Study on Mechanical Properties of P92 Steel Welded Joint of the Main SteamPipe of Ultra Supercritical Unit After 50,000 Hours Service

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Abstract: Combined with a scanning electron microscope, this paper carried out a tensile test and a bending test to study the mechanical properties of P92 steel welded joint of the main steam pipe after the joint was in service for 50,000 hours. The results show that the tensile strength and hardness of the P92 steel weld metal are higher than those of the base metal after it was treated at a high temperature for 50,000 hours, but the plasticity is lower than that of the base metal. This is related to the precipitation and growth of Laves and M₂₃C₆ phases in the steel during treatment; after the metal was treated at a high temperature for 50,000 hours, the number of Laves phases is larger and the size is bigger than that in the base metal. The Laves phases are precipitated rapidly along the austenite grain boundary and martensite lath boundary and then distributed in the grain boundary, lath boundary, and plate strip boundary, reducing the strength and toughness of the matrix.

1. Preface
Currently, thermal power is still the most important energy for electricity generation in China. It is expected that the proportion of thermal power for electricity generation will reach about 50% in 2030. Due to a huge pressure of energy saving and environmental protection, developing ultra-supercritical units is one of the effective methods for China to implement the strategy of energy saving and emission reduction. After entering the 21st century, China has become a major country to use ultra-supercritical units. How to ensure the safe operation of these units is one of the technical problems currently facing electricity generation¹⁻³. Therefore, it is an urgent task for electricity workers to carry out researches on the reliability of heat-resistant steel in units.

P92 steel is a fine-grained and heat-resistant martensitic steel that is subjected to controlled rolling and controlled cooling processes. This kind of steel is mainly used for making main stream pipes of
super ultra-supercritical units, high-temperature superheaters, and reheater headers. Although P92 steel is developed by Japan, the main consumption market is in China. The steel commonly used by Europe, America, Japan and other countries is P122 and E911 steel[4]. Because the cumulative service time of P92 steel is not long, researchers at home and abroad are still making intensive studies on the steel structure and performance. Especially, after a long time of service, whether the performance changes of P92 steel welded joint meets the usage requirements is of particular concern [5-7], and becomes a problem troubling the security and stability of USC units. This paper studied the mechanical properties of P92 welded joint after the joint was treated at a high temperature for 50,000 hours and the joint structures were changed, explored the performance change rules of P92 welded joint, and provided technical support for unit maintenance and metal monitoring.

2. Test Materials and Methods

The welded joint made of P92 steel used in the test comes from the main steam pipe of a 1000mw super ultra-supercritical unit after the joint was in service for 50,000 hours. The specification is $\Phi 370\,\text{mm} \times 60\,\text{mm}$. The welding material used is Thermanit MTS616, and welding specifications are $\Phi 3.2\,\text{mm}$ and $\Phi 2.5\,\text{mm}$. The chemical composition of the welded joint is shown in Table 1.

Table 1: Chemical composition of P92 steel pipes and welding rods (wt, %)

| Material                  | C  | Si | Mn | P  | S  | Cr  | Ni  | Mo  | Cu  | Nb | W  | V  | N  |
|---------------------------|----|----|----|----|----|-----|-----|-----|-----|----|----|----|----|
| P92 steel                 | 0.07≤ | 0.30≤ | ≤ | 0.01≤ | 0.04 | 1.50 | 0.15- | 0.030 | 8.5 | 0- | 0- | 0.047 |
| Thermanit MTS616 welding  | 0.10 | 0.22 | 0.74 | 0.00 | 6 | 8.5 | 6 | 0.61 | 0.04 | 1.72 | 0.19 | 8 | 0.047 |

The main steam pipe made of P92 steel was installed onsite by using GTAW and SMAW welding processes. Welding parameters are shown in Table 2 and the pipe was horizontally fixed in the 5G welding position.

Table 2: Welding parameters of main steam pipemade by P92 steel

| Welding Layer | Welding Method | Welding Rod | Specification | Polarity | Current | Voltage | Welding Speed |
|---------------|----------------|-------------|---------------|----------|---------|---------|--------------|
| 1-3           | GTA            | Thermanit MTS616 | $\Phi 2.4$ | DCEN     | 80-100  | 10-12   | 45-60       |
| 4-10          | SMA            | Thermanit MTS616 | $\Phi 2.5$ | DCRP     | 85-90   | 20-22   | 100-130     |
| 11-16         | SMA            | Thermanit MTS616 | $\Phi 3.2$ | DCRP     | 110-120 | 21-23   | 100-150     |
| 17-22         | SMA            | Thermanit MTS616 | $\Phi 4.0$ | DCRP     | 140-160 | 22-24   | 100-150     |

After P92 steel welded joint of the pipe was treated at a high temperature for 50,000 hours, the welded joint was cut off to make samples. Then samples were processed according to the specifications into samples designated for a tensile test, a bending test, an impact test, and a
hardness test. The WES-600D Hydraulic Universal Testing Machine was used in the tensile test and bending test. The ambient temperature for testing was room temperature. The bending test parameters were: diameter of indenter (30mm), support spacing (52mm), and bending angle (180 °). The impact test was carried out on the JB-30B impact testing machine, and the ambient temperature for testing was also room temperature. HVS1000 microhardness tester was used to test the microhardness of P92 steel. The test load was 200g with a loading time of 15s.

3. Test Results and Analysis

3.1. Tensile Performance
The tensile test results of P92 steel welded joint after 50,000 hours of service are shown in Table 3. Figure 1 shows a photo of the joint samples after being stretched. The two samples were stretched to break away from the weld base metal, showing that the tensile strength of the weld metal is higher than that of the base metal. After 50,000 hours of service, the welded joint has a higher tensile strength, and the base metal at the place of the fracture obviously shrunk, indicating that P92 steel still has a certain level of plasticity after service.

| No. | Sample Number | Rm/MPa   | A %  | Fracture Position |
|-----|---------------|----------|------|-------------------|
| 1   | HFLS1         | 653.22   | 16.13| Base metal        |
| 2   | HFLS2         | 658.78   | 17.44| Base metal        |

Figure 1. Photo of stretched samples of P92 steel welded joint after 50,000 hours of service

3.2. Bending Performance
The bending test was carried out on P92 welded joint after it was treated at a high temperature. Figure 2 shows the joint surface after the joint was bent deeply with an angle of 180 °. It can be seen that one sample has a brittle fracture in the welded area during bending and the other sample has cracks on the surface after being bent. The test results show that after a long time of high-temperature treatment, the plasticity of P92 steel welded joint is obviously not enough, and significant embrittlement can be found in the welded joint, particularly in the welded area.

Figure 2. Photo of bent samples of P92 steel welded joint after 50,000 hours of service
3.3. Hardness

Figure 3 shows the microhardness of each area of P92 steel welded joint after the joint was treated at a high temperature for 50,000 hours. It can be seen that the hardness of the base metal of P92 steel was lowest; the hardness of the heat affected zone was abruptly increased because the zone experienced a peak temperature in the thermal cycle during welding, among which the hardness of the fusion zone is the highest; the hardness of the weld metal is higher than the base metal due to the cast structure formed during the welding process and the precipitation of phases during the service process.

![Figure 3](image)

Figure 3 Hardness distribution diagram of P92 steel welded joint after 50,000 hours of service

Early results [5][8] showed that the matrix of P92 steel welded joint after being treated for 50,000 hours remains the martensite lath structure. In the structure, the number of precipitated phases is significantly increased and the size obviously becomes larger (see Figure 4). Most of the precipitated phases at the grain boundary and lath boundary are mainly Laves phases and M_{23}C_{6} phases. During the service process, the coarse columnar grains of the weld metal and composition segregation are beneficial for the precipitation, aggregation, and growth of Laves phases. Therefore, the number and size of Laves phases are greater than those of M_{23}C_{6} phases. Compared with the base metal structure, the number of Laves phases in the weld metal structure after service is larger and the size is bigger, resulting in the tensile strength and hardness of weld metal being higher than that of the base metal and further leading to the broken base metal of the welded joint sample in the tensile test and cracks and brittle fractures on the curved surface of welding area in the bending test. Therefore, it can be concluded that P92 steel welded joint is the weak part of the main steam pipe after service, which should be paid attention to during technical supervision.

![Figure 4](image)

Figure 4 SEM microstructure of P92 steel welded joint after 50,000 hours of service
4. Conclusions

(1) After 50,000 hours of service, the tensile strength and hardness of the weld metal made of P92 steel are higher than those of the base metal, but the plasticity is lower than that of the base metal. This is related to the precipitation and growth of Laves phases and M$_2$C$_6$ phases during service.

(2) After 50,000 hours of service, the P92 steel weld structure has more Laves phases with larger sizes than that of the base metal structure. Laves phases are precipitated rapidly along the austenite grain boundary and martensite lath boundary and then distributed in the grain boundary, lath boundary, and plate strip boundary, reducing the toughness of the structure at the surface and embrittling the grain boundary.

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