Development of an automated ultrasonic inspection device for quality control of spot welds

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Abstract. Spot welding is one of the most frequently used techniques for bonding metal plates, for example, in an automotive chassis, between 3000 and 4000 spot welds can be found. Using this technique it is possible to obtain at a low cost, easily automated versatile welds with high quality and speed of operation.

However, for such joints the inspection and quality control is more problematic than for other techniques. In fact, in the production process, welding parameters are set through "test / error" systems. The cost associated with this type of inspection is high, is an extremely laborious method, produces a significant amount of waste, and is unreliable because the problem is identified after a number of components have already been manufactured, which must be rejected.

In this paper an inspection system in order to determine the goodness of spot welds, minimizing human intervention in the evaluation of results is presented. The system allows an innovative coupling and a new signal processing technology, which improves the inspection reliability and allows for an automated process for online use in the production system.

1. Introduction

Resistance spot welding is the joining of overlapping metal sheets by applying pressure and electrical current. In a typical spot weld the pressure is applied via two electrodes on opposite side of the materials to be welded, which forces the metal pieces together while several thousand amperes of current are passed through the interface. Localized resistance heating produces a melted nugget joining the sheets together.

Vehicle manufacturers use spot welding because, using it, they can produce high quality welds at relatively low cost. However, inspection and quality assurance for this joining method are more problematic than is the case for other welding techniques.

For years the only way to tell if a spot weld was good or not was by destructive testing but the cost associated with this type of inspection is high, it's an extremely laborious method, produces a significant amount of waste, it's unreliable and when the problem is identified several components could have passed through the system that should be rejected.

Also, ultrasonic inspection of spot welds has been used for many years. From an A-Scan, it is also possible to classify defective spot welds. Some work has been carried out on signal processing techniques for plain steel, and manual ultrasonic testing (UT) has the advantage of 100% volume coverage and the test itself is fast, however, it is very operator dependent. Different inspections of the same weld may yield different results for different operators. This is mainly caused by difficultly in positioning the probe, non-uniformity of the surface and poor interpretation of the results.

In this paper a completely automatic in-line system for the inspection, evaluation and monitoring of spot welds via ultrasound and using artificial vision for position control in order to determine the quality of the joint minimizing human intervention in the evaluation of results.

The proposed system allows a new dry coupling technology (no messy membranes) and a new signal processing software, which improves the reliability of the inspection. So, the combination of an evolved ultrasonic coupling technique and robust and reliable evaluation algorithms facilitates automation, allowing the system to be used inline within the productive system. After each test, all inspection results are stored and readily available. Together with other data, such as the part reference, spot and weld gun identification, welding parameters, etc. the results can then be processed for monitoring, traceability and further action and continually giving feedback to the system management.

2. Inspection of spot welds

In a welding process, the materials to be welded are overlapped between the electrodes. A pressure, ensuring optimum contact, is applied and for a time "t" while an electric current of low voltage and high intensity passes through them. So the heat produced by Joule effect is able to partially melt the material.

The resistance welding is characterized by a rapid formation and easy automation, making spot welding a widely used process. It must be taken into account during its formation that the following variables could affect their quality [1]:

- micro-structure of material
- hot sparks or splash
- wear on the electrode

The optimum values for variables such as intensity, voltage, and application time depend on the nature of the material to be welded (resistivity, thermal conductivity, specific heat, latent heat of fusion, chemical composition, microstructure...) as well as the geometry of the pieces, surface condition and type of spot weld. Variations in any of these parameters could result in defective spot welds.

When the weldability diagram (typical for each material) is depicted, it's possible to study the weldability as a function of the current intensity and the application time. The curves represent the locus of the minimum values (initiation of melting of the material) and maximum values (to avoid excessive molten material). In this diagram, it is possible to define different areas (Figure 1).

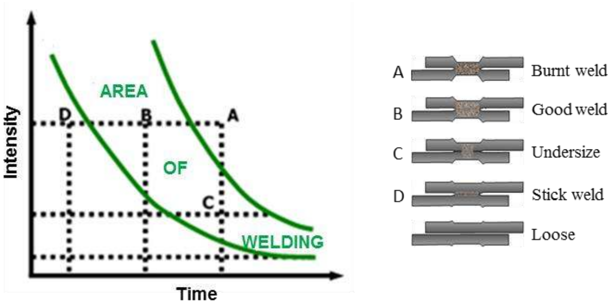

Fig. 1. Defects depending on the welding parameters

2.1 Destructive Testing

In a typical production line, the analysis of the quality of welds is performed by destructive or 'peel test' of sheets. After this process, the resulting area can be analyzed to determine the geometry, diameter and type of fracture The results of this test are used to verify that the welding parameters are satisfactory. Subsequent welds made using these parameters are assumed to be adequate, however, the assumption that the test spot weld is identical to the one on the car could be untrue. Furthermore, more modern cars are built from high strength steels [2]. The peel test cannot be applied to such steels because, when spot welds in such steels are subjected to peel testing, fracture often occurs in the nugget itself.

2.2 Non destructive Testing

Very few NDT methods are used -with partial satisfaction- such as visual inspection, thermography, radiographic testing, dynamic resistance test, acoustic emission method [3] [4] and various ultrasonic techniques such as through transmission, Lamb waves through transmission technique, air-coupled through transmission using focused transducers, immersion system using focused transducer, acoustic microscopy, systems using ultrasonic arrays [5] [6] [7] [8] [9]. However, the most widely used ultrasonic method is still manual pulse-echo [10] using high frequencies, broad banded and damped transducers. According to this technique, spot welds are classified by evaluating the echo positions on the time scale and their attenuation characteristics.

The distance between the echoes and the time origin is proportional to the path traveled by the beam, and its height is proportional to the acoustic pressure reflected in the hazard. Therefore, parameters as the number of echoes, position, attenuation... allow to obtain an estimation of the quality of the spot weld. The study and analysis of different signals [11] is needed to find the reference values in order to classify and parameterize each type of defect (Figure 2).

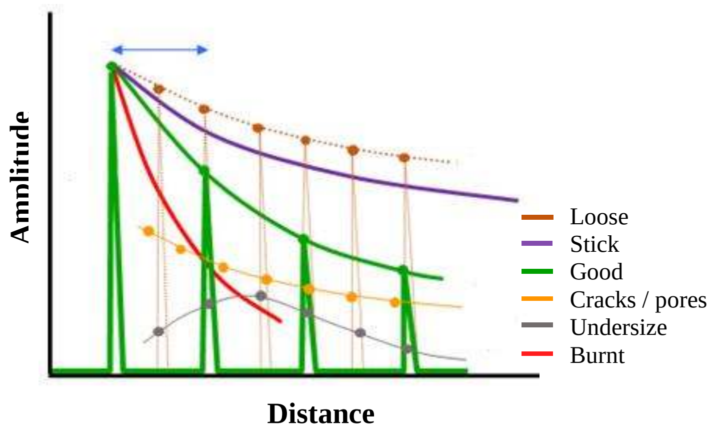

Fig. 2. Characteristics of the signals depending on the type of defect.

The objective of this work is the development of a technology that, given the variables related to geometry, materials and welding process, allows for detection of defects in spot welds. Thus, it must be possible to monitor the welding process and correct deviations to guarantee the level of quality required.

The application of this new methodology will be an important technological advance, and will help significantly to reduce environmental impact.

3. Implementation of the system

In this paper a new technique based on the ultrasonic propagation, with a new acoustic coupling and a new signal processing technology is developed in order to improve the reliability of the inspection, minimizing, almost eliminating the need for interpretation by end users. It can also be automated with robots for online use in the production system.

3.1 Coupling Media

The transducer is the active head of the system. The transducer is composed of a piezoelectric material which, when excited by electric pulse can generate an ultrasonic wave. Reciprocally, when an ultrasonic wave strikes the piezoelectric material an electronic signal is generated. The shape and the size of the piezoelectric crystal will impact on the sensitivity of flaw detecting, sizing accuracy and resolution.

The transducer used in the system for spot weld inspection has to generate a high frequency ultrasonic wave (15MHz 20MHz) in order to be sensitive to flaws in the joints of around 3mm thick.

In this case, the probes have a delay consisting of a water column, contained in a flexible membrane which facilitates coupling through a semi-liquid medium. The role of the coupling media is to allow the transmission of the ultrasound into the weld. The coupling media must be able to conform to the surface of the welds independently to its shape, diameter, and surface finish.

These membranes are made of elastic materials that vary in texture, elasticity and thickness. If any of these parameters varies, we can assume variations in the gain to be used during the inspection process. The state of the membrane is also an important factor, it must be discarded before it begins to deform, or when air bubbles appear therein, in order to avoid false values in tests.

For some years dry coupling has been used for inspections by means Ultrasonic Techniques. The areas where the dry coupling has been used are: Nodularity Testing, Roller probe (both single crystal and multi-crystal applications) and Sliding probes.

One of the main challenges of this study has been to replace the current coupling (water column – membrane - coupling medium) with new rubber that allows an interchangeable dry coupling interface with even better properties (with better signal / noise relationship and higher wear resistance) than existing materials based on polybutadiene. Taking these as a reference, were produced similar materials in different forms:

- with extra mixing
- with a faster curing cycle
- with added plasticizer
- with even more plasticizer
- with more filler

Properties and configuration of this range of materials have been analyzed. Furthermore, the performance of the coupling media has been tested on a range of weld shapes, diameters and surface finish.

Although some of these materials present an acoustic impedance similar to water and an appropriate ultrasonic behaviour, material hardness must be considered because the rubber has to conform to the profile of the surface, even for manual inspections by ensuring the contact area between the transducer and the sheet and avoiding signal losses without using any additional coupling.

3.2. Signal Processing

The ultrasonic method for spot-weld inspection detects multiple reflections from the back-wall and any intermediate interfaces of the welded structure. Extracting various parameters from these echo sequences, allows for the differentiation between good and defective spot-welds (stick, undersize, burnt, inside defects…).

Some materials show a clear distinction between the different types of spot welds, nevertheless, for more advanced materials that include thick corrosion resistance coatings, and high-tensile steels, intermediate echoes can be present even in "good" welds [12].

Sometimes the A-Scan is hard to interpret by a human expert, as a result, different studies have been performed to the automation of the interpretation of ultrasonic signals by means of pattern recognition tools in order to improve the quality control performance [13] [14].

So, in the course of this work a proper system configuration has been done to develop a software that allows the evaluation, classification and diagnosis of the state of spot welds, minimizing the need for interpretation by end users.

A database of initial settings from a thorough analysis of the signals has been obtained by varying the parameters corresponding to the characteristic triad (geometry-materials-process). This requires previous works examining multiple cases from reference samples.

For that, analyzing different reference samples on which the welding parameters were varied, it was obtained a database of initial settings.

After defining applicable configuration from the calibration samples, only a fine adjustment will be necessary to carry out the acquisition and automatic analysis of spot welds according to the qualification scheme:

- Level I: signal selection and data acquisition.
- Level II: selection of appropriate parameters to be used in configuration.

Another aspect to be considered was the suitable adjustment of pulser and receiver to work with the best signal/noise ratio and resolution for each frequency used. So, it's possible to capture up to 200 A-scan per second.

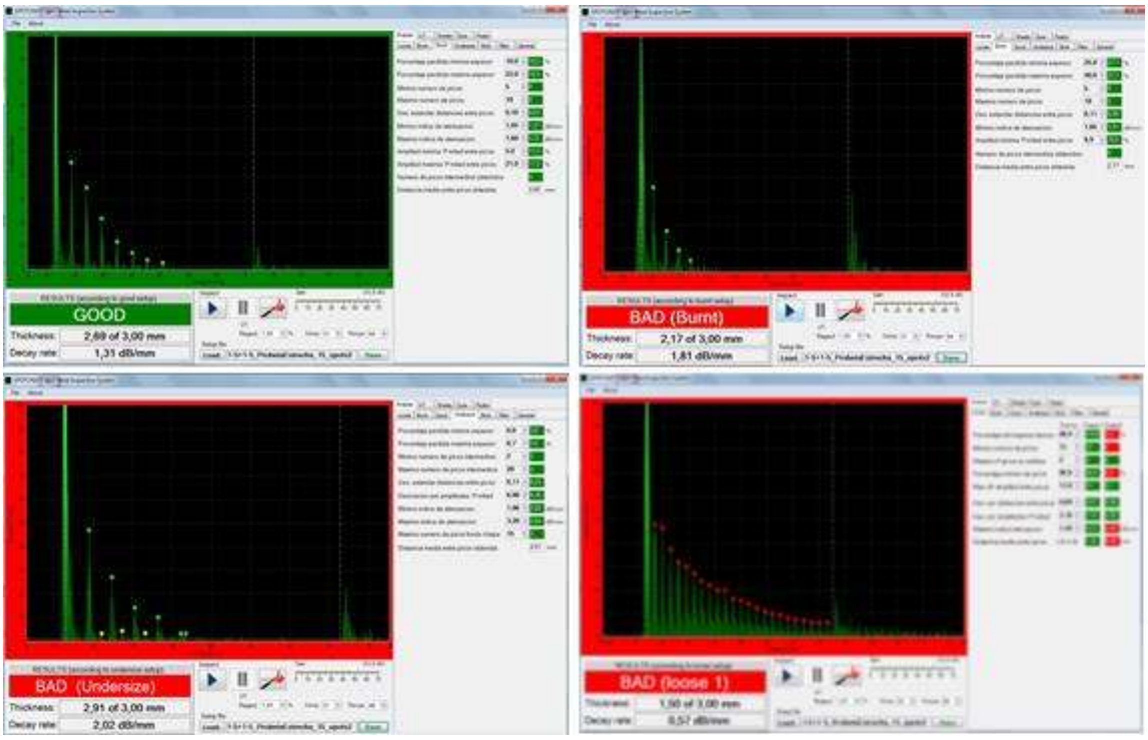

Fig 3. Spot weld evaluation

From all captured A-Scan the most appropriate is automatically selected by applying a set of objective criteria (beyond the relative height of the intermediate echoes and echoes and bottom echoes). The calculation is completed with attenuation coefficients, thickness and envelop of the amplitudes for intermediate echoes in order to make a more correct spot weld classification even for tight tolerances. Thus, will avoid confusing stick, good and burnt spots (which may have the same number of echoes, and nevertheless differ greatly regarding to attenuation coefficient). Furthermore, this calculation is independent of the gain and coupling conditions. Figure 3.

After each test, the data is available to make possible the correlation between the result and the spot weld (reference position, welding parameters...) to ensure the monitoring and traceability.

4. Automatization

This new technology and testing methodology, can be automated thanks to a module that allows both tracking of the weld points, and the correct positioning of the probe for inspection and automated diagnosis of spot quality. All this to integrate the inspection system in production line.

Each spot weld is tested following the pre-programmed sequence. A series of spots are tested in each part whilst keeping within the line cycle time. The sequence is automatically continued on subsequent parts coming into the cell (Figure 4).

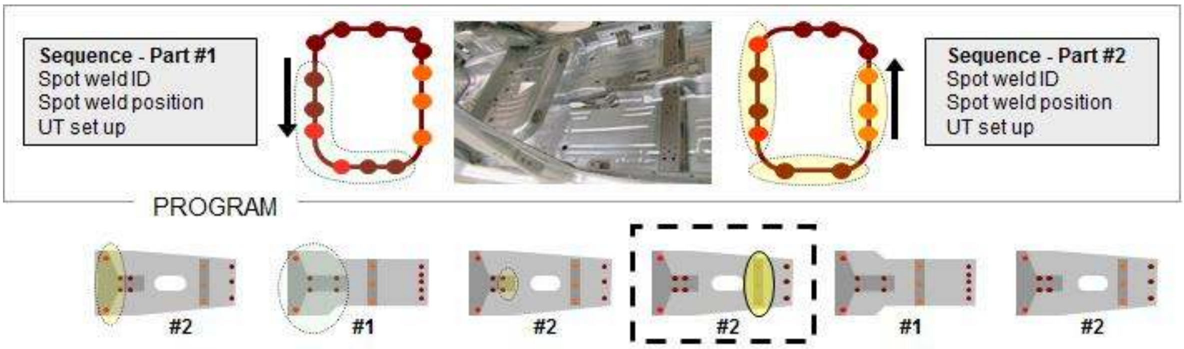

Fig. 4. Definition of inspection sequences

The test sequence can be defined independently for different parts that come through the line, according to a particular plant strategy and the production requirements. The ultrasonic test set up, as well as the applicable warning and rejection thresholds, can be defined for each spot weld.

For a cycle time T and a number of test spot welds N, each robot evaluates the total number of spots after 3N / T - 6N / T cycles. For component testing unconditioned by a fixed cycle time, the N spot welds are inspected at a time between 3N and 6N seconds.

4.1. Vision system

For testing each spot weld, an intelligent vision system searches the exact location of the spot weld around the programmed position, enabling a dynamic ultrasonic signal acquisition and evaluation of the spot weld as well as monitoring its location and orientation to the surface. (Figure 5). Both the ultrasonic sensor and a video camera are installed on the arm of a conventional robot and the testing sequence of the nominal spots' positions is programmed once for a particular component in the production line.

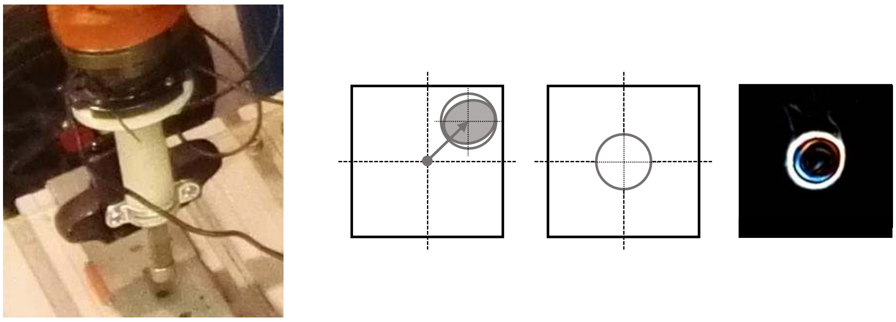

Fig. 5. Location and determination of the contact point of the probe

The probe is driven to the center of the weld for ultrasonic testing from the programmed position. A real-time evaluation of the weld position and shape is simultaneously performed.

4.2. Probe holder control

The ultrasonic transducer is fixed to a special holder in the manipulator's wrist that allows for a sweep in the x and y direction planes of the tool. With the probe on the centre of the spot, the system sweeps through all the possible angles in those two planes, until a suitable signal that allows a proper evaluation of the weld is obtained. Figure 6.

Fig. 6. Swept of the probe

After each test, all data are readily available and are also stored in a relational database. Together with existing data, such as the part reference, spot and weld gun identification, actual welding parameters, etc. the results can then be processed for monitoring, traceability and actions.

5. Conclusions

An automatic ultrasonic inspection system of spot welds has been presented, which introduces a type of probe with a new acoustic coupling and a new signal processing technology that enables automation for online use in production. This type of inspection has clear advantages over manual inspection:

- Can be used in production.
- Allows appropriate positioning of the probe. → Repeatability in results.
- Unaffected by nonuniformity in the surface.
- Reliability in the evaluation and interpretation of results.

The system allows to perform a thorough evaluation of the spot welds immediately after the welding process and the results can then be used for direct production control.

For future studies will be necessary to consider the configuration of the weld, sometimes formed by three plates, representing a new challenge to face.

This problem presents greater difficulty both the control in welding parameters as in the inspection process. All due to the increase in thickness (therefore a greater signal attenuation) and a more complex interpretation, with a greater presence of intermediate echoes or defects that can occur in any of the interfaces of the union.

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