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Nugget diameter in resistance spot welding: a comparison between a dynamic resistance based approach and ultrasound C-scan

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Abstract

Automakers today are challenged with improving the quality of spot welded structures, while reducing the costs associated with quality control. While ultrasonic C-scan testing has become a mainstay of quality control programs, it is not suitable for inspection of every weld in a high volume production due to the considerable operator skill required, and the requirement to take parts off-line for inspection. The dynamic resistance curve of a weld is known to contain information about the development of a weld, however there is not always a clear way to relate that directly back to the quality of a weld and exactly how a system may have arrived at that decision. Because the dynamic resistance data is available inline for every weld, developing a method of determining weld quality from the dynamic resistance would allow for process faults to be diagnosed sooner than would be possible with periodic off-line inspection.

In this paper we present a method of estimating nugget diameter directly from the dynamic resistance obtained during welding, by means of Principal Component Analysis (PCA), autocorrelation and multilinear regression. The accuracy of estimated nugget diameters is compared to ultrasound inspection in a production environment. The nugget diameter estimated by the dynamic resistance was found to be more accurate than ultrasound, with Mean Squared Error values of 2.26 for Ultrasound and 0.33 for the Dynamic Resistance Method. For welds with misaligned electrodes, the effectiveness of Ultrasound dropped significantly when the probe was unable to sit flat on the weld surface. The method presented in this paper is suitable for inspection of every weld in a high-volume production, and has been shown to outperform ultrasonic inspection in estimation accuracy.

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1. Introduction

Resistance spot welding (RSW) is a ubiquitous sheet metal joining technique in the automotive industry due to its low cost and quick cycle time. To monitor the quality of spot welds in industry, regular inspection (both destructive and non-destructive) is required to ensure the quality of welds produced in a high volume environment such as auto production. Though resistance spot welding is well established in industry, maintaining consistent, high quality weld production remains a challenge due to sensitivity to small process changes that uncontrollably drift and can be difficult to detect. Effective quality monitoring techniques rely on information about weld quality that is both; accurate (so that small changes can be reliably detected), and frequent (so that process changes can be detected and addressed quickly).

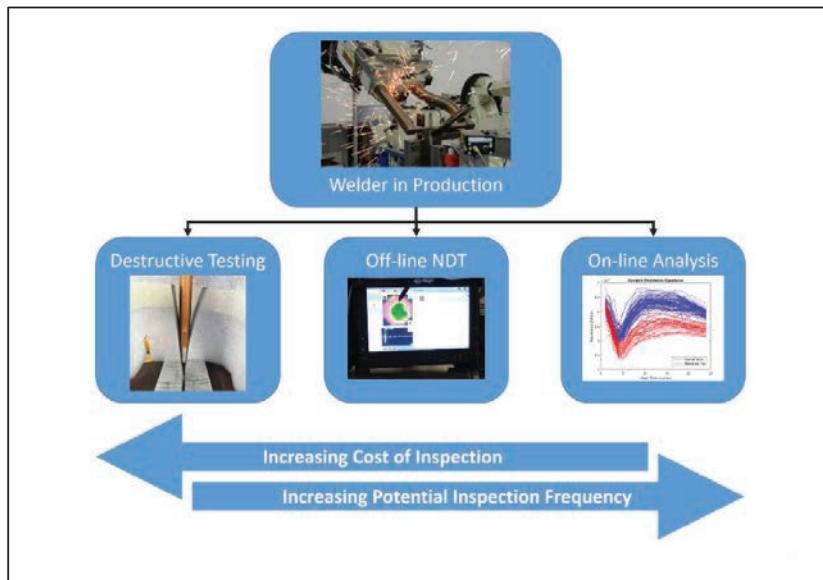


Figure 1: Inspection techniques have varying accuracy, frequency and cost

Given that weld nugget diameter is the output variable that is frequently monitored in most manufacturing settings, determining nugget diameter for as many welds as possible should be the priority, without requiring parts to be taken off the production line. The most common non-destructive testing method used in industry is ultrasonic C-scan, which uses an array of ultrasound transducers to produce a 2D image of the fused area in the faying surface [1]. From the 2D image the nugget diameter is measured and often compared to a benchmark that determines whether the nugget passes or fails quality control testing. Despite its popularity, ultrasound still currently requires a skilled operator, while the setup and scanning time make it unsuitable for inspection of every weld in a high-volume production.

Given the issues with Ultrasonic testing, alternative methods using information from the signals collected during welding have been investigated. The dynamic resistance signature (DRS) has long been known to contain information about the growth of the weld nugget and presence of expulsion [2], and for that reason is frequently used in monitoring and control systems [3]–[7]. Several attempts have been made to directly estimate the nugget diameter or strength from the dynamic resistance signature [8]–[10] resulting in an alternative form of non-destructive testing.

In this paper, the relative performance of two non-destructive nugget diameter assessment methods is compared: ultrasound C-scan and inference from the DRS. As is highlighted schematically in Figure 1, the methods being compared allow for varying frequency, accuracy and cost. The DRS nugget size estimation method offers the potential to be suitable for automated quality assurance of every weld in production, greatly increasing the chance of

individual faulty welds being detected, as well as process faults being diagnosed early. The purpose of this paper is to determine the accuracy to which nugget diameters can be reasonably estimated from the DRS, and if this method is suitable as a quality monitoring technique in industry.

To estimate nugget diameter from the DRS, parts of the signature that are significantly correlated to the nugget diameter are identified using a combination of Principal Component Analysis (PCA), and autocorrelation. Once the relevant components of the signal are identified, a simple multivariate linear regression is performed to create a model of nugget diameter.

To test the effectiveness of the method described above, a study was performed in a real production environment. Two sets of welds were created, some under controlled welding conditions and some with a misaligned welding gun. Estimated nugget diameters from both the DRS method and from ultrasound inspection were then compared against true nugget diameters measured from teardown.

2. Experimental Method

To compare the DRS based and ultrasonic inspection methods, an experimental trial was conducted in a manufacturing plant. This trial sought to determine the relative accuracy of nugget diameters inferred from the DRS to the nugget diameters measured from ultrasonic inspection. For all experimental samples, both the dynamic resistance and ultrasound methods were compared against nugget diameter measurements from a destructive chisel test performed in plant. After each destructive test, nuggets were measured on two orthogonal axes with Vernier callipers and the average value was taken as the true value of nugget diameter.

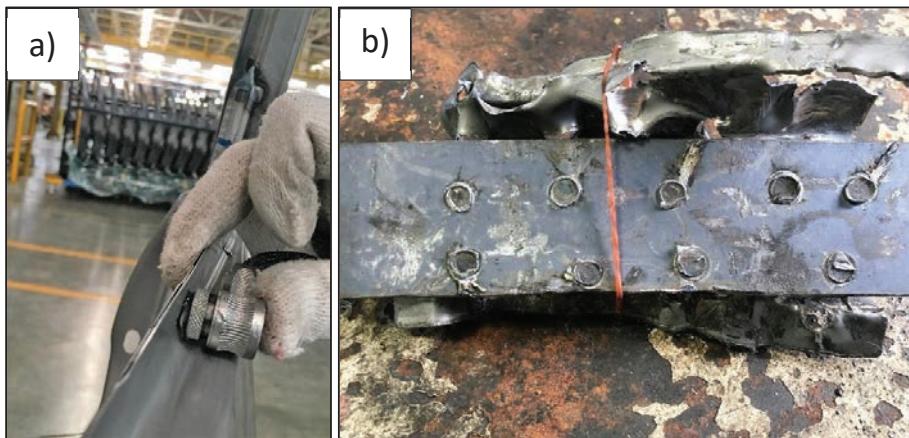


Figure 2: a) Ultrasonic Testing, b) Result of chisel test

A total of 126 experimental welds were produced on coupons using an MFDC Spot welder manually operated by a trained operator. The dynamic resistance signature was recorded for each weld from the weld controller, then each weld was subsequently inspected by ultrasound and destructively tested. Of the 126 welds, 87 were made with the weld gun intentionally misaligned from the workpiece to simulate a fault with the setup and produce poor quality welds, shown in Figure 3.

To estimate nugget diameter from the dynamic resistance signature, the experimental data was split into two groups: a training set subjected to PCA from which the regression coefficients could be determined, and 80 welds which were used to validate the model created from the training set. Both the training and validation sets contain the same proportion of misaligned welds as shown in Table 1. All welds were made using the settings shown in Table 2.



Figure 3: Misalignment of weld gun to produce poor quality welds

Table 1: Experimental datasets

	No. of Welds	No. of Welds Misaligned
Training Welds	46	31
Validation Welds	80	56

Table 2: Experimental welder settings

Parameter	Setting
Current	8.9 kA
Weld Time	350 ms
Electrode Tip Diameter	5 mm
Clamping Force	2.3 kN
Squeeze Time	400 ms
Hold Time	100 ms
Thickness	0.7 mm
Material	Zinc-coated steel

2.1. Analysis of the Dynamic Resistance

To estimate nugget diameter from the dynamic resistance, a predictive model was created by correlating signature shapes of the DRS to the measured nugget diameters. A training set was created by welding several samples spanning the range of operating conditions from normal to severely misaligned, producing undersized weld nuggets. During welding, dynamic resistance signatures were collected for each weld via the on-board voltage and current sensor in the weld gun secondary circuit.

To improve the efficiency of the modelling step and reduce computational overhead, the dimensionality of the dynamic resistance signature set was reduced through Principal Component Analysis (PCA). PCA re-states the dynamic resistance in terms of a new, more convenient basis that maximises the variation within each principal component [11].

To identify which principal components of the signature are correlated with nugget diameter, correlation coefficients and associated p-values are calculated between each principal component of the training set and the nugget diameters. Principal components with a correlation p-value of less than 0.001, and described more than 1% of the total variation of the training set, were determined to be significantly correlated to nugget diameter. A p-value of 0.001 was chosen given the high number of hypotheses being tested. With the selected relevant components of the signature, a predictive model for nugget diameter was created using multilinear regression and the significantly correlated principal component scores of each weld.

3. Results

To compare the two methods, the estimates from ultrasound and the DRS method were compared to the true values measured from the destructive chisel test. Ultrasonic testing of the 80 validation welds returned the result ‘no fusion’ for 32 welds, indicating that either there was no nugget, or the operator decided that the machine could not provide an accurate estimate of the nugget diameter. A ‘no fusion’ result indicates that the weld has failed the ultrasound quality control test. For the comparison of the two methods, all welds assessed as ‘no fusion’ were removed, so as not to skew the results. The results of this can be seen in Figure 4 with the estimated values from each method on the vertical axis and the true values determined through destructive testing on the horizontal axis.

The vertical distance of each point from the line labelled ‘Correct’ can be considered the estimation error in millimetres, with points above the line overestimated and points below the line underestimated.

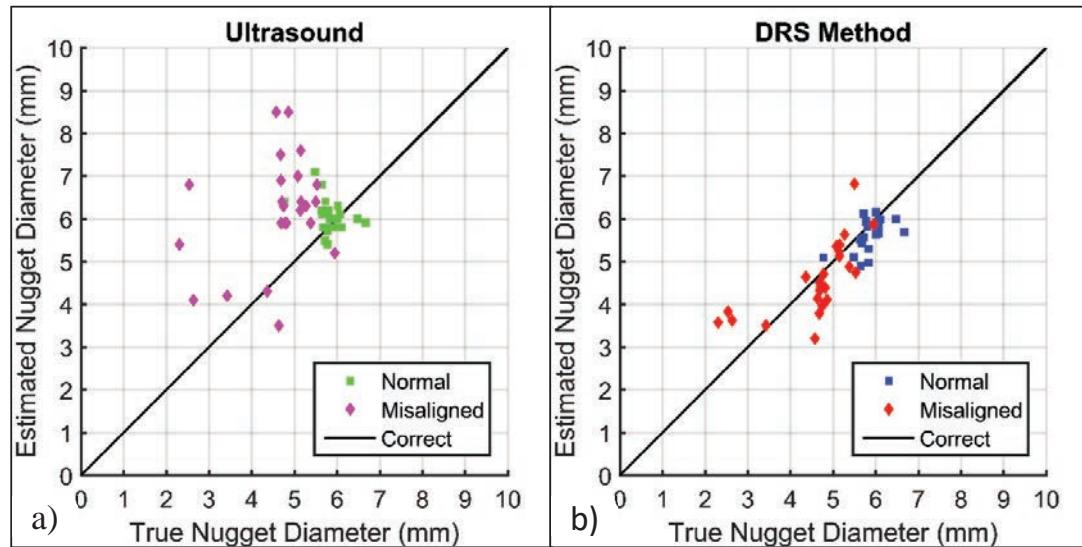


Figure 4: Direct comparison of Ultrasound and the DRS Method. a) Ultrasound, b) DRS Method.

4. Discussion

In Figure 4 the DRS method can be seen to perform better in terms of nugget diameter estimation than ultrasound, with values closer to the line of correct estimation. Ultrasound can be seen to over-predict the value for nugget diameter found through destructive testing which can be seen by the vertical distance of each point from the correct estimation line, especially in the case of misaligned welds. In addition, it should be acknowledged that estimation of these values takes much longer with ultrasound once the DRS Method has been trained given the parts have to be taken off the manufacturing line to be assessed.

4.1. Removal of welds that failed Ultrasound

For many of the welds that were created with a misaligned weld gun, the ultrasonic inspection returned a response of '*no fusion*'. In order to avoid misrepresenting the data, welds marked as '*no fusion*' were removed from the results presented above as they could not be given a nugget diameter by ultrasound. The result of '*no fusion*' was often due to the inability for the probe to sit flat on the measurement surface, preventing an accurate measurement from being made and requiring multiple attempts with the probe to confirm this diagnosis. These welds were still subjected to destructive testing subsequently, and their true nugget diameters were recorded given that all failed with nugget pull-out.

As a result, 32 welds with some real nugget diameter were labelled as '*no fusion*'. This significantly reduces the performance of ultrasound with many false positives, once the welds were subjected to destructive testing and found to have a measurable nugget diameter. Figure 5 shows the same results plot as Figure 4 a) with the '*no fusion*' results included labelled as '*Failed Ultrasound*'.

The '*no fusion*' welds, shown in Figure 5, labelled '*Failed Ultrasound*', can be seen to be predicted fairly well by the DRS Method, which significantly reduces the number of incorrectly rejected welds given that they were rejected by Ultrasound. It should be noted that all welds that were classified as '*no fusion*' were misaligned samples.

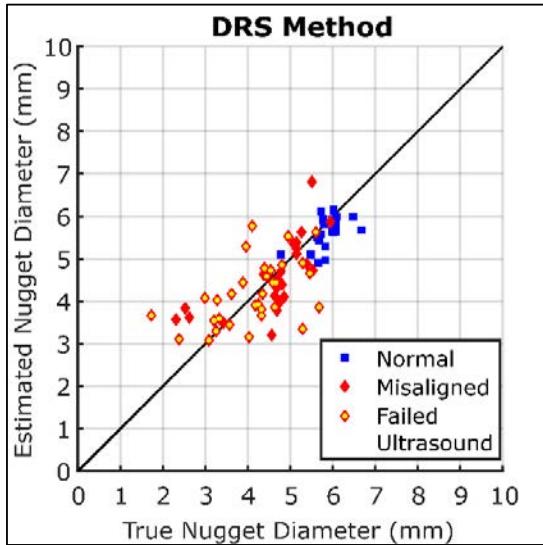


Figure 5: Nugget diameter estimation of the DRS Method with ‘No Fusion’ welds included (labelled as ‘Failed Ultrasound’)

The Mean Squared Error (MSE) values for each estimation method are shown in Table 3 to show the relative estimation accuracy. The mean squared error is calculated as shown in (1).

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - x_i)^2 \quad (1)$$

Where n is the number of welds, y_i is the nugget diameter determined from tear down and x_i is the estimated value from either Ultrasound or the DRS Method.

From Table 3, the MSE of the DRS method is shown to be significantly lower than that of Ultrasound when the ‘no fusion’ welds are removed. With the ‘no fusion’ welds included in the DRS Method estimation the MSE increases slightly, however it is still significantly lower than the Ultrasound prediction which does not include the ‘no fusion’ welds.

4.2. Sources of error for Ultrasound

The main source of error for the ultrasound scanner was ridges on the sheet surface being measured. With a non-flat sheet due to deformation caused by the gun misalignment, the probe was not able to achieve solid contact with the sheet, resulting in inconsistent ultrasound scans. This lead to welds failing the ultrasound test in the form of a ‘no-fusion’ diagnosis as discussed earlier. This results in higher than desirable false rejection rate in the case of misaligned welds, which in manually operated welding is a real possibility. This concept and example ultrasound results are shown in Figure 6.

Table 3: Mean Squared Error Values for Ultrasound and the DRS Method

Nugget Diameter Estimation Method	Mean Squared Error Value
Ultrasonic C-scan (‘no fusion’ welds removed)	2.26
DRS Method (‘no fusion’ welds removed)	0.33
DRS Method (‘no fusion’ welds included)	0.47

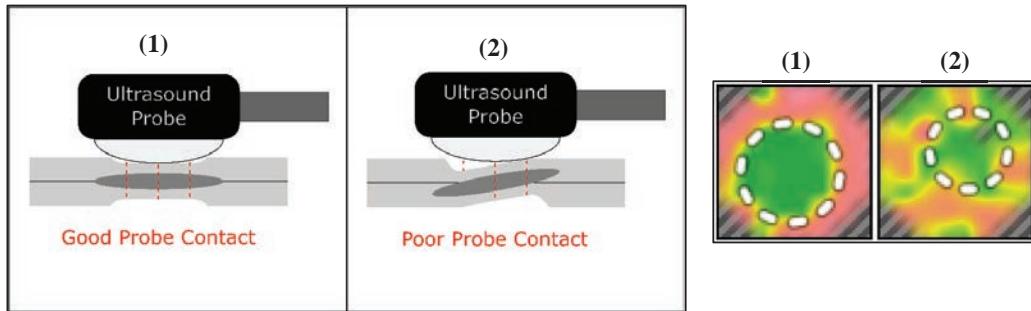


Figure 6: Poor ultrasound probe contact resulting in inconsistent reading

5. Conclusion

The quality of spot welds is critical to product quality control in the automotive industry. Ultrasonic testing has become the industry standard for non-destructive testing of spot welds due to its ability to provide an image of the subterranean weld nugget. However, Ultrasonic testing requires a trained operator to remove parts from the production line for testing, increasing manufacturing time and cost.

The Dynamic Resistance Signature nugget diameter estimation method presented in this paper was shown to outperform Ultrasonic C-scan nugget diameter estimation of weld nuggets produced in a production environment. From the results in Figure 4, the DRS Method can be seen to outperform Ultrasonic C-scan for nugget diameter estimation of welds that pass the ultrasonic test. In Figure 5 which includes the ‘no fusion’ welds that failed ultrasound, the DRS method can be seen to adequately predict the nugget diameters of the welds, reducing the number of falsely rejected welds, which has the potential to reduce production time and cost.

Given that the DRS Method presented in this paper can inspect every weld in production with higher accuracy than Ultrasonic testing, there is a strong case that estimating nugget diameter from the DRS is a valuable quality monitoring technique. Future work for this study will focus on analysis of the required training set size for accurate estimation of nugget diameter.

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