Study of Mechanical Behavior and Microstructure for Low-Hardness P92 Steel

Weixin Yu¹,²*, Zhen Dai¹,², Jifeng Zhao¹,², Lulu Fang¹,² and Yiwen Zhang¹,²

¹ Suzhou Engineering Research Center for Damage Monitoring and Failure Analysis, Suzhou 215123, China;
² China Power Huachuang Electricity Technology Research Company LTD., Suzhou 215123, China.
Email: wxyu@cpibj.com.cn

Abstract. The strength of P92 steel (tensile strength, specified plastic elongation strength) will decrease after its hardness is reduced, ferrite and carbides forming the structure. Carbides of grain size 5-6 are precipitated in the grains and grain boundaries. The martensite lath shape has completely disappeared. M₂₃C₆ carbide coarsened obviously, with a maximum size of about 500nm; The Laves phase is also aggregated and coarsened, connecting in a chain shape with a maximum size of more than 500nm. Evolution of microstructure, namely the obvious coarsening of M₂₃C₆ carbides and the aggregation and connection of Laves phases in a chain shape, are the main causes for rapid decrease in the stability of the material substructure and evident decline in mechanical properties and hardness. In addition, the MX phase did not change significantly, hardly affecting the hardness reduction of P92 steel.

Keywords. P92 steel; hardness reduction; mechanical behavior; microstructure evolution; precipitated phase; coarsening.

1. Introduction
Martensitic heat-resistant steel P92 (China steel grade10Cr9MoW2VNB), tends to appear hardness reduction in early service stage. There is no experience to refer to for the creep test performance and microstructure of P92 steel after the hardness is reduced.

In this study, the microstructure and precipitated phases of low-hardness P92 steel pipe sample were observed by SEM, EDS and TEM. Compared with P92 steel with normal hardness, the influence of microstructure evolution on hardness reduction was analyzed.

"The technical supervision codes metal in fossil-fuel power plant (DL/T438-2016) "defines the hardness of P92 steel as185～250HB [1]. During the maintenance of the thermal power plant, it was found that the hardness of the P92 steel main steam pipe which had been in service for 60,000 hours was reduced to 155HB. In order to study the mechanical behavior and microstructure after the hardness was reduced, sample 1 was made.

At the same time, for comparison, a new unused P92 steel pipe (with a hardness of 183HB) produced in the same batch as a spare part was sampled as sample 2.

2. Chemical Composition Analysis
The PMI-MASTER Smart spark direct reading spectrometer was used for chemical composition analysis. The results are shown in table 1, which meets the requirements of "Seamless steel tubes and pipes for high pressure boiler" (GB/T5310-2017) [2].
Table 1. Chemical composition.

|                | C  | Mn | P   | S   | Si  | Cr  | Mo | V  |
|----------------|----|----|-----|-----|-----|-----|----|----|
| Sample 1       | 0.10 | 0.45 | 0.017 | 0.008 | 0.037 | 9.21 | 0.37 | 0.22 |
| Sample 2       | 0.09 | 0.43 | 0.016 | 0.008 | 0.030 | 9.30 | 0.39 | 0.21 |
| Nb             | 0.042 | 1.71 | 0.017 | 0.007 | 0.19 | 0.0018 | 0.041 | -  |
| W              | 0.045 | 1.83 | 0.017 | 0.007 | 0.20 | 0.0018 | 0.044 | -  |

3. Tensile Test

The MTS C45.305 electronic universal material testing machine was used to conduct a tensile test at room temperature of 25°C. The results are shown in table 2. The high temperature tensile test was performed at high temperature of 600°C, and the results are shown in table 3.

Table 2. Tensile test result at room temperature of 25°C for sample.

|                | $R_m$ (Tensile strength) | $R_{p0.2}$ (Specified plastic elongation strength) |
|----------------|--------------------------|-----------------------------------------------|
| Sample 1       | 548 MPa                  | 263 MPa                                       |
| Sample 2       | 604 MPa                  | 414 MPa                                       |

Table 3. Tensile test result at high temperature of 600°C for sample.

|                | $R_m$ (Tensile strength) | $R_{p0.2}$ (Specified plastic elongation strength) |
|----------------|--------------------------|-----------------------------------------------|
| Sample 1       | 232 MPa                  | 161 MPa                                       |
| Sample 2       | 261 MPa                  | 222 MPa                                       |

At room temperature of 25°C, the Tensile strength and Specified plastic elongation strength of sample 1 with reduced hardness are obviously lower than those of sample 2 with normal hardness, decreased by 9.27% and 36.47% respectively.

At a high temperature of 600°C, the tensile strength and the specified plastic elongation strength of sample 1 with reduced hardness are obviously lower than those of sample 2 with normal hardness, decreased by 11.11% and 27.48% respectively.

It can be concluded that at room temperature of 25°C and high temperature of 600°C, the Tensile strength and Specified plastic elongation strength of sample 1 with reduced hardness are significantly lower than those of sample 2 with normal hardness, which indicates that material strength decreases with hardness decreasing, as shown in figure 1.

Figure 1. Variation of strength and hardness.
4. Microstructure Analysis
Zeiss Axio Observer.3m inverted optical microscope and Zeiss EV018 scanning electron microscope were used to observe the microstructure.

According to "Seamless steel tubes and pipes for high pressure boiler" (GB/T5310-2017) [2], the structure of P92 steel is tempered martensite or, tempered sorbite keeping the martensite phase.

Figure 2 shows the microstructure of sample 1 with reduced hardness is composed of ferrite and carbides. Carbides of grain size 5-6 are precipitated in the grains and grain boundaries, and the martensite lath morphology has completely disappeared. That does not meet the standard.

Figure 3 shows the microstructure of sample 2 with normal hardness is a typical tempered martensite structure with precipitated phases distributing along the martensite lath boundary. Although part of the martensite is decomposed, the lath morphology is clearly visible. That meets the standards.

![Figure 2. Microstructure for sample 1 with reduced hardness.](image1)

![Figure 3. Microstructure for sample 2 with normal hardness.](image2)

5. Precipitates
Literature [3-8] suggested that P92 steel matrix is distributed with various precipitated phases such as $\text{M}_2\text{C}_6$ carbide, Laves phase and MX.

Normally, the M in $\text{M}_2\text{C}_6$ is alloying element Cr. Also in many cases, some of the Cr elements will be replaced by Fe, W, Mo, Ni, etc., that is [Cr (Fe, W, Mo, Ni)]$_2\text{C}_6$ phase [9, 10].

Laves phase is an intermetallic compound, which is composed of alloying elements Fe, Cr, Mo, W, etc., namely (Fe, Cr)$_2$(Mo, W) phase [11-13].
The MX phase is mainly enriched with alloying elements Nb and V, namely (Nb, V)(C, N) phase [14-16].

JEOL-2100 transmission electron microscope and Oxford Aztec Energy 250 energy spectrometer were used for microstructure observation and energy spectrum analysis.

![Precipitates](image1)

**Figure 4.** Precipitated phase on the matrix of sample 2 with normal hardness.

Figure 4(a) shows that the light-colored M$_{23}$C$_6$ carbide on the matrix of sample 2 with normal hardness is distributed in the martensite lath boundary with a size of about 200nm; the dark phase is the Laves phase associated with the M$_{23}$C$_6$ carbide with a size of about 100~200nm; and the dispersed particles are MX carbonitrides, small in size (10-50nm) and dense in shape, they mainly distributed in the martensite lath. The energy spectrum analysis of each precipitated phase is shown in figure 4(b) to figure 4(d), which is consistent with the composition of each precipitated phase.

Figures 5 and 6 show that the precipitated phases on the matrix of sample 1 with reduced hardness are still M$_{23}$C$_6$ carbides, Laves phases and MX phases, and no Z phase is appeared. Apart from no obvious change in size of MX phase, coarsening of M$_{23}$C$_6$ is evident with a maximum size of about 500nm (see figure 5(a)); Laves phase also has obvious aggregation and coarsening, which are connected in a chain shape, and the maximum size has reached over 500 nm (see figure 6(a)). The compositions of each phase did not change significantly, as shown in figure 5(b) to figure 5(d) and figure 6(b) to figure 6(d).
Figure 5. Precipitated phase on the matrix of sample 1 with reduced hardness (view field 1).

Figure 6. Precipitated phase on the matrix of sample 1 with reduced hardness (view field 2).

6. Conclusions
For sample 2 with normal hardness, short rod-shaped M$_{23}$C$_6$ carbides (about 200nm) and Laves phases (about 200nm) precipitate along the grain boundaries or sub-grain boundaries, blocking dislocation movement by pinning effect at the grain boundaries. Dispersive distribution of finer MX phases in the
martensite lath hindered dislocations movement in grains by pinning effect. Each precipitated phase effectively inhibits the recovery of lath martensite in P92 steel, thus a number of strengthening mechanisms such as grain refining strengthening and dispersion strengthening are constituted.

For sample 1 with reduced hardness, the obvious coarsening of M$_{23}$C$_6$ carbides (about 500nm) and the aggregation and connection of Laves phases in a chain shape (about 500nm) are the main causes for rapid decrease in stability of material substructure and evident decline of mechanical prosperities and hardness.

Comparing the two samples, the MX phase did not change significantly, which indicates that MX rarely affect the hardness reduction of P92 steel.

References

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