Parameter selection in dissimilar friction stir welding of ODS ferritic steel and RAFM steel F82H

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Dissimilar joints of ODS ferritic steel and RAFM steel F82H would be required for the construction of advanced blankets to increase the flexible design margin and get the benefits from each material in a functional way. The welding parameter determines the formation of joint, the generation of welding defect and the microstructure of the joint. This study aims to achieve the defect-free joint by optimizing the welding parameters in dissimilar friction stir welding of the ODS and F82H steels. Four different welding conditions were applied to the welding processes, and the corresponding effects on defects and microstructures were investigated. Results show that neither the δ ferrite nor inter-metallic compound can be generated in the FSW joint of F82H and ODS steels. In order to achieve the defect-free joint and to prevent the stir tool from breaking, the "softer material" F82H should be arranged on the retreating side and the stir tool should be plugged into the F82H side.

Keywords: friction stir welding, dissimilar welding, ODS ferritic steel, RAFM steel F82H, parameter selection, welding defect analysis

1. Introduction

Nuclear materials demand special standards of performance and quality because of their severe surroundings of the high energy bombardment and the elevated temperature. The ODS ferritic steel, which has excellent mechanical properties at elevated temperature and great resistance to the irradiation induced swelling, is widely accepted as a structure material for advanced fusion blankets, while the F82H ferritic/martensitic steel has been considered as a promising candidate materials for the ITER fusion reactor. Dissimilar welding of ODS ferritic steel and F82H steel would be required for the construction of advanced blankets to increase the flexible design margin and get the benefits from each material in a functional way [1-4].

However, comparing with the welding of other steels, the dissimilar welding process of ODS and F82H steel is much more complicated and difficult. It has been found that conventional melting welding methods cannot be used to weld these two steels, as it can disturb the fine dispersion of oxide particles in the ODS steel, as well as significantly decrease the strength and toughness in F82H steel due to the generation of δ ferrite and inter-metallic compounds. Friction stir welding (FSW), which is a solid welding technology has been considered to be a promising way to weld these two materials [5-9]. As the welding parameter determines the formation of joint, the generation of welding defect and the microstructure of the joint, the selection of welding parameter is highly required.

Till now, only few works have been focused on the welding of ODS steels. Particularly, no related work concerning the parameter selection of dissimilar FSW of ODS and F82H steels has been reported. The present study aims to achieve the defect-free joint and characterize the effects of different parameters on the microstructures and defects of the dissimilar FS welded joints.

2. Experiment

The materials used in this study were the 15Cr-ODS ferritic steel and the RAF/M steel F82H with the compositions tabulated in Table 1. Both of ODS and F82H Plates were cut into pre-weld specimens with the dimensions of 1.5 mm thickness, 35 mm length and 10 mm width, and then subjected to FSW in a butting configuration.

Table.1 Chemical compositions of ODS and F82H steels (mass%)

Material	C	Cr	W	V	Ti	Ta	Y_2O_3	Fe
15Cr-ODS steel	0.02	14.9	1.9	-----	0.2	-----	0.34	Bal
F82H steel	0.1	8	2	0.2	-----	0.04	-----	Bal

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Ultra-temperature-resistant W-C based stir tools, which had shoulder diameter of 12 mm, pin diameter of 4mm and 1.3 mm pin length, were used. In the welding processes, tool tilt-angle was set as 3°. The dissimilar welding processes totally involved four different welding conditions, which were labled as FSW1, FSW2, FSW3 and FSW4 in Table 2. In all the conditions, the traverse speed were set as 50 mm/min, while two varied rotation speeds (200rpm, 250rpm) were used. During all the welding process, ODS steel was set on the AS (advancing side), and F82H was set on the RS (retreading side), while the plug positions of the stir tool were different. In conditions of FSW1 and FSW3, the stir tools were plugged into the ODS side, while the plugged positions of FSW2 and FSW4 were in F82H steel, a detailed schematic illustration of the plugged position of the stir tool is shown in Fig. 1. In each case, the tool probe was shifted a 2 mm toward the ODS or F82H side, and did not penetrate into the other steel.

Table. 2 Welding conditions of the dissimilar welding processes

Welding Condition	Traverse speed	Rotation speed	Plugged position
FSW 1	50 mm/min	200 rpm	ODS
FSW 2		200 rpm	F82H
FSW 3		250 rpm	ODS
FSW 4		250 rpm	F82H

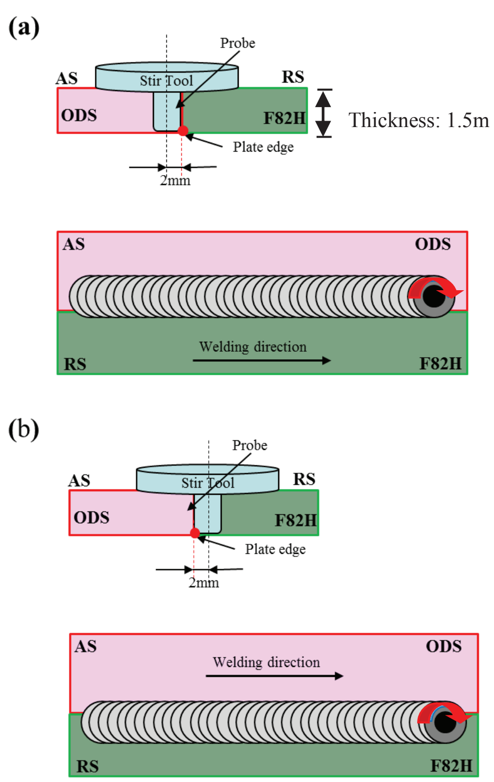


Fig. 1 Schematic diagram of the dissimilar FSW processes: (a) stir tool plunged into ODS steel on AS, corresponding to the conditions of FSW1 and FSW3; (b) stir tool plunged into F82H steel on RS, corresponding to the conditions of FSW2 and FSW4

Specimens welded by different conditions were cut perpendicular to the welding direction. The investigations of the welding defects and microstructures were undertaken on the transverse cross-section of the welds and carried out by an optical microscopy (OM) and a scanning electron microscopy (SEM, Zeiss, Ultra 55 FE-SEM). Energy dispersive X-ray spectroscopy (EDX) was performed to determine of the elements in special structures (e.g., the mixed structures of ODS and F82H steels and the lump-like welding defects). Combining with the EDX results, the demarcating function of Kikuchi lines in the EBSD system of Zeiss Ultra 55 FE-SEM was used to analyze the structure of the lump-like welding defects. In order to remove deformations and scratches of EBSD specimens, and to obtain highly reflective surfaces, samples were polished by emery paper, diamond paste and alumina colloidal silica, sequentially.

3. Results and discussion

The overviews of welding defects within the joints welded by different parameters are shown as Fig. 2. In these welding conditions, only the condition FSW4 (250rpm, plunged in RS-F82H side) can generate the defect-free joint, while different types of the welding defects (e.g., wormholes, dis-bonded defects and lump-like uncertain structures) can be found in all the other three joints by observing their macrostructures.

Remarkably, the wormhole defect can be detected in all the defective joints. Particularly, wormholes prevalently appear near the lump-like structures in FSW1 and FSW3. Comparing with the surrounding material, these lump-like structures are obviously different in microstructures (Fig. 3a, d and e), as well as the hardness of these structures are extremely high with an average value about 890 Hv. These lump-like structures seem belong to the inter-metallic compound. However, as the FSW process is far below the melting points of F82H and ODS steels, generation of the inter-metallic compound is unreasonable and illogical. The EDX analysis (Fig. 4) of the lump-like structure (Fig. 3e) shows that this structure has the W content about 82 wt%. Although F82H and ODS steels contain W, it can be firmly speculated this W enriched lump is not formed by the element segregation of the welding, because the W contents in the base metals (i.e., 1.9 wt% in ODS, 2 wt% in F82H) are too limited to form the lump like structures in such enriched W content and in such tremendous size. In addition, it is also impossible to occur such large-scale segregation during the transient welding process. The further analysis of the Kikuchi pattern of this lump-like structure (Fig. 5) shows that rather than the single tungsten, the lump has a W-C structure, as the detected Kikuchi

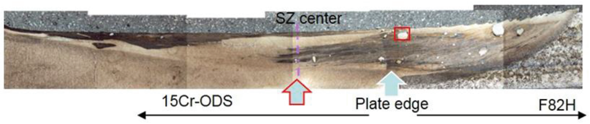
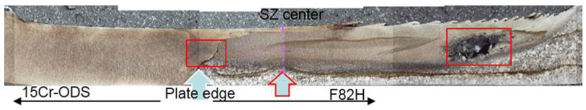
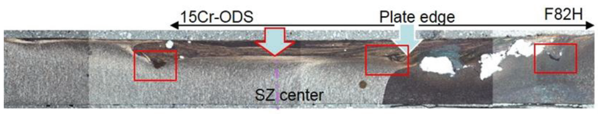
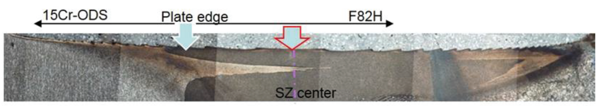
Welding Conditions	Overview of the joint (scale bar: 1 mm)	Detail of the defect	Defect type		
			Wormhole	Lump-like structure	Dis-bonded defect
FSW 1		Fig. 3 (a)	○	▭	Without
FSW 2		Fig. 3 (b) and (c)	○	Without	△
FSW 3		Fig. 3 (d) and (e)	○	▭	Without
FSW 4		Defect-free joint			

Fig. 2 Overview of the joints welded by different conditions; symbols (circle, squire and triangle) present different defects

pattern has the very high superposition with the criterion of W-C pattern. As the stir tool is made by the W-C based material, it can be firmly speculated that the lump-like structures are the fragments of the stir tool.

It is also mentionable that the lumps can only be found when stir tools are plunged into the ODS steels (i.e., in the conditions of FSW1 and FSW3). This characteristic should be attribute to the different welding force and temperature generated by varied plunged positions of stir tool. The comparison of FSW1 and FSW2 can be taken as an example. Although the rotation and traverse speeds of FSW1 and FSW2 are same, FSW1 processes much higher welding resistance impacted on the stir tool, because the plunged position of tool is set on the ODS side, and the ODS steel processes more outstanding mechanical

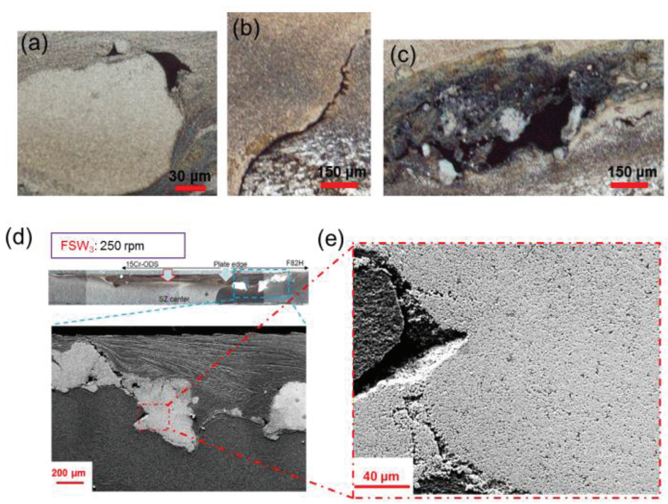


Fig. 3 Microstructures of the welding defects: (a)Wormholes near the lump structure in FSW1; (b) Dis-bonded defect in FSW2; (c) Wormholes in RS-TMAZ in FSW2; (d) and (e) detailed microstructures in FSW3

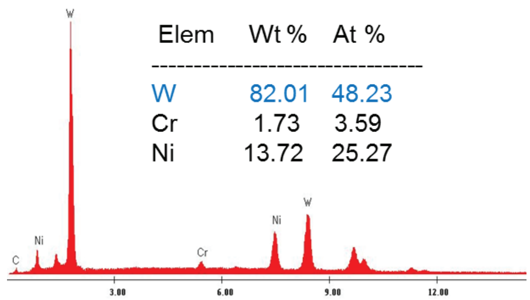


Fig. 4 EDX analysis of the lump-like structure

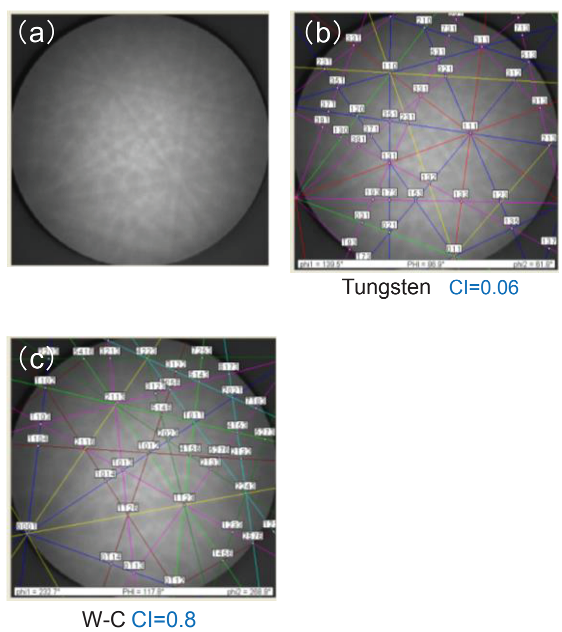


Fig. 5 Verification of the Kikuchi pattern: (a) the lump-like structure; (b) Kikuchi pattern of W; (c) Kikuchi pattern of W-C

properties than the F82H steel at the evaluated temperature. Due to the higher welding resistance in FSW1, the friction force between the tool and the material can be simultaneously increased, consequently the friction heat and the welding temperature are higher in FSW1. Comparing with FSW1, the welding temperature and welding force of FSW3 are further enhanced, due to the enhanced rotation speed (250 rpm). According to these analyses, among these three defective joints, FSW3 processes the highest values in the welding temperature and welding resistance force, while FSW2 has the lowest values. Those differences cause the damage of the stir tool in conditions of FSW1 and FSW3, and generate the lump structures.

As the welding temperature and the imposed force of stirring tool in FSW2 are low, during the welding process the material flowing is extremely insufficient. The insufficient flowing material results in the visible wormhole and dis-bonded defects in of FSW2. Particularly, in all these defective joints, the wormholes mostly emerge on the retreating side. This characteristic is considered to be related to the unique welding force of the FSW process. Fig. 6 shows that on the AS the rotational stress has the

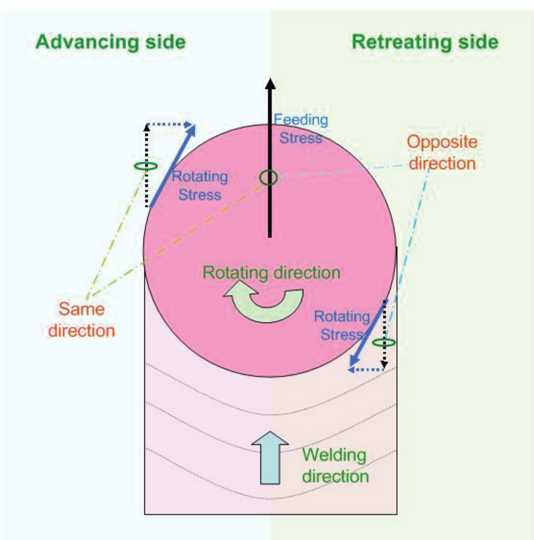


Fig. 6 Schematic diagram of the mechanical force in FSW process

component in the same direction with the feeding stress, while this component on the RS is opposite to the feeding stress. The difference of welding force causes the material flow on RS is not as drastic as the flow on AS, consequently, the defects caused by insufficient plastic flow are more prone to emerge on the RS [5].

Comparing with FSW2, when the rotation speed is enhanced to 250rpm in FSW4, the welding temperature can be increased, and the material flowing around the stir tool is more drastic and balanced, therefore, flow-related defects are eliminated in FSW4. The detailed observation in FSW4 joint also testifies that no evidence of δ ferrite and inter-metallic compound can be discovered. In view of the above comparison and analysis, during the dissimilar FS welding of ODS and F82H steels, the softer material F82H steel should be arranged on the retreating side and the stir tool should be plunged into the RS side.

4. Conclusion

The effect of welding conditions on the appearance, defect and microstructure of the dissimilar joints of ODS and F82H steels welded by FSW were investigated in the presented study. The main results are summarized as follows:

(1) The FSW can achieve defect-free joint of ODS and F82H steels.
(2) As the FSW is a solid welding process, neither the δ ferrite nor inter-metallic compound can be generated in dissimilar FSW joint of F82H and ODS steels.
(3) The dis-bonded defect is apt to appear in the condition of the insufficient heat input, while this kind of defect can be eliminate by properly enhancing the rotation speed.
(4) In order to achieve the defect-free joint and to prevent the stir tool from breaking, the "softer material" F82H should be arranged on the retreating side and the stir tool should be plugged into the F82H side.

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