Journal of Materials Processing Tech. 249 (2017) 463–470

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

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

# Thermo-mechanically affected zone in AA6111 resistance spot welds

Sainan Wu[a], Bita Ghaffari[b], Elizabeth Hetrick[b], Mei Li[b], Qing Liu[a,*], Zhihong Jia[a,*]

[a] College of Materials Science and Engineering, Chongqing University, Chongqing 400044, China
[b] Ford Research and Advanced Engineering, Ford Motor Company, Dearborn, MI 48124, USA

ARTICLE INFO

*Keywords:*
Resistance spot welding
Aluminum alloy
Thermo-mechanically affected zone
Heat affected zone
Finite element analysis

ABSTRACT

A hardened thermo-mechanically affected zone (TMAZ), measuring a few millimeters in width, was identified between the weld nugget and base metal in AA6111 resistance spot welds (RSW). The spatial distribution, microstructure, hardness and evolution of the TMAZ, and the impact on fracture morphology of spot welds were investigated through micro-hardness mapping, optical metallography, transmission electron microscopy, welding process simulation and quasi-static tensile tests. Strain hardening induced by the compressive force applied by the welding electrodes, as opposed to precipitation hardening induced by heat, was determined to be the dominant hardening mechanism in the development of the TMAZ in AA6111 RSW.

## 1. Introduction

Resistance spot welding (RSW) is one of the primary joining techniques for automotive body-in-white manufacturing according to Han et al. (2010) and Gould (2012). In the last years, aluminum alloy RSW has been studied extensively in weld controllers and transformers, electrode geometries, and weld schedules, as well as its implementation in the automotive industry such as Ford F-150 box floor and Cadillac CT6 body-in-white. However, fundamental efforts to deliver process understanding and fully characterization in weldment attributes have been more limited.

The RSW process involves joining metal sheets through fusion via a combination of Joule heating and the pressure applied by welding electrodes. Customarily, three regions have been distinguished in aluminum alloy RSW joints: base metal (BM), weld nugget and heat affected zone (HAZ) (Pereira et al., 2010; Sun et al., 2005). The BM region is sufficiently far from and not affected by the heat produced during the process. The weld nugget boundary is the location where the peak temperature reached the liquidus of the BM during welding. All material within the weld nugget boundary has been melted, then rapidly solidified. Between the weld nugget boundary and the BM, the metal microstructure and properties have been changed by the thermal input of the welding process, creating a transition zone traditionally identified as the HAZ. As stated by Totten and MacKenzie (2003), the exact modifications depend on the specific aluminum alloy, as well as the peak temperature and heating time experienced in the process. There exists a partially melted zone located just outside the weld nugget boundary in the HAZ, where the peak temperature was between the liquidus and solidus. Zhang and Senkara (2011) reported that equilibrium super-solidus melting and non-equilibrium melting of eutectic constituents along the grain boundaries could be observed in the region, leading to a drop in strength. Totten and MacKenzie (2003) also found that the HAZ would lose strength due to precipitation reactions involving dissolution and coarsening during welding in 6000 series heat-treatable aluminum alloys RSW.

Since the HAZ is relatively narrow and non-uniform in properties, it is difficult to conduct traditional tensile testing to measure its mechanical property. In recent years, instrumented nanoindentation tests were carried out to determine local properties such as stress-strain curves (Ullner et al., 2011), yield stress, elastic modulus, and strain-hardening exponent (Ambriz et al., 2011). However, since the diameter of the indenter is typically smaller than the grain size, the stress-strain properties obtained do not represent the macro mechanical properties. Generally, micro-hardness traverses across the welded joint are conducted for convenience, but results are inconsistent in the literatures. For example, for AA6111-T4 RSW, Shi and Guo (2013) observed that the HAZ was softer than the BM, but harder than the nugget. However, Sun (2010) reported that the HAZ was harder than both the BM and nugget, which themselves had similar hardness profile. With the same alloy and similar welding configurations, Wu et al. (2014) found the HAZ was harder than the BM, which was in turn harder than the nugget. The inconsistency in these results is possibly related to insufficient information about the weld hardness profile.

In the current study, detailed 2-dimensional mapping of Vickers micro-hardness was carried out on specimens of AA6111-T4 RSW to examine the material changes during welding. Further studies of the

* Corresponding authors.
*E-mail addresses:* qingliu@cqu.edu.cn (Q. Liu), zhihongjia@cqu.edu.cn (Z. Jia).

http://dx.doi.org/10.1016/j.jmatprotec.2017.06.037
Received 21 February 2017; Received in revised form 19 June 2017; Accepted 20 June 2017
Available online 23 June 2017
0924-0136/ 

material microstructure helped obtain a full understanding of the properties of different regions. The observed few-mm wide hardened zone between the weld nugget and BM could not be solely explained as a HAZ, but as a thermo-mechanically affected zone (TMAZ). The term TMAZ is commonly utilized in Friction Stir Welding (Elangovan and Balasubramanian, 2007), Friction Stir Spot Welding (Rosendo et al., 2011; Shen et al., 2013) to characterize the deformed region outside the stir zone, which experiences both moderate frictional heating and plastic deformation by the tool stirring action. This term is utilized here for a region that also experiences both heat and deformation, though in a substantially different proportion than in friction stir welding. The distribution, properties and formation of the TMAZ in AA6111 RSW were determined experimentally and numerically. Quasi-static fracture morphology was also investigated with attention to the impact of the properties of different regions in the weld.

## 2. Experimental procedure and numerical simulation

### 2.1. Materials

Commercial aluminum alloy AA6111-T4 sheets of 2 mm thickness were utilized throughout the study. The nominal chemical composition and measured tensile properties of the as-received AA6111-T4 sheets are listed in Tables 1 and 2, respectively.

### 2.2. Specimen preparation and testing

The AA6111-T4 sheets were cut into 95.0 mm × 25.4 mm strips, and then joined in tensile-shear (TS) and coach-peel (CP) configurations with a 25.4 mm × 25.4 mm overlap area using a servo-actuated, multi-step, medium-frequency direct current welding process with truncated cone welding electrode caps. Detailed specimen geometries are shown in Fig. 1. Varying force levels, welding currents and times were used to produce spot welds with different teardown button diameters, ranging from $4\sqrt{t}$ to $5\sqrt{t}$, where $t$ is the 2 mm sheet thickness.

Optical microscope and Vickers hardness testing system were used to obtain the microstructure and 2-dimensional micro-hardness maps of the spot welds. Three $4\sqrt{t}$ and three $5\sqrt{t}$ RSW specimens were cross-sectioned through the weld center along the short direction of the weld coupon, then cold mounted, mechanically ground and polished to 0.5 μm. Subsequently Keller's reagent was used to reveal the microstructure. Vickers micro-hardness testing was carried out on the polished surfaces, with a 200 g load indenter and grid spacings of 100 μm and 150 μm along the thickness and rolling directions, respectively. Grids of more than 4000 indentations were measured to completely cover the RSW joint, as shown in Fig. 2. Upon identification of the hardened TMAZ through the hardness measurements, focused ion beam (FIB) microscopy was utilized to prepare several transmission electron microscopy (TEM) specimens from each of the three distinct observed regions of the $5\sqrt{t}$ specimen displayed in this paper. Dislocations and precipitates in each region were observed using TEM. Quasi-static tensile tests, including five TS and five CP tests, were performed to observe the fracture modes and crack propagation paths in the two different load conditions. All tensile tests were carried out with a servo hydraulic test system with a constant cross-head speed of 10 mm/min.

### 2.3. Finite element modeling

The commercial finite element method package SORPAS was utilized for simulation of the spot welding process to calculate the heat and deformation history of the specimens. To calculate the time-dependent distributions of temperature, strain and stress in the base materials and electrodes, SORPAS couples electrical, thermal, metallurgical and mechanical models of material property evolution during welding (Zhang, 2003). The algorithm for coupling of the numerical models and the basic configuration of the finite element model utilized here are shown as Fig. 3. Standard databases of welding machines and material databases for the electrodes and workpieces, already embedded in SORPAS, were initially utilized. However, the aluminum alloy material database was modified to obtain the best possible match between the simulations and observed experimental results, for weld features such as nugget diameter, penetration, and surface indentation.

**Table 1**
Nominal chemical composition of AA6111 aluminum alloy.

| Element | Mg | Si | Cu | Mn | Fe | Cr | Zn | Ti |
|---|---|---|---|---|---|---|---|---|
| wt.% | 0.5–1.0 | 0.6–1.1 | 0.5–0.9 | 0.1–0.45 | 0.40 | 0.10 | 0.15 | 0.10 |

**Table 2**
Measured tensile properties of the as-received AA6111-T4 aluminum alloy sheet.

| Young's Modulus (GPa) | Yield strength 0.2% (MPa) | Ultimate strength (MPa) | Elongation |
|---|---|---|---|
| 70 | 172 | 290 | 28% |

## 3. Results and discussion

### 3.1. TMAZ in AA6111 RSW

The measured grid micro-hardness results for one of the $4\sqrt{t}$ and one of the $5\sqrt{t}$ specimens are shown in Fig. 4(a) and (b). The microscopy and hardness results were consistent for the other samples. Optical images of the $4\sqrt{t}$ and $5\sqrt{t}$ specimens prior to micro-hardness mapping are shown in Fig. 4(c) and (d). The hardness contour maps reveal the soft center (green) and hard surface (blue) of the BM sheets, approximately 80 HV and 93 HV, respectively. The increased hardness near the surfaces is most probably caused by the series of coiling and uncoiling processes experienced during manufacturing and preparation for use, in which dislocations are introduced into the outer surfaces. The nugget with a cast microstructure is the softest region. It contains equiaxed dendrites in the nugget center (red) and columnar dendrites (yellow) oriented along the heat flow direction in the weld nugget edge, as detailed in the optical images shown in Fig. 5(a) and (b). The microstructure transition is attributed to the changing cooling rate in the weld nugget. The columnar region is most likely harder than the nugget center (66 HV–76 HV and 45 HV–66 HV, respectively) because the average dendrite arm spacing in the nugget edge is smaller than that of the nugget center.

The region between the BM and weld nugget, which experienced both heat and indentation deformation during the welding process, is defined as the TMAZ, as shown in Fig. 4(c) and (d). From the hardness map, the width of the TMAZ is 1.5–2.0 mm for both the $4\sqrt{t}$ and $5\sqrt{t}$ specimens and displays very similar maximum hardness values for both nugget diameters. Further investigations reveal that the TMAZ can be divided into three regions according to hardness and microstructural differences, as shown in Fig. 4(c) and (d).

*TMAZ-I*

This part of the TMAZ is the partially melted zone and is located at the nugget boundary (coinciding with the green ovals at the perimeter of the nuggets in Fig. 4. It is about 3–4 grains wide for both specimens. It is harder than the nugget but softer than the BM. This region is clearly distinguished in optical metallographs of the specimens, which reveal that a small portion of the eutectic constituents along the grain boundaries are melted during welding and then solidified after welding, resulting in inter-grain dendritic growth in this region, as shown in Fig. 5(c) and (d).