Effects of Friction Pressure on Microstructures and Mechanical Properties of Friction Welded T92/Super304H Dissimilar Steel Weld Joints

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Abstract. In this paper, the T92 martensitic steel and 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 microstructures and mechanical properties of T92/Super304H dissimilar steel 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 second-phase particles precipitates increased. The Vickers hardness increased and the impact toughness decreased, the tensile fracture and fracture location didn’t change.

1. Introduction

Due to the problems of the earth environment such as the increase of carbonic acid gas and the fuel consumption, improvement of thermal efficiency is required in fossil fired power plants. Ultra super critical boilers that are operated under the condition of a temperature over 873K and steam pressure over 24MPa are expected as one of the higher heat efficiency plants. However, with the increase of steam parameters, requirements for the materials applied in the Ultra-super critical boilers components are becoming higher [1, 2]. In order to fulfill the tough parameters of the ultra-super critical power generation, traditional heat-resistant steels used in the subcritical and supercritical units have been replaced by those new heat-resistant steels. The recently developed Super304H (0.1C-18Cr-9Ni-3Cu-Nb-N) austenitic steel has shown considerable promise due to its high oxidation resistance, corrosion resistance and creep resistance. The Super304H has higher strength at elevated temperatures are required for super heater tubes in the boilers. This excellent creep rupture strength is based on finely precipitated particles such as Nb(C, N) and NbC. Thus, it is widely used for super-heaters and re-heaters, which have the abominable service environment in Ultra-super critical boilers. The T92 (9Cr-0.5Mo-2-W-V-Nb) martensitic steel approximately similar to T91 but with a little modification in chemical compositions for preferable high temperature properties. In comparison with T91 steel, the resistance to creep of T92 is about 30% higher. The T92 martensitic steel will certainly have a broad application prospect in forth coming ultra-super critical boilers. In this case, the welding between T92 and Super304H steels will be necessary.

At present, the T92 martensitic steel and Super304H austenitic steel are welded through the gas tungsten arc welding (GTAW) technique usually in engineering applications. The GTAW technique is mature and suitable for field welding. Nevertheless, the T92/Super304H joints welding through the conventional fusion welding still exhibit inferior mechanical properties. The reasons are: (i) The base metal near the fusion line during the fusion welding process is prone to form the wide heat affected...
zone with coarse grains; (ii) A transition layer (fusion zone) will appear in the welding zone near the weld line; (iii) The migration of carbon atoms occurred though the fusion line, and carbonization layers and decarburization layers are formed at the welding zone. The friction welding is a solid state welding process, and the welding temperature was under the melting temperature. This welding process nullifies adverse effects of the uncertainties in the filler metal selection by GTAW technique. The friction welding has a number of advantages over the conventional fusion welding process. The major advantage relies on the direct conversion of mechanical energy into thermal energy at the joint interface in contrast to fusion welding. The very high temperature gradient available in the joint area accounts for a very small heat affected zone. Owing to the narrow the heat affected zone, the welding distortion is kept minimum. Additionally, because it is a solid state process, the defects associated with melting solidification phenomenon such as porosity and slag are not present [3-5]. The aim of this paper is to fabricate a combination with higher better mechanical properties between the Super304H austenitic steel and the T92 martensitic steel by using continuous drive friction welding. The effect of friction pressure on the microstructures and mechanical properties of the welded joints were thus investigated.

2. Experimental procedures
The pipes of Super304H austenitic steel and T92 martensitic steel that in the sizes of Φ44.5mm x 9mm were used as base metals. The chemical compositions and room mechanical properties of the base metals were listed in Tables 1 and 2. The pipes of Super304H and T92 were friction welded by a continuous drive friction welding machine. In the process of friction welding, the friction speed was 1500 rpm. The friction pressure was 100 MPa of Process 1, 150 MPa of Process 2 and 200 MPa of Process 3. The upset pressure was 200 MPa and the friction time was 5s respectively. The metallographs 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 Vickers hardness values of the joints were tested using a Vickers hardness testing instrument. The tensile samples were tested using a testing instrument. The impact samples were tested using an impacting instrument.

| Chemical composition of Super304H and T92 |   |   | C | Si | Mn | Cr | Ni | Mo | Cu | Nb | N  | Al | B  |
|------------------------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T92                                      |   |   | 0.13 | 0.28 | 0.43 | 8.474 | 0.239 | 0.985 | 0.043 | 0.062 | - | 0.0057 | 0.002 |
| Super304H                                |   |   | 0.07 | 0.21 | 0.81 | 18.37 | 9.06 | 0.42 | 2.93 | 0.52 | 0.10 | 0.01 | 0.002 |
| Table 2 Mechanical properties of Super304H and T92 |
| $\sigma_0$/MPa | $\sigma_b$/MPa | $\delta$/% | $K_V$/J | Hardness/ HB |
| T92                                      | ≥440 | ≥620 | ≥20 | ≥40 | ≤250 |
| Super304H                                | ≥235 | ≥590 | ≥35 | - | - |

3. Results and Discussion
Figure 1 showed the X-ray diffraction profiles for the Super304H side and the T92 side of the welding joints welded by Process 2 respectively. It could be sure that the peaks with the highest intensity correspond to the $\gamma$-Fe phase and the precipitated phases $\text{Cr}_2\text{C}_6$ and NbC for the Super304H side. Therefore, the main phase of the Super304H side were the $\gamma$-Fe phase and the precipitated phases of $\text{Cr}_2\text{C}_6$ and NbC. The X-ray result indicated that the precipitated phases included the Cr and Fe elements [6]. The Cr element had a tendency to form carbides. So some C element and Cr element
were precipitated from matrix and formed the precipitated phases Cr$_2$C$_6$ at the grain boundary preferentially. Some N element replaces the element C, and a part of the NbC is converted into Nb(C, N). It was difficult to index the Nb(C, N) due to lower intensities peaks. Therefore, Cr$_2$C$_6$ and NbC were denoted precipitated phases in the X-ray diffraction profiles. It can be sure that the peaks with the highest intensity correspond to the $\alpha$-Fe phase and the precipitated phases Cr$_2$C$_6$ for the T92 side of the welding joints. Therefore, the main phase of the T92 side are the $\alpha$-Fe phase and the precipitated phases of Cr$_2$C$_6$ which were precipitated from supersaturated martensite grains. Because there were some trace elements of Nb and V in the T92 side. So the MX carbonitrides containing Nb and V should be precipitated theoretically. But it was difficult to index the MX carbonitrides due to lower intensities peaks.

Figure 1 the XRD patterns of for the Super304H side and the T92 side

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. It led to the deformation of the 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 produced a large number of recrystallized nucleation [7, 8]. The welding zone included a welding interface and the areas (about 50μm from the welding interface) on both sides of the welding interface. The centre of the welding zone was the welding interface that was straight and clear. Due to agglutinate and shear tear behaviour, there was the T92 lays appear in the Super304H side of the welding zone occasionally and the T92 lays were parallel to the welding interface. The Super304H side of the welding zone was mainly composed of fine equiaxed austenite grains because of grain refinement. The martensite grains which in the T92 side of the welding zone was austenitized due to the higher temperature generated by friction process, than it produced a large number of fine equiaxed austenitic grains by dynamic recrystallization. In the cooling process after welding, the recrystallization of the equiaxed austenitic grains takes place, resulting in the formation of the fine plate martensite grains. The welding zone of T92/Super304H dissimilar steel welded by fusion welding process had the typical coarse $\delta$-phase grains. The coarse $\delta$-phase grains were not formed in the welding zone by the friction welding. Because that the austenite grains and plate martensite grains on both sides of the welding interface was fine, so the welding zone of the Super304H/T92 welding joints exhibit excellent microstructures and mechanical properties. 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. 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 heat affected zone of the welding joints with the fine grains showed excellent microstructure and mechanical properties. With the distance from the welding zone increased, the size of the austenitic grains and the martensite grains decreased in the both heat affected zone, until the size of grains was equal to the size of grains in the base metal. The overheated zone with coarse δ-phase grains were not founded in the T92 heat affected zone too [9, 10]. So the friction welded Super304H/T92 joints with the fine grains in the welding zone and heat affected zone showed excellent microstructure and mechanical properties.

![Figure 2 The metallography of welded joints for Process 1 (a) the T92 heat affected zone (b) the welding zone, (c) the Super304H heat affected zone](image)

![Figure 3 The metallography of welded joints for Process 2 (a) the T92 heat affected zone (b) the welding zone, (c) the Super304H heat affected zone](image)

![Figure 4 The metallography of welded joints for Process 3 (a) the T92 heat affected zone (b) the welding zone, (c) the Super304H heat affected zone](image)

The surface temperature of the welding joints was equal to the temperature of the welding heat source in friction welding process. It affected the heating temperature, temperature distribution, deformation and diffusion of the metal of the welding joints directly. So the surface temperature of the welding joints had a great influence on the microstructure and mechanical properties of the welding joints. The welding heat source was considered to be a linearly propagated planar heat source in friction welding process. If the heat dissipation to the surrounding space was not considered, the surface temperature of the welding joints was calculated according to the Eq (1)
\[ T(t) = q\pi/(\pi\rho) \] (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)

\[ q = (\pi n T)/30 \] (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. When the friction speed was constant during the friction welding process, as the friction 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 frictional pressure increased, the heat input during the friction welding process increased in the heat affected zone, and the temperature of the heat affected zone increased accordingly. The size change of the austenite grains in the Super304H heat affected zone and the martensite grains in the T92 heat affected zone was not detectable, but the amount of the precipitated phases in the both heat affected zone increased obviously [11, 12].

Table 3 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 Super304H base metal for the different friction pressure. The fractographs of the tensile strength samples were shown in figure 4. As the friction pressure increased, the tensile strength change of the welding joints was not obviously and regularly. The fracture morphology was characterized by typical ductile fracture, and a lot of fine and shallow dimples distributed on the facture surface. Table 3 depicted the variation of the impact toughness as a function of the friction pressure. The grains size had a great influence on the impact toughness of each zone of the welded joints. When the grains size was smaller, the impact toughness was higher. The grain size of the heat affected zone with coarse grains was the larger, so the impact toughness of the heat affected zone was the lower. As the friction pressure increased, the dislocation density and lattice distortion energy in the welding zone increased, and the impact toughness of the welding zone decreased. The precipitation of the Cr23C6 carbides was main reason that the impact toughness of the heat affected zone decreased with the friction pressure increased. The fractographs of the impact toughness samples were shown in figure 6, 7 and 8. The fracture mode of the impact toughness samples was ductile fracture with the aggregation dimples on the facture surface. In the welding zone, the dimples were distributed densely and deeply, and the shapes of dimples were round. In the heat affected zone, the dimples were distributed sparsely and shallow, and the shapes of dimples were flat. Table 3 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. The dislocation density and lattice distortion energy in the welding zone increased as the friction pressure increased, and the Vickers hardness of the welding zone increased. The precipitation of the Cr23C6 carbides was the reason that the Vickers hardness of the heat affected zone increased with the friction pressure increased.

| Table 3 The mechanical properties of Super304H/T92 welded joints |
|---------------------------------------------------------------|
| Tensile strength /MPa | Impact toughness /J | Vickers hardness / Hv |
| \( R_{p0.2} \) | \( R_m \) Fracture position | Welding zone | Heat affected zone (Super304H/T92) | Welding zone /Hv | Heat affected zone (Super304H/T92) |
|----------------------|---------------------|----------------------|------------------|------------------|------------------|
|                      |                     |                      |                  |                  |                  |

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| Process | Tensile Strength | Base Metal | Yield Strength | Ultimate Strength |
|---------|-----------------|------------|----------------|-------------------|
| 1       | 422.38          | 653.15     | 78.5           | 312.5             | 224.1/321.5       |
| 2       | 413.11          | 644.41     | 76.9           | 349.6             | 248.9/358.9       |
| 3       | 435.71          | 644.43     | 70.6           | 379.9             | 282.9/381.4       |

(a) Process 1, (b) Process 2, (c) Process 3

Figure 5 The fracture appearance of the tensile strength samples (a) Process 1, (b) Process 2, (c) Process 3

Figure 6 The fracture appearance of the impact toughness samples for Process 1 (a) the T92 heat affected zone, (b) the welding zone, (c) the Super304H heat affected zone

Figure 7 The fracture appearance of the impact toughness samples for Process 2 (a) the T92 heat affected zone, (b) the welding zone, (c) the Super304H heat affected zone
Conclusions

The T92/Super304H dissimilar steel welded joints with excellent properties were welded by continuous drive friction welding technique. The welding interface was well combined, and the austenite grains and plate martensite grains in the welding zone was fine. The fracture position of the welding joints was in the Super304H base metal. The influence of friction pressure on the structure and properties of T92/Super304H dissimilar steel 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. The Vickers hardness increased and the impact toughness decreased, the tensile fracture didn’t change.

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