Journal of Materials Processing Technology 242 (2017) 12–23

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Research paper

Characterization of intermetallic compound at the interfaces of Al-steel resistance spot welds

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ARTICLE INFO

Article history:
Received 5 September 2016
Received in revised form
14 November 2016
Accepted 16 November 2016
Available online 17 November 2016

Keywords:
Al-steel joint
Resistance spot welding (RSW)
Intermetallic compound (IMC)
IMC thickness distribution
Welding parameters
Process simulation

ABSTRACT

This study characterizes the interfaces of Al-steel joints generated by resistance spot welding (RSW) processes. Two types of intermetallic compound (IMC) layers at the interface are characterized and discussed. The first type, located in central area of the interface, is composed of tongue-like Fe_2Al_5 adjacent to the steel and serrated-like $FeAl_3$ adjacent to the Al; the second type, a mixture of $FeAl_3$ and Al, lies in the periphery of the joint interface. Formation mechanisms of the two types of IMC layer observed are proposed and discussed in the paper. The thickness distributions of the IMC layer generated by different welding parameters are predicted based on the dynamic interfacial temperature histories from Al-steel RSW process simulation. The predicted IMC thickness distributions are validated against physical measurements and show good agreement. A bimodal IMC thickness distribution is found when an adequately long welding time is applied. This is found to be related to lower interfacial temperature at the center of Al-steel interface than what in the surrounding area after about 200 ms of welding due to strong cooling effect by the electrode.

1. Introduction

The joining of Al to steel has become inevitable with increased integration of lightweight materials such as Al alloys into conventional steel-dominant car body structures in order to achieve light weighting of automobiles. Resistance spot welding (RSW) is a major joining process for sheet components over the last several decades due to its low cost, high efficiency and ease of automation. It naturally becomes an ideal option for joining Al to steel compared with other spot welding methods, such as laser spot welding and friction stir spot welding, which drive heavy capital investment in existing body shops. However, the difference in physical properties and metallurgical incompatibility between Al and steel pose significant challenges to achieving a sound, high-quality weld between the two materials through the RSW process. The resistance joining of Al to steel, in contrast to conventional RSW of similar materials, in essence relies on the reaction of molten or solid Al with solid steel.

The intermetallic compound (IMC) layer at the faying interface is the result of a reaction between Al and steel, and also serves as the bond between the two materials. In order to study the IMC growth between Al and steel, researchers have been aluminizing steel in hot-dipping processes to grow the IMC layers. The studies mostly focused on characterization of IMC composition and morphology and its growth kinetics and mechanism. Eggeler et al. (1986) observed two intermetallic layers, a Fe_2Al_5 phase adjacent to the steel substrate with an irregular interface and a $FeAl_3$ phase adjacent to the aluminum. They also noticed that when the reaction time is long, the IMC growth showed negative deviations from the parabolic law as the result of increasing amounts of iron dissolution into the molten Al. Bouche et al. (1998) also observed the existence of a two-layered IMC structure at the interfaces of a steel substrate and Al coating. The Fe_2Al_5 phase adhering to the steel was observed to have a tongue-like morphology and the $FeAl_3$ phase adhering to the Al was serrate-like and rather uniform. The growth of these two phases is controlled by inter-diffusion after a non-parabolic initial transient period. However, Fe_2Al_5 phase is much thicker than $FeAl_3$ phase. The early work by Heumann and Dittrich (1959) explained the fast growth rate of Fe_2Al_5. They stated that the crystalline defects of Fe_2Al_5 possessed 30% vacancies along the c-axes, and offered a rapid diffusion path to increase the growth rate of Fe_2Al_5, and the anisotropic growth of Fe_2Al_5 eventually caused

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http://dx.doi.org/10.1016/j.jmatprotec.2016.11.017
0924-0136/

the tongue-like morphology. In addition, they discovered that the growth of Fe_2Al_5 obeyed a parabolic law, as also confirmed in the work by Springer et al. (2011). To study the effect of alloys in IMC growth, Qian and Gu (1994) characterized the microstructure and chemical composition of the IMC layer by hot dipping mild steel into molten Al containing 2% of Si. The results showed that the Si content concentrated in the IMC layer. Yin et al. (2013) studied the effect of Si content in molten Al on the growth kinetics of Fe_2Al_5, and discovered that at a fixed reaction temperature, the value of parabolic growth factor k_1 was reduced with the increase of Si content, which means Si restrained the growth of Fe_2Al_5. It should be noted that all the afore-mentioned work were based on IMC growth at constant temperature and for a long reaction time measured in hours and even days. This is very different from typical IMC growth conditions of an Al-steel RSW, where reaction times are short as measured in milliseconds while the interfacial temperature ranges from room temperature to over 1000 °C. In addition, in physical RSW, temperature histories vary from point to point along the Al-steel faying interface, resulting in varying IMC thickness, morphology, and even composition.

The thickness distribution and morphology of the IMC layer directly affect mechanical strength and failure mode of the Al-steel joint. Miyamoto et al. (2009) reported that a strong joint could be obtained when the IMC layer was discontinuous or had a thickness of less than 2 μm and was composed of fine grains in diameter less than 500 nm. Qiu et al. (2010) characterized the RSW joint between mild steel and Al alloy. They discovered that the a reaction layer consisting of Fe_2Al_5 and $FeAl_3$ existed in the central region of the interface, while in the peripheral region, only discontinuous $FeAl_3$ was founded, which was believed to have strong bond strength. Furthermore, their study showed the thickness of the reaction layer increasing as the center of the weld was approached. However, the study did not relate local temperature history to these peculiar characteristics of reaction layer. Various studies have been conducted concerning the effect of welding parameters on the IMC thickness distribution. For example, Zhang et al. (2010) optimized the geometry of electrodes on both sides of Al and steel to improve the strength of the RSW joint between AA6008 and galvanized high strength steel. Their simulation results showed that by application of optimized electrodes, the temperature at the center of the Al-steel interface could stay lower than that by conventional F-type electrodes during welding processes, resulting in lower overall IMC thickness and thus higher joint strength. However, comparison of the simulation results with their presented metallography indicated an insufficient accuracy in predicting nugget growth and joint deformation, which leaves in question their calculated interfacial temperature used for explaining the IMC growth. Wang et al. (2015) developed a fully coupled model to simulate the process of Al-steel RSW. The predicted temperature histories at different material points along the interface were used to predict IMC thickness distribution with consideration of the Si effect on the Al and iron inter-diffusion rate. Their comparison of predictions with physical measurements exhibited good agreement although the predicted voltage response had a slight deviation from the physical response. Wan et al. (2016) further developed the process simulation model through a better representation of thermal and electrical contact constraints at faying interfaces, which greatly improved the simulation accuracy in voltage prediction and IMC growth prediction.

In the following study, we first characterized the IMC interface of Al-steel RSW joints generated by a welding time of 800 ms, and then examined the temperature histories of different locations at the Al-steel interface calculated by the process simulation model established in Wan et al. (2016). The simulation was validated by comparing the predicted nugget profile and joint deformation against that derived by physical experiments. Furthermore, we used the model to simulate RSW processes by different parameters.

Table 1
Chemical compositions of 6022-T4 and HDG mild steel (mass, %).

HDG mild steel	C	Mn	P	S	Si	Al	Fe	–
	0.003	0.11	0.01	0.008	0.005	0.034	Bal.	–
AA6022-T4	Si	Cu	Mg	Fe	Mn	Zn	Ti	Al
	1.3	0.05	0.06	0.1	0.04	0.25	0.15	Bal.

The calculated dynamic interfacial temperature histories together with parabolic equations of IMC growth were used to predict IMC thickness distribution. The predictions were compared with physical IMC measurements to see how well the parabolic equation represents the physical IMC growth and also to study the effect of welding parameters on interfacial temperature history and thus IMC thickness distribution. The learnings are expected to provide guidance in designing weld schedules for controlling IMC growth during Al-steel RSW.

2. Experimental

The materials, welding stack-up, equipment and schedules used for generating the Al-steel welds for the IMC study are introduced in this section. The corresponding process simulation models were developed for calculating the interfacial temperature histories.

2.1. Materials and welding stack-up

A 1.2mm-thick Al alloy 6022-T4 sheet and a 2.0mm-thick 60G hot-dip galvanized (HDG) mild steel were welded in the present study. The chemical compositions of the two materials are listed in Table 1. The schematic of welding stack-up is presented in Fig. 1(a), where a pair of identical rounded-tip R25 electrode caps (dimensions demonstrated in Fig. 1(b)) is applied on both sheets. The Al sheet is placed on the positive electrode and the steel sheet is on the negative one. When electric current flows from Al to steel, due to Peltier effect, an extra small amount of heat is released from steel and absorbed by Al at the contact interface, which facilitates the growth of Al nugget to generate a strong weld. However, if the electric current flows in the opposite way (from steel to Al), heat by Peltier effect flows from Al to steel, which negates the purpose of growing Al nugget and is not preferred.

2.2. Welding equipment and schedules

The welding was performed using a calibrated mid-frequency DC RSW machine of pedestal type, controlled by a programmable logic controller. The welding schedule used for welding Al to steel is shown in Fig. 2, which has a preheating stage and a welding stage. The electrode force is 750 pounds. The weld coupons for characterizing the Al-steel interface are made with the peak values of preheating and welding currents being 5 kA and 13 kA, respectively. In the preheating stage, the current takes 30 ms to ramp up to 5 kA and then holds constant for 70 ms. The cooling time after the preheating stage is 10 ms. In the welding stage, a long welding time of 800 ms is applied to amplify all the effects and phenomena taking place during the interfacial reaction. The holding stage following the 800 ms welding lasts for 250 ms. To study the effect of welding parameters on IMC growth and distribution, we carried out the RSW tests using different welding times and currents. For the study of the welding time, we fixed the peak welding current at 13 kA, but varied the welding time from 400 ms to 800 ms at intervals of 200 ms; for study of welding current, we held constant the welding time at 200 ms, but varied welding current ranging from 13 kA to 15 kA at intervals of 1 kA.