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Review article

Review of Advanced Resistance Welding Technologies and Control Methods for Joining State-of-the-Art Materials in Lightweight and Electric Vehicle Manufacturing

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ABSTRACT

Resistance spot welding (RSW) remains a fundamental joining process in modern industrial manufacturing, particularly in the automotive sector. Ensuring consistent weld quality is critical, prompting the development and integration of various monitoring and control systems. This paper reviews the theoretical foundations of RSW and explores diverse control strategies from a control systems perspective. A comprehensive overview of contemporary quality assurance methods—including those leveraging artificial intelligence and machine vision—is provided. The paper also examines the evolving role of RSW in lightweight automotive design and the production of electric vehicles, where diverse materials and dissimilar metal combinations are increasingly common. To address the challenges of welding these advanced materials, state-of-the-art welding and joining technologies are discussed in detail.

Key words: *Artificial intelligence, Control systems, Machine vision, Resistance spot welding, Advanced joining technologies.*

1. INTRODUCTION

The history of resistance spot welding (RSW) and, in fact, welding as such began in 1857 when James Prescott Joule joined two wires with the help of electrical current. The first patents related to the RSW were filed by prof. Elihu Thomson [1]. When he tried to answer a question of a student by performing an experiment, he accidentally made the first resistance spot weld. With this he solved the problem of joining materials with high melting temperatures and also materials whose melting temperature differ significantly. Although he used a RSW machine as early as 1881, the first patents were filed in 1886 [2]. Russian scientist Nikolajevich Benardos managed to join two pieces of steel using graphite electrodes in 1887/88 and got a patent for that [2]. Approximately ten years later an important step was made by Kleinschmidt. He namely replaced graphite electrodes by copper ones and started a wider applicability of the process [3].

Nowadays RSW is a widely used welding process. In a typical car there are, for example, between 2000 and 5000 resistance spot welds [4]. The process is, however, also extensively used in other industries where joining of sheet metal components is to be performed [5]. It should therefore come as no surprise that a significant effort is being made in order to ensure the quality of the resulting welds.

2. BASICS OF RESISTANCE SPOT WELDING

A significant effort is being made in order to ensure the high quality of the weld joints. To deal with that, we need to fully understand the process of resistance welding. A graphical representation of a RSW is shown in Fig. 1.

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Our goal is to make a weld nugget of sufficient size on the faying surface of the two weldpieces. In order to achieve that we first need electrodes to enable the current conduction (see Fig. 2).

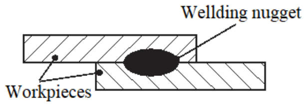

Fig. 1 *Schematic representation of a RSW*

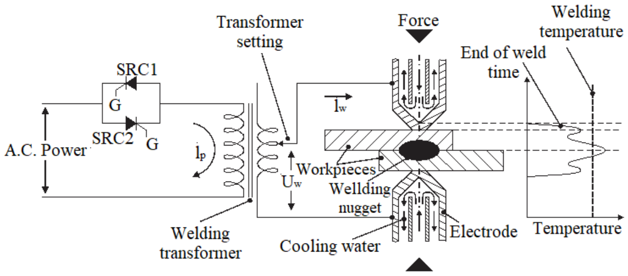

Fig. 2 *Schematic representation of a RSW process*

In order to understand Fig. 2, we need to discuss resistances in the electrical circuit formed during RSW process (see Fig. 3).

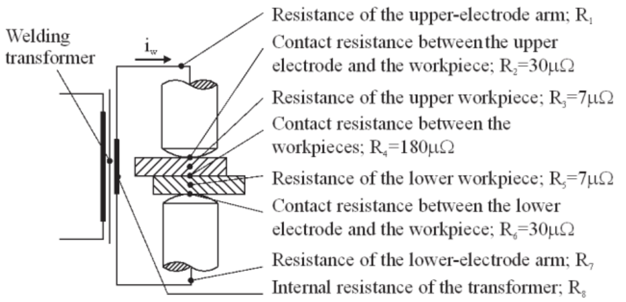

Fig. 3 *Resistances (mild steel) in RSW [6]*

We can see that the largest part of the total resistance is the contact resistance between the weldpieces. Consequently, we can expect the most intense heat generation at this spot. The contact resistances between electrodes and weldpieces are, however, also significant. Consequently, electrodes need to be cooled as shown in Fig. 2. The voltages associated with this process are pretty low, so we need a transformer to get the proper voltage. Beside that we need a system to generate a welding force. This is typically done by employing some pneumatic actuators. The temperature profile shown in Fig. 2 then moves to the right (increasing temperature) during the welding process. This is, of course, associated with the weld nugget growing in size as shown in Fig. 4.

The process has to somehow be controlled. This is typically done by some semiconductor based switches. Two Silicon Controlled Rectifiers (SCRs) are shown in Fig. 2 for this purpose. Their role is best explained by the waveforms shown in Fig. 5.

We can control the average amount of current flowing through the welding area by the moments in time when we open the SCRs by a pulse on the gate (the so called firing angle). The bigger the angle, the lesser the heat generation. So, in order to have a good quality weld, we expect that a certain combination of welding time and welding current is needed, as shown in Fig. 6.

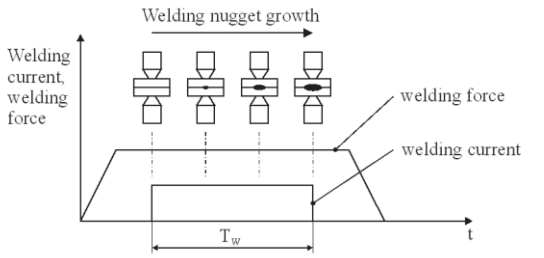

Fig. 4 *Weld nugget growth*

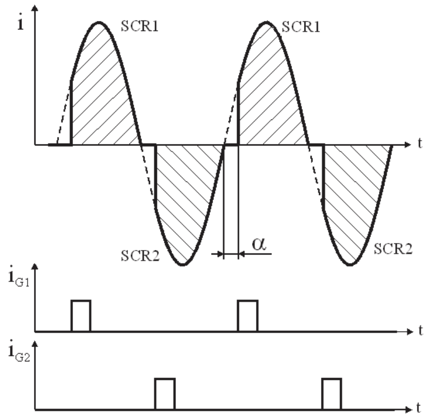

Fig. 5 *The role of SCRs*

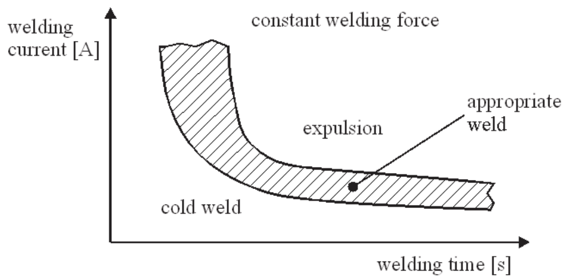

Fig. 6 *Appropriate combination of welding parameters [7]*

If not enough energy is delivered to the weld area a so called cold weld is being formed. It has insufficient weld strength for any real world application. If on the other hand we deliver too much energy into the weld region, the so called expulsion will occur. In this case the weld nugget grows so big that the surrounding material cannot withstand the welding force anymore and the weld region collapses with molten material being expelled. Although this might not affect the weld strength it increases the electrode wear, makes the welds' visual appearance problematic and also affects corrosion resistance of coated sheets.

In order to control the process, in a typical engineering problem we would try to make a mathematical model of it. In case of the RSW two partial differential equations are needed. The first one is electrical [8]:

$$\nabla \cdot (\sigma \nabla U) = 0 \quad (1)$$

and the second one is thermal [9]:

$$\rho \frac{\partial T}{\partial t} = \nabla (\nabla T) + \sigma \nabla U \cdot \nabla U \quad (2)$$

These equations are typically used as a starting point for RSW related simulations [10-12]. The problem is, however, that there are also significant heat losses associated with RSW (see Fig. 7)

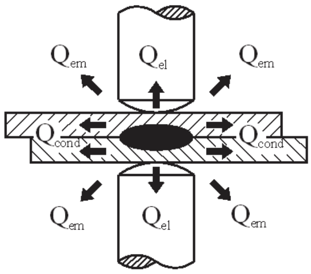

Fig. 7 *Heat losses associated with RSW*

Heat losses can amount to up to 90% of which the major part is being attributed to the cooling of the electrodes (between 60% and 70%) [13]. As a consequence, it is difficult to control the process based on this, even if we would know all the parameters appearing in the equation, which are all temperature dependent. There are also always disturbances associated with the process [14]:

- Variable contact area between electrodes and weldpieces which results in varying current density. This cannot be avoided due to electrode wear
- Variable surface conditions. Different roughness or surface being greasy influences the contact resistance
- The thickness of metal sheets (and possibly their coating) varies from weld to weld
- Nearby welds result in part of the current being deflected (shunting)
- Poor fit-up of the weldpieces
- Possible disturbances in power supply

For all these reasons it is better to design a control system ensuring appropriate quality of the weld, regardless of disturbances.

3. CONTROL SYSTEMS IN RESISTANCE SPOT WELDING

In general control systems can be either open loop or close loop. The two systems are shown in Fig. 8. The main difference between the systems is that in the case of the closed loop system we also have to measure the output signal (variable). Both types of systems appear in RSW control.

3.1 Open loop control systems

The advantage of an open loop control system in general is lower cost, as we don't need to take care of measuring the output variable. The most common approach that would fall within this category is the so called stepper (see Fig. 9).

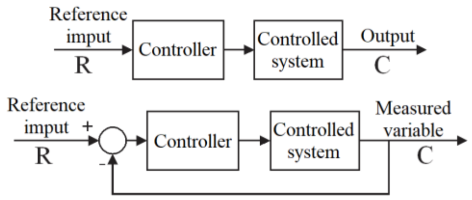

Fig. 8 *Open loop (top) and closed loop (bottom) control systems*

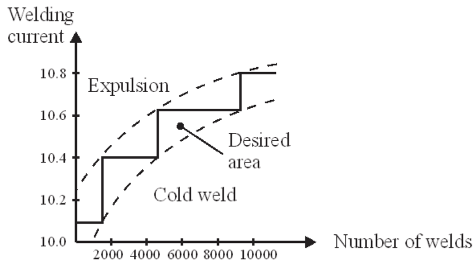

Fig. 9 *Stepper*

Using this approach, we count the number of welds being made and adjust the welding current appropriately. In combination with a welding schedule, shown in Fig. 10, this is a classical approach to get the welding parameters. However, with this approach we fail to address all the other disturbances.

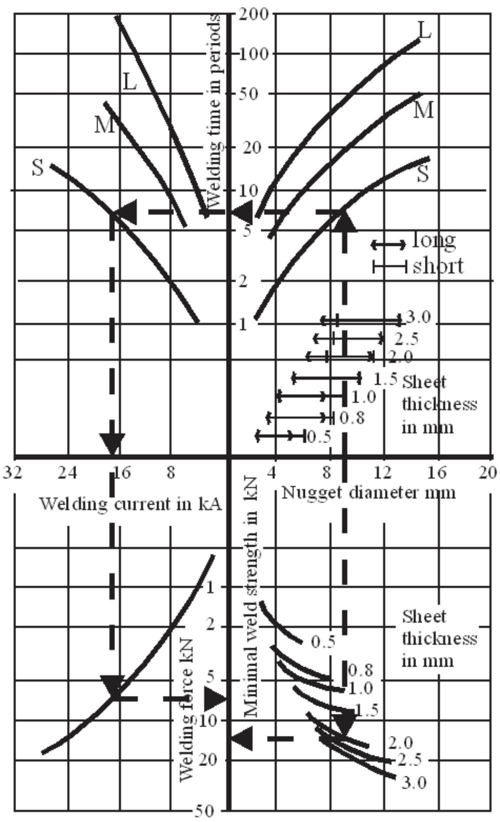

Fig. 10 *Welding schedule*

3.2 Close loop control systems

As noted above, we need to measure the output signal in the case of a closed loop control system. The first question that arises is, what is the output signal at all? Quality of the weld is namely a very vague term. We could, however, agree that weld strength is the signal we would most often be interested in, although other aspects, like visual appearance of the weld, might be of importance as well. But even if we agree on that, the problem is that we cannot measure it directly and definitely not in real time as the proper weld strength is only known after the weld cools down. For this reason, different other signals are being measured. The most common ones are [14]:

- Welding voltage, welding current and dynamic resistance [15-18]
- Electrode displacement [19-22]
- Welding force [23]
- Ultrasound transmission [24]
- Acoustic and sonic emission [25-27].

The schematic representation of a measuring system for the above mentioned signals is shown in Fig. 11. The raw signals we would typically get from such a setup are shown in Fig. 12.

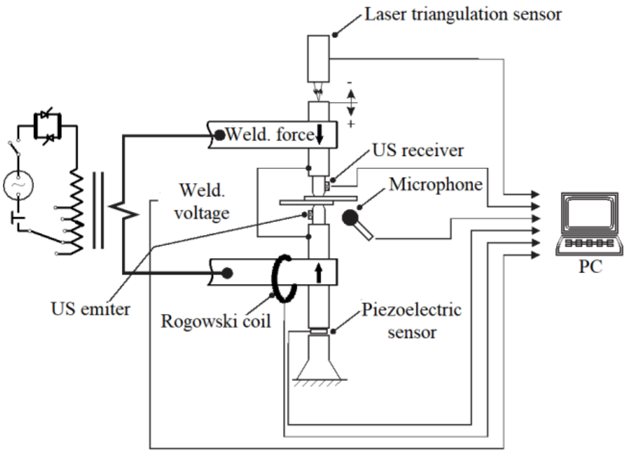

Fig. 11 *Schematic representation of a measurement system for measuring different variables*

RSW control systems can be divided into three groups [14]:

- Monitoring systems
- Weld to weld control systems
- Feedback control systems

In all three cases some kind of measurement is being made. In the first case, we only assess the weld strength after the weld is completed. If needed, another spot weld can be made in the vicinity to ensure the proper weld strength. The second case is similar to a stepper, but the current increase has to be based on some type of measurement. Only the last group (feedback control systems) are closed loop systems from the control theory point of view. Within this group, two types of approaches are being used. The first ones are the so called tracking systems. The idea is shown schematically in Fig. 13.

The idea is to get a reference curve (typically for dynamic resistance, ultrasound transmission or electrode displacement) for an ideal weld and then make the controller track this reference curve for all the other welds. The most common type of the control algorithm being used is some type of PID algorithm. This approach however needs a reference curve for each sheet thickness/material combination, which might be cumbersome to get. The other possibility is an on/off type of controller, which is shown schematically in Fig. 14.

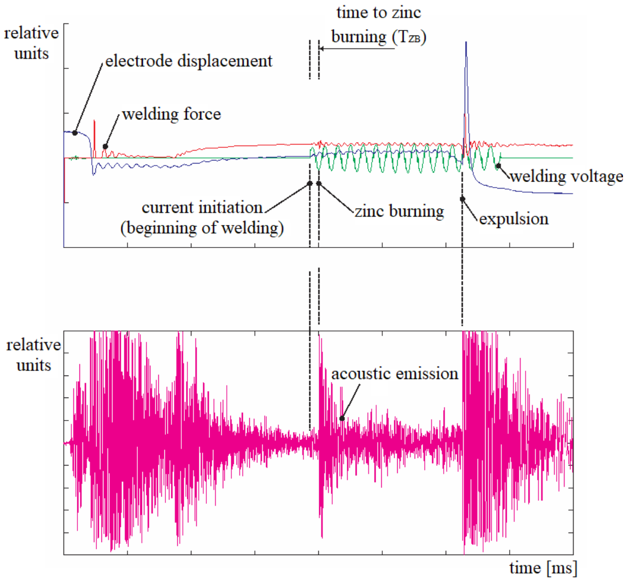

Fig. 12 *Raw signals from a measurement system*

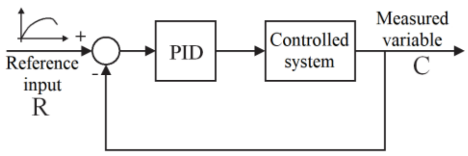

Fig. 13 *Tracking system*

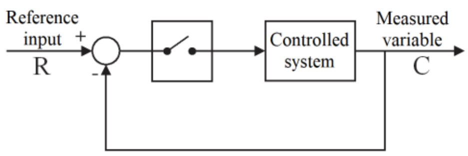

Fig. 14 *On/off type of control system*

In this case the idea is that the control system is measuring one or more system variables. As the weld nugget is increasing with time the problem reduces to the detection/prediction of the occurrence of expulsion. When the system detects/predicts the expulsion, the welding current is shut off. This approach is well suited for both sensor fusion and artificial intelligence application. In order to get the input data for a neural network we first observe the data points (vectors) presented in Fig. 15. This can be seen even better in Fig. 16, where data points for two signals are being presented. The plot on the left is associated with the electrode displacement and the plot on the right with dynamic resistance. The red crosses are normal points, and the blue circles are the expulsion points. In both case we can see that blue circles tend to differ from red crosses, but it would be impossible to make a clear boundary between them.

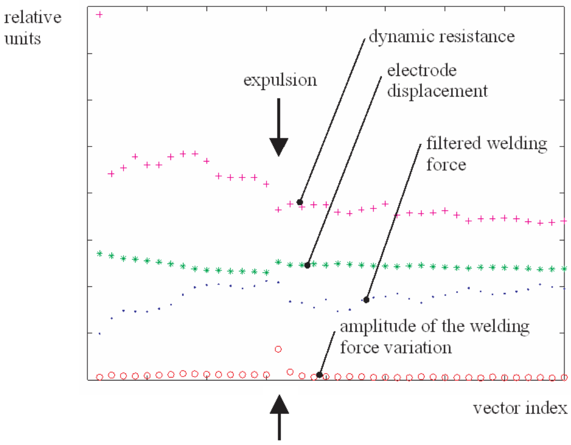

Fig. 15 *Vectors associated with the measurements*

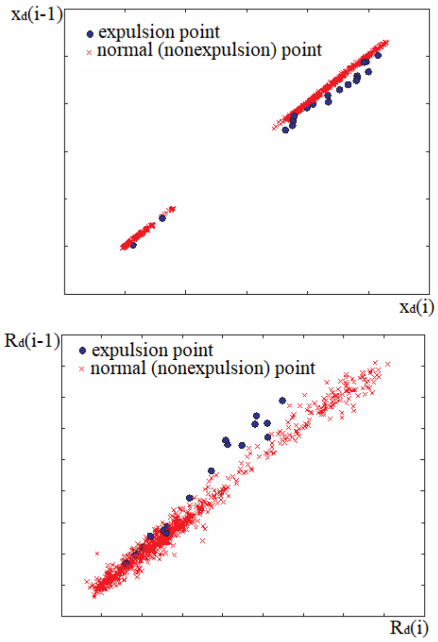

Fig. 16 *Data points for electrode displacement (up) and dynamic resistance (down)*

Fig. 17 is showing data points for a combination of electrode displacement and dynamic resistance. We can see that it would be much easier to make a distinction between data points if two signals are being used. This clearly demonstrates the benefits of signal fusion. If we measure more than two signals, the distinction between expulsion and normal points would be even more pronounced. It is, however, difficult to visualize a multidimensional system and determine an appropriate boundary just by the observation. This problem can be solved by applying some kind of an algorithm that solves this task automatically. One possible approach is the application of artificial intelligence. There are many different types of neural networks, but the one well suited for this task is the so called LVQ (Learning Vector Quantization) neural network [28]. It is shown schematically in Fig. 18. The goal of the network is to associate each of the input vectors to a certain prototype vector. Prototype vectors need to be properly placed during the learning phase of the neural network [29]. After that the controller can be used to detect/predict expulsion based on the type of current control system it is using (mainly depending on its frequency).

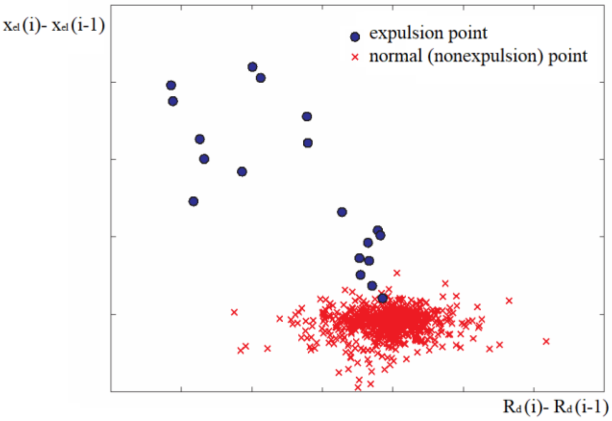

Fig. 17 *Vectors associated with the measurements*

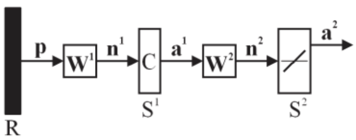

Fig. 18 *LVQ Neural Network [29]*

4. CHALLENGES IN WELDABILTY AND JOINABILITY OF MATERIALS

Resistance spot welding (RSW) is generally used technology in the automotive industry for joining metal sheets to produce a body in white. Commonly a body in white consists of the equivalent of 2000 - 5000 spot welds [30, 31]. The welding spot costs between 3 – 5 cents, which covers energy consumption, equipment depreciation, electrode wear, and labor costs. The ability of easy automation, together with the production speed makes the RSW first choice for welding of steel sheets in automotive industry. Automotive industry is lately under pressure to lower the CO2 footprint in the entire car lifetime. This includes the production of cars, their use, dismantling and recycling. European regulations limited the CO2 emissions to 95 g/km in 2020 and further 30% by 2030 [32]. Automotive industry is encouraged to produce lightweight body in white and at the same time use the materials with lower CO2 footprint and recycled materials. The car must at the same time be easily recycled. In the developed countries around 80% to 95% of the weight of an automobile is recycled.

Lowering emissions can be reached with lightweight design and electro mobility. A 10% weight reduction decreases the fuel consumption and CO2 emissions for 5.5 % [33]. The modern concept of lightweight design demands the use of materials with high strength to weight ratio and light materials for production of multi-materials construction i.e. with the use of optimal material at proper place (Fig. 19). A combination of different materials, like advanced high strength steels, aluminum alloys, magnesium alloys, and carbon fiber reinforced composites (CFRPs) are used considering their properties (static and dynamic strength, corrosion resistance,), weldability and joinability, costs, recyclability, lifetime, etc.

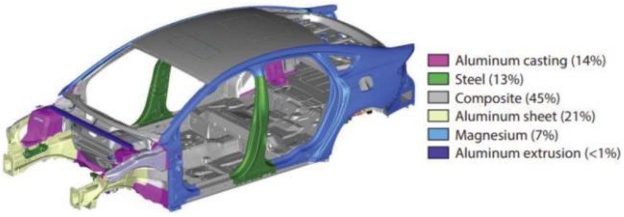

Fig. 19 *Vehicle Mach-II Body in White (BiW) using multi-material design (MMD) [34]*

Advanced high-strength steels (AHSSs) offer an exceptional combination of strength and formability (Figure 20), enabling enhanced vehicle crash performance without significantly increasing weight. However, the elevated alloying content of these steels poses challenges to their weldability. In particular, the thermal cycles associated with welding processes can disrupt carefully engineered microstructure, leading to a deterioration of mechanical properties in the weld joint. To improve the weldability of AHSSs, it is essential to develop a deeper understanding of their welding behavior, with particular attention to the effects of alloying additions and the influence of welding and post-welding thermal cycles on the metallurgical evolution of the weld metal and heat-affected zone (HAZ) microstructures [35, 36].

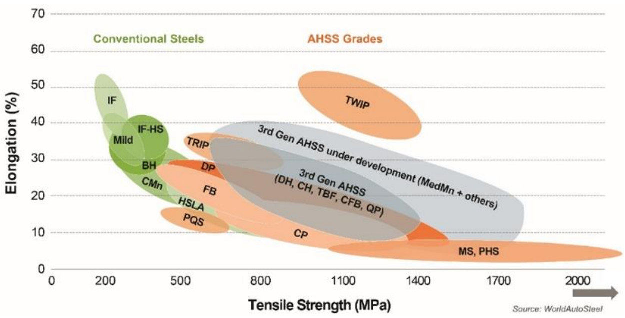

Fig. 20 *Elongation vs. strength of convential steels and advanced high strengths steels (AHSS) [31]*

In the production of electric vehicles (EVs), additional electrical components such as electric motors, batteries, and connectors are integrated into the vehicle structure. The assembly of these systems requires welding and joining of dissimilar materials, including copper alloys, aluminum alloys, steels, and nickel alloys. The resulting welds must exhibit not only excellent static and dynamic mechanical properties and resistance to vibration but also high electrical conductivity. However, during the welding of these materials—particularly aluminum alloys to copper or steel—undesirable brittle intermetallic compounds (IMCs) tend to form, compromising joint performance [37].

To mitigate the formation of brittle joints, it is necessary to improve weldability through the use of specialized joining technologies that minimize or eliminate IMC formation.

5. ADVANCED WELDING TECHNIQUES FOR JOINING OF AHSS AND OTHER DISSIMILAR MATERIALS

Various technologies are used for joining multi-materials, such as fusion welding, solid-state welding, mechanical joining and fastening, adhesive bonding and hybrid joining, where two different technologies are used to produce a welded joint. The use of advanced joining techniques is required to assemble multi-material "body in white" (BiW) or multi-material electrical connections, depending on the specific requirements. In this paper, we will focus on advanced resistance welding techniques that are particularly useful for the automotive industry. We discuss here: i) the Arplass system, ii) the hybrid joining consisted of adhesive bonding and RSW, iii) the magnetically assisted RSW and for joining dissimilar materials iv) Interlayer-assisted RSW, v) the resistance element welding (REW) and vi) the locked projection welding process (LPW).

The Arplass system was introduced in the automotive industry due to the need to create invisible spot welds (Fig. 21). This system is a resistance projection welding process in which specially designed indentations or projections are created on the weld plate while the other plate remains flat. The indentations act as controlled projection contacts, generating localised heating. Once the material is heated, it is soften and collapse, forming a structural and invisible weld. The system is used to create structural welds with minimal heat input. It utilises a range of different resistance welding parameters (electrical current, welding time and welding force) together with an advanced control system. The latter precisely controls the welding parameters to limit the heat-affected zone, stabilises the process, reduces spatter or expulsion of molten material and ensures consistent weld quality even when the metal surfaces are not perfectly flat [38].

Fig. 21 *Arplass system produces invisible welding spots [38]*

The hybrid joining technologies are combining two technologies to for one welding joint. For shipbuilding applications, laser welding and Gas Metal Arc Welding are combined in order to improve penetration depths, compensate the welding edge tolerances, and limit the deformation of welding structure and to increase productivity. In the caravanning industry for instance an adhesive bonding is assisted with ultrasonic welding to speed up the production process, since adhesives need a few hours to obtain strength. In the automotive industry RSW is combined with adhesive bonding to improve BiW strength and to obtain watertight seals. The adhesives can be electrically conductive or not. They are usually applied to the joint area just before RSW takes place [39].

The third process is magnetically assisted resistance spot welding (MA-RSW), in which an externally applied magnetic field interacts with the welding current to generate a Lorentz force. This force strongly drives the flow of molten metal (stirs) in a specific direction. A schematic illustration of MA-RSW is presented in Fig. 22.

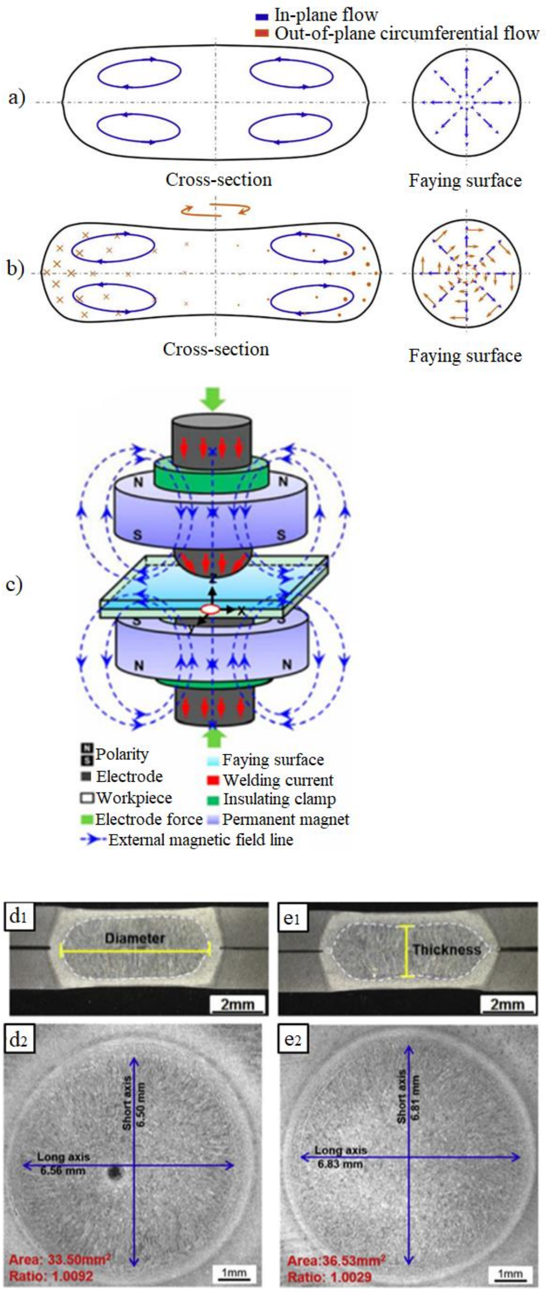

Fig. 22 *Molten metal flow patterns in a) traditional RSW and b) MA-RSW nugget. A schematic illustration of c) MA-RSW welding. Weld nugget of d) traditional RSW and e) MA-RSW [40]*

The induced stirring modifies the molten metal flow within the weld nugget during both melting and solidification, reducing the directionality of dendritic growth and diminishing the visibility of the faying surface. Furthermore, the intensive mixing of the liquid metal promotes the nugget diameter, grain refinement within the weld nugget, leading to enhanced mechanical properties compared to those achieved with conventional RSW [40].

The next three welding processes are especially useful for welding dissimilar materials, where IMCs are formed. At interlayer-assisted RSW (IA-RSW) (Fig. 23 a), a transition material such as thin foil or sheet or even coating is placed between workpieces before RSW takes place. During RSW the chemical composition of weld nugget and consequently its microstructure is modified. The intention of such modification is to improve the strength of the weld nugget by dilution of melted elements in fusion zone. Additionally the composition of the IMCs is controlled at the interface in dissimilar welding of steel, copper, aluminum alloy, magnesium alloy, Ti, and others [41].

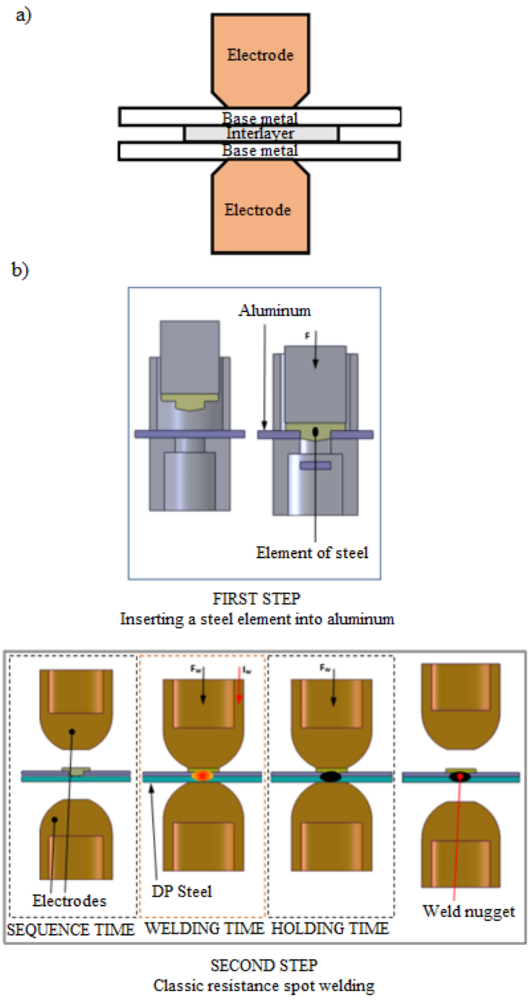

Fig. 23 *Schematic illustration of a) interlayer-assisted RSW (IA-RSW) [41] and b) Resistance Element Welding (REW) [30]*

The next process used for joining highly dissimilar materials is Resistance Element Welding (REW), which is especially used in the automotive and aerospace industry for joining different lightweight materials (aluminium alloy, magnesium alloy, carbon fiber reinforced plastic (CFRP), and others) to different steels. Figure 23 b illustrates the REW process. The first step is insertion of steel “rivet” into the lightweight material. Such samples are than RSW to the second steel sheet to produce the weld joint. In this was similar materials are welded together, without forming the IMCs. Manufacturing the parcel shelf for the VW’s Passat was one of the first applications of REW in mass production, saving over a kilogram of this component weight [42].

Locked projection welding (LPW) process is a novel resistance welding process that is suitable for joining highly dissimilar materials. This process is recommended for welding materials with significantly differing physical (much different melting temperature), and metallurgical properties, like aluminum alloy with copper or steel. The process is a variant of resistance projection welding where specially designed projection is done on the part with higher melting point and mechanical properties (Figure 24). This projection is not melted in the dissimilar interface of the weld joint, thus allowing mechanical penetration in the softer material as the latter melts. The researchers revealed that the solid-liquid process enables positive effect on metallurgical and mechanical properties compered to RSW, by increasing strength and not forming the IMCs. [43]

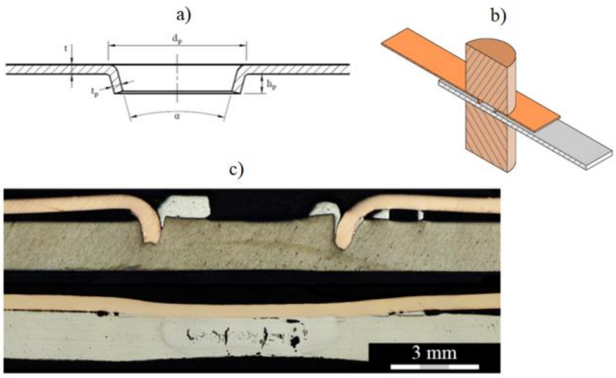

Fig. 24 *Schematic of LPW a) projection design, b) LPW process and c) comparison of macro-section of LPW (top) and RSW (bottom) weld [44]*

6. CONCLUSION

Resistance spot welding (RSW) remains a critical focus in the context of increasing industrial automation, particularly within high-throughput robotic manufacturing environments. In such settings, ensuring consistent weld quality is essential and can be most effectively achieved through the implementation of advanced control systems. These systems increasingly rely on artificial intelligence, sensor fusion, and real-time monitoring to enhance process stability and reduce defects. However, ongoing research is addressing the need for more cost-effective and reliable signal acquisition, along with the development of sophisticated control algorithms that can operate with minimal sensor input. Among emerging technologies, machine vision has shown particular promise in enabling real-time quality assessment and adaptive control.

In parallel, the automotive industry's shift toward lightweight design—driven by fuel efficiency standards and the rise of electromobility—has led to widespread adoption of advanced high-strength steels (AHSS) and other lightweight materials in body-in-white (BiW) structures. The integration of multi-material systems and dissimilar metal combinations, particularly in components such as battery packs and electric motors, presents new challenges for joining technologies. These applications demand welding solutions that ensure mechanical integrity, fatigue resistance, and, where applicable, high electrical conductivity. To meet these requirements, advanced welding and joining technologies are being developed and integrated with modern control strategies, enabling the reliable fabrication of next-generation electric vehicles.

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