



PENETRATION DEPTH IN LASER MARKING OF COMPOSITE MATERIALS WITH TEXTILE REINFORCEMENT PHASE

Simeon Tsenkulovski*

Technical University of Gabrovo, 5300 Gabrovo, Bulgaria

ARTICLE INFO

Article history:

Received 30 April 2025

Accepted 29 May 2025

Keywords:

laser marking, composite materials with phenolic matrix and textile reinforcing phase

ABSTRACT

This publication investigates the influence of the technological parameters of the laser marking process on the penetration depth of the laser beam in composite materials based on phenolic laminate with a textile reinforcing phase. Studies was conducted at the output power of the laser radiation - $P=5\div50$ W, marking speed - $V=50$ mm/s and pulse frequency - $f=50$ Hz. A graphical dependence of the obtained experimental results in comparison with the theoretical values is presented.

© 2025 Journal of the Technical University of Gabrovo. All rights reserved.

1. 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 [7].

The laser marking process in recent years, as part of electrophysical technologies, has entered the mass production of metal products and tools, semiconductor devices, glass and ceramic products [5, 6, 8, 16, 17]. It is becoming the norm for most manufacturing areas, as it offers several advantages, such as [1, 8, 12]:

- non-contact operation;
- high repeatability;
- high scanning speed;
- marking width comparable to the size of the laser spot;
- high flexibility;
- high process automation, etc.

Due to the need for identification in the above-described industries, laser marking has found increasing practical application in recent years [14]. It is the preferred method for achieving permanent and highly contrasting surface inscriptions, both on metal [6, 11, 13, 20, 21] and on a wide variety of non-metallic materials, ranging from glass [4], ceramics [9, 15, 16, 17], organic materials [2, 3, 5, 10, 18, 19], etc. The quality of the resulting marking depends on many factors [8]:

- marking geometry;
- heat affected zone expansion;
- presence of microcracks;

- durability under severe operating conditions;
- legibility, etc.

From the literature [13, 20, 21] it is found that the main technological parameters influencing laser marking are:

- average power;
- scanning speed (i.e. marking speed);
- pulse frequency, etc.

In this study, the influence of the output power of the laser installation on the depth of the resulting marking on composite polymer samples reinforced with textile fibers was monitored.

2. RESEARCH MATERIALS AND METHODS

In this study, 10mm thick textolite samples with mechanical characteristics according to DIN 7753/PFCC 202 and IEC 60893 Hgw 2082 - Table 1 were used. They are based on phenolic laminate with a reinforcing phase of cotton fabric, which due to its higher density has good dielectric and mechanical properties,

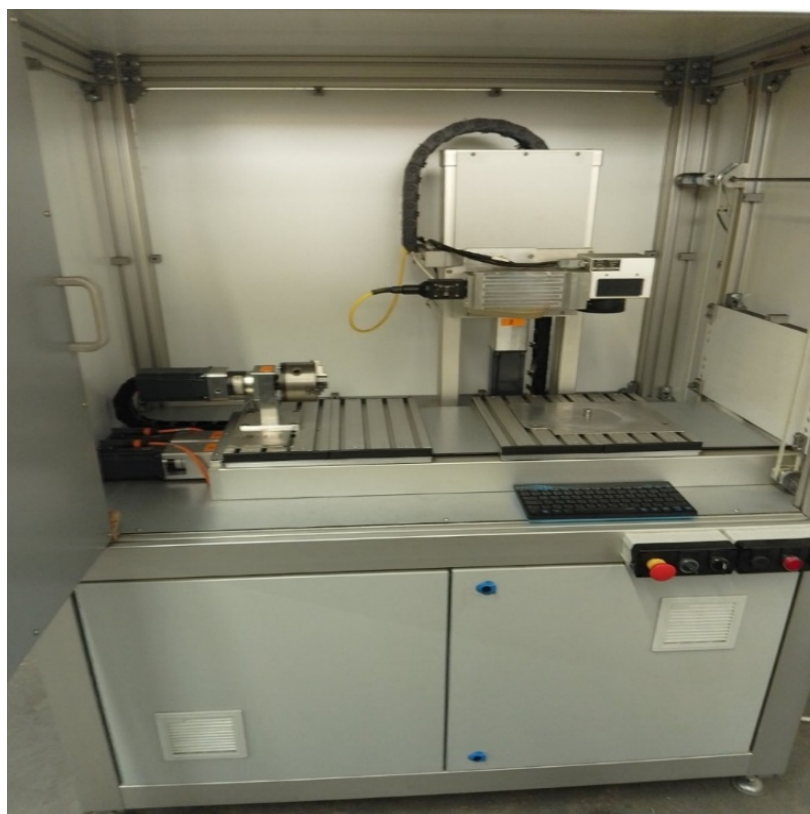
The marking of the samples was done using a laser installation – Fig. 1, developed on the territory of the company "Adtech", based on Fiber laser – RFFL-P-502B. Its main technological characteristics were presented in Table 2. The depth of the marking was studied on a measuring microscope – Fig. 2, using Insize ISD-V150/V250/V300 software.

The penetration depth was determined by zeroing the Z-axis values at the surface of the marking and taking into account the changes in focus at the bottom of the marked channel. The distance between individual points spaced 10 mm apart was determined by moving the measuring line along the X-axis.

* Corresponding author. E-mail: s.tsenkulovski@advanced-technology.eu

Table 1 Mechanical characteristics

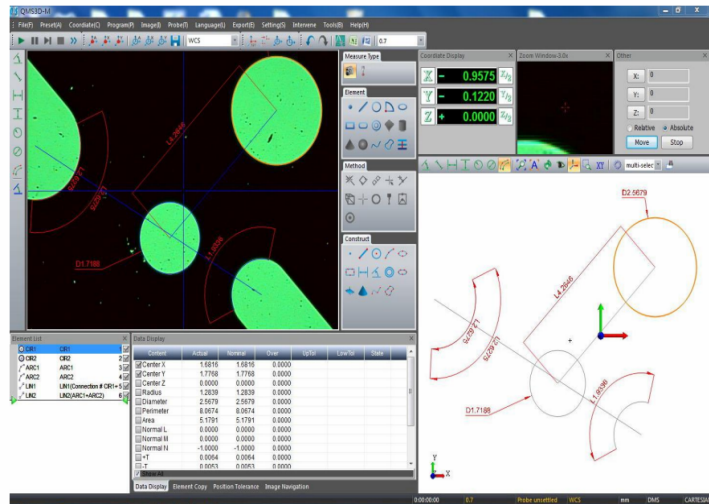
<i>Nº</i>	<i>Items</i>	<i>Unit</i>	<i>Standard</i>	<i>Test Value (Average value)</i>
1	Bending strength	MPa	130	130
2	Modulus of elasticity	MPa	7000	7000
3	Impact resistance without thread	kJ/m ²	30	30
4	Resistance to impact with a rifle	kJ/m ²	10/15	14
5	Tensile strength	MPa	80	80
6	Compressive strength	MPa	170	168
7	Brinell hardness	MPa	25÷30	30
8	Peel strength	N	2500	2500
10	Test voltage II / I	kV	8/5	8/5
11	Limit temperature	°C	110	110
12	Thermal conductivity	W/m.k	0,2÷0,3	0,2
13	Linear expansion	10-6/K	20÷40	32
14	Martens heat resistance	°C	150÷160	160
15	Specific heat	cal/ g.°C	0,35÷0,50	0,446
16	Evaporation temperature	°C	134÷732	700
17.	Density	g/cm ³	1,3÷1,4	1,4

*Fig.1. General view of Fiber laser – RFL – P – 50Q***Table 2** Characteristics of the laser installation

<i>Nº</i>	<i>Items</i>	<i>Unit</i>	<i>Standard Value</i>	<i>Variation Step</i>
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



a.



b.

Fig. 2. Overview of measuring microscope PHILIPS URD – a and software for 2D and 3D INSIZE ISD – V150 – b

3. EXPERIMENTAL PART

Samples were marked using the equipment shown in Fig. 1. The power values varied in the range 5÷50 kW, the marking speed was 50 mm/s with a focal spot diameter of 40μm and a pulse purity of 50 kHz.

The penetration depth of the laser beam was measured at 5 control points located along the marked line at a distance of 10mm. Some of the measurements are presented in Fig. 3, and all experimental results are shown in Table 3.

From Fig. 3 it is seen that the channel profile is not uniform along the length of the marking. This is also

proven by the experimental results in Table 3 and Fig. 4, where the values for δ vary in relatively wide intervals. At an output power of the laser radiation up to 20W, the measured values are in the range from 5 to 50 μm. When increasing the output power from 20 to 50W, the fluctuations of the experimental results are 50÷200 μm. These fluctuations in the values of the depth during marking are the result of the different evaporation temperature of the reinforcing and matrix phases that make up the polymer composite.

Table 3 Experimental data

№	P, W	δ, μm						
		p.1	p.2	p.3	p.4	p.5	Σp1÷p5 / 5	δmax, μm
V= 50mm/s								
1	5	85	94	85	90	90	89	91
2	10	162	164	161	150	158	159	182
3	15	220	232	225	224	219	224	273
4	20	315	298	290	288	269	292	364
5	25	405	398	397	402	413	403	455
6	30	476	492	490	480	497	487	546
7	35	610	605	608	618	599	608	636
8	40	725	720	710	709	721	717	727
9	45	701	700	708	705	706	704	818
10	50	667	655	658	660	685	665	909

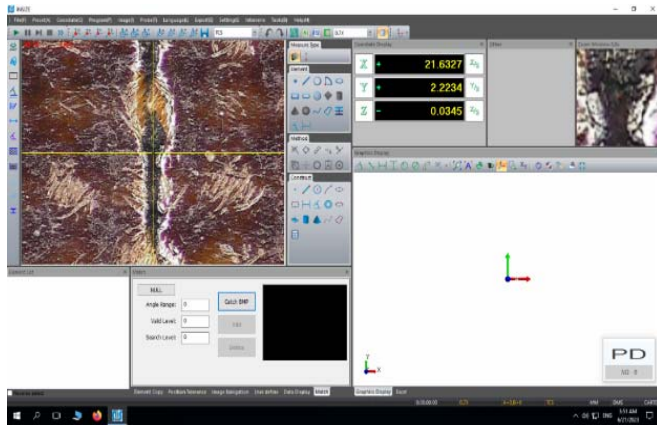
Theoretically, for non-metallic materials, the maximum penetration depth of the laser beam – δ_{max} , can be calculated using expression 1 [7]:

$$\delta_{max} = \frac{2P}{\pi \cdot r \cdot \rho \cdot c \cdot T}, \quad (1)$$

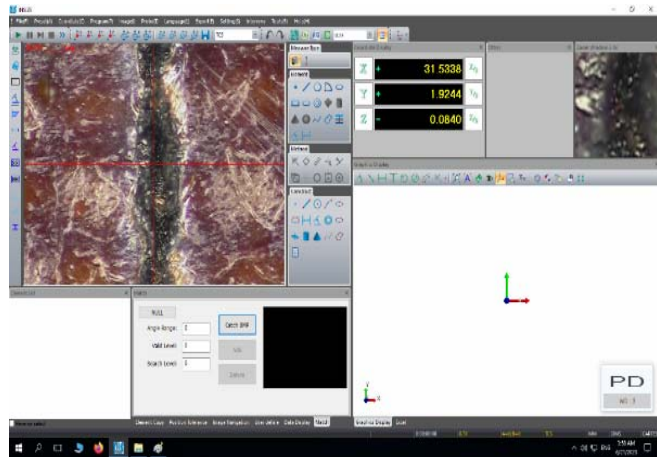
where: P - laser radiation power, W;
 r - focal spot radius, μm;
 ρ - density of the material, g/cm³;
 v - marking speed, mm/s;
 c - heat capacity of the material, J/kg.°C;
 T - evaporation temperature, °C.

Using the data from Tables 1 and 2, as well as reference data, the maximum theoretical values of the penetration depth during laser marking of the studied materials were calculated. (column 9 of Table 3).

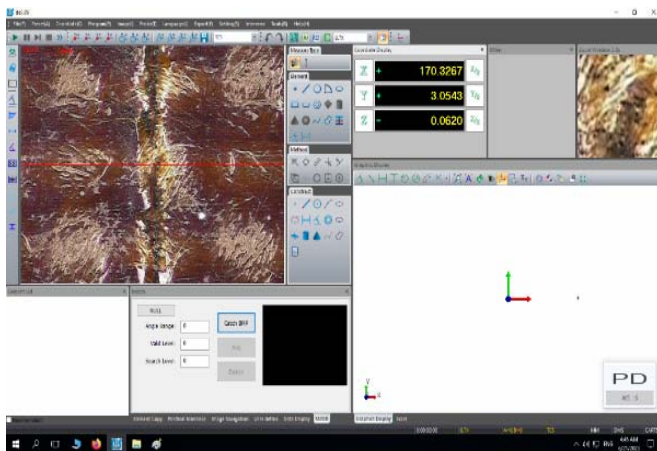
Comparing the theoretical and experimental results, it can be seen that according to formula 1, the penetration depth is linearly dependent on the power of the laser radiation. The experimental results obtained show that this is valid only for low marking powers - up to 20W. In these cases, the experimental results differ from the theoretical ones by less than 10%.



a.



b



c

Fig.3. Experimental results for marking textolite with $V=50\text{mm/s}$ and $f=50\text{kHz}$ a - 25W ; b - 35W ; c - 50W

With an increase in power above 20W, the depth of the marking decreases by 20÷30% compared to the theoretical one and the temperature curve is not linear, but acquires a parabolic character. This can be explained both by the difference in the evaporation temperature of the matrix and reinforcing phases, and by the increase in power losses due to absorption of the emitted particles by the aerosol released in the treated area.

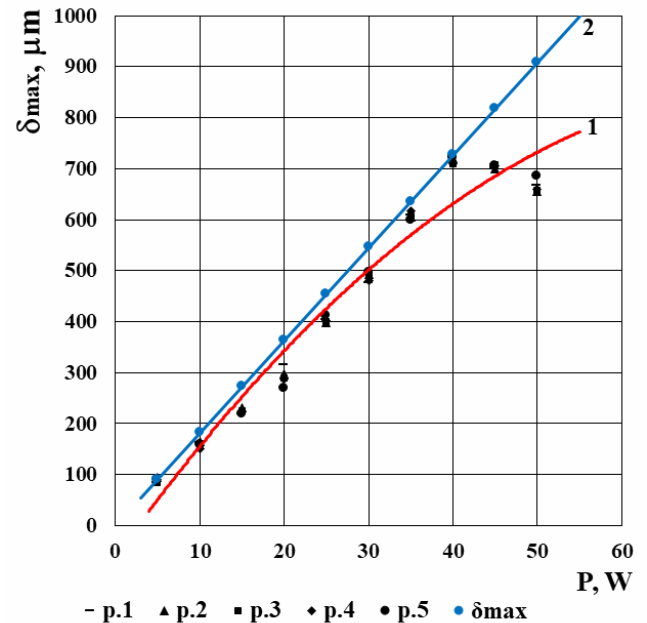


Fig. 4. Change in the bubble of the marking at $P = 5\div 50\text{W}$, $V = 50\text{ mm/s}$, $f = 50\text{Hz}$ – 1 and theoretical values 2

4. CONCLUSIONS

From the conducted research and the obtained results, the following important conclusions can be drawn:

- The depth of laser-marked composite materials based on phenolic laminate with a textile reinforcing phase has been studied at laser radiation output powers ranging from 5 to 50 W.
- It has been proven that the average marking depth was increased from 90 to 650 μm as the output power of the laser beam was increased from 5 to 50 W, while keeping the marking speed constant at 50 mm/s and the frequency at 50 Hz.
- It has been proven that, due to the different thermophysical characteristics of the matrix and the reinforcing phase in the composite, the measured values were found to vary within relatively wide limits. At an output power of up to 20 W, values of up to 100 μm were recorded, whereas at 50 W the values were observed to vary within the range of 100 to 300 μm .
- It has been proven that, unlike in single-component non-metallic materials, the depth of the marked layer in layered reinforced composites is not changed in a directly proportional manner with respect to the power. At powers up to 20 W, a directly proportional dependence was observed, but as the output power was increased to 50 W, the dependence was found to follow a parabolic curve. This behavior is attributed to power loss caused by the absorption of part of the radiation in the aerosols released during marking.

REFERENCES

- [1] Astarita A., Genna S., Leone C., Memola Capece Minutolo F., Squillace A., Velotti C. Study of the laser marking process of cold sprayed titanium coatings on aluminium substrates. *Opt Laser Technol* 83 (2016) 168–76 <https://doi.org/10.1016/j.optlastec.2016.04.007>
- [2] Chen M.F., Hsiao W.T., Huang W.L., Hu C.W., Chen Y.P. Laser coding on the eggshell using pulsed-laser marking system. *J Mater. Process Technol.* 209 (2009) 737–44 <https://doi.org/10.1016/j.jmatprotec.2008.02.075>

- [3] Chen M.F., Wang Y.H., Hsiao W.T. Finite element analysis and verification of laser marking on eggshell. *J Mater Process Technol.* 209 (2009) 470–6 <https://doi.org/10.1016/j.jmatprotec.2008.02.065>
- [4] Dumont Th., Lippert T., Wokaun A., Leyvraz P. Laser writing of 2D data matrices in glass. *Thin Solid Films* 453-454 (2004) 42–45 <https://doi.org/10.1016/j.tsf.2003.11.148>
- [5] Genna S., Leone C., Lopresto V., Tagliaferri V. An experimental study on the surface mechanisms formation during the laser milling of PMMA. *Polym Compos* 36(6) (2015) 1063–71 <https://doi.org/10.1002/pc.23442>
- [6] Jangsombatsiri W., Porter J.D. Laser direct-part marking of data matrix symbols on carbon steel substrates. *J Manuf. Sci Eng* 129(3) (2007) 583–91 <https://doi.org/10.1115/1.2716704>
- [7] Han A., Gubencu D. Analysis of the laser marking technologies. *Nonconventional Technol. Rev.* 4 (2008) 17–22
- [8] Leone C., Genna S., Caprino G., De Iorio I. AISI 304 stainless steel marking by a Qswitched diode pumped Nd:YAG laser. *J Mater Process Technol* 210(10) (2010) 1297– 303 <https://doi.org/10.1016/j.jmatprotec.2010.03.018>
- [9] Leone C., Genna S., Tagliaferri F., Palumbo B., Dix M. Experimental investigation on laser milling of aluminium oxide using a 30W Q-switched Yb:YAG fiber laser. *Opt Laser Technol* 76 (2016) 127–37 <https://doi.org/10.1016/j.optlastec.2015.08.005>
- [10] Leone C., Lopresto V., De Iorio I. Wood engraving by Q-switched diodepumped frequency-doubled Nd:YAG green laser. *Opt Lasers Eng* 47(1) (2009) 161–8 <https://doi.org/10.1016/j.optlaseng.2008.06.019>
- [11] Leone C., Genna S., Tagliaferri V. Cutting of AA6061 by a multimode pulsed Nd:YAG laser with high pressure gas: characterisation of kerf geometry and quality. *Int J Adv Manuf Technol* 94(1-4) (2018) 925–40 <https://doi.org/10.1007/s00170-017-0804-1>
- [12] Li J., Lu C., Wang A., Wu Y., Ma Z., Fang X., Tao L. Experimental investigation and mathematical modeling of laser marking two-dimensional barcodes on surfaces of aluminum alloy. *J Manuf Process* 21 (2016) 141–52 <https://doi.org/10.1016/j.jmapro.2015.12.007>
- [13] Li X.S., He W.P., Lei L., Wang J., Guo G.F., Zhang T.Y., Yue T. Laser direct marking applied to rasterizing miniature Data Matrix Code on aluminum alloy. *Opt Laser Technol* 77 (2016) 31–9 <https://doi.org/10.1016/j.optlastec.2015.08.020>
- [14] Niemenski G. Challenges for the laser job shop. *Industrial Laser Solutions* (2014) 31–4. January/February
- [15] Park Y.W., Kim T., Rhee S. Development of a monitoring system for quality prediction in laser marking using fuzzy theory. *J Laser Appl* 19(1) (2007) 55–63 <https://doi.org/10.2351/1.2402519>
- [16] Penide J., Quintero F., Riveiro A., Fernández A., del Val J., Comesana R., Lusquinos F., Pou J. High contrast laser marking of alumina. *Appl Surf Sci* 336 (2015) 118–28 <https://doi.org/10.1016/j.apsusc.2014.10.004>
- [17] Peter J., Doloi B., Bhattacharyya B. Parametric analysis of Nd: YAG laser marking on ceramics. *Int J Manuf Tech Manage* 24(1-4) (2011) 124–38 <https://doi.org/10.1504/IJMTM.2011.046764>
- [18] Petutschnigg A., Stöckler M., Steinwendner F., Schnepfs J., Güttler H., Blinzer J., Holzer H., Schnabel T. Laser treatment of wood surfaces for ski cores: an experimental parameter study. *Adv Mater Sci Eng* 2013 art. N°123085 <https://doi.org/10.1155/2013/123085>
- [19] Shin Y., Kim Y., Park S., Jung B., Lee J., Nelson J.S. Pit and rim formation during laser marking of acrylonitrile butadiene styrene plastic. *J Laser Appl* 17(4) (2005) 243–6 <https://doi.org/10.2351/1.2080405>
- [20] Tuz L. Quality of marks on metals made with the use of the Nd:YAG laser engraving method. *Metall Foundry Eng.* 39(1) (2013) 55–64 <https://doi.org/10.7494/mafe.2013.39.1.55>
- [21] Qi J., Wang K.L., Zhu Y.M. A study on the laser marking process of stainless steel. *J Mater Process Technol* 139 (2003) 273–6 [https://doi.org/10.1016/S0924-0136\(03\)00234-6](https://doi.org/10.1016/S0924-0136(03)00234-6)