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Effect of Intermetallic Compounds on the Strength of Dissimilar Friction Stir Spot Welded Al/Steel Joints

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1- Introduction

Aluminum (Al) to steel joints are attractive from application point of view since they provide simultaneous use of both materials in a hybrid part. While the steel part provides the required strength, the presence of Al decreases the final weight and improves the corrosion resistance of these structures.

Due to different physical, chemical and mechanical properties of Al and steel alloys, application of fusion welding processes such as resistance spot welding (RSW) encounter some problems during welding.

Friction stir spot welding (FSSW) process is a solid-state welding process which is able to solve some problems of RSW such as the preferential melting of Al as well as the formation of thick and brittle intermetallic phases at the joint interface.

FSSW has various parameters including tool geometry, tool rotational speed, tool penetration rate, dwell time and tool penetration depth. In the present study, the effect of two main parameters of rotational speed and dwell time on the formation of intermetallic compounds and consequently the strength of the welds has been studied.

2- Experimental

The materials used in the present study are Al-5083 aluminum and annealed St-12 steel sheets with the thickness of 3 and 1 mm, respectively. 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. The shoulder diameter, pin diameter and pin length of the tool were 20, 5 and 3.2 mm, respectively. Rotational speeds of 800, 900 and 1100 rpm were applied with the dwell times of 5, 10 and 15 s to weld the samples. Tensile test was carried out using an Instron tensile testing machine with a crosshead speed of 5 mm min. In the tensile-shear testing procedure, fixtures were used to reduce the eccentricity of the loading path. The interfacial microstructure, formation of intermetallic compounds at the joint interface and the fracture locations were studied using stereo, optical and scanning electron microscopy (SEM). Accordingly, the relationship between the joint interface microstructure and the joint strength was studied.

3- Results and Discussion

Fig. 1 presents a typical cross-section of the weld. As can be seen, the tool penetration in the lower steel sheet resulted in the material flow from the steel sheet towards the Al at the periphery of the exit-hole which paved the way for the formation of macroscopic mechanical locks called “hooks”.

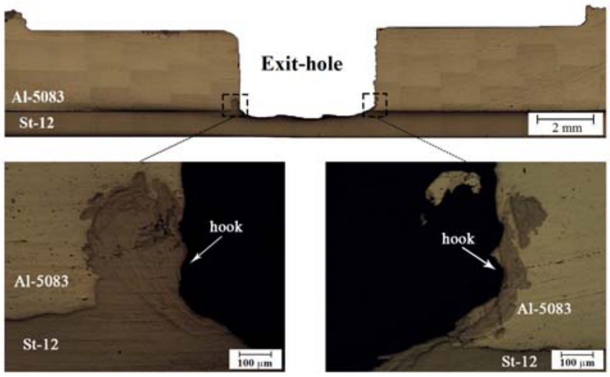

Figure 1 Macroscopic view of the FSSW joints in association with the enlarged micrographs of the hooks

A representative cross-section of the steel part of the welds after tensile testing fracture is displayed in Fig. 2. This figure shows that the welds experienced fracture from the hook periphery.

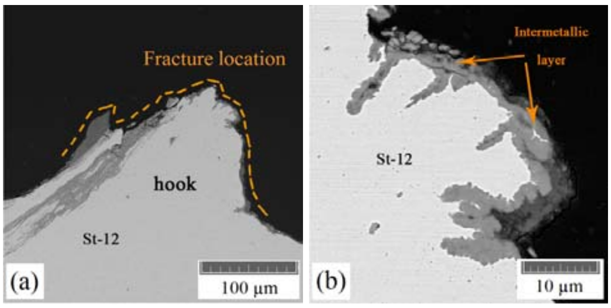

Figure 2 (a) SEM micrograph of the fracture location on the steel side; (b) enlarged SEM micrograph of the fracture location indicating continuous intermetallic layers at the fracture location

As indicated in Fig. 2(b), continuous intermetallic layers exist at the hook periphery. The formed intermetallic layers had different thicknesses depending on the applied welding parameters (Fig. 3).

In addition to the continuous intermetallic layers, some welds showed fracture from the Al part directly adjacent to the hook. Accordingly, microstructural observation of the Al part of welds adjacent to the hooks seems necessary. For this purpose, the fractured Al part of the specimen with the welding condition of

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1100 rpm- 15 s was observed before and after etching. Referring to Fig. 4, intermetallic layers are also observed on the separation location of the Al part from the steel side. This reveals that fracture of specimens during tensile testing has occurred mainly from the interface of the hook and the Al sheet where continuous intermetallic layers were formed.

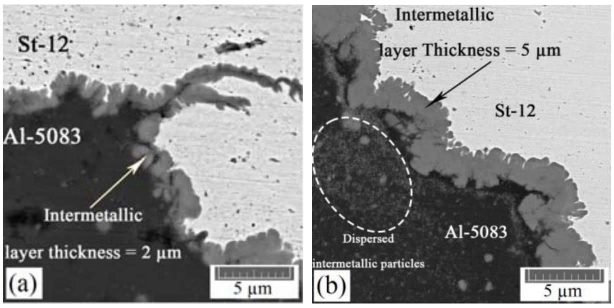

Figure 3 SEM micrographs presenting the intermetallic layers at the joint interface of specimens with the welding conditions of: (a) 900 rpm- 5s; (b) 1100 rpm- 15 s

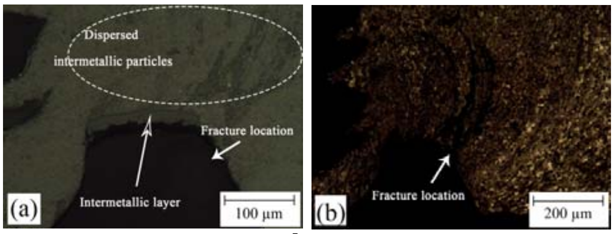

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Figure 4 Optical micrographs indicating cross-section of the fractured Al part at the joint interface: (a) before; (b) after etching

In addition to the intermetallic layers, very fine and dispersed intermetallic particles were observed in the Al part of welds (Figs. 3(b) and 4(a)). In fact, as the tool pin penetrates into the lower sheet, it passes the interface of Al and steel which contains intermetallic layers. The tool pin breaks the intermetallic layers and disperses them in the surrounding Al which results in the formation of a composite structure. Microstructural observation of this region revealed that it contained very fine and equiaxed grains which are the characteristic of the stirred zone. The dynamic recrystallization caused by pin stirring and friction heating during the welding process is considered as the reason for the formation of this zone.

The failure load results are presented in Fig. 5 as a function of welding parameters. The welds with the dwell time of 5 s had the lowest failure loads. Enhancement of dwell time from 5 to 10 and then to 15 s resulted in continuous increasing of failure load. Furthermore, for a given dwell time, higher rotational speeds were associated with higher failure loads.

Increase in the failure load with enhancement of the rotational speed and dwell time may be attributed to the generation of higher heat input which provides better interdiffusion of Al and Fe atoms at the joint interface to form the intermetallic layers with greater thicknesses. These intermetallic layers act as strong metallurgical bonds and increase the joint strength.

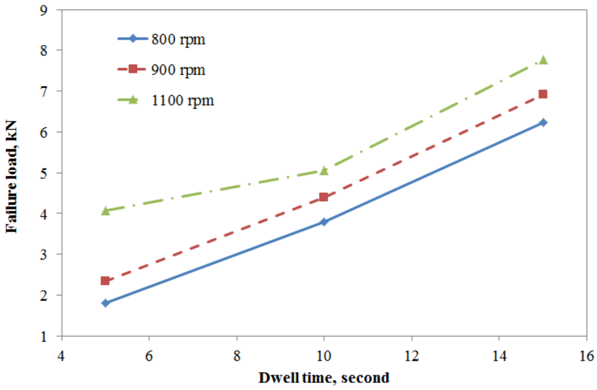

Figure 5 Failure load results as a function of welding parameters

As shown in Fig. 2, the fracture of welds occurred mainly from the continuous intermetallic layers at the joint interface while a portion of the fracture was related to the Al adjacent to the hooks. The observed fracture feature may be described as follows:

(i) The continuous intermetallic layers adjacent to the hook are susceptible to crack initiation and propagation due to their brittleness.

(ii) Strengthening of Al directly adjacent to the hook due to the grain refinement as well as the formation of composite structure prevents the fracture to be occurred totally from the Al part of welds.

Referring to the failure load results as well as the microstructural observations of the joint interface, increasing of the intermetallic layer thickness up to 5 µm in the present work improved the joint strength.

4- Conclusions

In the present study, the effect of tool rotational speed and dwell time on the structure-mechanical properties relationship of dissimilar friction stir spot welded Al/steel joints was explored. The main findings could be summarized as the following:

(1) For all of the applied rotational speeds, the joint failure load increased with the enhancement of dwell time.

(2) Higher rotational speeds showed higher failure loads at similar dwell times.

(3) The thickness of intermetallic layers formed at the joint interface was in the range of 2-5 µm.

(4) Increasing of the intermetallic layer thickness improved the joints failure load.

(5) The fracture of specimens occurred mainly from the intermetallic layers at the joint interface while a portion of that was from the Al part of welds adjacent to the hook.