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Multi-scale mechanical modeling of Al-steel resistance spot welds

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ABSTRACT

A multi-scale finite element modeling approach was developed to study the deformation and fracture behavior of Al-steel resistance spot welds. First, a micro-scale model was applied to simulate the mechanical responses of the intermetallic compound (IMC) layer having various morphologies and thicknesses under tensile and shear loading conditions. Second, the predicted tensile and shear strength of the IMC layer, that varied along the joint interface per the IMC layer morphology and thickness variation, was then introduced into 3D macro-scale models to predict the overall mechanical performance of weld coupons under coach peel, lap shear and cross-tension testing conditions. The numerical predictions agreed reasonably well with the experimental data.

1. Introduction

Automakers including General Motors (GM) are dedicated to advancing automotive-related technologies, including those that reduce the vehicle's energy consumption and CO_2 emissions. A key technology area is related to manufacturing of vehicle body structure components fabricated from a combination of high-strength and lightweight materials, such as advanced high strength steels (AHSS) with aluminum (Al) alloys, to meet customer demands and government policies to reduce greenhouse gas emissions.

Resistance spot welding (RSW) is the most widely-used joining method for automotive body-in-white (BIW) assembly because of its low cost and short cycle time, flexibility and robustness. The joining of steels to aluminum alloys has become inevitable because of the increasing usage of Al alloys in manufacturing traditionally all-steel vehicle bodies. The great differences in melting points, electrical conductivity, thermal conductivity and thermal expansion coefficient between steels and Al alloys create unique challenges in the joining of these two materials. Moreover, when the RSW process is used to join Al alloys to steels, a metallurgical reaction occurs between the two materials forming a layer of high melting point intermetallic compounds (IMC) which can have a significant effect on joint strengths. In RSW, the IMC phases are formed by reactive diffusion between solid steel and liquid aluminum alloy, i.e. the molten pool of the weld nugget. The thickness and morphology of the IMC layer varies along the RSW joint interface [1]. It has been found that the IMC layer thickness greatly affects the strength of Al-steel RSW [2], as well as Al-steel joints welded by other joining processes [3–5]. However, the mechanism of thickness and morphology dependent interfacial strength of the IMC layer and its influence on overall weld integrity of a weld are still unknown.

In this research, a multi-scale finite element (FE) numerical modeling technique is applied to study the effective interfacial strength of the IMC layer and the deformation and fracture of the overall Al-steel RSW under coach peel (CP), lap shear (LS) and cross tension (CT) testing conditions. The influence of the IMC morphology on the distribution of effective strength along the joint interface and the resultant mechanical behavior of welded coupons under CP, LS and CT loading conditions are investigated.

2. Multi-scale modeling framework

Typically, the IMC layer thickness is less than 10 μm, while the aluminum weld nugget penetrates the full sheet thickness and is 2 orders of magnitude greater than the IMC layer thickness. In order to simulate the effect of IMC upon the deformation and fracture of Al-steel spot welds appropriately, a multi-scale FE model was necessary to determine the effective strength of IMC layer (in micro-scale) and the overall mechanical behavior of Al-steel welds during CP, LS and CT tests (in macro-scale). Both micro and macro modeling efforts were carried out using ABAQUS/Explicit (version 6.14) with special user subroutines to assign the mechanical properties of aluminum and IMC interfacial strength that vary as a function of thickness/location. As illustrated in Fig. 1, micro-scale models, representing several 60 μm-wide regions along a joint interface with various IMC morphologies measured from an actual weld, were built to predict the effective local interfacial strength of the IMC layer. Then, the predicted interfacial

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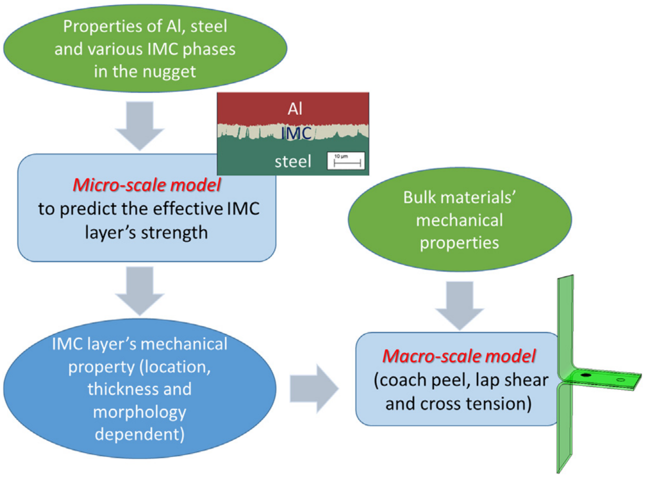

Fig. 1. Framework of multiscale IMC and Al-Steel RSW structural modeling.

strength distribution was incorporated into macro-scale models to estimate the overall mechanical behavior of welded coupons under CP, LS and CT loading conditions. The estimated mechanical behaviors from the macro-scale models were then compared to the experimental results. The mechanical properties of aluminum, steel and IMC phases needed in the models were from experimental measurements or literature data.

2.1. Material properties

Experimental characterizations were conducted to obtain the necessary information such as material's morphology and mechanical properties that are required in the numerical model, as well as the load-displacement curves of the RSW specimens under CP, LS and CT testing conditions.

The spot welds studied in this research were made of 1.2 mm-thick aluminum alloy (AA6022-T4) and 2 mm-thick hot-dip galvanized low carbon steel with a nominal zinc coating of 0.15–0.20% Al, 0–0.1% Pb or 0–0.5% Sb with the balance zinc and a thickness typically less than 10 µm. The base chemistries of the steel and aluminum alloy are presented in Table 1.

Welding was performed using a medium frequency direct current (MFDC) welding machine designed for spot welding aluminum alloys. The system used an inverter weld control from WTC (Welding Technology Corp, Farmington Hills, MI,) with MFDC transformers (RoMan Manuf., Grand Rapids, MI). Pneumatic actuators were used to apply weld force. Distilled water at ambient temperature was used to cool the welding electrodes at a flow rate of 1.5–2.0 gallons per minute. All material stack-ups were welded with the same CuZr C15000 copper alloy electrodes. GM's patented Multi-Ring Domed (MRD) electrode [6] was used on the aluminum alloy sheet while a smooth, ballnose electrode with a 5 mm face was used on the steel sheet. The required dissimilar electrode geometry was produced with a GM patented [7] rotary dressing blade (SEMTORQ Inc., Twinsburg, OH) where one side of the tool produces the MRD geometry and the opposite side produces the desired ballnose geometry. All weld tests were performed with the aluminum alloy sheet contacting the positive welding electrode.

Fig. 2a is a typical cross-section view of such joints. Further study reveals that the composition of IMC layer mainly consists of Fe_2Al_5 adjacent to the steel substrate and $FeAl_3$ [8] adjacent to the aluminum substrate. Fig. 2b is a plot of IMC layer thickness for two specimens as a function of distance from the centerline of the weld. One can notice a distinct variation of IMC layer thickness along the faying surface measured from two welds with a minimum towards the outer weld nugget diameter that then increases towards the center of the weld and roughly mirrors the weld nugget penetration into the aluminum substrate. Post-weld heat treatment at 175 °C for approximately 30 min was applied to mimic the automotive paint baking cycle during BIW assembly. The measured true strain-stress curves of aluminum and steel base metals (after baking) are plotted in Fig. 3. The paint bake process increases the strength of the aluminum alloy due to precipitation hardening [9], so the experiment to measure the true strain-stress curve was performed on baked aluminum alloys. The elastic moduli of the baked aluminum and the steel were 70 GPa and 200 GPa respectively.

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

HDG	C	Mn	P	S	Si	Al	Fe	-
mild steel	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.

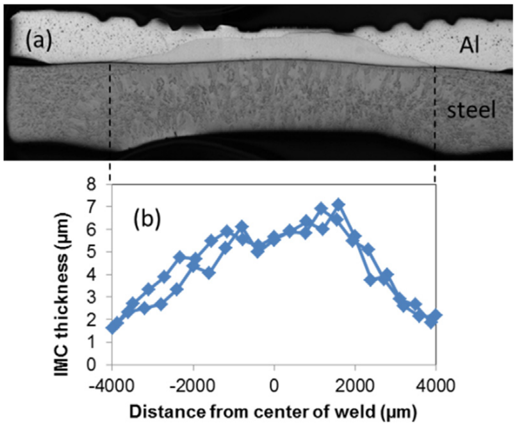

Fig. 2. (a) Photomicrograph of a polished cross-sectional view of a representative Al-steel weld (note the indentations from the welding electrode on the outer surface of the Al sheet and the aluminum weld nugget emanating from the Al/steel interface and growing to full penetration of the Al sheet thickness) and (b) thickness variation of the IMC layer along faying surface for two welds.

Measurement of hardness distribution within the weld nugget area (Fig. 4) was carried out using a LECO LM-series micro-hardness tester. The hardness of aluminum and steel in base metals (after baking process) were approximately 87HV and 102HV, respectively.

The elastic modulus of the IMC layer was measured by nano-indentation tests (Nano Indenter® XP) using a Berkovich triangular pyramid indenter. The maximum load was $p_{max} = 5$ mN. Tests were conducted in the continuous stiffness mode [10] at a constant loading rate $(dp/dt)/p = 0.05\,s^{-1}$. The measured elastic modulus of the IMC layer was 230.5 ± 6.5 GPa.

2.2. Micro-scale modeling of IMC layer

Previous investigations [2–5] have concluded that the strength of the IMC layer is thickness dependent. The typical morphology of nominally "thick" and "thin" IMC layers, characterized by scanning electron microscopy (SEM), is presented in Fig. 5. In both cases, IMC layer consists of a blocky Fe_2Al_5 phase adjacent the steel substrate with a very thin layer of needle-like $FeAl_3$ extended into the Al substrate, which was verified by Energy-dispersive X-ray spectroscopy [8]. The nominally thick IMC layer is roughly greater than 3 µm and normally observed near the weld center where materials have undergone high temperature exposure for a relatively long period during welding, and some needle-like steel remnant is occasionally present within the IMC region (Fig. 5a); whereas, the steel remnant within the thin IMC layer is much thicker (Fig. 5b) due to a lower formation rate of IMC at relatively low temperatures, typically at weld edges.

In order to understand the variation of IMC morphology on effective