Factors Affecting the Energy Consumption in Pulsed Nd: YAG Laser Cutting of Glass Fiber/epoxy Composite

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The main objective of this paper is to develop a complex experimental investigation and, by this way, to describe and analyze the influence of pulsed Nd: YAG laser cutting main parameters on the process energy consumption. The tested material was a Glass fiber/epoxy composite. The experimental program was performed by two approaches, factorial and classic. The design of experiments allowed the research results presentation as regression polynomial equation, Pareto effects diagram, response surfaces diagrams and single-factorial classic diagrams. A pertinent final discussion gave a global image and proved the validity of developed research.

Keywords: design of experiments, pulsed Nd: YAG laser cutting, Glass fiber/epoxy composite, energy consumption ratio

Glass fiber reinforced plastics and, particularly, Glass fiber/epoxy composites (GFRE) are generally used for structural applications in different fields. Their development is stimulated by high level properties as mechanical loading capacity to density ratio, corrosion resistance, damping behaviour in stressed structures, but also by their very special structural and geometrical technologic forming capabilities. However, many of GFRE parts, manufactured close to the near-net shape, need frequently, when small complex shape are required, the application of some complementary machining processes, particularly drilling and cutting [1].

Unfortunately, the usual mechanical technologies such as shape cutting or jet cutting, affect the parts quality and are low productive. Laser systems offer actually some of the most advanced today's technologies from the productivity, precision and flexibility points of view. Therefore, laser cutting represents a possible alternative to mechanical, traditional technologies, able to perform better and faster the needed processes in the manufacturing of GFRE parts.

Laser cutting of GFRE materials is state of the art today, but each such application in industrial environment put some important challenging problems [2]. The different properties of fiber and matrix-material and their particular behaviour to laser irradiation is the first of these problems. The second one is the unavoidable development of a heat-affected zone (HAZ) on the cut surfaces, as consequence of the thermal nature of infrared, CO_2 (λ= 10.6 μm) and Nd:YAG (λ =1.06 μm) laser action. The HAZ existence could influence the parts quality. In the case of GFRE composite, the resulted HAZ is characterized by the presence of fibers debonded from the matrix and thermal degradation of both fibers and matrix [3, 4].

There is also a third, apparently collateral, but yet important problem. That's about of laser cutting high energy consumption, which is depending on laser output power, operating parameters and material thermo-optical properties. Generally speaking, high energy consumption means a bigger risk for lack of parts quality, a more expensive laser machining and probably a worse ecologic impact [5]. Nevertheless, the scientific approach of energy consumption in laser applications is yet singular and under the industry requirements.

All these problems could be, more or less, solved by an intelligent, carefully design of laser process parameters in order to optimally correlate technologic energy requirements and delivered laser radiation energy. Correct solving of above problems must lead to a decrease of energy consumption and, at once, to a parts quality improvement.

A first approach of these problems and similar was carried out some years ago applying a PILOT experimental factorial program [6]. A pulsed Nd: YAG laser cutting equipment, 150 W output power and a composite sheet material 2 mm thick, were used. The aim was to study the process parameters influence on the kerfs geometry.

The main objective of this paper is to develop a more complex experimental investigation and, by this way, to describe and analyze the influence of laser cutting parameters on the process energy consumption. Specifically, the new, PRINCIPAL experimental program was performed by two ways , factorial and classic. A more powerful Nd: YAG cutting equipment, with 400 w output power and a set of the GFRE composite plates 1.5….4.6 mm thick, were used. To better describe the correlation among cutting parameters - laser power, pulse energy and frequency, cutting speed, material thickness etc - and energy consumption, a novel, integrative function, the energy consumption ratio Esp [J/mm^3] was introduced.

Experimental data processing with the STATGRAPHICS software [7] provided a comprehensive image of above mentioned correlations by means of statistic polynomial models, Pareto diagram, response surfaces and classic one-factorial diagram. Quantitative analysis of these elements allowed a prominence of some principles and actual measures for a better control of energy consumption in GFRE composite pulsed Nd: YAG laser cutting processes.

In the current period, the energetic and ecologic characteristics of industrial technologies became decisive in the development of new, innovative applications [8].

Experimental part

Experimental research strategy is a complex one. It has two main programs concepts, factorial and classic. [7, 9, 10]. The both programs use the same operating parameters (laser average power, cutting speed, focal position relative to the material surface, material thickness).

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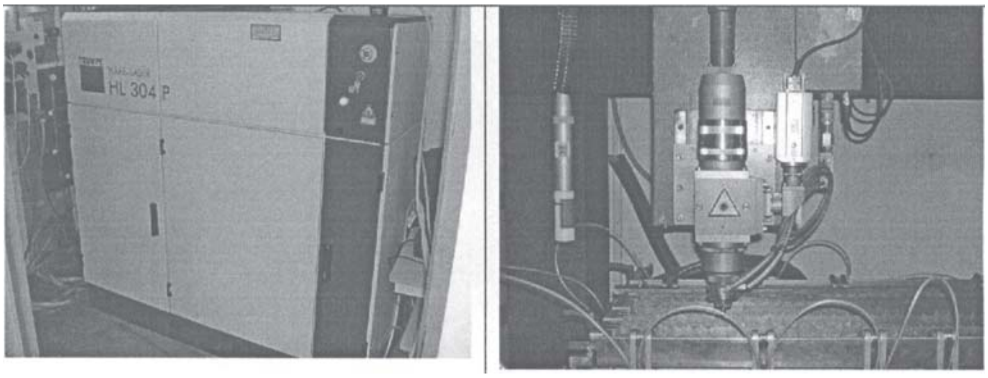

Fig. 1. The pulsed Nd: YAG laser TRUMPH HL304P, P_{max} = 400W and the associated laser cutting system

Table 1

SOME CHARACTERISTICS OF ND: YAG LASER TRUMPH HL 304P [11]

Characteristics	**Laser Trumph HL 304P**
Laser output peak power [W]	400
Laser peak power on the part surface [W]	330
Pulse peak power [kW]	9
Pulse energy [J]	0,1 – 70
Pulse duration [ms]	0,3 – 20
Optical fiber diameter [μm]	400
Absorbed peak power [kW]	18
Dimensions L x B x H [mm]	1608x1550x750

The first program is designed as factorial experiment 2^3, while the classic experiment, is partially build on the basis of the factorial experiment data and partially independent of this.

By courtesy of Institute Carnot Bourgogne, Creusot - France, where this program was performed, experimental research used a high-performance pulsed Nd: YAG laser equipment, namely TRUMPH HL 304P, with P_{max} = 400W, presented in figure 1. The main characteristics of this laser are given in table 1. The optical system of laser cutting head had a 200 mm length focusing lens. The diameter of focused beam spot was 0.2 mm. Laser cutting process was assisted with a coaxial air jet, injected at 5 bar input pressure. The air nozzle was settled at 2.5 mm height from de GFRE sheet surface.

The investigated material was a set of GFRE plates, obtained by hand lay-up technology, with length of 100 and 200 mm, width of 150 mm and thicknesses between 1.5 and 4.6 mm. The matrix was R601 epoxy resin and the reinforcing material was 0.1 and 0.2 mm thick, E glass fiber mat. Glass fiber weighting in composite was 75%.

During the designed laser cutting trials, different values of operating parameters, namely the laser average power P, the cutting speed v, the defocusing of parts irradiated surface δ and the GFRE plates thickness e, were selected. The setting of necessary P values was realized by appropriate modification of pulse energy Ep values, while the pulse frequence fp (30 Hz) and duration tp (1.5 ms) remained invariable. To have a larger image of real cutting conditions, it was aimed to obtain totally penetrated cuts as well as partially penetrated cuts. All trials were replicated.

Table 2

DESIGN MATRIX OF EXPERIMENTS IN PRINCIPAL FACTORIAL PROGRAM

Trial	Cutting speed **v** **[mm/min]**	Laser average power **P [W]**	GFRE Sheet thickness **e[mm]**
1.	50	180	2
2.	100	180	2
3.	50	270	2
4.	100	270	2
5.	50	180	4,2
6.	100	180	4,2
7.	50	270	4,2
8.	100	270	4,2
9.	75	225	2
10.	75	225	2
11.	75	225	2

The design matrix of experiments in PRINCIPAL factorial program is presented in the table 2. It has 2^3 = 8 trials and yet 3 supplementary trials in the central point of experiments.

Classic experiments were performed by 6 series of trials, related to 6 different values of material thickness e. The design matrix of experiments in classic approach is given in table 3.

The main carrier of information about laser cutting global efficiency is considered the kerfs geometry (fig. 2), related with a given set of operating parameters. The kerfs width refers to the width of the slot that is formed during through-thickness cutting and is normally narrower at the bottom surface of the work piece than at the top surface. The amount of material removed during the cutting process, is essentially wasted material; therefore, a smaller kerfs width is always desirable. Increases in laser power and reduction in cutting speed were found to result in increased kerfs' width [12].

In the figure 2, Bs and Bi are the top kerfs width and the bottom kerfs width, while e is the sample thickness.

The kerfs sections of laser cutting samples were examined by microscopic analysis, measuring the top Bs and bottom Bi kerfs width. Measurements were performed

Table 3

THE DESIGN MATRIX OF EXPERIMENTS IN PRINCIPAL CLASSIC PROGRAM

Trial	Laser cutting parameters P[w] and v [mm/min]											
	GFRE sheet thickness e [mm]											
	1,5		1,7		2,0		3,4		4,2		4,6	
	P	v	P	v	P	V	P	v	P	V	P	V
1	180	200	180	100	270	50	270	200	270	50	270	100
2	157.5	200	157.5	100	270	75	247.5	200	270	75	247.5	100
3	135	200	135	100	270	100	225	200	270	100	225	100
4	112.5	200	112.5	100	225	100	202.5	200	225	100	202.5	100
5	90	200	90	100	225	75	180	200	225	75	180	100
6	135	150	135	50	225	50	225	150	225	50	225	50
7	135	175	135	75	180	50	225	175	180	50	225	75
8	135	200	135	100	180	75	225	200	180	75	225	100
9	135	225	135	125	180	100	225	225	180	100	225	125
10	135	250	135	150	225	75	225	250	225	75	225	150
11	135	200	135	100	225	75	225	200	225	75	225	100
Obs.	δ = 0		δ = 0		δ = 0		δ = -2 mm		δ = -2 mm		δ = -2 mm	

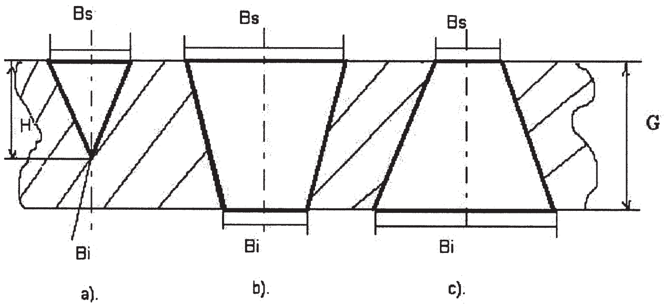

Fig. 2. The typical laser cutting kerfs' geometries a)Partially penetrated cut; b and c) Totally penetrated cut

with a Karl Zeiss Jena laboratory microscope having 0.001 mm accuracy.

Energy consumption ratio Esp, defined as consumed laser energy for the removal of a material unity volume, could be calculated by the following expression:

$$Esp = \frac{P}{Bm \, . \, e \, . \, v} \qquad [\mathrm{J/mm^3}] \qquad (1)$$

where P [w] is the laser average power, Bm = $\frac{Bs+Bi}{2}$ [mm] is the kerfs' average width and v [$\frac{mm}{s}$]is the laser cutting speed.

The individual Esp values were obtained, as shown before, by arithmetic and statistical treatment of measured data concerning kerfs geometry and related operating parameters.

Results and discussions

An adequate treatment of measured experimental data with Statgraphics software provided some significant informational morphologic elements of the developed research. It's about regression polynomial equation, Pareto effects diagrams, response surfaces diagrams and single-factorial classic diagrams. Each of these elements makes a particular description of the laser cutting parameters influence on the energy consumption ratio Esp. Hereinafter, these elements are presented and analyzed.

Final regression polynomial equation in terms of coded factors is:

$$Esp = 97.5034 - 24.5486.D + 9.39038.E - 38.0941.F - 13.9046.DE + \\ + 25.2714.DF - 15.0396.EF \qquad R^2 = 0.97 \qquad (2)$$

where R^2 = 0,97 is the correlation coefficient, D, E and F are direct equation factors, related to actual cutting speed v, laser average power P and material thickness e via some conversion formulae as:

$$D = 0.04v - 3; \quad E = 0.0222P\text{-}5; \quad F = 0.909e - 2.818; \qquad (3)$$

Besides the regression equation (2), the Pareto effects diagram, represented in figure 3 could provide complementary information concerning the influence of laser operating parameters on the Esp function.

Analyzing the regression equation coefficients, become obvious that material thickness, cutting speed and their interaction have a dominant influence on the Esp values. In given conditions, the role of laser average power seems to be negligible. Virtually, Esp reduction is feasible either by growing as much the cutting speed and the material

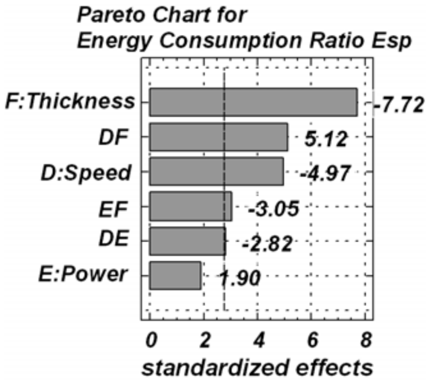

Fig. 3. Pareto effects diagram of energy consumption ratio

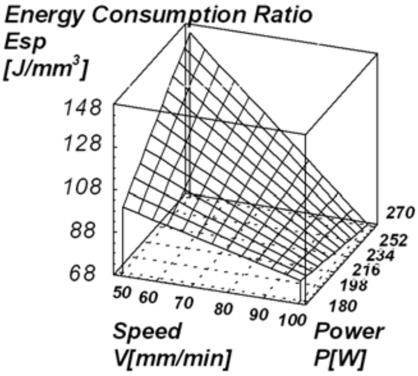

Fig. 4. Response surface diagram Esp = f (v, P)

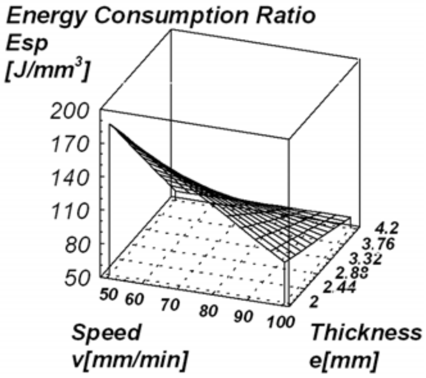

Fig. 5. Response surface diagram Esp = f (v, e)

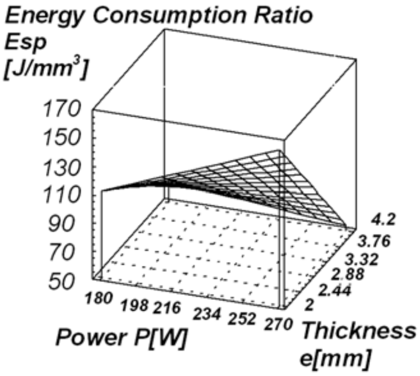

Fig. 6. Response surface diagram Esp = f (P, e)

thickness or by minimizing the laser average power. The Pareto diagram confirms the above facts, but mark additionally a significant threshold for the cutting parameters influence. Only the material thickness, cutting speed and their interaction have a statistically significant influence on actual Esp values.

The response surface diagrams represented in figures 4 to 6 include significant factors interaction and offer new aspects of quantitative correlations between the above analyzed lasers cutting parameters. Firstly, it can be seen (fig. 4) that the laser average power influence is stronger at smaller cutting speeds and mutually, the cutting speed influence on the Esp values is more important at bigger laser average power. Secondly (fig. 5), from the energy consumption ratio point of view, increase in cutting speed is more efficient at small material thicknesses than at bigger ones. On the other hand, to have minimal Esp values, the Nd: YAG laser cutting must be applied to as possible thicker materials. Thirdly (fig. 6), the best energy consumption ratio is obtained for the biggest values of P and e. At high thickness values, the Esp seems to be independent on laser average power.

All the above and other similar reasoning are dependent on laser cutting energetic requirements and on the complex interaction, advanced by figure 3, between laser power, cutting speed and material thickness.

It is now interesting to examine some results of performed classic experiments. Figure 7 highlight a local minimum domain in Esp variation with laser average power. The amplitude and location of this minimum are depending on e, v and δ. A virtually similar situation is obvious in the influence of cutting speed on the energy consumption ratio, as shown in figure 8, but the amplitude and location of this minimum is depending on e, P and δ. In both cases, the laser beam focal plane was displaced inside the material plate with δ = - 2 mm.

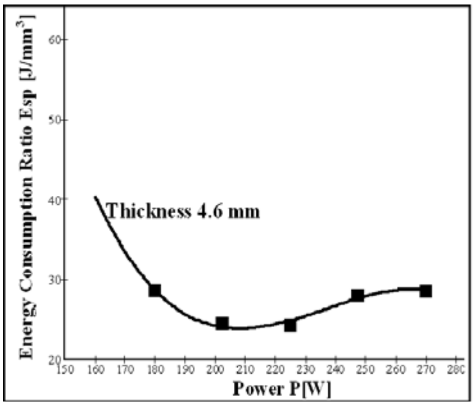

Fig. 7. Energy consumption ratio versus laser average power for v=100mm/min, e = 4.6 mm and δ = -2 mm

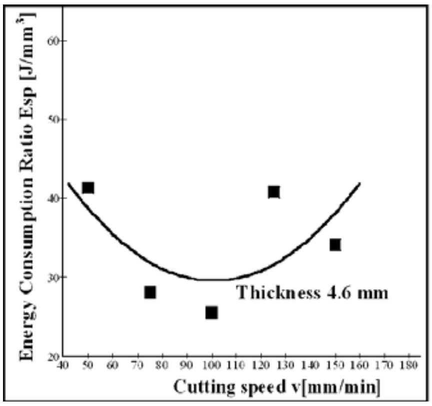

Fig. 8. Energy consumption ratio versus laser cutting speed for P=225 w, e = 4.6 mm and δ = -2 mm

The conventional character of classic single-factorial diagram is well known [7]. However, the curvature of response surfaces represented in figures 4 to 6 suggests the possibility of such local extreme values of energy consumption ratio.

As shown in the introductory part, laser cutting of GFRE materials is state of the art today, but each new application in industrial environment put some important challenging problems. These problems are complex, but could be approached at three elementary levels:

-technologic level, which define the final goals of laser cutting processes, namely part quality, global efficiency and environment protection;

-phenomenological level, which refers to specific energy and mass transformations induced by laser irradiation, able to lead to necessary technologic effects on the produced parts;

-energetic level, which controls the laser cutting process feasibility and stability toward the best available phenomenological and technologic conditions;

The present paper was centered on the third level problems and investigated the influence of laser cutting main parameters on the energy consumption ratio Esp.

For a better understanding of experimental research results it is important to survey some opinions concerning the feasibility and stability of laser cutting processes in the particular conditions of GFRE composite and a pulsed Nd: YAG laser cutting system.

There are 3 indispensable gradual steps in a laser cutting process, namely: 1.laser radiation-material energetic coupling, conditioned by at least partial absorption of laser energy in the irradiate material; 2.through material penetration of laser cutting erosive action, supported by the assistant gas jet; 3. developed laser cutting front stationary propagation along the programmed cut trajectory.

In pulsed Nd: YAG laser cutting of Glass fiber/epoxy composite case, the particular existing problems could be solved as follows. Polymeric and ceramic materials initial low absorbance of $\lambda = 1.06$ μm radiation energy will be compensated by pulsed irradiation and bigger values of pulse energy. The adequate pulsed irradiation will also realize the high values of laser radiation intensity on the material surface needed for a through material penetration. Finally, for a stationary displacement of laser cutting front, a harmonization of significant cutting parameters, described in this paper, have to be ensured.

It is clear that, in above situation, a modulated energy supply suitable to three mentioned steps could be an ideal solution. In industrial conditions, the laser radiation intensity is aligned to the maximal needed values of cutting process and is time independent. The delivered overweight energy is the first important source of laser cutting wasted energy, measured indirectly by energy consumption ratio. This overweight energy could affect also the parts quality.

The second important source of laser cutting wasted energy belongs to third above presented step, the cutting front stationary propagation.

The laser energy supplied to the cutting zone is distributed into two main parts namely: energy used in the cut development and the energy losses from the cut zone in environment. The energy used in cutting is, more or less, independent of the time needed to carry out the cut, while the energy losses from the cut zone are increasing with the cutting duration. Thereby, the energy lost from the cut zone decreases when cutting speed increases and the cutting process energetic efficiency is increasing. Any reduction in cutting speed leads to an increase in the wasted energy and the process becomes less efficient. The levels of conductive loss rise rapidly with increasing material thickness coupled with the reduction in cutting speed [2, 12]. By this way, the similar conclusions presented in the experimental results evaluation were confirmed.

The foregoing results clearly show the significant influence of the laser cutting parameters selection and setting on the technologic performances and energetic efficiency of all laser cutting processes.

Conclusions

In this work, a complex experimental program, including factorial and classic approach, was designed and performed. The main objective of this program was to identify the real factors affecting the energy consumption in pulsed Nd: YAG laser cutting of Glass fiber/epoxy composite. For this purpose, a novel indicator namely the energy consumption ratio was introduced and its correlations with some important laser cutting operating parameters were established.

The applied design of experiments allowed an accurate and intuitive presentation of these correlations as regression polynomial equation, Pareto effects diagram, response surfaces diagrams and single-factorial classic diagrams.

A systematic analysis of experimental results point out the particular hierarchy and the multiple interconnections of main laser cutting parameters. On this basis, a discussion about technologic, phenomenological and, with a special emphasis, energetic levels of laser cutting was realized. So, the validity of obtained experimental results was confirmed. Finally, some possible measures for the energy consumption reduction in pulsed Nd: YAG laser cutting of Glass fiber/epoxy composite were proposed.

Future researches concerning the energy consumption must be oriented toward an in-depth integration of technologic, phenomenological and energetic levels in all laser cutting processes analyze and evaluation.

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