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Development of a Model to Support the Management of the Resistance Welding Process

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Abstract: The work was carried out as part of a project to improve the corrosion resistance of welded joints. The optimal selection of input parameters reduces the consumption of welded material as well as the negative impact on the environment. The samples were welded by electrical resistance welding, more precisely by cross-wire welding. Electric resistance welding is a process for welding with electricity in which of high electrical resistance is used to generate heat at the contact point of the welded parts. Steel wire S235 with a diameter of 4 and 3 mm was used. The article shows the creation of the model to predict the percentage of setdown and weld strength as a function of the input parameters, welding current and welding time. The first task was to create a Design of experiments in which the process parameters or the range of input parameters are determined. The Design of the experiments was created for both wire diameters. This covers the range of parameters with which a welded joint of wires can be realised. A statistical analysis of the process follows, where it was found that for 4 and 3 mm diameter wires the percentage setdown increases with increasing welding current and time. An increase in strength as a function of welding current and welding time is also observed, but the results overlap in most cases and the range of their values is greater than that of setdown. The appearance of the weld was analysed for each sample. The visual inspection revealed seven categories of welds, which were divided into two groups, i.e. good and poor welds. All results were listed in a table with the percentage of expectation for a particular category of weld appearance. Based on the analysis, a model for determining the welding result parameters depending on the specified input parameters was developed, which can be used in practise to support the management of the electric resistance welding process.

Keywords: cross-wire welding; design of experiments; management; model; weld classification; welding process

1 INTRODUCTION

This research was carried out on the basis of work on the European Regional Development Fund project. Causal relationships were identified and empirical modelling of the process was carried out to predict the output parameters of the resistance welding process.

Resistance welding is one of the most important processes used in the automotive, electrical, construction, and aerospace industries as well as in the manufacture of household appliances. In resistance welding, the metals to be welded are brought into contact with each other, Fig. 1. The electrodes are connected to the secondary terminals of the welding transformer and a strong welding current flows through them, which heats the contact surface. The resistance at the contact surface generates heat and increases the temperature in its immediate vicinity, which increases the electrical resistance of the metal. The heat generated in the metal itself rises rapidly and quickly reaches the welding temperature, causing a weld nugget to form. The welding current is switched off and the weld nugget is scrubbed off, creating a solid metal bond between the two parts [1-4].

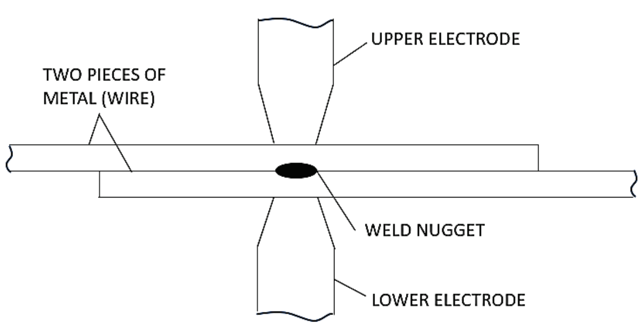

Figure 1 Where the weld is made

The principle is the same for different types of resistant welding, such as butt, spot, seam or even impact welding. The advantage of this method is that it can be used to join a variety of metal materials and is also suitable for welding the most commonly used metal-coated steel sheets [1-4].

The most important parameters in resistance welding are the welding current, the welding time and the pressure force of the electrode. The amount of energy introduced into the weld seam depends on the welding current and the welding time. A slight increase in the welding current quickly increases the diameter of the weld seam and thus its strength. The welding time has less influence on the size of the weld seam than the welding current. In resistance welding, short cycle times are generally preferred, which means a higher welding current and a shorter welding time. In this case, less heat is transferred to the areas immediately around the weld, so the thermal expansion remains at a lower level and the weld solidifies and cools down more quickly. The electrodes transfer the welding force and current to the desired location. One of the tasks of the electrodes is to cool the weld seam during the welding process. The contact between the electrodes and the workpiece is influenced by the force of the electrode. If the electrode force is too low, insufficient contact is made between the workpiece and the electrodes. This can lead to sparking, spattering, and faster wear of the electrode. If the electrode force is optimal, there is no spatter outside the area supported by the contact surfaces. In this case, the weld has a very good thermal balance. If the electrode force is too high, the electrodes press too hard on the workpiece, which can lead to indentation. In this study, the influence of the absolute value of the welding current and time at a constant electrode pressure force on the output parameters of the welding process, namely the setdown and the weld strength, was determined [3].

Cross-wire welding is a form of projection welding and a subtype of resistance welding. Cross-wire welding is mainly used in the electronics industry and in the manufacture of wire mesh. In his work, Knowlson [13] has given examples of cross-wire welding of various components such as diodes, resistors, capacitors, transistors, etc. In practice, a series of parallel wires are usually welded at right angles to one or more other wires or rods. In cross-wire welding, the electrodes exert pressure on the parts to be welded during and after the welding time in which a very strong electric current flows through them. The greatest resistance occurs at the contact surface of the two parts, which is why the greatest heat is generated there. This causes the two parts to join in the contact area. When the welding current is interrupted, the material in the heat-affected zone cools rapidly due to the cooler surrounding base metal, resulting in a solid weld [5].

The aim of this paper is to present a model that predicts the percentage of setdown and strength as a function of the input parameters of welding current and time, which was created for the purpose of the project. The welding process used in this work is cross-wire welding, and S235 steel wires with diameters of 4 and 3 mm are welded. Various studies can be found in the literature in which welding processes and process parameters are analysed. In their work, Kim et al. [6] determine the parameters of pipeline welding. They presented an intelligent system for determining the welding parameters for pipeline welding. In their work, Karadeniz et al. [7] investigated the effects of welding parameters on the setdown depth of Erdemir 6842 steel with a thickness of 2.5 mm, which was welded using robotic gas metal arc welding. Kim et al. [8] investigated the effect and contribution of welding current, electrode force, and welding time on joint strength during resistance spot welding of 316 LVM stainless steel cross wires with a diameter of 0.38 mm. Scotchmer [9] described the process of cross-wire welding in his work and presented the numerical modelling of cross-wire welding with SORPAS® with a very good comparison with the experiments carried out. Mikno [10] and Iatcheva et al [11] applied 3D simulation to the study of welded joints, and Nielsen et al [12] presented the development of a three-dimensional finite element computer programme for electro-thermo-mechanical industrial modelling of resistance welding, and the programme was applied to the simulation of projection welding of square nuts on sheet metal.

2 EXPERIMENTAL DETAILS

2.1 Material Details

For the purposes of the project and this study, S235 steel wire with diameters of 4h9 and 3h9 mm was used. The material S235 is part of the steel grade "S". This grade is mainly used for structural purposes in construction and mechanical engineering. In the designation S235, S means that it is structural steel, and 235 means that the minimum tensile strength of the steel is 235 MPa with a steel thickness of less than 16 mm [16].

2.2 Welding Process and Sample Preparation

The welding process was carried out in an industrial facility on a machine for electro-resistance welding. The wires cut to the same length are placed at right angles in the machine’s fixture. The number of wires used for one mesh is 18 and two electrodes are used for welding. The electrodes are designed in such a way that when they come into contact with the surface, they weld in three positions simultaneously. In cross-wire welding, the electrodes exert pressure on the wires to be welded, through which a very strong electric current flow. The greatest resistance occurs at the contact surface of the wires to be welded, which is why the greatest heat is generated at this point. This causes the wires to join in the contact area. If the welding current is interrupted, the material in the heat-affected zone cools quickly due to the cooler surrounding base metal, resulting in a solid weld [5, 14-16].

Once the welding process is complete, the grids can be cut to obtain smaller samples that are then used for analysis. There are 81 samples or 81 measurement points in each grid [14-17]. Each sample goes through three test phases:

1) Adjustment measurement
2) Visual classification of welds with regard to their appearance
3) Measurement of weld strength.

Measurements and welding tests were carried out in laboratory conditions.

2.3 Equipment Used for Sample Analysis

The equipment selected for setdown and strength measurement and visual inspection of welds consists of hardware and software components. A Mahr 40 EVR digital micrometre is used to measure setdown [14]. Two Basler industrial cameras with associated lenses and Pylon software and a Dino Lite digital microscope with tripod and integrated lighting are used for visual classification. A tensile testing machine and a Burster 8524 sensor are used to measure strength. The Burster is a sensor used to measure compressive and tensile loads in various application. It is supplied with the DigiVision software package, which is used to display, set and read the measurement results [15].

3 EXPERIMENTAL PROCEDURE

3.1 Design of Experiments (DOE)

DOE is a statistical tool consisting of a series of statistical techniques for process improvement and planning. DOE can be used to adjust the optimal parameters to achieve the best output levels and a robust process, i.e. a process with minimal variability [19]. Astakhov [20] describes in his paper the use of DOE in experimental studies on metal cutting, and Khanna [21] describes its use in research on metal cutting of titanium.

The most important input parameters for this type of welding are welding current, welding time and electrode pressure. In the preliminary results, it was found that the electrode pressure and the position of the electrode do not have as significant an influence as the welding current and welding time. Therefore, welding current and welding time at constant electrode pressure are used as input parameters for this study [14, 16].

Considering that the aim was to develop a more accurate model for predicting the output parameters of the welding process, it was, therefore, necessary to extend the range of input parameters. This include several parameters with which a welded joint of wires can be realised. In the Tab. 1 and Tab. 2 it can be seen the area marked with "x", which indicates that a weld was achieved with these parameters. The area marked with "-" indicates that the use of lower values for welding current and time does not result in welded joint in the contact points and the use of higher values of welding current and time results in excessive deformation of the mesh. Joints where no weld was achieved or the deformation of the mesh was too large for further processing were not included in the analysis.

A Design of experiments was drawn up, which was divided into two series: Series 1 for a wire diameter of 4 mm, Tab. 1, and Series 2 for a wire diameter of 3 mm, Tab. 2. A total of 972 experiments were conducted and the results obtained are analysed by the DOE using Minitab statistical software [22].

In Series 1, the wire diameter of 4 mm, the pressure of 3,5 kN, and the position of the electrode are constant. Two factors are observed: welding current and welding time. The welding current consists of 9 and the welding time of 7 levels, there are 9 repetitions for each mesh, which means that a total of 567 experiments were carried out.

Table 1 The range of input parameters used for a wire diameter of 4 mm

Series 1								
Wire diameter: 4 mm Pressure: 3.5 kN		Time, ms						
		20	50	100	200	300	400	500
Current, kA	8	-	×	×	×	×	×	×
	10	×	×	×	×	×	×	×
	12	×	×	×	×	×	-	-
	14	×	×	×	×	-	-	-
	16	×	×	×	×	-	-	-
	18	×	×	×	×	-	-	-
	20	×	×	×	-	-	-	-
	22	×	×	×	-	-	-	-
	24	×	×	×	-	-	-	-

Fig. 2 below shows a diagram of the main effect of the percentage of setdown as a solution for the Design of experiments.

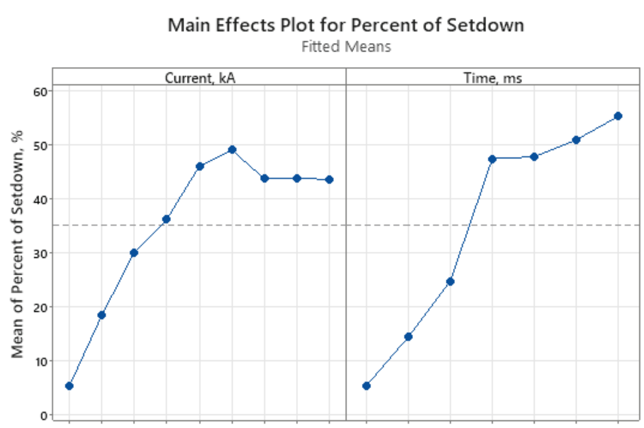

Figure 2 Main effects plot for percent of setdown for a wire diameter of 4 mm

The diagram shows that as the welding current increases, the percentage of setdown also increases up to a value of 49% and then decreases slightly. With increasing time, however, the percentage of setdown increases without decreasing.

Fig. 3 below shows a diagram with the main influences on the weld strength.

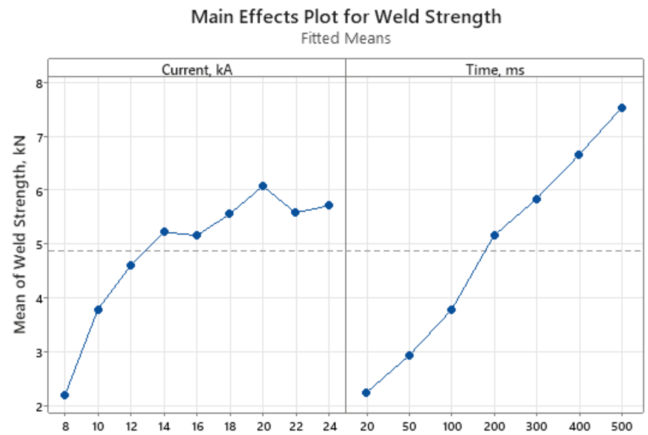

Figure 3 Main effects plot for weld strength for a wire diameter of 4 mm

The diagram shows that the strength of the weld increases as the welding current and welding time are increased. The welding current increases slightly, while the welding time shows an almost linear increase in weld strength as a function of time.

In Series 2, the wire diameter of 3 mm, the pressure of 3.0 kN, and the position of the electrode are constant. Two factors are observed: welding current and welding time. The welding current consists of 9 and the welding time of 5 levels, there are 9 repetitions for each mesh, which means that a total of 405 experiments were carried out.

Table 2 The range of input parameters used for a wire diameter of 3 mm

Series 2								
Wire diameter: 3 mm Pressure: 3 kN		Time, ms						
		20	50	100	200	300	400	500
Current, kA	6	-	-	×	×	-	-	-
	8	-	×	×	×	-	-	-
	10	×	×	×	×	-	-	-
	12	×	×	×	-	×	-	-
	14	×	×	×	-	-	-	-
	16	×	×	-	-	-	-	-
	18	×	-	-	-	-	-	-
	20	×	-	-	-	-	-	-
	22	×	-	-	-	-	-	-

Fig. 4 shows the influence of the main influences on the percentage of setdown when the wire diameter is 3 mm.

The diagram shows a similar situation to a wire with a diameter of 4 mm. Increasing the welding current also increases the percentage of setdown up to a value of 74%, after which it decreases slightly. Increasing the welding time leads to a sharp increase in the percentage of setdown.

Fig. 5 below shows a diagram of the parameters than influence the weld strength when the wire diameter is 3 mm.

The diagram shows a clear difference in the situation with a wire diameter of 4 mm. Increasing the welding current from 6 kA to 8 kA leads to an increase in weld strength.

Increasing the welding current from 8 kA to 10 kA leads to a slight decrease in weld strength. The same situation occurs when the welding current is increased from 12 kA to 14 kA and from 18 kA to 20 kA. Increasing the welding time also leads to an increase in weld strength up to a value of 200 ms. However, if the welding time increases from 200 ms to 300 ms, there is a sudden drop in weld strength.

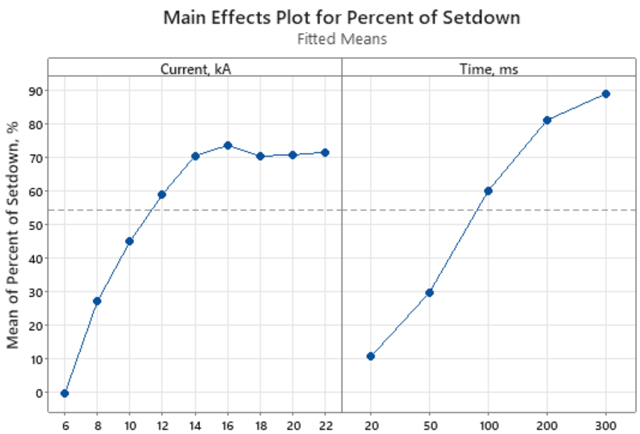

Figure 4 Main effects plot for percent of setdown for a wire diameter of 3 mm

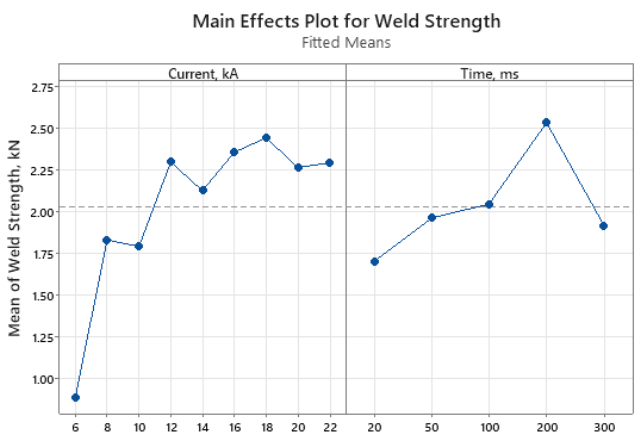

Figure 5 Main effects plot for weld strength for a wire diameter of 3 mm

It can be concluded from these diagrams that welding current and welding time have a major influence on the output parameters of the process, setdown and weld strength.

3.2 The Visual Classification of Weld Appearance

The welds were classified visually after each weld was inspected and photographed from all positions using a camera and digital microscope. After inspecting each weld, the weld is categorised into one of two basic categories: good or poor. A good weld is one whose surface is smooth or, in extreme cases, has a line, with no protrusions, splashes, spatter or needles, Fig. 6. A poor weld is one with needle-like protrusions, foam and larger, sharper irregularities, Fig. 7.

In the comprehensive analysis of visual weld quality, a total of 17,292 images of the appearance of the welds were taken, which were used to determine the classification of the welds, i.e. whether the weld is good or poor. In this study, there were 9 samples in each mesh, which means that there were 544 samples in total. Each sample was photographed 6 times to cover all sides of the weld. This is because in some cases a weld can be classified as good on one side and as poor on the other. The total number of images of welds in this study is 3,264 images.

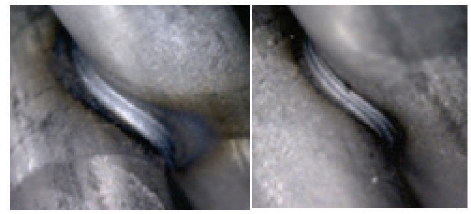

Figure 6 Good weld

Figure 7 Poor weld

4 RESULTS

4.1 Regression Equations

Based on the previous solutions, the following equations were obtained, which are the basis for creating the model to support the management of the welding process:

A. Regression equations for a wire with a diameter of 4 mm:

$$\begin{aligned} &Percent\ of\ Setdown = -0.1831 + 0.03201 \cdot current - \\ &-0.000790 \cdot time - 0.000897 \cdot current^2 + \\ &+0.000156 \cdot current\ time, \end{aligned} \tag{1}$$

With R_{sq} of 97.25 %, which mean that 97.25 % of the variation is explained by this regression equations.

$$\begin{aligned} &Weld\ Strength = -2.689 + 0.5789 \cdot current - \\ &-0.0205 \cdot time - 0.01560 \cdot current^2 + \\ &+0.001221 \cdot current\ time, \end{aligned} \tag{2}$$

With R_{sq} of 69.04 %, which mean that 69.04 % of the variation is explained by this regression equations.

B. Regression equations for a wire with a diameter of 3 mm:

$$\begin{aligned} &Percent\ of\ Setdown = -0.2298 + 0.03957 \cdot current - \\ &-0.000633 \cdot time - 0.001051 \cdot current^2 - \\ &-0.000002 \cdot time^2 + 0.000375 \cdot current\ time, \end{aligned} \tag{3}$$

With R_{sq} of 96.49 %, which mean that 96.49 % of the variation is explained by this regression equations.

$$\begin{aligned} &Weld\ Strength = -0.275 + 0.2546 \cdot current - \\ &-0.00447 \cdot time - 0.00780 \cdot current^2 + \\ &+0.001023 \cdot current\ time, \end{aligned} \tag{4}$$

With R_{sq} of 58.38 %, which mean that 58.38 % of the variation is explained by this regression equations.

C. Regression formula to determine the probability of occurrence of the good weld:

$$P(0) = \frac{exp(Y')}{(1 + exp(Y'))}, \quad (5)$$

a) For a wire with a diameter of 4 mm:

$$Y' = 51.0 - 4.17 \cdot current - 0.01740 \cdot time, \quad (6)$$

b) For a wire with a diameter of 3 mm:

$$Y' = 282 - 23.3 \cdot current - 0.205 \cdot time. \quad (7)$$

4.2 The Model

Based on the previously determined regression equations, a model was created to support the management of the welding process. To create the model, it was necessary to write code. The result is shown in Fig. 8.

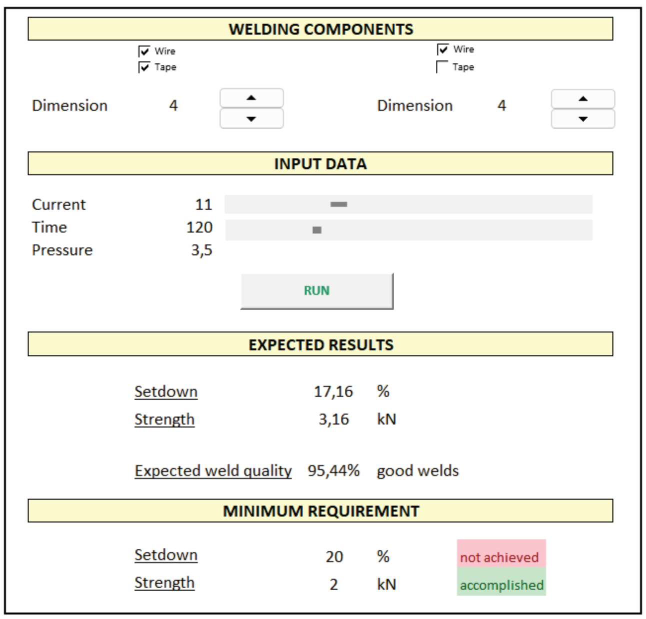

Figure 8 Model to support the management of the welding process

The model is divided into 4 categories:

1) Welding components represent the shape and diameter of the material used for the welding process. It is possible to choose whether the input material is a wire or a strip and what dimensions it has.
2) Input data are input parameters of the process. Various welding current, time and pressure parameters can be selected from the extended range resulting from the previous equations. After all input parameters have been selected, the model is started by pressing the "Run" button.
3) Expected results are obtained when the model is run. Based on the input parameters and the regression equations, the output parameters of the process are predicted as a solution, namely setdown and the weld strength. In addition, the probability that the weld will be good is shown.
4) The minimum requirement is the last category in which the user of the model enters the minimum requirements for the output parameters. If these requirements are met, the result is displayed as "accomplished", otherwise "not achieved".

5 CONCLUSIONS

A new Design of experiments was drawn up covering the range in which a welded joint can be produced from S235 steel wires with a diameter of 4 and 3 mm. The graph shows that the welding current and welding time have a major influence on the output parameters of the process, setdown, and the strength of the weld. The welds were also visually classified into two basic categories, namely good and poor welds. A good weld has no visible irregularities, while a poor weld has various dents, spatter, sharp spots, etc.

Based on the previous solutions, regression equations for setdown and weld strength for 4 and 3 mm wire and regression equations to determine the probability of the desired result were created. Based on the accumulated knowledge of the process and the research and analyses carried out, a model was created to support the management of the welding process. The aim of this model is to predict the output parameters of the welding process. In this way, the user can quickly and easily determine which form of input material and which input parameters should be used when welding with the specified minimum requirements.

The limiting factors of this model are that it was created for one material, for two dimensions of wires and the limited data set presented in this paper. These limitations provide room for further research and improvement of the model presented.

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