Experimental design using the Taguchi method for the development of conductive textiles used in flexible thermoelectric generators

DOI: 10.35530/IT.075.01.202360

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ABSTRACT – REZUMAT

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This paper presents several aspects of the robust experimental design methodology using the Taguchi method to develop electrically conductive textiles. These conductive textiles will be used to make thermoelectric generators based on the Seebeck effect. Since the experimental development involves the use of the magnetron sputtering method with more than three variables, the Taguchi method was selected to observe how different parameters (5 independent variables such as argon flow, power, pressure, deposition surface area and metal type used for solid targets) influence the mean and variance of the process performance defined by the thickness of the metal film deposited (dependent variable). In the experimental design framework, the analysis using the Taguchi method, followed by optimisation, helped select the optimal experiments from the set of possible experiments. This methodology reduced the number of experiments by 21–42% and minimised resource consumption (e.g., metal targets, argon, energy).

Keywords: *conductive, electrical resistance, experimental plan, Taguchi method, textile, thermoelectric generator*

Design experimental pe baza metodei Taguchi pentru dezvoltarea materialelor textile conductive pentru generatoare termoelectrice flexibile

Această lucrare prezintă câteva aspecte ale metodologiei designului experimental robust utilizând metoda Taguchi, pentru a dezvolta textile electroconductive. Aceste textile conductive vor fi folosite pentru realizarea generatoarelor termoelectrice bazate pe efectul Seebeck. Deoarece dezvoltarea experimentală implică utilizarea metodei de pulverizare magnetron cu mai mult de trei variabile, a fost selectată metoda Taguchi pentru a observa modul în care diferiți parametri (5 variabile independente, cum ar fi debitul de argon, puterea, presiunea, suprafața de depunere și tipul de metal pentru ţintele solide) influențează media și varianța performanței procesului definit de grosimea stratului metalic depus (variabilă dependentă). În cadrul designului experimental, analiza folosind metoda Taguchi, urmată de optimizare, a ajutat la selectarea experimentelor optime din setul de experimente posibile. Această metodologie a redus numărul de experimente cu 21–42% și a minimizat consumul de resurse (de exemplu, ţinte metalice, argon, energie).

Cuvinte-cheie: *conductiv, rezistenţă electrică, plan experimental, metoda Taguchi, textil, generator termoelectric*

INTRODUCTION

The transformation of the textile into an electrical thermoelectric generator (TEG) is a challenge for researchers. Scientific literature presents numerous methods for creating flexible thermoelectric generators integrated into garments by conducting polymers such as polyelectrolyte complex poly(3,4-ethylene dioxythiophene): poly(styrene sulfonate) (PEDOT: PSS) as the p-type material and sewing conductive yarns [1, 2], vertically aligned p-type PEDOT: PSS and carbon nanotubes [3-5] or PEDOT: PSS thin film (as p-type) and aluminium wire (as n-type) integrated [3] by the 3D printing method in TEG using the Seebeck effect. In addition, PEDOT: PSS, MWCNTs, and Bi2Te3 were reported to coat polyester yarns (P-type thermoelectric legs) connected by copper wires [6]. A scientific approach is to use the Taguchi method for designing TEG-based cubic-shaped P-type (Bi0.5Sb1.5Te3) and N-type (Bi2Se0.5Te2.5) thermoelectric leg-based Seebeck effects [7]. The materials used for P-type and N-type thermoelectric legs influence the performance of the final TEG (inner resistance, output voltage and power) [8].

EXPERIMENTAL PART

Based on the Seebeck effect, an experimental plan using the Taguchi method has been designed to develop conductive materials for thermoelectric generators. The specific parameters for the deposition of conductive layers using the magnetron sputtering method are:

- – the specific thickness (100 nm, 150 nm, 200 nm);
- – textile surface with area A (100 mm^2, 150 mm^2, 200 mm^2);
- – argon flow (40 sccm, 50 sccm, 60 sccm);
- – pressure (3×10^{-5} mbar, 4×10^{-5} mbar, 5×10^{-5} mbar);
- – RF generator power (80 W, 100 W, 150 W);
- – metal targets (silver, copper and nickel).

To create the experimental plan, 5 variable influence factors (table 1) and three levels (distinct values) were used for each factor, as follows: metal (copper, nickel, silver), pressure (3×10^{-5} mbar, 4×10^{-5} mbar, 5×10^{-5} mbar), generator power (80 W, 100 W, 150 W), argon flow (40 sccm, 50 sccm, 60 sccm) and the response variable the thickness of the deposited metal thin layer (100 nm, 150 nm and 200 nm) by the magnetron sputtering method.

To obtain conductive materials to generate electricity through the thermocouple effect, the minimum electrical resistance ($Rs = 10^3$) associated with the maximum value for the thickness of the metal layer [9] deposited (200 nm) by the magnetron sputtering method was considered.

ANALYSING THE EXPERIMENTAL DATA

The signal-to-noise ratios (S/N) and the thickness response variable were used depending on the independent variables (metal, metal deposition surface, pressure and argon flow) to analyse the Taguchi experimental plan. The signal-to-noise ratio (S/N) is a measure of robustness and can be used to identify the appropriate settings for factors to reduce the effect of noise on the response. The signal-to-noise ratio (S/N) was calculated separately for each combination of control factor levels in the experimental design. For the S/N ratio (equation 1), the static model 'larger is better' was chosen to maximise the response (thickness).

$$\frac{S}{N} = -10 \log\left[\sum(1/y^2)/n\right] \tag{1}$$

where y represents the responses given at the factor level and n is the number of factor-level responses.

For the influencing factors, the signal-to-noise responses are presented in table 2. The main effects plot (figures 1 and 2) shows how each factor influences the response characteristic (S/N ratio or mean values). A main effect exists when different factor levels (e.g., metal deposition surface) affect the S/N ratio differently. For a factor 'metal' with three levels, it is observed that there are increases and a reduction for three levels (200 mm^2, 150 mm^2 and 100 mm^2) compared to the average value of the S/N ratio. This aspect indicates that the deposition surface cannot precisely influence the thickness of the deposited layer because the distribution of the metal deposition

Table 1

EXPERIMENTAL PLAN FOR THE DEPOSITION OF CONDUCTIVE MATERIALS BY THE MAGNETRON SPUTTERING METHOD

No.	Metal	Surface area (mm^2)	Pressure (mbar)	Argon flow (sccm)	Power (W)	Thickness (nm)
1	Copper	100	$3x10^{-5}$	40	80	100
2	Copper	100	$3x10^{-5}$	40	100	100
3	Copper	100	$3x10^{-5}$	40	150	100
4	Copper	150	$4x10^{-5}$	50	80	150
5	Copper	150	$4x10^{-5}$	50	100	150
6	Copper	150	$4x10^{-5}$	50	150	150
7	Copper	200	$5x10^{-5}$	60	80	200
8	Copper	200	$5x10^{-5}$	60	100	200
9	Copper	200	$5x10^{-5}$	60	150	200
10	Nickel	100	$4x10^{-5}$	60	80	100
11	Nickel	100	$4x10^{-5}$	60	100	100
12	Nickel	100	$4x10^{-5}$	60	150	100
13	Nickel	150	$5x10^{-5}$	40	80	150
14	Nickel	150	$5x10^{-5}$	40	100	150
15	Nickel	150	$5x10^{-5}$	40	150	150
16	Nickel	200	$3x10^{-5}$	50	80	200
17	Nickel	200	$3x10^{-5}$	50	100	200
18	Nickel	200	$3x10^{-5}$	50	150	200
19	Silver	100	$5x10^{-5}$	50	80	100
20	Silver	100	$5x10^{-5}$	50	100	100
21	Silver	100	$5x10^{-5}$	50	150	100
22	Silver	150	$3x10^{-5}$	60	80	150
23	Silver	150	$3x10^{-5}$	60	100	150
24	Silver	150	$3x10^{-5}$	60	150	150
25	Silver	200	$4x10^{-5}$	40	80	200
26	Silver	200	$4x10^{-5}$	40	100	200
27	Silver	200	$4x10^{-5}$	40	150	200

Table 2

SIGNAL-NOISE RATIOS (S/N)					
Level	**Metal**	**Surface area**	**Pressure**	**Argon flow**	**Power**
1	43.18	40	43.18	43.18	43.18
2	43.18	43.52	43.18	43.18	43.18
3	43.18	46.02	43.18	43.18	43.18
Delta	0	6.02	0	0	0
Rank	3.5	1	3.5	3.5	3.5

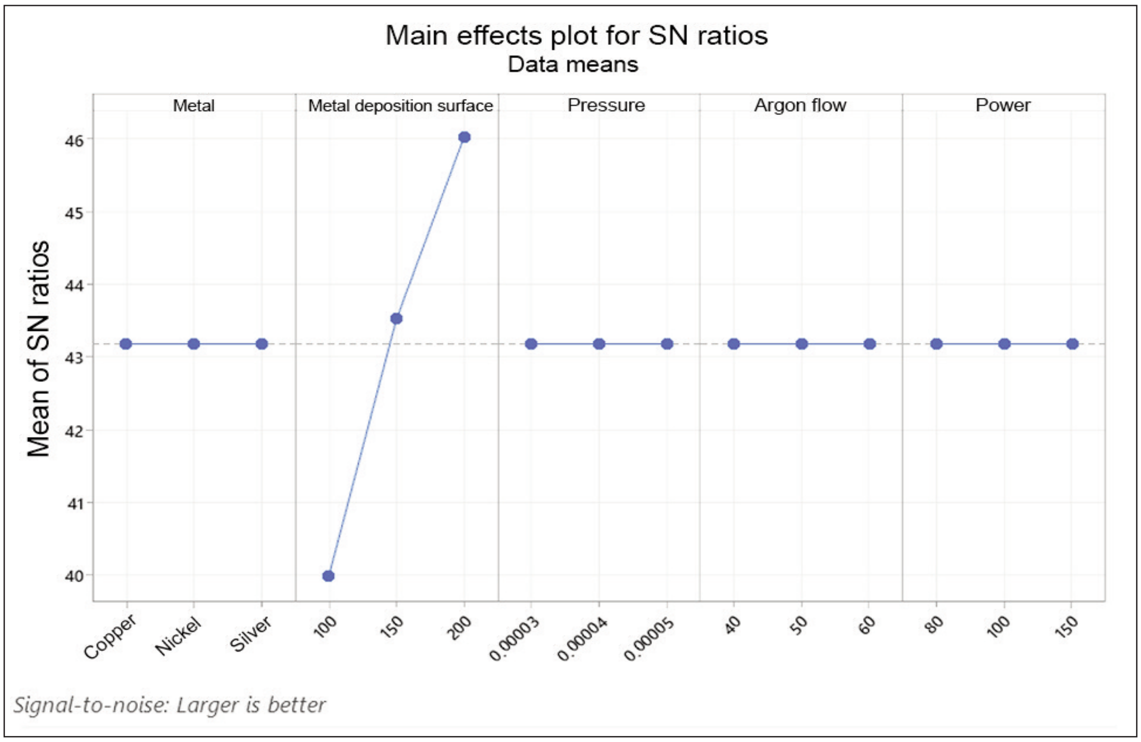

Fig. 1. Main effects plot for *S/N* ratios

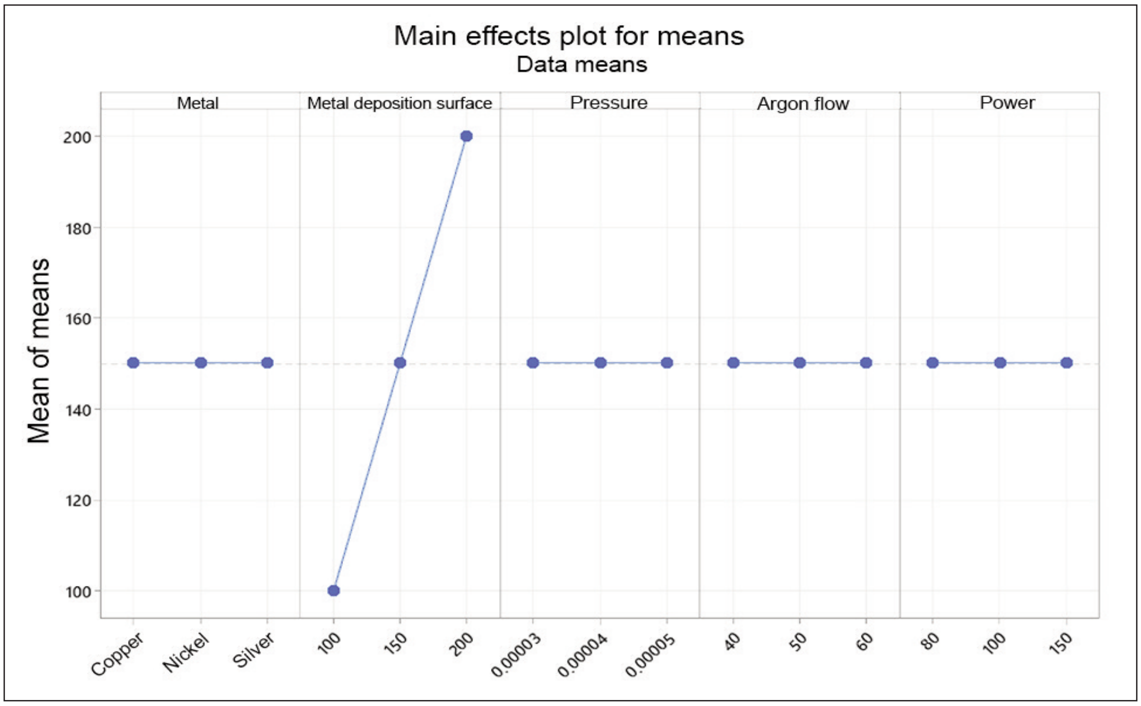

Fig. 2. Main effects plot for means

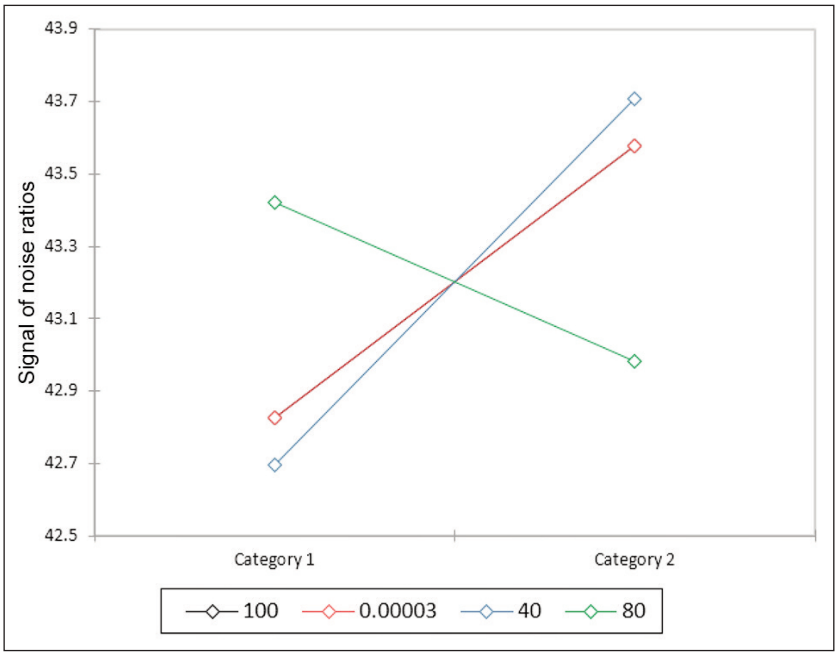

Fig. 3. LS means (Signal to Noise ratios)

Table 3

INFORMATION ABOUT CATEGORY 1 AND CATEGORY 2 FOR INDEPENDENT VARIABLES			
Variables	**Categories number**	**Category 1**	**Category 2**
Surface Area	2	150	200
Pressure	2	4×10^{-5}	5×10^{-5}
Argon Flow	2	50	60
Power	2	100	150

shows nonuniformity. In table 2, the Delta is the difference between each factor's highest and lowest mean response values. Ranks are assigned based on Delta values. Rank 1 corresponds to the highest Delta value.

Figure 3 shows the S/N ratio for the factor (independent variable) levels represented by categories 1 and 2 (table 3) of the independent variables pressure, argon flow and power. Table 4 presents the variance analysis for the signal-to-noise ratio.

Equation 2 for the signal-to-noise ratio (Rsz) model is shown below:

$$\begin{gathered} R_{sz} = 44.2387516318562 - \\ - 0.752574989159954{*}x_1 - 150 - \\ - 0.752574989159939{*}x_2 - \\ - 0.00004 - \\ - 1.00833760139685{*}x_3 - 50 + \\ + 0.440228147639218{*}x_4 - 100 \end{gathered} \tag{2}$$

The model that considers the average values of the influence factors (*Rm*) is presented in mathematical expression 3 below:

$$\begin{gathered} R_m = 165.625 - 12.5{*}x_1 - 150 - 12.5{*}x_2 - \\ - 0.00004 - 12.5{*}x_3 - 50 + 6.25{*}x_4 - 100 \end{gathered} \tag{3}$$

where x_1 is the surface of the metal deposit, x_2 – the pressure, x_3 – the argon flow, x_4 – the power.

In the experimental plan design by the Taguchi method, the robustness of the method is evaluated by identifying the control factors that reduce the variability of a product or process by minimising the effects of uncontrolled factors (noise factors). Control factors are those design and process parameters that can be controlled. Noise factors cannot be controlled during the production or use of the product, but they can be controlled during experiments. Tables 4 and 5 present the analysis of variance for the signal-to-noise ratio and the mean values.

Table 4

ANALYSIS OF VARIANCE (SIGNAL-TO-NOISE RATIOS)					
Source	**DF**	**Sum of squares**	**Mean squares**	**F**	**Pr>F**
Model	4	18.746	4.687	0.769	0.555
Error	27	164.454	6.091		
Corrected Total	31	183.201			

Table 5

ANALYSIS OF VARIANCE (MEANS)					
Source	**DF**	**Sum of squares**	**Mean squares**	**F**	**Pr>F**
Model	4	4062.500	1015.625	0.597	0.668
Error	27	45937.500	1701.389		
Corrected Total	31	50000.000			

Table 6

MODEL (1) PARAMETERS (SIGNAL TO NOISE RATIOS)

Source	Value	Standard Error (SE)*	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	44.239	0.976	45.347	**<0.0001**	42.237	46.240
100–150	–0.753	0.873	–0.862	0.396	–2.543	1.038
100–200	0.000	0.000				
0.00003–0.00004	–0.753	0.873	–0.862	0.396	–2.543	1.038
0.00003–0.00005	0.000	0.000				
40–50	–1.008	0.873	–1.156	0.258	–2.799	0.782
40–60	0.000	0.000				
80–100	0.440	0.873	0.505	0.618	–1.350	2.231
80–150	0.000	0.000				

Table 7

MODEL (2) PARAMETERS (MEANS)

Source	Value	Standard Error (SE)*	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	165.625	16.305	10.158	**<0.0001**	132.171	199.079
100–150	–12.500	14.583	–0.857	0.399	–42.423	17.423
100–200	0.000	0.000				
0.00003–0.00004	–12.500	14.583	–0.857	0.399	–42.423	17.423
0.00003–0.00005	0.000	0.000				
40–50	–12.500	14.583	–0.857	0.399	–42.423	17.423
40–60	0.000	0.000				
80–100	6.250	14.583	0.429	0.672	–23.673	36.173
80–150	0.000	0.000				

Tables 6 and 7 present the parameters of the models that take into account the S/N ratio and the average values of the influencing factors on 2 levels.

Standard Error is calculated with the following equation:

$$*SE = \sigma / \sqrt{n} \qquad (4)$$

where σ is the standard deviation and n – the number of samples.

RESULTS AND DISCUSSION

Using the Taguchi plan with the response variable, the thickness of the deposited layer (δ, the dependent variable) and applying the optimisation to maximise the value of the metal layer deposited by the magnetron sputtering method at 200 nm, with the help of the maximisation function $F(x) = y$ ($y = 200$ nm), a deposited metal layer with a maximum thickness of 200 nm can be obtained using experimental parameters such as pressure 1×10^{-5} mbar, argon flow 60 sccm, deposition surface 200 mm^2 and power 150 W (figure 4). The optimal parameters for the experiment (argon flow = 60 sccm, pressure 1×10^{-5} mbar, power = 150 W, deposition surface = 200 mm^2) lead to obtaining a surface with a metal layer 200 nm thick (figure 4).

CONCLUSIONS

In conclusion, the analysis by the Taguchi method and the realisation of experimental plans, followed by optimisation by maximisation, is essential because it can help to select the optimal experiment from the set of possible experiments. Thus, the number of experiments is reduced, implying the reduction of resource consumption (metal targets, argon, energy) to a few experiments (e.g., from 24 experiments to 5–10 experiments) to obtain conductive textile surfaces to develop electric thermoelectric generators.

ACKNOWLEDGEMENTS

This work was carried out through the Core Programme within the National Research Development and Innovation Plan 2022–2027, carried out with the support of MCID, project no. 6N/2023, PN 23 26 01 03, project title "Materiale electroconductive pe baza de metalizari multistrat pentru sisteme termoelectrice, ecranare electromagnetica si senzori biomedicali integrati in sisteme IoT (3D-WearIoT)".

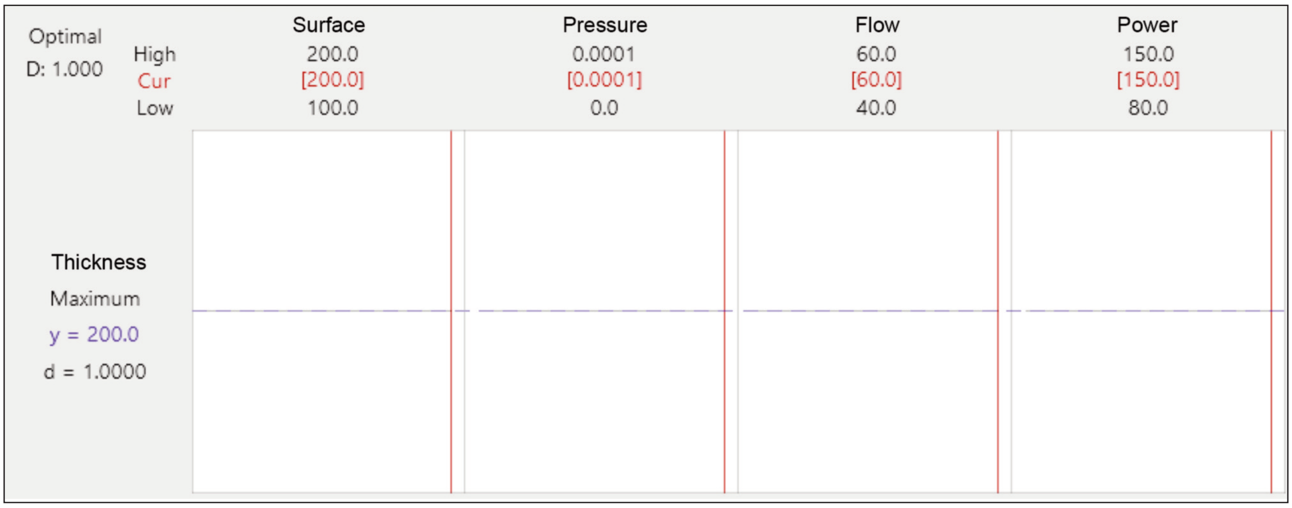

Fig. 4. Optimisation graph of experiments for the realisation of conductive materials for thermoelectric generators

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