International Journal of Heat and Mass Transfer 101 (2016) 749–763

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Numerical simulation of resistance spot welding of Al to zinc-coated steel with improved representation of contact interactions

Zixuan Wan [a], Hui-Ping Wang [b,*], Min Wang [a,*], Blair E. Carlson [b], David R. Sigler [b]

[a] Shanghai Key Laboratory of Materials Laser Processing and Modification, School of Material Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Manufacturing System Research, GM Global R&D, Warren, MI 48090, USA

ARTICLE INFO

Article history:
Received 4 January 2016
Received in revised form 3 May 2016
Accepted 6 May 2016

Keywords:
Resistance pot welding
Numerical simulation
Al to steel welding
Electrical contact resistance
Thermal contact resistance
Intermetallic compound

ABSTRACT

The resistance spot welding (RSW) process involves electrical, thermal, mechanical and metallurgical fields and contact interactions across faying interfaces. The contact interactions include mechanical, electrical and thermal contacts where the electrical and thermal conduction across the faying interface are affected strongly by the mechanical contact pressure and temperature at the interface in addition to material composition and surface conditions. However, representation of the contact interactions is often simplified with no or limited consideration of a combination of above-mentioned effects in state-of-the-art numerical simulation models due to extremely limited availability of electrical and thermal contact resistance data at various pressures and temperatures. As a result, existing numerical models, mainly to simulate the process of dissimilar RSW process like Al to steel, often have difficulties in accurately capturing the dynamic voltage response, especially during the initial stage when the contact interactions start to engage with rapid changes in interfacial temperature and pressure and in predicting progress of nugget growth and joint deformation all through the welding stage. In this study, we present an improved representation of both electrical contact resistance (ECR) and thermal contact resistance (TCR) in Al to zinc-coated steel RSW process. The calculation of ECR is based on analytical formulations and referencing experimentally measured contact resistance curves from existing literature, with multiple effects of interfacial temperature, contact pressure, zinc coating and Al oxide involved. The corresponding TCRs are obtained from the ECRs according to the Wiedemann–Franz Law for consistency. The model with the improved ECR and TCR representations is established in ANSYS, sequentially coupling mechanical field and electro-thermal field, and it is used to simulate a benchmark Al to zinc-coated steel RSW process using rounded-tip electrode where ECR and TCR are both critical respectively due to important heat generation by electrical contact resistance at preheat stage and significant imbalance of heat generation by Al sheet and steel sheet. Eventually, the simulation results provide a significantly improved prediction of the voltage response and weld profile compared to a conventional approach. It accurately captures the bulging of the steel sheet into the aluminum sheet, which was missed by previous work. The improved model is further used to study nugget development, heat generation and re-distribution and nuggets development during the whole RSW process. Finally, the temperature history at the Al–steel interface obtained from the model is used to predict intermetallic compound (IMC) growth and it accurately captures the bimodal profile of IMC thickness distribution along the Al–steel interface. Findings from the above-mentioned discussions are summarized and can be used to guide future welding schedule development or electrode geometry design for the RSW of Al to steel.

1. Introduction

Despite development of various competing novel welding methods such as laser spot welding, riveting, friction stir spot welding and ultrasonic spot welding, to date, resistance spot welding (RSW) still enjoys a dominant role in joining sheet components of car bodies because of its robustness, high efficiency and low capital investment. The process has been mostly used in joining similar materials up until now. With the increasing usage of mixed materials in manufacturing conventionally steel-dominate car bodies, researchers started to look into expanding its application to welding dissimilar materials such as Al alloys to steels. However, the RSW of Al alloys to steels, unlike the joining of similar materials, is almost impossible to get a single oval-shaped nugget across

---

* Corresponding authors.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.023
0017-9310/

the faying interface due to very different physical properties and incompatibility in one solid phase of these two materials. Instead, the RSW of Al to steel is in essence brazing-fusion welding relying on an intermetallic compound (IMC) layer forming at the interface as the result of the reaction–diffusion between molten Al and solid steel. Existing experimental studies have shown Al nugget size and IMC thickness distribution are two main factors determining joint strength. However how these two factors evolve during the RSW process is still unclear.

Numerical simulation has been applied as an alternative way to better understand the complicated physics involved in Al–steel RSW including thermal conduction, nugget growth, intermetallic compound growth and joint deformation. Simulation of the Al–steel RSW process, like conventional RSW of similar materials, consists of electrical, thermal, mechanical and metallurgical fields and their interactions, but it requires accurate representation of electrical, thermal and mechanical contact conditions and their interactions. Contact conditions play significant roles in dissimilar material RSW process due to the vast differences in electrical, mechanical and thermal properties between the two materials. Balances between these are achieved through contact interactions. In a similar material RSW process, the energy generation is relatively symmetrical with respect to the faying interface between the two sheets or with a very small imbalance because of alloying composition and/or sheet thickness differences. As a result, heat conduction across the faying interface between the two sheets is either zero or very small compared to the amount of energy being generated. In a dissimilar material RSW process, for example, the Al–steel RSW process, the majority of joule heat is generated in the steel because the electrical resistivity of steel is approximately 5 times that for Al. The joule heat is conducted into the Al sheet via contact interfaces, and eventually forms an Al weld nugget adjacent to the steel at the faying interface. Besides, mechanical contact in the Al–steel RSW process is more complicated than that in a similar RSW process due to very different mechanical properties between steel and Al. Mechanical deformation in the Al–steel RSW process is not symmetrical with respect to Al–steel faying interface. One sheet is often bulging into the other sheet at the center of the faying interface due to a large difference in temperature-dependent modulus, yield strength and hardening behavior. Furthermore, the growth of Al–Fe intermetallic compound(s) (IMC), which is critical to Al–steel weld strength, occurs at the Al–steel contact interfaces and is controlled by the thermal history and material composition at the Al–steel contact interfaces. Accurate prediction of Al nugget growth, joint deformation and the IMC growth, which are critical in an Al–steel RSW process simulation, requires accurate representation of mechanical, electrical and thermal contacts and their interactions.

Early work on contact condition representation in the RSW process simulations assumed region of contact at the outset of the analysis using a layer of elements or linkages between nodes face to face. These approaches were limited to simple contact interfaces with small deformation and small relative movement between linking nodes. For example, Nied [6] modeled mechanical, electrical and thermal contact effects using a layer of pre-aligned surface elements connecting faying interfaces. In the model, a flat-ended electrode was considered for simplicity. Interfaces were deemed in contact when the gap controlled by surface elements was zero. No electrical contact resistance was considered. Later on in early 1990s, Tsai et al. [2] and Tsai et al. [1] further developed Nied's work by using surface elements at the contact interfaces by adding consideration of temperature dependent electrical contact resistance for the surface elements. Still, only flat ended electrodes were modeled. In order to calculate changing contact area in domed electrodes, Browne et al. [3] and Browne et al. [4] developed a complicated model with two separate meshes: a finite element mesh with domed electrode for mechanical aspect and a finite difference mesh with flat-ended electrode for electro-thermal aspect. The electrical contact resistance from literature was added directly to the contacting nodes. No pressure and temperature dependence was considered though. The resistance stayed constant until the temperature reaches the Al melting point. In late 1990s, contact formulations involving contacting surface or element pairs started to be introduced into commercial finite element software products to represent non-overlapping and frictional mechanical contact conditions and also for electro-thermal contact conditions. This advancement allowed modeling contact interactions between any shapes and with large displacement, and enabled accurate prediction of dynamic contact status and pressure at contact interfaces. Therefore, consideration of pressure-dependent electrical and thermal contact conditions in the numerical model finally became feasible. Since then, works by Khan [9], Long [21], Li et al. [23] and Moshayedi and Sattari-Far [7] are all examples of using contact elements in representing mechanical, thermal and electrical contact conditions in the RSW process simulation. However, accuracy of electrical and thermal contact representations still strongly depends on availability of materials' temperature and pressure dependent electrical and thermal contact properties.

Study of materials' thermal, electrical and mechanical contact properties and their interactions can be dated back to Cooper et al. [10]. He expressed thermal contact conductance explicitly as a function of contacting material's thermal conductivity, micro-hardness, contact pressure and contacting surface roughness. James et al. [12] studied the effect of mechanical loading on the electrical contact resistance of coated Al and abraded Al. In his work, electrical contact resistance between Al sheets as well as that between electrode and Al sheet was measured under various contact loads at room temperature. Babu et al. [19] developed an empirical model to represent the temperature and pressure dependence of electrical contact resistance at steel–steel and steel–electrode interfaces. Their comparison of the model prediction with experimental measurements showed that the model worked well in the regime of low contact pressure (<100 Mpa), which is commonly expected in the RSW process using flattened electrode. Song et al. [15] presented an experimental method in investigating effect of temperature, pressure and base metals on electrical contact resistance in resistance welding, and measured pressure and temperature dependent electrical contact resistance for the contacts of mild steel, stainless steel and Al alloy. Rogeon et al. [11] characterized electrical contact conditions in spot welding assemblies for both electrode-sheet and sheet-sheet interfaces considering zinc-coated and non-coated steel sheets. The measurements were done for temperature ranging from 0 °C to 500 °C and at pressures of 40 MPa and 80 MPa.

As can be seen from the above literature, bits and pieces of test data on electrical and thermal contact properties were available for certain range of temperature and pressure, mostly for same material contacts or for electrode–Al or electrode–steel contacts. No work has been found on the electrical contact resistance and thermal contact resistance inherent at the Al–steel interfaces. Due to the limited pressure dependent data being available, many steel–steel or Al–Al welding simulations like Long [21], Li et al. [23] and Moshayedi and Sattari-Far [7] were done by considering only temperature dependent contact properties or limited dependency on pressure. The Al–steel RSW simulations were even more difficult due to lack of material contact properties. Inaccurate representation of the contact conditions led to discrepancy in numerical predictions of system's responses. As shown in Fig. 1 by Wang et al. [8], voltage prediction was off in the initial stage and bulging of steel sheet into Al was not captured by the simulation.