EMPIRICAL METHODS IN THE EVALUATION OF TECHNOLOGICAL PROCESSES

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ABSTRACT: Experimental or empirical modeling is used in the study of processing processes using unconventional technologies. Empirical modeling means finding mathematical formulas that link the various sizes called influence factors to measured sizes or related to them through calculations called objective functions. The paper presents the particular aspects of the application of experimental modeling in the industrial environment. This differs from the one in research projects because it narrows the researched experimental field and requires the rapid obtaining of some results in order to make some decisions. An experimental modeling for laser cutting for glass-fibre epoxy sheets was carried out. The organization of the experimental plan is presented. A complete factorial experimental design 2^2 was expanded into classical experimental series and an experimental design 2^3. The experiments carried out showed that the main factors that intervene in the process to achieve the penetration of the material and establish the shape of the cut are the cutting speed and the thickness of the material.
KEYWORDS: experimental (empirical) model, full factorial design, laser cutting, glass fibre epoxy, industrial application

1. INTRODUCTION

Non-conventional technological processing processes (with laser beam, plasma, electroerosion, electron beam, water jet) require the use of complex technological systems that require the adjustment of many parameters. In general, manufacturers of technological systems present parameter data for certain processing. So, that their utility and functionality are ensured. However, it is necessary to make certain changes in order to achieve the flexibility of the production process.

This requires experimental research applied in an industrial environment. It is characterized by the following:

- Uses a small number of parameters that can be continuously varied.

- The processing process and the processed object is evaluated more qualitatively.

- It is desired to obtain some easy-to-apply empirical models that allow quick decision-making.

- Statistical analysis is limited, an analysis of values is preferred.

An effective experimental research involves the use of statistical methods of dimensional and regression analysis, multifactorial programs and mathematical models used in determining the optimal fields of operation of technological systems.

Experimental (empirical) modeling consists in establishing mathematical relationships (correlation functions) between the modified parameters and the values of measured or calculated for objective functions. Obtaining these relations is accompanied by the statistical analysis of the obtained variations.

The purpose of the paper is to analyze the specifics of the application of experimental modeling in the industrial environment.

An important component in research is the experimental plan or experimental design. Based on this, the aim is to obtain mathematical models based on classical experimental series where a single factor varies and mathematical models based on factorial experimental plan where the simultaneous variation of several influencing factors is considered.

Based on the experiments carried out, the aim is to obtain information regarding the management and control of the technological process, the optimization of the process, the confirmation of some analytical models and theoretical results.

These represent the results of experimental research.

The experimental plan contains a finite number of trials limited by the resources regarding the operating cost of the technological system, the available materials, and the time allocated for processing. The creation of the experimental plan aims to achieve as many results as possible of the experimental research.

The interest for laser cutting of composite materials type resin reinforced with glass fibers was shown in works [4], [5], [7] and [9].

Studies for laser cutting of other composite materials are presented in [8], [10], and [11]. The experimental research considers the control of the cutting process and the quality of the cut surfaces [12]. The research use of an experimental design with multiple uses applied in laser cutting of composite materials is presented in works [13], [14] and [15].

2. EXPERIMENTAL MODELING

Experimental (or empirical) modeling represents the determination of the model through mathematical processing of input-output data, obtained through measurements [1].

In empirical modeling, the detailed analysis of the phenomena taking place in the system and the interaction between them is deliberately abandoned, aiming exclusively at the establishment, based on the principles of mathematical statistics and regression analysis, of the link between the response functions (performance indicators) and the independent variables of the system in a mathematical form as simple as possible (most often, polynomial), adaptable to automatic calculation and directly usable in practical applications.

The causal link that characterizes the functionality of technological systems is expressed mathematically in a general form, through an equation of the type:

$$y = f(x) \tag{1}$$

This type of relationship represents the correlation function between inputs and outputs, which in experimental research is also called "mathematical model" or "empirical model".

The functioning of technological systems is given by the interaction between their structure, the physical and chemical processes that take place and the transformation programs.

The operation of technological systems is subject to the action of two types of factors:
- controllable factors;
- uncontrollable factors or disturbances.

Controllable factors are divided into planned changes and imposed restrictions.

The planned changes represent the variation plan of the inputs and the restrictions contain a series of factors and situations fixed by the equipment settings that remain unchanged during the technological process.

Technological systems are concrete systems, having a structure consisting, at least in part, of physical elements with a determined functionality, through the ability to achieve specific transformations of substance, energy and information.

Inputs x represent actions (commands) exercised on the system. They coincide with parameters that can be varied continuously (or almost continuously, having a numerical value).

At a theoretical level, they can be identified as belonging to the following categories: materials, initial information and primary energy.

Outputs y are attributes of the system, modified due to variation in inputs. They are measured quantities for which there is an initial interest.

At a theoretical level, they can be classified into the following categories: (finished) products and waste, obtained information and transformed energy.

The functionality of technological systems is characterized by the connection between inputs and outputs.

The mathematical form of the function *f* is assumed independently of the studied technological process.

Experimental modeling is carried out after the experiments have been carried out. Experimental modeling does not directly show the physical phenomena that govern the technological process.

The results obtained through experimental modeling are limited not only by the experimental conditions but also by the particular values chosen for the influencing factors. These define the experimental domain. The statistical analysis of the variations of the objective function establishes the degree of confidence in the extension of the model to the experimental domain.This compares the variations due to influencing factors with those due to the existence of perturbations that affect the reproducibility of the experiment.

The experimental research in the processes of processing materials involves carrying out the processes under controlled conditions with well-established objectives. It is intended that the obtained results are reproducible and generalizable.

Experimental research differs fundamentally from knowledge through experience where the results obtained appear by chance and are valid only in the situation in which they were obtained. The definition of problems in experimental research is related to the structure and functioning of technological systems. The experimental research on a technological process consists in defining the inputs, called in this case also influence factors, the outputs also called objective functions, the controlled changes in the form of experimental plans and the restrictions in the form of experimental conditions and parameters kept constant.

As a result of the research, the connection function between inputs and outputs is obtained. This is called mathematical modeling.

The mathematical model obtained ensures the possibility of the proper solution of some fundamental engineering problems, such as:

- systems analysis – determining the structure and functionality of an existing technological system;
- synthesis of systems – designing a new system, having a certain structure and functionality;

- systems management - informational control of the evolution of technological systems, with the objective of optimizing functionality in relation to a given set of criteria and restrictions.

3. EXPERIMENTAL MODELING APPLIED IN INDUSTRY

The purpose of experimental research accompanied by mathematical modeling applied in industry is the following:

-Realization of the processing process under minimum conditions of quality and reproducibility for the processed object.

- Realization of the processing process in optimal conditions where a slight change in the parameters can lead to the improvement of the quality of the processed object, the reduction of the processing time, or the energy consumption.

Experimental research in the industrial environment touches both problems thus we have:

- The adaptation problem. In it, it is aimed that the processing process becomes feasible under the conditions of changing one of the fixed conditions, for example changing the processed material or one of its characteristics.

- The optimization problem. It is aimed that the processing process becomes optimal from a certain predetermined point of view.

Experimental research considers:

- Variable experimental conditions - these refer to parameters that can be varied. The interest is for the parameters that can be continuous variations.
- Fixed experimental conditions- It refers to the parameters for which the values are discrete and are hardly variable, requiring either complicated or time-consuming interventions in the technological system.

Disappears the notion of disturbing factors. These are considerations in the laboratory. In the industrial environment each processing process is somewhat unique. Disturbances do exist and affect the stability and reproducibility of the processing process.

Experimental or empirical modeling aims to know the processing process by obtaining a mathematical formula between the influencing factors and the objective functions.

If the field on which the influencing factors are varied is a wide one, situations may arise in which the process is not feasible.Thus, we must distinguish between the application of experimental modeling with the aim of fundamental research and that applied in the industrial environment. Here, the range of variation of the influencing factors is narrow. It leads to the application of the hypothesis that the variation of the objective functions with the influencing factors is linear.

In industry, there is a situation where, in order to meet some market requirements, the problem of implementing a new technology arises. In the present case it is about the laser cutting process. The element of novelty is the joining of a technological processing system and a material. Independently these two components exist and are known, the interaction between them is not known. In the present case we are referring to the laser cutting process applied to composite materials with direct application for polymer matrix materials reinforced with glass fibre. In the present case we are referring to the laser cutting process applied to composite materials with direct application for materials polymer matrix reinforced with glass fibre.

Through experimental research, quality requirements on the processed object can be identified. They are imposed by standards, by subsequent processability or self-imposed by the manufacturer to ensure a quality final product. Thus, at the level of principle, the experimental research leads to the obtaining of information of a particular character that lead to the successful realization of the processing process and which are not available from other sources.

The main elements that appear in experimental research are:

- identification of the factors that affect the processing process;
- identification of factors that can be varied and those that are fixed;
- selection of factors that can be varied relative to quality requirements on the process and/or ensuring energy efficiency (or economic in general);
- identification of the experimental range of variation for each factor (range of variation);
- the identification of factor values for carrying out the processing process under favorable processing conditions (usually called "optimal" conditions).

The problem contrary to the identification of favorable conditions is the identification of critical conditions where, due to the existence of incompatibilities between the values of the influencing factors, the realization of the process or the quality of the processed object is strongly affected.

The application of experimental research on an input-output model (influence factors-objective functions) accompanied by mathematical modeling (through correlation formulas, accompanied by statistical research of their adequacy will give the possibility of solving two problems:

- Calculation of objective function values for influence factor values;
- Calculation of values for influencing factors when known through imposed requirements) the values of one or more objective functions.

4. THE MAIN EXPERIMENT

In the experiment, closed cuts were made at both ends on plates of glass fibre epoxy [2], [3].The experimental plan carried out considered power, cutting speed and material thickness as factors of influence. To vary the thickness of the material, six plates of different thicknesses were used. A particular experimental program was created for each plate. Plates with thicknesses of 1.5, 1.7 and 2 mm will be called thin plates. They are close in thickness. For these plates, the laser beam was focused on the surface of the plate.
The material thickness variation for these plates being relatively small, the material thickness can be considered both as a controlled variable influencing factor and as a disturbing factor.

Plates with thicknesses of 3.4, 4.3 and 4.6 mm will be considered thick plates. For these, the focus of the laser beam was made inside the plate at 2mm below the surface of the plate.

For the experimental plan applied to each individual plate, two types of organization of the experimental trials were considered:
- classic experimental series;
- complete factorial experimental plan of type 2^3.

Table 1 Levels of influencing factors

Level\ Influence Factor	Cutting speed	
	v[mm/s]	**A[-]**
Low level	0.83	-1
High level	4.17	+1
	Laser power	
	P [W]	**B[-]**
Low level	182.4	-1
High level	240	+1
	Plate thickness	
	s[mm]	**C[-]**
Low level	3.4	-1
High level	4.6	+1

The factors varied in these experiments were cutting power and speed.
For plates with thicknesses of 1.5 and 1.7 mm, respectively plates with thicknesses of 3.4 and 4.6 mm, a classic experimental series in which the power was varied and a classic experimental series in which the cutting speed was varied was carried out on each plate.

To create the experimental plan, the following were taken into account:
- The values of the cutting speed decrease with the increase of the material thickness - the material thickness variation is small within the same category, thick plates respectively thin plates.
- Power values increase with increasing material thickness - the material thickness variation is large by passing from the range of thin plates to the range of thick plates.
- For the factorial plan, the range of variation for power and cutting speed was considered between the central points of those of the range used in the classic experimental series.

Table 2 The original factorial design

Test	**Cutting speed**		**Laser power**	
	[mm/s]	**[-]**	**[W]**	**[-]**
1	**3.33**	**+1**	**153.6**	**-1**
2	**1.67**	**-1**	**153.6**	**-1**
3	**3.33**	**+1**	**211.2**	**+1**
4	**1.67**	**-1**	**211.2**	**+1**
5	**2.50**	**0**	**182.4**	**0**

The organization of the experimental plan shows that it was built on the basis of a type 2^2 factorial experimental plan with the factors power and cutting speed.

Table 3 Adding the additional factor G to the factorial design - factorial design 2^3

Test	**Cutting speed**		**Laser power**		**Thickness (G factor)**
	[mm/s]	**[-]**	**[W]**	**[-]**	**-**
1	**3.33**	**+1**	**153.6**	**-1**	**-1**
2	**1.67**	**-1**	**153.6**	**-1**	**-1**
3	**3.33**	**+1**	**211.2**	**+1**	**-1**
4	**1.67**	**-1**	**211.2**	**+1**	**-1**
5	**2.50**	**0**	**182.4**	**0**	**-1**
6	**3.33**	**+1**	**153.6**	**-1**	**+1**
7	**1.67**	**-1**	**153.6**	**-1**	**+1**
8	**3.33**	**+1**	**211.2**	**+1**	**+1**
9	**1.67**	**-1**	**211.2**	**+1**	**+1**
10	**2.50**	**0**	**182.4**	**0**	**+1**

The following changes were made for it.
- The points of the factorial experimental plan 2^2 were transformed into classical experimental series with 5 levels keeping the original point as the central point figure 1.
It is observed that the experimental plan 2^2 contains 4 tests at the extremes of the experimental field to which one is added in the central point.
- An additional factor G (expressed as the association between the thickness of the plate expressed as thick, respectively thin plates and the focus at the surface of the plate, respectively inside the plate) with two levels

doubled the experimental plan 2^2.This became type 2^3.

Material thickness (associated with defocusing) was added as an additional factor G that doubled the original experimental plan. For this, the values +1 and -1 denote a qualitative aspect as follows:

-1 - thin plate, with the focus on the surface of the plate;

+1 - thick plate with the focus inside the plate.

- The 2^2 factorial design has been transformed into a 3^2 factorial plan which basically covers the initial plan and adds 5 additional trials.

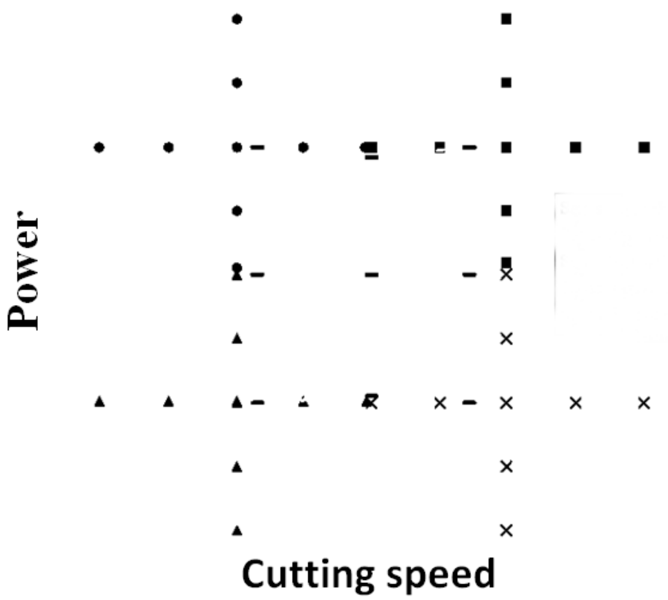


Figure 1 Evolution of the experimental design

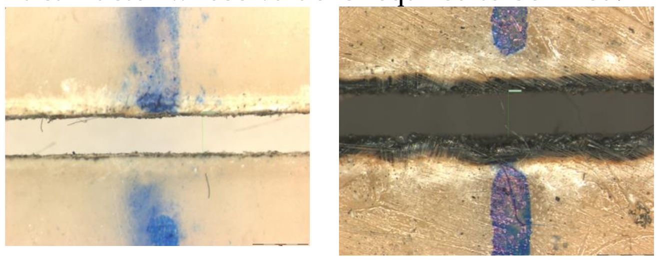
- An additional disturbing factor namely plate thickness has been added. Three thick plates and three thin plates were used. It is stated that the thickness of the plate was not directly varied and we worked with plates of available thicknesses.

Thus, a range of variation for the plate thickness was not considered. Plates of different thicknesses were associated with power and G-factor levels and a replication of the central point of the experiment.

It is observed that for each of the 4 points of the initial factorial experimental panel, two classic experimental series are obtained. This means that the power and speed levels are transformed into classical experimental series, with 5 experimental points around the corners of the square from the factorial design 2^2.

4. RESULTS OF EXPERIMENTAL RESEARCH

Experimental data processing was carried out using the methods from [6]. The analysis carried out shows that the factors of influence that have statistical significance on the processing process are the speed and the thickness of the material. Power behaves as a critical factor whose value is required to be fixed.



a) b)

Figure 2 Material degradation

a) top of plate b) bottom of plate

From a qualitative point of view, there is the problem of minimizing the burnt area on the lower surface of the plate, figure 2.

5. CONCLUSIONS

The paper studies the problems related to the experimental modeling applied to the technological processes of materials processing. This was applied to laser cutting for glass fibre epoxy plates. An experimental design was proposed to correlate the process parameters in the tests performed. The initial experimental plan 2^2 was expanded into classical experimental series and two experimental plans 2^3. This type of approach minimizes the number of tests performed and leaves the possibility to perform multiple processing of the experimental data. Experimental modeling aims to obtain maximum information about the technological process with a minimum of experimental attempts. In this sense, factorial experimental plans are combined with classical experimental series. Although each of these has a minimal composition, combined they provide a sufficient amount of information about the processing process. Applied experimental modeling does not always comply with some prescriptions related to conducting experiments. Thus, the thickness of the material was considered on the one hand an influencing factor and on the other hand a disturbing factor. The hypothesis was used that small variations in the plate thickness (0.5 mm for plates considered thin and 1.2 mm for plates considered thick) do not significantly change the physical conditions for the cutting process. Thus, they can be standardized in the factorial experimental plan, a value of the thickness of the material being recognized for thin plates and a value for thick plates. As an influencing factor, the thickness of the material poses the problem that the experimental field cannot be divided into equal intervals, but must be worked with the available plate thicknesses. Some previously acquired knowledge about the effect of parameters is used. Thus, for thin plates, the focusing of the laser beam was performed on the surface of the piece, and for plates considered thick, it was performed inside the piece.

Experimental modeling applied in the industrial environment differs from that used in research. Its purpose is to make certain adjustments or to make a certain adaptation of the process, and not the phenomenological knowledge of the processing process. Previously acquired knowledge or the manufacturer's prescriptions are used. The experimental plan is built around the central point where the process is feasible. The variations induced by the parameters are assumed to be linear. The interpretation of the results needs to be done quickly. Value analysis appears as an alternative to statistical processing of experimental data. Both methods must be approached and neither excluded in favor of the other. Experimental modeling applied in industrial conditions requires a certain flexibility both in the organization of the experimental plan and in the processing of experimental data. Experimental modeling faces the problem that for some points of the experimental plan the processing process is not feasible. In our case, non-penetrated cuts are obtained. In these cases it is not possible to obtain the model even if some quantities are measurable because the phenomena involved in the process differ. Another problem is, somewhat contrary, the situation in which, due to maintaining the realization of the processing process, we have experiments in which, although we have varied some parameters, the measured quantities do not vary significantly. Here, the objective functions must also include qualitative assessments.

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