

EXPLORATORY RESEARCH APPLIED FOR THE PRIMARY ANALYSIS OF TECHNOLOGICAL PROCESSES

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ABSTRACT: Exploratory research is applied in research programs and in knowing the capabilities of a technological system. An experimental program for laser cutting of glass fibre epoxy sheets is presented. Mathematical modeling aims to identify variation trends. Classical experimental series are used. The mathematical model is built using regression functions. The variation parameters are correlated with physical quantities directly measured on the processed object. The technological process is characterized by calculated functions. Their variation forms a specific patent for the processing process. It has been shown that the productivity of the laser cutting process increases with the cutting speed.

KEYWORDS:exploratory research, experimental methods, laser cutting, glass fibre epoxy, machining process productivity

1. INTRODUCTION

The development of composite materials involves studies on their mechanical properties. An important problem is their damage during thermal processing such as laser cutting.



Figure 1 Plate with the cuts made

Composite materials are materials formed in matrices, their physical, especially mechanical, properties depend on their formation process. The formation of composite materials is presented in the papers [11], [12], [13]. Experimental research in laser cutting aims to study the realization of the process and

the cut surfaces. The cutting process applied to metals was presented in the following recent studies [7],[8],[9].However, there is also an interest in cutting composite materials [10] [14] [15]. Experimental research is accompanied by mathematical (or empirical) modeling with the aim of knowing the process based on the correlation between input parameters (influence factors) and output parameters (objective functions).

The purpose of experimental research is to conduct practical applications or to confirm analytical models. Within the experimental research programs, exploratory research is constituted as a distinct part. It is justified in the case of processing composite materials where the mechanical and thermal behavior of the material in the processing process is difficult to predict through theoretical models.

Exploratory research is part of a research program. It aims to establish the variation trends of the variation parameters (influence factors) on the measured values (objective functions). Exploratory research aims to reproduce the functioning of the technological system at some values prescribed by the manufacturer. The main characteristic of exploratory research is the extended experimental field in which the differences between the minimum and maximum value of a parameter are large.

In the exploratory research, the objective is neither the realization of the process nor the qualitative aspects of the processed pieces. It is desired to identify the values of the parameters for which the processing process is feasible, and the processed pieces have an acceptable quality. The exploratory research is followed by applied experimental research in which precise objectives of quality or behavior of the material in the processing process are established.

In this, the input parameters that have small influences are eliminated, they become fixed. The experimental range for the remaining parameters is also reduced. The present paper presents an exploratory experimental research for cutting glass fiber epoxy plates according to [2], [3], the processing of the experimental results being carried out following the methods presented in [1] and [6].

2. EXPERIMENTAL CONDITIONS

The experiment consisted in the laser cutting of glass fiber epoxy plates. The cuts were made using a CO₂ laser technological system. The cuts made were closed at both ends (kerfs inside the plate) figure 1. Making the cuts without separating the two parts allowed measuring the width of the cut in good conditions. For these, the width of the cut at the upper part of the plate (the part directly irradiated by the laser beam) and respectively the width of the cut at the lower part of the part were measured. These were named top cut width respectively bottom cut width, figure 2.

The width of the cut provides information on the performance of the cutting process that is the basis for the calculation of other objective functions.

The directly measured quantities are:

B_f [mm] - the width of the cut at the top of the piece;
 B_v [mm] - the width of the cut at the bottom of the piece.

Based on the directly measured quantities, two important study themes were defined, namely:

- description and analysis of the characteristics of the cuts made;

- description and analysis of the laser cutting process.

For the first proposed theme, in addition to the width of the cut at the top and the width of the cut at the bottom directly measured sizes, the following sizes were also introduced:

- Average cut width as arithmetic mean of the two measured cut widths:

$$B_m = \frac{B_f + B_v}{2} \text{ [mm]} \quad (1)$$

- The angle of inclination of the walls of the cut in relation to the surface of the piece:

$$U = \arctg \frac{2s}{|B_f - B_v|} \text{ [}^\circ\text{]} \quad (2)$$

The introduction of these sizes considered the cross-section through the cut in the form of a trapezoid. This is shown in the figure.

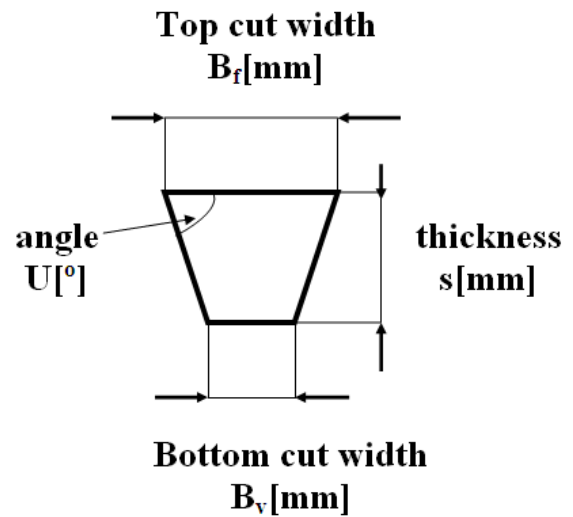


Figure 2 Diagram of the cross-section through the cut

For the study of the laser cutting process, values are introduced that consider directly measured values of the width of the cut at the upper part, respectively the lower part of the plate, but also values of the parameters varied in the experiment, the cutting speed and laser power. These are:

- Productivity-represents the volume of material eroded in the unit of time:

$$Pr = \frac{B_f + B_v}{2} \cdot s \cdot v \text{ [mm}^3\text{/s]} \quad (3)$$

- Volumetric energy- represents the energy consumed to remove the unit volume of material for a cut made under certain conditions:

$$E_v = \frac{2P}{(B_f + B_v) s v} \text{ [J/mm}^3\text{]} \quad (4)$$

Due to the way of definition, volume energy includes all measured and varied quantities (minus defocusing). This quantity is the main objective function of experimental research.

The influencing factors were identified for the laser cutting process.

Their action was identified relative to the two proposed research themes, namely the study of the characteristics of the cuts and the laser cutting process.

Thus, the following quantities were considered as influencing factors:

- v [mm/s] - cutting speed

- P [W] - laser power

- s [mm]- material thickness

- δ [mm]- the defocus- the distance between the focal plane of the laser beam and the surface of the piece.

For cutting thick materials, the laser beam is focused below the surface of the piece to ensure convergent propagation in the interaction zone. In this case, the defocus value is considered negative for focusing the laser beam into the material.

The experimental research organized according to the input (influencing factors)-output (objective functions) model requires, along with the definition of these quantities, a classification of them.

In the following, such a classification is presented. For the varied influencing factors in the experiments, we have the following classification of them:

- **influencing factors whose variation can be achieved continuously using the controls of the laser technological system (cutting speed, laser power).**

- **influencing factors whose variation is discrete and independent of the laser technological system (material thickness).**

- **influencing factors whose values is conditioned by other influencing factors (defocusing)**

For the objective functions, the classification has the following view along with the classification and the association made upon their introduction:

-**objective functions that partially characterize the results of the processing process** (top cut width, bottom cut width, average cut width, the angle of inclination of the walls of the cut, productivity);

-**objective functions that fully characterize the processing process (volumetric energy);**

A problem independent of the structuring of experimental research according to an input-output model is the evaluation of the irradiation conditions that are associated with varied factors.

For continuous irradiation, these factors have a relatively simple expression. They are characterized by the following sizes:

- linear energy - the ratio between power and cutting speed – is energy transmitted per unit length of the irradiated material.

$$E_l = \frac{P}{v} \text{ [J/mm]} \quad (5)$$

- duration of interaction between laser radiation and material

$$t_i = \frac{D}{v} \text{ [s]} \quad (6)$$

(D- diameter of the laser beam in the focal spot)

- the intensity of the laser beam in the focal spot

$$I = \frac{4}{\pi} \cdot \frac{P}{D^2} \text{ [W/cm}^2\text{]} \quad (7)$$

The quantities that characterize the irradiation conditions consider the power and the cutting speed as influencing factors (to which is added the diameter of the laser beam in the focal spot, a quantity that was not varied) which are independent of the thickness of the material.

Another way of expressing the duration of interaction and the intensity of the laser beam is relative to the surface of the piece. In this case defocusing produces effects through:

- increasing the spot of the laser beam on the surface of the part - increasing the interaction time between the material laser radiation;

- decrease in the intensity of the laser beam at the surface of the piece.

These effects (which to some extent offset each other) were considered to have little effect on the cutting process and the on cut.

Along with the direct effect of the influencing factors, knowing the quantities that express the irradiation conditions has an important role in understanding the experimental results.

3. EXPERIMENTAL RESULTS

In the following, the variation of the cut width will be analyzed for the classic experimental series with the cutting power and speed. For the tests carried out on plates 3 (thickness 2 mm) and 5 (thickness 4.3 mm) the variations with linear energy (the ratio between power and cutting speed) are presented because the variations with power and cutting speed as classic experimental series contained a small number of experimental points (3 points) to be used as regression functions.

Modeling with regression functions was also the main objective in the analysis of these variations.

Analysis of the variation of the cut width

a) Typical variations for thin plate

Figure 3 shows that the width of the cut increases linearly with laser power. Important differences between the width of the cut at the bottom and at the top of the part are obtained both at low powers and at high powers.

The differences are greater at low powers. It is observed that as the power increases, the thermal effects inside the material are favored, which lead to an increase the width of the cut at the lower part of the cut.

At the top of the cut the surface focus creates the conditions for the width of the cut to grow indefinitely while the width of the cut at the bottom stabilizes.

Although there is a linear increase in average width with power, neither top nor bottom width follows this pattern.

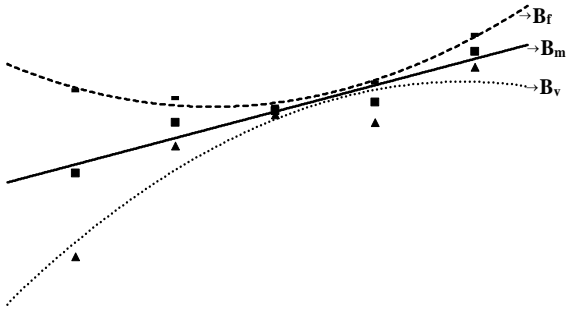


Figure 3 Variation of the width of the cut with the power, at the cutting speed 3.33 mm/s (thickness 1.5mm, defocus $\delta = 0$)

Figure 4 shows that the width of the cut decreases linearly with the cutting speed for the thin plate.

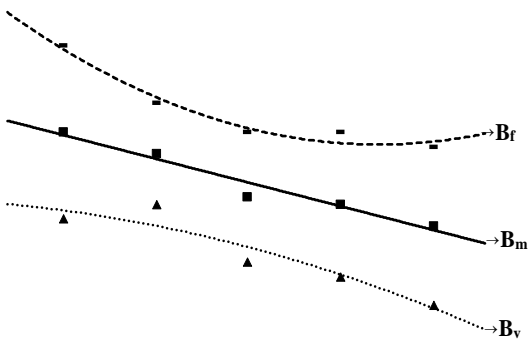


Figure 4 Variation of cut width with cutting speed at 153W power (thickness 1.5mm, defocus $\delta = 0$)

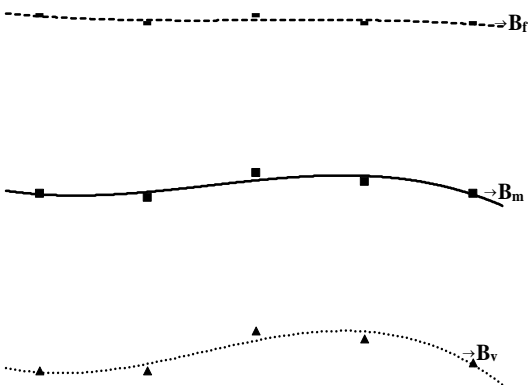


Figure 5 Variation of cut width with power at cutting speed 1.67mm/s (thickness 4.6 mm, defocus $\delta = -2mm$)

Both the width at the top and the width at the bottom have a quadratic decrease. At high cutting speeds the

width of the cut at the top increases and the width of the cut at the bottom decreases.

For the cuts made on the thin plate, it is observed that the values of the width of the cut at the top and at the bottom are relatively close.

b) Typical variations for thick plate

Figure 5 for the thick plate and focusing the laser beam inside the piece shows that there is no variation of the cut width with the power.

The cuts are wider than in the case of thin plate and the variation between the values of the width of the cut at the top and at the bottom is greater.

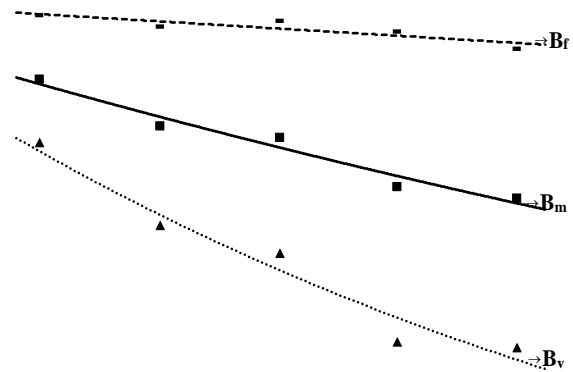


Figure 6 Variation of cut width with speed at 211.2W power (thickness 4.6 mm, defocus $\delta = -2mm$)

Figure 6 shows that for the thick plate there is a linear decrease in the width of the cut with the speed. This is more pronounced for the width of the cut at the bottom of the piece. In all cases analyzed, wider cuts were obtained at the top than at the bottom of kerfs. The width of the cut can be compared to the laser beam diameter of 0.2 mm.

Analysis of the calculated sizes

The calculated sizes characterize much better the conditions in which the processing takes place.

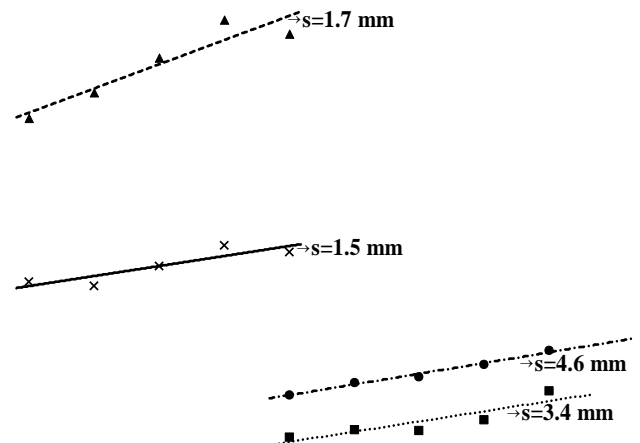


Figure 7 Variation of volumetric energy with power

Figure 7 shows the variation of volumetric energy with power. It is observed that there is an increase in volumetric energy with power. This means that the material removal process becomes energetically more expensive and with the increase in power, the thermal effects that do not remove the material, the thermally affected zone, increase.

On the other hand, each thickness of the material is associated with a certain level of volumetric energy, the variation with power being little significant. Thin plates require higher volume energy than thick ones. For each of the two categories there is a decrease in volume energy level with power.

Figure 8 shows the variation of volumetric energy with cutting speed. In all cases studied it is shown that there is a linear or logarithmic decrease.

This shows that increasing the cutting speed leads to an efficiency of the cutting process associated with the reduction of thermal damage to the material.

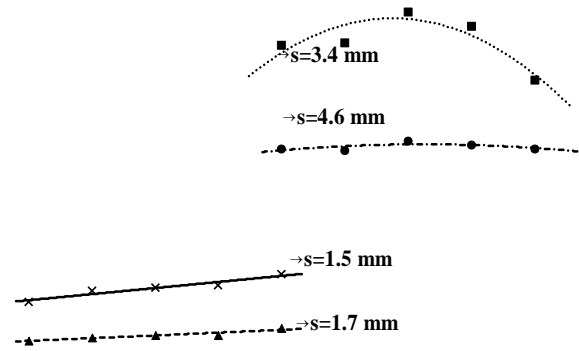


Figure 9 Variation of productivity with power

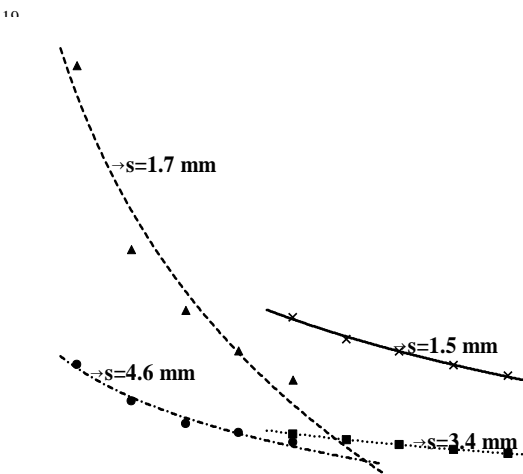


Figure 8 Variation of volumetric energy with cutting speed

Figure 9 shows the variation of productivity with power. It is observed that each thickness of the material is associated with a level of productivity. There is a tendency for productivity to increase with power, but it is not significant in the experimental field. Higher productivity is for thicker plates.

Figure 10 shows the variation of productivity with cutting speed. It is observed that there is a linear increase in productivity with cutting speed.

This shows a more efficient cutting process. Both the level and the slope of the regression line are higher for thicker plates than for thinner ones.

The variation of volumetric energy and productivity presents a specific patent for the laser cutting process. Thus, the processing process carried out can be compared with other experimental studies.

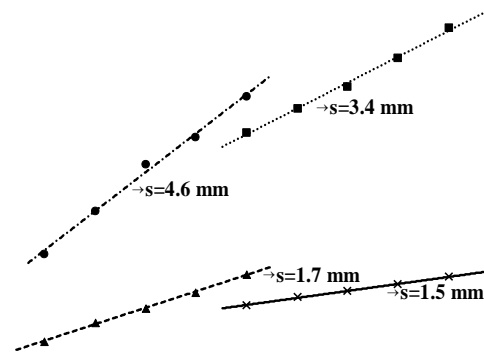


Figure 10 Variation of productivity with cutting speed

3. INTERPRETATION OF EXPERIMENTAL RESULTS

The work analyzes quantitatively the objective functions that were considered for the main research topic. Their analysis takes into account the following issues related to obtaining favorable conditions for carrying out the processing process. For the cut width (denoted by B [mm] and specified as top cut width B_f [mm], bottom cut width B_v [mm] and average cut width B_m [mm]) it is recommended that its values not be excessively high because they are associated with considerable thermally affected areas in the material. The small difference between the values of the width of the cut at the top and those at the bottom of kerf leads to obtaining straight cuts. Cuts with a small inclination are associated with U angle values as close as possible to 90° . The minimum values for the width of the cut mean the reduction of material consumption, but a narrow cut also means favoring the situation where the material cannot be removed from the cut. Therefore, obtaining minimum values for the width of the cut cannot be imposed as an objective. For the productivity P_r [mm³/s], the highest

possible values are desired. These mean efficient use of the energy delivered to the piece when removing material. For the volumetric energy E_v , from its definition it is found that it is directly proportional to the power and inversely proportional to the productivity. Thus, for this objective function, the minimum values will show the best conditions for performing the cutting process.

4. CONCLUSIONS

The paper studies the problems related to the experimental modeling applied to the technological processes of materials processing. This represents an exploratory research for laser cutting of composite material with the objective of achieving and managing the cutting process by making straight cuts. As a result of the experiments, it is obtained that the cutting speed and the thickness of the material are the main factors of influence. The power level needs to be associated with the thickness of the material. Thus, for future research, the association between material thickness and power can be considered a single influencing factor. A similar example is the association between defocus and piece thickness. The linear increase in productivity with cutting speed shows that there is an opportunity to optimize the process by increasing the cutting speed. It is shown that the definition of objective functions with technological significance is much more useful than the analysis of directly measured quantities.

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