.5 | 3 | 1 | 0.5 | 0.5 | 1 | 1 |
|              | Ti (CN) | - | - | 3 | 3 | - | - | 4 | 3 |
| AP1000       | Oxide and sulfide | 1 | 0.5 | 3 | 1 | 0.5 | 0.5 | 1.5 | 1 |
|              | Ti (CN) | - | - | 3 | 3 | - | - | 4 | 3 |
| HPR1000Ts-i1 | Oxide and sulfide | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 |
|              | Ti (CN) | 1 | 0 | 2.5 | 0.5 |

5 Conclusion
The final mill annealing heat treatment and the Thermal treatment (TT) of HPR1000 steam generator tubes are performed in continuous furnace under protective atmosphere and the requirements of HPR1000 tubes have lower temperature and shorter holding time than AP1000 tubes. Compared with AP100, HPR1000 tubes have similar composition requirements and AP1000 has relatively strict control over the element contents of Cr, Fe, Al, Ti, C. The room temperature tensile strength requirement of HPR1000 tubes is higher than the AP1000 tubes and the yield strength and tensile strength requirements are lower at high temperature.

The chemical composition, tensile properties, flare test, metallographic structures are tested and analysed, and all the results meet the requirements of HPR1000 steam generator tubes.

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