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Abstract: This work aims to respond to the need derived from the highly changing and competitive nature of the industrial environment in which the resistance spot welding (RSW) process is implemented, providing an updated and structured comprehensive overview of the advances that are being made in the field of quality control and the improvement of quality for this manufacturing process.

Keywords: welding processes; competitiveness; nondestructive testing; welding parameters

1. Introduction

Resistance spot welding (RSW) is a process characterized by its high speed and adaptability for automation that renders it suitable for mass production [1,2]. Therefore, resistance spot welding (RSW) is a key joining technology in the automotive industry [3,4], where competitiveness is increasing with each passing day [5]. This highly competitive industrial environment leads not only to the fact that, in recent times, the process has undergone numerous and significant advances in aspects such as quality control and the development of new strategies to improve weld quality, but also in the fact that interesting alternatives, such as (i) friction stir spot welding (which, as a solid-state process, is suitable for joining alloys with microstructures sensitive to high temperatures [6,7] or for joining dissimilar materials [8]), (ii) ultrasonic spot welding (which, as it is also a solid-state process, is an interesting option for joining aluminum alloys, where it also provides short welding times [9]), and (iii) laser spot welding speed, low heat input, and small deformation [10]), may be considered.

This paper aims to contribute significantly to the understanding of the most recent advances in the RSW process within the aspects outlined above.

2. Quality Control

The trend to reduce the number of RSW joints per vehicle is a logical consequence of (i) the high number of RSW joints per vehicle (typically between 4000 and 7000 [11]) and (ii) the aforementioned high competitiveness in the automotive industry. This trend leads to the optimization of quality control systems and decision support tools [12] because the fewer the spot welds per vehicle, the stronger the requirements for each of them [13].

The weld nugget is formed from the solidification of the molten metal after a heating by the Joule effect [14], and the weld nugget size, especially the nugget diameter, is used as an indicator of weld quality [15]. On the other hand, and given that, according to Özyürek [16], structures using RSW joints are typically designed so that these joints are loaded in shear when the parts are exposed to tension or compression loading, the tensile–shear strength of the spot weld, and particularly its tensile–shear load-bearing capacity (TSLBC), which



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). is the peak load value obtained during the tensile–shear test, is also a common quality estimation criterion [17]. In fact, both Hasanbaşoğlu and Kaçar [18] and Kong et al. [19] indicated that the most important factor affecting TSLBC is the size of weld nugget, and the standard JIS Z 3140 [20] establishes as acceptance criteria for RSW joints both the weld nugget diameter and the TSBLC.

As pointed out by Zhou and Yao [15], the study of the effects of different aspects of the welding process on RSW joint quality can be approached from (i) the use of auxiliary measuring signals from external sensors, or (ii) the use of intrinsic process variables. In addition, this study may be assisted by the use of models based on mathematical tools.

2.1. Use of Auxiliary Measuring Signals from External Sensors

Since destructive testing is not suitable for routine production monitoring, a range of nondestructive testing (NDT) methods have been developed for assessing weld quality in RSW [21].

Ultrasonic nondestructive testing is a promising technique for the quality control of RSW joints in the automotive industry [22], which allows for the possibility of reducing costs, but which requires human operators with some degree of qualification [23], especially when the complex material microstructure disturbs the ultrasonic wave propagation and makes it difficult to interpret the results obtained [24]. Since these results depend heavily on the human operator's experience [25], and the efficiency of the latter may be negatively affected by the task of repeatedly interpreting ultrasonic oscillograms for a long period of time [26], the tools that could help the human operator with the interpretation and classification of ultrasonic oscillograms can contribute to improving the evaluation by the ultrasonic nondestructive testing of RSW joints. The ultrasonic oscillogram obtained by the A-scan technique is a plot of wave amplitude versus time [27], where the ultrasonic beam is reflected when it reaches an interface, causing a series of echoes whose positions indicate the location of the reflecting interface and whose heights are a function of the sound attenuation, i.e., of the microstructure of the weld nugget [28]. Martín et al. [12] obtained a ten-component vector from each ultrasonic oscillogram and used a back-propagation multilayer feedforward artificial neural network (ANN) trained with the Levenberg-Marquardt algorithm to classify it, i.e., each ultrasonic oscillogram and its corresponding RSW joint, into four possible quality levels [29]: (i) good weld, (ii) undersize weld, (iii) stick weld, and (iv) no weld. Afterwards, and in light of the fact that ANNs are "black boxes" and do not have explanatory capacity, Martín et al. [13] proposed classification and regression tree (CART) and random forest techniques as pattern recognition models for the classification of ultrasonic oscillograms obtained from RSW joints, and they demonstrated that CARTs gave rise to an acceptable error rate with high interpretability, whereas random forests, compared with CARTs, reduced the error rate at the cost of reducing decision interpretability. With the aim of saving time, Hua et al. [30] developed an in situ ultrasonic detection system consisting of an electrode with an embedded probe, which made it possible to rapidly obtain the ultrasonic testing signal from the RSW joint. Wang et al. [31] proposed a particle swarm optimization support vector machine (PSO-SVM) to classify the maximum tensile-shear strength (MTSS) of RSW joints. Signal processing and mathematical statistics methods were used to extract the features of ultrasonic detection signals as input variables, and the MTSSs of the RSW joints were employed as output variables. Wavelet packet analysis was used by Qiuyue et al. [32] for the ultrasonic nondestructive evaluation of porosity size and location in stainless steel RSW joints and by Liu et al. [33] for the automatic identification and classification of ultrasonic echo signals obtained from stainless steel RSW joints by additionally using back-propagation neural network models. Moghanizadeh [34] studied, in the light of the effect of heat input on two microstructural features (grain size and phase content), the relationship between the attenuation coefficient of ultrasonic testing in low carbon steel RSW joints and the microhardness and, in turn, between the microhardness and the welding quality. Amiri et al. [35] investigated the relationship between the results

of ultrasonic testing with the tensile strength and fatigue life of three-sheet RSW joints using a single and dual-objective neural network.

According to Lindner and Deike [36], radiographic inspection is a reliable nondestructive testing method for the inaccessible intermediate sheet area, which is usable in the large-scale automotive industry. Consequently, the above-mentioned authors [36] used radiographic inspection for analyzing the liquid metal embrittlement (LME) crack characteristic, in relation to the surrounding conditions and welding parameters, inside the intermediate sheet area of dissimilar RSW joints, where the base metals were austenitic stainless steel, on the one hand, and microalloyed galvanized steel, on the other. The LME phenomenon can occur when, during the welding process, the liquid zinc penetrates into the grain boundaries of the austenitic stainless steel microstructure. Finally, regarding radiographic inspection, it should be mentioned that due to the fact that X-rays are harmful to the human body, the application of radiographic inspection to welding control quality in actual production is limited [37].

Another method for the nondestructive inspection of RSW joints is the magnetic technique, which, although when compared with the ultrasonic and radiographic techniques, it does not offer good morphology information, is, indeed, convenient and low-cost [38,39]. As indicated by Tsukada et al. [39], there are two main methods for carrying out magnetic based testing: (i) the magnetic flux leakage test (MFL), which employs the magnetic flux leakage from the sample surface when a low frequency magnetic flux is induced, and (ii) the eddy current test (ECT), which employs high frequency electromagnetic induction in conductive materials. Tsukada et al. [40] developed an MFL system using a magnetoresistive sensor for the nondestructive testing of RSW joints. Song et al. [41] applied an imaging method for analyzing the internal structure of RSW joints based on the phase of a magnetic field by using a wide range of frequencies from high to low. Vértesy and Tomáš [38] presented the magnetic adaptive testing (MAT) method, which is based on the systematic measurement and evaluation of magnetic minor hysteresis loops, as an alternative for characterizing quality in RSW, finding a good correlation between the welding current value and the magnetic descriptors. Regarding the ECT, Harada et al. [42] used it for the evaluation of RSW joints whose internal microstructure could be visualized by using multiple frequencies, and also for obtaining a good correlation between the measured magnetic field strength and the tensile-shear load.

Additionally, cameras or infrared (IR) thermography can be used to study the process of and assess the quality in RSW. Cho and Rhee [43] examined in RSW the nugget formation mechanism and its relation to the process parameters by using a digital high-speed camera and compared the results to the changes in dynamic resistance, finding that the weld nugget expanded in all directions and oscillated with twice the frequency of the welding current (60 Hz) along with a time lag according to the progression of the cycle. They found that the weld nugget size tended to be saturated with a certain size along with a decrease in oscillation and the dynamic resistance was affected by the variation in the area and length available for current flow, rather than the temperature after the saturation. Xia et al. [44] proposed an online evaluation of expulsion intensity by means of the amount of molten metal ejected during the expulsion; they used a multi-sensor monitoring and a high-speed camera system, and the obtained results showed that the amount of sudden decrease in the electrode force and displacement signals was proportional to the weight of the expelled metal, but no apparent relationship was observed between the dynamic resistance drop and the expulsion severity. The geometrical and metallurgical modifications undergone by the electrode due to degradations, as a result of the consecutive RSW of transformation induced plasticity (TRIP) steel with a 6 μ m galvannealed coating, were analyzed by Mahmud [45] using IR thermography. They found electrode geometrical degradation as the main aspect affecting the LME cracking because, indeed, as the electrode radius of curvature increased with the number of welds, the electrode-sheet contact area also increased and, therefore, the current density at the electrode-sheet interface decreased and the heat dissipation through the electrode increased, giving rise to a decrease in temperature and thermal stress at the electrode–sheet interface and, as a result, LME cracking severity decreased with consecutive RSW. On the other hand, the electrode metallurgical degradation did not affect the LME cracking in the early stages of consecutive welding (until 200 welds), but was evident thereafter. Stavropoulos et al. [46] introduced an online quality assessment approach that employed machine learning methods, on data captured from an IR camera, mounted on an RSW-robotized system. They found that the quality-prediction uncertainty of the models depended on the proximity of the points of the process parameter input space (each point is the pair formed by the values of welding current and welding time).

2.2. Use of Intrinsic Process Variables

As reported by Gedeon et al. [47], two of the most popular inputs for assessing the quality in RSW are dynamic resistance and electrode displacement.

Xing et al. [48] employed a random forest model for classifying RSW from dynamic resistance signals. This model adequately distinguished good welds from the other unacceptable welds such as cold welds and expulsions; in addition, the implementation of random forest based on the combination of welding parameters and dynamic resistance signals improved the accuracy of classification (by reducing the misclassification error between good welds and cold welds). Luo et al. [49] monitored in real-time the change of welding current and electrode voltage in the secondary circuit in the RSW process, and thus the dynamic resistance was analyzed to characterize the weld nugget growth. The results showed that (i) the whole process of nugget growth is composed of an initial stage, a growing stage, and a stable stage, (ii) different types of nugget growth show diverse curves of dynamic resistance, which is a way to assess the weld nugget growth and weld nugget quality, and (iii) welding current and electrode force can affect the nugget growth.

Zhang et al. [50] developed a method for evaluating the quality in RSW based on the extraction of nine time domain statistical features from the electrode displacement signal. These nine features were sketched as a Chernoff face which classified the welding quality in four levels (poor, good, excellent, and expulsion) through the different facial expressions, which made the diagnostic procedure for welding quality easily understood and interpreted. Xing et al. [51] studied the shunting effect in RSW (which, due to the presence of an adjacent and previous spot weld, gives rise to the reduction in the welding current flowing to the new spot weld, with a consequent decrease in its size and strength) from the electrode displacement signals; the results showed that the weld spacing and nugget diameter were polynomial-correlated, with a minimum weld spacing of approximately 20 mm. Zhang et al. [52] proposed a method for quality assessment in RSW by converting the electrode displacement waveform into binary image and then, by using binary matrices according to different weld qualities to train a probabilistic neural network, they created a quality classifier.

In addition to the two aforementioned inputs (dynamic resistance and electrode displacement), the quality in RSW can be directly assessed from the welding parameters, the most important of which are welding current, welding time, and electrode force [53,54] (Figure 1). Separately, the effect of welding current [55] and of welding time [56] on the tensile–peel strength and tensile–shear strength of RSW joints of microalloyed steel sheets with a 1.2 mm thickness was studied. Kianersi et al. [57] investigated the effect of both welding current and welding time on the macroscopic aspects (weld nugget diameter, welded penetration, width and thickness of heat affected zone (HAZ), and indentation depth of the electrode), mechanical properties (tensile–shear strength and failure energy, peak load, and failure mode), and metallurgical properties (formed phases in the welded nugget and HAZ) of the RSW joints of AISI 316L austenitic stainless steel.



Figure 1. RSW process diagram that shows: (i) the weld nugget (WN) formation after heating by the Joule effect, (ii) the principal welding parameters (welding current (WC), welding time (WT), and electrode force (EF)) [53,54], and (iii) two of the most popular inputs for assessing the quality in RSW (dynamic resistance (DR) [48,49] and electrode displacement (ED) [50–52]).

According to Tercan and Meisen [58], the digitization of the manufacturing industry and the ability to bring together data from manufacturing processes and quality measurements have boosted the use of machine learning and deep learning techniques in quality control, which may provide manufacturing companies with tools to make datadriven assessments about product quality based on process data. With regard to the use of machine learning in the processing of welding parameters for quality control in RSW, Pereda et al. [59] compared some of the most relevant and popular pattern recognition techniques for the classification of RSW joints using welding parameters as the inputs, confirming that knowing these welding parameters is sufficient for obtaining classification rates that are almost comparable with those obtained using nondestructive testing. Zamanzad Gavidel et al. [60] carried out a comparison of machine learning algorithms for predicting the weld nugget width of RSW joints, finding that the deep neural net weld nugget width prediction model outperformed the previous models. Martín et al. [61] proposed polynomial expansion and elastic net regularization as regression techniques for TSLBC prediction and quality control classification using the three most important welding parameters as inputs, and they found that quadratic regression expansion with elastic net regularization provided good predictive accuracy, being, at the same time, a simple and interpretable tool, which is its main advantage over other techniques that also may have good predictive accuracy but lack explanatory power. Pashazadeh et al. [62] investigated the effect of welding time, welding pressure, and welding current on the diameter and height of weld nuggets by using a hybrid combination of an artificial neural network and a multiobjective genetic algorithm. Additionally, the number of spot welds which should be performed before the electrode tip dressing operation was calculated. Martín et al. [63] demonstrated, by comparing a large number of classification algorithms, that the combined use of pre-welding inputs (welding parameters) and post-welding inputs (ultrasonic oscillograms) may significantly improve the already competitive approach based exclusively on ultrasonic nondestructive testing, and that the use of stacking of tree ensemble models as classifiers dominates the classification results in terms of accuracy, F-measure, and area under the receiver operating characteristic curve metrics. Dai et al. [64] developed a network model for small object detection based on deep learning for detecting the position and quality of the RSW joints of a car body. Zhao et al. [65] employed the entropy weight method to convert four welding quality indexes (nugget diameter, maximum displacement, tensile-shear load, and failure energy) into a comprehensive welding quality index, and they developed a second-order regression model to quantify the relationship between this comprehensive welding quality index and the input variables (welding current, welding

time, and electrode force) in the RSW of TC2 titanium alloy sheets. Zhao et al. [66] predicted the quality of RSW joints of TC2 titanium alloy by means of two regression models and an artificial neural network model. They studied the effects of welding parameters on the dynamic resistance signals by using principal component analysis (PCA) to eliminate the redundant information in the dynamic resistance curve, and then, with a linear regression model, they quantified the relationship between the weld nugget diameter and the principal components from the dynamic resistance signal. Some statistical characteristics of the dynamic resistance signal were also extracted to study the relationship between the weld nugget diameter and dynamic resistance, and the results showed that the regression model based on the PCA technique was much more robust than that developed on the basis of the features manually extracted from the dynamic resistance signal. In addition, a neural network model was used to predict the weld nugget diameter of the RSW joints from the extracted features. Zhou et al. [67] proposed 12 machine learning pipelines for quality monitoring in RSW. The 12 machine learning pipelines were developed in two dimensions: (i) settings of feature engineering (four feature settings were considered), and (ii) machine learning methods (three machine learning methods were considered: linear regression, multilayer perception, and support vector regression).

3. Development of New Strategies to Improve Weld Quality

3.1. New Process-Based Strategies

Safari et al. [68] investigated the effects of process parameters on the tensile–shear strength of dissimilar RSW joints of AISI 304 austenitic stainless steel sheets and AISI 409 ferritic stainless steel sheets by using response surface methodology. They concluded that the tensile–shear strength of RSW joints was increased with increasing welding current, welding time, and electrode force.

Given the problems associated with the formation of brittle martensitic structures in the fusion zones of martensitic stainless steel welds, Pouranvari et al. [3] and Aghajani and Pouranvari [69] proposed an in situ rapid tempering technique via applying a second pulse current after the first melting/solidification pulse during the RSW of AISI 420 martensitic stainless steel sheets, which was used as a pathway to enhance the toughness of the fusion zone. Under the appropriate second pulse conditions, the hardness reduction in the fusion zone was accompanied by a decomposed martensitic structure with nanosized carbide precipitations. The improved toughness due to this modified microstructure caused a remarkable enhancement of the peak load and energy absorption in comparison with the single-pulse RSW joints. Along the same lines, but with regard to the formation of brittle martensitic structures in the fusion zones of RSW joints of dual phase steels, Soomro et al. [70] also proposed an in situ post-weld heat treatment that used a doublepulse welding scheme in order to improve the mechanical behavior of DP590 steel RSW joints, achieving improvements, compared to traditional single-pulse welding, of 17 and 86% in peak load and failure energy, respectively.

Since electrode force plays an important role in ensuring electrical contact [71] and preventing the expulsion phenomenon [72], Wohner et al. [73] proposed the design of an electrode force profile (a variation in the electrode force during the whole welding process) as a way of improving weldability and quality in the RSW process.

Huang et al. [74] applied an external magnetic field in the RSW of 3 mm thick AA 6061-T6 sheets (which are paramagnetic in nature) with the aim of improving the weld quality; in this way, an additional circumferential flow was generated, resulting in a reduction in the cooling rate and a change in the solidification mode, and, finally, in an enhancement of the tensile properties by increasing nugget diameter, eliminating defects, and complicating the crack propagation path.

3.2. New Material-Based Strategies

Chabok et al. [75] studied the effects of chemical composition on the microstructural evolution and mechanical properties of two DP1000 steels welded by RSW, and they

demonstrated that the strength and/or hardness of the weld nugget is the key parameter in the tensile–shear strength of the RSW joints, while the fracture toughness is the dominant parameter in the cross-tension strength.

Shirmohammadi et al. [76] investigated the effect of the initial base metal microstructure (ferritic microstructure in the annealed condition versus partially tempered martensitic in the quench and tempered condition) on the microstructure–properties relationship of martensitic stainless steel RSW joints. They found that (i) when the initial base metal was in the annealed condition, the RSW joint exhibited HAZ hardening due to the formation of a complex martensite/carbides microstructure, (ii) when the initial base metal was in the quench and tempered condition, the RSW joint exhibited softening in the sub-critical HAZ due to tempering of the initial martensite, and (iii) the peak load of the martensitic stainless steel RSW joints was determined by the fracture toughness of the fusion zone.

Badkoobeh et al. [77] investigated the role of silicon on the behavior of dual phase RSW joints. They found that (i) the increase in silicon content from 0.34 to 2.26 wt% led to an increase in the weld nugget size, which was due to the increase in electrical resistance and the reduced thermal conductivity which resulted in a higher generated heat at the faying interface; (ii) the increase in silicon content from 0.34 to 2.26 wt% led to a yield strength reduction and, therefore, to the restraint degree of the base metal decrease, which, in turn, gave rise to the reduction in the contraction amount caused by the solidification of the weld pool and then to a smaller shrinkage cavity.

3.3. New Equipment-Based Strategies

Chen et al. [78] studied the effect of a slightly concave electrode on the RSW joints of Q&P1180 quenching and partitioning steel. They found that by employing a slightly concave electrode, a ring-shaped distribution of current density formed at the initial stage, and due to the lower current density and the stronger corona bond zone after the formation of the weld nugget, the slightly concave electrode reduced the possibility of early expulsion, resulting in larger upper limits on the weld nugget and a wider welding current range. In relation to the LME cracking of RSW joints of galvannealed TRIP steels, Mahmud et al. [45] investigated the effect of the geometrical degradation of the electrode and Murugan et al. [79] investigated the influence of different geometric design parameters of the electrode.

Tang et al. [80] studied the influence of the mechanical characteristics of RSW machines, such as stiffness, friction, and moving mass, on the RSW process and on the weld quality. They found that: (i) machine stiffness had a positive influence on expulsion prevention and weld quality because of reduced electrode misalignment, increased expulsion limits, and the provided forging effect; (ii) machine friction had a negative effect on weld quality, especially on the internal discontinuities; and (iii) machine moving mass had no influence on weld quality.

Sun et al. [81] studied the effects of sealant on the weldability, mechanical property, and failure mode of 301L austenitic stainless steel RSW joints, with the aim of improving the sealing performance of stainless steel metro car bodies. They discovered that the use of insulating sealant gave rise to an earlier weld nugget initiation, a bigger weld nugget size, and a higher heat utilization ratio than the traditional RSW process. On the other hand, (i) the thermal decomposition products had spread to the weld nugget and existed in the form of pores and inclusions, (ii) the proportion of residual δ -ferrite was decreased due to the long-lasting heat preservation effect of the surrounding sealant, and (iii) the tensile strengths and RSW joints with sealant were undesired and resulted from the local softening and dispersedly distributed gas pore and inclusion defects. Nevertheless, these adverse effects of sealant can be eliminated by appropriately increasing the welding current.

4. Conclusions

The RSW process serves highly competitive industrial environments, thus requiring continuous advances in quality control and quality improvement strategies. The study

of the effects of different aspects of the welding process on RSW joint quality can be approached from (i) the use of auxiliary measuring signals from external sensors (NDT techniques, cameras, or ID thermography), or (ii) the use of intrinsic process variables (dynamic resistance, electrode displacement, or welding parameters such as welding current, welding time, and electrode force). These studies, given the aforementioned highly competitive nature of the industrial environments in which RSW is implemented, may be assisted by the use of models based on mathematical tools, such as those provided by machine learning. The new strategies to improve weld quality may be based (i) on the process itself (i.e., the introduction of a second pulse current after a first melting/solidification pulse, with the aim of generating a tempering effect, or the design of an electrode force profile as a way of improving quality), (ii) on the base metal to be welded (i.e., the influence of the chemical composition and the initial microstructure on the RSW joint performance), and (iii) on the employed equipment (i.e., the electrode geometry or the mechanical characteristics of the RSW machine).

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