Resistance Element Welding of Magnesium Alloy/austenitic Stainless Steel

S M Manladan1,2, F Yusof1,2*, S Ramesh1,2, Y Zhang4, Z Luo4,5, and Z Ling4

1 Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
2 Center for Advanced Manufacturing and Materials Processing (AMMP), Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
3 Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano, 3011 Kano, Nigeria
4 School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China
5 Collaborative Innovation Center of Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China

E-mail: farazila@um.edu.my

Abstract. Multi-material design is increasingly applied in the automotive and aerospace industries to reduce weight, improve crash-worthiness, and reduce environmental pollution. In the present study, a novel variant of resistance spot welding technique, known as resistance element welding was used to join AZ31 Mg alloy to 316 L austenitic stainless steel. The microstructure and mechanical properties of the joints were evaluated. It was found that the nugget consisted of two zones, including a peripheral fusion zone on the stainless steel side and the main fusion zone. The tensile shear properties of the joints are superior to those obtained by traditional resistance spot welding.

1. Introduction
Multi-material design is an efficient way to reduce the weight of vehicle structures, improve crash-worthiness, balance cost, and reduce environmental pollution [1]. Magnesium alloys and stainless steels have been identified as excellent materials for the next generation vehicles. Mg alloys possess remarkable properties such as superior specific strength, high elastic modulus, hot formability, good cast ability, and recycle ability [2, 3]. On the other hand, austenitic stainless steels (ASS) have excellent combination of corrosion resistance, decorative appearance and mechanical properties, such as high strength, unique work-hardening behavior, superior energy absorption ability, and high formability. They are commonly used in construction of the body frame of buses and passenger rail vehicles [4]. Furthermore, the next generation vehicle project shows that ASSs can replace carbon steels in crash-relevant components, thereby reducing weight without compromising vehicle crash-worthiness [5].

With the growing interest in multi-material design and the fact that both Mg alloy and ASSs are increasingly attracting attention in the transportation industry, it is imperative to develop an efficient technique to join them in dissimilar combination. The main sheet joining technique in the transportation industry is resistance spot welding (RSW) because it is inexpensive, easy to operate and automate, fast and reliable, etc. [6, 7]. However, it is difficult to join Mg alloy to steels by RSW because of large differences in physical and metallurgical properties [8]. A variant of RSW, known as resistance element welding (REW) was recently developed for joining dissimilar steel/light alloys.
combinations that are metallurgical incompatible and difficult to weld together [9]. The techniques involve punching a technological in the light alloy and inserting a steel rivet (an auxiliary element) into the hole, followed by RSW on the rivet/steel [10, 11]. So far, it has been used to join Al alloys to steels [10, 11] and AlSi-coated 22MnB5 steel to LITECOR® [12]. The mechanical performance of the joints obtained using this technique was found to be superior to those obtained by traditional RSW [10, 11].

This technique has not yet been applied to join Mg alloy to steel. Owing to the industrial importance of Mg alloy and ASS, the present study investigates the microstructure and mechanical properties of dissimilar Mg alloy/ASS joints. Traditional RSW was also conducted to compare the mechanical performance of the joints.

2. Experimental Procedure

The materials used in this study were 1.5 mm thick AZ31 Mg alloy and 0.7 mm thick AISI 316L ASS. Both materials were cut into rectangular specimens (100 x 25 mm) in accordance with AWS D17.2 Standard [12], and alcohol was used to clean all the specimens. In addition, abrasive paper was used to grind the surfaces of the Mg alloy specimens in order to remove surface oxides. A hole with diameter of 5 mm was punched at the center of the overlap area of the Mg alloy, and Q235 steel rivet was inserted into the hole as shown in Figure 1.

![Figure 1. Schematic illustration of (a) REW process and (b) tensile shear test specimen.](image)

The welding process was conducted using a 220 kW, medium-frequency direct current RSW machine with a capacity of 2–22 kA welding current. Asymmetrical electrodes were used with the aim of improving the heat balance [13]. A spherical electrode (50 mm sphere radius, 20 mm face diameter) was used on the Mg alloy side and a truncated cone electrode (10 mm tip diameter) was used against the rivet. Both electrodes were made of copper alloy (RWMA class II). The welding current was varied from 5-9 kA in 1 kA increment while the welding time and electrode force were kept constant at 250 ms and 3.6 kN, respectively.

For metallographic studies, samples were cut at the center of the joints, ground and polished in accordance with standard metallographic procedures. The Mg side was etched with a solution of 5 g picric acid, 10 ml H₂O, 5 ml acetic acid, and 100 ml ethanol. A solution 4% nital was used to etch the Q235 steel side while a solution of 10 g FeCl₃, 30 ml HCl, and 120 ml H₂O was used to etch the ASS side. The macrostructural and microstructural observations were conducted with an Olympus SZX12 stereomicroscope and Olympus GX51 microscope, respectively. Hardness tests were conducted under a load of 200 g and a dwell time of 15 s using Huayin HV-1000A Vickers micro-hardness tester. A CSS-44100 material testing system was used to conduct tensile shear tests at a cross-head speed of 2 mm/min. The samples configurations are shown in Figure 1. Three samples were tested for each
welding condition and the average was evaluated. Fractography was conducted using a Hitachi SU1510 scanning electron microscope (SEM).

3. Results and Discussion

3.1. Macrostructures and microstructures

The typical macrostructure of the REW joint is shown in Figure 2 (a), and it can be seen that an asymmetrical nugget was obtained. The final solidification line and the larger part of the nugget are in the Q235 steel rivet. The formation of asymmetrical nugget can be attributed to the differences in electrical resistivity and thermal conductivity. The nugget can be divided into two zones, namely, peripheral FZ (FZ1) and main FZ (FZ2), as shown in Figure 2 (b). The peripheral FZ, as shown in the figure, formed only on the ASS side. Two-zone nugget formation during RSW involving ASSs was attributed to the differences in volume fraction of delta ferrite between the main nugget and the periphery [14]. The solidification mode in ASS RSW occurs in ferrite-austenite (FA) mode, as follows [14]:

\[
L^I \rightarrow L + \delta^I \rightarrow L + \delta + \gamma^III \rightarrow \delta + \gamma
\]

The microstructure of the base metal (BM), which is austenitic, transforms into austenite and intercrystalline delta ferrite. As a result of higher cooling rate at the periphery because of its closeness to the water-cooled electrodes, there is limited time for stage III reaction to occur. Therefore, the delta ferrite volume fraction is higher in the periphery.

![Figure 2](image-url)

**Figure 2.** Macrostructure and microstructure of REW joint (a) macrostructure, (b) higher magnification of region B in (a), (C) microstructure of region C in (b), and (d) microstructure of region D in (b).
Figure 3 shows the microstructures in the heat affected zone (HAZ). As shown in Figure 3 (b), the HAZ can be divided in two different zones, namely; (i) the upper-critical HAZ (UCHAZ): the maximum temperature that is attained in this zone is above $A_{c3}$, and the BM completely transforms into austenite. As a result of the fast cooling rate inherent in RSW, the austenite transforms into martensite after cooling. (ii) inter-critical HAZ (ICHAZ): the peak temperature reached in this zone is between $A_{c1}$ and $A_{c3}$, and the BM microstructure transformed into a mixture of ferrite and austenite. After cooling, the austenite transformed into pearlite while the ferrite is retained. Thus, the microstructure consisted of a mixture of ferrite and pearlite (Figure 3 (c)). The BM microstructure also consisted of ferrite and pearlite (Figure 3 (d)), but the volume fraction of the pearlite is less than that of the ICHAZ.

As shown in Figure 3 (d), the microstructure of the BM can be divided into BM1 (rivet shank) and BM2 (rivet cap). Both consisted of ferrite and pearlite. However, BM2 grains are deformed because of coldworking.

![Figure 3. HAZ and BM microstructure of the Q235 steel rivet: (a) microstructural gradient, (b) higher magnification of region B in (a), (c) higher magnification of region C in (a), and (d) BM microstructure.](image)

### 3.2. Hardness characteristics

The typical hardness profile of the REW joint is shown in Figure 4, indicating microstructural gradient across the weldment. The average hardness value of FZ2 is 401.3 HV, and that of FZ1 is 331.5HV. The high hardness value of FZ2 has been associated with some martensitic transformation [15]. An average hardness value of 427 HV, 282.3 HV, and 244.3 HV is obtained in the UCHAZ, ICHAZ, and BM respectively. The highest hardness value of 448 HV is obtained in the UCHAZ, close to FZ2. The average hardness of the BM2 is 331.5 HV and that of BM1 is 244.3 HV. An average hardness value of 197 HV is obtained for ASS HAZ, which is lower than the hardness of the BM (212 HV). This hardness reduction is attributable to the loss of work hardening in the BM.
3.3. Tensile-shear performance

Figure 5 shows the influence of welding current on the nugget diameter, energy absorption and peak load of the joints produced by REW. It can be seen that as the welding current is increased from 5 to 8 kA, the peak load and energy absorption increased from 1.85 kN and 2.85 J to 3.71 kN and 10.19 J, respectively. This increase in peak load and energy absorption is as a result of increase in nugget diameter. However, when the welding current was increased to 9 kA, the peak load and energy absorption dropped significantly despite the increase in nugget diameter. This is because the Mg alloy around the rivet melted excessively at this welding current, leading to the widening of the rivet hole.

For the purpose of comparison, joints were also produced using traditional RSW. The peak load obtained by REW is 3.71 kN and that obtained by RSW is 2.3 kN. The energy absorption for REW is significantly higher, which is very important for passenger safety in the event of a crash. The maximum energy absorption obtained by REW is 10.2 J while that obtained by RSW is 1.14 J. In addition, the REW joints were obtained at lower welding currents. The peak load and maximum energy absorption are significantly higher for REW compared to RSW.
The REW joints failed in interfacial failure (IF) mode at a welding current of 5 kA. With further increase in welding current, pullout failure (PO) mode, which has higher energy absorption, occurred. Figure 6 (a) and (b) show the fracture surfaces of the joints that failed in IF mode, which has a quasi-cleavage (combined ductile and brittle) characteristics. The PO mode fracture surface (Figure 6 (d)) has larger and deeper dimples, which indicate a ductile fracture.

4. Conclusion
The present study investigated the microstructure and mechanical properties of dissimilar joints between 1.5 mm AZ31 Mg alloy and 0.7 mm 316L ASS produced by REW processes. Traditional RSW joints were also produced to compare the mechanical performance. The following conclusions can be drawn:

- A two-zone nugget, consisting of a peripheral FZ on the stainless steel side and the main nugget at the rivet/stainless steel interface, was formed. Both the peripheral FZ and the main FZ consisted of austenite and inter crystalline delta ferrite.
- The mechanical performance of the REW joints is superior to that of traditional RSW joints.
- The failure mode of the REW joints changed from IF to PO with increase in welding current.

Acknowledgement
The authors would like to acknowledge University of Malaya, Malaysia and Tianjin University, China for providing the resources and facilities for this research. This research is funded by the Postgraduate Research Fund (PPP) with Grant No: PG020-2015A and University Malaya Research Grant (UMRG) with Grant No.: RP035A-15AET.

References
[1] Haddadi F 2016 Microstructure reaction control of dissimilar automotive aluminium to galvanized steel sheets ultrasonic spot welding Materials Science and Engineering: A 678 72-84
[2] Babu N K Brauser S Rethmeier M and Cross C 2012 Characterization of microstructure and deformation behaviour of resistance spot welded AZ31 magnesium alloy *Materials Science and Engineering: A* **549** 149-156

[3] Manladan S Yusof F Ramesh S and Fadzil M 2016 A review on resistance spot welding of magnesium alloys *The International Journal of Advanced Manufacturing Technology* **865** 1805-1825

[4] Pouranvari M Khorramifar M and Marashi P 2016 Ferritic-austenitic stainless steels dissimilar resistance spot welds: metallurgical and failure characteristics *Science and Technology of Welding & joining*

[5] Schuberth S Schedin E Frohlich T and Ratte E 2008 Next generation vehicle engineering guidelines for stainless steel in automotive applications 6th *Stainless Steel Science and Market Conference* Helsinki, Finland: The Swedish Steel Producers’ Association

[6] Behravesh S Bahed H and Lambert S 2011 Characterization of magnesium spot welds under tensile and cyclic loadings *Materials & Design* **3210** 4890-4900

[7] Manladan S Yusof F Ramesh S Fadzil M Luo Z and Ao S 2017 A review on resistance spot welding of aluminum alloys *The International Journal of Advanced Manufacturing Technology* **901** 605–634

[8] Liu L Xiao L Chen D Feng J Kim S and Zhou Y 2013 Microstructure and fatigue properties of Mg-to-steel dissimilar resistance spot welds *Materials & Design* **45** 336-342

[9] Holtschke N and Jütter S 2016 Joining lightweight components by short-time resistance spot welding *Welding in the World* 1-9

[10] Ling Z Li Y Luo Z Feng Y and Wang Z 2016 Resistance Element Welding of 6061 Aluminum Alloy to Uncoated 22MnMoB Boron Steel *Materials and Manufacturing Processes* just-accepted

[11] Qiu R Wang N Shi H Cui L Hou L and Zhang K 2015 Joining steel to aluminum alloy by resistance spot welding with a rivet *International Journal of Materials Research* **1061** 60-65

[12] AWS 2007 Specification for resistance welding for aerospace applications D17.2 *American Welding Society*

[13] Liu L Xiao L Feng J C Tian Y H Zhou S Q Zhou Y 2010 The Mechanisms of Resistance Spot Welding of Magnesium to Steel *Metallurgical and Materials Transactions A* **41** (10) 2651-2661

[14] Pouranvari M Alizadeh-Sh M and Marashi S 2015 Welding metallurgy of stainless steels during resistance spot welding Part I: fusion zone *Science and Technology of Welding and Joining* **206** 502-511

[15] Marashi P Pouranvari M Amirabdollahian S Abedi A and Goodarzi M 2008 Microstructure and failure behavior of dissimilar resistance spot welds between low carbon galvanized and austenitic stainless steels *Materials science and engineering: A* **4801** 175-180