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Analysis of Solidification Crack in ERNiCr-3 Nickel-Base Filled Welding Metal

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Abstract. Through the observation of microstructure and crack morphology, the crack properties and causes of F92/Super304H dissimilar steel welding joint filled with ERNiCr-3 wire was analyzed. Results show the crack was distributed along the crystal and located between dendrites or subcrystals in the center or near the center of the 4th and 5th weld layers. Both dendrites with consistent direction and crystal cells formed on the free solidification surface can be observed on the crack surface. The crack can be identified as welding solidification crack because of its typical morphological characteristics of weld metal solidification crack. The reason for the crack was the weld width of the 4th and 5th layers with 16 ~ 21mm and one weld bead for each layer. The wide weld bead caused the weld metal to stay at high temperature for a long time, and the weld metal generated coarse and developed dendrites with consistent direction. Elements such as Ni, Nb, Si and Ti have segregated between dendrites or subcrystals to form low melting point eutectic such as Ni-Nb and Ni-Si. Cracks were generated along dendrite grain boundaries or subcrystals because of the effect of solidification shrinkage strain. The inherent solidification crack sensitivity of nickel-based welding material and the factors of welding process were the main reasons for the crack.

Keywords. ERNiCr-3 wire, nickel-based welding material, solidification crack, dendrite, low melting point eutectic, element segregation

1. Introduction

It has become a consensus to use nickel-based welding consumables as filler materials for the dissimilar steel joints with austenitic stainless steel base metal on one side when its service temperature exceeds 425 °C [1-4]. However, the hot crack susceptibility of the nickel-based filler weld metal, the diversity of the base metal combination and the early failure tendency of the fusion line area on the non-austenitic steel side of the joint make the selection of nickel-based filler materials and the control of the welding process always concerned. Although the nickel-based alloy filler material has greatly eliminated carbon migration and promoted material creep strength matching of the dissimilar steel joints, there are still problems such as welding crack sensitivity and low

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melting point eutectic equality [5-10]. Failure of dissimilar steel joints using nickel-based welding consumables has not been completely avoided so far.

A large-area crack was found in the F92/Super304H dissimilar steel joint of a power plant boiler superheater using nickel-based filler material after 3 years of service. The crack was located in the weld in metal. During the construction and service of dissimilar steel joints for high-temperature components of high-parameter and large-capacity ultra (ultra)critical thermal power units that have been put into production in recent years, many similar nickel-based filler weld metal cracks have been found one after another [11-15]. Regarding the type of these defects, they are basically considered to be welding crystallization cracks or solidification cracks, but there are different conclusions about the causes and control measures of the cracks. For the nickel-based filled weld cracks in the above projects, we intend to find out the nature and causes of the cracks through microstructure analysis and crack morphology observation.

2. Samples and Defects

The specification of superheater tube in a power station boiler with F92/Super304H dissimilar steel welding joint is OD 48mm × 13mm, manual tungsten argon arc welding and ERNiCr-3 welding wire filling. After 3 years of service, it was found that there were cracks on the surface of some dissimilar steel joints, as shown in figure 1. A large number of welds crack defects were found in subsequent x-ray testing. Some tiny cracks which exceeded the sensitivity of x-ray detection were found in the metallographic examination in the laboratory.

The analytical sample was cut by machining. The microstructure was observed by Zeiss Axiovert 200 MAT optical microscope, the crack morphology was observed by Zeiss Sigma 300 scanning electron microscope, and the element content was analyzed by OXFORD Instruments X-max^n spectrometer.

Figure 1. Crack morphology on-site superheater tube.

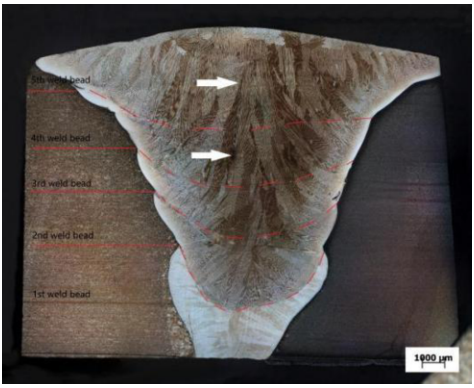


Figure 2. Weld Bead Layout and Crack Location.

3. Observation and Measurement Results

More than ten joints sampled were observed and measured, and their common characteristics were extracted as follows.

3.1. Macroscopic Morphology of Weld Metal

As shown in figure 2, there are 5 layers of welds with one weld bead for each layer, which is consistent with the requirements of the welding procedure specification. Among the 5 layers of weld bead, the 1st, 4th and 5th layers are slightly thicker, ranging from about 2.5mm to 3.5mm, and the 2nd and 3rd layers are relatively thin, about 1.5 to 2.0mm. The bead width of the 4th and 5th layers increased significantly.

3.2. Cr and Ni Contents Analysis

The contents of Cr and Ni in the central area of the weld shown in figure 2 were analyzed by semi-quantitative spectrometer. The Ni content from 1st to 5th layers is 21.5%, 35.8%, 46.0%, 48.0%, 50.8% sequentially, and the Cr content is 16.5% %, 18.7%, 19.0%, 19.5%, 19.5% sequentially. According to the changes of Cr and Ni content, it can be seen that the weld dilution rate is significantly reduced from 4th and 5th layer.

3.3. Crack Morphology

Macroscopically, the cracks are distributed longitudinally along the weld (figure 1), and cracks are only observed in the 4th (figure 3) or 5th welds, and some cracks are continuous or extend from the 4th to the 5th weld (figure 2), even part of the crack extending to the surface of the 5th pass (figure 1). The cracks are all located in the center or near-center area of the weld, as shown in figure 2 and figure 3. Some welds have only one crack, and some welds have multiple cracks (figure 4).

Microscopically, the cracks are distributed along the grain boundary, most of the cracks are located between the austenite columnar dendrites, and a small amount of cracks are also located between the sub-dendritic crystals (figure 4). The ends of the cracks are round and blunt.

The crack section was broken and observed under SEM. It was found that the crack surface had columnar crystals with uniform orientation and free crystallizing unit cells, commonly known as "potatoes", which had the characteristics of free solidification crystal morphology, as shown in figure 5.

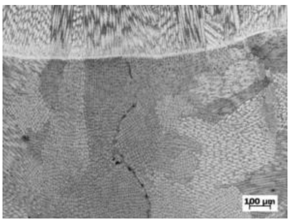


Figure 3. Crack morphology in the 4th weld pass.

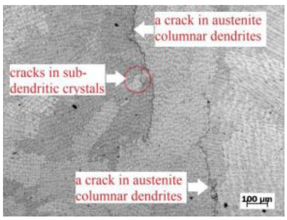


Figure 4. Crack Micromorphology.

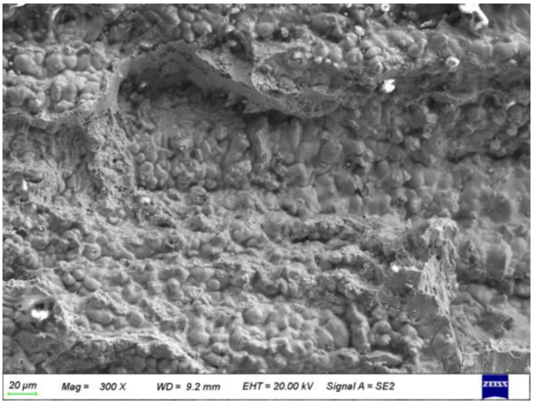


Figure 5. Crack section morphology.

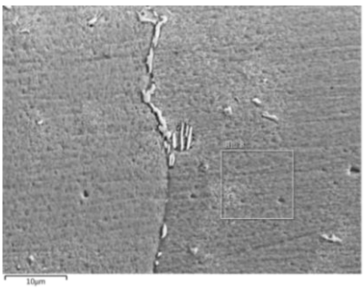
3.4. Observation of Weld Metal Microstructure and Elemental Analysis

The weld metal structure is coarse developed austenite columnar grains and subgrain boundaries (figure 2-figure 4), and the growth direction of the columnar grains is consistent with the heat dissipation direction. White precipitations can be observed on the grain boundaries, as shown in figure 6. They were confirmed Ni- and Nb-rich phases by X-max^n spectrometer analysis.

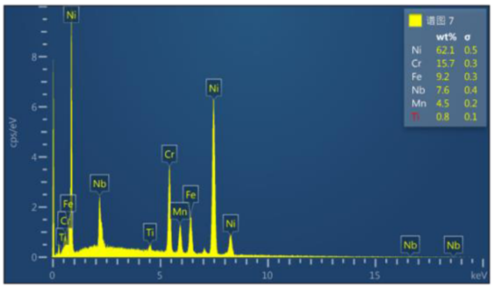
White precipitates and needle-like structures were presented near the cracks (figure 7), which was obviously different from the non crack region (figure 6).

SEM analysis shown that elements Ni, Cr, Nb, Si, Ti and Mn have obvious segregation, especially Ni, Nb, Si and Ti, as shown in figure 7. Their content in the crack area were much higher than that in other areas, for example, the highest Nb content measured is 10.9%, far exceeding the average content by 3.0%.

There are inclusions inside some cracks (figure 8). The energy spectrum analysis of the inclusions shows that there are relatively high contents of elements such as O, Ti, and Al, indicating that they are deoxidized products during welding. Inclusions were not observed in some cracks, which may be crack propagation segments.



(a) Precipitate morphology



(b) Precipitation phase energy spectrum analysis

Figure 6. Morphology and composition of grain boundary precipitates.

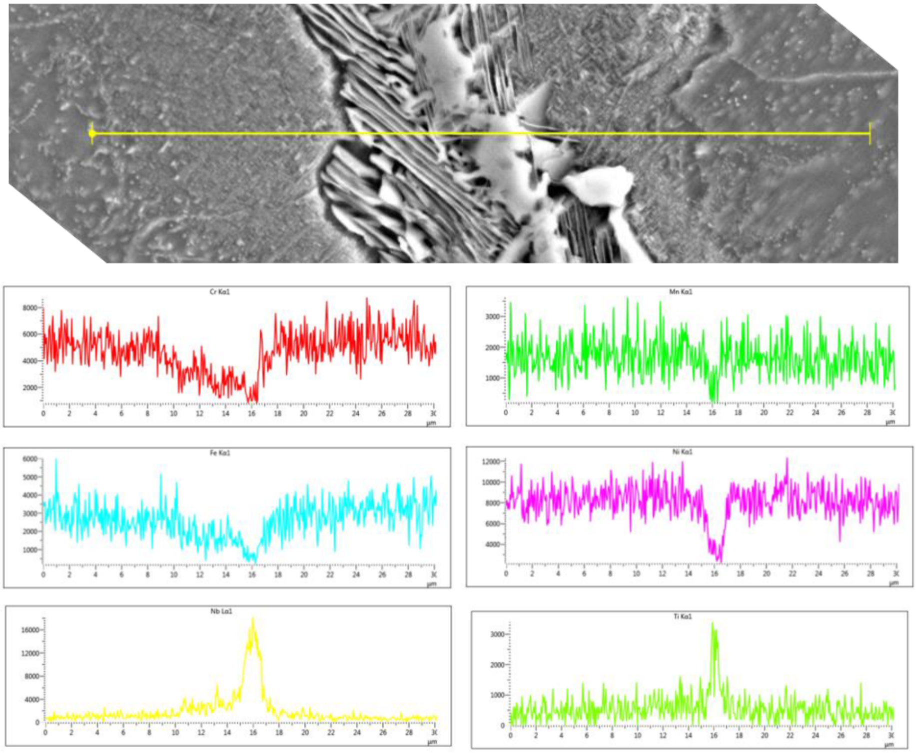


Figure 7. Element Distribution in Crack Area.

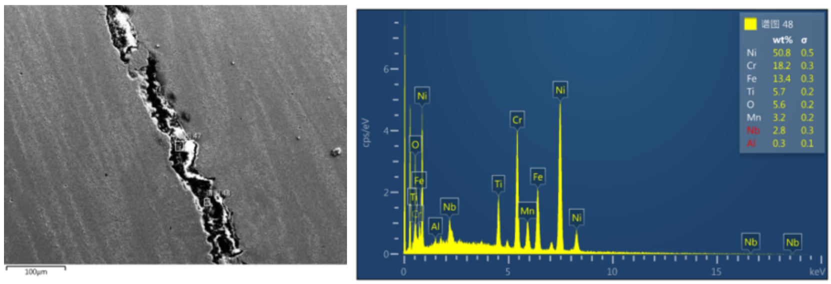


Figure 8. Inclusions in Cracks.

4. Analysis of the Weld Crack Property

Based on the morphology characteristics of the dozens of cracks observed, it can be determined the weld crack as a welding solidification crack. The observed cracks are all located in the interdendritic crystallites, and a few are located in the subgrain intergranular. These regions are the last solidified regions of the weld, typical solidification crack location. Al, Ti, O and other elements exist on some crack surfaces, which further indicates that the cracks are formed during the solidification process of the weld metal. No inclusions are observed on some crack surfaces, which is the result of crack propagation after generation. The "potato"-like free-growing unit cell observed on the crack section is the morphological feature of free solidification crystallization, indicating that no solid-state bond has formed between the crack surfaces, and the crack is the result of the separation of the local weld metal in the liquid state, which is the characteristic morphology of solidification cracks or crystallization cracks that distinguish them from other cracks. According to these characteristics, it can be determined that the ERNiCr-3 nickel-based filler weld crack of the F92/Super304H dissimilar steel joint is a welding hot crack, and it belongs to the solidification crack of the hot crack.

5. Weld Crack Cause Analysis

The metallurgical factor of the crack is attributed to the formation of highly directional coarse dendrites, and the segregation of Ni, Nb, Si, Ti and other elements to form low melting point eutectic during solidification of weld metal. The process factor of the crack is attributed to the wide 4th and 5th layers of weld beads, which leads to the weld staying at high temperature for a long time, developed coarse dendrites and serious element segregation.

The observed coarse and well-developed dendrites and severe segregation of Ni, Nb, Si, Ti and other elements are related to the composition of the deposited metal of ERNiCr-3 welding wire. The ERNiCr-3 deposited metal contains 2.0% to 3.0% Nb, and the Ni content is ≥67%. Nb can reduce the susceptibility of nickel-based alloys to DDC, but can increase the susceptibility to solidification cracks. When the Nb content exceeds 1.2%, segregation is likely to occur during the solidification process, causing solidification cracks and liquation cracks [5,11]. Temperature at which Nb forms Laves phase is about 1150-1200 °C [1]. Melting point of Nb and Ni eutectic phase is only 1175°C under equilibrium conditions, and even lower under non-equilibrium soldering conditions [5]. On the observed cracks, the measured Nb content was much higher than the average, up to 10.9% (figure 7), indicating that severe Nb segregation occurred. The high Ni content in the ERNiCr-3 deposited metal is also one of the reasons for promoting hot cracking. High Ni content can keep the weld metal as austenite in a wide range of base metal composition and a large fusion ratio, which is one of the main reasons for choosing nickel-based filler materials for dissimilar steel weld joints. However, when the weld metal solidifies with austenite mode, the weld metal is approximately not subject to phase transformation, forming a highly directional austenite columnar crystal and promoting element segregation. The segregated elements form a low melting point eutectic film, while At the same time, the liquid film has the tendency to wet the austenite grain boundaries, which makes the nickel-based filler weld metal have inherent susceptibility to solidification cracks [1,3]. In addition, Ni can also form a low-melting eutectic with many elements, For example, the final crystallization temperatures of Ni-P, Ni-S, Ni-B, and Ni-Si are only 870 °C, 637 °C, 1093 °C, and 1143 °C, respectively [1]. According to the element distribution analysis in figures 6 and 7, it is preliminarily determined that the formed low melting point eutectic is Ni-Nb and Ni-Si eutectic.

The process reason for the segregation of elements such as Ni, Nb, Si, and Ti and the formation of a low melting point eutectic phase is caused by the welding process. The width of the 4th and 5th layers of the dissimilar steel joint is about 16-21mm, far exceeding the width of the 1st to 3rd layers of welds. As the width increases, the swing of the welding wire increases, and the residence time of the weld bead at high temperature increases, so the columnar crystals of the 4th to 5th layers are far more developed than the 1st to 3rd layers, as shown in figure 2 and figure 3. The weld width increases, the weld fusion ratio decreases, and the content of Ni, Nb, Si, Ti and other sensitive elements that promote hot cracking in the weld is higher, which can be seen from the content of Cr and Ni in each layer.

To sum up, the formation process of the crack can be obtained: for the F92/Super304H dissimilar steel joint with a specification of OD 48mm×13mm, when the fourth and fifth layers of weld bead are formed, the wire swing width is large, and the weld bead stays at high temperature for a long time, to generate coarse and well-developed austenite dendrites with strong orientation. The coarse and well-developed dendrites strongly promote the segregation of elements such as Ni, Nb, Si, and Ti, forming a low-melting-point eutectic. Low-melting eutectic forms liquid seals between primary developed inter-dendrites and sub-crystals. These enclosed liquids crack along dendrite or subgrain boundaries under shrinkage strain at the solidification boundary. Some cracks propagate during service.

6. Conclusion

1) The observed cracks are welding solidification cracks. The cracks are distributed along the grains and are located between the dendrites or subcrystals. The dendrites with the same direction and the "potatoes" formed by the free solidification surface can be observed on the crack surface. The crack has the typical morphological characteristics of solidification crack of weld metal, which is the solidification crack in the hot crack of weld metal. During service, some cracks propagated.

2) The inherent solidification crack susceptibility of ERNiCr-3 weld metal and joint welding process factors are the main reasons for the crack. The width of the 4th to 5th layers is 16 to 21mm, each layer is a single bead, and the weld metal stays at high temperature for a long time, so that the weld metal solidified in the austenite crystallization mode forms a coarse and well-developed shape with strong directionality. The dendrites of Ni, Nb, Si, Ti and other elements are strongly segregated between dendrites or sub-crystals, forming low melting point eutectics such as Ni-Nb and Nb-Si, and cracks are generated under the action of solidification shrinkage strain.

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