The influence of welding speed on friction stir welded of duplex stainless steel

Zhongxue Jia, Yunqiang Zhao*, Chunlin Dong, Shu Miao, Chungui Wang and Yaoyong Yi

Guangdong Provincial Key Laboratory of Advanced Welding Technology, Guangdong Welding Institute (China-Ukraine E. O. Paton Institute of Welding), Guangzhou, China

*Corresponding author e-mail: zhaoyq@gwi.gd.cn.

Abstract. Friction stir welding of 4 mm thick 2205 duplex stainless steel was carried out. When the welding speed is low, the well-formed joint without defects can be obtained. When the welding speed is reach 70 mm/min, the hole defect occurs in the bottom of the joint. After recrystallization, fine equiaxed crystals are formed in the stirred zone. The ferrite content in the whole joint is in the range of 48 to 60%, and the ferrite content in the stirred zone decreases with the increase of welding speed. With the increase of welding speed, the hardness and tensile strength of the stirred zone increase. When the welding speed is 50 mm/min, the joint performance reaches the optimal level. The tensile strength is 824 MPa, 97.3% of the base material.

1. Introduction

Duplex stainless steel (DSS) is consisted of austenite (γ) and ferrite (α) phases, which ferrite provide high tensile strength, austenite provide good toughness. Due to its excellent comprehensive performances, it is widely used in petrochemical, paper, and shipbuilding industries [1]. In general, when the ratio of α/γ is 1:1, duplex stainless steel has the optimal performance [2, 3].

Welding is one of the most common processing methods of duplex stainless steel, but the melting and solidification process in the traditional welding destroys the optimized dual phase structure of duplex stainless steel [4]. Conventional fusion welding process with large heat input make the microstructure of heat affected zone and fusion zone is large, and have high ferrite content. Meanwhile, during conventional fusion welding, hard and brittle intermetallic compounds will be produced, thus affecting the mechanical properties of duplex stainless steel welds [5, 6]. How to improve the welding quality of duplex stainless steel is the key technology to be solved in the practical production.

2. Experimental procedures

The base material used in this study is 4 mm thick 2205 duplex stainless steel plates (tensile strength 847 MPa), its chemical composition is shown in table 1. The plates dimensions is 300×100×4 mm. The length of the stirring tool is 3.8 mm, and the shoulder diameter is 20 mm. The rotational speed is 600 r/m, welding speeds varied 30, 50, 70 mm/min was carried in this experiment.

Feritscope FMP30 equipment is used to measure the ferrite content of joint, three points in a region are selected for measurement and get average as the final results. Metallographic examination was
carried out using microscopy, the specimen first polish and then electro etched in 35%KOH at 7V for 20s. The Vickers hardness of the joint was measured on the center of cross-section, and the load was 2.94 N (300 gf) for 10 s. Three tensile samples were selected for the joints which obtained by each parameter and the average value was taken as the tensile property evaluation standard. The fracture of the tensile samples was analyzed and observed by scanning electron microscope (SEM).

| Table 1. Chemical composition of 2205 duplex stainless steel |
|-------------|-----------|-----------|-----------|-----------|-----------|-----------|
| C           | Si        | Mn        | Ni        | Cr        | N         | P         |
| 0.02        | 0.57      | 1.25      | 5.30      | 22.57     | 0.14      | 0.03      |
| Mo          | Fe        |           |           |           |           |           |
| 3.04        | Bal.      |           |           |           |           |           |

3. Results and discussion

3.1. Weld formation

3.1.1. Weld surface morphology. Weld formation of 2205 duplex stainless steel FS welds at different welding speeds are shown in Fig. 1. The surface defect free welds can be obtained under the selected welding speeds.

![Figure 1. Weld formations at different welding speeds (a) υ=30 mm/min (b) υ=50 mm/min (c) υ=70 mm/min](image)

When welding speed is 30 mm/min, obvious toe flash is formed on both sides of the weld, and the surface is relatively rough (Fig. 1a). This is due to the high heat input at a lower welding speed, which leads to a greater softening degree of weld material, and material can’t fully rotate with the stirring tool. Finally, the material remaining near the shoulder is extruded and form toe flash. At the same time, higher welding temperature leads to more serious oxidation on the surface of material, which leads to rough surface. With the increase of the welding speeds, the welding heat input decreases, and the flow capacity of the material increases with the stirring tool, meanwhile, the oxidation degree of the surface metal decreases. So the weld toe flash decreases significantly, the weld surface is smooth (Fig 1b and 1c).

3.1.2. Cross-section characteristic. Cross section characteristic of joints obtained at different welding speeds are shown in Fig. 2. The 2205 duplex stainless steel FS welds can be divided into four zones: base material zone (BMZ), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and stirred zone (SZ). According to the flow of materials, the joint can be divided into advancing side (AS) and retreating side (RS).
When the welding speed is 30 mm/min and 50 mm/min, internal defect-free joints can be obtained (Fig. 2 and 2b), but when the welding speed is 70 mm/min (Fig. 2c), there are holes at the bottom of the SZ (as shown in Fig. 3 after magnification). This is because the heat input is insufficient with rapid welding speed, decreasing the amount of material which reaches the plasticizing state. There are no enough material rotate with stirring tool, the inside material can’t be completely closed therefore forming the hole defect.

Figure 2. Cross-sections of weld joints at different welding speeds (a) $v=30$ mm/min (b) $v=50$ mm/min (c) $v=70$ mm/min

Figure 3. Microstructure of welding defects

3.2. Microstructure of duplex stainless steel joints

3.2.1. Grain morphology. Fig. 4 shows the microstructure morphology at different regions of FS weld. The grain in BM shows a typical rolling morphology. The grains in the HAZ is growth because grains only affected by the heat thermal cycle. TMAZ is a transition zone, which produces a certain degree of heat input and plastic deformation, but it is smaller than the SZ. The grain deformation direction of the TMAZ is consistent with the plastic flow direction.

Figure 4. Microstructures of joint at various zones (a) BM (b) HAZ (c) TMAZ

Fig. 5 shows the microstructure of the SZ at different welding speeds. We can see that the grain size of the SZ tend to decrease with the increase of welding speeds. The grain size in the SZ is mainly refined by the dynamic recrystallization. According to the research, the austenite grain size in the SZ is refined.
by the continuous dynamic recrystallization mechanism and the ferrite by the continuous dynamic recrystallization mechanism in the friction stir welding of duplex stainless steel [10]. Sellars [11] proposed a power exponent model to describe the stable grain size of dynamic recrystallization:

\[
d_{DRX} = C Z^{-nD}
\]

(1)

Where, \(C\) and \(nD\) are experimental constants, \(d_{DRX}\) depends on \(Z\) parameter, and \(Z\) is zener-hollomon parameter.

\[
Z = \dot{\varepsilon} \exp(Q/RT)
\]

(2)

Where, \(Q\) is the deformation activation energy, \(R\) is the gas constant, \(\dot{\varepsilon}\) is the strain rate, and \(T\) is temperature. In the process of friction stir welding, the increase of welding speeds give rise to the increase of strain rate, and the increase of \(Z\) value with the decrease of temperature. The grain size of recrystallization \(d_{DRX}\) decreases with the increase of \(Z\) value, so the grain size of \(SZ\) decreases with the increase of welding speeds.

![Figure 5. Microstructures of stir zone at different welding speeds (a) υ=30 mm/min (b) υ=50 mm/min (c) υ=70 mm/min](image)

3.2.2. Ferrite proportion. One of the advantages of duplex stainless steel FS welds is that heat input is lower than fusion welding, so it can overcome high ferrite content in welds. The ferrite content of joint is shown in Fig.6 (υ=50 mm/min). In the process of friction stir welding, all regions except the base material are affected by thermal cycle. As the ferrite is more stable than austenite at a higher temperature [10], the ferrite content in both the \(SZ\) and the TMAZ is slightly higher than that of the base metal. Moreover, the cooling rate in the \(SZ\) is slower than that in the TMAZ, the ferrite transformation to austenite increases, so the ferrite content in the \(SZ\) is slightly lower than that in the TMAZ. The overall ferrite content of the joint is maintained at 50%–60%, which indicates that the ferrite content is controlled effectively.

![Figure 6. Profile of ferrite content in the joint (υ=30 mm/min)](image)

Ferrite content in \(SZ\) at different welding speeds is shown in Fig. 7. The heat input is reduced with the increase of welding speed, so the volume of austenite to ferrite transformation is decreased. And friction stir welding cooling speed is faster, ferrite has no enough time transform to austenite. So ferrite content in \(SZ\) is decreased with the increase of welding speed.
3.3. Mechanical properties of duplex stainless steel joints

3.3.1. Microhardness. Hardness distribution of joints at different welding speeds are shown in Fig. 8. The hardness is lowest in HAZ, which is significant because the larger grain size. The hardness increase in the SZ related to refined grains which by recrystallization. When the welding speed is 30 m/min, the hardness of the TMAZ and SZ is lower than that of the base material. With the increase of welding speed (υ=50 mm/min and 70mm/min), the hardness of the SZ is basically consistent with the base material. The higher welding speeds reduce the grain size of ferrite and austenite and increase the hardness in SZ. At different welding speeds, the lower hardness are the regions near the TMAZ and the HAZ.

3.3.2. Tensile property. Mechanical properties at different welding speeds are shown in Fig. 9. The proportion of ferrite to austenite and the grain size of two-phase have great influence on its mechanical properties. Ferrite content and grain size are decreased with the increase of welding speeds. As the welding speed increases and grain size is refined, the tensile property of the weld is improved correspondingly. However, when the welding speed is 70 mm/min, the tensile strength and elongation of the joint decreased due to the hole defect in the joint. When the welding speed is 50 mm/min, the tensile strength and elongation of the joint reach the highest, respectively 824 MPa and 7.9%, and the tensile strength reaches 97.3% of the base material.
4. Conclusion
Friction stir welding of 4mm thick 2205 duplex stainless steel was carried out.

(1) When the welding speed is 30 mm/min and 50 mm/min, well-formed and defect-free joints can be obtained. When the welding speed is 70mm/min, there will be holes in the weld.

(2) The microstructure in the stirred zone forms fine equiaxed crystals after recrystallization, and the grain size in the stirred zone decreases with the increase of welding speed. The ferrite content in the whole joint is between 50 and 60%, and the ferrite content in the stirred zone decreases with the increase of welding speed.

(3) When the welding speed is 50 mm/min, the joint performance reaches the optimal level, with the tensile strength of 824 MPa, 97.3% of the base material, and the elongation is 7.9%.
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