# PHYSICAL SEQUENTIAL MODELS FOR LASER CUTTING

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ABSTRACT: Laser cutting of composite materials requires improving physical models applied to laser cutting process. In setting of machining parameters knowledge of physical phenomena occurring in the material plays important role. Material penetration, cutting front stabilization origin and propagation of cutting material are stages in attaining laser cutting. It shows an association of processing parameters (power, cutting speed) with these stages. Laser beam intensity and interaction time between laser radiation and material are sizes that show the physical phenomena occurring in the material. The paper presents an application for cutting of composite materials. There was considered a similar theoretical treating of thermal fracturing of the material with phase transformation. Power and cutting speed are technological parameters set for laser cutting. The relationship between these parameters in the physical and technical conditions partial determined was studied.
KEY WORDS: laser cutting, composite materials, thermal decomposition of the material.

## 1. INTRODUCTION

Knowing the physical phenomena occurring at laser cutting has practical importance in setting the processing parameters. Industrial lasers had a great development in recent years. These devices allow control of several parameters and processing conditions are not always reproducible from one application to another. In this context, understanding the conditions for phase transformation and removal of the material id important. They may become common points for machining using different laser beam and workpieces of different thicknesses. The quantitative aspect of physical phenomena and their order of magnitude are reflected in the parameters used and the qualitative aspect of cuts. Exclusion of physical phenomena that do not affect processing parameters and considering some phases of laser cutting process (sequences) are elements that lead to a physical modeling for laser cutting.

Laser cutting polymer matrix composite materials are an area with wide applicability. The characteristics of these materials are very different, sometimes for the same material. Thus, models are necessary to highlight comparable elements for laser cutting process.

The effect of process parameters (laser power and cutting speed) have been the subject of several experimental studies. In Duphal (2008) [1], laser cutting of cylindrical parts of alumina ($Al_2O_3$) using laser Nd:YAG was studied. In Huang (2010) [2], the use of $CO_2$ laser for making PMMA semi finished products for the electronics industry was investigated. In Eltawahni (2010) [3], it is shown an experiment for optimization of polyethylene laser cutting with $CO_2$ laser. In Kurt (2009) [4], cutting of several types of polymeric materials used in engineering using $CO_2$ laser was studied. Huehnlein (2010) [5] presents an experimental study for laser cutting of thin plates of alumina $Al_2O_3$ using a Nd:YAG laser with a power of 500 W and a $CO_2$ laser 200 W power. Davim (2008) [6] studied laser cutting for PMMA using $CO_2$ laser. Choudhury (2010) [7] investigated laser cutting of three polymeric materials PP (polypropylene), PC (polycarbonate) and PMMA (polymethyl meta acrylate). There have been varied laser power, cutting speed, and the pressure of the assistant gas (air). As objective functions, the size of the heat affected zone (HAZ), surface roughness and compliance with dimensions of the piece were studied. Yang (2010) [9] presents experiments which aimed fracturing several layers of glass with a thickness of 2.5 mm. In the experiments, power between 50-300 W and cutting speed of 3-19 mm /s, laser beam diameter between 2.5 and 5 mm were used. There have been used several positions of the focal plane relative to the workpiece surface. It has been shown that the radiation from the $CO_2$ laser is absorbed at workpiece surface, and the laser radiation emitted from the Nd: YAG laser is absorbed in the interior of the workpiece. Yamamoto

(2010) [8] presents controlled cracking of the glass using a $CO_2$ laser. Wang (2007) [10] showed cleavage experiments for glass plates named "soda-lime glass". There was used a cylinder lens to form an elliptical spot with the large axis of and small axis 15 mm by 0.7 mm. A power of 42 W and a cutting speed of 5000 mm/min were used. In experiments, the glass surface was rotated relative to the laser beam. Thermal cycle and conditions for obtaining glass fracturing were modeled with ABAQUS software. Laser cutting experiments for glass are presented in works elaborated by Nisar (2009) [11], Nikumb (2005) [12], Mitsuishi (2008) [13], Kuo (2008) [14], Jiao (2008) [15] and Jiao (2009) [16].

Caiazzo (2005) [17] presents a cutting process with $CO_2$ laser of 1.5 kW maximum power for thermoplastic polymeric materials such as polyethylene (PE), polypropylene (PP) and polycarbonate (PC). Yung (2007) [18] developed experiments for laser drilling using Nd:YAG laser for a composite material - epoxy / aluminum nitrite.

These experimental studies are useful in understanding the laser cutting of glass fiber reinforced resin.

In this paper, we will present a theoretical approach to laser cutting process applicable to laser cutting of composite materials.

## 2. STAGES IN LASER CUTTING

Construction of a sequential model of laser cutting means a combination of physical phenomena related to any particular event. It is considered that the laser cutting process has three stages (fig. 1):

- Penetration of the material;
- Stabilization of the cutting front;
- Propagation of cutting front into material.

**Material penetration**. Material penetration is given by the conditions of irradiation, intensity of the laser beam at the workpiece surface and the interaction time between the laser radiation and material. These parameters are controlled by the laser power and cutting speed. Assistant gas role is neglected at this stage. Material penetration is due to the change of the aggregate state. The material loses its solid state. There are two important ways in which this is done:

- In a single step - by evaporation, ablation or chemical decomposition of the material;
- In two steps - with the formation of a melt. In this case, the molten material acts like a heat source independent from the laser beam. It radiates as molten material.

**Stabilization of the cutting front.** This means the possibility of evacuation decomposed material and formation of kerfs in the material. At this stage, laser beam irradiation is considered not at the workpiece surface, but at zone of intersection between the cutting front and laser beam. Irradiated surface increases and defocusing depth appears as an important parameter; this is the distance between the focal spot and the workpiece surface.

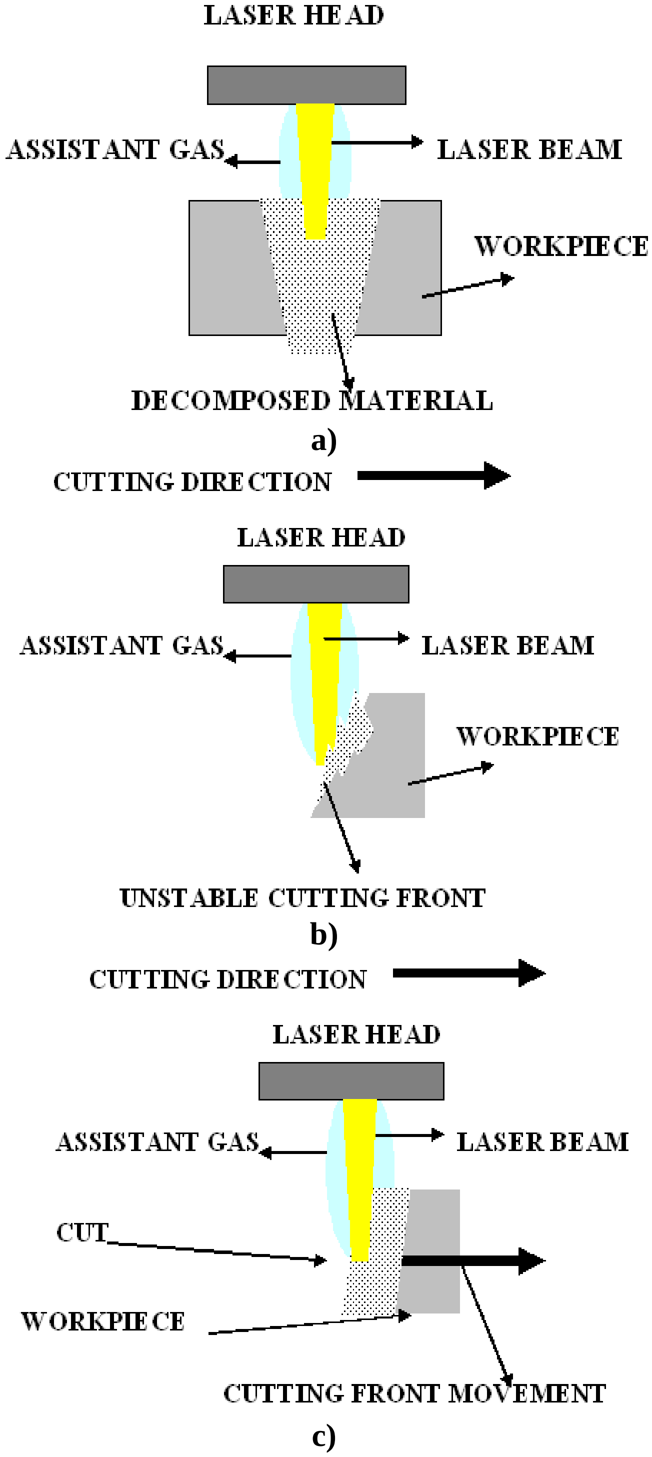


**Figure 1.** Laser cutting process steps: a - material penetration; b - cutting front stabilization; c - propagation of the cutting front into the material

**Propagation of cutting front into material**. This means creating conditions that cutting front to be moved through material following laser beam. At this stage, the assistant gas has an important role. Laser cutting resin reinforced with fiberglass takes place by thermal decomposition of the material. This means a model in one step. In the following, we present the physical aspects of material decomposition.

**The burning of the polymer matrix.** Burning epoxy resin is the first effect of the laser radiation and at workpiece surface temperature of 490°C is obtained. Burning resin will give to exothermic contribution to process; the heat of reaction will be added to that provided directly by the laser beam. This explains the lower level of power used for laser cutting than specific values of other metallic materials and ceramic materials. The oxygen from air used as the gas assistant will support the reaction of burning material.

**The fracturing of the glass fiber**. Thermal fracturing of the glass fibers occurs due to the temperature difference and the thermal stress developed in the material caused by it. Localized fracturing of glass fiber determines mass erosion of the material to be cut and thus the feasibility of laser cutting process could be considered as a whole. The existence of this phenomenon leads to easier obtain the material decomposing and the ability to perform cutting.

**Softening glass fiber.** Loss of glass fiber stiffness occurs at temperature of 846 °C (or between 800 °C and 860 °C). This phenomenon is important because loss of stiffness of glass fiber lead to the failure of its breaking glass in solid state.

**Melting of glass fiber and warming polymer material by glass fiber**. These two physical phenomena have a secondary role in obtaining material penetration. The melting of the glass fiber is obtained on the inner surface of the cut. This requires a energy higher than that for glass fiber breakage. Conduction of heat through the glass fiber favors conditions for burning the polymer matrix around the glass fiber. This leads to fiber glass ends at material surface that will give an irregular inner surface of the cut.

## 3. THERMAL MODELS

Laser cutting of the composite material is performed by decomposition of the material. This instance means a fracture of glass fiber and resin burning. The cut is formed in the area where into material there is a loss of mechanical strength and assistant gas can remove the cut material. In the following, there is presented an estimation of the effects of a heat on material surface that generates heat flux density able to produce burning of resin and decomposition of the fiber glass.

The absorption of the laser radiation is produced in a thin layer from the surface of the material.

In order to analyze the thermal effects that occur in the material, there is considered a heat source with heat flux density q [W/cm$^2$], which is equivalent to the laser beam absorbed.

For the main component of glass fiber $SiO_2$ at radiation with a wavelength of 10.6 μm, the absorption coefficient is 0.8. Applying relations presented in Rykalin (1978) [21], we present the following estimations:

**- Heat flux density q necessary to produce the ignition temperature of the polymer matrix.**

It is considered that there is a gradual warming into polymer matrix without producing the material phase transformations. The evolution of the temperature at workpiece surface is given by:

$$q = \frac{0.885\, k_e\, T}{\sqrt{a_e t}} \text{ [W/cm}^2\text{]}, \tag{1}$$

where:

$k_e$ is thermal conductivity of the epoxy resin, $k_e$=0.35 W/m K;

$a_e$ - thermal diffusivity of the epoxy resin $0.18\cdot10^{-6}$ m$^2$/s.

At temperature T= 490 °C, material combustion takes place. It is considered a higher value of temperature for which resin combustion is complete and that there is an association between burning and removing material (cut formation) (T= 550° after Nasedkin, 1999) [19].

**- Heat flux density necessary to thermo mechanical fracturing of glass fiber.**

The breaking of the glass fiber when it is applied on a constant heat flux density is the result of a thermo-mechanical phenomenon, which can be treated similar to a phase transformation of the material. This is achieved by equivalence of breaking material with energy needed to heat the material in a phase transformation. The following relationships are obtained:

$$q = \sigma \cdot u \text{ [W/cm}^2\text{]}, \tag{2}$$

where:

u [cm/s] is the speed of breaking propagation into fiberglass;

$\sigma$ [ MPa]- breaking tension.

**Heat flux density level required breaking glass fiber.** The minimum amount required is that which ensures breakage of the glass fiber in time of laser pulse and it can be calculated by the formula:

$$q_1 = \sigma \frac{z}{t_p} \text{ [W/cm}^2\text{]}, \quad (3)$$

where z is the thickness of the glass fiber.

Heat flux density $q_1$ for fiber fracturing with $z = 0.1$ mm thickness is calculated in table 1.

Estimation of heat flux density for the glass fiber breakage takes place at full speed during the laser pulse is done by the relationship Ready (1997) [20]:

$$q_2 = \sigma \sqrt{\frac{a_s}{t_p}} \text{ [W/cm}^2\text{]}, \quad (4)$$

where:

$a_s$ is glass fiber thermal diffusivity, $a_s = 0.34\,10^{-6}\, m^2/s$ (for various types of glass, there are considered approximate values 0.5-0.88 $10^{-6}\, m^2/s$);

breaking tension $\sigma = 3500$ MPa.

The results obtained for $q_1$ and $q_2$ are reproduced in table 1.

**Table 1**. Heat flux density for material disintegration.

| **Interaction time $t_p$[ms]** | **q [W/cm$^2$ × 10$^3$]** | **$q_1$ [W/cm$^2$ × 10$^3$]** | **$q_2$ [W/cm$^2$ × 10$^3$]** |
|---|---|---|---|
| 96.09 | 1.29 | 0.36 | 0.65 |
| 128 | 1.12 | 0.27 | 0.57 |
| 191.61 | 0.91 | 0.18 | 0.46 |

From the table 1, it is observed that the heat flux density to get the burning of resin is superior to that corresponding to fracture the glass fiber for both ways of calculation. This shows that the burning of the resin is compatible with the destruction of the glass fiber by fracturing.

The intensity of the laser beam absorbed by the material in the case of the $CO_2$ laser beam is used to exceed at least one order of magnitude to obtain the required value for the burning the resin.

It looks so that the real interaction time for continuous irradiation is too big to be associated with a particular phenomenon burning resin or glass fracturing fiber. Assuming that successive layers of material irradiated participate, interaction time decreases and increases the heat flux density, but the relative relationship between heat flux density levels remains the same.

## 4. EXPERIMENTAL STUDY

For laser cutting of composite materials most information is provided by cut width. The cut width was measured to the top of workpiece $B_f$ [mm] and to the bottom of the workpiece $B_v$ [mm]. It has been calculated the average cut width $B_m$ [mm]. Cut width variation was studied by means of average power. It was analyzed cutting for thin plate, respectively for thick plate. Modeling the variations in cut width was performed using the regression function.

Figure 2 shows the variations for cut width for a thin plate with thickness of 1.5 mm. Here the laser beam was focused on the workpiece surface.

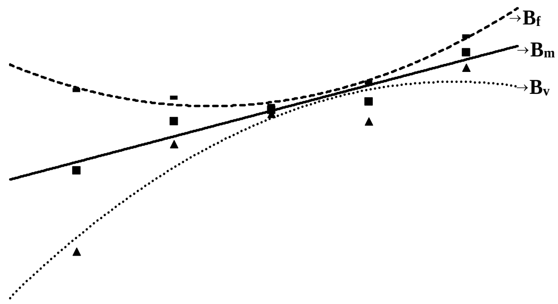


**Figure 2.** Variation of cut with power at cutting speed 3.33 mm/s, plate thickness 1.5mm, focusing at piece surface

Regression models with functions and correlation coefficient associated with cut with variations from figure 2 are given by the relations:

$$B_f = 6.2003968 \cdot 10^{-5} P^2 - 0.017936508\, P + 1.8964762\, ; R^2 = 0.9749 \quad (5)$$

$$B_v = -6.5448633 \cdot 10^{-5} P^2 + 0.023647487\, P - 1.5049841\, ; R^2 = 0.8956 \quad (6)$$

$$B_m = 0.0023263889\, P + 0.235666; R^2 = 0.9102 \quad (7)$$

It is noted that in the central part of the experimental field for power, straight cuts are obtained. At high values of power, it is observed a decrease of cut width at the bottom and an increase of the cut width at the top. This shows a decrease in penetration of material. The explanation for this situation is that with increasing power, the glass fiber softens and can not be fractured. The radiation is not sufficient to melt the glass. In cases of non-penetrative or distorted cuts, glass deposits were observed. Burning resin provides enough energy to melt glass. But the melt must be heated to have a low viscosity and to be removed from the kerf. In other words, the presence of molten glass produces unfavorable conditions for cutting performance.

Figure 3 shows the variation of cut width for thick plate. Focusing the laser beam was performed under the workpiece surface. It is noted that the cuts are wider at the top than at the bottom of the plate. Cut shape is maintained all over the experimental field of power variation. At higher powers, there is an increase in the bottom cut width. This shows a favorable situation for fracturing glass fiber.

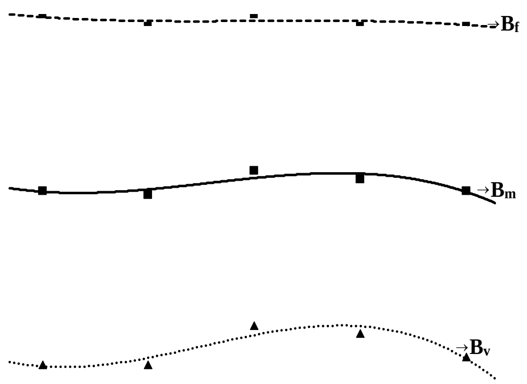


**Figure 3** Variation cut width power at cutting speed 1.67 mm/s, plate thickness 4.6mm focusing at 2 mm below the workpiece surface

Regression models with functions and correlation coefficient associated with cut width variations from figure 3 are given by the relations:

$$B_f = -2.7908165 \cdot 10^{-7} P^3 + 1.7682613 \cdot 10^{-4} P^2 - 0.037287809 P + 3.71091; R^2 = 0.4167 \quad (8)$$

$$B_v = -1.9535715 \cdot 10^{-6} P^3 + 1.1964469 \cdot 10^{-4} P^2 - 0.24216545 P + 16.878395 ; R^2 = 0.8539 \quad (9)$$

$$B_m = -1.1163266 \cdot 10^{-6} P^3 + 6.8663654 \cdot 10^{-4} P^2 - 0.13972663 P + 10.294654 ; R^2 = 0.7256 \quad (10)$$

A case where the cut is not completely penetrated does not offer a comparable situation to penetrate cuts for top cut width. There is an increase in width of the groove (or top cut width for unpenetrated cut), because of decomposed material, which is removed on top of piece. The study of cut width shows the cumulative effect of the three stages of laser cutting.

It has been shown that the laser power can be linked to the qualitative aspect of the physical phenomena that take place in the material. This is directly related to the step of laser cutting, providing a penetration of the material. Cutting speed is related to the stabilization of the front cutting and give the order of magnitude of the physical phenomena that take place in the material. Assistant gas has a significant effect on the stabilization front cutting.

## 5. CONCLUSIONS

We presented the elements that lead to understanding of physical phenomena that take place in the laser cutting resin reinforced with fiberglass.

Control and optimization of the laser cutting process may be carried out by associating each parameter with one of the stages of the laser cutting process. Such a parameter effects are more predictable than for association with the whole process. For example, experimental research for irradiation conditions (laser beam intensity and interaction time between the laser radiation and material) may be associated with material penetration. The pressure of the assistant gas jet may be associated with stabilization of cutting front. In establishing of its important role, there is used a relationship between cut width at the top of the piece and cut width at the bottom of the piece. Setting the cutting speed can be associated with cutting front propagation on material.

For research related to physical conditions in which the laser cutting process takes place, one can express following findings:

- Laser cutting of the composite material of glass fiber-reinforced resin is made by burning of the polymer matrix and fracture of the glass fiber.
- The conditions under which these phenomena are controlled are achieved mainly by average laser power transmitted to cutting workpiece.
- Softening and melting of glass fiber as induced phenomena in given conditions by laser irradiation can cause:
- reducing the possibility of glass fiber fracture;
- blocking the cut with solidified deposits of molten glass;
- achieving an incomplete cutting process.
- The irradiation conditions used do not allow removal of the glass in a molten state.
- Low cutting speed, in combination with the reduced thickness of the piece, results in the transmission of heat through glass fiber and resin combustion around the glass fiber, resulting large and irregular heat affected zones.

Modeling thermal phenomena occurring into material is difficult for resin reinforced with fiberglass because of inhomogeneous structure of the material.

Glass fiber length has a significant influence. Heat is driven by glass fiber increasing thermal damage to the material.

For cutting of the plates of material type composite resins reinforced with glass fiber, intensity of the laser beam of the order of $10^7$ W/cm$^2$ and duration of laser-material interaction of order $10^{-3}$s are required. At experimental level, there was revealed influence of the laser beam power on the cut width. The variation was expressed by means of regression functions models. As further research, there was proposed to specify parameters for each stage of the cutting process and adequate setting of their values. It is also proposed to apply thermal models for heterogeneous materials.

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