Study on the Conversion Relation between Brinell Hardness and Leeb Hardness of SA335 P92 Steel Welded Joint

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Abstract: In this paper, the Brinell hardness tester and the Leeb hardness tester are used to test the hardness of the welded joints of P92 steel under different heat treatment conditions. A new conversion relationship between Brinell hardness and Leeb hardness of the welded joints of P92 steel is obtained by data fitting. The results show that the Brinell hardness of welded joints of P92 steel obtained from the original conversion relationship of the Leeb hardness tester is lower than that of the actual ones, because the chemical composition, microstructure and strengthening mechanism of P92 steel are obviously different from those of the low-carbon steel, low-alloy steel and cast steel. The new conversion relationship can accurately characterize the hardness of P92 steel components, solve the problem of the accuracy of the existing Leeb hardness tester to characterize this kind of material, and provide an accurate basis for the welding process and metal supervision of materials for ultra-supercritical units.

1. Introduction

Ultra-supercritical (USC) units, as a mature, advanced and efficient clean coal power generation technology in the world, have become one of the important measures to optimize the energy structure and achieve the strategic goal of energy saving and emission reduction in China [1] [2]. At present, China has become the country with the largest number of USC units in the world. With the construction and operation of USC units, 9% Cr~12% Cr ferritic heat-resistant steels (such as T/P91 steel, T/P92 steel and T/P122 steel) are more and more widely used, and the quality supervision of materials and the quality evaluation of post-weld heat treatment are becoming more and more important. In the manufacture, installation and maintenance of thermal power plant equipment, hardness has become an important monitoring index of material welding or welding heat treatment [3] [4]. HBW value of Brinell hardness is used as the monitoring index of hardness in the standard [3-5]. However, at present, portable Rinell hardness tester is widely used to detect the hardness of metals under field conditions, and then converted to HBHLD of Brinell hardness according to the conversion table provided in standard [6] [7] for effective judgment. In the actual production process, it is often found that there is a big gap between the Brinell hardness HBHLD measured by Leeb hardness tester and the actual Brinell hardness HBW of materials. Therefore, whether the existing Brinell hardness...
HBHLD converted by Leeb hardness tester can accurately reflect the properties of such materials becomes a question, which brings great difficulties to the actual production of manufacturers and power plants, and has become an urgent problem to be solved.

Because Leeb hardness is closely related to the elastic modulus of materials, and the conversion relationship in the standard only applies to low carbon steel, low alloy steel and cast steel. For P92 high alloy heat resistant steel, its elastic modulus has changed greatly [8-10]. If the original conversion relationship is still used, there will be great uncertainty. Because the hardness of the material depends on the structure state of the material, the change of the hardness of the same material reflects the different structure state of the material. In this paper, the relationship between Brinell hardness and Leeb hardness of this kind of steel is studied by using different tempering temperatures to change the structure state of P92 steel. A simple and practical conversion relationship of 9% Cr~12% Cr ferrite heat resistant steel is obtained, which provides a basis for effective implementation of metal supervision.

2. Test materials and methods

2.1 Test materials

SA335 P92 steel is selected as test material with the specification of φ 455 mm × 70 mm. The chemical composition measured by SPECTROLAB quantitative spectrometer (wt, %) is 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, V 0.20. There is non-standard prescribed element Cu in steel, the content of which is about 0.11%. A small amount of Cu can stabilize creep fracture strength and inhibit the formation of δ ferrite [11].

MTS616 electrode is selected as welding material for P92 steel. The specifications are Φ2.4mm and Φ3.2mm. The measured chemical compositions (wt,%) are C 0.10, Si 0.22, Mn 0.74, P 0.009, S 0.006, Cr 8.56, Ni 0.61, Mo 0.55, Cu 0.03, Nb 0.41, W 1.72, V 0.20.

2.2 Test methods

The welded joints of P92 steel are welded by manual tungsten argon arc welding as backing welding, filled and covered by electrode arc welding. After heat treatment, the internal and external quality of the welded joints is qualified. The hardness test samples of P92 steel and weld metal are processed according to the standard [12]. The specifications are 100 mm × 50 mm × 30 mm. The test samples are put into SX2 12-16 box resistance furnace for heat treatment under air conditions. After normalizing at 1050 ℃, the test samples are tempered at different temperatures from 200 ℃ to 800 ℃, respectively. The holding time is 2 hours. Grinding the sample to be tested, and the surface roughness Ra should not be more than 1.6 μm.

The hardness test is carried out at room temperature. According to the standard [12], the Brinell hardness HBW of the sample is tested by 320HBS-3000 digital Brinell hardness tester. The diameter of tungsten carbide ball indenter is 2.5 mm, and the test force is 187.5 kgf. The application time and holding time of the test force are 15s. According to standard [13], the Leeb hardness HLD of the sample is tested by TH-160 Riesler hardness tester and converted to Brinell hardness HBHLD, with the D type impact device. Test procedure: Firstly, the Brinell hardness of each sample is tested on the Brinell hardness tester. At least five indentations of Brinell hardness are measured for each sample. The average value of five effective values is taken as the Brinell hardness value HBW of the sample. The distance between any two indentation centers is not less than 7.5 mm, and the distance between indentation centers and the edge of the sample is not less than 6.5 mm. Clamping to fix samples. At least 7 Leed hardness HLD are tested around each Brinell hardness indentation and converted into HBHLD. The average values of 7 effective values are taken as the HLD and HBHLD of the samples. The distance between Leed hardness point and Brinell hardness indentation should be as close as possible, but not less than the minimum distance specified in the standard. The distance between any two indentation centers of Leed hardness should not be less than 3 mm, and the distance between indentation center and sample edge should not be less than 5 mm.
3. Test results and analysis

3.1 Brinell hardness and Leed hardness of welded joints of P92 steel

The Brinell hardness HBW of P92 steel welded joint samples in different states is measured by Brinell hardness tester and the Brinell hardness HBHLD is measured by Leed hardness tester and converted with its own conversion relationship. It is found that there is a great deviation between the two. Some experimental data are shown in Table 1. From Table 1, it can be seen that the HBHLD converted by Leed hardness tester is obviously smaller than the actual Brinell hardness HBW, and the error between the two is more than 20%. This indicates that there is a great inaccuracy in supervising the hardness of P92 steel by using the existing conversion relationship of Leed hardness tester.

| Serial number | Actual brinell hardness HBW | Brinell hardness is measured according to the Leed hardness tester HBHLD | The difference between HBW and HBHLD | Error between HBW and HBHLD (%) |
|---------------|-----------------------------|------------------------------------------------------------------------|--------------------------------------|----------------------------------|
| 1             | 428.4                       | 353                                                                   | 75.4                                 | 17.60                            |
| 2             | 394.8                       | 321.4                                                                 | 73.4                                 | 18.59                            |
| 3             | 341.4                       | 270.6                                                                 | 70.8                                 | 20.74                            |
| 4             | 308.2                       | 260.9                                                                 | 47.3                                 | 15.35                            |
| 5             | 274.6                       | 214                                                                   | 60.6                                 | 22.07                            |
| 6             | 237                         | 185.3                                                                 | 51.7                                 | 21.81                            |
| 7             | 205.2                       | 167.3                                                                 | 37.9                                 | 18.47                            |

3.2 Establishment of conversion relationship between Leed hardness and Brinell hardness

The hardness data of HBW, HBHLD and HLD of P92 steel welded joints obtained from the experiment are plotted in Fig. 1. From the curves of the hardness data, it can be seen that there is a good correspondence among them.

Fig. 1 The curves of Brinell hardness HBW and Leed hardness HBHLD and HLD of P92 steel

The Brinell hardness HBW and the Brinell hardness HBHLD converted by the Leed hardness tester under different conditions are fitted. If it fits in the form of power function:

\[ HBW = A \times HBHLD^B \] (1)

\( A = 1.83, \ B = 0.9298 \) and correlation coefficient \( R = 0.9883 \) are obtained.

If linear fitting is used, the relationship is as follows:

\[ HBW = A \times HBHLD + B \] (2)

\( A = 1.15, \ B = 21.69 \) and correlation coefficient \( R = 0.9902 \) are obtained.

The closer the correlation coefficient \( R \) is to 1, the higher the fitting degree is. Comparing the \( R \) value of correlation coefficient between linear fitting and power function fitting, it can be seen that linear fitting is better than power function fitting. The linear fitting curves of Brinell hardness HBW...
and Leed hardness HBHLD are shown in Fig. 2, and they have a good linear relationship.

![Fig. 2 Relation curve of Brinell hardness HBW and HBHLD converted by Leed hardness of P92 steel](image)

In order to facilitate field measurement and make the obtained hardness values more intuitive and convenient, the conversion relationship between the Brinell hardness HBW and the Leed hardness HLD of P92 steel welded joints will be established directly. The HBW and HLD of P92 steel welded joints under different conditions are fitted, as shown in Fig. 3.

![Fig. 3 Relation curve between Brinell hardness HBW and Leed hardness HLD of P92 steel](image)

There is a good linear relationship between the Brinell hardness HBW and the Leed hardness HLD of P92 steel welded joint. As shown in formula (3), the correlation coefficient \( R = 0.98 \) and the fitting degree is relatively high.

\[
HBW = 1.27HLD - 369.28 \tag{3}
\]

The error between theoretical value and measured value of Brinell hardness calculated by formula (2) is less than 6%, and some of the data are shown in table 2. The error between theoretical value and measured value of Brinell hardness calculated by formula (3) can also be controlled within 8%, as shown in table 3.

| Serial number | HBW   | HBHLD | Calculate the result according to formula (2) | Error between the measured and theoretical value of HBW (%) |
|---------------|-------|-------|-----------------------------------------------|----------------------------------------------------------|
| 1             | 428.4 | 353   | 428.35                                        | 0.01                                                     |
| 2             | 394.8 | 321.4 | 391.94                                        | 0.72                                                     |
| 3             | 341.4 | 270.6 | 333.42                                        | 2.34                                                     |
| 4             | 308.2 | 260.9 | 322.25                                        | 4.56                                                     |
| 5             | 274.6 | 214   | 268.22                                        | 2.32                                                     |
| 6             | 237   | 185.3 | 235.16                                        | 0.78                                                     |
| 7             | 205.2 | 167.3 | 214.42                                        | 4.49                                                     |
Table 3 Comparison of Brinell hardness HBW, Leed hardness HLD and their theoretical calculating value of P92 steel welded joints

| Serial number | HBW  | HLD  | Calculate the result according to formula (3) | Error between the measured and theoretical value of HBW (%) |
|---------------|------|------|-----------------------------------------------|----------------------------------------------------------|
| 1             | 428.4| 619.6| 417.61                                       | 2.52                                                     |
| 2             | 394.8| 600  | 392.72                                       | 0.53                                                     |
| 3             | 341.4| 557.7| 339.00                                       | 0.70                                                     |
| 4             | 308.2| 551.8| 331.51                                       | 7.56                                                     |
| 5             | 274.6| 506.4| 273.85                                       | 0.27                                                     |
| 6             | 237  | 474.5| 233.34                                       | 1.55                                                     |
| 7             | 205.2| 452.6| 205.52                                       | 0.16                                                     |

3.3 Microstructure of P92 steel welded joints

The microstructure of each zone of P92 steel welded joint is tempered lath martensite, as shown in Fig. 4. The austenite grains in the base metal are fine, and the size of martensite lath is uniform and fine. There is fine and dispersed precipitated phase distribution in the martensite lath and between the laths. The morphology of precipitated phase is mainly granular. The orientation of martensite lath in weld structure is closely related to the crystallization direction of weld metal. In the crystallization direction of weld metal, the length of martensite lath is much longer than that of martensite lath in other directions. After welding thermal cycle and post-weld heat treatment, a certain amount of precipitated phase is precipitated in the weld seam, which is massive, strip and fine grains on the grain boundary of the original austenite, and mostly fine grains at the boundary of the lath. The results show that the precipitated phase in the welded joints of P92 steel is mainly M$_2$C$_6$ carbide and MX Nb/V carbonitride [14][15].

![Microstructure morphology of P92 steel welded joint](image)

(a) Metallographic structure of base metal; (b) SEM of base metal; (c) Metallographic structure of weld seam; (d) SEM of weld seam

Fig.4 Microstructure morphology of P92 steel welded joint
4. Analysis and discussion

Hardness is a comprehensive index of mechanical properties such as strength, plasticity and toughness. It is not only related to the surface roughness, temperature and vibration of the test site, but also closely related to the elastic modulus and elastic limit of the material. The conversion relationship in the standard is only applicable to low carbon steel, low alloy steel and cast steel [6] [7]. P92 steel for ultra-supercritical unit belongs to high alloy heat-resistant steel. The grade of steel is higher than that of low carbon steel, low alloy steel and cast steel. The structure and strengthening mechanism of materials are also obviously different. Therefore, the Brinell hardness converted by existing Leed hardness tester cannot accurately reflect the properties of P92 steel.

The principle of Brinell hardness test is that a certain diameter tungsten carbide composite ball is pressed into the surface of the sample by test force, and the test force is removed after holding for a certain time. The diameter of the indentation on the surface of the sample is measured. The Brinell hardness value is proportional to the test force divided by the indentation surface area. Brinell hardness reflects the ability of material surface to resist plastic deformation caused by a certain indenter under test force, which is related to indentation size. The principle of Leed hardness tester is that the impact body of a certain mass is impacted on the surface of the sample under a certain test force, and the impact speed and rebound speed of the impact body at 1 mm from the surface of the sample are measured, which are expressed by the ratio of the rebound speed and the impact speed of the impact body. The rebound speed is determined by the rebound energy which is equal to the total initial impact energy minus the energy consumed (including elastic and plastic deformation work). Leed hardness reflects the resistance of the tested sample to elastic and plastic deformation, which depends on the magnitude of elastic deformation work. Therefore, the Leed hardness value is closely related to the elastic modulus of the material. The elastic modulus of P92 steel is 191 GPa [16], while that of low carbon steel, low alloy steel and cast iron is 210 GPa [6] [7]. It can be seen that the elastic modulus of P92 steel is smaller than that of the material in the hardness tester. If the original conversion relationship of hardness tester is still used, the elastic deformation work of P92 steel will be smaller, and the Brinell hardness value obtained by conversion will be lower. Using the conversion formulas obtained in this study, the Leed hardness HLD and HBHLD of materials are tested by Leed hardness tester under field conditions, and the Brinell hardness values of materials can be calculated conveniently and quickly by substituting them into formulas (2) and (3). This not only solves the problem of the accuracy of the existing Leed hardness tester to characterize such materials, but also provides an accurate basis for the welding process and metal supervision of ultra-supercritical unit materials.

5. Conclusion

(1) The microstructures of welded joints of P92 steel and high alloy steel are tempered lath martensite. There are some precipitated phases in the base metal. The Brinell hardness of P92 steel can be calculated accurately by using the conversion relationship between Brinell hardness and Leed hardness.

(2) The new conversion relationship between Brinell hardness and Leed hardness of P92 steel solves the problem of adaptability of Leed hardness tester for this kind of material at present, provides correct hardness index for post-weld heat treatment of this kind of material, and improves the accuracy and pertinence of metal supervision.

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