Mechanical Properties of Main Steel Pipeline P92 Steel in Ultra-Supercritical Unit after 50,000 h Service

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Abstract: The mechanical properties of P92 steel after 50,000 h service were explored using the mechanical property tests, such as tensile test, bending test, and impact test by means of scanning electron microscopy (SEM) and energy disperse spectroscopy (EDS), etc. The results show that the strength, elongation, and plasticity of P92 steel after the 50,000 h high-temperature service meet the requirements specified in the related standards, with a certain aging embrittlement phenomenon, which is closely related to the structure aging after the service. The precipitates after the high-temperature service are mainly M23C6, Laves, and compounds of Nb, where the first two phases, which are large, present weak binding force to the matrix with embrittled grain boundary, but the dispersed fine compounds of Nb can be effectively pin the dislocations, and have outstanding solid solution strengthening effect, which is good for improving the strength, plasticity, and toughness of P92 steel.

1. Introduction

By virtue of unique advantages such as high quality and efficiency, energy conservation, and environmental protection, the ultra-supercritical (USC) unit has become an important measure used to optimize the energy structure, and realize the strategic goals of energy conservation and emission reduction in China, and now China owns the largest quantity of USC units across the globe [1-3]. The rapid development of USC units firstly benefits from the development and application of heat-resistant steel with superior high-temperature performance. P92 steel is a fine-grain strengthening and toughening martensitic heat-resistant steel adapting to the development of USC units. Based on P91 steel, P92 steel is developed by replacing the partial Mo element with 1.5%-2% of W element through super-clean smelting, controlled rolling, microalloying, etc., and it is mainly applied to USC unit header, main steam pipeline, and reheat steam pipeline [4-6].

However, the high-parameter USC units have a short history of application in China, and whether they can realize the stable operation depends upon some key technologies, one among which is the evaluation and repair technology for the change and damage of structure properties during the service process of heat-resistant steel. Although P92 steel is developed in Japan, it is mainly used in China, and those mainly used in Europa and America, Japan, etc. are P122 steel and E911 steel [4][5]. With short accumulative service time of P92, the domestic (Chinese) and foreign theories and practices regarding the structure properties of this steel are still in the in-depth research phase, and the problems
like the structure property degradation of P92 after the long-term service have especially aroused high attention [6-11], so whether it can satisfy the continuous service conditions has become the present research emphasis and hotspot. The main steam pipeline P92 steel in a USC unit after 50,000 h service was cut, and by investigating the mechanical properties of P92 steel after the service, the property change laws of P92 steel after the long-term high-temperature service were discussed, in an effort to provide a technical support for the unit maintenance and metal supervision.

2. Test Materials and Methods
The P92 (Φ370 mm×60 mm) steel used in the test was the main steam pipeline in a 1000 MW USC unit from a power plant, and its chemical components were tested via SPECTROLAB quantitative spectrometer as follows (wt, %): C 0.12, Si 0.22, Mn 0.51, P 0.016, S 0.005, Cr 8.62, Ni 0.20, Mo 0.40, Cu 0.11, Nb 0.05, W 1.79 and V 0.20.

The post-service P92 steel pipe specimens were intercepted and processed according to standard requirements [12-15]. The tensile specimens were intercepted from the inner and outer layers along the direction of wall thickness (two specimens at each layer); the bending specimens were side bend specimens, which were taken from the inner and outer layers (two specimens at each layer); the tensile test and bending test were carried out using WES-600D hydraulic universal testing machine at indoor temperature, and the bending test parameters were as follows: The diameter of pressure head was 30 mm, the support spacing was 52 mm, and the angle of bending was 180°. The impact specimens were intercepted from three layers—outer layer, middle layer, and inner layer (three specimens at each layer), and their dimensions were 10 mm×10 mm×55 mm, with “V”-shaped groove; the impact test was performed on the JB-30B impact testing machine at indoor temperature. The microhardness of P92 steel was tested via a HVS1000 microhardness meter under the following conditions: The test load was 200 g, and the loading time was 15 s.

3. Test Results and Analysis

3.1. Tensile properties
The tensile test results of P92 steel after service for 50,000 h are listed in Table 1, and the macrophotographs of the specimens after the stretching are shown in Figure1. It could be observed that P92 steel still had high strength after the service, and obvious constriction took place at the

| Serial No. | Specimen No. | ReL/MPa | Rm/MPa | A %  | Location     |
|------------|--------------|---------|--------|------|--------------|
| 1          | MCLS1        | 554.86  | 688.85 | 22.67| Outer layer  |
| 2          | MCLS2        | 593.45  | 689.27 | 22.00| Outer layer  |
| 3          | MCLS3        | 564.13  | 688.88 | 22.00| Inner layer  |
| 4          | MCLS4        | 572.03  | 692.78 | 22.00| Inner layer  |
|            | GB5310       | ≥440    | ≥620   | ≥20  | (longitudinal)|
Figure 1. Photo of P92 Steel Tensile Specimens after 50,000 h Service
fracture part of the tensile specimen, indicating that P92 steel was still under a certain plastic level
after the service. The tensile strength, yield strength, and elongation of P92 steel after 50,000 h
high-temperature service conform to the requirements specified in Seamless Steel Tubes and Pipes for
High Pressure Boiler (GB5310).

3.2. Bending properties
The bending test results of P92 steel after the service are presented in Table 2 and Figure 2. It could be
observed that the tensile surfaces of the 4 side bending specimens were intact during the bending
process, without any crack, manifesting that P92 steel was still plastic to some extent after the service.

| Location | Specimen No. | Bending form | Bending test result |
|----------|--------------|--------------|---------------------|
| Outer side | MCCW1 | Side bending | The specimen surface is intact in the bending test |
|           | MCCW2 | Side bending | The specimen surface is intact in the bending test |
| Inner side | MCCW3 | Side bending | The specimen surface is intact in the bending test |
|           | MCCW4 | Side bending | The specimen surface is intact in the bending test |

Figure 2. Photo of P92 Steel Bending Specimens after 50,000 h Operation

3.3. Impact properties
The impact energies at outer layer, middle layer, and inner layer of P92 steel after the service are
shown in Figure 3. In comparison with the supply-state base metal (impact energy: 64 J), the impact
energy of P92 steel after the high-temperature service was reduced, which manifested the aging embrittlement phenomenon of P92 steel.

![Figure 3. Impact Test Results of P92 Steel after Service](image)

### 3.4. Hardness

The microhardness results of P92 steel after the 50,000 h service are seen in Table 3. The average microhardness HV$_{0.2}$ of P92 steel after the service was 228.4, and the hardness value (HV) of 10Cr9MoW2VNB (T/P92) steel is required not to be greater than 265 as specified in *Seamless Steel Tubes and Pipes for High Pressure Boiler* (GB5310).

| Measuring point No. | Hardness detection point | Average hardness value |
|---------------------|--------------------------|------------------------|
| Detection point 1   | 231.3                    |                         |
| Detection point 2   | 228.1                    |                         |
| Detection point 3   | 234.5                    |                         |
| Detection point 4   | 226.8                    |                         |
| Detection point 5   | 229.8                    |                         |
| Detection point 6   | 221.1                    |                         |
| Detection point 7   | 227.2                    |                         |
|                     | 228.4                    |                         |

### 3.5. Microstructural changes

The matrix structure of P92 steel was lath martensite under supply state, and the precipitates were mainly M$_{23}$C$_{6}$ carbides, along with a small quantity of MX-type carbonitrides [12]. Following the 50,000 h high-temperature service, the matrix structure still presented the clear form of lath martensite, but the martensite lath experienced the recovery, and a substructure was formed; the precipitates were continuously precipitated out, aggregated, and grew up during the service process, the quantity of precipitates was then continuously increased, so where their sizes, where the large precipitates were mainly distributed at the grain boundary and lath boundary (Figure 4). Besides the M$_{23}$C$_{6}$ phase, a large quantity of Laves phases, and a small quantity of MX-type carbonitrides were also precipitated out [7].

![Figure 4. Microstructures of P92 Steel](image)
4. Analysis and Discussion

The matrix structure of P92 steel, which is strengthening and toughening fine-grain martensitic heat-resistant steel, is tempering lath martensite. Fine granular precipitates exist inside the martensite lath and between the laths, mainly including M$_{23}$C$_6$, along with a small quantity of Nb compounds, which present the dispersive distribution. The martensite lath form of P92 steel is still clear after the 50,000 h high-temperature service, the quantity of precipitates in the structure is apparently increased with enlarged sizes, and the massive precipitates distributed at the grain boundary and lath boundary are mainly Laves and M$_{23}$C$_6$. The roughening rate of Laves phase is obviously higher than that of M$_{23}$C$_6$ during the service process [16]. The large M$_{23}$C$_6$ and Laves show weak binding force to the matrix, the grain boundary toughness and embrittlement of the structure at the interface are reduced, and the phases can be easily peeled off the matrix under the action of stress. With high stability, the compounds of Nb cannot easily grow up in the service process, and moreover, they can effectively pin the dislocations, with outstanding solid solution strengthening effect, which contributes to the strengthening of P92 steel. The aging phenomenon of P92 steel structure becomes obvious after the 50,000 h service, the aging embrittlement phenomenon takes place to some extent, but its indexes like strength, toughness and plasticity still meet the requirements of the related standard. In consideration of the aging embrittlement phenomenon occurring to P92 steel after the service, close attention should be paid to the running state of P92 steel parts. Furthermore, timely investigating and mastering the structural property changes of P92 steel after the long-term high-temperature service will be of great realistic significance for facilitating the safe and stable operation, and healthy development of UCS units.

5. Conclusions

(1) The tensile strength, yield strength, and elongation of P92 steel after the 50,000 h high-temperature service satisfy the requirements specified in the standard. Although the aging embrittlement phenomenon occurs to a certain degree, it still shows a certain plastic level.
The structure aging phenomenon of P92 steel after the service is obvious, and the main precipitates are M23C6, Laves, and compounds of Nb. The large M23C6 and Laves show weak binding force to the matrix, and the grain boundary toughness and embrittlement at the interface are reduced. However, the compounds of Nb cannot easily grow up during the service process, and can effectively pin the dislocations, and their solid solution strengthening effect is outstanding, which is good for improving the strength, plasticity, and toughness of P92 steel.

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