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Technical Report

Resistance spot welding of 6061-T6 aluminum: Failure loads and deformation

R.S. Florea [a,*], K.N. Solanki [a], D.J. Bammann [b], J.C. Baird [a], J.B. Jordon [c], M.P. Castanier [d]

[a] Center for Advanced Vehicular Systems, 200 Research Blvd., Starkville, MS 39759, USA
[b] Mississippi State University, Mail Stop 9552, 210 Carpenter Bldg., Mississippi State, MS, USA
[c] The University of Alabama, 259 Hardaway Hall Tuscaloosa, AL 35487, USA
[d] US Army TARDEC, 6501 E. 11 Mile Rd., MS157, Bldg. 215, RDTA-RS, Warren, MI 48397, USA

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ABSTRACT

This study offers a novel research approach to compare weld quality for different welding conditions in order to achieve optimal end-product results. Using electron back scatter diffraction (EBSD) scanning, tensile testing, and laser beam profilometry (LBP) measurements along with optical microscopy (OM) images, failure loads and deformation of 6061-T6 aluminum alloy, resistance spot welded (RSW) joints were experimentally investigated. Three welding conditions, nugget and microstructure characteristics were quantified according to predefined process parameters. Quasi-static tensile tests were used to characterize the failure loads in specimens based upon these same process parameters. Profilometer results showed that the larger the applied welding current, the deeper the weld imprints. In addition, good correlation was obtained between the EBSD scans and the welding conditions. A strong dependency was found between the grain size and orientation and the welding parameters.

1. Introduction

Manufacturing industries currently seek to better understand the complicated microstructural changes that occur in crystalline materials during welding operations. These welding operations often involve high strains and deformation temperatures that result in microstructures which continually evolve away from that of the base material. A non-homogeneous distribution of the material microstructure often exists due to the non-uniform distribution of temperatures and strains inherent during most joining operations, such as resistance spot welding (RSW). The residual microstructures present in crystalline materials post-welding influence the overall strength and performance of the manufactured components. Therefore, understanding the influence of welding process parameters, such as force, weld time, and current, on microstructural changes provides manufacturers with opportunities to optimize the welding processes in order to achieve the most desirable material properties and microstructures for their end-products.

Concurrent to manufacturing industries' efforts to optimize welding processes, transportation industries seek to address energy and emission concerns through wide-spread use of lightweight metals like aluminum alloys to decrease the weight of the vehicles they produce. Essential to maximizing the weight reduction derived from these lightweight components is decreasing welding post-processing costs, and specifically avoiding the necessity for excessive sanding and painting processes needed to ensure acceptable appearance of the final product. In fact, resistance spot welding produces sufficient joints to successfully mitigate the need for extensive post-processing.

Resistance spot welding (RSW) is a joining process for thin metal sheets during which, in contrast to other welding processes, no filler metals or fluxes are used. Instead, pressure exerted by electrodes joins the contacting metal surfaces via heat obtained from resistance to the electrical current flow. RSW provides accelerated speed and adaptability for automation in high-volume and high-rate production; however, the technique suffers from inconsistent quality between welds due to the complexity of the process itself and many variables involved in the joining process. Further implementation and improvement of existing processes, including weld quality and time improvement, electrode life extension, maintenance cost reduction and development of new techniques for RSW, will greatly impact the above noted industries due to the large numbers of spot welds they perform in their manufacturing processes [1,2].

The complexity of optimizing RSW process arises from the integration of mechanical, metallurgical, thermal and electrical phenomena. The interaction between thermal and metallurgical phenomena results in a continually evolving microstructure. Second, thermal and mechanical phenomena result in non-uniform thermal strains and residual stresses. Electrical and thermal effects strongly correlate and involve high temperature gradients and non-uniform weld strength. From metallurgy and mechanical perspectives, complex interactions between the base metal (BM), heat affected zone (HAZ) and fusion zone (FZ) involve non-homogeneous distribution of the material microstructure.

* Corresponding author. Tel.: +1 662 325 8839; fax: +1 662 325 5433.
E-mail address: rf2@msstate.edu (R.S. Florea).

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The interactions between electrical and mechanical effects refer to contact conditions between electrodes and welding sheets. Considering these sometimes divergent factors, it is difficult to computationally simulate and measure the performance of RSW in different joints, materials and applications. However, experimental studies [3–5], have been executed on various engineering materials, and the influence of the welding time, current, and applied forces has been evaluated accordingly. In addition, numerical and FEA studies have been conducted [6–11] to explore methods and resolve the effect of various welding parameters. Despite progress made toward the complexities of the RSW process, we still lack a clear understanding of the phenomena that occur in RSW.

In order to maximize the use of RSW in high conductivity metals like aluminum, optimization of resistance spot welding (RSW) is needed to reduce production cost and to enhance efficiency and quality. Notably, RSW of aluminum is more complex than it is with steel because of aluminum's higher thermal conductivity requires higher power and current requirements. As such, the experimental and modeling techniques for aluminum welding are more complex as well. This paper investigates the experimental RSW parameters for an aluminum 6061-T6 (AlMg1SiCu per ISO nomenclature) alloy spot welded in a lap-joint configuration. The scientific contributions of this work include the quantification of the electrode imprint using laser profilometry as well as the establishment of consistency in failure loads as a function of different welding conditions. Furthermore, this study offers microstructure quantification of the spot welds as way to understand the effect of the welding parameters on the quasi-static tensile behavior of the RSW'ed lap-joints.

2. Materials and experiments

The wrought aluminum 6061-T6 alloy used in this study exhibits high yield strength and good ductility properties [3,18,19]. Material thickness is 2 mm and each sheet comprises two pieces, 100 mm long and 35 mm wide. The uncoated sheets overlap 35 mm with one spot weld located in the center of the overlap. From a welding perspective, aluminum and magnesium are considered Group 1 materials [3,13] and require special procedures for oxide coating removal, cleaning, fit-up and joint thickness. As such, prior to welding, each sheet of aluminum alloy was mechanically and chemically cleaned to remove the natural oxide layer. In order to provide relevant results for industry, lap-shear coupons were produced to meet or exceed MIL-W-6858D Military specification [3,13], where the minimum nugget size is 5.7 mm and minimum shearing force is 3.8 kN per weld.

A servo-gun with weld control was used to manufacture the specimens for this study, and copper–zirconium alloy electrodes were used to join the aluminum sheets. The power supply and current transformer had a mid-frequency direct current with 8 V on the secondary voltage. Water was applied as a cooling agent at a rate of 4 L/min. Welded specimens of various nugget sizes were produced. Florea et al. [3,17] described in detail the equipment used in this study, which is capable of the weld-and-forge operation for reducing the porosity and solidification cracking prevalent when aluminum alloys are RSW'ed. To meet the metallographic requirements, three iterations of welding were performed in order to identify the most suitable welding condition. To confirm the quality during specimen manufacturing, periodic peel tests were performed after each batch of 20 specimens. Following the production of the samples at "nominal" condition, the weld time and/or weld current were adjusted to "low" condition for producing slightly smaller (average 4.5 mm) and to "high" condition for slightly larger (average 6.5 mm) weld nuggets [3]. During the welding process, the electrodes were re-dressed at intervals of approximately every 100 welds. Table 1 lists the weld parameters for "low", "nominal", and "high" conditions.

Table 1
Weld parameters for "low", "nominal", and "high" conditions.

Welding condition	Electrode force (kN)	Welding time (s)	Welding current (kA)	Average nugget size (mm)
"Low"	3.8	0.115	26	4.5
"Nominal"	3.8	0.115	30	5.7
"High"	3.8	0.115	38	6.5

Following each test cycle, a laser profilometer was used to nondestructively examine the welds on nine coupons, three at each welding condition. To assure measuring consistency, consecutive specimens were analyzed (for example coupon #96, #97 and #98). The samples were scanned in *x*- and *y*-directions, 20 mm by 20 mm at the top and bottom of the resistance spot welds. The measuring speed was 30 mm/s with 100 μm spacing and a resolution of 130–150 points. After proper focus, the *z*-coordinate was constantly maintained and the laser scan moved along the other two axes. This technique provided information about the weld profiles and nugget areas, the volume of a dimple or a peak, as well as the 3D axonometric meshes.

Cross-sections of the weld nugget were made at each of the three conditions and were prepared for optical microscopy (OM) analysis. After cutting, the coupons were hot mounted in resin powder and then mechanically ground and polished. After polishing, the coupons were etched using Keller's reagent (95 mL water, 2.5 mL HNO_3, 1.5 mL HCl and 1.0 mL HF). De-ionized water and ethanol were used to neutralize the coupons after etching. All samples were then cleaned for 20 min in an ultrasonic bath using ethanol, then dried and placed in a desiccator until microscopy analysis.

In order to quantify the microstructure of each set of welding parameters, electron back scatter diffraction (EBSD) mapping was performed. To reduce EBSD scan time, each cross section was analyzed by scanning half of the weld nugget in the longitudinal direction (in the rolling direction). "Grain dilution clean-up" function was performed with 5° tolerance angle and 2 μm minimum grain size.

For tensile tests, a mechanical testing apparatus was used along with a laser extensometer at 50 mm at full-scale gage length. Force, displacement, and time were captured. The displacement rate was 0.01 mm/s, and failure was defined as a 20% drop in the peak load. Ten specimens were tensile tested as follows: three at nominal condition (30 kA current), four at low condition (26 kA), and three at high condition (38 kA). Complete failure of all specimens was observed.

3. Results and discussion

3.1. Laser beam profilometry

One of the main objectives of this study was to quantify the weld indentation depths that occurred on specimens subjected to different forces and electric currents. In RSW, as the current increases, the indentation produced on the surface of the sheet deepens. In order to check the quality and the appearance of the welds, the maximum and mean average depths and heights of the indentations were measured using laser beam profilometry (LBP) for nine specimens at the three different welding conditions. The maximum average depth for the "high" weld condition was 0.128 mm, which is necessary to achieve the smooth profile required to avoid post-welding and pre-coating surface preparation.

Notably, the LBP technique is frequently used in corrosion science to measure weight loss of corrosive environments [14]; how-