Nugget Formation and Dynamic Resistance in Resistance Spot Welding of Aluminum to Steel

H. S. Chang

Abstract

Auto industry has employed resistance spot welding(RSW) to join steel sheets for structural rigidity of automobile body. Driven by the need to reduce weight and fuel consumption, car companies have been evaluating aluminum intensive vehicles(AIVs) as a way to reduce vehicle weight without downsizing. During the transition from all steel-construction vehicle body to aluminum intensive body, joining aluminum to steel sheets emerges as a serious contender in automobile body. This paper deals with application of transition material to RSW aluminum to steel. Placing transition material insert between the aluminum/steel interface was found very effective to overcome physical incompatibility between aluminum and steel. Use of transition insert allows for two separate weld nuggets to be formed in their respective aluminum/aluminum and steel/steel interfaces. This RSW processes was monitored with the aid of dynamic resistance sampling. Typical patterns in sampled dynamic resistance curves indicated formation of sound nugget. The growth of two separate nuggets was examined by micro-cross section test.

Key Words : Resistance spot welding ,Transition insert, Dynamic resistance, Nugget growth.

1. Introduction

Resistance Spot Welding (RSW) has been widely used in the sheet metal industry that requires high productivity and dimensional accuracy. Automobile manufacturers have employed RSW to join steel sheets for structural rigidity of auto body. Driven by the need to reduce weight and fuel consumption while improving handling, performance, and safety, a number of major car companies have been evaluating or, have produced aluminum intensive vehicles (AIVs) as a means for dramatically reducing vehicle weight without downsizing. During the transition from all steel-construction vehicle body to aluminum intensive body construction, joining aluminum to steel sheets emerges as a serious contender in auto body assembly using the RSW processes.

It is well known that metallurgical bonds are difficult to achieve between aluminum and steel using the fusion-welding process. RSW is a fusion welding process. In addition, due to the inherent discrepancies in electrical, thermal and mechanical properties between the two materials, the conventional RSW process and welding schedules are not readily capable of making good aluminum to steel welds. Several new ideas for obtaining sound metallurgical bonds between the two materials using RSW have been proposed by researchers. RSW aluminum to steel using a transition material insert has been studied by Johnson[1)] and Chang et als[2)]. Johnson has worked on the manufacturing process of the transition inserts. In process monitoring of RSW using the inserts has been studied by Chang et al. Extensive experimental work on corrosion resistance of RSW joints with transition materials has been performed by Baboian[3)].

This paper deals with application of transition material to RSW aluminum to steel. Nugget growth

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phenomena are examined in connection with sampled dynamic resistance signals. Based on these, signature analysis of the dynamic resistance for the case of aluminum/steel spot welds are presented.

2. RSW aluminum-to-steel sheet metal joints

The problems associated with aluminum to steel welds are twofold: metallurgical incompatibility and significant differences in the electrical, thermal and mechanical properties between the two materials.

For the fusion welding processes such as RSW, little or no mutual solubility of aluminum and steel exists. The intermetallic compound that is formed between the metals often results in cracking, brittleness, and susceptibility to corrosion. The microstructure of this intermetallic compound is extremely important to determine the weldability of aluminum to steel using RSW. Other factors that influence the weldability of aluminum to steel include widely differing melting temperature, thermal conductivity, thermal expansion coefficient, electrical resistivity, and Modulus of Elasticity. The thermal conductivity and thermal expansion coefficient of aluminum are approximate 2.77 times and 2 times that of steel, respectively. For other properties, the electrical resistivity and the Modulus of Elasticity are 0.3 times and the melting temperature (Celsius) is 0.46 times.

In view of the above drastic difference in material properties, it is very difficult to obtain sound nugget using conventional resistance spot welding. Because of the wide difference in melting temperatures, aluminum and steel melt at different times during RSW and the two molten zones don't mix. An intermetallic compound forms at the interface due to lack of mutual solubility and wide difference in material properties. Therefore, unequal electrode tip diameters on the aluminum and steel sides are usually used to minimize the thermal unbalance between the two metals[4].

Fig. 1 shows two nuggets are formed in the RSW aluminum to steel joint. Because of the relative lower melting temperature of aluminum, melting initiates in the aluminum part during the first weld cycle. As the size of molten aluminum increases, the aluminum/steel interface is wetted by the molten aluminum. The steel part begins to melt when the steel/steel interface temperature reaches its melting temperature and forms the steel nugget during the later weld cycles. Subsequent solidification and cooling of aluminum causes an aluminum nugget mechanically locked to the interface. A magnified macro-sections of the interface is shown in the Fig. 2. In the middle part of the Fig. 2, very thin layer at the interface between the upper steel structure and the lower structure can be observed. The layer is so called intermetallic layer, which is brittle intermetallic compound.

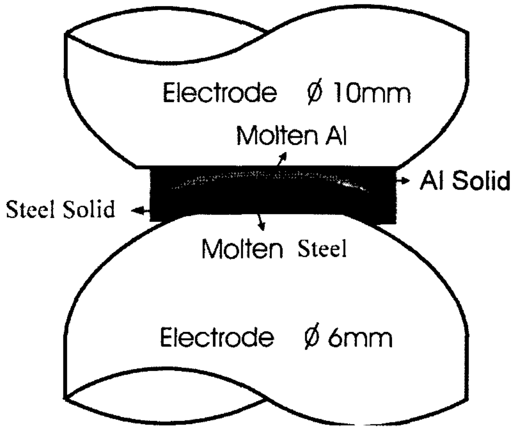


Fig. 1 Two Nuggets in Aluminum to Steel Spot Joint

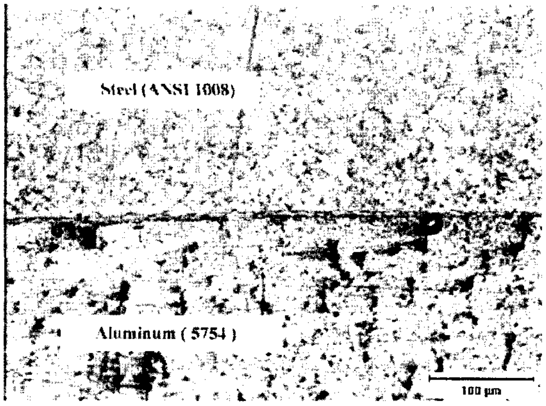


Fig. 2 Intermetallic layer
at the aluminum/steel interface

3. Transition material for aluminum to steel joint

Use of transition materials placed between the dissimilar metal interface is a common practice in fusion welding[4]. Recently, new transition materials have been developed for RSW aluminum to steel joints[1,2]. Utilization of this transition insert allows two separate weld nuggets formed in their respective aluminum/aluminum and steel/steel interfaces. Bonding at the aluminum/steel interface is preformed during the insert manufacturing process and dubbed as "aluminum clad steel transition insert".

An "aluminum clad steel transition insert" is manufactured by a cold rolling/bonding process, followed by an annealing process. This process can be characterized as one between friction welding and mechanical cladding. Cleaned steel and aluminum strips are placed in contact with each other and fed into a multi-stage rolling/bonding mill. This creates an initial mechanical bond at the interface of the strips. The clad material is then annealed to allow diffusion between the two materials, which completes the metallurgical bonding and recrystalization process.

The "aluminum clad steel transition insert" converts the aluminum to steel joint into two separate joints of similar materials during RSW. When RSW aluminum to steel with a transition insert, two weld nuggets of similar materials are formed (Fig. 3). With proper insert thickness and welding parameters, reliable joints can be achieved without the formation of brittle intermetallic compounds at the aluminum/steel interface as observed without the transition material. RSW that uses a proper insert material is a promising substitute for mechanical joining methods (e.g. die forging, crimping, riveting, bolting) in aluminum to steel constructions.

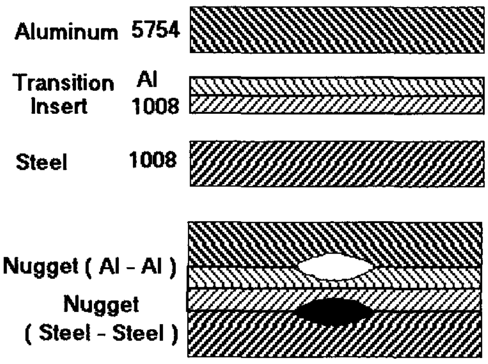


Fig. 3 Transition material inserted for aluminum/steel joint

4. Electrode design

The electrode design is crucial in RSW aluminum to steel. Since the two metals have widely differing electrical, thermal and mechanical properties, the unbalanced heating in the two dissimilar metals should be minimized with an appropriate electrode design. The heat balance could be achieved by using different geometry and material for electrodes in contact with aluminum and steel parts of the joint. From a practical point of view, it is practical to use electrodes of the same material, but with different tip geometry. In this paper, discussions are based on a recent study conducted at The Ohio State University[2]. A Cu-Cr, dome-type electrode with 5 mm tip diameter was used for steel and an R-type electrode with tip radius, R = 200 mm was used for aluminum. Because of lower aluminum melting temperature, approximately 46% of the steel melting temperature, an attempt was made to reduce weld current density in aluminum with the R-type electrode.

5. Nugget growth and dynamic resistance patterns

Dynamic resistance (i.e. instantaneous electrical resistance between the electrodes) has been used as an important process variable that could be monitored during the RSW process. Many commercial weld monitors are being used for sampling of the dynamic resistance. Various patterns of the dynamic resistance responses indicate continuous changes in the thermophysical process during the weld cycles. The thermoelectric process includes Joule heating, temperature increase in the base metal, subsequent softening at the interfaces followed by local melting, and nugget growth. Thus, monitoring of dynamic resistance between the electrodes is an indirect measurement of, but has a relationship with, the nugget growth.

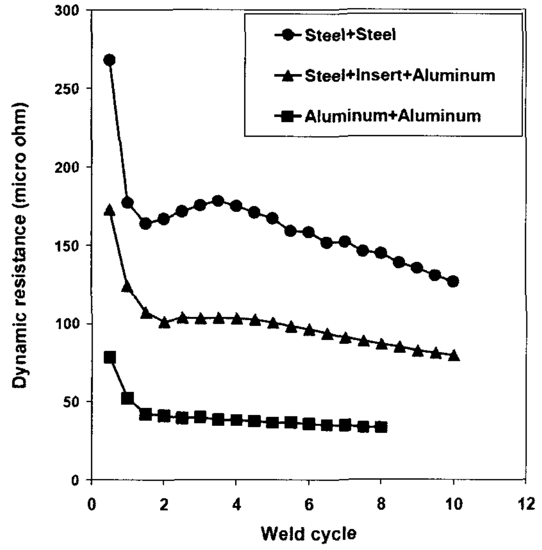


Fig. 4 Typical dynamic resistance patterns

Fig. 4 shows dynamic resistance curves sampled during the RSW for three spot welds. In the case of steel/steel weld, dynamic resistance drops suddenly during the first few weld cycles due to breakdown of the surface impurities and oxide layers. As the base metals heat up by Joule heating, the bulk resistivity of the base metals increases. Hence the dynamic resistance increases after the initial drop. When local melting begins at the steel/steel interfaces, weld current flows mostly through the molten zones. This causes reduction in constriction resistance and trades off the bulk resistance increase. Hence, the total dynamic resistance increases toward the peak value, where the rate of bulk resistance increase gets even with the rate of constriction resistance decrease. After the peak point on the resistance curves, gradual decrease in the dynamic resistance is due to decrease in the constriction resistance as the nugget size increases. "Resistance drop" is defined as total drop of resistance from its peak to its final value sampled during the final weld cycle. This resistance drop has proved to have strong correlation with the nugget size in the case of steel/steel welds.

In the case of aluminum/aluminum weld, as shown in the lower part of the Fig. 4, dynamic resistance shows similar initial drop. Since the aluminum base metal become soft due to Joule heating, drastic increase in contact area at the interface reduces the constriction resistance. This effect is continuously prevailing over the bulk resistance increase and hence dynamic resistance shows continuous decaying trend.

A notable curve in the middle of the Fig. 4 shows dynamic resistance pattern sampled during aluminum/steel spot weld which was made with the transition material(insert). This pattern indicates that the weld specimen has gone through thermophysical phenomena in between the two characteristic processes described above.

Fig. 5 shows dynamic resistance signals sampled during RSW of 5754 to 1008 without transition insert. Major finding in Fig. 5 is that spot welding of aluminum to steel is inherently unstable processes. The fluctuations in the dynamic resistance indicates unstable bulk heating, softening, and local melting followed by initial break down of surface irregularities. In view of this finding, transition inserts play an important role by converting dynamic resistance pattern in Fig. 5 to sound pattern in Fig. 4.

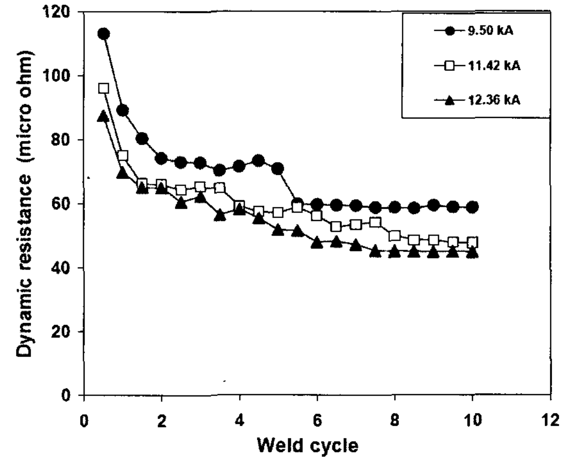
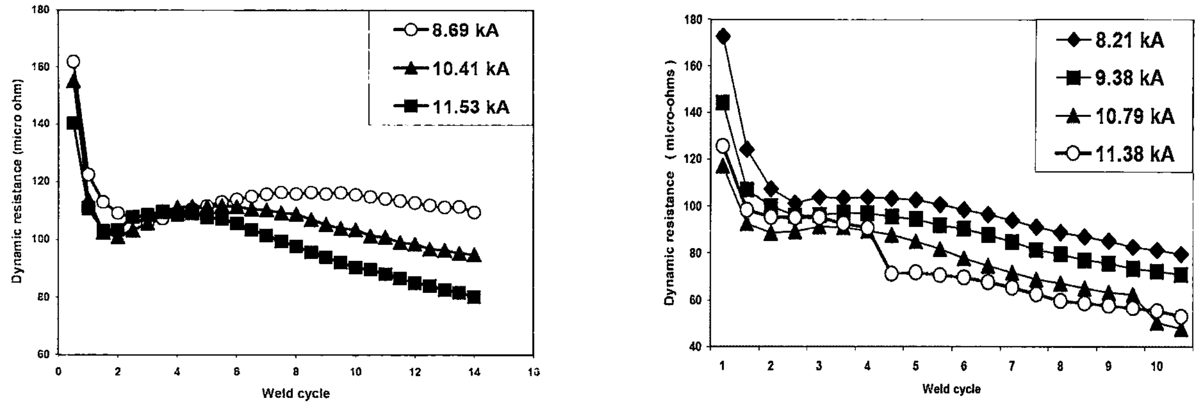
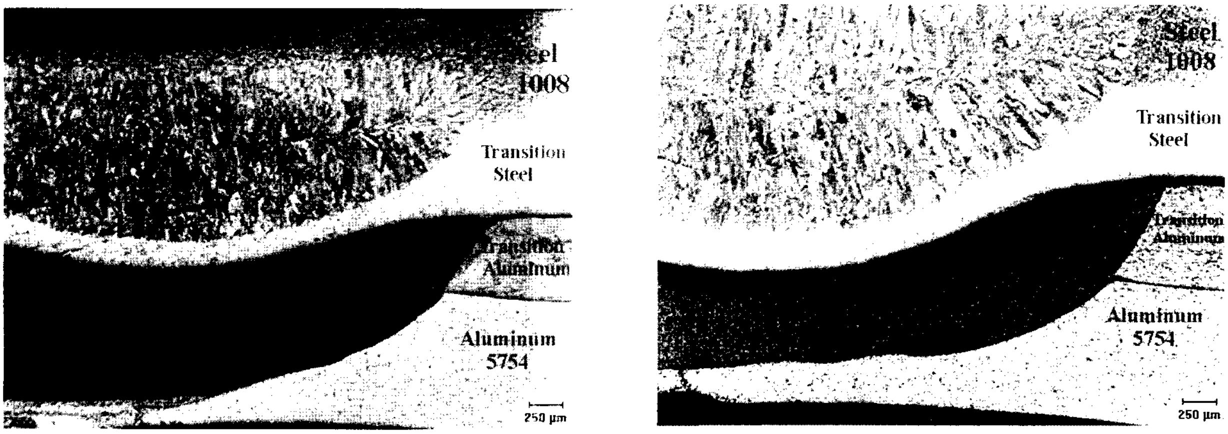


Fig. 5 Dynamic resistance patterns of 5754/1008(t=2.0 mm) spot welds



(a) 5754/Insert/1008(t=2.0 mm) spot welds (b) 5754/Insert/1008(t=1.0 mm) spot welds

Fig. 6 Dynamic resistance patterns



(a) 5754/insert/1008(t=1.0 mm)spot weld (b) 5754/insert/1008(t=2.0 mm) spot weld

Fig. 7 Microphotograph

By inserting transition material in between 5754 and 1008 sheets, good dynamic resistance signals have been sampled as shown in Fig. 6. Fig. 6(a) shows three patterns of dynamic resistance obtained for various weld currents. Higher weld current causes larger nugget size and greater resistance drop as explained with Fig. 4. Fig. 6(b) shows the thickness effect of steel on the dynamic resistance pattern. Change in steel thickness from 2.0 mm (Fig. 6(a)) to 1.0mm (Fig. 6(b)) results in only a smaller increase in the dynamic resistance after the initial drop. This is due to the fact that local melting occurs sooner in the case of thicker(2.0 mm) steel and results in earlier decrease of the constriction resistance. This phenomenon continues to prevail over the remaining weld cycles since the relatively lower increase rate of bulk resistance in the thinner steel joint(1.0mm) attributes little to the increase of the dynamic resistance.

Excessive increase in the weld current causes expulsion. Sudden resistance drop in the later half weld cycles indicates expulsion of the molten metal. Figure 6(b) shows that 10.79 kA causes expulsion at the 9th weld cycle (18th half cycle). Further increase of weld current(11.38 kA) results in earlier expulsion at the 7th half cycle.

A notable trend in the dynamic resistance curves, as shown in Figs. 6(a) and 6(b), is that "resistance drop" gets larger with increase in the weld current. This trend can also be found in the case of steel/steel spot welds. The analogy in the dynamic resistance patterns between aluminum/steel welds and steel/steel welds suggests that actual transition has been achieved with the transition insert from an aluminum/steel joint to a double nugget joint that contains an aluminum/aluminum joint and a steel/steel joint.

6. Weld quality

In practice weld quality is usually evaluated based on the nugget size and the shear-tension strength of the nugget. For the double-nugget, aluminum/steel spot weld, the size of both nuggets was examined. As shown in Fig. 7(a), the upper nugget indicates the molten zone at the interface between the base steel (i.e. 1008, thickness=1.0 mm) and the transition steel. The lower nugget is a fused bond between the base aluminum (i.e. 5754, thickness=0.73 mm) and the transition aluminum. Dendrite solidification structures surrounded by the heat-affected-zone (HAZ) can be observed in the steel nugget. Shrinkage voids are shown in the aluminum nugget. The shrinkage voids are caused by fast cooling of aluminum due to higher thermal conductivity (i.e. approximately 277% of steel). Similar nuggets are shown in the Fig. 7(b) when the thickness of the steel is doubled (i.e. thickness=2.0 mm). Similar to the results shown in Fig. 7(a), four layers of different metallurgical zones are observed.

7. Further research issues

The thermoelectric and thermomechanical phenomena associated with the RSW process is a complex issue. Analytical design methods become a common approach to gain knowledge of the RSW process. Dynamic contact resistance at the interfaces of RSW joints needs to be studied for a better understanding of the process phenomena.

Contact resistance variation at the two similar faying metal interfaces and the bonded metal interface of the transition insert is a subject that requires further investigation using an integrated experimental and analytical approach. The effect of the thickness ratio in the transition material is also a significant parameter that influences the nugget formations. From the recent OSU study[2)], thickness of the transition steel was found to play a decisive role in RSW aluminum to steel. This thickness effect needs to be investigated in order to develop knowledge for appropriate insert designs. In addition, the vulnerability of aluminum to steel transition welds that is subject to galvanic corrosion in service is also a research issue. The in-process monitoring technique for detecting the shrinkage voids in the aluminum nugget is another area subject to research and development.

8. Conclusion

1. The electrode design is crucial when the transition insert is used in RSW aluminum to steel. The electrode tips need to be configured in accordance to the properties of the dissimilar base and insert materials to maintain a balanced Joule heating at both interfaces between aluminum/aluminum and steel/steel.

2. Lobe curves obtained from the recent OSU study[2)] on RSW aluminum to steel suggest that the weld schedules be primarily governed by the steel/steel interface. Therefore, the selection of the process parameters would be strongly influenced by the geometry and properties of steel in RSW aluminum to steel.

3. The growth of weld nuggets in the RSW aluminum to steel joints can be monitored by continuous measurement of the dynamic resistance history during the weld cycles. Monitoring the dynamic resistance between the electrodes can be accomplished with a simple electrical measuring device. This provides a practical and viable means to assure the weld quality. The dynamic resistance in RSW aluminum to steel, which has a characteristic pattern similar to the steel/steel RSW process, provides a valuable information to ensure weld quality.

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