Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume IV, 407-411

Modeling the Penetration Depth During Laser Marking of Layered Reinforced Composites with a Polymer Matrix

Simeon Tsenkulovski
Dep. "Mechanical Engineering and Instrumentation"
Technical university of Gabrovo
Gabrovo, Bulgaria
s.tsenkulovski@advanced-technology.eu

Petko Naydenov
Department of Management
Technical University of Gabrovo
Gabrovo, Bulgaria
petkonaydenov@abv.bg

***Abstract*— The paper studies the penetration depth of the laser radiation during marking of layered reinforced composite materials with a polymer matrix. The generated radiation is from Fiber laser – RFFL-P-502B. The study of the marking depth was carried out on a measuring microscope using Insize ISD-V150/V250/ V300 software. To derive the mathematical model of the process, a cybernetic scheme with two input factors and one objective function was used. The output power of the laser radiation – P=5÷45W and the marking speed – V=50÷250 mm/s were selected as input quantities. The penetration depth – δ[µm] was the objective function. Based on the derived mathematical models, graphical dependencies in two and three coordinate systems are presented. A dispersion analysis was conducted based on mathematical models and graphical relationships are presented for the influence of the laser beam power and marking speed on the depth of the marking stroke.**

Keywords*— *dispersion analysis, fiber laser, llayered composites, marking depth.

I. Introduction

The ever-increasing dynamics of change is one of the few constant characteristics of the reality surrounding us. Technological innovations in industry are continuous and comprehensive. The developing directions of "Industry 4.0" lead to the dynamic development of unconventional electrical technologies, powder metallurgy and other energy-saving technological processes [1] - [4]. New electrothermal technologies enable the processing of new materials (essential for the development of the electrical industry, electronics, medicine and other sectors of the economy) with increased operational properties, extended life and increased reliability. The laser marking process as part of electrophysical technologies is massively entering the production of metal products and tools, semiconductor devices, glass and ceramic products [5] - [7]. In recent years, it has also become increasingly widespread in marking non-metallic materials used in industry, as an alternative to traditional marking methods [8] - [12]. This is an innovative method that differs greatly from marking in any other way, without the use of consumables, no chemicals, no ink ribbons or other materials are needed. When laser systems are used for marking, the surfaces of the products are processed extremely accurately, qualitatively, quickly and with clear contours by the laser beam. Laser marking is a non-contact effect on the structure of the processed material, the result of which is obtaining a permanent contrast image. Information can be applied to the surface of the product with this method in the form of inscriptions, identification symbols (letters and numbers), bar codes – fig.1.a, matrix codes (2D) – fig.1.b, special characters, serial numbers, images, decoration, etc.

a. b.

Fig.1. Marking codes: a – matrix; b – 2D.

In practice, with the help of a laser, it is possible to very easily create an arbitrary image of one's own design. The quality of this image is directly dependent on both the type of workpiece being processed and a number of technological factors affecting the contrast of the image, as well as the type of laser source used. The purpose of the present study is to determine the penetration depth during laser marking of layer-reinforced composites with a

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol4.8438

polymer matrix. Based on the experimental results obtained, mathematical models of the technological process are developed and a dispersion analysis is performed for the influence of the input variables (laser radiation power and marking speed) on the objective function (marking depth).

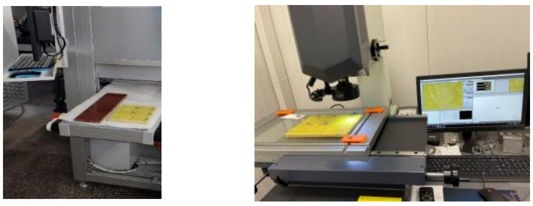
II. MATERIALS AND METHODS

In this study, two types of samples of textolite and glass textolite were used. The textolite samples are 10mm thick – Fig. 2.a and mechanical characteristics according to DIN 7753/ PFCC 202, and IEC 60893 Hgw 2082. The textolite is a composite material based on phenolic laminate with cotton fabric. Due to the higher density of the cotton fabric, the composite has good dielectric and mechanical properties, The glass textolite samples are type PTGC 201 with a thickness of 10mm – Fig. 2.b and mechanical characteristics according to IEC/EN 60893-3-1. This is a glass fiber phenolic laminate, in which glass fibers or glass fabrics are used as a filler. Epoxy resin is used as a binder. To increase the vibration and chemical resistance of the material, some of the glass fibers have been replaced with polyester fibers.

a. b.

Fig.2. Marked samples: a – textolite and b – glass-textolite.

The marking of the samples was done using a laser installation – Fig. 3,a, based on Fiber lazer – RFFL-P-502B. Its main technological characteristics are presented in Table 1.



a. b.

Fig. 3 Equipment, a – marking, b - measuring

TABLE 1. CHARACTERISTICS OF THE LASER INSTALLATION

№	Items	Unit	Standard Value	Variation Step
1.	Output Power	w	5÷50	25
2.	Frequency	kHz	50÷100	25
3.	Marking Speed	mm/s	1÷2000	1000
4.	Defocusing	+/- from the focal length		
5.	Focal spot	µm	37÷42	1

The depth of the marking was examined using a measuring microscope – Fig. 3.b, using Insize ISD-V150/V250/V300 software.

III. RESULTS AND DISCUSSION

The main technological parameters in laser marking of layered composite materials on a polymer basis are the marking speed and the output power of the laser unit. To derive the mathematical model of the process, a cybernetic scheme with two input factors and one objective function was used. The input factors and the factor space were selected on the basis of preliminary experiments [6], [10] and analysis of literature sources [7], [14], [15]. In it, the output power of the laser radiation – X1, and the marking speed – X2 were selected as input quantities. As objective functions, the penetration depth – Y1 for glass-textolite samples and - Y2 for textolite samples was studied. The studies were conducted at constant values of: θ the frequency of the laser pulse – f = 50kHz; θ the inclination of the raster – α = 0º; θ defocus – S = 0mm; θ marking repeatability – R = 1. θ wavelength – λ= 1064 nm; θ focal spot diameter - df = 40µm The main levels and ranges of variation of the input quantities are presented in Table 2.

TABLE 2. FACTORS VARIATION

Factors levels	X_1, P, W	X_2, V, mm/s	Coded value
$X_{i0} + \Delta X_i$	45	250	+1
X_{i0}	25	150	0
$X_{i0} - \Delta X_i$	5	50	-1

At the values fixed in Table 2, marking strokes were made, and their depth was measured. The results obtained are plotted in the experimental plan - Table 3.

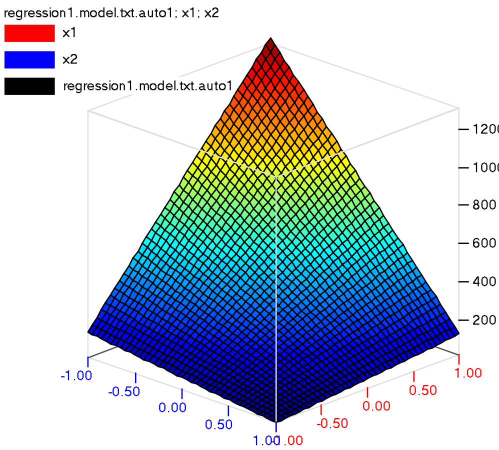
TABLE 3 EXPERIMENT PLANS

№	X_0	X_1	X_2	$X_1 X_2$	X_1^2	X_2^2	Y_1	Y_2
1	+1	+1	+1	+1	+1	+1	281	182
2	+1	-1	+1	-1	+1	+1	31	18
3	+1	+1	-1	-1	+1	+1	1440	818
4	+1	-1	-1	+1	+1	+1	160	91
5	+1	+1	0	0	+1	0	469	273
6	+1	-1	0	0	+1	0	52	30
7	+1	0	+1	0	0	+1	156	91
8	+1	0	-1	0	0	+1	800	455
9	+1	0	0	0	0	0	260	152

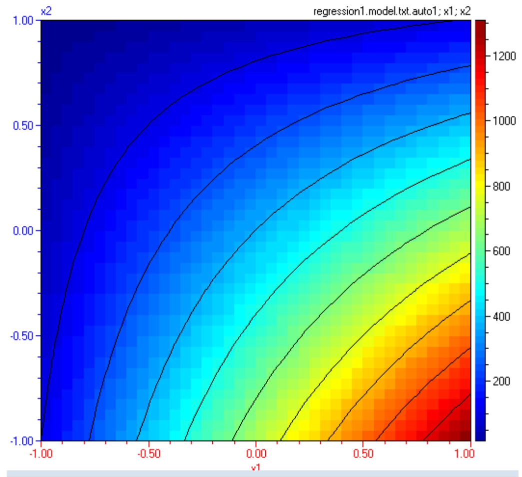
The processing of the obtained results for the investigated objective function – Y1, leads to the determination of a linear regression equation of type 1, and for Y2 – 2

$$Y_1 = b_o + b_1x_1 + b_2x_2 + b_{12}x_1x_2 \quad (1)$$

$$Y_2 = b_o + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + b_{11}x_1x_1 \qquad (2)$$



a.



b.

Fig.4.Graphic presentation of $Y_1 = f(X_1, X_2)$
a- tridimensional; б – bidimensional

The coefficients of the regression equation are calculated by 3, 4 and 5 [7], [14], [15]. The obtained values are shown in Table 4.

$$b_0 = d_1 \sum_{u=1}^{N} x_{0u} Y_u + d_2 \sum_{i=1}^{m} \sum_{u=1}^{N} x_{iu}^2 Y_u \qquad (3)$$

$$b_i = d_3 \sum_{u=1}^{N} x_{iu} Y_u \qquad (4)$$

$$b_{ij} = d_4 \sum_{u=1}^{N} (x_i x_j)_u Y_u \qquad (5)$$

TABLE 4 REGRESSION COEFFICIENTS

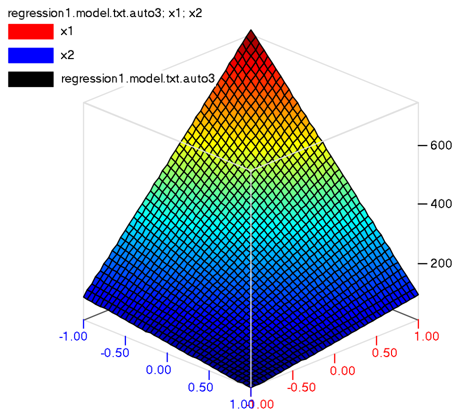
b	b_0	b_1	b_2	b_{12}	b_{11}
Y_1	405,444	324,500	-322,00	-257,50	-
Y_2	232,667	189,000	-178,83	-140,75	2,667

Based on the obtained values in Table 4, the regression equations for glass textolite and textolite, respectively, 6 and 7, have been derived.

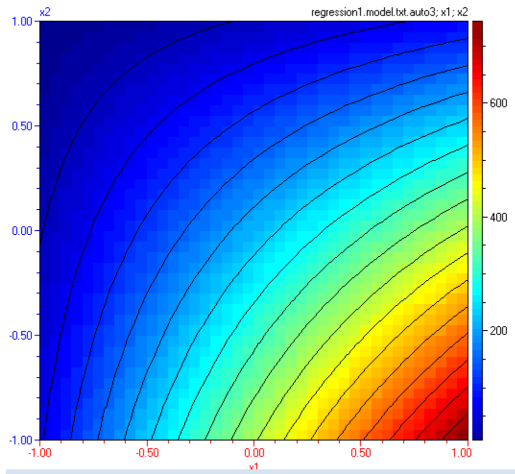
$$Y_1 = 405{,}444 + 324{,}500X_1 - 322{,}000X_2 - 257{,}500X_1X_2 \qquad (6)$$
$$Y_2 = 232{,}667 + 189{,}000X_1 - 178{,}833X_2 - 140{,}750X_1X_2 + 2{,}667X_1X_1 \qquad (7)$$

Fig. 4 and Fig. 5 present the graphical dependencies of the derived regression equations in three-dimensional and two-dimensional coordinates.

When conducting the analysis of variance of the obtained mathematical models, the computer program AnoVA was used. Its results for the penetration depth for glass-textolite samples are presented in Fig. 6, and for textolite samples in Fig. 7.



a.



b.

Fig.5.Graphic presentation of Y2 = f (X1, X2).a- tridimensional, b – bidimensional

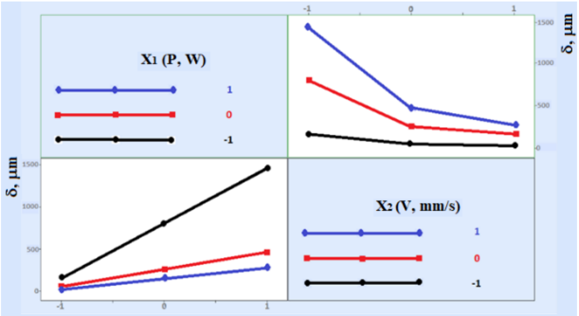


Fig.6.Dispersions analysis of $У_1 = f(X_1, X_2)$.

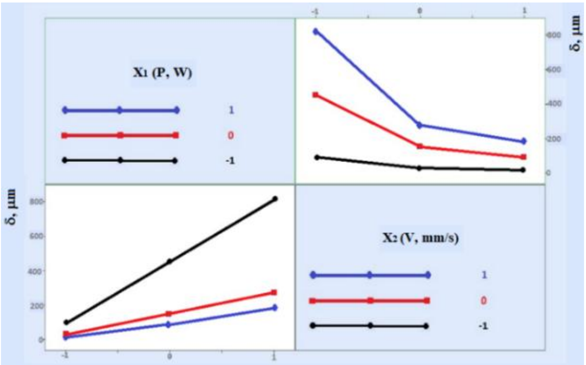


Fig.7.Dispersion analysis of $У_2 = f(X_1, X_2)$

IV. CONCLUSIONS

From the conducted research and the results obtained, we can formulate the following more important conclusions:

- The penetration depth during laser marking of layered reinforced composite materials with a polymer matrix (textolite and glass-textolite) with a thickness of 10mm was studied.
- When building the mathematical models, the laser radiation power – P = 5÷45W, and the marking speed – V = 50÷250 mm/s were selected as input factors. The laser beam penetration depth – δ,µm was studied as an objective function.
- The regression equations for the studied objective functions were derived and checked for adequacy. Graphical dependencies in two and three coordinate systems of the objective functions were constructed depending on the laser radiation power – P, W and the marking speed – V, mm/s.
- Based on dispersion analysis, graphical dependences for the change in the marking depth depending on the power of the laser radiation and the marking speed have been derived. From them, with a sufficient degree of accuracy, the penetration depth of the radiation - δ,µm, in the two studied composite materials can be determined.
- It has been proven that the maximum marking depth is achieved at the studied maximum power - 45 W and minimum marking speed - 50 mm/s. For glass textolite samples it is about 1500 µm, and for textolite samples it is about 800 µm

REFERENCES

[1] D. Petrova, B. Vlahova, A. Lengerov,Tz. Zlateva-Petkova, “Improvement of Constructive-Technological Approaches Reducing Innovative Obsolescence of Industrial Technologies in the Context of Industry 4.0”, presented at the 14th International Scientific and Practical Conference on Environment, Technology, Resources, ETR 2023, Rezekne, Latvia, June, 2023, Volume I, pp. 180–186.

[2] D. Petrova, B. Vlahova, A. Lengerov, Tz. Zlateva-Petkova, “Study of the State of Innovation Development and Obsolescence in the Republic of Bulgaria of Companies from the Mechanical Engineering Sector”, presented at the 14th International Scientific and Practical Conference on Environment, Technology, Resources, ETR 2023, Rezekne, Latvia, June, 2023, Volume I , pp. 187–194.

[3] D. Petrova, N. Nikolova, A. Lengerov, “Modeling business process reengineering in the digital era of industry 4.0”, presented at the 11th International Scientific Conference “TechSys 2022” – Engineering, Technologies and Systems, 2022, pp. 070013-1 - 070013-7.

[4] D. Petrova, “Innovative Obsolescence in Mechanical Engineering and Singleness of Indicators”, presented at the 15th International Scientific and Practical Conference on Environment, Technology, Resources, ETR 2024, Rezekne, June 2024, Vol. 3, pp 221 – 224.

[5] G. Karlovski et al., “Selection of Instrumentation Based on Statistical Analysis”, presented at the 32nd International Scientific Symposium “Metrology and Metrology Assurance”, MMA 2022, Sozopol, 7-11 September 2022.

[6] S. Tsenkulovski, I. Mitev “Influence of the Parameters of the Lasser marking process of the depth of penetration in layer-reinforced composites”, presented at the 15th ISPC “Environment Technology Resources”, V.Turnovo, Bulgaria, 27 and 28 06.2024, Vol. 3, pp 319-324.

[7] I. Mitev, “Determining the diffusion coefficient in simultaneous saturation with boron and carbon austenite alloyed with cooper in powder metallurgy structural materials”, presented at AIP, vol. 2980, 2024, p.060016-1÷060016-7.

[8] L. Lazov, Hr. Deneva, P. Narica, Laser Marking Methods, Rezekne Higher Education Institution (Rēzeknes Augstskola), Rezekne ,2015.

[9] C. Leone C et al., “Wood engraving by Q-switched diodepumped frequency-doubled Nd:YAG green laser.”, Optics and Lasers in Engineering, 2009, Vol. 47(1), pp. 161–168.

[10] I. Mitev, S. Tsenkulovski, “Local Processing of Non-Metal Materials with Concentrated Energy Flow”, presented at the 14th International Scientific and Practical Conference on Environment, Technology, Resources, ETR 2023, Rezekne, Latvia, June, 2023, Volume 3, pp.183÷186.

[11] J. Peter et al., “Parametric analysis of Nd: YAG laser marking on ceramics.” International Journal of Manufacturing Technologies and Management, 2011, Vol. 24(1-4), pp. 124–138.

[12] A. Petutschnigg et al., "Laser treatment of wood surfaces for ski cores: an experimental parameter study.", Advances in Material Science and Engineering, 2013, vol.11, pp. 1-7.

[13] Y. Shin et al., "Pit and rim formation during laser marking of acrylonitrile butadiene styrene plastic.", Journal of Laser Applications, 2005, Vol. 17(4), pp. 243–246.

[14] I. Alexandrova, Fundamentals of engineering research, Vasil Aprilov University Publishing House, Gabrovo, 2003.

[15] I, Mitev, "Optimizing the quantity of liquid phase at the sintering of powder construction materials from system Fe-Cu-Sn" presented at AIP, vol. 2980, 2024, p.060017-1÷060017-7.