Research on the Relationship between Carbon Precipitation and Mechanical Properties of Dissimilar Steel Welds

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Abstract—After the room temperature tensile test of the pearlite heat-resistant steel and austenitic stainless steel welds after operation, it was found that 75% of the fracture locations were on the austenite side weld line and 25% of the fracture locations were on the austenite side. The maximum tensile strength of the pipe wall under the operating temperature of 530°C and 540°C is 480 MPa and 580 MPa, respectively. Metallographic examination found that there was a "uphill diffusion" near the weld. Through theoretical calculations, after 90,000 hours of operation, on the austenite side of the weld, the difference in carbon increase in the "uphill diffusion" per unit area under the two conditions is about $1.3833 \times 10^8$. Based on the analysis of the relationship between the difference in carbon increment and the mechanical properties, it can be deduced that the dissimilar steel weld of this type of screen superheater tube can continue to serve for about 25,000 hours.

1. INTRODUCTION

The welding of austenitic heat-resistant steel and ferritic heat-resistant steel is currently the most typical dissimilar steel connection method in boiler equipment of power plants. In the course of operation, carbon migration will inevitably occur at dissimilar steel welds [1-6], resulting in decarburized and carbonized layers on both sides of the fusion line. Whether the hardness increases or decreases, it is easy to cause early weld failure [3,4].

Many scholars have reported about carbon migration in dissimilar steel welding. As early as the 1950s, Darken [1] observed in the experiment that "uphill diffusion" occurs at the weld seam, and tried to explain the cause by the activity of carbon. Eckel [2] et al. Pointed out in the diffusion study of dissimilar metal welding heads that there are two types of carbon migration methods at the joints of low carbon steel and austenitic stainless steel: diffusion migration and atomic displacement migration. Ni Ruicheng [5] and others found that the carbon migration at this location mainly occurred in two different time periods through the study of the welding line of 12AlMoV steel welding head, and according to this, the carbon
migration was divided into the first type of carbon migration (when welding) and the second type of carbon migration (after welding), and a systematic analysis of the principles of the second type of carbon migration from a thermodynamic and kinetic perspective.

Through continuous in-depth research on the principles of atomic dynamics and thermodynamic diffusion, a unified understanding of the diffusion mechanism of C during the failure of steel has been formed, that is, the carbon migration at the welded joint during service is mainly completed by gap diffusion. However, few studies have been conducted on the effect of carbon migration (or change) on weld mechanical properties. In this paper, by exploring the relationship between the amount of carbon change and the mechanical properties of welds during the aging process of dissimilar steel welds, a new method for evaluating the life of dissimilar steel welds is given.

2. RESEARCH OBJECT
The screen superheater tube, high temperature superheater tube and high temperature reheater tube of a power plant are made of 12X1MΦ heat resistant steel and 12X18H12T stainless steel. The working conditions are shown in Table 1.

| Name                      | Test piece number | Working temperature ℃ | Working pressure MPa |
|---------------------------|-------------------|------------------------|----------------------|
| Screen superheater tube   | 1                 | 530                    | 23.5                 |
| High temperature superheater tube | 2          | 540                    | 23.5                 |
| High temperature reheater tube | 3           | 540                    | 3.2                  |

3. EXPERIMENTAL RESEARCH

3.1. Tensile test
The test pieces 1-3 were respectively subjected to room temperature tensile tests. The experimental results statistically found that 75% of the test pieces fractured at the welded weld of dissimilar steel, and 25% of the fractures occurred at 20 µm from the weld (austenitic side), and the fracture at the weld is silver-gray, and the macroscopic appearance is brittle fracture. The tensile strength distribution of the sample is shown in Figure 1. The dotted lines $R_{m, min}$ and $R_{p0.2}$ in the figure are the lower limit of tensile strength and yield strength of 12Cr1MoVG in GB / T5310. It can be seen from the data in the figure that the maximum tensile strengths of test piece 2 (high temperature superheater tube) and test piece 3 (high temperature reheater tube) are 480 MPa and 467 MPa, respectively, which are basically close to the standard lower limit of 470 MPa. The maximum tensile strength of the screen superheater tube is 580 MPa.
3.2. Metallographic analysis

Figure 2 shows the metallographic analysis of three types of specimens. The equipment uses a laser confocal metallurgical microscope with a magnification of 50 times. The metallographic pattern is shown in Figure 2. The structure morphology on both sides of the weld is austenite (Left) and bainite structure (right). The structure near the austenite side has obvious carbide precipitation (i.e., carbon-increasing layer). There is an obvious dense carbide precipitation layer near the weld fusion line, the width is about 20µm. No obvious decarburization layer was observed on the bainite side of the three sets of metallographic pictures. The screen superheater tube is broken, and the fracture is located on the austenite side, and the fracture position occurs near the fusion line.

![Metallographic structure of weld-fusion line](image)

3.3. Hardness testing

Intercept the welding seam of the high-temperature superheater tube for fiber hardness testing. The test uses a 402MVD microhardness tester with an applied pressure of 1kgf and a load retention time of 10s. Table 2 shows the test results of the fiber hardness of the high-temperature superheater tube, in which the hardness of the accessory of the fusion line is significantly higher than that of the tissues on both sides, with the maximum fiber hardness reaching 470HV.
TABLE 2. FIBER HARDNESS OF WELD ATTACHMENT OF HIGH TEMPERATURE SUPERHEATER TUBE

| Device Name | 12X1MΦ side | Fusion line | 12X18H12T side |
|-------------|-------------|-------------|----------------|
| 1           | 150         | 470         | 175            |
| 2           | 154         | 468         | 177            |
| 3           | 153         | 470         | 178            |

4. TEST ANALYSIS

4.1. Carbide precipitation analysis
Because the carbon content of 12X1MΦ heat-resistant steel and 12X18H12T stainless steel is not much different, and a large amount of carbide precipitation is found on the austenite side in the metallographic diagram, indicating that carbon migration has occurred at the weld seam- uphil diffusion, it is mainly because 12X18H12T stainless steel has a strong affinity for carbon and can form a more stable carbon chromium compound [5,7]. The driving force of carbon diffusion in "uphill diffusion" is mainly affected by the chemical potential gradient. Lundin [8] made a series of studies on the diffusion of carbon in the ferrite and austenite at the weld seam, and gave the carbon Diffusion formulas in ferrite and austenite and related thermal physical parameters [9]:

\[ D = D_0 e^{-Q/(RT)} \]  

Where \( Q \) is the diffusion activation energy, \( R \) is the gas constant, and \( T \) is the absolute temperature. \( D_0 \) is the diffusion coefficient.

Table 3 shows the thermal physical parameter values of carbon in steel and the diffusion coefficient of carbon in ferrite and austenite at the same temperature. The calculation results show that the carbon diffusion coefficient in ferrite is much larger than that in austenite, that is, the diffusion rate of \( C \) in ferrite is higher than that in austenite.

Table 3. The thermophysical properties of carbon [9]

| Unit          | Austenite | Ferrite          |
|---------------|-----------|------------------|
| \( D_0 \) cm²/s | 0.2       | 0.2              | 0.006            |
| \( Q \) J/mol  | 135000    | 135000           | 80000            |
| \( T \) K      | 843       | 853              | 843              |
| \( D \) m²/s   | 8.6248E-14| 1.08098E-13      | 6.6213E-12       |

It can be seen from the metallographic microscopic observation that there is no obvious decarburization layer on the heat-resistant steel side, because at the same temperature, the diffusion rate of carbon in ferrite is much faster than that in austenite. During long-term operation, the carbon atoms in the matrix far away from the weld can supplement the poor carbon atoms at the weld.

4.2. Analysis of fiber hardness changes
The Vickers hardness analysis of the austenite side of the weld seam of the high-temperature superheater tube found that the maximum value of the hardness near the fusion line reached 470 HV, and the hardness value was approximately converted to a tensile strength of about 1520 MPa [10]. Although the welding is affected by the heat zone, the tensile strength of similar steel super304H is about 700MPa, which is much lower than the value detected by the fusion line. Part of the reason for this phenomenon is that the attachment structure of the fusion line is a bainite structure, So that the weld line attachment structure can be slightly higher than the strength of the base structure, but this increase in strength is far from enough to
make the weld line attachment strength reach 1520 MPa. Then the reason for the increase in strength here can only be due to the production of harder precipitates. Combined with the characteristics of the material, this precipitate can only be a compound formed of carbon and chromium. However, the tensile test results at room temperature show that the tensile properties after operation are significantly reduced, and the bonding strength of the material is also reduced. Multiple tensile fractures occur on the fusion line, and the fracture surface of the tensile fracture is relatively uniform, and the fracture accessories are not obvious. Based on the above factors, due to the continuous precipitation and growth of carbon chromium compounds, the grain boundaries and sub-grain boundaries near the fusion line and the fusion line are gradually widened, and the hardness of the fusion line accessories increases, but the atoms The bond strength between the two is reduced, resulting in a decrease in the tensile properties of the material.

4.3. Analysis of remaining life of screen superheater tubes
Since the diffusion coefficient of Cr element in austenite is much lower than that of C element [11], the precipitation and growth of carbides at the weld line are mainly affected by the carbon content of the weld, and the weld fusion There are two sources of carbon content at the line: (1) Desolved from the carbon atoms originally dissolved in the austenite. (2) It is diffused from the heat-resistant steel side at the fusion line. The carbon atoms in the original austenite will be dissolved to a certain extent to improve the mechanical properties of the material [12], so the carbon atoms in the precipitated carbide that cause the material properties to decline significantly are mainly caused by the other side of the fusion line Diffuse from heat-resistant steel. That is, there is a certain correlation between the increase in carbon and the degree of decline in material properties.

The diffusion at the welds of 12X1MΦ heat-resistant steel and 12X18H12T stainless steel meets Fick’s second quantity:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad (2)$$

Since the C diffusion coefficient on the heat-resistant steel side is much greater than that on the austenite side, when the diffusion time is sufficient, under the action of chemical potential diffusion, the active carbon atoms at the weld fusion line diffuse to the austenite side. Therefore, the diffusion of carbon atoms on the austenite side can be regarded as a constant source diffusion:

$$C = \frac{M}{2(\pi D t)^{1/2}} \exp \left( -\frac{x^2}{4Dt} \right) \quad (3)$$

For a screen superheater tube with a medium temperature of 530℃ after 90,000 hours of diffusion, the carbon increment per unit area is approximately $M_1 = D_1 \cdot t$

The carbon increment in the first layer is $\delta C_1$, that is, when $x = 0$,

$$\delta C_1 = \frac{M}{2(\pi D t)^{1/2}} = \frac{D_1 t}{\sqrt{4\pi}} \quad (4)$$

For the high-temperature superheater tube and the high-temperature reheater tube with a medium temperature of 540℃ after 90,000 hours of diffusion, the carbon increment per unit area is about $C_2 = D_2 \cdot t$

The carbon increment in the first layer is $\delta C_2$, that is, when $x = 0$,

$$\delta C_2 = \frac{M}{2(\pi D t)^{1/2}} = \frac{D_2 t}{\sqrt{4\pi}} \quad (5)$$
After 90,000 hours of operation at different medium temperatures, the difference in carbon increase at the first layer on the austenite side of the fusion line is \( \delta C = \delta C_2 - \delta C_1 \). The quantity \( \delta C = 1.3833 \times 10^8 \).

After 90,000 hours of operation, the maximum tensile strength difference of the pipe wall under two different medium temperatures is about 100 MPa, that is, the main factor that causes the change in the tensile strength of 100 MPa is the increase in carbon content \( \delta C = 1.3833 \times 10^8 \). According to the relationship between the increase in carbon and the amount of change in tensile strength, a graph of the relationship between weld strength and running time can be drawn, as shown in Figure 3.

![Graph](image)

Figure 3. relationship between running time and tensile strength

According to the requirements of DL/T438, the minimum tensile strength of the 12Cr1MoV operating tube wall is 470 MPa, then when the tensile strength of the screen superheater tube with a medium temperature of 530°C reaches 470 MPa, it needs to be re-diffused \( \delta C = 1.5 \times 10^8 \) carbon atoms on the first interface, so it is estimated that the dissimilar steel welds of the screen superheater tube can operate for another 25,000 hours.

5. CONCLUSIONS
(1) After 90,000 hours of operation, an "uphill diffusion" occurred on the austenite side of the weld, with a significant carbon layer. However, the metallography on the heat-resistant steel side shows that the decarburized layer is not obvious.

(2) During the operation of dissimilar steel welds, the carbon content on the austenite side continues to increase, causing the carbon chromium compounds near the fusion line to nucleate and grow, resulting in a decrease in the weld joint strength. When the number of carbon atoms per unit area increases by \( 1.3833 \times 10^8 \), the tensile strength of the weld joint is reduced by 100 MPa.

(3) According to the estimation of the carbon diffusion at the welding seam, the screen superheater tube with the operating medium temperature of 530°C can still be operated for another 25,000 hours.

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