OPTIMIZATION OF RESISTANCE SPOT WELDING BY COUPLING CENTRAL COMPOSITE DESIGN AND BFGS ALGORITHM

José Enrique Vargas
PhD Candidate, University of Brasilia, Graco, Campus Darcy Ribeiro, 70910-90
jevargas@hotmail.com

Sadek C. Absi Alfaro
Ph.D. Full Professor, University of Brasilia, Graco, Campus Darcy Ribeiro, 70910-90
sadek@unb.br

Louriel O. Vilarinho
Ph.D. Associate Professor, Federal University of Uberlândia, Laprosolda, Campus Santa Mônica, Bloco 1M, 38400-032
vilarinho@mecanica.ufu.br

Abstract. *In the Resistance Spot Welding Process a good quality, reflected on the physical and mechanical characteristics of the weld nugget, is obtained throught good control of parameters. Due to amount of the parameters in the process, factorial methods in experimental design can be used to guarantee a trustworth statistics as well as analyzing the influence of chosen factors in the responses with a feasible number of runs. In this work, using the Central Composed Design (CCD), it will be executed 27 runs for 5 factors at 3 levels to analyze 3 responses named Indentation, Spot Diameter and Mechanical Resistance. The CCD results in a empiric model (polynomial function) obtained by statistical regression that is used as an objective function, which will be optimized by using an algorithm BFGS. Thus the optimum working point of the process for each response will be found. The work verifies that optimization algorithm and the whole methodology can be used in Resistance Spot Welding.*

Keywords*: Resistance Spot Welding, Optimization techniques, BFGS method.*

1. INTRODUCTION

The Resistance Spot Welding (RSW) is one of the most employed manufacturing processes in the automotive industry, due to its simplicity, easy operation, high productivity (more than 20 spots/minute), low-cost and simple equipment for AC (alternating current) power sources and straightforward adaptation for automatic production lines. In this process, metal sheets are joined by the accomplishment of welded spots from the localized melting due to heat generated by the material resistance of current passage (Gedeon et al., 1984). The main parameters of the process are the Upslope Time, Current Time, Downslope time and Electrode Force, which are responsible for a quality accomplishment of the spot. Also the water flow is important for electrode life and as guarantee of the electrical resistance pattern along the system (Choo & Ree, 2000).

The use of galvanized steels (hot-dip-galvanized, electrogalvanized and hot-dip-galvannealed), as a response against corrosion resistance and cost reduction in tailored-blanks, brought difficulties while welding this material, once these steels have a zinc layer that has different properties from the base material (melting point, electrical and thermal conductivity, etc).

Once the reasonable number of parameters must be assessed during welding at different levels for the spot success, Experimental Design comes with a handy solution for reducing the number of runs, but keeping the confidence level, and statistical methods can be used for studying and analyzing the effects of those parameters, covering a wide range of possibilities (Barros Neto et al., 2002).

In order to provide a situation where the experimental design could be applied under similar condition, as normalization, Vargas (2006) recently proposed a method known as Specific Energy Method. In this method, it is proposed to keep the product of current versus time constant, instead of simple changing the current level, as it is done in conventional research. The relationship between current and time is described in Eq. 1. It should be pointed out that this energy level is, in fact, a specific level, defined by the division of the energy (Joule effect) by the electrical resistance. Since the electrical resistance varies, this is an approximation, which was validated by Vargas (2006).

$$E_{esp} = \frac{E}{R} = I_{rms}{}^{2} \cdot T_{s} \tag{1}$$

where Eesp is the specific energy, E is the energy generated by Joule effect, R is the electrical resistance, Irms is the rms value for the welding current and Ts is the total welding time.

An important result from the experimental design is the empirical model, which correlates the responses to the factors. This empirical model is a polynomial equation that can promptly used by an optimization algorithm for searching the optimum working point in a given configuration. Since the equation is polynomial, the search for this optimum is not complicated one. Thus, direct optimization algorithm, such as BFGS can be used (Vanderplaats, 1984).

Thus, in this work is proposed to assess the influence of the cited parameters on the resistance spot welding of galvanized steels at two different thicknesses (2.0 mm and 1.2 mm) by using experimental design and the Specific Energy Method. With the empirical model done, a BFGS optimization algorithm is employed for searching the optimum condition for different responses, which in this case are indentation, spot diameter and mechanical resistance.

2. EXPERIMENTAL PROCEDURE

The welding was made by a alternating-current spot welding machine composed by a transformer (manufacturer Soltronic HT75 2 MF, 440 V, 75 kVA, 170 A in the primary circuit) and a controller (manufacturer Fase Saldatura with maximum nominal power of 54 kVA) was used to supply a water-cooled electrodes with pneumatic pressure from 87 to 261 kgf, with the welding current (secondary circuit) varying from 2 to 6 kA and maximum welding cycle of 100. The electrodes (caps) are 16-mm external diameter, spherical type, Class A, Group 2, hardness of 75 HRb and 75% IACS, cooled by water refrigeration system.

The metal sheets are galvanized ones (hot-immersion technique with 40 μm of coating thickness) and they are clamped together and the spot welding is carried out in the center of one side in order to guarantee repeatability. All sheets have dimension of 100 x 25 mm. Three different configurations are employed, namely A, B and C. Configuration A makes use of sheet thickness of 2.0 and 2.0 mm; configuration B uses sheets of 2.0 and 1.2 mm of thickness, whereas configuration C employs sheet thickness of 1.2 and 1.2 mm. These sheets were sheared, deburred, aligned and isolated (from each other by a piece of paper in of the ends) in order to avoid shunt effects. The surfaces were cleaned up by detergent and dried in high-pressured air.

Preliminary runs (Vargas, 2006) were carried out to determine the operational envelopes. These envelopes characterize operational ranges varying from minimum values of current, force and cycles, where the joint is not accomplished, to maximum values where neither material expulsion nor deep depression (indentation) is observed.

Once five parameters (factors or variables) will be investigated (Upslop Time: T_{sub}, Current Time: T_{cor}, Downslope Time: T_{des}, Electrode Force: F_{el} and Water Flow: V_{az}), the experimental design chosen was the Central Composite Design (CCD). Specifically the 5/1/27 design was picked up, which means 5 factors and 1 block (Specific Energy) were selected, which lead to 27 runs (16 central points, 10 face points and 1 origin point). The CCD requires that an α value must be selected according to the need of the design be rotational, orthogonal or centered face. Due to the operational limits established in the operational envelopes, the face centered design was select, i.e., $\alpha = 1.0$, resulting in the experimental design shown in Table 1. These values were selected from the operational envelopes from Vargas (2006). It must be pointed out that each runs is composed by three averages, from the minimum number of samples theory based on the Type II error. All the statistical analyses were performed by using a commercial software – Statistica ®.

After the runs, the indentation value for each spot was measured by using a caliber. After, the plates were bent, according to AWS D8.9 standard (2002) for tension/shear test in a MTS machine with maximum force of 100 kN. The stress-strain curve was recorded and the maximum value of each one was selected. After, the remain spot on the plate was selected for diameter measurement according to the cited standard.

3. RESULTS AND DISCUSSION

The results and discussion are following divided by the group of studied responses: indentation, spot diameter and mechanical resistance.

3.1. Indentation

The measurements for indentation from the different runs required by the CCD are shown in Table 2, for the three plate configurations: A, B and C. After performing the statistical analyses, the significance of each factor (parameter) and its correlation to others were calculated and shown in Table 3 for plate configuration A, as an example. Also in this table, the coefficients for the regression analysis are shown. From these coefficients, it is possible to write down the empirical model (Eq. 2). The bold terms are the ones that presented statistical significance ($p \leq 0,05$), according to Table 3. Thus, the equation made by the bold terms is used as the input of the optimization BFGS algorithm.

$$\text{Indentation} = \mathbf{16.67416} + 0.06972{*}Tsub - 2.59780{*}Tsub^2 \mathbf{- 6.32417{*}Tcor + 3.36220{*}Tcor^2} - 0.57667{*}Tdes + 2.25470{*}Tdes^2 - 0.10833{*}Fel - 0.91030{*}Fel^2 - 0.81694{*}Vaz + 2.08720{*}Vaz^2 + 0.20531{*}Tsub{*}Tcor - 0.96656{*}Tsub{*}Tdes - 0.38781{*}Tsub{*}Fel + 0.53344{*}Tsub{*}Vaz + 0.65844{*}Tcor{*}Tdes + \mathbf{2.39344{*}Tcor{*}Fel} - 0.03906{*}Tcor{*}Vaz - 0.25844{*}Tdes{*}Fel + 0.49656{*}Tdes{*}Vaz + 0.08531{*}Fel{*}Vaz \qquad (2)$$

Table 1. Employed experimental design.

Factors Runs	T_{sub} (cycles)	T_{cor} (cycles)	T_{des} (cycles)	F_{el} (kN)	V_{az} (l/seg)
1	0	20	0	2	0,06
2	0	20	0	6	0,03
3	0	20	6	2	0,03
4	0	20	6	6	0,06
5	0	50	0	2	0,03
6	0	50	0	6	0,06
7	0	50	6	2	0,06
8	0	50	6	6	0,03
9	6	20	0	2	0,03
10	6	20	0	6	0,06
11	6	20	6	2	0,06
12	6	20	6	6	0,03
13	6	50	0	2	0,06
14	6	50	0	6	0,03
15	6	50	6	2	0,03
16	6	50	6	6	0,06
17	0	35	3	4	0,043
18	6	35	3	4	0,043
19	3	20	3	4	0,043
20	3	50	3	4	0,043
21	3	35	0	4	0,043
22	3	35	6	4	0,043
23	3	35	3	2	0,043
24	3	35	3	6	0,043
25	3	35	3	4	0,03
26	3	35	3	4	0,06
27 (C)	3	35	3	4	0,043

The analyses of the results indicate that the Current Time (Tcor) is the most significant parameter and has a negative tendency, i.e., the greater its value the lower the indentation. This suggest that low values of Tcor must be used, which leads to employ high current levels. This result agrees with the technical literature on RSW, where it is traditionally informed to the RSW users that they should use the lowest possible time and highest possible current levels. Therefore, the obtained results from the thorough scientific methodology confirm the technical literature on this subject.

Considering now the results after the optimization algorithm, similar equations were build up for plate configurations B and C (they are not shown, just because of the lack of space in the paper, but are available at Vargas, 2006), considering their significance levels. The tree equations (empirical models for indentation of plate configurations A, B and C) are entered in the BFGS optimization algorithm and the search for the most suitable point reaches the values shown in Table 4, for each plate configuration.

Table 2. Indentation measurement results.

Run	**Tsub (cycles)**	**Tcor (cycles)**	**Tdes (cycles)**	**Fel (kN)**	**Vaz (l/s)**	**Indentation (10^{-2} mm)**		
						A	**B**	**C**
1	0	20	0	2	0,06	28,00	21,59	23,00
2	0	20	0	6	0,03	27,66	30,83	31,25
3	0	20	6	2	0,03	31,00	20,00	23,04
4	0	20	6	6	0,06	24,66	29,07	28,96
5	0	50	0	2	0,03	11,96	9,91	6,75
6	0	50	0	6	0,06	14,09	11,55	8,63
7	0	50	6	2	0,06	12,13	11,55	5,96
8	0	50	6	6	0,03	18,50	14,46	9,84
9	6	20	0	2	0,03	32,66	22,17	28,50
10	6	20	0	6	0,06	25,96	27,41	28,67
11	6	20	6	2	0,06	28,63	19,13	21,96
12	6	20	6	6	0,03	21,59	26,92	26,30
13	6	50	0	2	0,06	12,13	11,00	6,29
14	6	50	0	6	0,03	17,84	12,25	7,67
15	6	50	6	2	0,03	11,91	9,13	5,92
16	6	50	6	6	0,06	15,58	12,16	8,46
17	0	35	3	4	0,043	12,41	20,25	19,25
18	6	35	3	4	0,043	15,38	17,67	14,54
19	3	20	3	4	0,043	23,75	25,88	28,29
20	3	50	3	4	0,043	15,96	15,50	7,00
21	3	35	0	4	0,043	20,79	22,79	18,25
22	3	35	6	4	0,043	16,70	21,75	15,21
23	3	35	3	2	0,043	15,29	17,13	13,75
24	3	35	3	6	0,043	15,88	18,91	13,00
25	3	35	3	4	0,03	19,95	20,16	16,29
26	3	35	3	4	0,06	17,20	20,25	16,29
27	3	35	3	4	0,043	18,13	20,38	15,38

Table 3. Regression (empirical) model obtained by the CCD for plate configuration A.

Factor	**P**	**Coefficent**
Mean/Interc,	**0,000001**	**16,67416**
(1)Tsub (L)	0,891839	0,06972
Tsub (Q)	0,099371	-2,59780
(2)Tcor (L)	**0,000014**	**-6,32417**
Tcor (Q)	**0,045235**	**3,36220**
(3)Tdes (L)	0,285154	-0,57667
Tdes (Q)	0,141891	2,25470
(4)Fel (L)	0,832860	-0,10833
Fel (Q)	0,520382	-0,91030
(5)Vaz (L)	0,147552	-0,81694
Vaz (Q)	0,168643	2,08720
1L by 2L	0,707322	0,20531
1L by 3L	0,113152	-0,96656
1L by 4L	0,485038	-0,38781
1L by 5L	0,345667	0,53344
2L by 3L	0,253446	0,65844
2L by 4L	**0,003727**	**2,39344**
2L by 5L	0,942707	-0,03906
3L by 4L	0,637714	-0,25844
3L by 5L	0,377620	0,49656
4L by 5L	0,875383	0,08531

Table 4. Optimum results for the indentation after the BFGS optimization algorithm.

Plate Configuration	Optimum point	Indentation (10^{-2} mm)
A	Tsub= 3,3957	34,6755
	Tcor= 20	
	Tdes= 0	
	Fel= 2	
	Vaz= 0,03	
B	Tsub = 2,7768	31,5231
	Tcor = 20	
	Tdes = 0	
	Fel = 5,5438	
	Vaz = 0,0308	
C	Tsub = 0	32,3638
	Tcor = 20	
	Tdes = 0	
	Fel = 4,8012	
	Vaz = 0,03	

3.2. Spot Diameter

Performing the same procedure for the indentation analyses, Table 5 is achieved by direct measurement of the spot diameter, Table 6 is obtained after the statistical analyses and Table 7 shows the optimum points concerning the spot diameters. The results send back to the considerations previously made while indentation analyses, which confirms the technical literature once more.

Table 5. Spot diameter measurements.

Run	**Tsub (cycles)**	**Tcor (cycles)**	**Tdes (cycles)**	**Fel (kN)**	**Vaz (l/s)**	**Spot diameter (mm)**		
						A	**B**	**C**
1	0	20	0	2	0,06	4,79	4,69	4,34
2	0	20	0	6	0,03	4,88	4,74	4,55
3	0	20	6	2	0,03	5,13	4,48	4,30
4	0	20	6	6	0,06	4,71	4,64	4,47
5	0	50	0	2	0,03	3,85	3,48	3,39
6	0	50	0	6	0,06	4,02	3,15	3,00
7	0	50	6	2	0,06	3,74	3,41	3,20
8	0	50	6	6	0,03	3,99	3,33	3,19
9	6	20	0	2	0,03	4,88	4,43	4,38
10	6	20	0	6	0,06	4,81	4,59	4,44
11	6	20	6	2	0,06	4,71	4,42	4,12
12	6	20	6	6	0,03	4,73	4,57	4,39
13	6	50	0	2	0,06	3,63	3,30	3,23
14	6	50	0	6	0,03	3,68	3,02	3,01
15	6	50	6	2	0,03	3,74	3,43	3,32
16	6	50	6	6	0,06	3,67	3,08	3,01
17	0	35	3	4	0,043	4,18	4,18	3,92
18	6	35	3	4	0,043	4,15	4,06	3,71
19	3	20	3	4	0,043	4,72	4,48	4,37
20	3	50	3	4	0,043	3,91	3,52	3,00
21	3	35	0	4	0,043	4,26	4,10	3,73
22	3	35	6	4	0,043	4,29	4,20	3,67
23	3	35	3	2	0,043	4,16	3,91	3,62
24	3	35	3	6	0,043	4,31	4,09	3,52
25	3	35	3	4	0,03	4,15	3,93	3,59
26	3	35	3	4	0,06	4,36	4,20	3,73
27	3	35	3	4	0,043	4,25	4,13	3,65

Table 6. Optimum results for the spot diameter after the BFGS optimization algorithm.

Plate Configuration	Optimum point	Spot diameter (mm)
A	Tsub= 1,5384	5,0994
	Tcor= 20	
	Tdes= 6	
	Fel= 2	
	Vaz= 0,03	
B	Tsub = 0	4,8422
	Tcor = 20	
	Tdes = 0	
	Fel = 4,5792	
	Vaz = 0,0522	
C	Tsub = 0	4,6008
	Tcor = 20	
	Tdes = 0	
	Fel = 4,4922	
	Vaz = 0,03	

3.3. Mechanical Resistance

Confirming the previous results, Tables 7, 8 and 9 show the results from the applied methodology. These results were already expected, since bigger spots provide higher mechanical resistance.

Table 7. Mechanical resistance measurements.

Run	**Tsub (cycles)**	**Tcor (cycles)**	**Tdes (cycles)**	**Fel (kN)**	**Vaz (l/s)**	**Mechanical resistance (kN)**		
						A	**B**	**C**
1	0	20	0	2	0,06	4,2736	1,8371	1,6116
2	0	20	0	6	0,03	3,6188	1,8533	2,3140
3	0	20	6	2	0,03	3,4644	1,8511	1,9806
4	0	20	6	6	0,06	3,5590	1,9164	2,1547
5	0	50	0	2	0,03	2,0082	0,5578	0,0000
6	0	50	0	6	0,06	0,0000	0,0000	0,0000
7	0	50	6	2	0,06	1,7529	1,0382	0,0000
8	0	50	6	6	0,03	0,5017	0,0000	0,0000
9	6	20	0	2	0,03	3,5746	0,5578	2,2374
10	6	20	0	6	0,06	2,7462	1,8503	1,5557
11	6	20	6	2	0,06	4,1093	1,7650	1,7579
12	6	20	6	6	0,03	3,0615	1,9003	1,9398
13	6	50	0	2	0,06	1,7132	0,9269	0,0000
14	6	50	0	6	0,03	0,0000	0,0000	0,0000
15	6	50	6	2	0,03	0,6236	0,0000	0,0000
16	6	50	6	6	0,06	0,0000	0,0000	0,0000
17	0	35	3	4	0,043	1,0817	1,7650	0,8134
18	6	35	3	4	0,043	1,4149	1,6118	1,0818
19	3	20	3	4	0,043	4,1880	1,8583	2,4833
20	3	50	3	4	0,043	0,0000	0,5587	0,0000
21	3	35	0	4	0,043	2,5271	1,8434	1,6037
22	3	35	6	4	0,043	1,7710	1,6822	0,6748
23	3	35	3	2	0,043	4,9571	1,8409	1,5247
24	3	35	3	6	0,043	0,0000	1,3362	0,0000
25	3	35	3	4	0,03	2,1218	1,6162	0,0000
26	3	35	3	4	0,06	2,1310	1,3362	1,2494
27	3	35	3	4	0,043	2,3029	1,7243	0,6110

Table 8. Optimum results for the mechanical resistance after the BFGS optimization algorithm.

Plate Configuration	Optimum point	Mechanical resistance (kN)
A	Tsub= 2,8917	5,2421
	Tcor= 20	
	Tdes= 0	
	Fel= 2	
	Vaz= 0,06	
B	Tsub = 0	2,3283
	Tcor = 23,1890	
	Tdes = 6	
	Fel = 3,2578	
	Vaz = 0,0447	
C	Tsub = 0	2,5366
	Tcor = 20	
	Tdes = 0	
	Fel = 4,1210	
	Vaz = 0,0396	

A final compilation of the obtained results for the significance levels and regression coefficients are shown in Table 9.

Table 9. Final compilation of the obtained results from the statistical analyses.

Response	Plate configuration	Factors	p	Coefficient
Indentation	A	Tcor	0,000014	-6,32417
		Tcor^2	0,045235	3,36220
		Tcor*Fel	0,003727	2,39344
	B	Tcor	0,000001	-6,41583
		Fel	0,000205	2,33222
		Fel^2	0,019861	-2,49439
		Tcor*Fel	0,003914	-1,40750
	C	Tcor	0,000001	-9,63694
		Fel	0,012640	1,53306
Spot diameter	A	Tsub	0,043189	-0,071833
		Tcor	0,000002	-0,507139
	B	Tcor	0,000001	-0,628917
		Tcor*Fel	0,034264	-0,096375
	C	Tsub^2	0,035819	0,150326
		Tcor	0,000000	-0,611139
		Tcor*Fel	0,003418	-0,101906
Mechanical resistance	A	Tcor	0,002079	-1,44421
		Fel	0,041645	-0,72165
	B	Tsub	0,049366	-0,122598
		Tcor	0,000009	-0,683775
		Tcor^2	0,012935	-0,473095
		Vaz	0,040800	0,129643
		Tsub*Fel	0,054817	0,125960
		Tcor*Fel	0,003125	-0,252015
		Fel*Vaz	0,022377	-0,161711
	C	Tcor	0,000698	-1,00194

4. CONCLUSIONS

The proposed strategy (CCD experimental design that leads to empirical model, which is used by a BFGS optimization algorithm for searching the optimum point) was successfully applied, where the results corroborate to the technical literature, which affirms that the higher the welding current and the lower the welding time, the better.

5. ACKNOLEGMENTS

The authors would like to acknowledge Universidade Federal de Uberlândia (UFU) – LAPROSOLDA and Universidade de Brasília (UnB) – Graco.

6. REFERENCES

Gedeon, S.A. et.al., 1984, Metallurgical and Processs Variables Affecting the Resistance Spot Weldability of Galvanized Sheet Steels. Society of Automotive Engineers, Inc., pp. 1 – 9.

Cho, Y.; Rhee, S. 2000, New technology for measuring dynamic resistance and estimating strength in resistance spot welding. Meas. Sci. Technol., 11, p. 1173–1178.

Barros Neto, B.; Scarminio, I.S.; Bruns, R.E., 2002, Como Fazer Experimentos. 2º edição, Unicamp, 412p.

Vargas, J. E., 2006, Estudo da Formação, Geometria e Resistência do Ponto na Soldagem por Resistência: uma Abordagem Estatística. Dissertação (Mestrado em Engenharia Mecatrônica) - Universidade de Brasília, 164 p.

Vanderplaats, G. N., 1984, Numerical Optimization Techniques for Engineering Design with Applications, McGraw Hill, 333p.

AWS/SAE D8.9M. 2002, Recommended Practices for Test Methods for Evaluating the Resistance Spot Welding Behavior of Automotive Sheet Steel Materials. International Standard Book Number: 0-87171-672-0. American Welding Society. 550 N. W. LeJeune Road, Miami, Florida 33126. 2002, Printed in the U.S.A.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.