Analysis of the Cross-Wire Welding Process Stability

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Abstract: The research paper was prepared within the framework of a project whose aim is to improve the durability of the corrosion protection properties of the product by regulating the input parameters of the cross-wire welding process. Cross-wire welding is a subtype of electric resistance welding. Products made by the cross-wire welding process are widely used in everyday life and can be found in the form of grids, gratings, fencing systems, baskets, guards, etc. The subject of the research work is a preliminary analysis of the stability of the cross-wire welding process. The results of the performed analysis will serve as a starting point for the second phase of the project. Since the recorded values of the set down output parameter differ significantly from the expected values, this parameter is considered as an indicator of the process stability. From the specific trend of the results in the performed analysis, it was concluded that the position of the electrode has a significant influence on the result, which was confirmed by comparing the test results before and after the preliminary tests.

Keywords: cross-wire welding; electric resistance welding; process stability; welding process

1 INTRODUCTION

This research is being conducted for the purpose of working on the European regional development fund project. It is expected that causal relationships and empirical modelling of the process will be established through this and future research to gain insight into the behaviour and stability of the resistance welding process.

Resistance welding is a highly efficient production method, most commonly used in mass and automated production, but also suitable for small batch production due to its flexibility and simplicity [1, 2]. The weld is formed by contact of the parts with electrodes through which electric current is passed, heating them until they melt and bond at the point of contact. The current and pressure are then turned off and the weld is cooled, creating a strong metal bond between the two parts [1]. In the project and the research conducted, the subtype of resistance welding used is cross-wire welding.

Cross-wire welding is a form of projection welding in which local welding current and force are used to weld at the contact point of two perpendicular wires [3]. In electronics, various components such as resistors, capacitors, diodes, and transistors are usually welded using this method [4]. In this paper, a wire mesh is used on which three welds are welded simultaneously in one step.

Setdown as one of the output parameters of the cross-wire welding process has a significant effect on the appearance, shape, and quality of the weld. If the setdown is too low, the weld will have low strength, and interfacial failure will occur, also known as cold welding. Cold welding occurs due to insufficient welding current, welding time, or electrode wear [5]. However, if too strong a current is used or the cylinder rotates too slowly, then expulsion occurs [3]. Whether a setdown is too large or too small is determined by measurement. The measured values and pre-defined setdown range requirements are used to determine whether a process improvement is required.

The objective of this paper is to perform a stability analysis of the cross-wire welding process on a test series before moving to the next phase of the project, where detailed testing of wire meshes will be performed. By measuring and analysing the values obtained, setdown variations within the mesh were determined for the same welding parameters. The variability of the process decreased after electrode adjustment.

2 CROSS-WIRE WELDING PROCESS

In cross-wire welding, one or more rows of parallel rods or wires are welded together at right angles [6]. The material of the wire is S235 steel, which is supplied in large spools weighing up to several tons. As with any type of welding, the wire must be clean, free of dirt, paint, heavy grease, or high-strength coatings [6]. Before welding, the wires are cut to a specific length using a cutting machine. The operator then inserts them into a special fixture on the robot arm. The operator sets the input parameters (welding current, time, pressure, etc.) on the control panel and starts the program to begin the welding process. Welding begins by pressing the wires between the two electrodes. The force applied to the electrodes is transferred to the wires, whereupon current flows through the electrodes and heats the wires at the contact points. The material melts, mixing occurs, and after cooling, a strong joint is formed.

The welding force or pressure is determined by the wire diameter, setdown percentage, desired appearance, required weld strength, and the electrical and mechanical capacity of the welding machine. The welding force determines the appearance of the weld. Its value must be accurately determined to avoid the uneven appearance of the weld without increasing welding time and decreasing productivity [6]. The welding time is also determined by the diameter of the wire. According to [6], the most consistent welding results are obtained with automatic welding timers with synchronous precision.

The welding current is determined by the wire diameter, the setdown percentage, and the welding time. The current should be slightly lower than that which causes spitting or

ejection of metal to obtain a weld of good strength and pleasing appearance [6].

The electrode material is copper. The electrode acts with a concentrated force on the outer surfaces of the wires to be welded. Due to their low electrical resistance, these electrodes can achieve large currents per workpiece without significant heat loss. In addition, their high thermal visibility allows more accurate control of weld formation as well as the rate of cooling and heat dissipation from the workpiece [7]. It is specifically designed to weld three positions, Fig. 1, on the wire mesh simultaneously with one stroke of the electrode, which reduces welding time and increases productivity.

Figure 1 Upper cross-wire welding electrode

Contact locations of electrode and mesh can be easily noticed on Fig. 1. Those positions of the electrode are darker than the rest of the electrode due to the passage of weld current. Exact position identification is shown on Fig. 7. The lower cross-wire welding electrode is shown in the following Fig. 2.

Figure 2 Lower cross-wire welding electrode

Fig. 3 shows the final product obtained by welding process of wire, where electrodes shown in Fig. 1 and Fig. 2 were used.
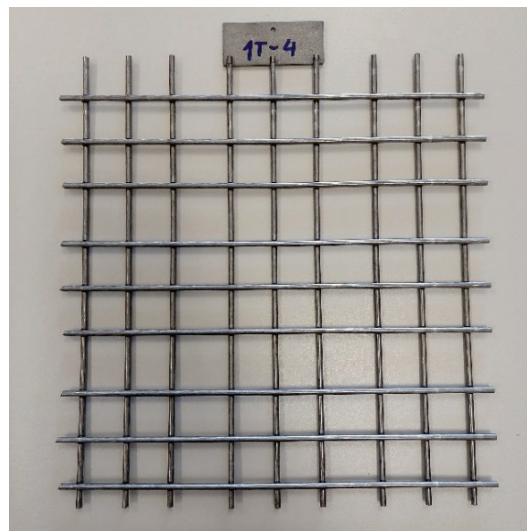

Figure 3 Final product – wire mesh

2.1 Cross-wire Welding Process Stability

The second phase of the project, will test and validate the solutions under real conditions, monitor the results obtained, and determine the necessary improvements. Before the implementation of the second phase, the stability of the cross-wire welding process must be verified on a test series of welded meshes.

The main characteristic of the quality of the production process is variability. By analysing certain product characteristics, it is possible to determine whether changes need to be made to the process. Significant variations indicate the need to redesign and improve the process. They are influenced by a variety of parameters and elements of the process; in cross-wire welding, these can be a machine, operator, material, electrode, environment, etc. If variations occur as a result of common causes, which is considered a natural phenomenon in any process, regardless of its quality, then it can be said that the process is stable or under statistical control. A stable process results from the complete elimination of variations caused by special causes.

Therefore, the main task is to use statistical "signals" to warn of the presence of variations in the process, and control charts are used for this purpose. Control charts monitor a characteristic of the product taken from the process [9]. In this paper, setdown is used as a measure of process stability. Setdown is one of the characteristics of a weld that determines its quality [5] and directly affects the strength of the welded parts [8].

An evaluation of the capability of the cross-wire welding process is also performed. The process capability indices C_p and C_{pk} are used to evaluate the process capability. The higher their value, the lower the variability of the process and the more capable the process is. The process is considered incompetent if $C_p < 1$, at the limit of acceptability for $C_p = 1$,

and capable if $C_p \geq 1,33$. The potential capacity of the process is measured by C_p and the actual C_{pk}. When $C_{pk} > 1$ at least 99,73% of all measurements are within the limits, and when $C_{pk} < 1$, the process should be improved because products are produced that do not meet the requirements. The tolerance field is the difference between the upper and lower limits of the requirements and can be defined by standards, regulations, and customer requirements [9]. For this project and research, the limits are defined based on practical experience. To achieve a setdown of 0,600 mm or 15%, which is the initial value in this case, the tolerance is ±10%, which means that the lower limit is 13,50% and the upper limit is 16,50%.

The first step consists in cutting samples from the mesh. The second step consists in measuring the thickness of the two welded wires. Due to the geometry of the samples, simplicity, speed, and precision, the Mahr 40 EVR digital micrometer is used. The main specifications of the micrometer are the measuring range 0-25 mm, the resolution 0,001 mm, and the measuring error of 4 μm. The outside micrometer is clamped in the stand, which facilitates the placement of the specimens between the anvil and the spindle and the reading of the values, Fig. 4.

Figure 4 Measurement of setdown on samples using a digital micrometer

Another advantage is the LCD screen and the connection and transmission of readings to the computer. The wire diameter is Ø4h9 mm for all samples in the test series. The diameter of the wires was measured after cutting, the values obtained are within the tolerance limits. The percentage of setdown is calculated according to [6] as follows in Fig. 5.
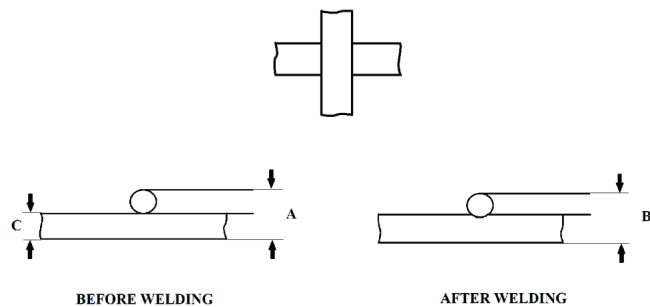

Figure 5 Measurement parameters setdown

Equation for calculation of the percent setdown:

$$PERCENT\ SETDOWN = \frac{A-B}{C} \cdot 100\ \% \qquad (1)$$

where:
A - Sum of diameters of two wires before welding, mm
B - Sum of diameters of two wires after welding, mm
C - Wire diameter (diameter of one wire before and after welding is the same or approximately the same), mm

3 RESULTS

In this part of the paper, the results of the stability of the cross-wire welding process are presented. The requirement was a setdown of 0,600 mm, which corresponds to 15%. The meshes on which the tests were performed were made with the same input parameters (welding current, time, pressure) in order to compare the results obtained. Percent setdown data through time by electrode position and trajectory before and after its adjustment are shown in Tab. 1.

Table 1 Setdown data

	Position 1			Position 2			Position 3	
S	B	A	S	B	A	S	B	A
1	12,51	15,21	28	17,02	15,44	55	20,43	15,39
2	13,41	15,66	29	17,29	15,66	56	19,50	15,54
3	12,66	15,34	30	17,09	15,24	57	20,03	14,91
4	12,23	15,81	31	16,59	15,54	58	19,97	15,54
5	12,51	14,81	32	16,42	14,46	59	18,67	14,19
6	12,38	14,96	33	16,09	14,71	60	19,72	14,59
7	13,68	15,61	34	18,05	15,09	61	18,92	14,79
8	12,91	14,86	35	16,54	15,39	62	18,52	15,01
9	12,76	14,89	36	16,67	14,84	63	18,30	14,56
10	13,13	15,26	37	16,97	15,09	64	18,97	14,81
11	12,88	14,84	38	16,92	14,39	65	18,62	14,19
12	12,86	15,04	39	16,44	14,66	66	18,40	14,21
13	12,71	15,29	40	16,82	15,04	67	19,32	14,69
14	12,36	14,66	41	16,64	14,81	68	18,37	14,79
15	12,26	15,04	42	16,84	14,94	69	18,85	15,11
16	12,68	15,61	43	16,97	15,46	70	19,15	15,39
17	12,26	14,41	44	16,57	14,46	71	19,00	14,54
18	12,81	14,89	45	17,09	14,99	72	19,15	14,61
19	12,31	14,76	46	17,12	15,16	73	20,05	15,29
20	12,48	14,86	47	16,92	15,16	74	18,90	14,96
21	12,11	14,91	48	16,67	14,89	75	18,80	14,91
22	18,62	15,96	49	17,27	15,44	76	13,43	15,54
23	12,86	14,16	50	16,74	14,89	77	18,80	14,81
24	14,11	14,54	51	17,29	14,74	78	17,72	14,66
25	13,41	15,14	52	17,19	15,06	79	19,45	15,16
26	12,53	14,69	53	16,87	14,84	80	18,65	14,64
27	12,78	14,79	54	16,99	14,89	81	19,15	14,79

where from the table:
S - sample
B - before electrode adjustment
A - after electrode adjustment

Fig. 6 shows a control chart for 81 samples from one mesh. The electrode welds three welds simultaneously during one working stroke. Therefore, in order to check the stability, an analysis was performed as a function of the position of the electrode, which is shown in control charts and a boxplot.
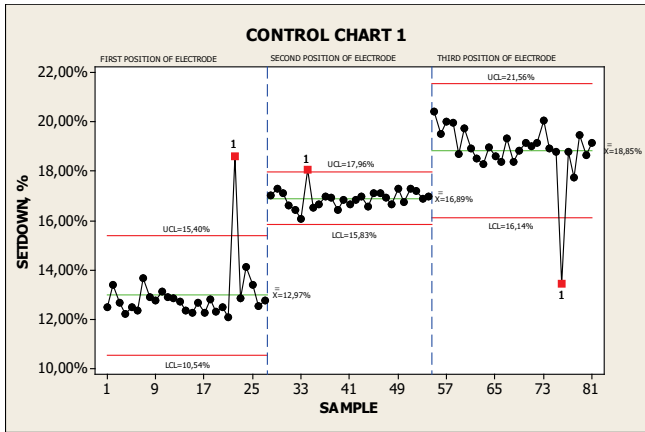
Figure 6 Control chart according to electrode position before adjustment

The ordinate of the control chart, consisting of the centre line of the process, the upper and lower control limits, takes on different values depending on the position of the electrode. It can be seen in the control chart that at each electrode position there is a point outside the control limits (UCL or LCL), which is an indication that the process is out of control. In this case, the required 15% setdown was not achieved, and the causes of the variability need to be addressed.
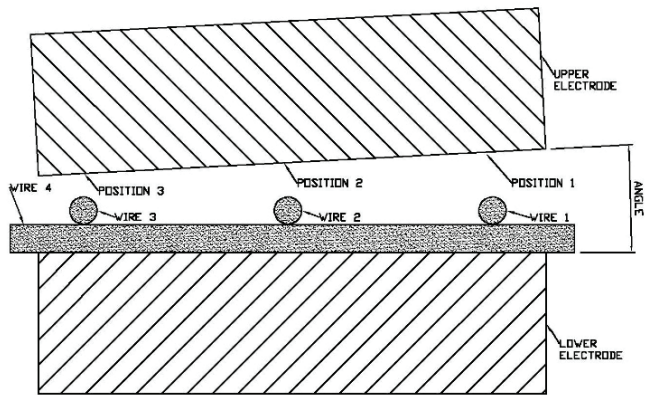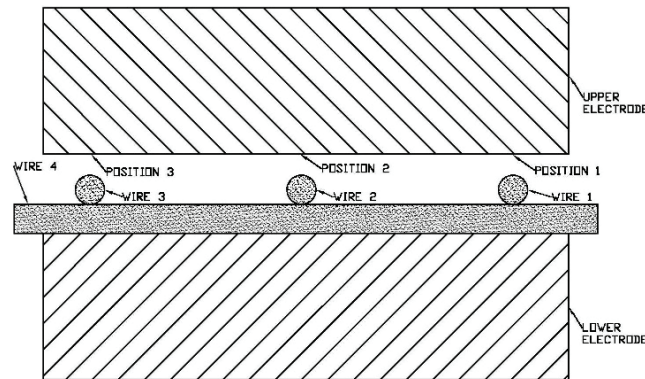

Figure 7 The angle between the electrodes

Figure 8 Electrode parallelism after angle adjustment

The electrode is considered as a possible cause, as the setdown values are different depending on the position, indicating a possible deviation of the electrode from parallelism. Electrode check was performed and as found condition is shown at Fig. 7.

In order to achieve target results electrodes must be in parallel relation. During electrode check the angle between the electrodes was detected, what led to uneven welding at all three contact positions. Therefore, precise adjustment of upper electrode position was performed to cancel out detected angle, and result can be seen in the Fig. 8.

In order to confirm that the unwanted angle has been removed and that the electrode is the cause of variability, a second series was made whose results are shown in Fig. 9.
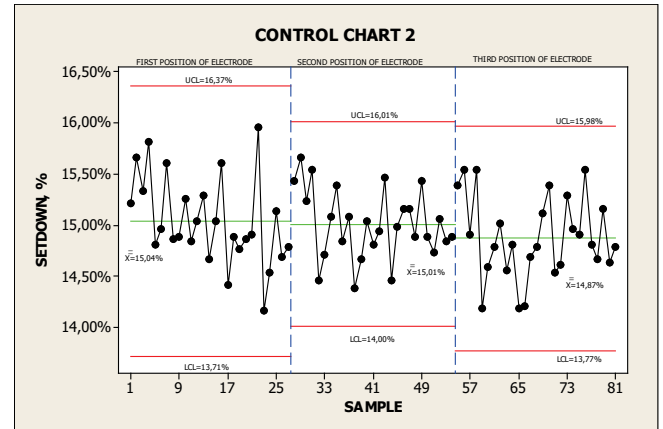

Figure 9 Control chart according to electrode position after adjustment

After the adjustment, there is an improvement in the welding process. The process is now under control and the indicators are the points that are within the control limits. The deviations from the electrode position are minimal and all measured values are now at 15%, meeting the original requirement.

Following Fig. 10 shows comparison of welding percent setdown results obtained before and after adjustment of electrode angle. The boxplot diagram shows range and average value of percent setdown by electrode position.
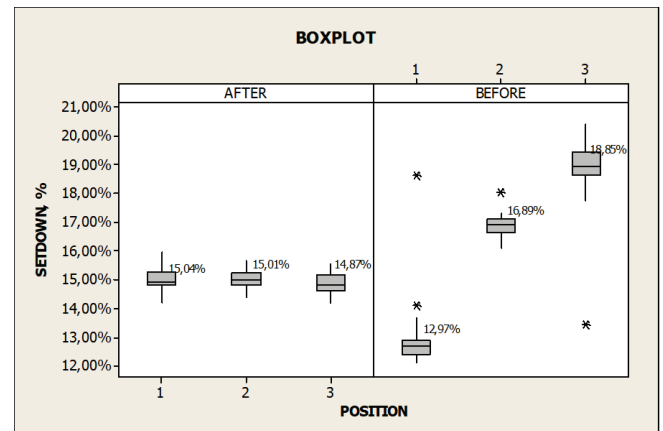

Figure 10 Comparison of results percent setdown by electrode position

Capability of the process before the adjustments of the electrode angle can be seen in the following Fig. 11.
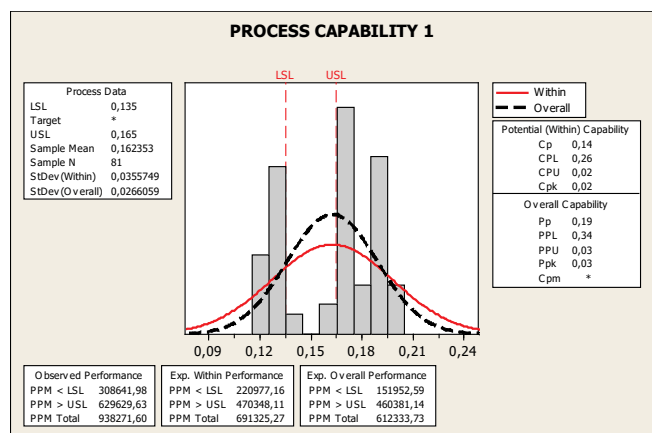
PROCESS CAPABILITY 1

Process Data
LSL 0,135
Target *
USL 0,165
Sample Mean 0,162353
Sample N 81
StDev(Within) 0,0355749
StDev(Overall) 0,0266059

Potential (Within) Capability
Cp 0,14
CPL 0,26
CPU 0,02
Cpk 0,02

Overall Capability
Pp 0,19
PPL 0,34
PPU 0,03
Ppk 0,03
Cpm *

Observed Performance		Exp. Within Performance		Exp. Overall Performance	
PPM < LSL	308641,98	PPM < LSL	220977,16	PPM < LSL	151952,59
PPM > USL	629629,63	PPM > USL	470348,11	PPM > USL	460381,14
PPM Total	938271,60	PPM Total	691325,27	PPM Total	612333,73

Figure 11 Process capability before electrode adjustment

It can be seen that the process indices are $C_p = 0,14$ and $C_{pk} = 0,02$, which is an indication that the process is incapable and that it is necessary to improve it. After adjusting the electrode, the process capability indices are $C_p = 1,82$ and $C_{pk} = 1,79$, which can be seen on the Fig. 12.
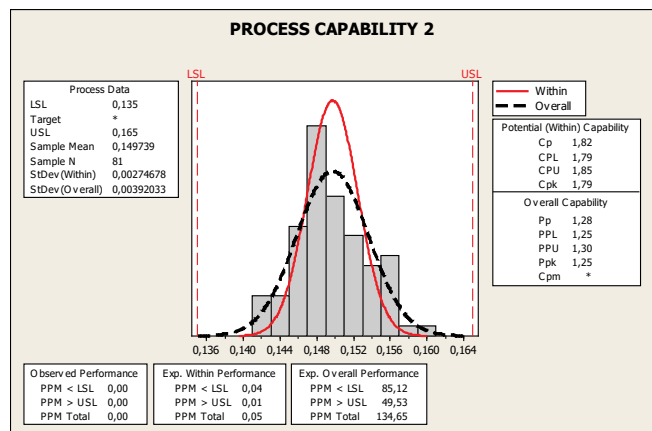
PROCESS CAPABILITY 2

Process Data
LSL 0,135
Target *
USL 0,165
Sample Mean 0,149739
Sample N 81
StDev(Within) 0,00274678
StDev(Overall) 0,00392033

Potential (Within) Capability
Cp 1,82
CPL 1,79
CPU 1,85
Cpk 1,79

Overall Capability
Pp 1,28
PPL 1,25
PPU 1,30
Ppk 1,25
Cpm *

Observed Performance		Exp. Within Performance		Exp. Overall Performance	
PPM < LSL	0,00	PPM < LSL	0,04	PPM < LSL	85,12
PPM > USL	0,00	PPM > USL	0,01	PPM > USL	49,53
PPM Total	0,00	PPM Total	0,05	PPM Total	134,65

Figure 12 Process capability after electrode adjustment

4 CONCLUSION

The test meshes were tested based on the analysis of the stability of the cross-wire welding process using control charts and boxplot. The control charts determined the instability of the process and the process out of control. The cause of variability was the electrode.

Due to the deviation from parallelism, a percent setdown value of 12,97% was obtained for the first position of the electrode, while the value for the third position was 18,85%. This is an indication that the electrode was slightly raised forward (first position), which is why it had more contact with the samples in the third position, where a larger setdown value was achieved. By adjusting the angle between the electrodes, the process is under control and the range between the minimum and maximum setdown percentages is reduced from 8,32% to 1,8%. The setdown percentage is around 15% and a requirement that is now met. Welding current and pressure can also have a large influence on the welding output parameters, but they are constant throughout the process and their influence did not need to be explore separately.

The process performance indicators C_p and C_{pk} were well below acceptable limits before electrode adjustment, which was also an indication that process improvement was needed. Process capability was achieved after the adjustment, and the reported process capability indices are now above the limits to be achieved.

To ensure the existing condition of the process, it is necessary to perform continuous controls, define elements (Poka-Yoke) or mechanisms to prevent the recurrence of electrode non-parallelism.

Acknowledgement

Notice

The paper will be presented at MOTSP 2022 – 13th International Conference Management of Technology – Step to Sustainable Production, which will take place in Primošten/Dalmatia (Croatia) on June 8–10, 2022. The paper will not be published anywhere else.

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