Reliability of a resistance spot welding process based on characteristics parameters

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Abstract

In this paper, the reliability of a resistance spot welding (RSW) process is studied by monitoring the quality of the corresponding welding points. Each welding point is uniquely represented by a resistance curve over time. Five learning resistance curves, the good quality of the related welding points was verified by means of experimental non-destructive ultrasonic techniques, are available. The corresponding learning maximum, minimum and average resistance curves, as a reference to check the quality of the welding points related to different process resistance curves, are obtained. In order to estimate the quality of a generic welding point, two different parameters comparing the corresponding process resistance curve with the learning maximum, minimum and average resistance curves are considered, i.e., Euclidean distance and ascent/descent velocity. Both good quality and defective welding points are observed, where Euclidean distance allows the presence of the defect to be detected, while ascent/descent velocity allows the typology of the defect to be diagnosed.

1 Introduction

RSW is a typology of welding that uses the heat produced by Joule effect from the passage of electric current between two sheets pressed each against other by two copper electrodes housed on a clamping plier. The electric machine generates a high intensity electric current (1000÷100000 A) for a short time (fractions of one second), and the passage of electric current develops a high amount of heat in a small area on the contact surface of the sheets (where the electrical resistance results maximum). The heat increases the temperature of the metal until it reaches its melting value, and the sequent solidification of the metal, which takes place while the electrodes are still pressed on the two sheets, leads to the formation of the welding point [1-2].

RSW process is extensively applied for the production in series of metallic components due to the very high precision level, operative velocity and automation degree [3-4]. In particular, RSW process is used for thin aluminum or steel sheets in automobile field, such as for car chassis, floor, side wall, doors and body [5-8]. A review of the current state of the art of RSW process monitoring can be found in Refs. [9-13].

In the present work, RSW process is applied on a specific steel component located in the front part of the car body, having the task of absorbing both frontal and lateral impacts suffered by the car frame. The RSW process reliability is studied by investigating the quality of the welding points corresponding to resistance curves that are continuously recorded by means of the acquisition system. Five learning resistance curves are available, where the quality of the corresponding welding points was experimentally verified by means of the non-destructive ultrasonic method. The related learning maximum, minimum and average resistance curves are derived, which are taken as reference to check the quality of the welding points related to different process resistance curves.

To estimate the quality of a generic welding point, two different characteristic parameters comparing the corresponding process resistance curve with the learning maximum, minimum and average resistance curves are adopted, i.e., Euclidean distance and ascent/descent velocity. The aim of the present work is initially to detect the presence of defective welding points and subsequently to diagnose the typology of the defects.

2 Data set description

In this paper, RSW process is considered to weld the different sheets of a specific steel component located in the front part of a car body. The main task of this structural mechanical component is to absorb the energy generated by high-speed front and side collisions suffered by car chassis, so as to better protect the occupant of the car.

A large data set is available consisting of a set of electric current, resistance, voltage and power characteristic curves, which were acquired using several sensors placed on RSW machine. The full data set is divided into learning and process data sets. The learning data set consists of five characteristic curves, the good quality of the related welding points was experimentally verified by means of the non-destructive ultrasonic method. On the other hand, the process data set comprises all the other characteristic curves, the quality level of the corresponding welding points is monitored in the present work by different data analysis techniques.

In this paper, only resistance characteristic curves are studied, because the other electric curves present the same behavior over time; moreover, each resistance characteristic curve refers to one single welding process (impulse) that produces one welding point in the time period of 260 ms. The main goal of the data analysis is to identify potentially dangerous (i.e., low quality) welding points to be properly checked after production by means of non-destructive ultrasonic tests.

2.1 Learning resistance curves

In Figure 1, the five different learning resistance curves of the learning data set as a function of the welding time are plotted. Since the quality of the welding points corresponding to these five resistance curves was preventively verified experimentally via non-destructive tests, then these curves will serve as a reference to analyze the quality of the welding points related to the resistance curves of the process data set. Starting from the five learning resistance curves of Figure 1, the corresponding learning maximum, minimum and average resistance curves are found, see Figure 2, which will be used in the following comparisons with the process resistance curves. In particular, the learning maximum resistance curve is given by the points that, in every time instant, have the highest value among the five learning resistance curves available; the learning minimum resistance curve is given by the points that, in every time instant, have the lowest value among the five learning resistance curves available; the learning average resistance curve is given by the average, in every time instant, between the learning maximum and minimum resistance curves.

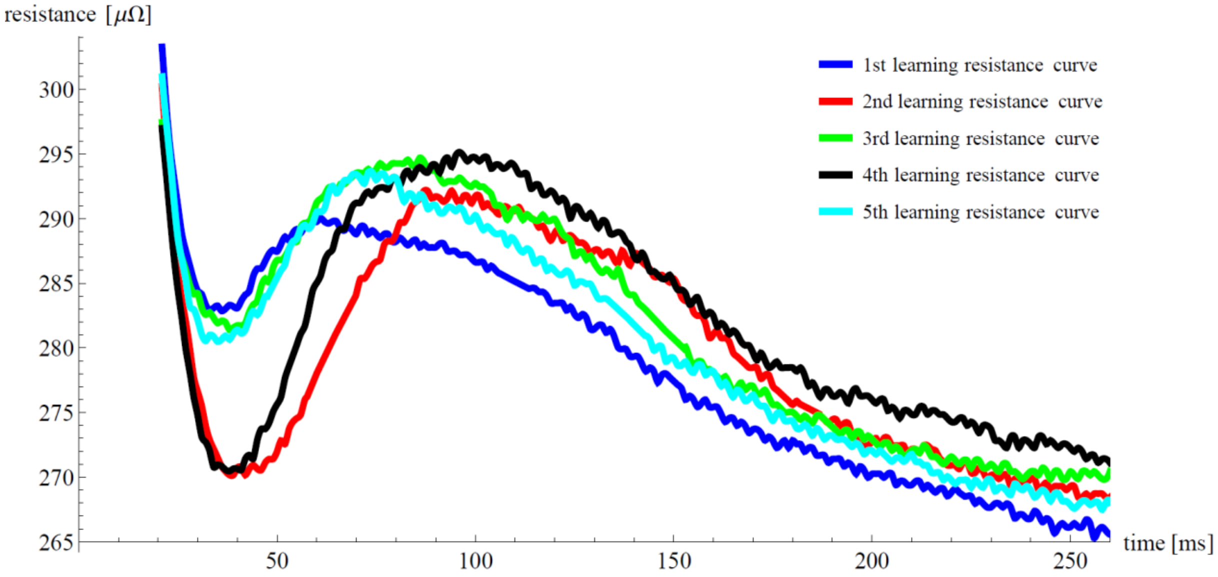

Figure 1: Five learning resistance curves as a function of the welding time

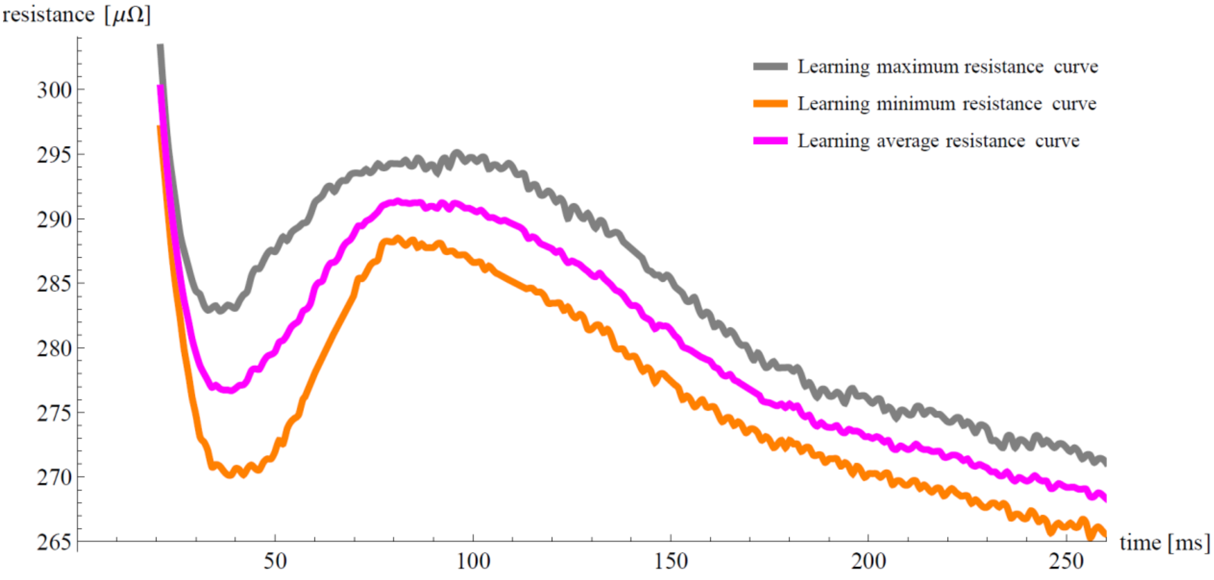

Figure 2: Learning maximum, minimum and average resistance curves

2.2 Process resistance curves

The main indices of RSW process with regard to the related resistance curve are: (i) metal melting speed for the ascent phase, (ii) joint cooling speed for the descent phase, see Figure 3. In data analysis section, cases of both good quality and defective welding points will be presented.

A generic welding point is defined of good quality (i.e., good spot) when the corresponding resistance curve provides indices close to the ones of the learning resistance curves. In this case, a correct value of thermal energy is involved in the welding process, and the nugget diameter and penetration depth have a proper size. On the other hand, starting from these indices, three different types of welding defects can be recognized.

First, a welding is absent of peak if the growth rate of its resistance curve before melting (melting speed) is much lower than the learning resistance curves. This is caused by an insufficient heat energy, which has not guaranteed the proper grain growth, meaning that the nugget diameter is lower than the nominal value (small nugget).

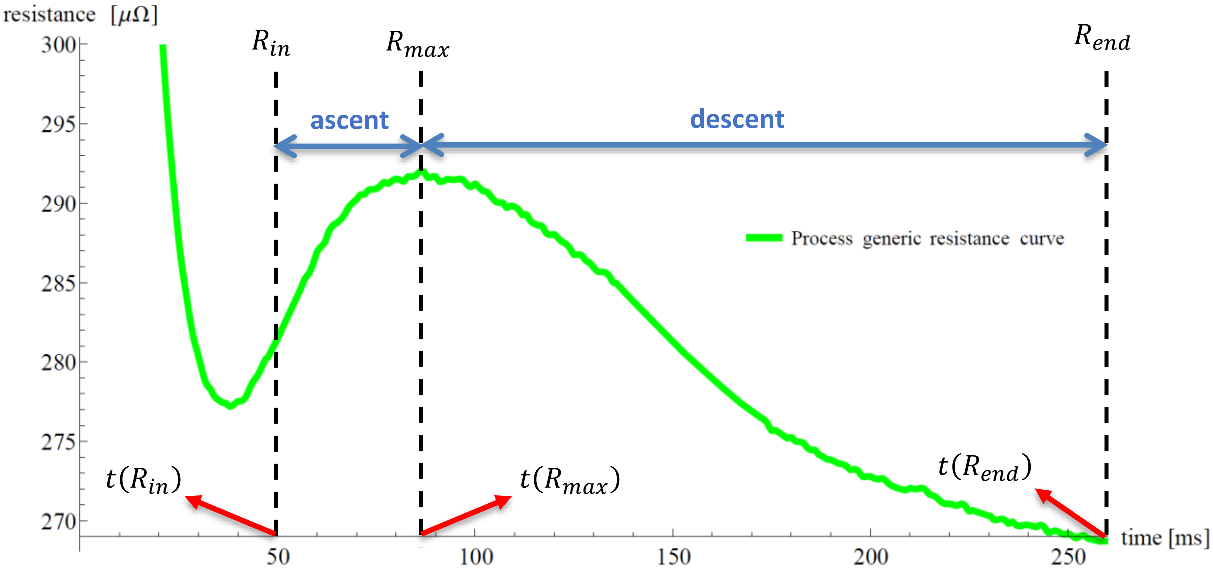

Figure 3: Process generic resistance curve. Ascent and descent phases

Second, a welding is squeezed if the degrowth rate of its resistance curve after melting (cooling speed) is much higher than the learning resistance curves. This is due to a much higher amount of thermal energy that has been released at the welding point than the learning one, which involves the presence of welding material expulsion and therefore a sharp drop in the resistance curve (burnt spot).

Third, a welding is glued if the degrowth rate of its resistance curve after melting (cooling speed) is much lower than the learning resistance curves. This is due to a much lower amount of heat energy that has been released at the welding point than the learning one, meaning that the metal sheets are not jointed or they are jointed only at the interface contact points (cold spot).

3 Characteristics parameters

To properly identify the quality of a generic welding point, in the following, two characteristics parameters comparing the corresponding process resistance curve with the maximum, minimum and average learning resistance curves are adopted, i.e., Euclidean distance and ascent/descent velocity.

3.1 Euclidean distance

The first technique adopted for the monitoring of the quality of the welding points is the Euclidean distance.

Euclidean distance d_{eucl} between two vectors $(x, y) \in R^n$ with equal length is defined as the square root of the sum of the squared absolute values of the differences between the single elements of the two vectors:

$$d_{eucl}(x, y) = \sqrt[2]{\sum_{i=1}^{n} |x_i - y_i|^2} \tag{1}$$

Similarly, Euclidean distance d_{eucl} between two curves $(F_1(t), F_2(t))$ with equal time duration is defined as the square root of the time integral from the initial t_i to the final t_f time instant of the squared absolute value of the difference between the two corresponding functions:

$$d_{eucl}(F_1(t), F_2(t)) = \sqrt[2]{\int_{t_i}^{t_f} |F_1(t) - F_2(t)|^2 dt} \tag{2}$$

By taking as reference the learning average resistance curve, which corresponds to a welding point of good quality, Euclidean distances of the process generic and learning maximum resistance curves were calculated and measured in $\mu\Omega$. It should be underlined that, in this work, the learning average resistance curve, having been taken as reference, has zero Euclidean distance, while the learning maximum and minimum resistance curves, for how the learning average resistance curve has been obtained, present the same value of Euclidean distance.

Regarding the reliability of a resistance spot welding process, it was assumed that, given a process generic resistance curve, if its Euclidean distance is lower than the Euclidean distance of the learning maximum resistance curve, then the quality of the corresponding welding point is good (good welding); if, on the other hand, its Euclidean distance is higher than or equal to the Euclidean distance of the learning maximum resistance curve, then the quality of the corresponding welding point is not good (defective welding).

It is emphasized that the process Euclidean distance, calculated as the distance between the process generic resistance curve and the learning average resistance curve, returns a single value as a response for the whole process resistance curve. Therefore, Euclidean distance provides a preliminary estimate of the quality of the welding (good or defective), which allows the presence of a possible defect to be observed (fault detection), but which does not allow the specific typology of the defect itself (e.g., small nugget, burnt or cold spot) to be identified (fault diagnosis).

3.2 Ascent/descent velocity

To fill the previous gap, the process generic resistance curve has been divided into two parts, i.e., ascent and descent phase, see Figure 3, and two new characteristics parameters have been introduced, i.e., ascent and descent velocity, identified as significant indices for monitoring the quality of the welding process.

Given a generic resistance curve, the ascent velocity is defined as the ratio between the ascent resistance difference and the ascent time, where the ascent resistance difference is given by the difference between the maximum resistance R_{max} and the initial resistance R_{in} of the curve, and the ascent time is given by the difference between the time instant t corresponding to the maximum resistance R_{max} and the time instant t corresponding to the initial resistance R_{in} of the curve:

$$v_{asc} = \frac{R_{max} - R_{in}}{t(R_{max}) - t(R_{in})} > 0 \tag{3}$$

The ascent velocity, which corresponds to the nugget melting process, is measured in $\mu\Omega/\mathrm{ms}$.

Given a generic resistance curve, the descent velocity is defined as the ratio between the absolute value of the descent resistance difference and the descent time, where the descent resistance difference is given by the difference between the final resistance R_{end} and the maximum resistance R_{max} of the curve, and the descent time is given by the difference between the time instant t corresponding to the final resistance R_{end} and the time instant t corresponding to the maximum resistance R_{max} of the curve:

$$v_{desc} = \frac{|R_{end} - R_{max}|}{t(R_{end}) - t(R_{max})} > 0 \tag{4}$$

The descent velocity, which corresponds to the nugget cooling process, is also measured in $\mu\Omega/\mathrm{ms}$.

Regarding the reliability of a resistance spot welding process, it was assumed that, given a process generic resistance curve, if its ascent velocity is comprised between the ascent velocities of the learning maximum and minimum resistance curves, and if at the same time its descent velocity is comprised between the descent velocities of the learning maximum and minimum resistance curves, then the quality of the corresponding welding point is good (good welding); otherwise, the quality of the corresponding welding point is probably not good (defective welding).

Therefore, the ascent and descent velocities, returning a single value as a response for each of the two parts into which the process resistance curve has been divided, provide an accurate estimate of the quality of the welding (good or defective), allowing the defect to be located along the curve (melting or cooling process) and therefore the specific type of the defect itself (e.g., small nugget, burnt or cold spot) to be recognized.

4 Data analysis

In this Section, the results obtained by implementing the data analysis techniques for the monitoring of the quality of the welding points introduced in Section 3 are reported, i.e., Euclidean distance and ascent/descent velocity, as applied to the corresponding process resistance curves.

These results refer to the analyses carried out on the data provided by FIAT Research Centre (CRF) and coming from the FCA plant in Melfi (Italy) as a part of the Research Project ARS01_00861 “Integrated and

Collaborative Systems for Smart Factory - ICOSAF" financially supported by Italian Ministry of University and Research (MUR).

4.1 Good welding (good spot)

In Figure 4, the learning maximum, minimum and average resistance curves, which have been defined in Section 2, together with a process resistance curve relating to a generic welding point whose quality is to be evaluated, are shown. The ascent and descent phases of the curves are enclosed within two different dashed ovals. The values of Euclidean distance and ascent/descent velocities of the considered resistance curves are reported in Table 1.

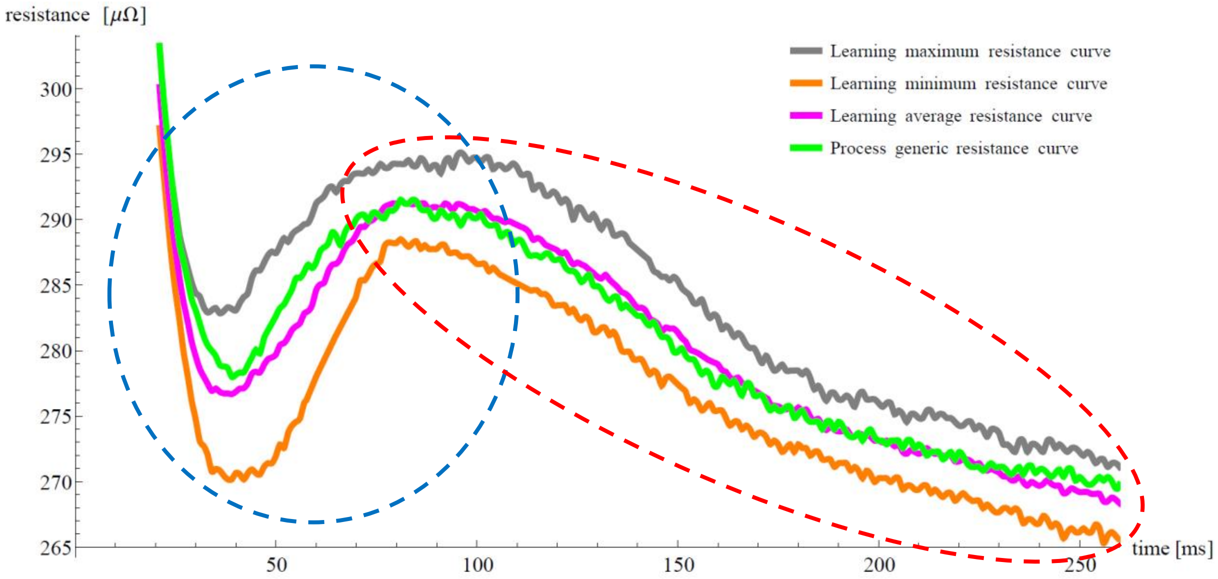

Figure 4: Learning and process resistance curves. Good spot

In this case it is obtained that the Euclidean distance of the process generic resistance curve is lower than the Euclidean distance of the learning maximum resistance curve, and therefore it can be expected that the quality of the corresponding welding point is good. This result is confirmed by the fact that, in Figure 4, the process generic resistance curve is contained within the learning maximum and minimum resistance curves along the entire time duration of the welding pulse.

Table 1: Euclidean distance, ascent and descent velocity of the resistance curves of Figure 4

Resistance curve	Euclidean distance [$\mu\Omega$]	Ascent velocity [$\mu\Omega$/ ms]	Descent velocity [$\mu\Omega$/ ms]
Learning maximum	63.56	0.161	0.146
Learning minimum	63.56	0.519	0.128
Process generic	**20.96**	**0.209**	**0.134**

From Table 1 it can be observed that the ascent velocity of the process generic resistance curve is included between the ascent velocities of the learning maximum and minimum resistance curves, which implies the prediction of good welding for the ascent phase. Again from Table 1 it is noted that also the descent velocity of the process generic resistance curve is included between the descent velocities of the learning maximum and minimum resistance curves, which implies the prediction of good welding also for the descent phase.

Therefore, from the study of the ascent and descent velocities, the initial prediction of good welding obtained by calculating the Euclidean distance is confirmed, and a good spot is estimated.

4.2 Defective welding (burnt spot)

In Figure 5, the learning maximum, minimum and average resistance curves, and a process resistance curve relating to a generic welding point, different from the previous one, whose quality is to be evaluated, are shown. The values of Euclidean distance and ascent/descent velocities of the considered resistance curves are reported in Table 2.

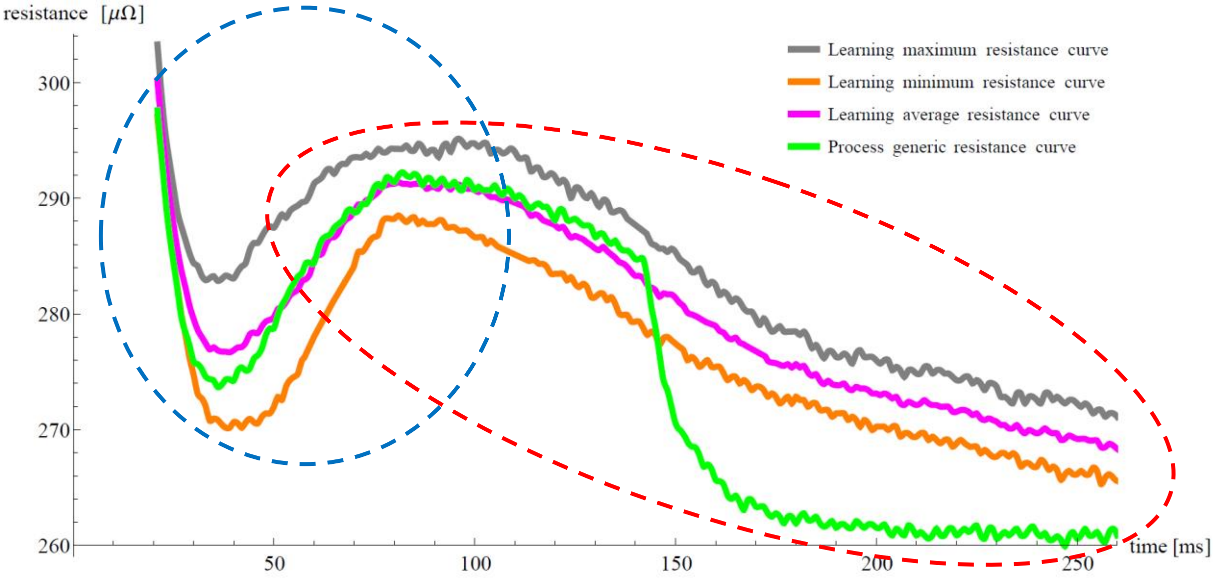

Figure 5: Learning and process resistance curves. Burnt spot

In this case it is obtained that the Euclidean distance of the process generic resistance curve is higher than the Euclidean distance of the learning maximum resistance curve, and therefore it can be expected that the quality of the corresponding welding point is bad. This result is confirmed by the fact that, in Figure 5, the process generic resistance curve is not contained within the learning maximum and minimum resistance curves in the final part of the welding pulse, presenting a sharp drop in the descent phase.

Table 2: Euclidean distance, ascent and descent velocity of the resistance curves of Figure 5

Resistance curve	Euclidean distance [$\mu\Omega$]	Ascent velocity [$\mu\Omega/\mathrm{ms}$]	Descent velocity [$\mu\Omega/\mathrm{ms}$]
Learning maximum	63.56	0.161	0.146
Learning minimum	63.56	0.519	0.128
Process generic	**119.4**	**0.311**	**0.176**

From Table 2 it can be observed that the ascent velocity of the process generic resistance curve is included between the ascent velocities of the learning maximum and minimum resistance curves, which implies the prediction of good welding for the ascent phase. Again from Table 2 it is noted that the descent velocity of the process generic resistance curve is not included between the descent velocities of the learning maximum and minimum resistance curves, which implies the prediction of defective welding for the descent phase.

Therefore, from the study of the velocities, the initial prediction of defective welding obtained by calculating the Euclidean distance is confirmed. In particular, since the defect is due to a descent velocity of the process resistance curve that is too high compared to that of the learning average resistance curve, and that this sharp drop in resistance in the descent phase can be due to the presence of an excessively high thermal energy that in turn causes the expulsion of parts of incandescent sheet metal, then in this case the presence of a squeezed welding and therefore of a burnt spot can be estimated.

4.3 Defective welding (cold spot)

In Figure 6, the learning maximum, minimum and average resistance curves, and a process resistance curve relating to a generic welding point, different from the previous ones, whose quality is to be evaluated, are shown. The values of Euclidean distance and ascent/descent velocities of the considered resistance curves are reported in Table 3.

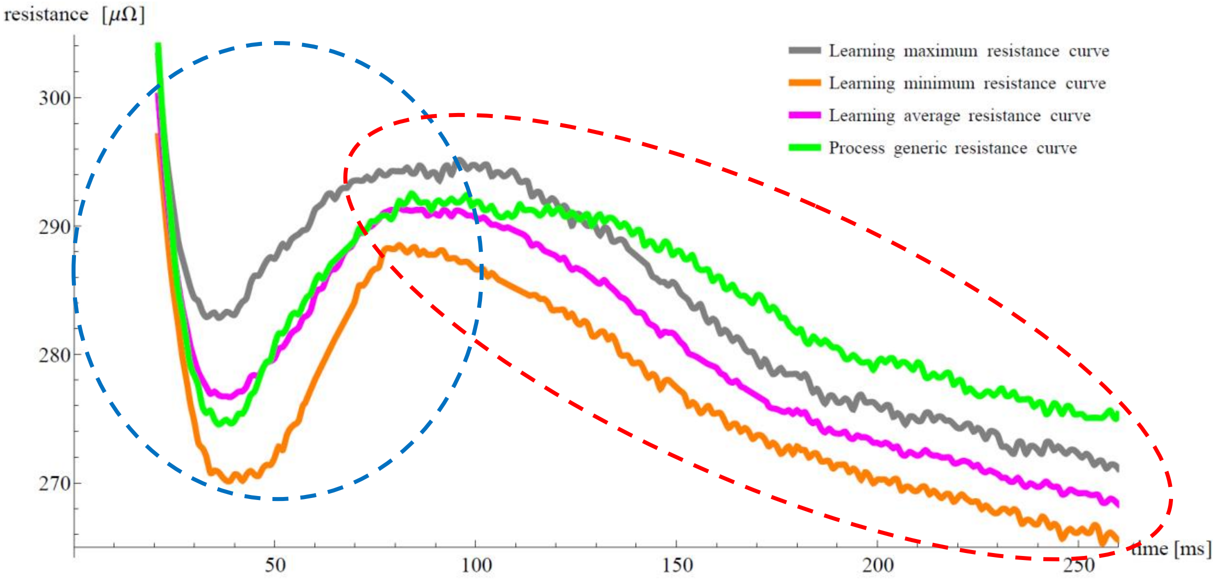

Figure 6: Learning and process resistance curves. Cold spot

In this case it is obtained that the Euclidean distance of the process generic resistance curve is higher than the Euclidean distance of the learning maximum resistance curve, and therefore it can be expected that the quality of the corresponding welding point is bad. This result is confirmed by the fact that, in Figure 6, the process generic resistance curve is not contained within the learning maximum and minimum resistance curves in the final part of the welding pulse, presenting a reduced drop in the descent phase.

From Table 3 it can be observed that the ascent velocity of the process generic resistance curve is included between the ascent velocities of the learning maximum and minimum resistance curves, which implies the prediction of good welding for the ascent phase. Again from Table 3 it is noted that the descent velocity of the process generic resistance curve is not included between the descent velocities of the learning maximum and minimum resistance curves, which implies the prediction of defective welding for the descent phase.

Table 3: Euclidean distance, ascent and descent velocity of the resistance curves of Figure 6

Resistance curve	Euclidean distance [$\boldsymbol{\mu\Omega}$]	Ascent velocity [$\boldsymbol{\mu\Omega}/\mathbf{ms}$]	Descent velocity [$\boldsymbol{\mu\Omega}/\mathbf{ms}$]
Learning maximum	63.56	0.161	0.146
Learning minimum	63.56	0.519	0.128
Process generic	**76.40**	**0.286**	**0.097**

Therefore, from the study of the velocities, the initial prediction of defective welding obtained by calculating the Euclidean distance is confirmed. In particular, since the defect is due to a descent velocity of the process resistance curve too low compared to that of the learning average resistance curve, and that this reduced drop in resistance in the descent phase can be due to the presence of an excessively reduced thermal energy that causes the non-fusion of the sheet metal and therefore the lack or limited formation of the weld nugget, then in this case the presence of a glued welding and therefore of a cold spot can be estimated.

From the results illustrated in Figures 5-6, and reported in Tables 2-3, the importance of the descent velocity of the process resistance curve was deduced, as a characteristic parameter directly linked to the solidification or cooling process of the welding nugget, which can provide a significant estimate of the quality of a weld, allowing a good welding (i.e., correct formation of the weld nugget) or a faulty welding (squeezed or glued) to be correctly identified.

4.4 Defective welding (small nugget and burnt spot)

Another significant estimate of the quality of a welding point is provided by the ascent velocity of the related resistance curve. In fact, if the ascent velocity of a process generic resistance curve is not included between the ascent velocities of the learning maximum and minimum resistance curves, then this can lead to an incorrect melting process of the welding nugget and therefore to the realization of a defective welding. It will be the subsequent calculation of the descent velocity of the resistance curve to provide more detailed and complete information on the specific type of defect.

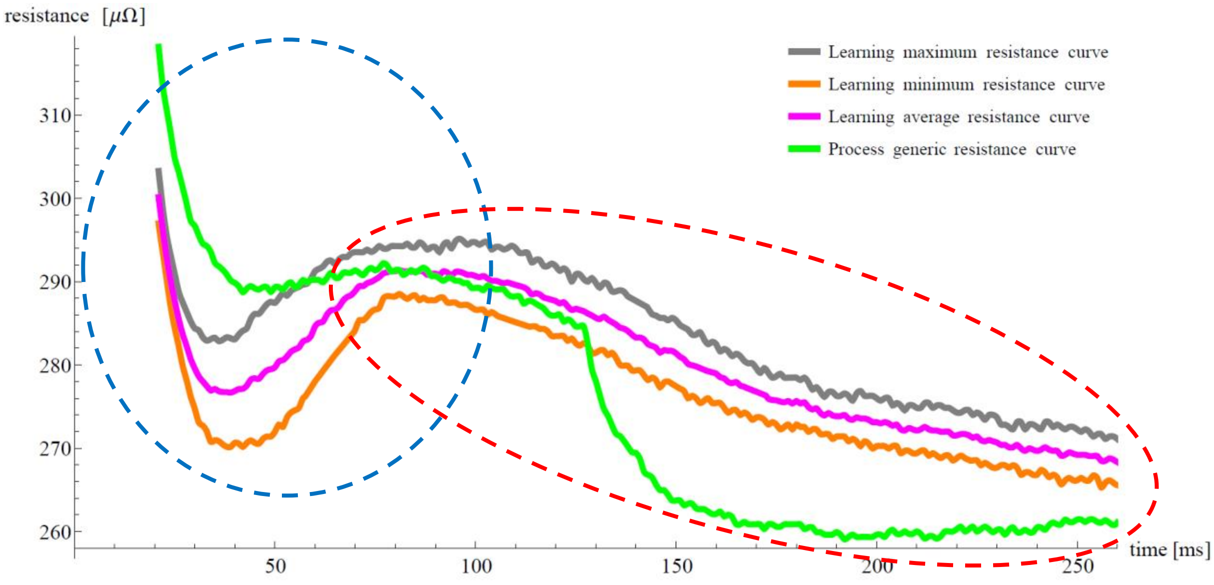

Figure 7: Learning and process resistance curves. Small nugget and burnt spot

In Figure 7, the learning maximum, minimum and average resistance curves, and a process resistance curve relating to a generic welding point, different from the previous ones, whose quality is to be evaluated, are shown. The values of Euclidean distance and ascent/descent velocities of the considered resistance curves are reported in Table 4.

Table 4: Euclidean distance, ascent and descent velocity of the resistance curves of Figure 7

Resistance curve	Euclidean distance $[\mu\Omega]$	Ascent velocity $[\mu\Omega/\mathrm{ms}]$	Descent velocity $[\mu\Omega/\mathrm{ms}]$
Learning maximum	63.56	0.161	0.146
Learning minimum	63.56	0.519	0.128
Process generic	**173.7**	**0.085**	**0.169**

In this case it is obtained that the Euclidean distance of the process generic resistance curve is much higher than the Euclidean distance of the learning maximum resistance curve and it can be estimated that the quality of the corresponding welding spot is not good (defective welding). This result is confirmed by the fact that, in Figure 7, the process generic resistance curve is not contained within the learning maximum and minimum resistance curves both in the initial and in the final part of the welding pulse, presenting a very low increase (almost flat behaviour) in the ascent phase and a sharp drop in the descent phase.

From Table 4 it is observed that the ascent velocity of the process generic resistance curve is not included between the ascent velocities of the learning maximum and minimum resistance curves, in particular it is lower than the ascent velocity of the learning maximum resistance curve: this can lead to an incorrect melting process of the welding nugget, since the melting temperature of the metal has not been reached, and therefore to the production of a defective welding.

From Table 4 it is also noted that the descent velocity of the process generic resistance curve is higher than the descent rate of the learning maximum resistance curve, and this, as seen above, involves the prediction of a squeezed welding. Therefore, from the study of the velocities, the estimate of a defective welding is derived for the welding point in question, in accordance with what was previously obtained by means of the calculation of the Euclidean distance. In addition, the defective welding (no peak) detected by the analysis of the ascent velocity is completed, in this case, as a squeezed welding by the analysis of the descent velocity.

From a technological point of view, it can be said that a very low ascent velocity leads to a process resistance curve that does not have a well-defined peak at the melting point (maximum resistance value R_{max}) due to the fact that the correct melting temperature of the metal has not been reached (i.e., reduced thermal energy), and therefore the corresponding welding point is defective.

In some cases (see Figure 7), an incorrect melting process is followed by an accumulation of thermal energy that causes the expulsion of parts of incandescent metal sheet (squeezed weld). Therefore, it is necessary to compute both the ascent and the descent velocity of the process resistance curve corresponding to a generic welding point in order to obtain an accurate estimate of its quality, identifying the correct formation of the nugget (good welding) or observing the presence of a defective weld (no peak, squeezed or glued welding).

5 Conclusions

The reliability of a RSW process was studied by monitoring the quality of the corresponding welding points. This was obtained by comparing the related process resistance curve with the learning maximum, minimum and average resistance curves. Two different characteristics parameters were adopted, i.e., Euclidean distance and ascent/descent velocity. Both good quality and defective welding points were observed. It was obtained that the Euclidean distance, returning a single value as response for the whole process resistance curve, provides a preliminary estimate of the quality of the welding point, allowing the presence of the possible defect to be observed (i.e., fault detection). On the other hand, it was derived that the ascent/descent velocities, returning a single value as response for each of the two parts (ascent and descent phases) of the process resistance curve, provide an accurate estimate of the quality of the welding point, allowing the specific typology of the defect itself (small nugget, burnt or cold spot) to be identified (i.e., fault diagnosis).

Acknowledgements

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