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Resistance spot welding of ultrafine grained/nanostructured Al 6061 alloy produced by cryorolling process and evaluation of weldment properties

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ABSTRACT

Resistance spot welding process was used to produce ultrafine grained/nanostructured Al 6061 alloy joints. In this regard, ultrafine grained/nanostructured 6061 aluminum sheets were first produced by cryorolling and then joined by resistance spot welding. For this purpose, the samples were solution treated at 530 °C for 3 h and subsequently cryorolled up to 90% reduction in thickness. In order to improve strength and ductility, the cryorolled sheets were then subjected to ageing treatment. The average size of fine grains of the peak aged alloy reached to ~60 nm. In peak aged condition, an ultimate tensile strength of 365 MPa, a hardness of ~140 HV and a ductility of 11.8% was obtained. The cryorolled, peak aged, and also 6061-T6 Al alloy sheets (witness samples) were then resistance spot welded. Results showed that the cryorolling process can effectively increase the electrical resistivity of Al 6061 alloy. From tensile-shear tests, the highest peak load of spot welds was obtained for the cryorolled specimens. This is due to higher electrical resistivity of the cryorolled samples which increases the nugget diameter and therefore the peak load of the spot welds. A decrease in microhardness was observed in the fusion zone due to dissolution of Mg_2Si strengthening precipitates in this region during welding process.

1. Introduction

Due to the need for lighter and stronger structures, nowadays Al alloys are considered in many manufacturing processes [1,2]. Aluminum 6000 series alloys have wide applications in aerospace and automotive industry because of their very high strength to weight ratio, favorable mechanical properties, weldability, and excellent corrosion resistance [3–5]. Despite the mentioned advantages, these alloys have some disadvantages such as low strength in some applications, poor wear behavior [6], and low thermal stability [7]. Growing demand for improved performance of these alloys has caused to efforts to more enhancing in their mechanical properties [3]. Therefore, development of ultrafine grained/nanostructured material by severe plastic deformation (SPD) methods has been considered for this purpose [8].

Aluminum alloys used in various applications are mainly in the form of sheets or foils [3,9]. Cryorolling is a SPD method that utilizes ultra-cold temperatures (liquid Nitrogen temperature) to modify the microstructure of materials [10,11]. During cryorolling, dislocation density is increased due to suppression of dynamic recovery [8]. Kralia et al. [9] found that the mechanical properties (yield strength, ultimate strength, and hardness) of Al-6063 alloy improve after cryorolling when compared with solution treated bulk alloy. The improvement in the strength of cryorolled alloy is attributed to the effect of higher dislocation density, grain refinement, solid solution strengthening and suppression of dynamic recovery. Also, Panigrahi et al. [3] indicated that solution treatment before cryorolling combined with subsequent ageing treatment (130° C–30 h) can improve tensile strength (362 MPa) and ductility (10.7%) in the Al 6061 alloy. However, Due to the size and shape limitation of SPD processed materials, the application of them for production of large or complex parts is limited. Hence, to develop the application of these materials, joining of them is necessary [12].

The microstructural sensitivity of ultrafine grained/nanostructured materials to temperature increase is a serious challenge in welding of these materials during commonly used fusion welding process [12,13]. Due to short welding times and small molten pool, resistance spot welding (RSW) process can mitigate detrimental microstructural changes. RSW is a rapid joining technique widely used to join sheet metals, especially in the automotive industry [14–16]. There are approximately 6000 spot welds in a modern vehicle. RSW has been employed as an

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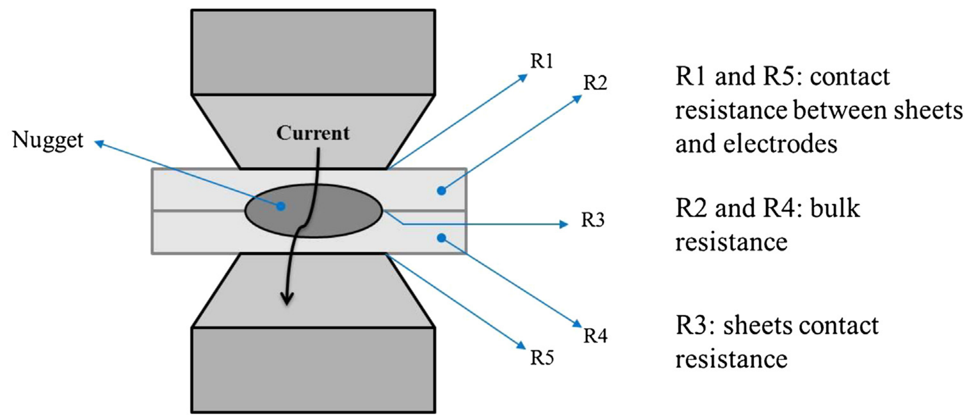

Fig. 1. Schematic of resistance spot welding (RSW) process.

Table 1
Composition of the Al 6061 alloy (wt.%).

Other	Ti	Zn	Cr	Mg	Mn	Cu	Fe	Si	Al
0.15	0.0239	0.0908	0.231	0.975	0.0540	0.279	0.442	0.48	97.27

profitable technique for joining Al alloys in automotive industry, especially in body-in-white construction [5,17]. Some advantages of RSW process are high speed, low cost and the possibility of automation [18–20]. In this process, no filler metal or fluxes are used and the pressure applied by electrodes joins the contacting surfaces via heat obtained from resistance to the electrical current flow (Fig. 1) [21]. Pressure is exerted before, during, and after the flowing of current to inhibit arcing at the faying surfaces and to forge the nugget during post heating. The process needs to a specified cycle time to complete [22]. A heterogeneous microstructure is created in the spot weld and its surrounding region. The fusion zone (weld nugget), heat affected zone (HAZ), and base metal (BM) are the three zones that exist in spot weld and the area around it [18]. Pandy et al. [23] indicated that the welding current is the most significant parameter that controls the weld tensile strength of AISI-1008 steel weldment. Florea et al. [21] showed that the welding current have a great influence on the quality of the RSW joints and the larger current leads to the deeper weld imprints. A strong dependency between the welding parameters and grain size and grain orientation was observed in their work.

Despite studies regarding microstructure and mechanical properties of Al 6061 alloy weldment, there is insufficient information regarding fusion welding of ultrafine grained/nanostructured aluminum. Recently, a great attention has attracted to ultrafine grained/nanostructured materials due to their excellent physical and mechanical properties. In this research, the weld zone properties of ultrafine grained/nanostructured aluminum spot welds are investigated and compared with spot welded joints having conventional grained microstructures.

2. Experimental methods

2.1. Cryorolling process

Al 6061 alloy plates with a thickness of 13 mm were used in this study. Table 1 shows the chemical composition of the plates. These plates were solution treated at 530 °C for 3 h, quenched in water (0 °C) and subsequently cryorolled up to 90% reduction in thickness. The rolling thickness reduction per pass was 5% of the initial thickness. For cryorolling, the solution treated alloy was immersed in liquid nitrogen for 20 min prior to the first rolling pass. The specimen was also immersed in liquid nitrogen for 3 min between consecutive passes. The roll diameter was 125 mm and the rolling speed was 8 rpm. Afterwards, the cryorolled sheets were peak aged at 130 °C for 25 h in order to improve the mechanical properties.

Solution treated (ST), cryorolled (CR), and cryorolled and peak aged (CR + PA) samples were then subjected to hardness and tensile tests to assess strength and ductility. Vickers microhardness (HV) was calculated on the plane parallel to the rolling direction by applying a load of 50 g for 10 s. The tensile test specimens were prepared as per ASTM-E8 sub-size specifications parallel to the rolling direction and the tensile test was performed using a Hounsfield H25KS machine. For identifying the precipitates present in the ST and CR samples, X-ray diffraction (XRD) analysis was conducted by Philips Xpert instrument using Cu Kα radiation. The Williamson-Hall method [24] was used for calculating the grain size of CR and CR + PA samples. Electrical resistivity of CR, CR + PA and T6 samples was measured by standard 4-point probe method. For microstructural characterization of CR and CR + PA samples EM208S transmission electron microscope (TEM) operating at 100 kV was used.

2.2. Resistance spot welding process (RSW)

Cryorolled sheets with a thickness of 1.3 mm were subjected to resistance spot welding process in the as-rolled and peak aged condition. Aluminum and its alloys naturally form a thin surface layer of aluminum oxide (Al_2O_3) on contact with oxygen in the atmosphere. Removing the oxide layer before welding to avoid defects such as incomplete penetration, porosity, and oxide film entrapment is required. Therefore, in order to remove the natural oxide layer, each sheet of aluminum alloy was subjected to mechanical and chemical cleaning. For joining of the sheets, a DC type resistance spot welding machine was used. Water cooled copper-cadmium electrodes with a diameter of 16 mm and face diameter of 7 mm were employed. The welding current was changed from 40 to 100 kA while the electrode force and welding time were kept at 3 kN and 0.1 s, respectively. Also, the conventional-grained 6061-T6 Al alloy sheets of the same thickness of the nanostructured sheets were prepared as witness samples. The witness samples were then RSWed with the above welding parameters as shown in Table 2. Tensile-shear test is a common test for investigating mechanical performance of spot welds under static condition [1,18,21]. The peak load extracted from the tensile-shear test load-displacement curve is usually used to evaluate mechanical behavior of spot welds. Tensile-shear test specimens were prepared according to MIL-W-6858D standard as shown in Fig. 2. A Hounsfield H25ks machine was used for tensile-shear test with displacement rate of 0.01 mm/s.