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Analysis of Al-steel resistance spot welding process by developing a fully coupled multi-physics simulation model

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ABSTRACT

This paper discusses the development of a simulation model for Al-steel resistance spot welding process, which directly couples the thermal, electrical and mechanical fields and thereby solves the equations simultaneously. For an accurate representation of strong interactions between thermal, electrical, metallurgical and mechanical phenomena in the process, the model considers temperature-dependent material properties and thermal/electrical/mechanical contact interactions at all interfaces. Its calculation accuracy is validated by comparing calculated weld nugget dimensions and electrical potentials with experimental measurements. The newly developed model provides valuable information on dynamic current flow, heat generation and transfer, nugget growth, and mechanical deformation during the process. Further on, the Al-steel intermetallic compound (IMC) thickness, which is critical to weld strength, is calculated based on the thermal history at the Al-steel contact interface and the parabolic kinetics mode of growth. The calculation is verified by experimental IMC thickness measurements. This fully coupled process simulation model provides a powerful tool for understanding the fundamental physics involved during the Al-steel resistance spot welding process and provides a significant improvement in economy over prior approaches of numerical calculation in designing welding process parameters such as electrode geometry and weld schedule prior to costly physical testing.

1. Introduction

With the increasing usage of Al alloys integrated into the manufacturing of conventional steel-dominated vehicle bodies for mass reduction and ultimately improved fuel efficiency, the joining of Al alloys to steel alloys becomes necessary. There are many challenges in joining Al alloys to steels because of the very different physical properties of the two metals. The electrical resistivity of steel is 5 times that of Al which means that there will be a severe heat imbalance during resistance spot welding leading to a nugget offset with respect to the Al-steel faying interface. Furthermore, Al conducts/spreads heat 5 times faster than steels which makes it difficult to heat the Al sheets in a small designated area to initiate a weld nugget. Because Al has twice the thermal expansion rate compared to steel, residual thermal stresses in the Al-steel joints can be created upon solidification because of the mismatch of shrinkage between the two materials. These thermal stresses negatively affect joint durability. And lastly, the two metals are nearly insoluble and as such highly brittle intermetallic compounds (IMCs) are rapidly formed at the Al-steel interface. As shown in Table 1, a typical Aluminum alloy has a melting point of 660 °C while steel's melting point is above 1425 °C. Thus, a typical resistance spot welded joint is typically a "solder" joint where the molten Al wets the steel surface and an IMC layer is formed at the faying interface. If the heat is so great as to melt the steel, the excessive heating can lead to expulsion of the Al, resulting in a loss of fusion material, possibly porosity and cracking of the Al side of the weld.

There has been a continuous body of research on applying conventional fusion welding processes such as resistance spot welding, laser welding and arc welding to the joining of Al to steels, especially in recent years with the increasing application of the two materials. Many developments are based on the resistance spot welding (RSW) process since it is one of the most economic, reliable and commonly used welding methods in the automotive industry. Most studies have focused on understanding the IMC growth conditions including composition and morphology and its effect upon joint strength by either using hot dip aluminizing, immersion and liquid metal corrosion processes, or Al-steel RSW under various schedules [1–8]. These studies provide evidence that

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Table 1
Comparison of physical properties of Al alloys and steels.

Parameters	Melting point (°C)	Thermo conductivity (W/(m K))	Electrical resistivity (Ω m × 10^{-8})	Specific heat (J/kg K)	Density (kg/m^3)	Thermal expansion rate (m/(m K) × 10^{-6})
Al alloy	660	205–250	2.82	900	2700	22.2
Steel	1425–1540	47–54	14.3	460	7870	13.0

the very brittle Al-rich IMC layer consisting of $FeAl_3$ and Fe_2Al_5 easily forms along the iron-Al interface and grows with time and temperature, resulting in weak Al-Fe joints. Within the IMC layer, the Fe_2Al_5 appears to grow out of the iron substrate which then transitions to $FeAl_3$ as it interfaces to molten Al with the Fe_2Al_5 layer being much thicker than the $FeAl_3$ layer. A strong joint could be obtained when Al-Fe interface is IMC-free, is composed of a discontinuous IMC layer or an IMC layer thickness of less than 2 μm and a granular morphology consisting of grains smaller than 500 nm in diameter [3]. Since the IMC growth rate is highly dependent upon the dynamic temperature at the Al-steel interface region, knowledge of the precise temperature history during the welding process becomes critical in order to prevent or control IMC formation at the iron-Al interface. Unfortunately, this type of internal thermal history is nearly impossible to measure using experimental methods during welding. On the other hand, numerical simulation of the welding process, if done accurately, can provide detailed information on the process with respect to the physics being modeled.

The main challenges in modeling the RSW process are representation of the multi physics involved in the process and their interactions, which requires a high level of coupling among the thermal, electrical, metallurgical and mechanical fields and consideration of the electrical, thermal and mechanical contact conditions [9]. Solution of these highly nonlinear equations often encounters issues with convergence if the model is not set correctly and the numerical algorithm being used is not sufficiently robust. Early simulation work focused on heat transfer analysis with no consideration of thermo-mechanical coupling [10–13]. In 1984 Nied [14] developed a finite element model considering thermo-mechanical coupling and contact behavior for the first time and employed temperature dependent material properties. Furthermore, the electrode and workpiece deformation were predicted in his work. However, the model was limited to elastic deformation. Also, contact conditions were not updated based on the welding thermal cycle [15]. Subsequently, Tsai et al. [16] used surface elements at the contact interfaces to account for the thermo-mechanical coupling effects. However, electrical–mechanical coupling was still not considered. The simulation used a one–way coupling procedure, which started with a thermo-electrcial analysis and moved to a mechanical analysis with the calculated temperatures being imposed upon the solid elements. In 1995, Browne and Chandler et al. [17] modeled the RSW process using a sequentially coupled electro-thermal and mechanical fields, and considered a limited update on contact conditions to represent the change of contact resistance and current density at the faying surfaces. Khan et al. [18] developed a model with an iterative update to account for the interaction between electrical, thermal and mechanical fields so that thermo-electrical and mechanical calculations could be more tightly coupled. This iterative update with sequential calculation of thermo-electrical field and thermo-mechanical field, also called the incrementally coupled method, was well accepted by other researchers. One significant advantage of this method is that it reflects the interactions between the fields at a certain point through frequent updates and avoids the convergence difficulty in solving fully coupled fields. Because of this, there are many subsequent works further developing this coupled model with the iterative scheme for various conditions and also for inclusion of additional physical aspects in the process [19–23]. For example, Yongbing Li et al. [24] considered magnetic fields in the model and studied its effect on the molten pool flow and hence heat transfer. However, no work has been found on the direct coupling of the electrical, thermal and mechanical fields due to the complexity of the solution algorithm and difficulty in numerical convergence. Recently, commercial multiphysics calculation software ANSYS made coupled field elements such as plane 223 and solid 226 available in version 15 and improved its numerical solver for better solution convergence, which opened up the possibility of direct field coupling and simultaneous solution of the multi-physics fields.

Besides the challenges in mathematical modeling and physics representation discussed above, obtaining material properties required for accurate material behavior representation remains a significant challenge. The nature of thermal, electrical, metallurgical and mechanical coupling requires the material properties be temperature dependent, phase dependent and pressure dependent to reflect the actual material behavior. Although steel-steel welding has been modeled by many researchers [15,20,25–28], the temperature-dependent steel and copper properties and contact properties across the interfaces can only be found for a number of steel-steel stack-ups. The thermodynamic material and contact data for the Al-Al welding process is even more limited with only a few Al-Al resistance welding process simulation works published [29,30]. No modeling work has been found on the direct Al-steel resistance spot welding process, no work has been found on the material properties inherent at the Al-steel interfaces such as electrical contact resistance and thermal contact resistance. In the one short paper published in Welding Research in 2004 [31], Al-steel welding with a transition material was modeled with incremental coupling of multi physics but with no consideration of contact interactions. A significant discrepancy in deformation was shown.

In the current study, a numerical model simulating the Al-steel RSW process is developed. The model intends to accurately represent the electrical, thermal, metallurgical and mechanical phenomena and their interactions. It directly couples the electrical, thermal and mechanical fields by using the newly available coupled field elements in ANSYS v15, considers electrical, thermal and mechanical contact conditions, and employs temperature dependent material properties. The detailed model construction is described in Section 2. Section 3 provides the model validation where the calculated nugget dimension and electrical potential are compared with experimental measurements. Discussions on heat generation and transfer, current flow and nugget growth in the Al-steel welding process are given in Section 4. The temperature history at the Al/steel interface is further used for the calculation of IMC growth based on diffusion theory and verified by experimental measurement. Section 5 summarizes the study and presents conclusions.

2. Development of an Al-steel resistance spot welding simulation model

The basis for the resistance spot welding process is joule heating which is derived by passing a current through the metal sheets to be welded thereby generating heat by both bulk material resistance as well as interfacial resistance (electrode/substrate and faying interface). Sufficient heat is created to heat, melt and fuse the