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Safety Performance Assessment Strategies of P91 Steel Based on Leeb Hardness

Dengke Li^{1*}, Sheng Hu¹, Xing Liu², Yi Xie¹ and Chao Feng¹

¹State Grid Hunan Electric Power Corporation Research Institute, Changsha, Hunan, 410007, China

²State Grid Huaihua Power Supply Company, Huaihua, Hunan, 418000, China

*Corresponding author's e-mail: 118095657@qq.com

Abstract. A study on the low hardness problem of P91 steel was conducted in this paper by a variety of analytical testing methods, including hardness testing, chemical composition analysis, metallographic examination and mechanical properties testing. A significant discrepancy was revealed between the hardness HBHLD, which is converted from Leeb hardness, and Brinell hardness HB. The intrinsic correlation between hardness and metallographic microstructure and mechanical properties was then established. At last, we have concluded the safety performance assessment strategies of P91 steel based on Leeb hardness testing results.

1. Introduction

P91 steel belongs to improved 9Cr-1Mo high strength martensitic heat-resistant steel. It not only has high oxidation resistance and high temperature steam corrosion resistance, but also has good impact toughness and excellent thermal strength. It is widely used in the main steam pipeline, reheated steam pipeline and its branch, high temperature header and other high temperature components of ultra (ultra) critical units where the temperature is higher than 566 C^[1]. However, in the process of maintenance and metal inspection, it is found that abnormal hardness of P91 steel exists universally, especially the problem of low hardness appears repeatedly^[2]. During class C maintenance of unit 3 of a thermal power plant, seven low hardness areas were found in the main steam P91 steel pipeline, which is with a specification of $\phi 333.05 \times 30$ mm and $\phi 450 \times 40$ mm. The hardness value was as low as 113~132 HBHLD, which was far below the requirement of 180 HB stipulated in DL/T 438-2009 "Technical Supervision Regulations for Metals in Thermal Power Plant". In this paper, the methods of hardness testing, metallographic microstructure analysis and mechanical properties testing were used to systematically study the internal relationship between hardness, microstructure and mechanical properties of P91 pipes with different hardness values. Then, the strategy of safety performance assessment of low hardness P91 steel is summarized, which can guide the rapid assessment of low hardness P91 pipes in the process of technical supervision and metal inspection in thermal power plants.

The test material is a P91 main steam pipe with abnormal hardness. Its specification is $\phi 450 \times 40$ mm and its length is 650 mm. Hardness on the outer surface and radial section of the pipe was measured using portable Leeb hardness tester and desktop Brinell hardness tester. The metallographic observation was carried out under Axio observer Alm microscope. The etchant was iron trichloride solution. The chemical constituents were determined by FOUNDRY-MASTER Pro full spectrum



spectrometer. Tensile specimens with a specification of 10×50 mm were tested on the UTM5150 universal material testing machine. The V-notched impact test specimens with a specification of 10×10×55 mm were tested on the JBN-300 impact test equipment.

2. Experimental

2.1 Hardness test

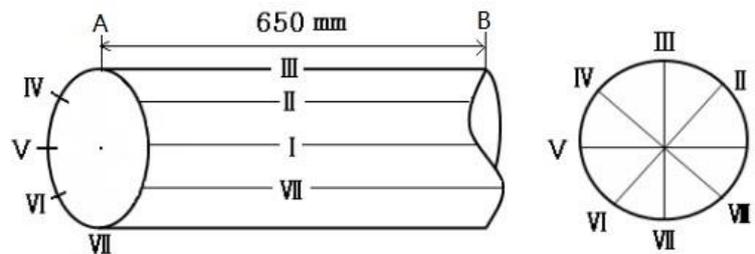


Figure 1. Schematic diagram of hardness testing position.

The pipe segment is divided into eight equal parts along the radial direction from the outer surface, and the bisectors are marked from I to VIII, as shown in figure 1. The surface hardness at different locations is measured by Leeb hardness tester after grinding, as shown in table 1. The pipe is cut along lines II and VI to measure the hardness at different positions in the axial section. The results are shown in table 2. It can be seen from the tables that the minimum hardness of the section is 112 HBHLD, and the hardness distribution along the thickness direction is uniform on the axial section, while the hardness of the inner surface is slightly higher than that of the outer surface.

Table 1. Hardness at different positions on the surface (HBHLD).

Position	Distance from end A/mm				
	100	200	300	400	500
I	124	120	117	147	175
II	142	119	116	152	177
III	148	121	122	148	176
IV	145	117	116	145	171
V	120	114	116	143	162
VI	122	112	114	137	166
VII	126	119	119	143	169
VIII	146	114	118	142	176

Table 2. Hardness at different positions of axial section (HBHLD).

Position		Distance from end A/mm				
		100	200	300	400	500
II	10 mm from the outer surface	145	120	122	159	180
	20 mm from the outer surface	147	124	124	164	178
	30 mm from the outer surface	148	126	127	161	179
VI	10 mm from the outer surface	124	118	120	142	174
	20 mm from the outer surface	129	120	123	145	180
	30 mm from the outer surface	135	119	117	150	181

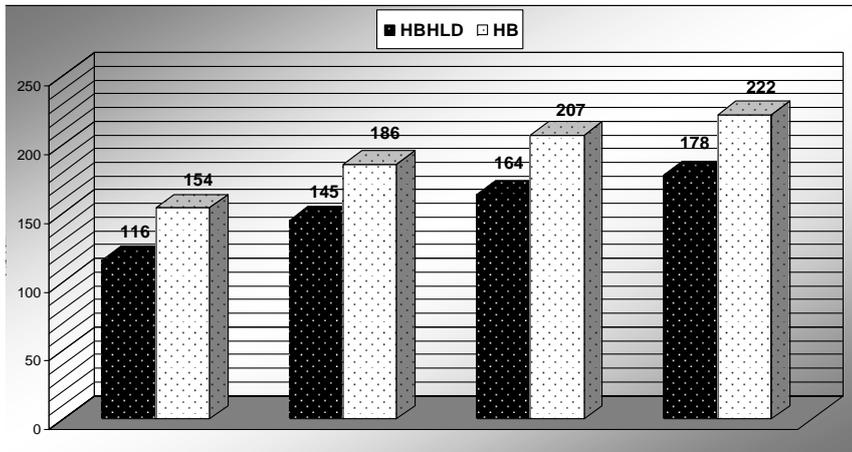


Figure 2. Comparison between HBHLD and HB.

For P91 steel, the experimental results show that the hardness HBHLD measured by portable Leeb hardness tester is about 40 lower in value than the hardness HB measured by desktop Brinell hardness tester, as shown in figure 2.

2.2 Chemical composition analysis

Table 3. Chemical composition of P91 samples with different hardness, and the standard requirements are also listed.

Element	C	S	P	Si	Mn	Cr	Mo	V	Nb	N
Standard	0.08~0.12	≤0.010	≤0.020	0.20~0.50	0.30~0.60	8.00~9.50	0.85~1.05	0.18~0.25	0.06~0.10	0.030~0.070
116 HBHLD sample	0.106	0.0022	0.0197	0.224	0.337	8.72	0.996	0.208	0.102	0.0605
178 HBHLD sample	0.0918	0.0018	0.0159	0.222	0.327	8.68	0.962	0.206	0.105	0.0396

The chemical compositions of 116 HBHLD and 178 HBHLD samples are within the allowable range of ASME SA-213 standard, as shown in table 3.

2.3 Microstructure analysis

Metallographic photographs of 178 HBHLD and 116 HBHLD samples at different magnification are shown in figure 3. It can be seen from that the sample with 178 HBHLD hardness has typical tempered martensite structure. Grain boundary of the original austenite is visible. The grain size of the austenite is about 30 micron. There are several black and white slabs in the original austenite grain, and the fine structure of the slab is obvious. However, the metallographic structure of 116 HBHLD sample has almost no tempered martensite morphology. Its structure is identified as tempered sorbite after careful analysis.

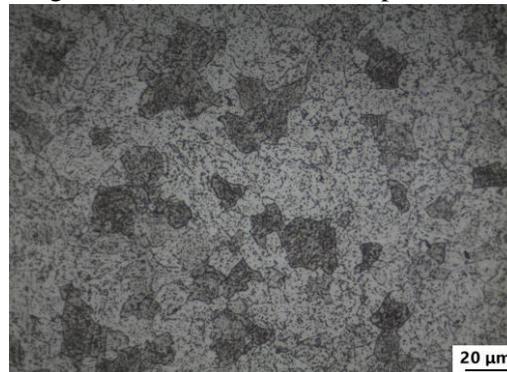
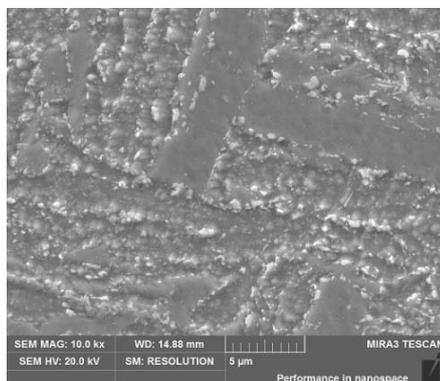
Figure 3(a). 178 HBHLD sample $\times 200$ Figure 3(b). 178 HBHLD sample $\times 500$ Figure 3(c). 116 HBHLD sample $\times 200$ Figure 3(d). 116 HBHLD sample $\times 500$ 

Figure 4(a). 178 HBHLD sample

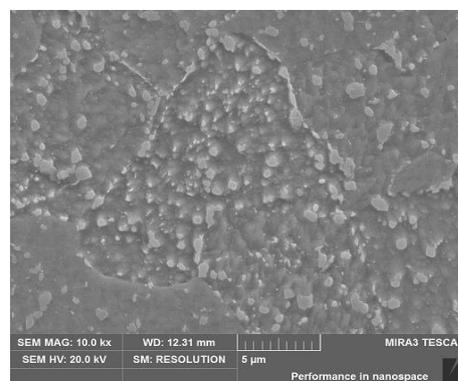


Figure 4(b). 116 HBHLD sample

The scanning electron microscopic photographs of 178 HBHLD and 116 HBHLD samples are shown in figure 4. It can be seen from the figure that the average diameter of precipitated phase particles in 178 HBHLD samples is about 0.2 micron, while that in 116 HBHLD samples is about 0.5 micron. The precipitated phase has obviously coarsened in the 116 HBHLD samples.

2.4 Room temperature mechanical properties

The room temperature mechanical properties of P91 specimens with different hardness are shown in table 4. It can be seen from the table that the room temperature mechanical properties of samples with hardness 145 HBHLD and above meet the requirements of ASME SA-213 standard. The higher the hardness, the higher the strength, but the worse the plasticity. The elongation after fracture and impact absorption energy of the 115 HBHLD samples are higher than that of other specimens. However, the tensile strength and yield strength of the 115 HBHLD samples are lower than the standard requirements, which are 90% and 61% of the standard lower limit respectively.

Table 4. The room temperature mechanical properties of P91 specimens with different hardness, and the standard requirements are also listed.

Hardnes	Tensile strength R _m /MPa	Yield strength RP _{0.2} /MPa	Elongation after fracture A/%	Impact absorption
115 HBHLD	526	253	36	144
145 HBHLD	628	456	27	87
160 HBHLD	697	523	25	114
180 HBHLD	763	657	22	102
Standard	≥585	≥415	≥20	—

3. Discussion

Due to the conversion relationship between hardness and mechanical properties such as tensile strength, hardness testing is usually used to quickly evaluate the quality of materials in field inspection. Although Brinell hardness has high accuracy and good repeatability, it needs to be measured in the laboratory after cutting and sampling. The inspection cycle is long and the metal parts are damaged, so it is not suitable for rapid and mass detection. Therefore, portable Leeb hardness tester is often used in field testing, which is based on GB/T 17394-1998 "Metal Leeb Hardness Test Method". The standard clearly stipulates that the tested objects are low-carbon steel, low-alloy steel and cast steel. If materials are beyond the scope, comparative tests should be carried out to find out the corresponding relationship so as to accurately determine their true hardness. Article 8.2 of GB/T 17394-1998 stipulates that "The conversion of Leeb hardness to other hardness shall be avoided as far as possible". Article 8.3 stipulates that "For other hardness converted by Leeb hardness, the corresponding hardness symbol shall be attached before the Leeb hardness symbol. For example, 400 HVHLD denotes that the Vickers hardness converted from the Leeb hardness measured by D-type impact device is 400"^[3].

P91 is a high-alloy steel, so it is necessary to find out the corresponding relationship between HBHLD hardness converted by Leeb hardness and Brinell hardness in order to accurately measure the true hardness of P91 steel. For P91 steel, experimental results show that the HBHLD hardness measured by portable Leeb hardness tester is about 40 lower than that measured by desktop Brinell hardness tester, as shown in figure 2. Considering that the measurement results of Leeb hardness are influenced by the surface state of materials and the direction of testing, it is reasonable that HBHLD is 35 lower in value than HB. That is 145 HBHLD is equivalent to 180 HB, 125 HBHLD is equivalent to 160 HB.

For P91 steel, reasonable heat treatment process is the key to ensure its best strength and toughness. If the tempering temperature and time are not properly controlled, the high temperature recovery can be completed, which means the overtempering has occurred. Thus, the size of sub-crystalline block grows up, martensite lath merges and widens, dislocation density decreases greatly, carbide particles precipitate and grow along grain boundary and lath boundary, and even a large number of massive ferrite appears, which will lead to abnormal microstructures of P91 steel, and sharp decrease in hardness, mechanical properties and creep strength^[1,4]. The microstructures of 116 HBHLD samples have almost no the typical morphology of tempered martensite, as shown in figure 3. The precipitated phase particles have obviously matured, as shown in figure 4. So their room temperature strength is much lower than the standard requirements, as shown in table 4. Some studies have shown that the room temperature mechanical properties of P91 steel with 180 HB hardness can meet the requirements of the standard at the lower limit, and the high temperature properties also decrease greatly compared with that of 223HB, while the durability of 100,000 hours is equivalent to the recommended values of the standard. However, the mechanical properties of P91 steel with 160 HB hardness have been

greatly reduced, and its endurance strength has been reduced by half compared with the standard recommended value, which can not meet the requirements of safe operation^[5].

4. Conclusion and suggestion

When testing the hardness of P91 steel with portable Leeb hardness tester, the deviation between the Brinell hardness converted from Leeb hardness (in HBHLD) and the hardness measured by desktop Brinell hardness tester (in HB) must be fully taken into account. That is, the former is about 40 less than the latter in value.

It is suggested that the following strategies could be adopted when conducting safety performance assessment for P91 pipes in thermal power plants: (1) It can be judged to be qualified when the hardness value is higher than 145 HBHLD. (2) When the hardness value is in the 125~145 HBHLD range, metallographic examination should be carried out to determine whether the structure is abnormal or not, and strength checking should also be carried out when necessary. For the pipes that can be determined to continue to use, the inspection cycle should be shortened and supervision and management strengthened. (3) When the hardness value is lower than 125 HBHLD, its high temperature performance and endurance strength can not meet the use requirements, so it must be replaced.

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