Int J Adv Manuf Technol (2017) 91:2257–2265
DOI 10.1007/s00170-016-9928-y

ORIGINAL ARTICLE

Magnetic pulse welding of aluminum to steel using uniform pressure electromagnetic actuator

Haiping Yu [1,2] · **Yanchen Tong** [1]

Received: 10 August 2016 / Accepted: 18 December 2016 / Published online: 31 December 2016

Abstract The joining of dissimilar metals is required for lightweight structures. The efficient and mechanically robust uniform pressure electromagnetic actuator (UPEA) was used to magnetic pulse welding (MPW) dissimilar metal sheets in this study. This study explored the feasibility of MPW of AA 1060 to Q235 steel sheet. The effects of discharge voltage, vertical gaps between two sheets, and the effect of the width of the joining zone on the connection quality were investigated. The metallurgical joints were obtained under a discharge voltage above 9.5 kV, and the weldability window of AA1060 to Q235 steel sheets was established. Microstructure observations of the MPW joint revealed that the interface of the joint is close to flat. EDS mapping showed mutual diffusion of basic elements across the interface.

Keywords Magnetic pulse welding · Sheet · Dissimilar metals · Weldability window · UPEA · Aluminum · Steel

1 Introduction

Currently, lightweight materials and structures are inevitable trends in the development of future car manufacturing. Among them, aluminum alloy sheets are widely used to form covering parts. However, with the development of smelting and rolling technology, steel sheets are still the main material to produce the white body of cars. Therefore, the connection of aluminum sheets to steel sheets is inevitable [1]. The combination of steel and aluminum sheets combines the advantages of two different metals, which can save material, reduce weight, and extend the functionality of the single material component. The hybrid material, lightweight structures can improve fuel efficiency and reduce exhaust pollution. However, due to significant differences of physical and chemical properties of these two basic materials, brittle intermetallic compounds are easily generated by traditional welding methods within the interface, where the stress gradient is maximal. Therefore, it is hard to obtain joints with high strength and high sealing performance.

So far, several methods have been investigated to join steel with aluminum sheets, such as riveting, bolting connections, self pierce riveting, and friction stir welding. Traditionally, in the process of mechanical clinching, steel and aluminum sheets are joined by local hemming with a punch and die [2]. Although mechanical clinching has the advantage of being a simple process, the structure is heavy and the strength is low. The strength of joints is also low in the process of adhesive bonding. Bolt connection is a conventional process for joining two or more sheets via bolts. In the process of bolt connection, airtightness is insufficient for the use of workpieces. Briskham et al. (2006) reported the fabrication of automobile body panels via spot friction joining, which is characterized by extended processing times for thick materials, generating an intermetallic compound around the interface of the joints [3].

Magnetic pulse welding (MPW) is a high-velocity impact welding process for joining either two similar or two dissimilar metals via electromagnetic forces. It is an

✉ Haiping Yu
haipingy@hit.edu.cn

1 School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

2 National Key Laboratory for Precision Hot Processing of Metals, Harbin Institute of Technology, Harbin 150001, China

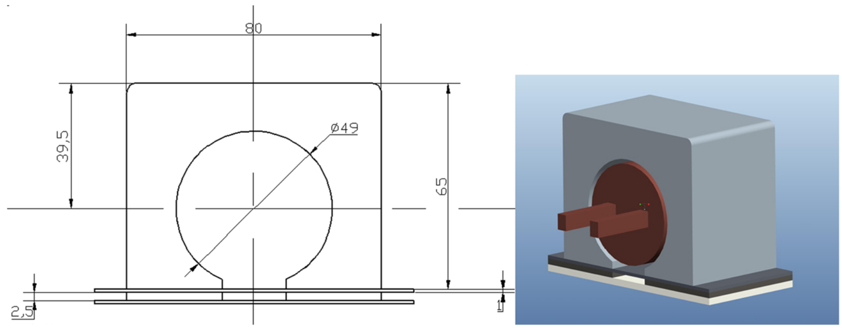


Fig. 1 Dimension and schematic diagram of the UPEA

environmentally friendly and cost-effective process of combining the advantage of joining at lower cost, resulting in higher strength, and reduced weight of dissimilar metals [4, 5]. Furthermore, MPW generates no pollutants, such as fume, spatter, and heat. Jassim et al. compared MPW with other welding methods and summarized that MPW is a green process, which can be achieved without any heat affect zone and thus build light structures with high strength, consequently reducing weight and required energy [5]. Zhang et al. (2011) reported that joints generated by high-velocity impact could restrain the formation of intermetallics [6]. Aizawa et al. [7] investigated the application of steel and aluminum alloy sheets jointing and reported the process parameters. In their experiments, they designed a new coil, which is a one-layer E-shaped flat coil to improve the quality of joints. Geyer et al. noted that process parameters, such as charging and standoff distance, have a strong influence on the magnetic pulse welds and that perpendicular grooves enhance joint performance [8]. Kore et al. [9] welded copper (Cu) to stainless steel (SS) sheets by electromagnetic (EM) impact technique, and the tensile shear strength test and the metallographic studies were investigated for Cu-to-SS EM welds. Therefore, MPW is an effective way to join dissimilar metal sheets and can potentially reduce the weight of the resulting workpiece.

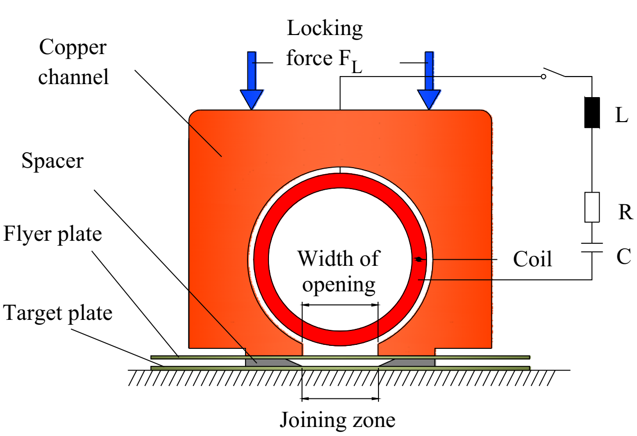


Fig. 2 Schematic of MPW with UPEA

Joints of dissimilar metals with high strength and good airtightness can be achieved via MPW technology. A variety of disadvantages of conventional joining techniques can be overcome by MPW, such as the existence of heat-affected zones near the interface, high productivity, no need to fill material (solder) and associated problems, and no need for protective gas. MPW is an environment friendly joining technique.

It is desirable and necessary to join different metal sheets to improve fuel consumption and to reduce the weight of automobiles. Since aluminum and steel are used for lightweight designs, automobiles have an extensive requirement of aluminum and steel sheets, e.g., automobile body panels are often composed of steel sheets. Here, aluminum can be employed to partly replace the steel to decrease the weight, while retaining strength. However, it is difficult to weld both dissimilar materials due to the low melting point of aluminum and the high melting point of steel. This results in an urgent need to explore a new combination technology of aluminum and steel sheets.

The vertical spacing between both sheets to be welded is called “air gap” and is one of the main parameters for the MPW process. Manogaran et al. [10] used a single-turn coil to join AA1199 aluminum sheet with EN355 steel sheet. In contrast to multi-turn coil joining, the process with a single-turn coil required a higher discharge power. Nassiri et al. [11] observed a wavy pattern interface between the basic materials, which is similar to the results shown in [10].

Lee et al. [12, 13] achieved lap jointing of low carbon steel (SPCC)/A6111 aluminum alloy sheets via the MPW method. The joint interface showed a wavy morphology similar to that of explosive welding. The transition zone

Table 1 Parameters of coil

Materials	Axial length, mm	Turns	Outer diameter, mm	Turn’s cross-section, mm^2
Copper	49	9	47	5×7

of joints is characterized by fine aluminum grains (around 100 nm in diameter), which can be seen via TEM.

In contrast to utilize a single-turn coil [10–13], a uniform pressure electromagnetic actuator (UPEA) was used in this study that has multiple turns and can generate uniform pressure over the area waiting for joining during the MPW process [14, 15]. This is beneficial to form a homogeneous joining zone. Furthermore, it reduces the requirements of MPW equipment. Therefore, UPEA is more beneficial than a typical single-turn coil for MPW of dissimilar metal sheets. In 2014, Weddeling et al. [14] used UPEA to join the same type of aluminum sheets and obtained a metallurgical joint. So far, there have been few investigations on the effect of electric as well as structural parameters (the vertical spacing and the width of joining zone) of the welding joint qualities of dissimilar metals via UPEA. This study explored the possibility to attain a metallurgical joint between AA 1060 and Q235 steel sheets via MPW with UPEA, focusing on the effects of several key parameters on the welding result. A tensile shear test was carried out to validate the joint strength of AA1060 to Q235 steel sheets and a weldability window was established. Morphology and microstructure of the interface were observed and analyzed.

The coil used in the process of magnetic pulse welding was a single turn, which lowered the energy usage rate and induced an uneven Lorentz force above sheets, restricting and impairing the equipment. Thus, the authors used multi-turn coils to join the aluminum and steel sheets via magnetic pulse welding. The UPEA generates a very uniform pressure on the joining sheets in the process of MPW.

In the present work, the authors use the advantages of MPW technology to join aluminum and steel sheets via UPEA. The effects of main process parameters, such as gap, width of joining zone, and discharge voltage on welding quality, were analyzed, and the weldability window was defined by varying gaps and discharging voltage for the welds. The authors furthermore investigated the microstructure of the interface and evaluated the mechanical properties of the joints via tensile shear test.

2 Experimental details

The main part of MPW equipment is a 100-μF capacitor, with a maximum charging voltage of up to 20 kV and a stored energy of up to 20 kJ. The equipment discharges energy through a 5 mm × 7 mm, nine-turn coil made of copper strip. The coil inserted inside the channel.

Aluminum 1060 and mild steel Q235 were used for this investigation. The aluminum sheet has a length of 100 mm and a width of 50 mm, with a thickness of 0.8 mm. The mild steel sheet has the same length and width with a thickness of 1.0 mm.

Figure 1 shows the dimension and schematic diagram of UPEA. It can be seen that UPEA with an inner diameter of 49 mm is made of 80 × 50 × 65 mm brass.

The induced current flows in a closed circuit formed by the brass and aluminum sheet; hence, it is important that the brass and aluminum sheet keep close contact in the process of MPW. The contact surface of brass was polished by abrasive paper and cleaned with absolute ethanol and acetone. The surface prepared for experimental plan of steel sheet was also cleaned with the same method.

The process parameters, which are key factors affecting the quality of joining, include the discharge voltage, the width of the joining zone, and the gap between flyer sheet and target sheet. The discharge voltage determines output energy and further influences the impact velocity, which is a main factor deciding whether the joint will be formed or not. The width of the joining zone directly affects the length of the joint and the deformation behavior of the sheet in the process of collision. The acceleration of flyer sheets varies with the distance between flyer sheet and target sheet, which means that the gap will have an impact on the collision velocity of the sheet.

The experimental setup for MPW is shown in Fig. 2, including UPEA, locking setup, and spacer. The UPEA consists of a solenoid coil and an eddy current channel. The channel has an opening on one side opposite of the flyer sheet. The robust channel and flyer sheet compose a closed path for the eddy current under the locking force. Due to a transient discharge of the capacitor bank, a

Table 2 Performance parameters of A1060 aluminum sheet and Q235 steel sheet

Material	Yield strength, MPa	Tensile strength, MPa	Density, kg/m^3	Resistivity, Ω·m
1060	40	123	2700	2.83×10^{-8}
Q235	235	376	7870	1×10^{-7}

Fig. 3 Magnetic pulse welding setup with UPEA

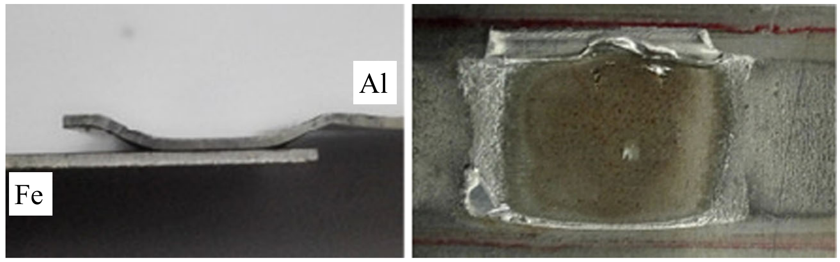


Fig. 4 MPW samples

damped high current runs through the coil that generates a magnetic field around it. The magnetic field induces a secondary current flowing through the channel and flyer sheet. Then, Lorentz force generated between both sheets drives the flyer sheet to accelerate and deform. Therefore, the flyer sheet collides with high velocity with the target sheet and forms a metal-to-metal impact contact. The coil windings are the primary current path. The channel and flyer sheet constitute a secondary loop for eddy current. According to the principle of magnetic pulse welding technology, the flyer sheet will be accelerated up to speed of several hundred m/s. The eddy current channel realizes adequate electrical contact between channel and flyer sheet under locking force F_L. Compared with the existing MPW setup of sheets, the main advantage of this setup is to produce a uniform magnetic pressure in the joining zone, which makes it easy to obtain high quality of the joint. The parameters of the coil are listed in Table 1.

The materials used in these MPW experiments are AA1060 and Q235 steel sheets, and their parameters are shown in Table 2. AA1060 has properties of corrosion resistance, electrical and thermal conductivity, as well as weldability, while steel Q235 is widely used in the manufacture of structural parts due to its excellent mechanical properties. The flyer sheet is AA1060 sheet, and the fixed and target sheet is Q235 steel. To ensure uniformity of AA1060, it was annealed at temperatures of 400–420 °C for 0.5 h. The joining zone of both sheets was polished and cleaned via sandpaper and anhydrous ethanol before trial. The dirt, impurity, and oxide film of the surface were removed. The experimental setup used is shown in Fig. 3.

The joint of the aluminum steel sheet was tested via tensile test to evaluate the bond strength, as shown in Fig. 4. The gap was 1.5 mm, and the width of joining zone was 15 mm for different discharge voltages.

The specimens used for tensile test has a length of 100 mm and a width of 50 mm with varied vertical gap and joining zone width and were tensioned by tensile testing machine at a speed of 2 mm/s.

Changing discharge voltage can vary the impact velocity, and the collision angle depends on the flyer material properties, flyer thickness, as well as gap and width. The degree for a MPW joint ranges from 5 to 15° [12, 13].

3 Results and discussion

3.1 Mechanical properties

Figure 4 shows a cross-section of the MPW joint and a vertical view of the welding zone. The maximum tensile force of the joint is 2.83 kN, and the tensile strength of the joint is 71 MPa, as shown in Fig. 5. This tensile strength value is not the tensile strength of the joint in case of fracture within the aluminum sheet rather than the connecting zone. The results reveal that the joint strength is higher than the strength of the weaker parent metal after MPW process. Because of the intense deformation occurring in the flyer sheet during the MPW

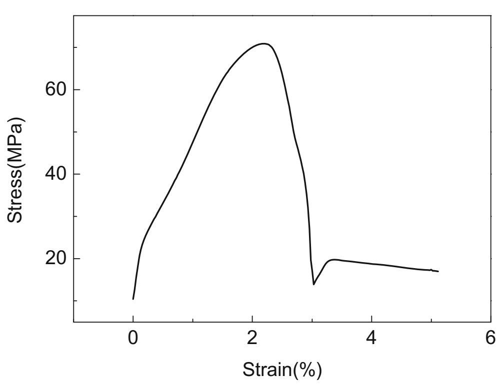


Fig. 5 Load-displacement curve

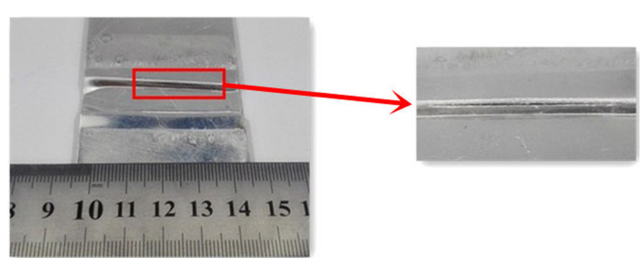


Fig. 6 Cracks in the parent sheet

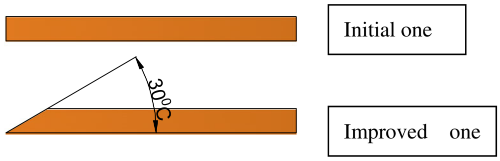


Fig. 7 Schematic of partition

process and defects produced within it, the flyer sheet within joint fractures at low tensile load.

The initial partition used in the experiment has a vertical edge, which led to a crack of the flyer sheet, as shown in Fig. 6. This suggests that the deformation in the edge region is more severe than its adjacent region in one process of the MPW. To improve this situation, the improved partition was used, as shown in Fig. 7. The improved partition has one region with a tilt angle of 30° and provides a transition zone for the deformation of the flyer sheet. All other experiments were performed based on the improved clapboard structure.

3.2 Effects of process parameters

The input energy during MPW can be adjusted via discharge voltage. Hence, the magnetic pressure Pm (t) acting on flyer sheets changes accordingly, as shown in Equation (1). The higher the discharge voltage, the higher the pressure.

$$p_m(t) = \frac{\mu}{2}\left(\frac{A_{coil}}{A_{coil}+A_{gap}}\right)^2 \frac{U^2C}{L_e}\left(1-e^{-\frac{2x_d}{\delta}}\right) \tag{1}$$

Where p_m is the Lorentz force (Pa), μ is the magnetic permeability (H/m), N represents the turns of the coils, A_{coil} is the area enclosed by conductor (m^2), A_{gap} is the area of gap between coil and channel or sheet (m^2), δ is the skin depth (m), $I(t)$ is the current in the reduced RLC-circuit (A), and x_d represents the thickness of the workpiece (m). Some parameters were given in Table 3.

MPW experiments were performed under conditions of 1.5 mm vertical gap and 15 mm joining zone width. Results indicate that the joint is easy to stretch to separate at low discharge voltage, and when the discharge voltage increases to 9.5 kV, the tensile fracture occurred in the

Table 3 Value of the parameters

Magnetic permeability, μ	$4\pi \times 10^{-7}$ H/m
The number of the coils, N	6
The area, A_{coil}	1735×10^{-6} m^2
The area of gap, A_{gap}	204×10^{-6} m^2

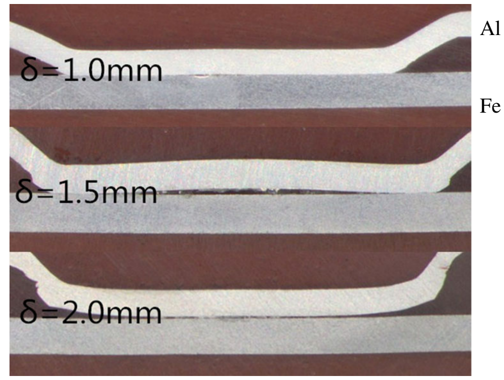


Fig. 8 Cross-section of the joint under different gaps

transition zone of the aluminum sheet near the joining zone.

The gap between the sheets plays a critical role in influencing the quality of the joint. The appropriate gap contributes to achieving an acceptable joint. However, there is a minimum value of the gap, which may be associated with the mechanical properties and geometric dimensions. If the gap is insufficient, the flyer will be accelerated to a velocity that provides an inadequate collision pressure for bonding. Then, metallurgical bonding cannot be obtained. However, if the gap is too large, the flyer sheet will accelerate to the maximum velocity and then begin to slow down. In this situation, the collision pressure is also insufficient to form metallurgical bonding, as illustrated in Fig. 8. The used conditions were 10 kV discharge and 10 mm width of joining zone.

Further experiment was performed to investigate the influence of the joining zone width during the process of MPW. The discharge voltage was 10 kV, and the gap was 1.5 mm, while the joining zone width varied from 5, 10 (as shown in Fig. 8), 15, and 20 mm, as illustrated in Fig. 9. Typical failure modes were observed, such as rib and bubble (shown in Fig. 9.) as well as hole (shown in Fig. 10). An excessive joining zone width was considered to be the cause of an uneven surface. If the width

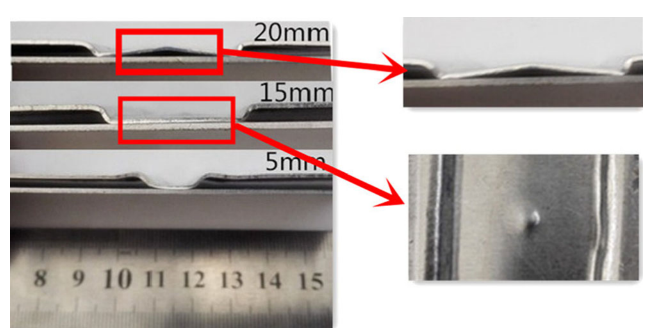


Fig. 9 Cross-section and failure modes under different joining zone widths

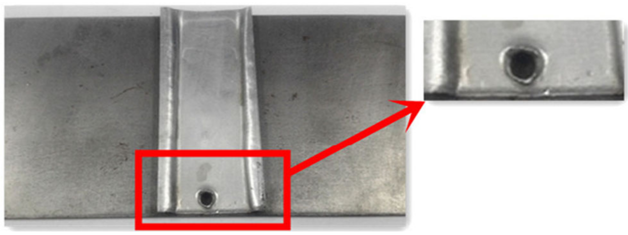


Fig. 10 Bubble bursts forming a hole

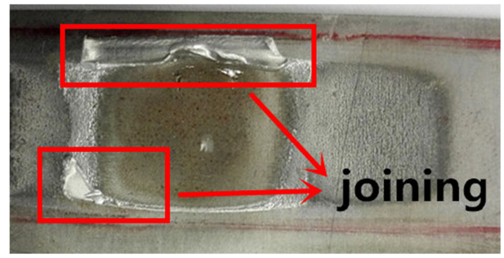


Fig. 12 Top view morphology of the weld interface

exceeded a specific value (15 mm), the rib and bubble form in the surface and the flyer sheet burst into a hole. This phenomenon is caused by a large amount of air in the joining zone producing air pressure during the MPW process.

The welded joint of the aluminum steel sheet was pulled off for discharge voltages below 9.5 kV, indicating that the tensile strength of the joint is lower than that of the parent metals. When the discharge voltage was up to 9.5 kV, the MPW joint under tensile loads began to break on the Al sheet, revealing that the strength of the welded joint is higher than the weaker parent material. Furthermore, similar results were obtained with the rising voltage. However, it is hard to obtain the true joint strength.

The joint of aluminum and steel sheets not pulled off was peeled artificially. The welded joint was fixed at one end, and pliers were used to pull at the other end by force so that the aluminum sheet either broke or separated from the steel sheet. The result is shown in Fig. 11, which reveals that at the edge of the joint, there were white impact marks on the surface of the target sheet. With increasing discharge voltage, the white mark tended to be brightened, indicating that impact velocity gradually improved via high discharge voltage.

When the discharge voltage reached 10.5 kV, the samples became hard to strip. It can be clearly seen that the white linear traces prolonged and the metal bonding on the steel sheet increased significantly. It can be concluded that the increasing input voltage contributed energy to the improvement of the collision speed between the flyer and the target sheet. The impact became violent at a discharge voltage above 9.0 kV and aluminum and steel sheets began to be welded.

Figure 12 shows the top view morphology of the weld interface. The joining between both sheets mainly occurred in the loop edge rather than in the middle part of the initial joining zone. For the MPW process, the appropriate combination of impact velocity and impact angle between both sheets is the key factor to obtain a metallurgical joint. In this study, the angle was 0° in the middle of the joining zone at the start of collision, which is not suitable for a successful weld joint. At the edges of the joining zone, the collision angle can reach the lower limit for welding, as shown in Fig. 13.

3.3 Weldability window

The weldability window can present process parameters affecting the quality of joining and has a practical guidance for production. MPW experiments were performed by changing the process parameters (discharge voltage, vertical gap, and joining zone width), and the joint quality was evaluated by artificial stripping. All MPW results were analyzed and then added to a data sheet, where discharge voltage was used as the ordinate and vertical gap as the abscissa. The weldability windows of aluminum and steel sheet under different width of joining zone are shown in Fig. 14.

Weddeling et al.[14] reported that the magnetic pressure that acts on the flyer would change with discharge voltage when the other parameters were kept constant

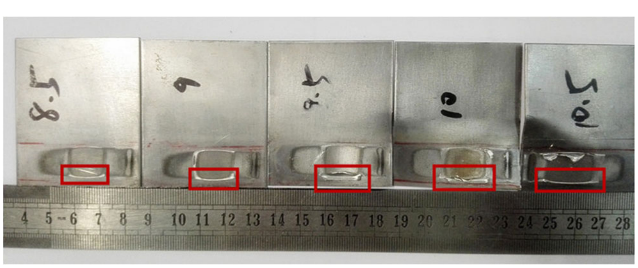


Fig. 11 MPW samples after tensile tests under varied voltage

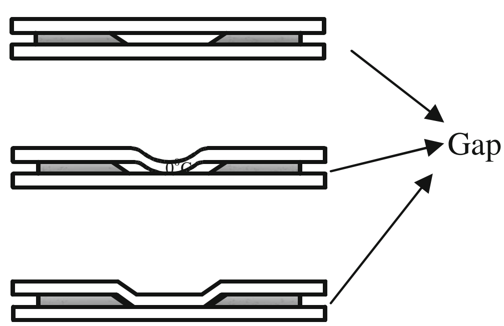
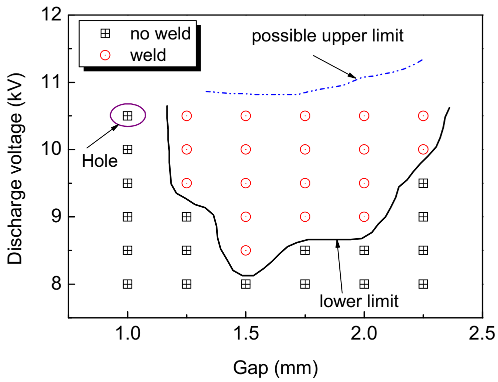
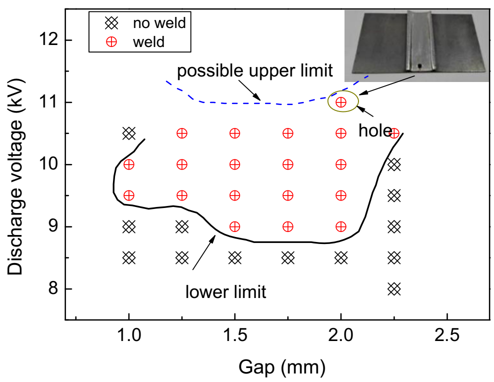


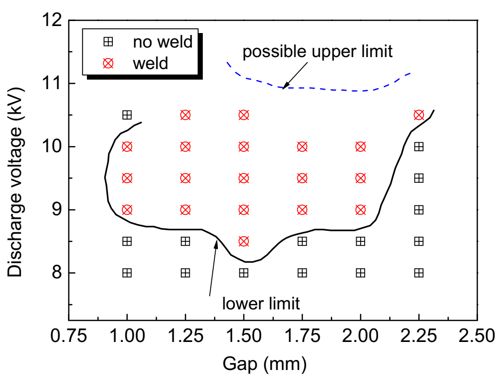
Fig. 13 Process of MPW of sheets



(a) Weldability window with 20 mm joining zone



(b) Weldability window with 15 mm joining zone



(c) Weldability window with 10 mm joining zone

Fig. 14 Weldability windows

during the MPW process. When the magnetic pressure exceeds the yield strength of the sheet, plastic deformation of flyer sheet occurred and started to move [14]. The flyer sheet can achieve a high impact velocity in a short period of time, and a metallurgical interface can be obtained via impact on the target sheet. Consequently, the discharge voltage has a minimum value. A vertical air gap, which provides the accelerating space for the flyer sheet, is needed to generate the impact velocity required to produce welds. Different voltages correspond to the

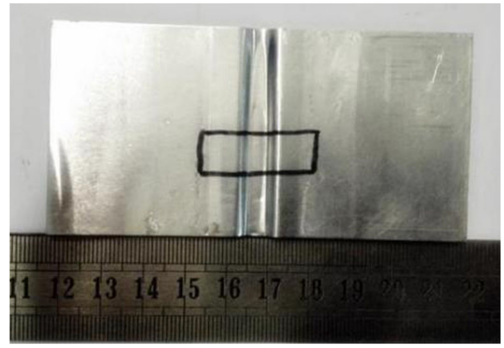
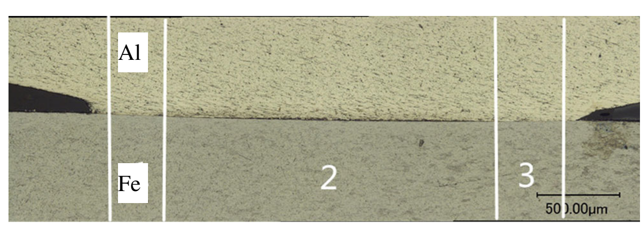


Fig. 15 Sample of aluminum steel sheet welding (discharge voltage of 9.5 kV, gap of 1.5 mm and the width of joining zone of 10 mm)

varied gap of sheets, and the metallurgical joining formed within a certain scope of both factors. Therefore, the combination of discharge voltage and vertical gap composed a suitable parameter range for the metallurgical MPW joint of AA1060 and Q235 sheets. It is shown in Fig. 14, where the lower limits of the windows are illustrated. The width of the joining zone will influence the collision angle between both connection sheets and then the joining quality at the loop edge of the joining zone. From these experimental results, the width (above 15 mm) might be too large to form air bubbles and easily ribs in the middle of joining zone. The air bubbles even burst into a hole if the discharge voltage increases beyond a critical value (shown in Fig. 10). In Fig. 14a, for a discharge voltage of 10.5 kV and a vertical gap of 1.0 mm, several air bubbles were trapped within the interface and the air pressure was intensely increased during the MPW process.

Furthermore, the exceeding pressure in the trapped bubble resulted in perforation rupture, causing a no weld joint. In Fig. 14b, with increasing voltage to 11 kV and vertical gap to 2.0 mm, similar perforation rupture of trapped air bubble was produced. In contrast to the result shown in Fig. 14a, a weld joint was obtained. To summarize, the larger width of the joining zone leads to a lower stiffness flyer sheet that contributes to an uneasy connection between dissimilar sheets with small vertical gaps especially. With enlarged gaps and a width of joining zone between 10 and 20 mm, the connection quality was



1,3 - welded region; 2 - unwelded region

Fig. 16 Morphology of aluminum steel magnetic pulse welding joint

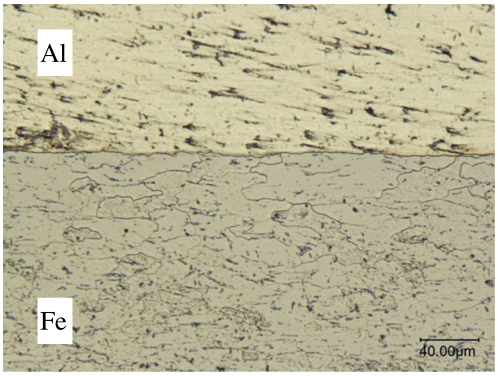


Fig. 17 The optical micrograph of aluminum steel joint via MPW

insensitive to the discharge voltage. Furthermore, when the width of the joining zone is small (below 5 mm), it is hard to reach the required collision angle. Furthermore, the stiffness of the flyer sheet is too high to deform, leading to failure to generate a metallurgical joint.

3.4 Microstructure of magnetic pulse welding joints

To investigate the microstructure of MPW joints, the sample was cut along the longitudinal direction, as shown in Fig. 15. The optical micrograph of the interface of aluminum steel joint is shown in Fig. 16. It reveals that the not welded region in the middle of the interface (region 2) and the other two regions (regions 1 and 3) present good welding. Figure 17 shows the optical micrograph of the interface in region 3.

The weld interface was observed via SEM, and the back-scattering electron image is shown in Fig. 18, where Fe appears bright and aluminum appears dark. An intermediate layer (also called transition zone) in gray can be clearly seen within the weld interface. Careful observation revealed that a flat morphology was dominant in the weld interface. The morphology is flat between aluminum and the intermediate layer, while the morphology between intermediate layer and steel is relatively wavy. The small waviness can increase the intimate contact area, thus forming interlocking between both metal surfaces for strong joining. The bright spots in the intermediate layer are considered to be grain refinements of steel.

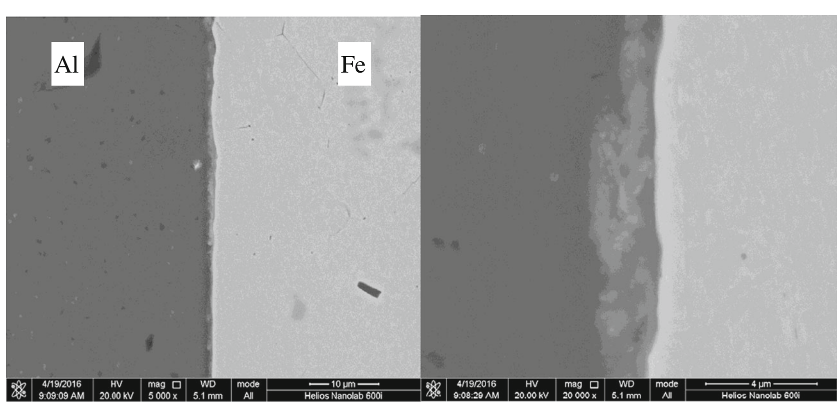
Composition analysis of the intermediate layer via line-energy spectrum scanning was carried out via SEM-EDS. The atom ratio of Al and Fe is shown in Fig. 19. One scanning route across a wavy intermediate layer was chosen. With the intermediate layer, mutual diffusion of basic elements could be observed. The compositions of Fe and Al gradually change within the intermediate layer and then decrease to zero. It can be concluded that some intermetallic is likely produced in the intermediate layer. Such intermetallic is limited to regions with a width of 3 μm, as presented with the shadow in Fig. 19.

4 Conclusions

In this study, the aluminum steel sheet has been welded via MPW with UPEA and shows that the UPEA is well suitable for MPW. The major conclusions are summarized in the following:

1. When the discharge voltage is up to 9.5 kV, a metallurgical joint between AA 1060 and Q235 steel sheets was obtained via MPW with UPEA. The tensile properties of MPW joints reveal that the joint strength is higher than the weaker parent metal.
2. Modification of the structure of the partition led to avoidance of cracks in the transition zone. The maximal tensile strength was 71 MPa. Unsuitable gaps led to ribs and bubbles, and too large gaps led to mechanical joining and interference fit.

Fig. 18 SEM observation of joint interface



(a) Interface of the aluminum-steel sheet joint; (b) back-scattering electron image

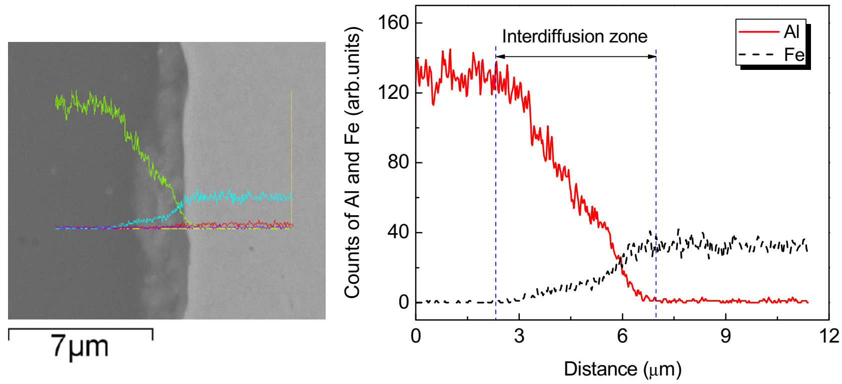


Fig. 19 Microstructures and EDS results of the welded joint

3. The weldability window was presented by changing the process parameters (discharge voltage, gap, and width of sheet) to illustrate the influence of process parameters.
4. The interface of aluminum steel sheets of MPW was flat and did not weld in the middle of the joining zone. SEM images and EDS mapping reveal mutual diffusion.

Acknowledgements This work was financially supported by the National Natural Science Foundation of China [Grant Nos. 51675128 and 51475122]. The work was also supported by State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology. The authors would like to take this opportunity to express their sincere appreciation.

References

1. Manesh HD, Taheri AK (2003) Bond strength and formability of an aluminum-clad steel sheet[J]. J Alloys Compd 361(1-2):138–143
2. Abe Y, Mori K, Kato T (2012) Joining of high strength steel and aluminium alloy sheets by mechanical clinching with dies for control of metal flow[J]. J Mater Process Technol 212(4):884–889
3. Briskham, P., Blundell, N., Han, L., Hewitt, R. et al. Comparison of self-pierce riveting, resistance spot welding and spot friction joining for aluminum automotive sheet. SAE Technical Paper 2006-01-0774, 2006, doi:10.4271/2006-01-0774.
4. Raoelison RN, Buiron N, Rachik M et al (2013) Study of the elaboration of a practical weldability window in magnetic pulse welding[J]. J Mater Process Technol 213(8):1348–1354
5. Jassim AK (2011) Comparison of magnetic pulse welding with other welding methods[J]. J Energy Power Eng 12:1173–1178
6. Zhang Y, Babu SS, Prothe C et al (2011) Application of high velocity impact welding at varied different length scales[J]. J Mater Process Technol 211(5):944–952
7. Aizawa T, Kashani M, Okagawa K (2007) Application of magnetic pulse welding for aluminum alloys and SPCC steel sheet joints[J]. Weld J 86:119-s-124-s
8. Geyer M, Rebensdorf A, Böhm S (2014) Influence of the boundary layer in magnetic pulse sheet welds of aluminum to steel[C]. In: Proceedings of 6th International Conference on High Speed Forming, Technische Universität Dortmund, Daejeon, Korea, 26-29 May, 2014
9. Kore SD, Date PP, Kulkarni SV et al (2011) Application of electromagnetic impact technique for welding copper-to-stainless steel sheets[J]. Int J Adv Manuf Technol 54(9):949–955
10. Manogaran AP, Manoharan P, Priem D et al (2014) Magnetic pulse spot welding of bimetals [J]. J Mater Process Technol 214(6):1236–1244
11. Nassiri A, Chini G, Kinsey B (2014) Spatial stability analysis of emergent wavy interfacial patterns in magnetic pulsed welding [J]. CIRP Ann Manuf Technol 63(1):245–248
12. Lee KJ, Kumai S, Arai T et al (2007) Interfacial microstructure and strength of steel/aluminum alloy lap joint fabricated by magnetic pressure seam welding [J]. Mater Sci Eng A 471(1):95–101
13. Kore SD, Date PP, Kulkarni SV (2008) Electromagnetic impact welding of aluminum to stainless steel sheets [J]. J Mater Process Technol 208(1):486–493
14. Weddeling C, Hahn M, Daehn GS et al (2014) Uniform pressure electromagnetic actuator—an innovative tool for magnetic pulse welding [J]. Procedia CIRP 18:156–161
15. Thibaudeau E, Kinsey BL (2015) Analytical design and experimental validation of uniform pressure actuator for electromagnetic forming and welding [J]. J Mater Process Technol 215:251–263