Effects of Friction Pressure on Microstructures and Mechanical properties of friction welded Super304H austenitic welding joints

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Abstract. In this paper, the Super304H austenitic steel were welded by continuous drive friction welding technique. The friction welding joints exhibited good mechanical and metallurgical properties. The influence of friction pressure on the microstructure and mechanical properties of Super304H welding joints was investigated. With an increase in the friction pressure, the grains in the welding zone and the heat affected zone didn’t grow up and the number of the precipitated phases increased. The fracture location of tensile strength samples was in the heat affected zone. With an increase in the friction pressure, the Vickers hardness and the tensile strength increased.

1. Introduction
Increased heat efficiency is always the innovative driving forces in the development of ultra-supercritical boilers for fossil power plants, whose steam temperature is up to 600°C and pressure exceeds 25MPa. Under this ultra-supercritical condition, the heat efficiency can rise to around 45%. Many ultra-supercritical boilers have been built and successfully operated all over the world. At present, the worldwide aspirations for ensuring energy safety with simultaneous tightening of the requirements of the act on permissible emission of pollutants into the atmosphere have contributed to the development of materials that allow the improvement of steam working parameters resulting in units designed for ultra-supercritical steam parameters. The construction of boilers with ultra-supercritical steam parameters between 550 and 760°C requires the use of new materials with higher mechanical parameters and more complex manufacturing process for making the components of boiler pressure section out of them [1].

In order to fulfill the tough parameters of the ultra-supercritical power generation, traditional heat-resistant steels used in the ultra-supercritical units have been replaced by those new heat-resistant steels. To meet the critical demands for the ultra-supercritical critical power generation, a new austenitic steel Super304H (0.1C-18Cr-9Ni-3Cu-Nb-N) has been developed. The Super304H has higher strength at elevated temperatures are required for super-heater tubes in fossil fired boilers. The conventional fusion welding joints of austenitic steel exhibit inferior mechanical properties due to the formation of intermetallic compounds at the joint interface, and the excessive residual stresses. The friction welding can be more suitable than fusion ones since many problems associated with melting are eliminated or reduced [2, 3]. The aim of this paper is to fabricate a combination the Super304H austenitic steel by using continuous drive friction welding with better mechanical properties. The effect of friction pressure on the microstructure and mechanical properties of the welded joints were investigated.
2. Experimental procedures

The pipes of Super304H austenitic steel that in the sizes of Φ44.5mm x 9mm were used as base metals. The pipes of Super304H were friction welded by a continuous drive friction welding machine. In the process of friction welding, the friction speed was 1500 rpm, the upset pressure was 150 MPa and the friction time was 5s. The friction pressure was 100 MPa of Process 1, 150 MPa of Process 2 and 200 MPa of Process 3 respectively. The metallography and fractographs of the welding joints were performed by an optical microscope and a scanning electron microscope respectively. The X-ray XRD patterns were examined by X-ray Diffraction. The tensile samples were tested using a testing instrument, and Vickers hardness values were tested using a Vickers hardness testing instrument.

3. Results and Discussion

Figure 1 showed the X-ray diffraction profiles for the Super304H welding joints welded by Process 2. It could be sure that the peaks with the highest intensity correspond to the γ-Fe phase and the precipitated phases of Cr$_{23}$C$_6$ and NbC. Therefore, the main phases were the γ-Fe phase and the precipitated phases of Cr$_{23}$C$_6$ and NbC. The Cr element had a tendency to form carbides, some C element and Cr element were precipitated from matrix and formed the precipitated phases Cr$_{23}$C$_6$ at the grain boundary preferentially. Some N element replaces the element C, and a part of the NbC were converted into Nb(C, N). It was difficult to index the Nb(C, N) due to lower intensities peaks. Therefore, Cr$_{23}$C$_6$ and NbC were denoted precipitated phases in the X-ray diffraction profiles [4, 5].

![XRD pattern](image)

Figure 1: the XRD patterns of for the Super304H welding joints

Figure 2, 3 and 4 shows the metallurgy of the welding joints with different friction pressure respectively. During the friction welding process, the welded zone produced agglutinate and shear tear behaviour, which led to the deformation of the austenitic grains in the welding zone, and the dynamic recrystallization driving force and lattice distortion energy increased. The thermoplastic deformation temperature and unit volume free energy of recrystallized grains decreased, which produce a large number of recrystallized nucleations that leading to the fine grained dynamic recrystallization structure of the weld zone. The welding interface that was straight and clear, and the welding interface is well combined. The welding zone of austenitic steel welded by fusion welding was typical dendritic morphology with large grains. Compared with the conventional fusion welding joints, the welding zone were mainly composed of fine equiaxed austenite grains because of grain refinement. So the welding zone exhibit excellent microstructure and mechanical properties [6]. The friction welding was solid state welding techniques, the melting process did not occur in the welding zone and the heat affected zone. So the heat input during the friction welding process was much less than the heat input.
during the fusion welding process. The width of the heat affected zone caused by friction welding process were much smaller than the width of the heat affected zone caused by the fusion welding process[6]. The tendency of grains growth during the friction welding process was less obvious than the tendency of grains growth during the fusion welding process. So the friction welded Super304H joints with the fine grains in the welding zone and heat affected zone showed excellent microstructure and mechanical properties.

![Figure 2](image1.png)

**Figure 2** The metallography of Super304H welding joints for Process 1

![Figure 3](image2.png)

**Figure 3** The metallography of Super304H welding joints for Process 2

![Figure 4](image3.png)

**Figure 4** The metallography of Super304H welding joints for Process 3

The surface temperature of the welding joints was equal to the temperature of the welding heat source in friction welding process, so the surface temperature of the welding joints had a great
influence on the microstructure and mechanical properties of the welding joints. The surface temperature of the welding joints was calculated according to the Eq (1)

$$T(t) = \frac{qt}{\pi \lambda C} \quad (1)$$

$T$ was referred to the surface temperature of the welding joints, $t$ was referred to friction time and $q$ was referred to friction heating power. It was calculated according to the Eq (2)

$$q = \frac{\pi n T}{30} \quad (2)$$

$T$ was referred to the friction torque, $n$ was referred to the friction speed, and $q$ was referred to the friction heating power. The friction heating power was mainly depended on the friction torque and the friction speed. During the friction welding process, when the friction speed was constant, as the welding torque increased, the friction heating power and the surface temperature of the welding joints increased correspondingly. The friction torque was mainly depended on the friction pressure and the coefficient of friction, so the friction torque was proportional to the friction pressure. Therefore, as the friction pressure increased, the friction heating power and the surface temperature of the welding joints increased. Because that melting process did not occur in the welding zone, although the surface temperature of the welding joints increased, the size change of the grains in the welding zone was not detectable. As the friction pressure increased, the heat input during the friction welding process increased and the temperature of the heat affected zone increased accordingly. The size change of the austenite grains which in the heat affected zone was not detectable, but the amount of the precipitated phases $\text{Cr}_2\text{C}_6$ and $\text{NbC}$ in the both heat affected zone increased obviously [7, 8].

Table 1 depicted the variation of the yield strength and tensile strength as a function of the friction pressure. It was detected that the fracture position of the welding joints was in the heat affected zone for the different friction pressure. The fractographs of the tensile strength samples were shown in figure 5. As the friction pressure increased, the tensile strength of the welding joints increased gradually. The friction heating power and the temperature of the heat affected zone increased during the friction welding process with the friction pressure increased. The amount of the precipitated phases $\text{Cr}_2\text{C}_6$ and $\text{NbC}$ increased obviously in the heat affected zone, the dispersion strengthening effect of the $\text{Cr}_2\text{C}_6$ and $\text{NbC}$ carbides was main reason of the tensile strength increased. The fracture morphology was characterized by typical ductile fracture, and a lot of fine and shallow dimples distributed [9]. Table 1 depicted the variation of the Vickers hardness as a function of the friction pressure. When the grains size was smaller, the Vickers hardness was higher. The grains size of the welding zone with fine grains was the smaller, so the Vickers hardness of the welding zone was the higher. As the friction pressure increased, the dislocation density and lattice distortion energy in the welding zone increased, and the Vickers hardness of the welding zone increased. The precipitation of the $\text{Cr}_2\text{C}_6$ carbides was the reason that the Vickers hardness of the heat affected zone increased.

![Figure 5](image_url)  
**Figure 5** The fracture appearance of the tensile strength samples
Table 1 The mechanical properties of Super304H welded joints

| Process | Tensile strength /MPa | Vickers hardness / Hv |
|---------|-----------------------|----------------------|
|         | $R_{p0.2}$ | $R_m$ | Fracture position | Welding zone | Heat affected zone |
| Process 1 | 456.29 | 736.66 | heat affected zone | 333.71 | 265.92 |
| Process 2 | 493.14 | 764.51 | heat affected zone | 367.80 | 282.22 |
| Process 3 | 518.99 | 788.29 | heat affected zone | 402.21 | 305.71 |

4. Conclusions
The Super304H austenitic steel welded joints with excellent properties were welded by continuous drive friction welding technique. The welding interface was well combined, and the austenite grains in the welding zone was fine. The fracture position was in the heat affected zone. The influence of friction pressure on the microstructure and properties of Super304H joints was investigated. With an increase in the friction pressure, the grains of weld zone didn’t grow up and the number of second-phase particles precipitates increased. With an increase in the friction pressure, the tensile strength and the Vickers hardness increased.

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