Influence of lap sequence on the Al/Steel FSKSW weld quality

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Abstract. The joining of dissimilar metals of 5A02 aluminum alloy and DP600 galvanized steel was carried out by keyhole-free FSSW technique (FSKSW). The effect of lap sequences on the microstructure and mechanical properties of welded joints was also investigated. It was found that all keyholes of both stacking sequences were filled, and the steel on top of Al alloy could be stirred more thoroughly than that vice versa. The microstructure of WNZ contained fine equiaxed grains, and TMAZ formed fully developed plastic flow, while HAZ had coarse grains. The temperature of two stacking sequences was similar during the welding process. Still, the axial force of the joints of steel on aluminum alloy was higher than that of aluminum alloy on steel. Similarly, the joint strength of the steel on aluminum alloy was also higher than that of aluminum alloy on steel. It was necessary to place the steel plates on the aluminum alloy sheets for metal plasticity and heat distribution.

1. Introduction

As the structures of aluminum and steel dissimilar metals have the advantages of lightweight, high strength, etc., which can develop all benefits of aluminum alloy and steel at the same time, they can have a very good application prospects of rail passenger industry under the premise of safety and reduce the heavy of bodywork [1]. The connection of dissimilar metals like aluminum and steel has become a hotspot [2]. It is very hard to form continuous dissimilar metals joints of aluminum alloy and steel by using conventional welding technologies [3]. Friction stir welding (FSW) is a solid-phase connection technique, which can effectively avoid the generation of harmful intermediate phases, pores, cracks, and other defects [4]. Consequently, FSW is widely used for welding of dissimilar materials.

At present, many researchers study the FSW process of aluminum alloy/steel dissimilar material joints. Das [5] investigated the influence of energy induced from process parameters on the mechanical properties of lap joints of aluminum alloy on steel FSW and found that the joint strength was significantly influenced by the combined effect of rotational speed and travel speed as well as the energy input. Lee [6] considered the impact of welding conditions on the joint strength and weld interface between aluminum alloy and low-carbon steel by FSSW. Yang [7] investigated the influence of alloy elements on the microstructure and mechanical properties of laser dissimilar Al/steel joint. Xing [8] adopted the orthogonal design experiment to analyze the welding deformation of steel–aluminum sheet parts and proposed the response surface model to establish the relationship between welding deformation and welding parameters by finite element analysis. Zhang [9] researched the interface behavior and impact properties of the friction stir spot welding of dissimilar metals AA6082 Al alloy, and DP600 galvanized steel. This paper mainly studied the effect of lap sequence on the microstructure and mechanical properties of welded joints of aluminum alloy 5A02 and galvanized steel DP600 keyhole-free FSSW.
2. Experiments
The specimens were aluminum alloy 5A02 sheets and galvanized steel DP600 sheets. Their dimensions were, respectively, 100mm×50mm×3mm and 100mm×50mm×1mm. The chemical composition and mechanical properties of 5A02 and DP600 are listed in Table 1. Experiments of keyhole-free FSSW were carried out in spot welding equipment. The welding parameters are given in Table 2. Figure 1 shows different lap sequences of steel and Al alloy.

Table 1. Chemical compositions and mechanical properties of 5A02 and DP600.

| Material | Chemical composition (in wt%) | Mechanical properties |
|----------|-------------------------------|-----------------------|
| 5A02     | Si 0.4 Fe 0.4 Cu 0.10 Mn 0.4 Mg 0.15 Ti 0.6 Fe+Si | $\sigma_b$ 204 (MPa) $\varepsilon$ 38 (%) |
| DP600    | C 0.09 Mn 1.84 Si 0.36 Al 0.05 Mo 0.01 Cr 0.02 Cu 0.03 | $\sigma_b$ 235 (MPa) $\varepsilon$ 26 (%) |

The microstructures of the cross-section of welded samples were characterized by optical microscopy. The microstructure of the steel was observed after etching in 3% nitric acid solution, while Keller's solution was used to observe the microstructure of the aluminum alloy. The microstructures of joints were observed by MeF optical microscopy. The tensile tests were performed in a WE-100 Universal tensile machine according to the ASTM D1002-2001 standard.

![Figure 1](image-url)  
(a) Steel on aluminum alloy  
(b) Aluminum alloy on steel

Figure 1. The schematic diagram of keyhole-free FSSW in different lap sequences

3. Results and Discussion

3.1. The macrostructure
The joints of aluminum alloy 5A02 and galvanized steel DP600 were connected by keyhole-free FSSW with different lap sequence. The weld appearances of steel on aluminum alloy and aluminum alloy on steel were respectively shown in Figure 2. It can be seen that joints of two lap sequences had been filled with metal by keyhole-free FSSW. Simultaneously, the cross-sections of joints were machined and presented in Figure 3 to examine the joint quality. It can be seen in Figure 3 that both joints with different
lap sequences were successfully welded by keyhole-free FSSW from the cross-sections of joints, and a mechanical bond was formed at the interface of weld nugget zone (WNZ).

It can be seen that the material of the steel and aluminum alloy can be fully stirred at the interface as shown in Figure 3(a), but only a thin layer of steel was stuck down and rolled up by the bottom of the pin at the joints of aluminum alloy and steel as shown in Figure 3(b). With the rotation of the pin, it directly heated up the steel sheet beneath it and continued to plunge down. It acts as a punch/hook.

This difference between Figures 3(a) and 3(b) may be caused by different friction-induced heat values and metal flows generated by the high rotational speed. When the steel is placed on the top of the aluminum alloy, the heat was mostly mainly produced at the steel sheet due to the frictional heat between the shoulder and steel sheet, so that steel could be easily stirred at high temperatures and stirring forces. At the same time, the aluminum alloy has better plasticity, and there is significant flow to fill the keyhole at the conducted heat and the stirring force by the pin, as shown in Figure 3(a). Although the temperature of aluminum alloy sheet was sufficient to ensure the deformation of FSKSW, as shown in Figure 3(b), that of steel sheet, which was mostly contributed by the frictional heat between the pin and steel sheet, was not. The other reason is that the thermal conductivity of the aluminum is high; the heat will be quickly dissipated when aluminum alloy sheet is placed on the top, and consequently, it is difficult for the steel to get the required heat. Thus, the steel sheet cannot be plasticized due to low temperature of the steel sheet.

3.2. Microstructure

Figures 4 and 5 depict the microstructures of keyhole-free FSSW joints of steel on aluminum alloy and aluminum alloy on steel, respectively. By comparing Figure 4(a) and Figure 5(a), it can be found that the microstructures of steel at heat affected zone (HAZ) were similar. The grains of steel placed under aluminum alloy at HAZ grew less intensively than those in steel placed over the aluminum alloy. The upper steel was mainly affected by the frictional heating, and the steel grains grew larger than those at the bottom steel, which were affected by the conductive heat. Figures 4 (b) and 5 (b), respectively,
represent the thermomechanically affected zone (TMAZ) on steel sides and reveal that the material has been plastically deformed. The grains of the upper steel at TMAZ formed significantly plastic flow as the steel had been stirred more fully than that at the bottom. The mixture of steel and aluminum alloy can be seen in these zones. The microstructures of steel at WNZ in Figure 4(c) and Figure 5(c) were fine equiaxed grains with a much smaller size compared to the large elongated grains at HAZ. This zone was a fine-grain region where dynamic recrystallization occurred under the stirring force and high temperature. By observing the microstructures of aluminum alloy sheets, it can also be found the aluminum alloy side had the same characteristics as the steel side.

**Figure 4.** Microstructures of different regions of keyhole-free FSSW joints of steel on aluminum alloy; The steel side: (a) HAZ; (b) TMAZ; (c) WNZ; The Al side: (d) HAZ; (e) TMAZ; (f) WNZ.

**Figure 5.** Microstructures of different regions of keyhole-free FSSW joints of aluminum alloy on steel: The steel side: (a) HAZ; (b) TMAZ; (c) WNZ; The Al side: (d) HAZ; (e) TMAZ; (f) WNZ.
3.3 Shear Strength

Figure 6 shows the shear strength of keyhole-free FSSW joints with different lap sequences. It was found that whether steel on aluminum alloy or not, the shear strength of the joints decreased with the increase in the pin rotation speed.

![Figure 6. The shear load of keyhole-free FSSW joints for different lap sequences.](image)

It can be seen that the maximum shear strength of joints reached 4.88 kN where steel on top and the failure load of joints of steel on aluminum alloy were all generally higher than that of aluminum alloy on steel. Although it was difficult to stir the steel fully when the steel was placed on the top of Al, and a mechanical bond was formed at the interface. This mechanical bond was likely attributed to the characteristics of the steel and aluminum alloy. Conversely, if Al was placed on the top of steel, a significant amount of the frictional heat was produced at the aluminum alloy sheet. Since aluminum alloy has better thermal conductivity and lower yield strength than steel, the generated frictional heat softened and plasticized the aluminum alloy sheet. With the increase of welding time, most of the frictional heat diffused to the aluminum alloy sheet instead of the steel sheet. As a result, the temperature of the steel sheet was still relatively low and hardly plasticized. Consequently, the joints had poor quality.

![Figure 7. The axial load and temperature curves in the welding process.](image)

Figure 7 shows the curves of the axial load and temperature signals in the welding process of different lap sequences from the data acquisition system. The curves on the upper side were the real-time acquisition data of axial load signals and temperature signals on the lower side. It can be seen from Figure 7(a) and (b) that there was a significant difference in the axial load and small difference in the temperature curves.

By comparing the axial load with different lap sequences, it can be concluded that the axial load of steel as the upper sheet was more fluctuant than that of aluminum alloy as the upper sheet. The difference
between the axial loads was due to the different hardness values of steel and aluminum alloy. Steel needed a larger force to soften and form plastic deformation in the welding process.

The peak temperature of the joint of steel on aluminum alloy was similar to that of aluminum alloy on steel. This is because the thickness of the steel was thin as 1 mm, and the friction heat was rapidly transferred to the aluminum alloy sheet.

In general, the stacking sequence of steel as the upper sheet was more suitable than that of aluminum alloy as the upper sheet, because the higher axial force and stir force were provided.

3.4 Material Flow
Figure 8 shows the microstructure features observed at different lap sequences. It can be seen that both steel and aluminum alloy had been stirred and mixed fully in the two stacking sequence.

Although a mechanical bond was formed at the interface, it was difficult to stir the steel fully when the steel was placed on the bottom of aluminum alloy, and hole defects readily appeared along the interface, as shown in Figure 8(a).

However, it can be seen that it was easier to stir the steel and aluminum alloy when steel was used as the upper sheet, and the interface of steel on aluminum alloy was better than that of aluminum alloy on steel. This is because steel could be stirred more thoroughly at high temperatures and large stirring forces. At the same time, aluminum alloy at the bottom of the joint can also be stirred in the superplastic state. The joint with better quality and fully developed plastic flow was produced, as shown in Figure 8(b).

4. Conclusions
a. The cross-sections and the microstructure features of keyhole-free FSSW joints were observed. Although the keyhole in the two stacking sequences all can be filled, steel as the upper sheet can be stirred more fully than aluminum alloy as the upper sheet. Simultaneously, the microstructure of WNZ featured fine equiaxed grains, TMAZ had fully developed plastic flow, while HAZ had coarse grains.

b. The lap sequence strongly influenced the shear strength. The shear strength of the steel on the top was higher than that of aluminum alloy on the top.

c. The temperatures and axial forces were investigated in dissimilar metals of aluminum alloy and steel keyhole-free FSSW during the welding process. The axial forces of steel as the upper sheet were higher than that of aluminum alloy as the upper sheet, and the temperature was similar in the two stacking sequences.

d. The optimal stacking sequence is to place the steel sheet on the top of the aluminum alloy, which improves the metal plasticization and heat distribution.

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