Magnetic Pulse Spot Welding: Application to Al/Fe Joining

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Abstract

Magnetic pulse welding is a rapid process (takes place within few micro seconds) that joins both homogeneous and heterogeneous materials in the solid state. The process involves applying variable high current on an inductor to generate Lorentz forces on to the conductive primary part (flyer). To realize the weld it is necessary to accelerate the flyer to impact on to the secondary stationary part (base material) at a very high velocity attained over the distance, called air gap, between the parts. It is typically possible to perform welding of tubes and sheets provided there is an optimized air gap between the parts to be welded. As part of our work we have developed an innovative approach (Magnetic Pulse Spot Welding-MPSW) that eliminates the delicate task of maintaining the aforementioned air gap between the plates. The proposed method opens better viable perspectives for heterogeneous assembly of automotive structures or connecting batteries in a quasi-cold state. The developed approach has been validated on the heterogeneous assembly Al/Fe by tensile tests (quasi-static and dynamic) that attested the quality of welds.

Keywords

Welding, Magnetic pulse spot welding, Dissimilar Al/Fe joining

1 Introduction

Resistance spot welding is the most suitable method used for joining steel plates for motor vehicles. On average, it accounts to 4000 spot welds per car [1]. To reduce the fuel consumption of the vehicle, automotive manufacturers started to replace/join steel parts with parts made of aluminum or magnesium alloys [2,3,4]. This raises the problem of assembling these parts. Even though there are many methods to join steel with aluminum or magnesium alloys (magnetic pulse, laser, friction, etc.) [5], they are rarely compatible with the constraints of automotive (cadence, positioning sheets, geometry, spot weld strength, etc.).

Among these methods we propose an evolution of the magnetic pulse welding process (MPW). Figure 1 shows the principle of MPW for joining two tubes together. The circuit is charged by accumulating a large amount of electrical energy in a capacitor bank. When the circuit is discharged, it liberates all the stored electrical energy to a high current solenoid (the inductor) in a very short time (within a few microseconds). If a conductive part (here an aluminum tube) is placed near the solenoid, it is subjected to a changing magnetic field which induces current at the skin of the aluminum tube (skin effect). This current is itself subjected to this magnetic field, resulting in generation of Lorentz forces on the surface of the tube and the tube starts to greatly accelerate away from the solenoid at very high velocity to impact on to the inner core (steel). The controlled impact of the aluminum tube on to the steel allows under certain conditions to produce a weld. This method is similar to explosive welding. Micrographic analysis of the weld in each case indicates a "corrugated/wavy" interface welding (Figure 2.a) [6].

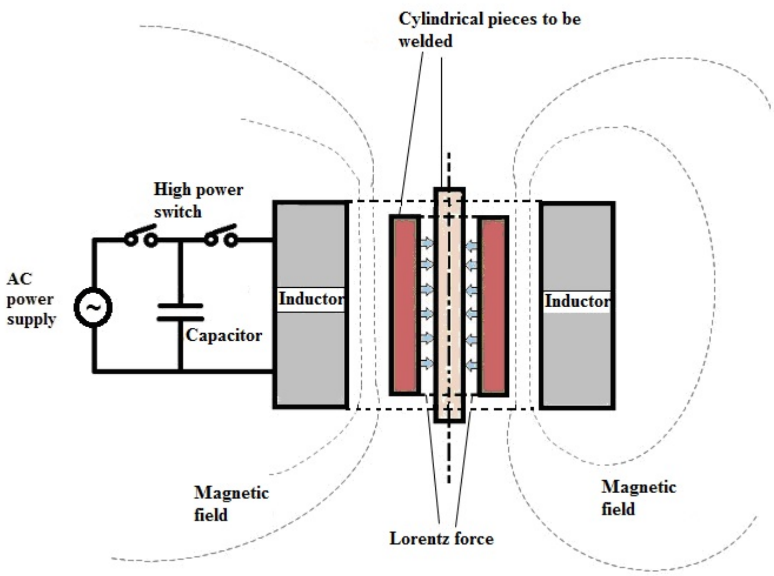
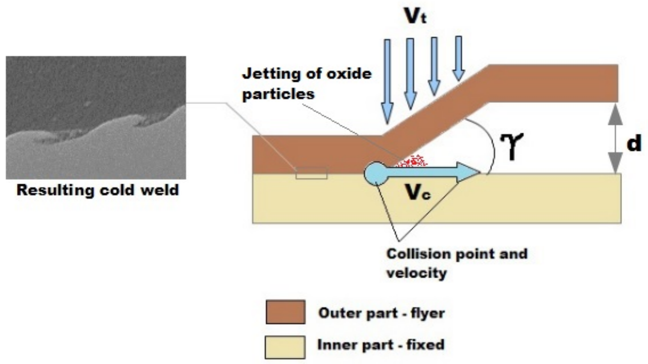


Figure 1: *Schematic diagram of the magnetic pulse welding.*

To achieve dynamic welding, be it explosive or magnetic pulse, it is necessary (Figure 2.b):

- To accelerate one of the parts sufficient enough to generate an impact on to the other to produce a very short but intense heat. This is achieved by means of an air gap between the two parts to be assembled with a generated impact velocity.
- To break away the oxides on the surface. This is ensured by the progressive collision of the flyer part on to the fixed part at a certain collision angle and collision velocity, so that the air jet formed expels the oxides away with it. By this way, the two contacting parts are provided with inter-atomically clean surfaces to form a metallurgical bonding.

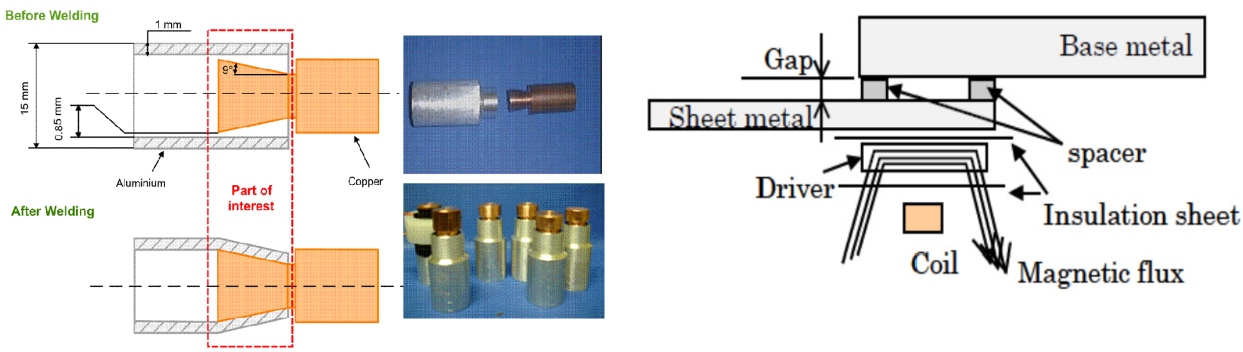


a. b.

Figure 2: *(a) Micrograph of the wavy interface, (b) Parameters of magnetic pulse welding.*

Almost 40 years after its invention, the only magnetic pulse welding configuration used commercially till the start of 2000s was tube/tube welding (Figure 3.a) [7,8]. Aizawa et. al. (2004) [9] developed a new method of magnetic pulse seam welding two flat plates by means of a double layer H shaped single-plane inductor coil (Figure 4.a). Here, the air gap was provided by means of an insulator placed between the two sheets. In 2007, the same team proposed a simple inductor: an E shaped one layer flat coil [10] (Figure 4.b) and more recently they have proposed a way of spot welding (single or multi spots) using an insulating mask between the two sheets (Figure 4.c and 4.d) [11]. In all the above cases, the requirement of ensuring an acceptable air gap of distance for each part to be welded makes it challenging to be implemented in automotive industry.

In our study we propose an evolution to the magnetic pulse welding process which produces spot welds between similar or dissimilar materials under conditions compatible with respect to the constraints in the automotive industry (cadence, robotics, resistance, etc.). The process is named as “Magnetic Pulse Spot Welding”.



a. b. c.

Figure 3: *(a) MPW of two tubes, (b) Cu/Al parts before and after welding [8], (c) Schematic of the magnetic pulse seam welding process [9,10].*

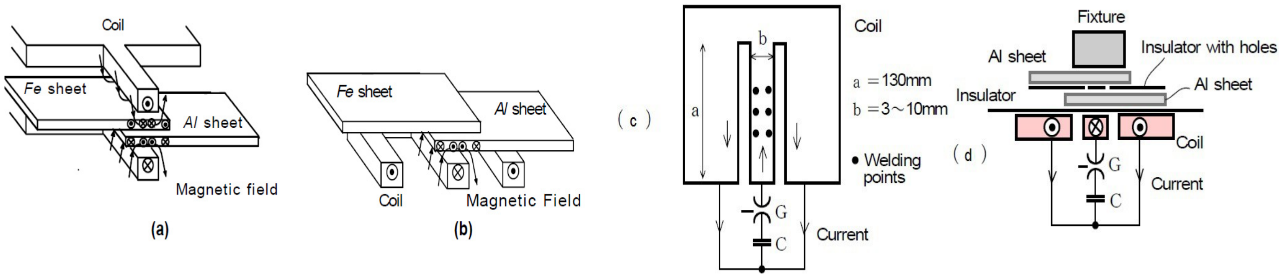


Figure 4: *(a) Double layer H shaped single-plane inductor coil [9], (b) Monolayer E shaped flat coil [10], (c) Spot welding with the help of insulating mask, (d) Welding system [11].*

2 Magnetic Pulse Spot Welding: Principle

Figure 5 shows the principle of Magnetic Pulse Spot Welding (MPSW) for spot welding two sheets together. As said earlier, the two plates are always in contact with each other before and after welding. So, in order to ensure that there is necessary gap between the plates for intended acceleration and impact of the flyer plate on to the parent plate (Figure 2); and also to ensure correct positioning of the sheets on each other before and after welding, we propose to carry out a prior local stamping, called "hump" (Figure 5). This hump geometry combined with the inductor geometry is critical in ensuring both the necessary collision rate and the removal of surface oxides. The inductor is designed in such a way that it is placed just above the hump. When the current is discharged, according to the MPW principle, the hump deforms and impacts on to the other material at a very high velocity to realize spot welding. Here, the geometry of the hump determines the size of the spot weld. Generally, the sheet with good electrical conductor is chosen as the flyer part, in our case, aluminum.

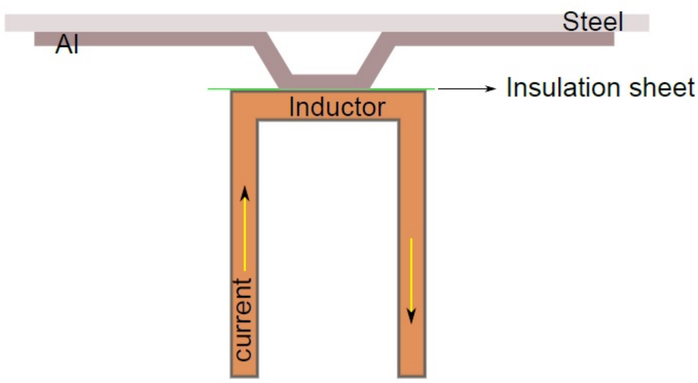


Figure 5: *Schematic of the magnetic pulse spot welding process (MPSW).*

3 Materials and Experimentation

To validate the principle of MPSW process we have chosen the heterogeneous assembly of Aluminum to Steel. The materials used are steel sheet (EN355) having a thickness of 1.5 mm, and aluminum sheet (AA1199) with a thickness of 0.5 mm. The MPSW process utilizes a monolayer I shaped flat inductor that concentrates magnetic flux at the surface of the hump of the flyer sheet. Figure 6 shows the hump configuration and the intended spot welding location – hump on AA1199 aluminum sheet. The generator used for carrying out welding is developed at Ecole Centrale de Nantes which has a capacitance of 272 µF, 0.5 µH inductance and maximum energy of 30 kJ. Three different energies – 2.8 kJ, 3.4 kJ, 4.15 kJ are chosen to carry out spot welding and are compared.

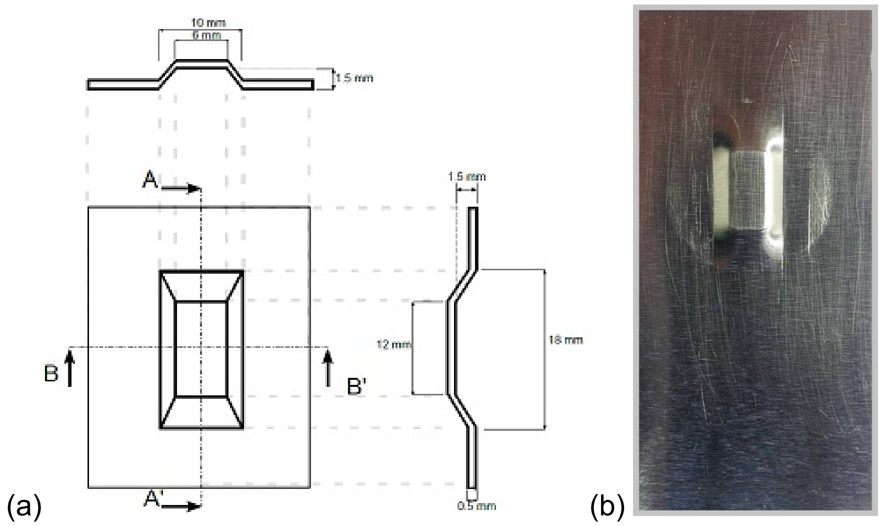


***Figure 6:** (a) Hump configuration, (b) Intended spot welding location – "hump" in the AA1199 aluminum sheet.*

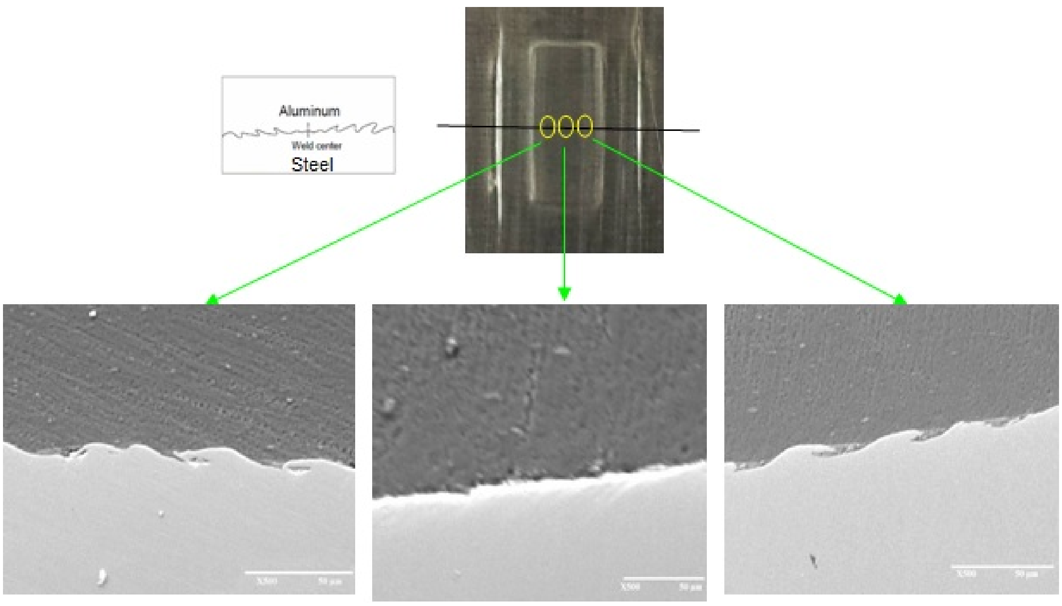


Figure 7: Micrographic analysis using SEM for Al/Fe magnetic pulse spot weld for 3.4 kJ energy.

4 Results and Discussion

Figure 7 shows the micrographic analysis of the welded area done using scanning electron microscope. We observe a characteristic corrugated/wavy interface typical to dynamic welding processes (explosive/magnetic pulse). However, unlike these processes, the waves on the interface are in opposite directions from the center. Moreover it can be verified that the center part of the part is not welded. The weld zone typically shows a rectangular region with no weld at the center as shown in Figure 7. A rectangular weld region is formed on the sheets which correspond to the side edges of the coil placed above it and no welding took place in the area between them i.e. at the center. Since, the process is rapid, only very thin intermetallic layers (2-5 μm) are formed and that too only around those wavy regions.

The size of the no-weld zone at the center was measured to be 1 x 6 mm^2 for all the weld specimen sets done by peel tests. Figure 8 shows the peel test results for different energies. In all the cases, the weld was good and only the aluminum sheet around the weld sheared off.

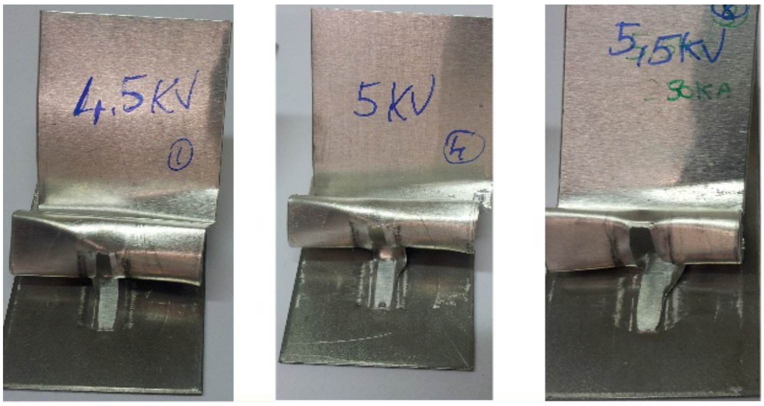


Figure 8: *Peel test carried out for different welding energies.*

Tensile tests were carried out on spot welded specimens for different discharge energies viz. 2.8 kJ, 3.4 kJ and 4.15 kJ. Figure 9 shows an example of tensile test results both quasi-static and dynamic tests. Quasi-static tests were carried out on a tensile/compression testing machine from Instron and dynamic tests are carried out on a machine developed by GeM, Ecole Centrale de Nantes. In all cases, the aluminum sheet were sheared off around the spot weld zone and the spot welds were in contact through out. We also see that, as we increase the discharge energy, the tensile failure load also increased indicating that the area of the spot weld has a great influence in the test results. This suggests that our welds are satisfactory and are stronger than the weaker base material (aluminum).

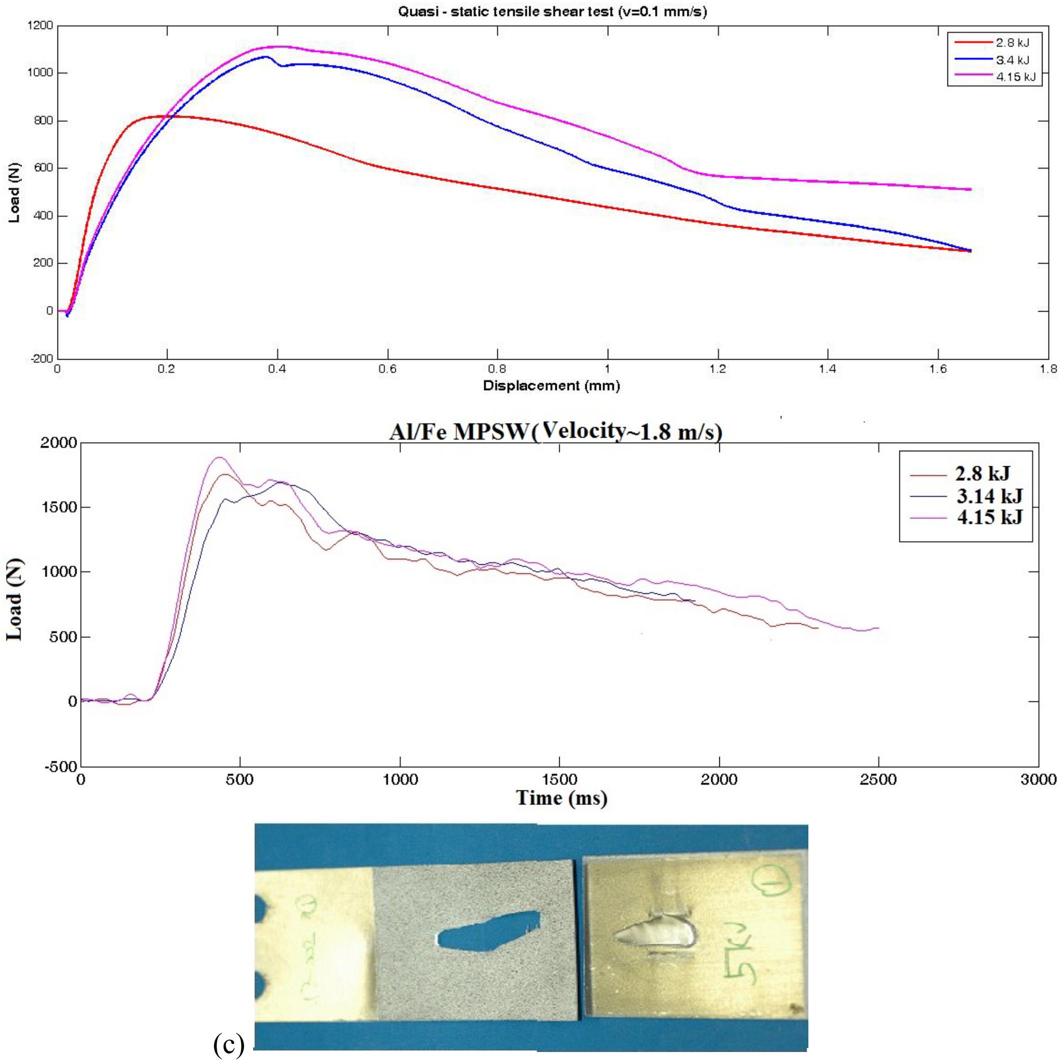


Figure 9: *(a) Quasi-static tensile test results, (b) Dynamic tensile test results, (c) Spot welded specimen after dynamic tensile test.*

5 Conclusion

In this study we developed a new method for spot welding two different sheets. The process is named as "Magnetic Pulse Spot Welding - (MPSW)". Like Magnetic Pulse Welding, it is a cold welding process which allows spot welding both homogeneous and heterogeneous materials. As the welding process is very rapid (takes place within few microseconds), the formation of thick intermetallic layers are avoided; for example, in case of Al/Fe joining, intermetallic formation cannot be avoided. From this process only very thin intermetallic layers (2-5 µm) are formed and that too only around those wavy interfaces. This makes it a very interesting process for spot welding heterogeneous materials especially, Al to steel for automotive applications.

In order to obtain spot welds, it is necessary to make a local stamping called “hump” on the flyer sheet where you intended to realize a spot weld. The welding operation (once the sheets are in place) lasts only a few microseconds. The sheets are always in contact with each another before and after welding. This suggests the possibility of using this spot welding method in the automotive industry for joining light materials such as Al/Mg with steel.

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