Assessment of coil design and pulse unit parameters for the optimization in the electromagnetic forming process of metal sheet

Evandro Paese[1], Martin Geier[2], Roberto Homrich[2], Rodrigo Rossi[2], Pedro Rosa[3]

[1] Universidade de Caxias do Sul, Bento Gonçalves, RS 95700-00, Brazil
[2] Universidade Federal do Rio Grande do Sul, Porto Alegre, 90035-190, Brazil
[3] Instituto Superior Técnico, Universidade de Lisboa, 1049-001, Lisboa Portugal

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I. INTRODUCTION

The development of the EMF process has demanded a constant reassessment of which process parameters are significant and how they can optimize the process based on the chosen criteria of the parameters. This work proposes the regression equations based on the RSM (Response Surface Methodology) analysis to predict the electrical and mechanical process responses and consequently to find controllable factor settings that optimize the EMF of sheet metals using a flat spiral coil according to desired criteria.

II. MATERIALS AND METHODS

Process parameters may affect quantitatively the EMF responses, so the analysis of the process in this study included key independent variables, such as capacitance C, energy U, and the number of coil windings n, while the response variables were the maximum electromagnetic force F_{max} (numerically calculated), the workpiece height h, the rise time t_{rise} and peak of the discharge current I_{peak} (Tables I and II). The capacitance is varied by changing the circuit connection of two 50µF and 5,000 V capacitors.

Table I – EMF parameters

	Parameter	Value
Spiral coil	Outer diameter (D_0)	67.5 mm
	Inner diameter (D_i)	7.5 mm
	Cross section (A_a)	20 mm^2
	Gap between coil and workpiece	1 mm
Workpiece	Material	AA1100 (annealed)
	Diameter	110 mm
	Thickness	1 mm
	Cavity diameter	80 mm
	Cavity depth	40 mm

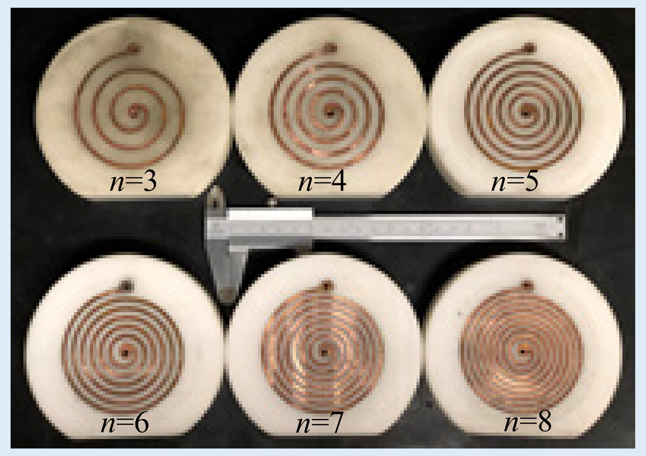

Figure 1 – Spiral coils used for parametric experiments.

The experiments design were established with custom designs by using the Design Expert Software (Table III) and, as example, Fig. 2 shows the variable h for workpiece height.

Table II – Controllable factors and levels

Controllable Factors	Levels 1	2	3	4	5	6
U (J)	1000	1100	1200	-	-	-
C (µF)	50	100	200	-	-	-
n	3	4	5	6	7	8

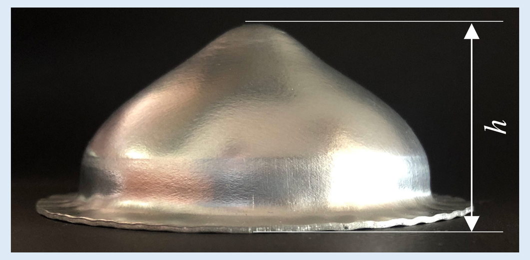

Figure 2 – Variable h (workpiece height).

Table III – Design of experiments

Run	Factor 1 A:A J	Factor 2 B:B µF	Factor 3 C:C	Response 1 R1 kN	Response 2 R2 kA	Response 3 R3 mm	Response 4 R4 µs
1	1100	50	5	0.9655	23.5	13.79	20.5
2	1200	100	3	0.8129	22.22	8.9	26
3	1100	50	5	0.9655	27.3	13.51	20.4
4	1100	100	3	0.7452	21.78	8.22	26.5
5	1200	200	7	1.486	20.38	23.2	39.5
6	1100	200	3	0.6517	19.6	8.39	35
7	1000	200	3	0.5925	16.71	8.2	35
8	1200	50	6	1.46	21.61	17.68	20.85
9	1000	100	5	0.8288	21.2	14.29	27
10	1000	100	5	0.8288	22.2	14.27	26.9
11	1200	100	5	0.9946	25.7	16.16	27
12	1200	50	8	2.482	20.59	22.83	22
13	1000	50	6	1.217	19.6	16.32	21
14	1100	100	3	0.7452	20.91	8.2	26.25
15	1000	200	8	1.647	16.99	23.85	40
16	1100	100	8	2	21.78	24.18	30.75
17	1000	50	8	2.068	19.79	20.24	22
18	1100	100	8	2	21.35	23.03	30
19	1000	50	3	0.7874	23.09	7.6	19.3
20	1100	200	6	1.035	18.3	19.34	38.4
21	1200	100	5	0.9946	24.83	15.98	27.75
22	1100	200	6	1.035	17.42	19.36	37.1
23	1200	200	4	0.7478	22.65	14.52	35
24	1100	100	8	2	19.17	23.76	30
25	1200	50	4	0.9102	28.75	13.2	19.5
26	1000	100	7	1.321	20.91	20.08	29.5
27	1000	200	6	0.9412	16.99	18.1	37
28	1200	200	7	1.486	20.04	24.16	39.5

III. RESULTS

Table IV – R1 (F_{max}) ANOVA

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	7.01	7	1.00	514.04	< 0.0001	significant
A-A	0.2210	1	0.2210	113.49	< 0.0001	
B-B	0.3188	1	0.3188	163.73	< 0.0001	
C-C	5.51	1	5.51	2827.66	< 0.0001	
AC	0.0336	1	0.0336	17.27	0.0005	
BC	0.0333	1	0.0333	17.09	0.0005	
B²	0.0179	1	0.0179	9.19	0.0066	
C²	0.6625	1	0.6625	340.26	< 0.0001	
Residual	0.0389	20	0.0019			
Lack of Fit	0.0389	12	0.0032			
Pure Error	0.0000	8	0.0000			
Cor Total	7.05	27				

$$F_{max} = 1.87437 - 0.000341U - 0.002664C - 0.638796n + 0.000265Un - 0.000349Cn + 0.000011C^2 + 0.058552n^2 \quad (1)$$

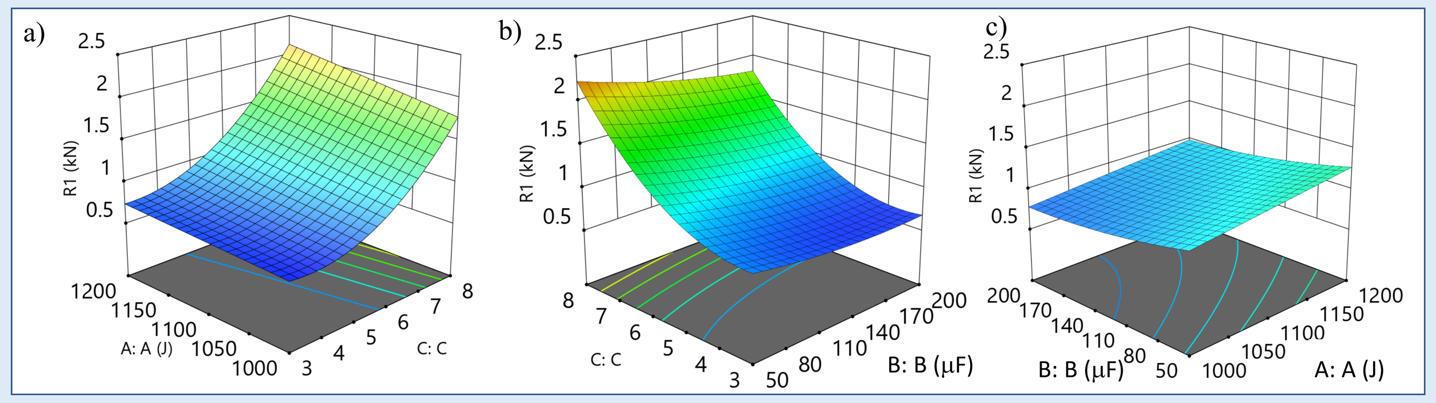

Figure 3 – Effect of significant factors on R1 (F_{max}): (a) AC, (b) CB and (c) AB.

Table V – R2 (I_{peak}) ANOVA

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	164.77	6	27.46	8.39	0.0001	significant
A-A	45.39	1	45.39	13.87	0.0013	
B-B	86.24	1	86.24	26.35	< 0.0001	
C-C	16.89	1	16.89	5.16	0.0338	
AB	1.63	1	1.63	0.4985	0.4879	
AC	3.68	1	3.68	1.13	0.3008	
BC	6.76	1	6.76	2.07	0.1654	
Residual	68.72	21	3.27			
Lack of Fit	55.88	13	4.30	2.68	0.0834	not significant
Pure Error	12.84	8	1.60			
Cor Total	233.49	27				

$$I_{peak} = 2.95693 + 0.025026U - 0.109313C + 1.95471n + 0.000048UC - 0.002731Cn + 0.004855Cn \quad (2)$$

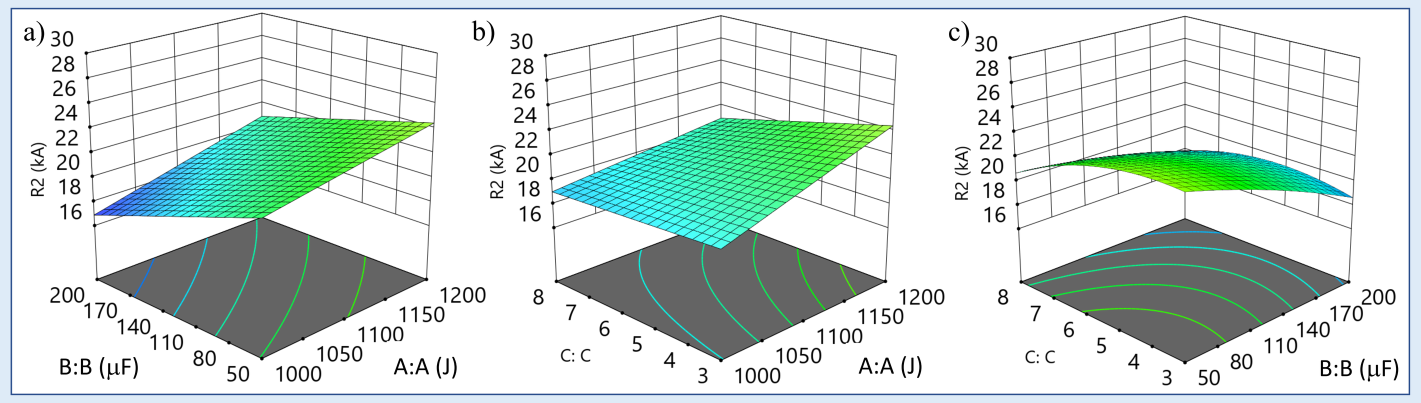

Figure 4 – Effect of significant factors on R2 (I_{peak}): (a) AB, (b) AC and (c) BC.

Table VI – R3 ANOVA

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	842.84	7	120.41	365.83	< 0.0001	significant
A-A	19.42	1	19.42	59.01	< 0.0001	
B-B	20.13	1	20.13	61.17	< 0.0001	
C-C	795.06	1	795.06	2415.64	< 0.0001	
AB	0.2895	1	0.2895	0.8795	0.3595	
AC	0.1783	1	0.1783	0.5418	0.4702	
BC	3.38	1	3.38	10.27	0.0044	
C²	2.27	1	2.27	6.91	0.0161	
Residual	6.58	20	0.3291			
Lack of Fit	5.39	12	0.4490	3.01	0.0631	not significant
Pure Error	1.19	8	0.1493			
Cor Total	849.43	27				

$$h = -7.65709 + 0.004697U - 0.027737C + 3.11709n + 0.000020UC + 0.000601Un + 0.003520C^2 \quad (3)$$

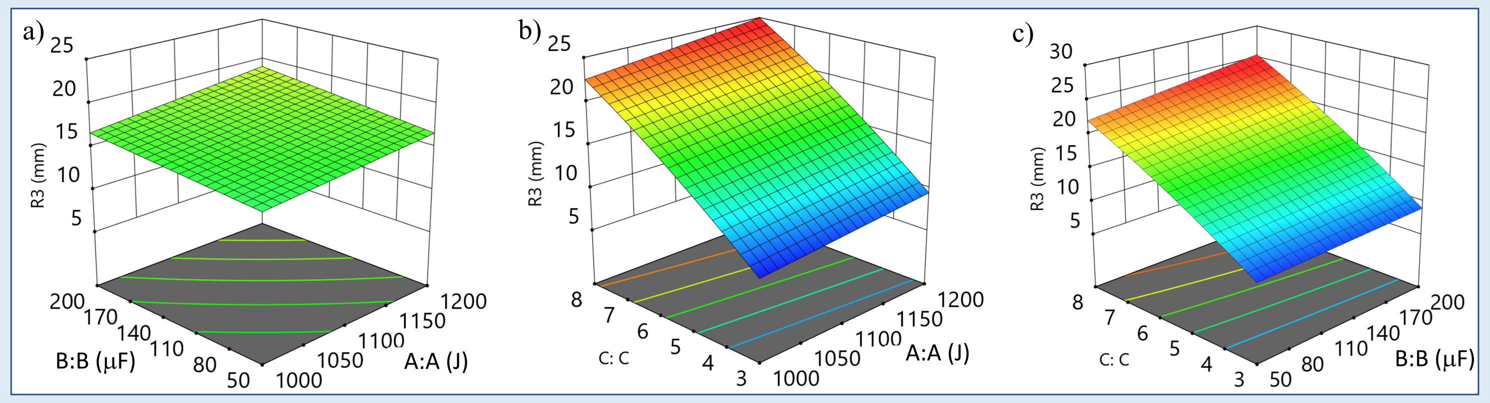

Figure 5 – Effect of significant factors on R3 (h): (a) BA; (b) AC and (c) BC.

Table VII – R4 ANOVA

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1264.48	8	158.06	775.75	< 0.0001	significant
A-A	0.1030	1	0.1030	0.5055	0.4857	
B-B	1175.55	1	1175.55	5769.52	< 0.0001	
C-C	65.81	1	65.81	322.99	< 0.0001	
AB	0.1835	1	0.1835	0.9004	0.3546	
AC	0.3043	1	0.3043	1.49	0.2366	
BC	3.84	1	3.84	18.85	0.0004	
B²	18.90	1	18.90	92.78	< 0.0001	
C²	1.06	1	1.06	5.18	0.0346	
Residual	3.87	19	0.2038			
Lack of Fit	2.33	11	0.2117	1.10	0.4589	not significant
Pure Error	1.54	8	0.1928			
Cor Total	1268.35	27				

$$t_{rise} = 17.49603 - 0.005658U + 0.162099C - 1.28655n + 0.000016UC + 0.000798Un + 0.003520C^2 + 0.074067n^2 \quad (4)$$

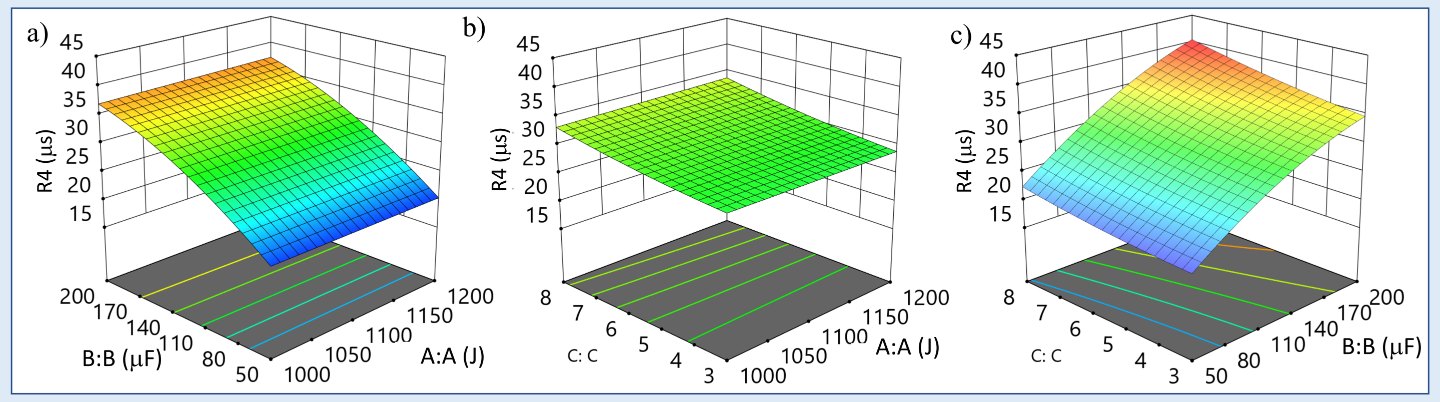

Figure 6 – Effect of significant factors on R4 (t_{rise}): (a) AB, (b) AC and (c) BC.

Table VIII – Constraints for case analysis #1

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Energy	minimize	1000	1200	1	1	3
B:Capacitance	is in range	50	200	1	1	3
C:Windings	is in range	3	8	1	1	3
Maximum electromagnetic force	is in range	0.5925	2.482	1	1	3
Peak of the discharge current	is in range	16.71	28.75	1	1	3
Maximum workpiece height	maximize	7.6	30	1	1	3
Rise time of the of the discharge current	maximize	19.3	40	1	1	3

Table IX – Solution for case analysis #1

Number	Energy	Capacitance	Windings	Maximum electromagnetic force	Peak of the discharge current	Maximum workpiece height	Rise time of the of the discharge current	Desirability	
1	1034.504	200	8	1.699	16.71	24.774	40.44	0.859	Selected

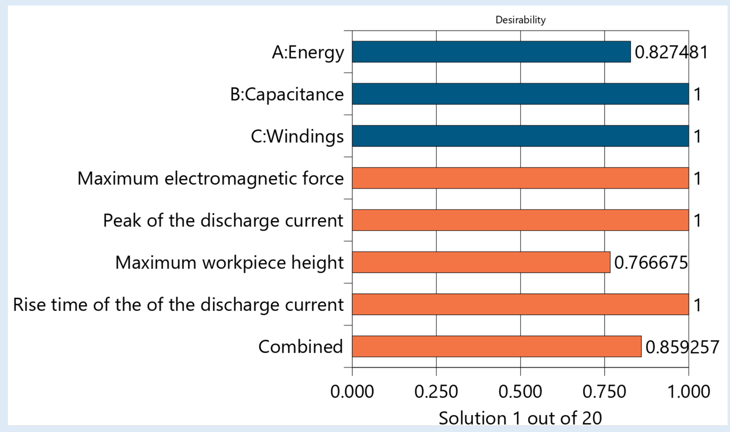

Figure 7 – Desirability for case analysis #1

Table X – Constraints for case analysis #2

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Energy	minimize	1000	1200	1	1	3
B:Capacitance	is in range	50	200	1	1	3
C:Windings	is in range	3	8	1	1	3
Maximum electromagnetic force	is in range	0.5925	2.482	1	1	3
Peak of the discharge current	maximize	16.71	28.75	1	1	3
Maximum workpiece height	maximize	7.6	30	1	1	3
Rise time of the of the discharge current	maximize	19.3	40	1	1	3

Table XI – Solution for case analysis #2

Number	Energy	Capacitance	Windings	Maximum electromagnetic force	Peak of the discharge current	Maximum workpiece height	Rise time of the of the discharge current	Desirability	
1	1035.592	100	8	1.917	19.639	22.487	30.128	0.513	Selected

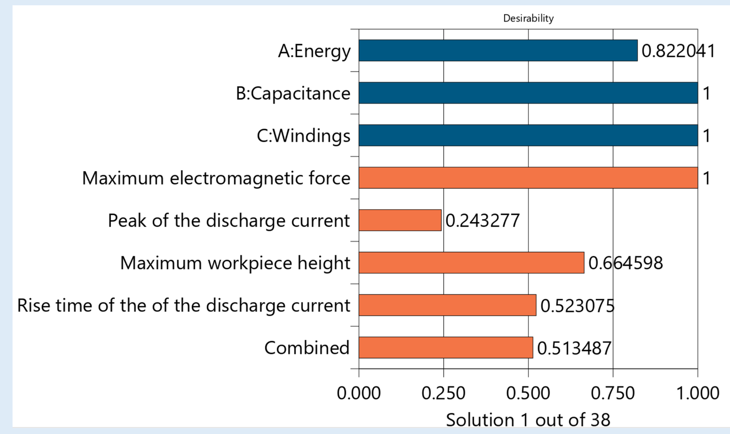

Figure 8 – Desirability for case analysis #2

IV. CONCLUSION

From this study, the following conclusions are drawn:

- Empirical relationships were developed using statistical tools to predict selected responses of the free bulging EMF process using a flat spiral coil.
- The 3D surfaces can show the main and interactions effects of significant process parameters.
- Despite the discharge current peak being an important response of EMF pulse units, the rise time of the discharge current was essential to reach the higher workpiece height.
- The maximum workpiece height h of 24.77 mm was achieved for the combination U=1034. 5J, C=200 µF, and n=8. It can be noted that the coil winding number is significant to improve the forming process.
- Finally, the significant process parameters were identified, outlining optimum geometry and pulse unit parameters, which can aid the design of flat spiral coils and electrical components for the EMF process. Multi-response optimization by desirability analysis can also improve the EMF process efficiency, enhancing the forming process with minimal energy.