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Effect of Welding Parameters on Dissimilar Friction Stir Spot Welded Al-5083/St-12 Alloy Sheets

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1- Introduction

Joining of aluminum (Al) to steel is of a great technical interest since it provides the production of Al/steel hybrid parts in a wide range of industrial applications such as transportation systems and aerospace industries. However, producing a strong joint between Al and steel by conventional fusion welding processes is a technological issue because of the obstacles resulting from the major difference between the melting points of Al and steel alloys as well as the formation of thick and brittle intermetallic compounds (IMC) at the joint interface. Compared to fusion welding processes, solid state welding processes seem to be more applicable for joining of Al to steel mainly due to their lower heat input.

Friction stir spot welding (FSSW), a newly invented solid-state spot welding technique, is expected to be a more appropriate approach for joining of parts made of lightweight metals due to its advantages over the resistance spot welding (RSW) including lower heat distortion and superior mechanical properties.

2- Experimental

In the present study, lap joining of Al and steel sheets was performed using a newly developed friction stir spot welding (FSSW) process in which the welding tool tip did not penetrate into the lower steel sheet. The thicknesses of Al-5083 aluminum and St-12 steel sheets were 3 and 1 mm, respectively. The base sheets were cut with the length and width of 100 and 35 mm, respectively. Prior to welding, the faying surfaces of the sheets were wire brushed to develop a suitable surface quality resulting in superior joining of the sheets. The Al-5083 alloy sheet was placed on the St-12 alloy sheet with an overlapped area of 35×35 mm^2 and the welds were located at the center of the overlapped area. Furthermore, a hole with the diameter of 1.5 mm having a distance of 5 mm from the center of the weld was drilled in the lower steel sheet to record the temperature variation at the joint interface during the process using a K-type thermocouple. The length of the tool pin was 2.8 mm. Accordingly, as the tool shoulder touched the upper surface of the Al sheet, a thin Al layer with the thickness of 0.2 mm was left on the steel surface. The applied welding process paved the way for the formation of metallurgical bonds as well as intermetallic compounds at the joint interface which subsequently resulted in the joining of the sheets.

The effect of the rotational speed and dwell time on the joint interface microstructure and tensile-shear strength of friction stir spot welded sheets was investigated. The applied rotational speeds were 900 and 1100 rpm while the dwell times were selected in the range of 5 to 15 s to weld the samples. Tensile tests were carried out using an Instron tensile testing machine under the crosshead speed of 5 mm min^{-1}. In the tensile-shear testing procedure, the fixtures were used to reduce the eccentricity of the loading path. Interfacial microstructure, formation of intermetallic compounds at the joint interface and the fracture locations were studied using stereo, optical and scanning electron microscopy (SEM).

3- Results and Discussion

Fig. 1 presents a typical cross-section of the weld zone. As can be seen, the tool penetration depth was controlled which resulted in the remaining of a thin Al layer with a thickness of ~0.2 mm under the tool pin and on the steel sheet.

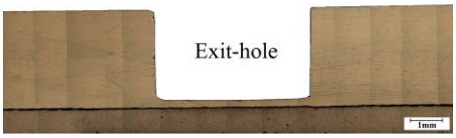

Fig. 1 Macroscopic cross-section of the FSSW specimen

The maximum temperatures generated at the joint interface for different welding conditions are presented in Fig. 2. As can be seen, increase in the tool rotational speed and dwell time led to an increase in the maximum interface temperature.

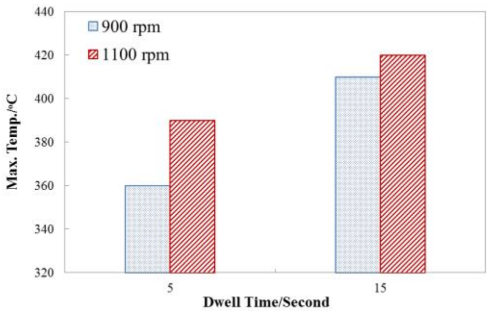

Fig. 2 The maximum temperature at the joint interface

The average failure load of the samples welded with different processing conditions are shown in Fig. 3. According to the results, for both of the applied rotational speeds, failure load first increased and then declined with increasing dwell time.

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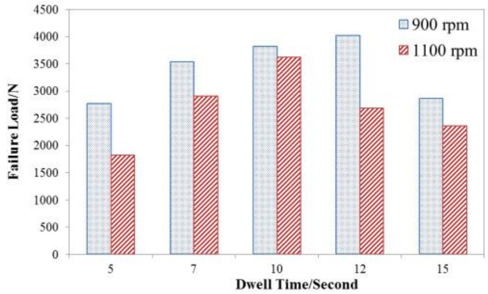

Fig. 3 Variation of the joint failure loads as a function of rotational speed and dwell time

The joint interfaces of 1100 rpm- 5 s, 1100 rpm- 10 s and 900 rpm- 15 s samples were observed by SEM. The associated microstructures are shown in Figs. 4(a), (b) and (c), respectively. The joint interface of 1100 rpm- 5 s specimen was free of IMC while the samples with the welding conditions of 1100 rpm- 10 s and 900 rpm- 15 s had IMCs with the thicknesses of 2.3 and 2.9 µm at their joint interfaces, respectively.

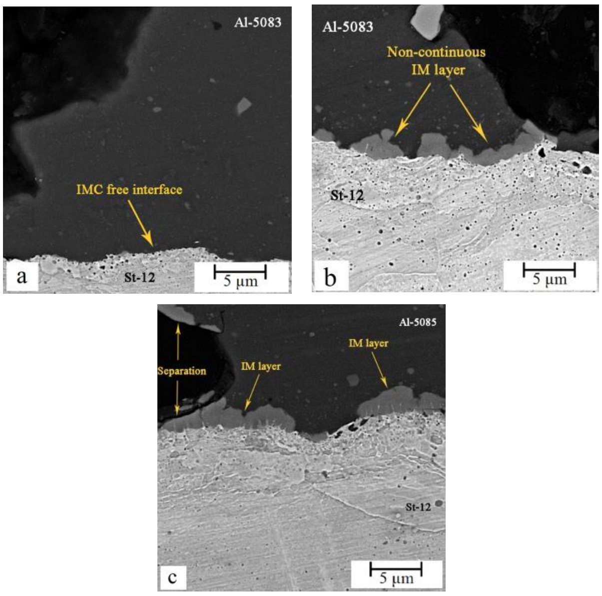

Fig. 4 SEM images of the joint cross-section after failure for specimens with the welding conditions of: (a) 1100 rpm- 5 s, (b) 1100 rpm- 10 s and (c) 900 rpm- 15 s

The Al microstructure of the 1100 rpm- 15 s specimen directly adjacent to the weld exit-hole, where the final fracture occurred, is presented in Fig. 5. As the general feature of the micrograph shows, very fine and equiaxed grains have been formed adjacent to the weld exit-hole which is the characteristic of the stirred zone (SZ) and can be attributed to the dynamic recrystallization (DRX). DRX occurred as a result of the simultaneous effects of the pin stirring and frictional heat during the FSSW process.

Microstructural analysis indicated the formation of some relatively coarse grains distributed in a matrix of finer grains which could be caused by abnormal grain growth phenomenon.

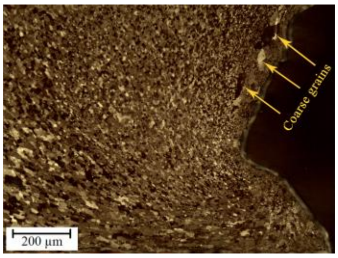

Fig. 5 The microstructure of the aluminum region adjacent to the exit-hole periphery of the 1100 rpm- 15 s specimen

The low fracture loads for the welds with the processing conditions of 900 rpm– 5 s and 1100 rpm- 5 s could be attributed to their IMC free interfaces since a sudden change in the chemical composition occurs at the joint interface by moving from the Al sheet towards the steel side. As the dwell time increased from 5 to 10 s at the rotational speed of 1100 rpm, a thin IMC layer with the thickness of 2.3 µm was formed at the joint interface and consequently the failure load improved from 1830 to 3632 N which was approximately twice as much. Achievement of stronger joints under longer dwell times (10 s compared to 5 s) may be attributed to the formation of IMCs at the joint interface which was affected by the following phenomena:

(i) A longer diffusion time was provided for Al and Fe atoms to move through the joint interface and form IMCs.

(ii) The maximum temperature at the joint interface increased with increased dwell time. Consequently, the growth constant of the IMC layer increased.

It is noteworthy that compared to the samples with the dwell time of 10 s, the joint strength decreased gradually for the specimens with the dwell time of 15 s. The sharp loss of the joint strength for the specimens with longer dwell times may be related to the formation of a relatively thick IMC layer at the joint interface as well as the grain growth of Al sheet adjacent to the weld exit-hole.

4- Conclusions

In this work, a FSSW process in which the tool pin did not penetrate into the lower steel sheet was used to join Al-5083/St-12 alloy sheets. The effect of the rotational speed and dwell time on the formation of the Al/Fe IMC layers as well as the joint strength was explored. The results showed that the joint strength first improved and then declined with increase in the dwell time. The increasing trend in the tensile-shear strength as a function of the dwell time was attributed to the formation of IMC layers with the thicknesses less than 2.3 µm at the joint interface. The decreasing trend was also related to the formation of IMC layer with the thickness of 2.9 µm and the growth of Al grains adjacent to the weld exit-hole.