Chapter 45
Dissimilar Welding Using Spot Magnetic Pulse Welding

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Abstract Magnetic Pulse Welding (MPW) is a solid state joining technique which have increased development in the past few years due to the industrial need in joining dissimilar materials and difficult-to-weld ones. It is an impact welding technique, such as explosive welding (EXW) and laser impact welding (LIW), which share the same basic joining principle, impact-driven solid state welding, but applied to different scales: EXW for larger parts and LIW for smaller. Defined as a fast, reliable and cost-effective technique, MPW struggles with the lack of knowledge about the welding process despite of the extensive existing literature. The work conducted aimed at joining Al to steel in spot welding configuration widely used in automotive industry. Welds were characterized in order to understand and improve the process.

Keywords Magnetic pulse welding · Spot welding · Solid state joining · Aluminum alloys · Steel

45.1 Introduction

MPW uses the concepts of electromagnetism in its fundamentals [4, 5]. When a very high AC current in the order of 1 million ampere is forced to passed through a conductive coil, or inductor near an electrically conductive material, an intense magnetic field is locally produced that generates a secondary current in the flyer according to the Lorenz law. The effect of this current moving in the magnetic field

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of the primary current generates a Lorenz force which accelerates the flyer at a very high velocity of about 800 m/s. When the flyer targets a base material a very strong collision occurs creating a jet consisting of both metals, air and surface oxides removed from materials surfaces. The parts are forced to bond together in a solid state weld. The kinetic energy of the flyer is transformed into heat by the intense plastic deformation of the material surfaces [3]. The generated heat locally increases the temperature softening the material or producing strain hardening depending on the materials characteristics. Eventually, highly localized fusion may occur. The time interval for heating and cooling is very rapid, in the order of milliseconds, so heat is rapidly dissipated into the bulk material and no heat affected zone is observed. The process is considered in solid state since no fusion of bulk material occurs and the joint is produced by severe plastic deformation of the interfaces contacting at high speed. So, it is particularly adequate to join dissimilar materials with very distinct thermophysical properties and melting points as Al allows and steels used in automotive industry [1].

Recently, advances have been made to adapt the process to spot welding configurations replacing resistance spot welding. Air gap is an important requirement to accelerate one of the parts at a high velocity to impact on to the other to form a joint. The specificity of magnetic pulse spot welding (MPSW) is that both the sheets are in contact with each other without any gap before and after welding. So, in order to achieve spot welding using magnetic pulse, a previous local stamping is performed on the spot welding location, to form a "hump" on the flyer part. When the two sheets are placed together to perform spot welding, this hump made on the flyer part forms an air gap with the other fixed part. The inductor is designed in such a way that it is placed just above the hump. When the current is discharged, the hump deforms and impacts onto the fixed material at a very high velocity, resulting in a spot welding. Generally, the sheet with good electrical conductor is chosen as the flyer part [2] and the hump geometry determines the size of the spot weld.

45.2 Experimental Procedure

In this study Magnetic Pulse Welding spots of AA1199 with 0.5 mm thick to mild steel EN355 with a thickness of 1.5 mm was performed. The process uses a monolayer I shaped flat inductor that concentrates the magnetic flux on the surface of the flyer hump as schematically depicted in Fig. 45.1.

The generator used for carrying out welding is developed at Ecole Centrale de Nantes which has a capacitance of 272 μF, an inductance of 0.5 μF and maximum energy of 30 kJ. Trials were performed with energy varying between 2.8 and 4.1 kJ.

Figure 45.2 shows the inductor and the connector before welding and the hump in Al sheet is shown in Fig. 45.3. The standoff distance between the coil and the flyer material was of 0.2 mm.

Samples were welded and cut for microstructural analysis under optical and scanning electron microscopies.

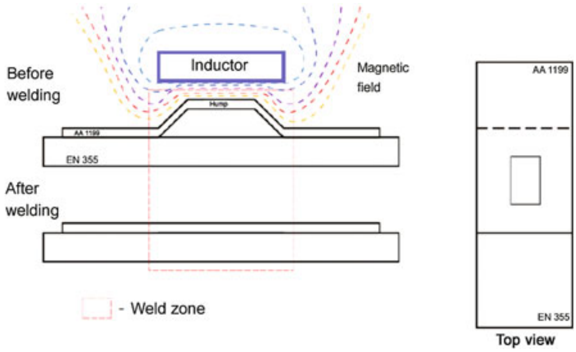


Fig. 45.1 Schematics of MPW for spot welding

Fig. 45.2 Inductor and connector clamped before welding

Fig. 45.3 Humps in the Al plate

45.3 Results and Discussion

The optical analysis revealed a welding characterized by an unbound region at the centre with two welded zones on each side as shown in Fig. 45.4.

Marya et al. [4] reported that the high collision velocity is sufficient to peel off the oxide layer on the surface of the colliding contact area. The center part of the hump metal is sprayed at the collision apex and forced outward with high velocity in two directions opposite from the center. The mixture of the peeled surface oxide and the surrounding gas forms the jet that propagates along the two colliding surfaces in a swirl motion in both the directions opposite from the center and cleans the metal surface layer.

The two clean metal surfaces are thus pushed into intimate contact by the short time duration high pressure, which leads to the metallurgical bonding across the interface. As long as the jetting is sufficient, the continuous wave interface can be

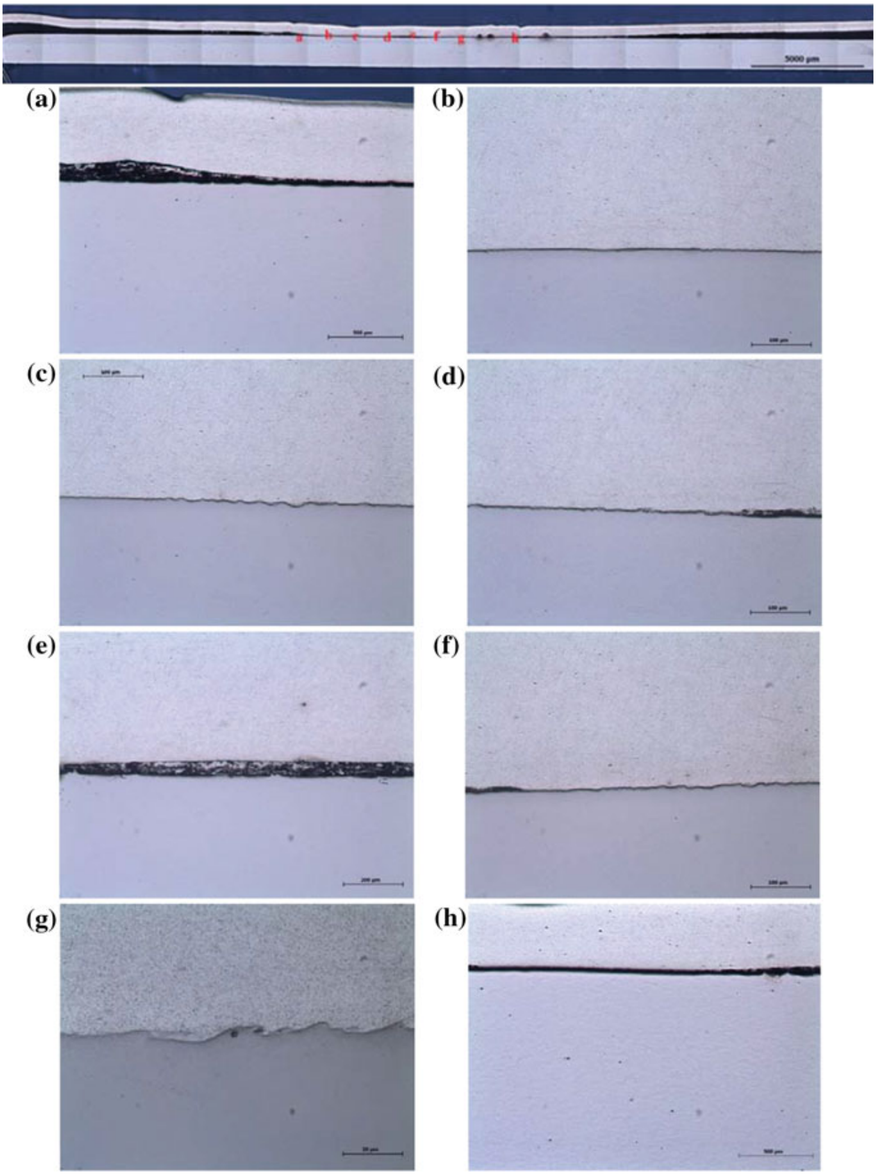


Fig. 45.4 Macrograph of the weld cross section and details

formed. If there is insufficient jetting, the metal surfaces will result in little or no bonding.

The important conditions for jetting to form depend on the collision point velocity and the collision angle. At the critical collision angle, if the jetting exceeds the

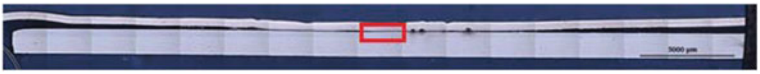


Fig. 45.5 SEM analysis zone

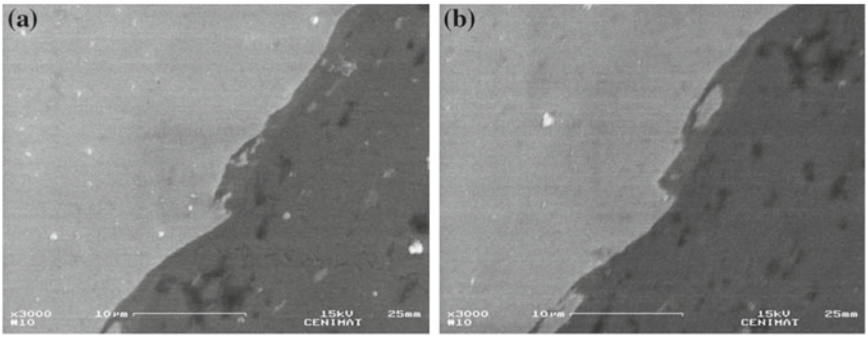


Fig. 45.6 SEM detail of the bonded zone (secondary electron analysis mode)

dynamic elastic limit of the materials, the plastic deformation occurs on the metal surface and bonding can be formed. However, unlike the explosive welding process, the wavy surfaces in the MPSW are in two opposite directions from the center of the hump. The high velocity impact welded interface morphology resulted from jet effect can be classified into two types: (1) flat interface at the center of the weld, (2) wave interface with pocket type and continuous transition layer along the interface in the bond zone in two different directions from the center.

As it can be seen in the details presented below, a bonding wavy interface is visible on both sides (detail c and f) of the unbound central region (detail e) presenting similar welding lengths. Furthermore, the welding zone is centred with the deformed zone. The centre unbounded zone presented trapped debris (detail e).

SEM analysis was carried out in the zone marked in Fig. 45.5 which represents one of the bonded zones. In the details presented below the darker region represents the aluminium. Figure 45.6 detail (a) shows that bonding was achieved while in detail (b) embedded steel particles can be seen in the aluminium. Figure 45.7 shows the wavy interface, typical feature of impact welding and in (b) a wave detail with a steel particle embedded in aluminium.

The wave amplitude is found to be around 2–5 μm from the center of the interface and the wave length is around $2 \times 10\ \text{mm}^2$ across the weld interface. Beyond that, there is no waves because, the critical collision angle and velocity is not sufficient for jetting to occur.

In Fig. 45.8, the beginning of the unbounded centre region is visible despite the wavy interface formed due to the high impact velocity. So the shape of the hump may have an effect on the jet direction and this is to be studied in order to improve bonding in the central part of the spot.

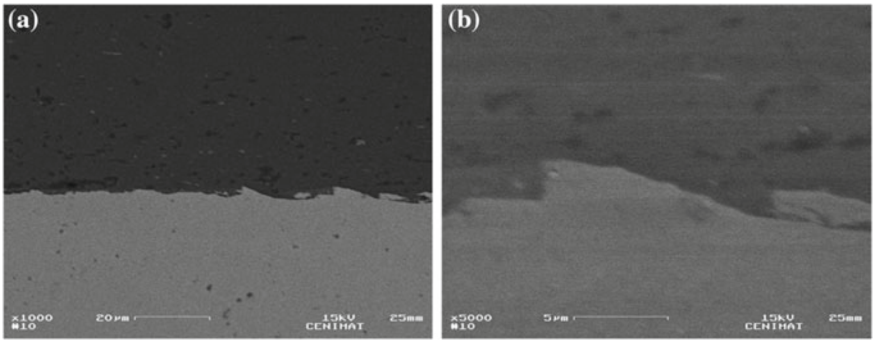
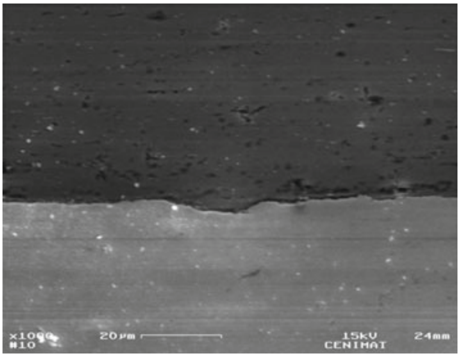


Fig. 45.7 **a** Bonded interface (backscattered electron analysis mode). **b** Detail of the previous (secondary electron analysis mode)

Fig. 45.8 Centre unbounded region



45.4 Conclusions

From this study the following can be concluded:

- MPSW was tested in thin sheet dissimilar steel/aluminium lap joint configuration.
- The spot was analyzed and it was seen that there was no bonding at the center, there are two bonded areas symmetrically located on each side of the central unbonded area. Considering the hump geometry these may be due to the absence of the jet effect in the spot center.
- In the adjacent areas the temperature and pressure were high enough to create bonding due to inter-atomic diffusion.
- From SEM analysis of the spot welds made by MPSW process, there are two different weld zones (a) flat interface, where no weld is seen and (b) weld interface with wave pockets in two opposite directions from the center of the weld (rectangular hump geometry).

- According to Al-Fe phase diagram intermetallics Fe_2Al_5 and $FeAl_3$ can form with a thickness of 0–2 µm and its distribution is discontinuous which may be due to the interlocking of intermetallics on to those wave pockets.

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