Empirical Modelling of a Prototype Resistance Spot Welding Machine

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Abstract
Resistance spot welding (RSW) has been extensively used in the automotive and aerospace industries over the years. The weld quality of spot welds is affected by the welding parameters like electrode force, weld time, electrode current and workpiece size/shape parameters like workpiece thickness. This study focuses on the effect of electrode force, weld time and workpiece thickness on the weld quality of mild steel samples where the aim is to correlate the weld strength to welding parameters of a portable RSW machine installed at the Nigerian Liquefied Natural Gas (NLNG) laboratory of the Department of Mechanical Engineering, University of Nigeria, Nsukka. Lap shear weld samples are tested for strength, and the results are used to develop an empirical model. The developed model has a coefficient of determination of 0.6365 and a correlation coefficient of 0.7978. Hypothesis testing at 5% significance level discovered that the most significant predictor is the cross interaction of the workpiece thickness and electrode force with p-value of 0.02367 and that the model is significant with a p-value = 0.0453. The model is validated by further welding operations and tensile shear tests which gave a percentage error not exceeding 12.92% but was as low as 6.35%.

Keywords: resistance spot welding; statistical regression; central composite design; weld strength; weld nugget; tensile shear test

1. Introduction
In RSW, coalescence is produced by application of heat and pressure. The heat derives predominantly from the electrical resistance of the interface between the workpieces to be joined to the flow of electric current in a circuit completed by the workpieces. Thus, it is based on the Joule heating effect, where heat energy is generated by passing an electric current through the joint to be welded over a given period. The resistance of the welding circuit should be maximum at the interface of the parts to be joined, and the heat generated there must reach a high value able to cause localized fusion under pressure. The heat generated melts the metal, forming a nugget at the faying interface of workpieces. The application of RSW in the world today is widespread, featuring in the areas of ship building, automotive production, railway construction, etc [1]. Its advantage over traditional welding techniques in the industry comes from the fact that it is an automatic and fast process, and requires no filler rod. It also presents the outstanding advantages of efficient energy use, limited workpiece deformation and narrow heat affected zone. However, the weld strength of RSW is significantly lower than other welding methods, making the process suitable for only certain applications, notably welding involving sheet metals [2].
A lot of research effort have been devoted to the understanding, prediction and optimization quality parameters of resistance spot welding. A study of RSW for the processes involved and common failure modes by Al-Mukhtar [3] concludes that weld strength is proportional to the diameter of the fused zone (weld nugget). This implies that in the absence of the means for measuring the strength of welded members (the most common being the tensile tests), a measure of weld nugget sizes of failed samples can be used to estimate the weld strength. However, direct strength testing is a better option because of greater accuracy. The experimental results of Raut and Achwal [4] showed that the welding parameters electrode force, welding current and time are the important factors for strength of a spot welded joint, and a combination of the suitable values of these parameters is necessary for the maximum strength of the joint. Their experiment, however, did not consider the effect variation of workpiece thickness has on the resulting weld: this work bridges this gap. The failure load relations developed by Chao [5] indicate that cross tension samples always fail at lower loads compared to the lap-shear samples, both containing similar spot welds. Since the maximum attainable weld strengths is sought for, lap-shear configuration is adopted in this work.

Zhou et al. [6] provided a systematic understanding on the influence of specimen sizes on the strengths of spot welds and proposed critical values for practical use. Their critical length, which is adopted in this research, is 150mm. The authors also suggested the need for equality in the overlap and width of workpieces. This precaution is observed in this work. Welding current, welding time, and welding force are inputs in the second-order empirical modelling of shear strength and indentation of Transformation Induced Plasticity (TRIP) steel and galvanized TRIP steel with a zinc-coated layer [7]. The influence of squeeze force, welding force and forging force (that is, the three stages of electrode force) and variable electrode force controlled by a servo gun on the quality of welds has been optimized using the design of experiment [8]. Based on experimental study using plate of 1.5mm thickness under different welding current, weld time and hold time, Muhammad et al. [9] simultaneously optimized weld nugget and heat affected zone using multi-objective Taguchi method. Zhao et al. [12] investigated the effects of welding parameters on the welding quality of titanium alloy sheets and optimizes them in small scale resistance spot welding process. The work was based on use of multiple quality characteristics (signal-to-noise ratios of weld nugget diameter, penetration rate, tensile shear load and the failure energy) to construct an independent quality index using principal component analysis. Models based on nonlinear stepwise regression analysis have been created for using welding time, welding current and electrode force in the prediction of nugget diameter of resistance spot welded dual-phase steel DP600 with a thickness of 1.7 mm [13].

Artificial intelligence has also been applied in the modelling and quality monitoring of resistance spot welding. Wan et al. [14] compared the back propagation neural network and probabilistic neural network for weld quality prediction. They found that while the former is more proper in failure load estimation the latter is more appropriate in quality level classification for production improvement of engineering materials. This work considers workpiece thickness, electrode force and welding time as the predictors of strength. The prototype RSW machine is designed for welding metals within 4 mm total thickness. The aim is to simplify the task of selecting the welding parameters from the control panel of the prototype RSW machine for given strength requirements by empirically correlating workpiece thickness, electrode force and weld time with weld strength.
There is a special interest here to unravel the effect of workpiece thickness and its interactions with the other variables on weld strength.

2. Materials and Methods

The prototype RSW machine shown in Figure 1 is equipped with a control panel through which any allowable combination of the predictors (workpiece thickness [mm], electrode force [N] and weld time [weld time level numbers on the machine]) are made. The machine is equipped with electrodes of diameter of approximately 1.2 cm. The specimens are of the thicknesses 0.8, 1.0, 1.2, 1.5 and 2.0mm, all of which were of length 150mm, width 36mm and overlap of 36mm. Experimental welding schedule was designed for the study based on circumscribed central composite design and executed. The responses are the measured strengths of the samples under tensile shear tests. The tests were carried out with a universal testing machine of 2500kgf rated capacity. The machine was maintained at a speed of 50mm/min during the tests. Validity of this work requires certain precautions which are observed. One of such precautions is ensuring that the overlapping surfaces of the workpiece are perfectly clean and free from rust (this is achieved by cleaning these surfaces with emery cloth) as rust and other foreign bodies at the electrode-workpiece interface may lead to a weak spot weld or no weld at all. The duty cycle recommended by the manufacturer of not exceeding 3 spots per minute and not exceeding combined work thickness of 4 mm are observed.

![Figure 1. The prototype spot welder; Clarke CSW13T](image)

With the measured responses as the targets and the designed experimental coordinates as the predictors, statistical regression is used to develop empirical models for representing the strength of spot welds in terms of the welding parameters. Goodness-of-fit indices are statistical error indices used to quantify the accuracy of predictions relative to the targets. In developing experimental models, outliers must be identified and treated. Here, outliers are detected as the values that lie outside the range

\[ Q_{25} - \alpha(Q_{75} - Q_{25}), Q_{75} + \alpha(Q_{75} - Q_{25}) \].

(1)

where \( Q_i \) is the \( i \)th percentile of the data set and \( \alpha \) is a constant value which contracts or broadens the range. The \( \alpha \)-values of 1.2 and 1.5 are adopted for this work. The detected outliers are deleted.
The statistical error indices considered here are the coefficient of determination $R^2$ and correlation coefficient ($r$), given respectively as

$$R^2 = 1 - \frac{\sum_{i=1}^{k}(y_{EI}-\bar{y}_{EI})^2}{\sum_{i=1}^{k}(y_{EI}-\bar{y}_{E})^2},$$

(2)

$$r = \frac{\sum_{i=1}^{k}(y_{EI}-\bar{y}_{EI})(y_{EI}-\bar{y}_{E})}{\left(\sum_{i=1}^{k}(y_{EI}-\bar{y}_{EI})^2\sum_{i=1}^{k}(y_{EI}-\bar{y}_{E})^2\right)^{\frac{1}{2}}},$$

(3)

where $k$ is the number of experimental runs, the subscript "E" indicates an experimentally determined value, the subscript "P" indicates a predicted value and $y$ is the response.

3. Results and Discussions

A fully quadratic polynomial model correlating the predictors and the responses is developed via statistical regression. The model reads

$$y = 11931.09 - 5585.11x_1 - 22.89x_2 + 994.28x_3 + 19.40x_1x_2 + 1.22x_2x_3 - 1603.51x_1x_3 + 2016.3x_1x_2x_3 + 0.003855x_2^2 + 416.70x_2 + 416.70x_1^2 + 0.003855x_2^2,$$

(5)

where $y$ is the weld strength in Newton’s, $x_1$ is the workpiece thickness in millimeters, $x_2$ is the electrode force in Newton’s and $x_3$ is the weld time level indicated on the prototype RSW machine. The results are plotted in Figure 2 on the plane of the predicted versus the measured strength values. A coefficient of determination of 0.6365, meaning that the developed model explains 63.65% of the variability of weld strength, and a correlation coefficient of 0.7978 are computed for the model. A substantial statistical correlation between the target and the predicted responses is concluded since a benchmark value of 0.35 for coefficient of determination is set by Mendenhall [18] for statistical correlation to be subsumed. To test the relative significance of the coefficients in the model, the following are computed: the standard error of the coefficients (SE), $t$-statistic given as (coefficient value)/SE, the $F$-statistic and the $p$-values for testing the null hypothesis (H0) that a coefficient is zero. It is found that the most significant predictor is the cross interaction of the workpiece thickness and the electrode force represented as $x_1x_2$ with the $p$-value of 0.02367 that clearly indicates significance at 5% significance level. The next significant coefficient but (but not significant at 5% significance level) is that of the self-interaction of weld time represented in the model by $x_3^2$ with $p$-value of 0.06080. At 5% significance level, the model overall is significant with a $p$-value = 0.0453.

When outliers are treated with $\alpha = 1.5$, the model and the statistical error indices remain unchanged but when $\alpha = 1.2$ is used in the treatment, the model reads

$$y = 16999.57 - 7027.73x_1 - 17.09x_2 - 2915.00x_3 + 9.22x_1x_2 + 1.15x_2x_3 + 433.63x_1x_3 - 1044.64x_1^2 + 0.002859x_2^2 + 376.86x_3^2,$$

(6)

and the statistical error indices slightly improve to coefficient of determination of 0.6525 and a correlation coefficient of 0.8078. Though outlier treatment with $\alpha = 1.2$ changed the magnitude, and sometimes the signs, of the coefficients of the model, the results of hypothesis testing are
identical with those of model Equation (5), therefore, it can be concluded that there are no outlier effects in the results thus Equation (5) is adopted as the working model.

The model is validated with additional experimental runs carried out in triplicates. The experimental coordinates for the validation, the mean results and the percent error are shown on Table 1. Considering the experimental validation given in the first row of the table with percentage error of 59.01% as an outlier, it can be seen that the percentage error did not exceed 12.92% and was as low as 6.35%, indicating validity of the developed model as guide for future use of the machine. The deviations in experimental and predicted strength values are generally attributed to circumstances beyond the control of the experimenter such as small discrepancies in the metallurgical conditions of the samples as a result of corrosion and other environmental factors like surface oxidation and scaling. These effects could still occur despite the efforts for uniformity that was made by purchasing samples from the same supplier as well as cleaning the surfaces to be welded with emery paper before welding. Also, weld current variation at the different runs of welding may have come into play.

![Figure 2. Predicted versus the measured failure strength of spot welds](image)

Table 1: Errors between experimental and predicted spot weld strength

| Thickness $x_1$ [mm] | Electrode force $x_2$ [N] | Weld time $x_3$ [level] | Average experimental Strength, $\bar{y}$ [N] | Predicted strength $\hat{y}$ [N] | Percentage error, $\frac{|\bar{y} - \hat{y}|}{\bar{y}} \times 100$ |
|----------------------|--------------------------|-------------------------|------------------------------------------|-------------------------------|----------------------------------|
| 0.8                  | 600                      | 4                       | 3599.43                                  | 5723.50                       | 59.01                            |
| 1.0                  | 600                      | 4                       | 5495.80                                  | 4925.80                       | 10.37                            |
| 1.5                  | 1000                     | 2                       | 5858.70                                  | 5486.60                       | 6.35                             |
| 2.0                  | 1000                     | 2                       | 6430.90                                  | 7262.00                       | 12.92                            |
4. Conclusion

In this work, an empirical model is developed for a real RSW machine stationed at the NLNG lab of the Department of Mechanical Engineering, University of Nigeria, Nsukka. The methodology for the study involves use of lap shear weld samples of different thicknesses produced using the machine at different electrode forces and welding times in tensile shear tests to failure, and using the results to develop empirical models through statistical regression. Then, validating the models by further welding operations and tensile shear tests. Using statistical error indicators, the developed model is shown to out-perform the benchmark for statistical correlation by far: the indices include a coefficient of determination of 0.6365, a correlation coefficient of 0.7978 and, under validation, a percentage error not exceeding 12.92% but was as low as 6.35%. Through hypothesis testing of the developed model at 5% significance level, it is discovered that the most significant predictor is the cross interaction of the workpiece thickness and electrode force with p-value of 0.02367 and that the model is significant with a p-value = 0.0453. Since the model gives the strength of spot welds in terms of the welding process parameters (electrode force and weld time) and workpiece size parameter (thickness), it can guide users towards achieving needed weld performance within the technological range of the machine.

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