DOI: 10.2478/aucts-2023-0005

ACTA UNIVERSITATIS CIBINIENSIS – TECHNICAL SERIES

Vol. 75 2023

# SPIF ON POLYMERS – EXPERIMENTAL DATA DESIGN AND PROCESSING

***ROȘCA Nicolae***
***Faculty of Engineering, Department of Industrial Engineering and Management, „Lucian Blaga" University, Sibiu, Romania, nicolae.rosca@ulbsibiu.ro***

***OLEKSIK Mihaela***
***Faculty of Engineering, Department of Industrial Engineering and Management, „Lucian Blaga" University, Sibiu, Romania, mihaela.oleksik@ulbsibiu.ro***

***ROȘCA Liviu***
***Faculty of Engineering, Department of Industrial Engineering and Management, „Lucian Blaga" University, Sibiu, Romania, liviu.rosca@ulbsibiu.ro***

**Abstract:** The paper's aim is to describe the stages of the experimental research as well as the processing of data measured in the SPIF of some polymeric materials using methods such as the Taguchi method, ANOVA analysis, and establishing the regression equation to determine the relevant factors of influence.

**Keywords:** incremental forming, SPIF, polymeric materials, Taguchi, ANOVA

## 1. Introduction

The single point incremental forming process (SPIF) arose due to the need to produce unique or semi-finished products in small series production at low costs and at the same time friendly to the environment [1].

The need to use lighter materials in the automotive industry to reduce the vehicle's mass and thus increase its autonomy, as well as the biocompatibility with the human body, has made polymeric materials increasingly used [2].

Most of the research on SPIF has been done on the forming of metallic materials [3], but in recent years, starting from the 2000s, they have also gained momentum on polymeric materials [4].

In the process of plastic forming, the forming force, the deformations, and the thinning of the semi-finished product is of interest, the present paper discusses aspects regarding the preparation of experimental research and the statistical processing of the measurement results. Since the forming force is one of the most important process parameter in SPIF [5], the study of this force was pursued in the present work.

## 2. THEORETICAL ASPECTS REGARDING EXPERIMENTAL DATA PROCESSING

The theoretical results usually obtained by numerical simulation must be validated through experimental research. In turn, experimental research undergoes statistical analysis to be processed.

### *2.1. Taguchi method*

The Taguchi method aims to obtain very good quality products with minimal costs by reducing the variables that influence the production process. H.C. Taguchi proposed an experimental model described by an orthogonal matrix that organizes the parameters involved in the process and their levels of variation [6].

In the case of SPIF, it is aimed that the deformation is carried out at the lowest possible force values and therefore, in the research presented below, the aim was to reduce these values [5].

Following research on the current state of SPIF of plastic materials, the main influencing factors were selected, namely [7]:

- Material type MAT (polycarbonate PC and polyvinyl chloride PVC) – two levels of variation;
- The step on vertical direction p (0.5mm, 0.75mm and 1mm) – three levels of variation;
- Punch diameter Dp (6mm, 8mm and 10mm) – three levels of variation;
- Part wall angle α ($50^0$, $55^0$ and $60^0$) – three levels of variation.

Using the Taguchi orthogonal matrix method to design the experiments resulted an orthogonal matrix:

$$L_{18} = 2^1 \, x \, 3^3$$

where:

- $2^1$ – a parameter with two levels of variations,
- $3^3$ – three parameters with three levels of variations.

thus resulting in nine measurements, each measurement being repeated twice to reduce the errors [7].

Since the deformation force in the Z direction is always greater than the deformation forces in the other directions (X, Y) [7], only this force will be considered in the present paper.

During any manufacturing process, process-disturbing factors may occur, such as ambient temperature, different machine operating parameters, different quality of processed materials, and factors that are difficult to control. Thus, when designing experiments, it is imperative to limit the effect of these disturbing factors, also called noises. In the case of the presented experiments, the "smaller is better" case of signal-to-noise ratio was considered. This ratio, between the factors that influence the process and the disturbing factors, was selected because the aim is to minimize the force during the forming process.

*2.2. The experimental results obtained*

Experimental measurements were made using a KUKA KR210-2 robot and a force transducer mounted on the robot flange (figure 1) [7].

Following the measurements, the results in Table 1 were obtained for the force Fz.

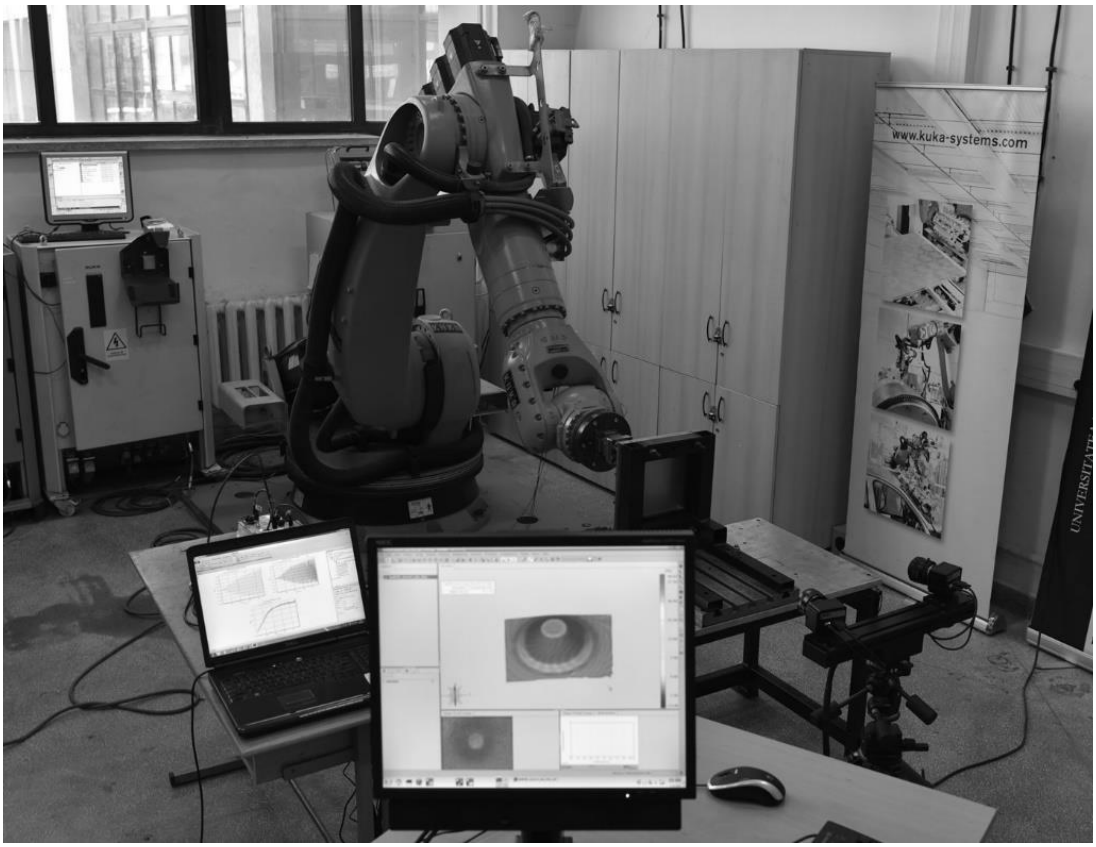



**Figure 1: Experimental setup [7]**

After running the Taguchi analysis in the statistical program Minitab [8], the results presented in Table 2 were obtained. These data are the input data for the ANOVA method and for obtaining the regression equation.

**Table 1: Numerical results for Fz force**

| Codification | Material | Angle [$^0$] | Punch Diameter [mm] | Step [mm] | Fz1 [kN] | Fz2 [kN] |
|---|---|---|---|---|---|---|
| Fz_1 | PVC | 50 | 6 | 0.5 | 0.9600 | 0.9528 |
| Fz_2 | PVC | 50 | 8 | 0.75 | 1.3133 | 1.3087 |
| Fz_3 | PVC | 50 | 10 | 1 | 1.7036 | 1.7049 |
| Fz_4 | PVC | 55 | 6 | 0.75 | 1.0839 | 1.0851 |
| Fz_5 | PVC | 55 | 8 | 1 | 1.4900 | 1.5004 |
| Fz_6 | PVC | 55 | 10 | 0.5 | 1.3050 | 1.3397 |
| Fz_7 | PVC | 60 | 6 | 1 | 1.1991 | 1.2020 |
| Fz_8 | PVC | 60 | 8 | 0.5 | 1.1587 | 1.1283 |
| Fz_9 | PVC | 60 | 10 | 0.75 | 1.5393 | 1.5337 |
| Fz_10 | PC | 50 | 6 | 0.5 | 0.6778 | 0.6337 |
| Fz_11 | PC | 50 | 8 | 0.75 | 0.9897 | 0.9830 |
| Fz_12 | PC | 50 | 10 | 1 | 1.3626 | 1.4188 |
| Fz_13 | PC | 55 | 6 | 0.75 | 0.7351 | 0.7406 |
| Fz_14 | PC | 55 | 8 | 1 | 0.9918 | 0.9967 |
| Fz_15 | PC | 55 | 10 | 0.5 | 0.9771 | 1.0689 |
| Fz_16 | PC | 60 | 6 | 1 | 0.8137 | 0.7453 |
| Fz_17 | PC | 60 | 8 | 0.5 | 0.8461 | 0.8550 |
| Fz_18 | PC | 60 | 10 | 0.75 | 1.0838 | 1.1086 |

**Table 2: Statistical results for Fz force obtained in Minitab**

| Material | Angle | Punch | Step | Fz1 | Fz2 | Signal to Noise Ratio | Standard Deviation | MEAN | Coefficient of Variation |
|---|---|---|---|---|---|---|---|---|---|
| PVC | 50 | 6 | 0.50 | 0.9600 | 0.9528 | 0.3871 | 0.0051 | 0.9564 | 0.0053 |
| PVC | 50 | 8 | 0.75 | 1.3133 | 1.3087 | -2.3521 | 0.0033 | 1.3110 | 0.0025 |
| PVC | 50 | 10 | 1.00 | 1.7036 | 1.7049 | -4.6307 | 0.0009 | 1.7043 | 0.0005 |
| PVC | 55 | 6 | 0.75 | 1.0839 | 1.0851 | -0.7046 | 0.0008 | 1.0845 | 0.0008 |
| PVC | 55 | 8 | 1.00 | 1.4900 | 1.5004 | -3.4940 | 0.0074 | 1.4952 | 0.0049 |
| PVC | 55 | 10 | 0.50 | 1.3050 | 1.3397 | -2.4277 | 0.0245 | 1.3224 | 0.0186 |
| PVC | 60 | 6 | 1.00 | 1.1991 | 1.2020 | -1.5876 | 0.0021 | 1.2006 | 0.0017 |
| PVC | 60 | 8 | 0.50 | 1.1587 | 1.1283 | -1.1655 | 0.0215 | 1.1435 | 0.0188 |
| PVC | 60 | 10 | 0.75 | 1.5393 | 1.5337 | -3.7307 | 0.0040 | 1.5365 | 0.0026 |
| PC | 50 | 6 | 0.50 | 0.6778 | 0.6337 | 3.6603 | 0.0312 | 0.6558 | 0.0476 |
| PC | 50 | 8 | 0.75 | 0.9897 | 0.9830 | 0.1193 | 0.0047 | 0.9864 | 0.0048 |
| PC | 50 | 10 | 1.00 | 1.3626 | 1.4188 | -2.8664 | 0.0397 | 1.3907 | 0.0286 |
| PC | 55 | 6 | 0.75 | 0.7351 | 0.7406 | 2.6406 | 0.0039 | 0.7379 | 0.0053 |
| PC | 55 | 8 | 1.00 | 0.9918 | 0.9967 | 0.0501 | 0.0035 | 0.9943 | 0.0035 |
| PC | 55 | 10 | 0.50 | 0.9771 | 1.0689 | -0.2062 | 0.0649 | 1.0230 | 0.0635 |
| PC | 60 | 6 | 1.00 | 0.8137 | 0.7453 | 2.1553 | 0.0484 | 0.7795 | 0.0620 |
| PC | 60 | 8 | 0.50 | 0.8461 | 0.8550 | 1.4059 | 0.0063 | 0.8506 | 0.0074 |
| PC | 60 | 10 | 0.75 | 1.0838 | 1.1086 | -0.7984 | 0.0175 | 1.0962 | 0.0160 |

*2.3. Signal-to-noise ratios*

The Taguchi method provides information on signal-to-noise ratios. Since the size of the forming forces is desired to be as low as possible, the condition "smaller is better" is used. This is how the results presented in Table 3 of the signal-to-noise ratios for the Fz force were obtained.

**Table 3: S/N response for force Fz**

| Level | Material | Angle | Punch | Step |
|---|---|---|---|---|
| 1 | -2.1895 | -0.9471 | 1.092 | 0.2757 |
| 2 | 0.6845 | -0.6904 | -0.9062 | -0.8044 |
| 3 | | -0.6201 | -2.4434 | -1.7289 |
| Delta | 2.874 | 0.327 | 3.5354 | 2.0047 |
| Rank | 2 | 4 | 1 | 3 |

The data from Table 3 shows the following, depending on the delta (highest value minus average value) and the rank of the factor (the order of the factors in decending order): the diameter of the punch has the greatest influence on force Fz among the four parameters considered followed by the material of the semi-finished product, step and angle. The graphic representation is presented in figure 2. It is observed that to obtain a minimum force Fz the optimal values for the four factors considered are: polycarbonate material, $60^0$ wall angle, 6mm punch diameter, and 0.5mm step.

*2.4. ANOVA method*

Analysis of variance (ANOVA) or dispersion analysis, invented and named by R.A. Fisher [9], is a statistical method for analyzing measured experimental data that depends on one or more factors with simultaneous action and aims to establish their influence on the objectively analyzed function [10]. In other words, in the present case, the analysis of variance indicates how is the z-axis forming force influenced by material, step, wall angle, and punch diameter.

An ANOVA table indicate how important the influencing factors considered are and contains:

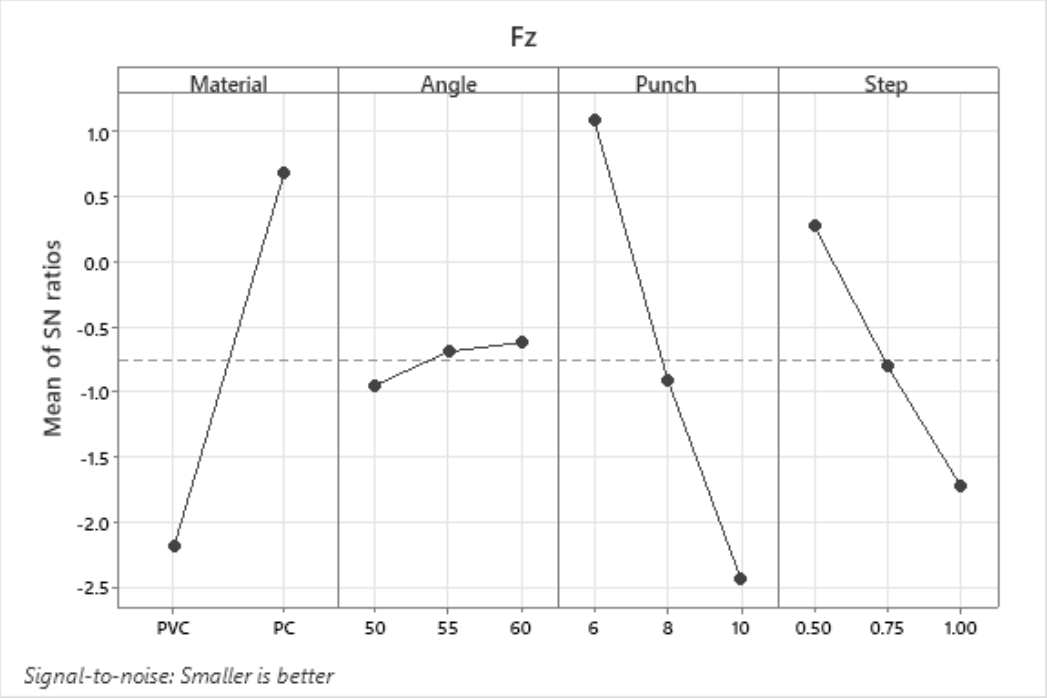



***Figure 2 Main Effects Plot for SN ratios***

- influencing factors (Source): material, wall angle, punch diameter, step, as well as the interaction between them – material*punch, material*step;
- degrees of freedom (DF) for each of the sources;
- the squares' sum of measured data (SS);
- the mean of the squares (MS) of the measured data;

- the value of Fischer's indicator or the F test measures the degree of dispersion of the measurements compared to the average;
- the p-value is an indicator of the relevance of the measured data and can take values between 0 and 1. In the case of scientific research, the requirement is that this value be at most 0.05 [10].

From the Table 4, results of ANOVA, it can be seen that the value of the angle and the values of the interactions between material-punch and material-step are greater than 0.05 and therefore these factors are considered insignificant for the force Fz.

**Table 4: ANOVA table for Fz**

| Source | Degrees of Freedom | Sequential Sums of Squares | Adjusted Sums of Squares | Adjusted Mean Squares | F | P |
|---|---|---|---|---|---|---|
| Material | 1 | 37.169 | 37.169 | 37.169 | 262.12 | 0 |
| Angle | 2 | 0.3556 | 0.3556 | 0.1778 | 1.25 | 0.351 |
| Punch | 2 | 37.7085 | 37.7085 | 18.8543 | 132.96 | 0 |
| Step | 2 | 12.0801 | 12.0801 | 6.0401 | 42.59 | 0 |
| Material*Punch | 2 | 0.9885 | 0.9885 | 0.4942 | 3.49 | 0.099 |
| Material*Step | 2 | 0.0848 | 0.0848 | 0.0424 | 0.3 | 0.752 |
| Residual Error | 6 | 0.8508 | 0.8508 | 0.1418 | | |
| Total | 17 | 89.2373 | | | | |

*2.5. The regression equation*

Regression is the statistical modeling process of obtaining an equation, called a regression equation, that establishes a relationship between input and output parameters. The most common form of this equation is the linear form, which is considered to be the closest fit to the experimental data.

Table 6 shows that the wall angle and the constant are factors with insignificant influence because the values of p are above the accepted value of 0.05. Therefore, the regression analysis will be repeated without the two insignificant factors resulting in the data from Table 7 and the regression equation (1).

**Table 5: Minitab Regression Analysis for force Fz and PVC**

| Termen | Coefficient | Standard Error of Coefficient | T-Value | P-Value |
|---|---|---|---|---|
| Constant | 0.217 | 0.742 | 0.29 | 0.774 |
| Angle | -0.0061 | 0.0122 | -0.5 | 0.626 |
| Punch | 0.1042 | 0.0306 | 3.4 | 0.004 |
| Step | 0.545 | 0.245 | 2.23 | 0.043 |

$$F_Z = -0.119 + 0.1042D_p + 0.545p \quad (1)$$

## 3. CONCLUSIONS

The paper aims to present an approach to how the stages of an experiment are established, the order of measurements, and the analysis of these data by statistical methods to establish the determinants of the production process. The specific case of the SPIF process of polycarbonate (PC) and polyvinyl chloride (PVC) was considered as an example.

The four parameters that can influence the variation of the z-axis deformation force in the SPIF process, such as the material, the punch diameter, the wall angle, and the step on vertical direction, were statistically analyzed. Following the statistical analysis, the weight of the influence of these factors resulted, among the most important being the material to be processed and the diameter of the punch. Thus, the optimal parameters for the given conditions were obtained, namely, if polycarbonate is processed with a

punch diameter of 6mm, a step of 0.5mm and a wall angle of $60^0$, a minimum of the forming force on the Z axis is obtained.

## References


1. Ben Said, L., *The incremental sheet forming; technology, modeling, and formability: A brief review*, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. Vol. 236(6), pp. 2729–55, (2022).
2. Hassan, M., Hussain, G., Wei, H., Qadeer, A., AlKahtani, M., *Progress on single-point incremental forming of polymers*. Int J Adv Manuf Technol. Vol. 114(1–2), pp. 1–26, (2021)
3. Behera, A.K., de Sousa, R.A., Ingarao, G., Oleksik, V., *Single point incremental forming: An assessment of the progress and technology trends from 2005 to 2015*. Journal of Manufacturing Processes. Vol. 27, pp. 37–62., (2017)
4. Zhu, H., Ou, H., Popov, A., *Incremental sheet forming of thermoplastics: a review*. Int J Adv Manuf Technol. Vol. 111(1–2), pp. 565–87, (2017)
5. Rosca, N., Trzepieciński, T., Oleksik, V., *Minimizing the Forces in the Single Point Incremental Forming Process of Polymeric Materials Using Taguchi Design of Experiments and Analysis of Variance*, Materials, Vol. 15(18): 6453, (2022).
6. Taguchi, H.C., *Method as a Robust Design Tool. Quality Control - Intelligent Manufacturing, Robust Design and Charts*, IntechOpen, (2021)
7. Rosca, N., *Incremental forming on polymeric materials*, [PhD Thesis], University „Lucian Blaga" of Sibiu, Sibiu, Romania, (2022).
8. Minitab. Minitab, LLC; (2022).
9. Fisher, R.A. *The Correlation Between Relatives on the Supposition of Mendelian Inheritance*, Philosophical Transactions of the Royal Society of Edinburgh, Vol. 52, pp 399–433 (1918).
10. Tabachnick, B.G., Fidell, L.S., *Experimental Designs Using ANOVA*. Vol. Library of Congress. (2020).