Article

Analysis of the Behavior of Dynamic Resistance, Electrical Energy and Force between the Electrodes in Resistance Spot Welding Using Additive Manufacturing

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Received: 23 March 2020; Accepted: 15 May 2020; Published: 24 May 2020

Abstract: This work is aimed at the analysis of the dynamic resistance, electrical energy and behavior of the force between electrodes (including thermal expansion) during welding at optimized parameters, referring to the process of spot welding using additive manufacturing (AMSW). For comparative purposes, this analysis also includes the conventional resistance spot welding process (RSW). The experiments were done on low carbon-zinc-coated sheets used in the automotive industry. The results regarding the welding process using additive manufacturing (AMSW), in comparison to the conventional resistance spot welding (RSW), showed that the dynamic resistance presented a different behavior due to the collapse of the deposition at the beginning of the welding, and that a smaller magnitude of electrical energy (approximately <3.35 times) is required to produce a welding spot approved in accordance with the norm. No force of thermal expansion was observed during the passage of the current, in contrast, there was a decrease in the force between the electrodes due to the collapse of the deposition at the beginning of the welding.

Keywords: resistance spot welding; additive manufacturing; automotive industry; dynamic resistance

1. Introduction

The resistance spot welding process (RSW) is generally used to join sheets with similar thickness and chemical compositions. The main advantages of this process include ease of automation and high-speed welding. This process has been widely used for decades, particularly in the automotive industry [1–5]. Although this process may seem simple, it is necessary to control a large number of variables to produce satisfactory welding in an automated, high-speed production environment. In recent years, in order to meet the demand for lighter, economical and low-cost vehicles, the automotive industry’s manufacturing sector has undergone a revolution, in relation to the use of combinations of sheet steel with high mechanical strength, various chemical compositions and of different thicknesses. The chemical composition and surface conditions of the material to be welded are two variables that have an important effect on weldability [6–11]. In order to improve the weldability of the different sheets that constitute the current vehicle bodies, a new spot welding process using additive manufacturing (AMSW) was used in this work [12], due to its intrinsic characteristics of performing a deposition before welding from several types of materials, in different geometric formats with considerable precision [13–15].

This new process of spot welding using additive manufacturing (AMSW), under optimized conditions, has higher mechanical resistance in static shear stresses (tensile shear tests) and static
stresses perpendicular to the weld spot (cross-tension tests) compared to the resistance spot welding process (RSW). These best results found in spot welding using additive manufacturing (AMSW) are related to the lower HAZ (heat-affected zone), the absence of indentation and also the greater mechanical resistance of the alloy deposited in relation to the base material [12], as shown in Figure 1.

Although this new welding process (AMSW) is similar to projection welding, it has completely different characteristics regarding mechanical and metallurgical properties. For example: AMSW welding has no sheet thickness limit; the height of the projection is unique for any thickness (0.3 ± 0.1); the geometry of the projection can be changed; and it is possible to transform a weld spot with fragile characteristics to ductile by changing the chemical composition of the deposition [12]. It is important to highlight that this new spot welding process using additive manufacturing (AMSW) was patented by the authors of this article (U.S. Patent 15,442,655).

Therefore, this work aims to better understand the phenomena that occur during welding in relation to this new spot welding process using additive manufacturing (AMSW) on zinc-coated sheets used in the automotive sector. For this purpose, the behavior of the dynamic resistances, the magnitudes of the welding energies, the force between the electrodes and the thermal expansion of the weld spot were studied and analyzed. By way of comparison, welding spots were also made by the conventional resistance spot welding process (RSW), aiming at the quantification of the effect of the welding variables on the spots produced by the two processes. Figure 2 shows the typical behavior of the electrical resistance (dynamic) in steel sheets during resistance spot welding (RSW). This behavior can be basically divided into five stages [16–21]. Figure 2 also shows the correlation between the dynamic resistance and the formation of the welding spot.

Figure 1. (a) Macrography related to the conventional resistance spot welding process (RSW). (b) Macrography related to the process of spot welding using additive manufacturing (AMSW) [12].
This behavior can be basically divided into five stages [16–21]. Figure 2 also shows the correlation between the dynamic resistance and the formation of the welding spot.

Another important phenomenon during welding is the thermal or volumetric expansion of the base material. This phenomenon occurs during the heating of the metal in the solid state, as well as in the stage of transformation from solid to liquid and also during the heating in the liquid state. However, a free volumetric expansion of the metal in the liquid state during welding is not possible due to the compression of the electrodes. This compression is necessary to maintain the electrical and thermal contact at the interfaces, and to avoid the expulsion of the liquid metal during welding [22,23].

2. Materials and Methods

2.1. Characteristics of the Specimens

Additive manufacturing spot welding (AMSW) was performed, as well as, by way of comparison, resistance spot welding (RSW), and approximately 150 samples were produced and analyzed for each welding process. The sheets were overlapped and welded through a spot made in the middle of this area, and the dimensions of the specimens were based on AWS B4.0 standard, as shown in Figure 3.
For the accomplishment of the experiments, low carbon steel sheets of the automotive sector, with 0.8 mm of thickness and coated with zinc by the process of hot immersion were used. Table 1 presents the main elements regarding the chemical composition of the sheet.

**Table 1. Chemical composition of the steel sheet used in the experiments.**

| Alloy | C       | Mn     | P       | S       | Si     | Cu     | Ni     | Cr     | Mo     | Al     | Ti     |
|-------|---------|--------|---------|---------|--------|--------|--------|--------|--------|--------|--------|
| wt%   | 0.0030  | 0.6100 | 0.0330  | 0.0046  | 0.0770 | 0.0180 | 0.0056 | 0.0230 | 0.0020 | 0.0500 | 0.0480 |

Table 2 shows the mechanical properties of the zinc-coated steel sheet used in the experiments.

**Table 2. Mechanical properties of the steel sheet used in the experiments.**

| Property                  | Value       |
|---------------------------|-------------|
| Yield Strength [MPa]      | 88 ± 17     |
| Tensile Strength [MPa]    | 372 ± 1.5   |
| Ductility [% Elongation]  | 44 ± 0.6    |

2.2. Additive Manufacturing Spot Welding process (AMSW)

Additive manufacturing spot welding (AMSW) was performed in two stages. In the first stage (Figure 4a) the deposition of the spot with a predetermined geometry (height and diameter) on individual sheets was performed. The equipment used in the experiments to perform laser deposition with metallic powder was the RPMI 535 model, manufactured by RPM INNOVATIONS, INC (Rapid City, SD, USA). In the second stage (Figure 4b) the sheets were overlapped, one sheet with deposition and the other one without, as shown in Figure 4. Then, the electrodes with flat contact face were positioned on the sheets at the same coordinates of the deposition for the execution of the resistance spot welding [12].

![Figure 4. Stages of AMSW process: (a) schematic drawing (mm) of the laser deposition (additive manufacturing) using metallic powder (first stage); (b) also showing the overlapping sheets, one sheet with deposition and the other one without for the execution of the welding (second stage), respectively. Adapted from [12].](image-url)

The metallic powder used in the experiments, through the laser deposition process, was the 316L austenitic stainless steel manufactured by the gas atomization process. Table 3 shows the chemical composition of the metallic powder used in the experiments.
### Table 3. Chemical composition of the metallic powder—316L Stainless Steel.

| Alloy | C  | Mo | Ni  | Mn | Cr | Si | Fe  |
|-------|----|----|-----|----|----|----|-----|
| wt%   | 0.015 | 2.6 | 13.1 | 1.6 | 17.2 | 0.7 | Balance |

2.3. Characteristics of the Resistance Spot Welding Equipment used in the Experiments

In order to capture and monitor the magnitudes of voltage, current, force and displacement between the electrodes, digital oscilloscopes, as well as load sensors and linear displacement sensors were used. Subsequently, the captured signals were processed by a software named RAFT, developed by the company: WTC—Welding Technology Corporation (Farmington Hills, MI, USA) to perform dynamic resistance calculations [24]. In this experiment, a stationary spot welding equipment (Figure 5a) with a maximum force capacity of 5.0 kN between the electrodes and a medium frequency direct current was used. The geometry of the contact (electrode/sheet) used during the experiments, referring to spot welding using additive manufacturing (AMSW), was the flat face, with a diameter of 16 mm and a height of 20 mm (Figure 5b). For the welding with the resistance spot welding (RSW) process, an electrode with a spherical contact face and a radius of 8 mm, a diameter of 16 mm and a height of 20 mm was used. Figure 5 shows an overview of the equipment and accessories used in the experiments.

![Resistance spot welding equipment and accessories](image)

![Geometry of the contact](image)

2.4. Optimized Welding Parameters and Weld Point Acceptance Criteria

For the selection of the optimized welding parameters, the minimum dimensions for the approval of the diameter of the spot weld were observed, as well as the minimum resistance for tensile shear tests, as shown in Table 4.

### Table 4. Dimensions and minimum tensile strength used for welding spot approval.

| Sheet Thickness (mm) | Spot Diameter (Macrography Test) (mm) | Spot Diameter (Peel Test) (mm) | Minimum Strength: Tensile Shear Test (kN) |
|----------------------|--------------------------------------|--------------------------------|------------------------------------------|
| 0.8                  | 3.1                                  | 3.6                            | 2.3                                      |

Table 5 presents the optimized parameters for the execution of the experiments for both resistance spot welding (RSW) and spot welding using additive manufacturing (AMSW).
Table 5. Optimized welding parameters for the execution of the experiments.

| Welding Process | Current (kA) | Time (ms) | Force (kN) | Holding Time (ms) |
|-----------------|--------------|-----------|------------|------------------|
| RSW             | 7.8          | 225       | 2.9        | 300              |
| AMSW            | 8.0          | 60        | 1.1        | 300              |

3. Results and Discussion

3.1. Analysis of the Dynamic Resistance Behavior between the Spot Welding Process using Additive Manufacturing (AMSW) and the Conventional Resistance Spot Welding Process (RSW)

Figure 6 shows the comparison of the dynamic resistance, using the optimized parameters, between the spot welding process using additive manufacturing (AMSW) and the resistance spot welding (RSW) process on zinc-coated sheets.

By the analysis of Figure 6, it can be noticed that the initial dynamic resistance of the spot welding using additive manufacturing was 15.2% greater when compared to the conventional resistance spot welding (RSW). This fact is due to the greater electrical resistivity of the material of deposition, and also the smaller area for the passage of the current when compared to the conventional resistance spot welding process. It can also be observed that the behavior of the dynamic resistance for the resistance spot welding process on zinc-coated sheets was as expected, i.e., (1) there was an initial decrease of the electrical resistance due to oxide fragmentation, and to the increase of the contact area, through the collapse of the roughness at the interfaces of the sheets. Subsequently, (2) there was a small increase in dynamic resistance because of the increase of the temperature, followed by a small drop in dynamic resistance (3). This small drop is related to the burning of zinc. After the zinc burns, the highs and lows of the roughness of the base material meet and then their collapse occurs. This collapse increases the contact area by decreasing the dynamic resistance. After this fact, the dynamic resistance increased again due to the increase in temperature (4). And in the last stage, (5) there was a decrease of the dynamic resistance caused by the increase of the contact area through the penetration of the electrodes on the surfaces of the sheets.

In relation to the spot welding process using additive manufacturing (AMSW) on zinc-coated sheets, a drop of the dynamic resistance occurred from the beginning of the welding to around 40 ms.
(6), where a curve inflection occurred (7). A possible explanation for this drop in the dynamic resistance (6) is the increase of the contact area due to the collapse of the deposition. With respect to the curve inflection (7) this may be related to the temperature raise due to the increase of the melted mass between the deposited material and the base material at the final moments in the formation of the welding spot. Shortly after the inflection of the curve, there was a sudden drop in dynamic resistance, or more precisely in 46 ms (8). This fact is related to the zinc burning, as previously explained in stage (3).

3.2. Comparative Analysis of Electrical Energy between the Spot Welding Process using Additive Manufacturing (AMSW) and the Conventional Resistance Spot Welding Process (RSW)

Figure 7 shows the comparison of the electrical energy, through the optimized parameters, between the spot welding process using additive manufacturing (AMSW) and the resistance spot welding (RSW) process on zinc-coated sheets. It can be observed that the total electrical energy related to the spot welding process using additive manufacturing was 782 J, and for the resistance spot welding process was 2624 J, i.e., the electric energy was 235.54% higher when compared to the spot welding process using additive manufacturing. This result is due to a higher concentration of energy in a predetermined area, performed through the laser deposition, and also due to the greater electrical resistivity, and lower thermal conductivity of the deposited material. These facts result in lower losses, and greater efficiency in the generation of thermal energy during welding.

Figure 7. Comparison of electrical energy between the spot welding process using additive manufacturing (AMSW) and the resistance spot welding (RSW) process on zinc-coated sheets.

3.3. Comparative Analysis of the Behavior of the Force between the Electrodes Referring to the Spot Welding Process using Additive Manufacturing (AMSW) and the Resistance Spot Welding Process (RSW)

Figure 8 shows the comparison of the force behavior between the electrodes, through the optimized parameters, in relation to the spot welding process using additive manufacturing (AMSW), and the resistance spot welding (RSW) process on sheets coated with zinc.
The behavior of the dynamic resistance related to the spot welding process using additive manufacturing when compared to the spot welding process using additive manufacturing, i.e., a decrease of 77.27% was observed, i.e., an increase of 10%. This fact is due to the melting between the sheets, the metal in the liquid state has a larger volumetric expansion than in the solid state. On the other hand, there was a decrease in the force between the electrodes from 1.1 kN to 2.5 kN during the passage of current (2) when compared to the spot welding process using additive manufacturing, i.e., a decrease of 77.27%. This result is related to the instantaneous collapse of the deposition during the passage of the current, causing a partial loss of contact of the electrodes from the surfaces of the sheets.

As shown by the behavior of the dynamic resistance, referring to the process of spot welding by the resistance spot welding process, a thermal expansion force (2) that came from 2.90 kN to 3.19 kN was observed, i.e., an increase of 10%. This fact is due to the melting between the sheets, the metal in the liquid state has a larger volumetric expansion than in the solid state. On the other hand, there was a decrease in the force between the electrodes from 1.1 kN to 2.5 kN during the passage of current (2) when compared to the spot welding process using additive manufacturing, i.e., a decrease of 77.27%. This result is related to the instantaneous collapse of the deposition during the passage of the current, causing a partial loss of contact of the electrodes from the surfaces of the sheets.

Figure 8 also shows the behavior of the force (versus time) of the entire welding process sequence, that is, the stabilization of the force (1), the behavior of the force during the passage of the current (2), and the force for solidification or cooling of the welding spot (3).

4. Conclusions

Based on the materials used, the experiments carried out and the results obtained, it is possible to conclude that:

1. The behavior of the dynamic resistance related to the spot welding process using additive manufacturing (AMSW) was different when compared to the conventional resistance spot welding process (RSW). This result is related to the collapse of the deposition due to its heating in the first milliseconds of welding.

2. As shown by the behavior of the dynamic resistance, referring to the process of spot welding using additive manufacturing (AMSW), the formation of the welding spot occurs at the final moments of the passage of the electric current. This fact is evidenced by the burning of the zinc represented in stage 8 of the Figure 6.

3. The spot welding process using additive manufacturing (AMSW) requires smaller magnitudes of electrical energy (approximately <3.35 times) to produce an approved welding spot according to the standard when compared with the conventional resistance spot welding (RSW).

4. A thermal expansion force during the electric current flow was observed for the resistance spot welding process (RSW). On the other hand, for the spot welding process using additive manufacturing (AMSW), there was a decrease in the force between the electrodes due to the collapse of the deposition at the start of welding.
5. Patent

The process of resistance spot welding using additive manufacturing (AMSW) was patented by the authors of this article. Patent Number: 15442655–USA.

Author Contributions: M.B., V.F. and S.D.B. conceived and designed the experiments; M.B. and V.F. performed the experiments; M.B. and S.D.B. analyzed the data; and M.B. and S.D.B. wrote the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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