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Influence of variable processing conditions on the quasi-static and dynamic behaviors of resistance spot welded aluminum 6061-T6 sheets

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ABSTRACT

The mechanical properties of the weld regions of a 6061-T6 resistance spot welded lap joint are determined. The change in mechanical properties resulting from RSW are linked to the changes observed in the microstructure. Processing currents and strain rates are varied to probe the effects of processing temperature at strain rates from 10^{-3} to 10^{3} s^{-1}. Results show that material strength decreases within the heat affected zone (HAZ) and fusion zone due to precipitate dispersion. Further, decreased ductility results at quasi-static strain rates from accelerated crack growth arising near voids formed during weld formation, but the short time scale at higher strain rates limits the ability for crack growth from these voids allowing the material to exhibit higher ductility. Overall, significant changes in the mechanical behavior across the weld resulting from a change in microstructure congruent with precipitate dispersion are apparent for all processing conditions.

1. Introduction

More stringent requirements on vehicle performance (e.g., increased fuel efficiency and decreased emissions) in the automotive and defense industries require the implementation of lightweight alloys. However, the commonly employed method of resistance spot welding (RSW) presents a problem in lightweight alloys as the high heat and deformation of the welding process result in complex microstructures that dramatically alter the mechanical properties of these alloys decreasing their effectiveness. Great advances have been made in understanding weld microstructures especially in steels [1–7]; however, lightweight alloys present new challenges and are still limited by gaps in the understanding of the interaction of microstructural changes with the resulting change in mechanical behavior as a result of welding processes in such alloys. Attempts have been made to characterize the effects of welding processes on aluminum alloys, but more work is needed to understand the local change in mechanical properties due to the changing microstructure resulting from the high heat and deformation of welding [3,8–11].

In order to quantify the effects of process-induced microstructural changes on the mechanical properties of RSW joints, researchers such as Zhang and Senkara [12] and Williams and Parker [13] have compiled detailed reviews of several experimental and theoretical studies investigating the mechanical and physical properties of RSW joints, but some questions regarding the link between processing effects on microstructure and mechanical strength throughout the weld still remains open. One such question to be explored here is that of the effect of processing temperature (i.e., current) on the mechanical properties of the individual regions within the weld. However, quantifying the deleterious effects of thermo-mechanical-electrical joining processes (i.e., RSW) on the strength and failure behavior of metal components is a highly complex undertaking. In fact, experimental studies and computational modeling of the RSW processes have received much attention in an effort to ascertain the effects of welding parameters on joint strength and failure [9,11–33]. Following the idealized parameters obtained from these works, welding parameters which follow the MIL-W-6858D military specification are used here as the nominal condition.

Certain mechanical properties of these optimized welds have been thoroughly studied. Specifically, the mechanical strength under shear at quasi-static strain rates has been investigated [9–11,34,35]. These studies indicate that welding parameters do influence the mechanical behavior of these joints, and parameters such as nugget size and plate thickness are crucial to the mechanical performance of the joint under monotonic loading. However, despite the depth of research into RSW, the local mechanical properties (including strength and ductility) across the welded joint and their link with the varied microstructure have only

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received little attention.

Further, despite the possibility for these weld joints to see strain rates in excess of 10^3 s^{-1}, e.g., in the case of a high-speed vehicle crash, the dynamic behavior of these welds has only received little attention. In order to develop material models with higher accuracy, dynamic tests (10^2–10^4 s^{-1}) must be performed to characterize material behavior within a weld. Specifically, as lightweight metals, such as 6061-T6, become more commonly used in automotive structures, the need for mechanical properties of the welded material under dynamic strain rates becomes increasingly important. Also, to our knowledge, shear properties as a function of position throughout the entire weld are not present in the existing literature. However, a systematic characterization of structure-property relationships of the individual sections of welded joints will be an important first step in the path to control mechanical properties through the use of design of experiment approaches (e.g., varying weld process parameters).

To this end, we use a combination of small scale tensile testing at quasi-static (10^{-3} s^{-1}) and high (800 s^{-1}) strain rates, shear punch testing (SPT), hardness measurement, and microstructural characterization including optical microscopy, scanning electron microscopy (SEM) with electron backscatter diffraction (EBSD), and high resolution transmission electron microscopy (HRTEM) to characterize individual microstructural zones within RSW 6061-T6 aluminum lap joints processed with varying currents and develop a structure-property database for use in finite element analyses.

2. Experimental procedures

For this study, a servo-gun with weld control and copper-zirconium alloy electrodes was used to manufacture the specimens from a sheet of 6061-T6 aluminum. The standard composition of the 6061 alloy is seen in Table 1 below. The aluminum sheets were approximately 127 mm long, 38.1 mm wide, and 2 mm thick. The power supply and current transformer used was a mid-frequency direct current power transformer with an 8 V secondary voltage. Water was applied as a cooling agent at a rate of 4 liters/minute. For further detail about the weld sample preparation please refer to [10]. Electrode force (3.8 kN), weld time (0.115 s), and weld current (30 kA) (see [10]) were manually optimized to produce a minimum nugget size of 5.7 mm with minimum shearing force of 3.8 kN per weld. The optimized welds met or exceeded the MIL-W-6858D military specification [36]. The weld parameters are listed in Table 2. The weld current was varied in the values of 26 kA (low condition), 30 kA (nominal condition), and 36 kA (high condition) in order to determine the effects of processing temperature on the microstructure and mechanical properties of the welded joint.

Small, rectangular, dog-bone shaped specimens were cut from the center of the weld nuggets as well as the parent material using wire electric discharge machining (EDM) for both quasi-static and high rate tensile testing. Specimens were cut with gauge length along the rolling direction of the aluminum sheet. Dimensions for these specimens can be found in Table 3. Quasi-static tensile tests were performed at a strain rate of 10^{-3} s^{-1} on an electromechanically driven load frame. No fewer than three tests were run for the weld region and the parent material. Images were taken normal to the fracture surfaces using SEM after the testing was completed. These tests revealed a significant reduction in tensile strength and ductility for the weld section.

High strain rate tests (approximately 800 s^{-1}) were performed on a 7075-T6 Kolsky bar adapted for use under tensile loading. The details of Kolsky bar testing can be found in Gama et al. [37]. For our application, a tensile load was stored on the incident end of the apparatus and released toward the specimen using a breaker pin to rapidly release the clamp that stored the tensile load. This tensile pulse then traveled the remaining length of the incident bar until it encountered the specimen where the pulse split into reflected and transmitted waves. These strain waves give information about the stress and strain in the specimen by

$$\dot{\varepsilon} = \frac{2c_s\varepsilon_R}{l_s} \quad (1)$$

$$\sigma = \frac{A_b E \varepsilon_T}{A_s} \quad (2)$$

where c_s, A_b, and E are the wavespeed, cross-sectional area, and elastic modulus, respectively, of the 7075-T6 bar, l_s and A_s are the gauge length and cross-sectional area of the specimen, respectively, and ε_R and ε_T are the reflected and transmitted strain pulses measured in the incident and transmitted bars, respectively.

SPT utilizing a punch diameter of 1 mm with punch-die clearance of approximately 30 μm was performed at a normalized displacement rate of 10^{-3} s^{-1} through the welds in the rolling, transverse, and normal directions of the original rolled plates. Specimens for SPT were prepared by slicing 1 mm thick sections and mechanically grinding the specimens to a 4000 grit surface finish. The fine finish is intended to reduce roughness induced stress concentrations. The SPT fixture drives a solid cylindrical punch through a thin plate specimen into a hollow cylindrical die. Here, the displacement is normalized by the specimen thickness providing a consistent comparison between the test results [38]. Consecutive tests were spaced approximately 1.5 mm apart from the center of each test indent. The comparison of the mechanical behavior at different sections of the weld region shows the profound effect of the solidification-induced microstructure.

Microhardness tests were also performed through the weld along the transverse direction to verify SPT results and further investigate the role of process-induced microstructure on the material strength. Vickers hardness was measured through the parent material, heat affected zone (HAZ), and fusion zone at points spaced 0.25 mm (0.01 in.) apart. Tensile yield and ultimate strengths correspond to the microhardness by a constant factor that varies as a result of strain hardening in the material [39]. Variability in the strain hardening behavior resulting from the welding process causes the correlation between hardness and tensile strengths to vary throughout the weld. A best estimate of the

Table 2
Welding process parameters.

Electrode force	3.8 kN
Time	0.115 s
Low current	26 kA
Nominal current	30 kA
High current	36 kA
Voltage	8 VDC
Water flow rate	4 L/min

Table 3
Tensile specimen dimensions.

Gauge length	4.75 mm
Gauge width	2 mm
Gauge thickness	2 mm

Table 1
6061-T6 composition.

Chemical composition (in wt%)	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other each	Other total	Al
Max	0.8	0.7	0.4	0.15	1.2	0.35	0.25	0.15	0.05	0.15	Balance
Min	0.4	–	0.15	–	0.8	0.04	–	–	–	–	Balance