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FORMATION OF A DESTRUCTIVE LAYER IN SPECIAL RUBBERS DEPENDING ON CO_2-LASER PROCESSING MODES

Special rubbers proceeding by laser engraving is the investigation object. Rubber products quality improvement was solving by means of laser engraving, which allows to achieve a high level of details, to get a complex geometry and sustainable quality having a minimum of the tool worn out. Experimental measurements of destructive layer depth inside different samples of rubber in dependence on the modes of CO_2-laser processing were conducted. Rubber engraving proceeding by a wavelength of 10.6 μm CO_2-laser was considered in the pulse mode series to provide the cutting edge correct geometry keeping fixed conditions of beam movement speed and acceleration.

Concerted experimental results (rubbers AERO Laserrubber, OLIO Laserrubber, TEMPO Laserrubber, CLASSICO Laserrubber and ECO Laserrubber) revealed a sustainable increasing the depth of the destructive layer on average by (1.0 ... 1.2) μm every 5 W along with increasing of CO_2-laser power in the range of (30 ... 55) W.

Stabilization or slight fluctuations of the destructive layer depth were stated when power supplied exceeded of 60 W.

Obtained graphs show a high degree coincidence with analytical model and confirm the feasibility of laser engraving appliance exactly within the range of (35 ... 50) W to provide a precise and clean processing of high-quality rubber products

Keywords: rubber, laser engraving, destructive layer depth, CO_2 laser power, quality improvement

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1. Introduction

Using laser for technical rubber engraving is the most technologically flexible and efficient processing at the manufacturing of products such as dies, seals, flexible molds, microstructured gaskets and seals. In spite of mechanical milling, laser engraving allows to achieve high level of details, to get a complex geometry and sustainable quality having a minimum of the tool worn out.

Among all types of industrial lasers, CO_2-laser with a perfectly absorbed by organic polymeric materials wavelength of 10.6 μm is the most often used at rubber processing. At the same time, there is no any mechanical influence on the processing material – the effect occurs only by thermophotonic evaporation (ablation), which allows to keep an integrity of the product structure [1].

Regardless of these advantages, the technology has a number of crucial restrictions. One of the main ones is the formation of a destructive layer – a thermally damaged zone at the edges of the engraving element. This layer is forming due to the exceeding heat affect. This phenomenon causes a polymer partial burning, a surface color or texture changes, a material elasticity or chemical stability failure, a microcracks appearance. Moreover, the next changes have place: located close to the ablation zone layers inside the material have got temperature deformations [2], the treated material surface roughness is changing [3].

Taking in account technical problems described above an investigations focused on rubber destructive layer depth measurements and its dependence of laser engraving parameters are actual regarding an efficient mode statement to improve the quality of rubber products.

2. Literature sources analysis and the problem statement

Radiation effect on polymer component of the certain composition in adhesion zone between sealant and solid surface investigation is performed by authors [1]. At the same time, the final zone of destruction and its magnitude were not taken into account.

The process of dissemination of temperature deformations could be simulated and a spatial picture of their distribution can be reproduced [2]. But a destructive layer formation problem is still not solved. The destructive layer is a thermally damaged zone at the edges of the engraving element.

A method of surface roughness control by using sliding laser irradiation according to interference scattering patterns is proposed [3]. Roughness, as a treated surface quality parameter, could be related directly to the obtained destructive layer, which is defined on the laser processing technological parameters. This layer existence reduces accuracy, adhesion, product wear resistance and requires either mechanical modification or a repeated processing cycle.

A literature comprehensive review focused on CO_2-laser cutting of polymeric materials was carried out by authors in [4]. An analysis of key parameters (laser power, cutting speed, auxiliary gas pressure, frequency, nozzle type, distance to the focal point) influence on cutting quality (cutting width, roughness, heat exposure zone, burring) is presented. This analysis is performed for main types of polymers such as polyolefins (PP, LDPE, HDPE), polycarbonate (PC), polymethyl methacrylate (PMMA). The content in [4] summarizes the optimal ranges of laser processing modes, proposes a farther research way in terms of automation, minimizing the heating zone, improving speed and quality, but in the same time elastomers are not taken in account. Issues considered by authors in [4] require further research on the polymeric materials varieties' investigation and their optimal parameters clarification to improve cutting quality regarding CO_2-laser cutting.

A unique method of CO_2-laser supplied with a copper cooling basement and vacuum press equipment processing of polypropylene and polystyrene (PS) with a thickness of about 300 μm is investigated in [5]. This approach provides partially thin areas up to 50 microns with a reverse side minimal thermal damage. Owing to this, deformations and overheating could be avoided. The method is integrated into existing equipment without complex changes and could be implemented as an alternative to convective cooling. The excess heat existence at the laser treatment of polystyrene area is clarified as well as one of the ways to eliminate this heat are considered. Probably, a similar approach could be used at the radiation exposure intensification at rubber processing technology but this possibility is not mentioned in [5].

Similar studies of rear cooling basement effect on heat removing for different materials were carried out in [6]. Problem of the material overheating and reducing the temperature load at the processing area was considered. The definite depth and width of a thin cut depending on laser energy and polymer properties are demonstrated. Heat removement through the basement methods and heating mode stabilization for the most common spectrum of polymers, excluding elastomers, are analyzed. It is only possible to assume that elastomers behavior will be close to polyethylene terephthalate (PETF), behavior but this needs to be verified.

Research [7] is focused on applying the machine algorithms training to predict slice geometry (Kerf Open Deviation, KOD). Number of parameters data have been collected, a numerical model has been developed that allows to predict the cut quality with high accuracy. This is an important step towards automation and smart control of the processes named above. The cut quality was considered on examples of the manufacturing of molding tools, but the processing generalizations regarding of various materials were not given, for example, the same problem arises during CO_2-laser cutting of polymers and rubbers, etc.

Occurrence of thermally induced defects (microcracks, delamination, decomposition) during CO_2-laser cutting of carbon compositions (CFRP) was considered in [8]. Authors on the base of the anisotropic material model established a relationship between the damage topology and the mechanical strength of the cutted samples. Effect of different processing modes on defect formation has been highlighted on the base of experiments, but CFRP is not a homogeneous isotropic material. The resulting sections have many irregularities due to layers with different properties. Consequently, experimental sizing due to the uncertain geometry of the cut becomes problematic.

In [9] the problem of insufficient quality and accuracy of printed samples made of polylactic acid (PLA) is investigated. The surface quality and geometric accuracy improvement of was achieved by combination of 3D printing technologies and CO_2-laser processing. With the help of experiment planning and RSM (response surface methodology), it is shown which laser cutting parameters affect the morphology of the surface PLA samples. However, the reduction of roughness due to laser surface post-treatment is also associated with partial evaporation of the material. Thus, the problem of changing the dimensions of parts after finishing is remained.

The paper [10] focuses on the problem of dispersed particulate matter and gas emission during CO_2-laser cutting of acrylic sheets and its associated emissions. The amount of particulate matter released will vary depending on factors such as cutting time and design, and more research is needed to determine which cutting style can generate the highest concentration of particulate matter. The methods of observation and spectral analysis were used to assess the environmental impact of the processing process. The work opens an analogy for the study of the emission of dispersed particles and gases during the processing of specialized rubbers. The experimental part of the research was carried out at a specific workplace on the installed industrial equipment and did not provide for studies of a wide range of processed materials or going beyond the technical limitations of the equipment. make a broad generalization both in terms of modes and processed materials.

Modern research demonstrates the active development of the direction of CO_2-laser processing of polymeric materials, which is directly related to the problems of forming a destructive layer in the process of engraving technical rubber. Thus, in the paper [11] highlights the problem of controlling roughness and adhesion on treated surfaces through the modes of CO_2-laser treatment PETF and PE. This confirms that the variation in the radiation power directly affects the quality of the treated surface, similar to the formation of the depth of the destructive layer in rubber materials. It was found that PETF does not demonstrate linear absorption of CO_2-laser radiation, so the problem of developing appropriate laser processing parameters remains.

The research in the paper [12] is devoted to laser texturing of the surface of polymers for biomedical applications. The studies have established that the creation of microstructures with a CO_2-laser significantly changes the surface properties of materials and affects their functionality. Laser surface texturing has been mainly studied on common polymers, but the processing of composites for biomedical applications has not been extensively studied. Therefore, the problem is partially covered. Generalized conclusions can be drawn by expanding the range of materials studied, in particular composites and rubbers. Laser texturing modifies the surface not only at the micrometric scale, but also at the nanometric scale. nanometric scale, or homogeneous surface chemistry at the nanometric scale. These issues may stimulate future research.

The paper [13] presents an experimental and model study of CO_2-laser labeling on polyamide (PA), which made it possible to establish "mode-structure" relationships based on a new technique of direct laser carbonization of writing (DLWc) and a model of photothermal transformation without free parameters. The simulation concerned the determination of key processing parameters – laser power, irradiation duration and focus level, which have a significant impact on the size of the destructive layer, morphology and carbonization features created by DLWc. It has been demonstrated that even minor changes in radiation parameters lead to noticeable changes in the microstructure of the surface of samples. However, the carbonization behavior due to laser irradiation in the thickness direction was not correctly predicted by this model.

In the paper [14], attention was focused on the creation of microchannels in polymethyl methacrylate (PMMA) in the multi-pass mode of the CO_2-laser. It is shown that the problem of obtaining a high-quality profile and the required depth of the channel can be solved in several passes of the beam. Thermal analysis was carried out by considering the laser beam as a heat flux of a body with a moving heat source. It was observed that the thermal impact zone tends to decrease with increasing laser cutting speed. In the process of laser cutting, it is found that the width of the upper cut increases with an increase in laser power, as well as with an increase in the number of passes at a given laser power and cutting speed. It is also assumed that with an increase in laser cutting speed, the cutting width for a given laser power decreases. Looking at the problem of the depth of the destructive layer of technical rubber, this confirms the feasibility of multi-pass technology as a way to control the depth of the destructive layer without excessive thermal damage. However, the paper does not indicate how exactly the depth of the destructive layer affects the accuracy of measuring the upper and lower cuts.

Reducing the surface roughness of the destructive layer during the processing of polymer films was considered in the paper [15]. A comparative analysis of the processing of polymer films in continuous and quasi-pulse modes of the CO_2-laser was carried out. Continuous decent wave irradiation caused the formation of sintered grooves on the surface of the film and a decrease in roughness parameters (up to 40–45 μm) for most films. Processing in a quasi-pulsed raster mode led to the formation of dimples without pronounced sintered areas on the film surface and an increase in the roughness of most samples. It was found that the impulse action significantly reduces the thermal zone of damage. This is consistent with the findings that pulse modes are promising for minimizing the destructive layer when engraving rubber materials. The problematic component of the study is that the CO_2-laser was used in the modes of continuous wave (3 W; 2 m/s) and quasi-pulse mode (13.5 W; 1 m/s), that is, it is not possible at all to make up the dependencies of the experimental parameters on the change, at least the power of radiation.

The paper [16] investigated the problem of thermal effects of deep CO_2-laser cutting of wood-plastic composites. Gas cooling has reduced the thermal impact zone to ~ 50% and eliminated most of the charring without compromising the required performance or depth. Studies have focused on the delivery rate and pressure of auxiliary cooling gas, leaving unanswered questions about the impact of other technological parameters.

The work [17] focuses on the problem of rapid synthesis of polymer-metal nanocomposites using CO_2-laser irradiation. Although the study focuses on nanomaterials, the authors described the mechanisms of local thermal exposure to CO_2-laser irradiation, which are similar to that which forms a destructive layer in a polymer and rubber base. Some research problem is the use of a Gaussian irradiation profile acting on an 8 mm surface. This generates a not very uniform thermal effect. From there, inaccuracy of temperature measurements with a thermocouple with a diameter of 1 mm is possible, although it is not difficult to convert a Gaussian beam profile into a flat-top profile using a beam former.

The paper [18] investigates the effect of CO_2-laser parameters on the ratio of width and depth of microchannels in samples for the manufacture of microfluidic chips. The task concerned samples of polymethyl methacrylate, polystyrene, polycarbonate and polyethylene terephthalate. They chose the most acceptable (according to the authors) of the three modes of operation of the CO_2-laser for each material. Unfortunately, only the radiation power (8, 12, 16) W varied at the same speed (10 mm/s) and distance to the surface (7.5 mm). Therefore, it has not been proven that the choice of processing modes is adequately performed.

The work [19] systematizes knowledge about laser ablation of polymers, including CO_2-lasers. The main effects are summarized – the formation of microcracks, thermal degradation, optimal ranges of parameters. This work is of fundamental importance, since it explains the general mechanisms of the formation of the destructive layer and indicates ways to minimize it.

Based on the analysis of approaches to determining the optimal parameters of laser engraving of various materials to ensure the improvement of the quality of finished products, it is possible to conclude that this issue can be solved in various aspects. Despite a number of problems that have already been investigated that arise in CO_2-laser processing of polymers, the problem of dependence of the depth of the destructive layer of cross-linked rubbers on the parameters of technological process.

3. The aim and objectives of the study

The aim of the study is to get derivation on the depth of the destructive layer formation at CO_2-laser processing of specialized rubbers. It will result to calculate an operate parameters of CO_2-laser radiation power on the level that minimizes defects at specialized rubbers engraving.

To achieve the aim of the study it is necessary to solve the following objectives:

– to obtain an experimental data for specialized rubbers depth of the destructive layer at different levels of CO_2-laser power;

– on the base of experimental data to get the relationships that approximate the depth of the destructive layer derivations vs the power of the CO_2-laser for some specialized rubbers.

4. Materials and methods

The object of the study is specialized rubbers in the process of laser engraving.

The main hypothesis is that there must be a direct dependence of the depth of the destructive layer on the power of laser radiation during rubber processing. This hypothesis is tentatively confirmed by a similar study [4] for polyolefins. It is assumed that under the condition of other laser processing parameters recommended by the manufacturer for similar materials, the main impact on the studied depth of the destructive layer will be the power of laser radiation.

The work did not consider the surface roughness after processing, the presence and magnitude of temperature deformations as secondary ones. The research methodology is simplified by limiting the laser power in the range (30 ... 80) W, fixed speed of the laser beam (50 mm/s) at an acceleration of 1200 mm/s^2.

The work is aimed at an experimental study of the depth of the destructive layer, which is formed during engraving of specialized Laserrubber rubber at different levels of CO_2-laser power.

The experiments were performed by laser engraving on the Laserbot 900 CO_2-laser machine. Laserbot 900 is a modern laser engraver for semi-industrial use [20].

The Laserbot 900 machine has the following characteristics: water-cooled CO_2-gas discharge laser with a power: 100 W (the values used in the experiment are from 30 to 80 W); radiation wavelength of 10.6 μm (recommended for organic materials by the equipment manufacturer [20]). Platform with automatic lift and manual focus calibration. LightBurn [21] and Ruida Works software for CO_2-lasers with a Ruida controller [22] were used to control the processing process. The focal length optimized for flat materials was 25.5 mm. Working field: 900 × 600 mm. Engraving and cutting modes, pulse processing (PWM), acceleration 1200 mm/s^2.

The engraving took place in the mode of serial pulse delivery to maintain the correct geometry of the cutting edge.

To study the destruction zone, a Micron Tools MT-PRO10PLUS digital microscope [23] with the following characteristics was used. Sensor: CMOS 2 MP (1600 × 1200 pix.); optical zoom × 10, digital zoom up to × 200 (applied magnification × 36 selected experimentally for stable visualization of the groove profile); depth, diameter, area measurement software, built-in 2.8″ TFT screen for preview; multi-LED lighting system with adjustable angle and brightness. The microscope made it possible to obtain a series of cross-sectional images and build an engraving profile in the format of 2D scans.

Flat rubber samples manufactured by Trodat GmbH, Austria were processed. Five types of special rubber were selected according to the criterion of the greatest popularity in a particular production. These are the materials AERO Laserrubber (gray), CLASSICO Laserrubber (gray), ECO Laserrubber (green), OLIO Laserrubber (black), TEMPO Laserrubber (orange). CLASSICO Laserrubber is one of the five main types of laser rubber manufactured by Trodat GmbH, widely used in engraving due to its stable structure and high print quality [24].

The AERO Laserrubber material is an industry standard in the production of rubber molds for laser engraving. The rubber has the following main characteristics. The composition is vulcanized rubber with an admixture of titanium dioxide (up to 10%), which ensures stability to radiation. The color is gray (provides a clear contrast of engraving); thickness (2.3 ... 2.5) mm; the structure is uniform without inclusions. Temperature stability: short-term heating up to 300°C without breaking; non-toxic, low smoke emission, not classified as a hazardous substance by REACH (Registration, Evaluation, Authorization and Restriction of Chemicals). Thus, this substance does not contain dangerous chemical compounds in concentrations that may pose a risk. Its use is not subject to restrictions or special authorization requirements under this regulation. In the production or processing of this material, no special safety measures other than standard ones are required.

Standard processing modes (35 ... 45) W, above 60 W, there is a zone of ignition and deformation. The material practically does not emit smoke during processing, does not stick to the focal glass and is well fixed during engraving.

CLASSICO Laserrubber material is designed for the production of text plates and dies. Composition – vulcanized rubber with an admixture of titanium dioxide (0.3–1)%; color gray; stable and safe under local heating; no toxicity, not classified as a hazardous substance by REACH.

ECO Laserrubber material. The composition is vulcanized rubber with an admixture of titanium dioxide (1 ... 3)%, zinc oxide and stabilizers are present. The color is green. Easy to dispose of. Despite the fact that it is positioned by the manufacturer as an eco-friendly formula with minimal smoke emission and is not classified as a hazardous substance under REACH, it nevertheless contains traces of potentially toxic substances in free form.

OLIO Laserrubber material. The composition is vulcanized rubber with an admixture of zinc oxide (1 ... 3)% and organic additives. The color is black. Density 1.31 g/cm^3. Maintains stability under typical engraving conditions, excellent flexibility and elasticity. It has increased clarity of engraving on a dark background.

TEMPO Laserrubber material. The composition is vulcanized rubber with an admixture of titanium dioxide up to 10%, zinc oxide, sulfur, dye and antioxidants. The color is orange. The density is 1.11 g/cm^3. It is intended for high-speed laser engraving. It is characterized by high heat resistance and stability of the structure under short-term heating. The formula contains minimal amounts of substances that can cause allergic reactions in an untreated state.

Laser rubber sheets were used for the experiment. The dimensions of each sheet were 148 × 210 mm (A5 format). The surface was pre-cleaned with a degreased cloth material to remove dust and dirt. Fig. 1 shows a sample of rubber after laser engraving.

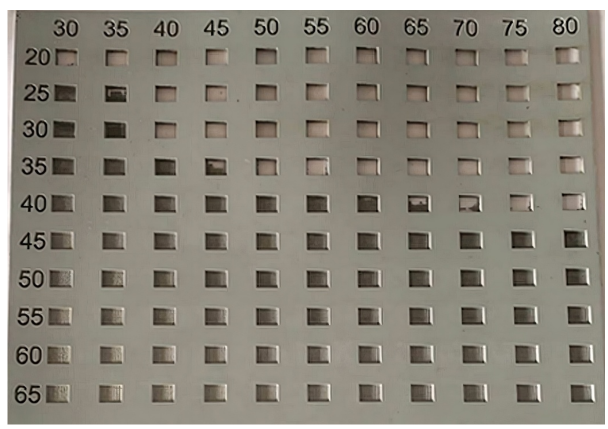

Fig. 1. Rubber sample after laser engraving

With the help of RDWorks software, an engraving grid was created – a matrix of 121 separate squares measuring 8 × 6 mm, placed at intervals between elements. Each square corresponded to a further unique combination of engraving parameters, in particular, laser power.

The following processing conditions were established. The mode of operation of the laser is engraving (Scan). The power of the CO_2-laser varied in the range from 30 to 80 W in increments of 5 W. The speed of the laser beam remained constant (50 mm/s), and the acceleration was fixed at 1200 mm/s^2.

Once engraving was complete, each sample was cooled for 15 minutes at room temperature. Next, washing with distilled water was carried out in order to eliminate the remnants of destruction products without mechanical intervention.

Taking measurements and recording the results is based on the traditional method of light microscopy. The depth of the destructive layer was estimated by the MT-PRO10PLUS digital microscope at a magnification of × 36. In each engraving mode, five samples were used, and in each square, 10 independent measurements were made in different sections of the engraving contour. Next, the average value was calculated, each of which was analyzed for correctness. Individual values were excluded from the analysis due to significant deviations – local structural anomalies, focal instability, or as ejections, which presence negatively affected the accuracy of the models.

5. Results of the study of the depth of the destructive layer depending on the modes of CO_2-laser treatment of some special rubbers

5. 1. Experimental data on the depth of the destructive layer of specialized rubbers under the condition of different levels of CO_2-laser power

The obtained values of the depth of the destructive layer conditions at different CO_2-laser power for each type of rubber were entered into Tables 1–5, which are listed below.

Table 1

Summary results of the depth of the destructive layer (μm) of AERO Laserrubber rubber

Power, W	No. 1	No. 2	No. 3	No. 4	No. 5	Average
30	6.00	5.00	–	9.50	10.50	7.75
35	9.00	8.00	6.50	11.00	12.00	9.30
40	–	7.00	12.00	10.00	8.00	9.25
45	8.00	7.00	13.00	–	9.00	9.25
50	9.00	13.00	4.00	11.00	12.00	9.80
55	7.00	11.00	9.00	12.00	8.00	9.40
60	6.50	13.00	10.00	14.00	15.00	10.00
65	12.00	6.00	13.00	10.00	11.00	10.40
70	10.00	13.00	12.00	11.00	9.00	11.00
75	–	11.00	12.00	13.00	10.00	11.50
80	12.50	14.00	9.00	11.00	12.00	11.70

Table 2

Summary results of the depth of the destructive layer (μm) of OLIO Laserrubber rubber

Power, W	No. 1	No. 2	No. 3	No. 4	No. 5	Average
30	6.00	10.00	8.00	8.00	7.00	7.80
35	8.00	6.00	11.00	–	11.50	9.13
40	9.00	5.00	–	10.50	12.00	9.13
45	10.00	8.00	12.00	9.00	8.00	9.40
50	8.00	6.00	8.00	9.50	8.00	9.88
55	8.00	9.00	10.50	11.00	9.00	9.50
60	–	11.00	10.50	11.00	9.00	10.38
65	10.00	11.00	9.00	10.50	11.00	10.30
70	–	10.00	9.50	13.00	12.00	11.13
75	9.00	11.00	14.00	11.00	10.50	11.10
80	10.00	–	12.50	14.00	12.00	12.13

Table 3

Summary results of the depth of the destructive layer (μm) of TEMPO Laserrubber rubber

Power, W	No. 1	No. 2	No. 3	No. 4	No. 5	Medium
30	7.00	7.00	9.00	9.00	10.00	8.40
35	10.00	11.00	8.00	7.00	9.00	9.00
40	7.50	8.00	11.00	11.00	–	9.38
45	–	11.50	10.00	9.00	8.00	9.63
50	13.00	8.00	9.00	6.00	11.00	9.40
55	12.00	11.00	–	10.00	9.00	10.50
60	10.00	9.00	11.00	11.00	10.00	10.20
65	11.00	11.00	–	9.00	12.00	10.75
70	10.00	11.00	11.00	9.00	10.00	10.20
75	13.00	9.00	10.00	11.00	12.00	11.00
80	–	11.00	12.00	13.00	14.50	12.63

Table 4

Summary results of the depth of the destructive layer (μm) of CLASSICO Laserrubber rubber

Power, W	No. 1	No. 2	No. 3	No. 4	No. 5	Medium
30	5.00	4.50	10.00	11.00	8.00	7.70
35	7.50	8.00	–	8.00	9.00	8.13
40	3.00	6.00	11.50	12.00	–	8.13
45	–	7.00	8.00	8.00	9.00	8.00
50	9.00	8.00	7.00	12.00	8.00	8.80
55	9.00	6.00	12.00	10.00	9.00	9.20
60	–	8.00	11.50	12.00	9.00	10.13
65	9.00	8.00	–	11.00	10.00	9.50
70	10.00	9.00	11.00	10.00	11.00	10.20
75	–	8.50	14.00	9.00	13.00	11.13
80	10.00	15.00	16.50	12.00	10.00	12.70

Table 5

Summary results of the depth of the destructive layer (μm) of ECO Laserrubber rubber

Power, W	No. 1	No. 2	No. 3	No. 4	No. 5	Medium
30	7.00	5.50	9.00	–	10.00	7.88
35	5.00	8.00	11.50	8.00	9.00	8.30
40	6.50	7.00	11.00	–	10.00	8.63
45	9.00	7.00	11.00	8.00	9.00	8.80
50	11.00	9.00	9.00	10.50	7.00	9.30
55	9.00	–	7.00	11.00	12.00	9.75
60	7.00	10.00	–	10.00	9.50	9.13
65	–	7.00	9.00	12.00	10.00	9.50
70	9.50	15.00	8.00	9.00	12.50	10.80
75	10.00	12.00	10.00	11.00	10.50	10.70
80	12.00	10.00	12.50	14.00	12.50	12.20

Further, the summary experimental data in the tables of Tables 1–5 to detect the effect of changes in CO_2 laser power on the depth of the destructive layer for five types of laser gums under study.

5. 2. Determination of the dependence of the depth of the destructive layer on the power of the CO_2-laser for some specialized rubbers

For the studied specialized rubbers, the Excel program (USA) calculated the average values and plotted the dependence of the depth of the destructive layer on the power of the CO_2 engraving laser.

According to the experimental summary results of the depth of the destructive layer for AERO Laserrubber, OLIO Laserrubber and TEMPO Laserrubber rubber, the dependence of the depth of the destructive layer on the power of the CO_2-laser during laser engraving was constructed (Fig. 2).

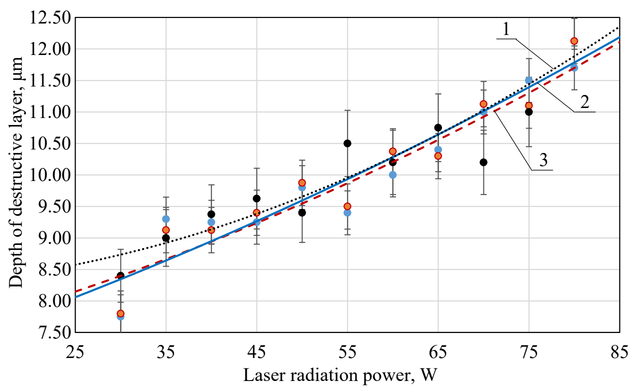

Fig. 2. Dependence of the depth of the destructive layer (μm) on the power of the CO_2 laser (W) for AERO Laserrubber (1), OLIO Laserrubber (2) and TEMPO Laserrubber (3) rubber

The results of three coordinated experiments (AERO Laserrubber, OLIO Laserrubber and TEMPO Laserrubber rubbers) revealed a steady trend of increasing the depth of the destructive layer with an increase in the power of the CO_2-laser in the range (30 ... 55) Tue. After that, stabilization or a slight fluctuation in the depth of the destructive layer was observed (Fig. 2).

The average increase in the depth of the destructive layer was (1.0 ... 1.2) μm for every 5 W, which is consistent with the laser ablation characteristics of vulcanized polymers [24]. All three graphs demonstrate a high degree of consistency with the analytical model and confirm the feasibility of using laser engraving within (35 ... 50) W for precise and clean machining.

Approximate dependencies of the depth of the destructive layer on the power of the CO_2-laser for the studied rubbers are given in Table 6.

The results of mathematical processing of experimental data on the depth of the destructive layer in the power range (30 ... 80) Ws are approximated with sufficient accuracy by second-order equations.

In the range of more than 60 W, zones of darkening, partial carbonation and microcracks were recorded on the surface of the samples, impairing the accuracy of the product. These defects are visually confirmed on micrographs (Fig. 3).

Fig. 3 shows the microstructures of surfaces obtained by scanning electron microscopy (SEM) and their elemental composition determined by energy dispersive spectroscopy (EDS) [25]. The presented samples are not rubber materials, however, attention should be paid to the characteristic morphological features, such as microrelief, cracks and local defects may also be typical for rubber surfaces after CO_2-laser treatment. This is due to similar processes of local heating, melting and evaporation of the material under the influence of intense laser radiation, leading to the formation of irregularities and microcavities. A microscopic texture is visible with elements of topographic, hilly structures on a scale of approximately (2 ... 10) μm. This morphology is close to the expected destructive layer of rubber samples in CO_2-laser treatment with a power of 85 W, where the depth (14.5 ... 15.0) μm may be redundant for process tolerances.

Original micrographs of rubber materials with a layer depth of about 15 microns are not common in open sources. However, the above image well illustrates the nature of the surface after intensive CO_2-laser ablation [26].

Microstructures of surfaces and their elemental composition are presented in Fig. 3, *a–d*, which are obtained using scanning electron microscopy (SEM) at different magnifications (100X, 1000X and 2500X), which are structured by a femtosecond laser in Fig. 3 [26].

Samples with a moderate structure exhibit features in the submicrometer range (Fig. 3, *a*). In these structures, it is generally distributed homogeneously, but a periodic pattern corresponding to the line pitch during the laser process can also be observed. Large, conical, spike-like structures are arranged in the form of a comb vertically to the direction of laser scanning, which are covered by a porous cauliflower-like substructure. As shown by laser scanning microscopy measurements shown in Fig. 3, *d*, the conical structures are about 50–70 μm high, and the recesses and holes are about 110 μm deep. In addition, the differences between samples with or without nickel inclusion are quite small.

It can be predicted that with a CO_2-laser power of 85 W, an increase in the depth of the destructive layer is expected to (14.5 ... 15.0) μm, which is excessive for process tolerances.

According to the experimental summary results of the depth of the destructive layer for CLASSICO Laserrubber and ECO Laserrubber rubber, the dependence of the depth of the destructive layer on the power of the CO_2-laser during laser engraving was constructed (Fig. 4).

Approximate dependencies of the depth of the destructive layer on the power of the CO_2-laser for the studied rubbers are given in Table 7.

Table 6

Approximating the dependencies of the depth of the destructive layer on the power of the CO_2-laser for AERO Laserrubber, OLIO Laserrubber and TEMPO Laserrubber rubbers

Rubber	Dependence for determining the depth of the destructive layer *Y*, μm, on the power of the CO_2 laser *x*, W	Coefficient of determination
AERO Laserrubber	$Y = 0.0006x^2 + 0.0007x + 8.2046$	0.8444
OLIO Laserrubber	$Y = 0.0002x^2 + 0.0456x + 6.7893$	0.9166
TEMPO Laserrubber	$Y = 0.0003x^2 + 0.0342x + 7.133$	0.9014

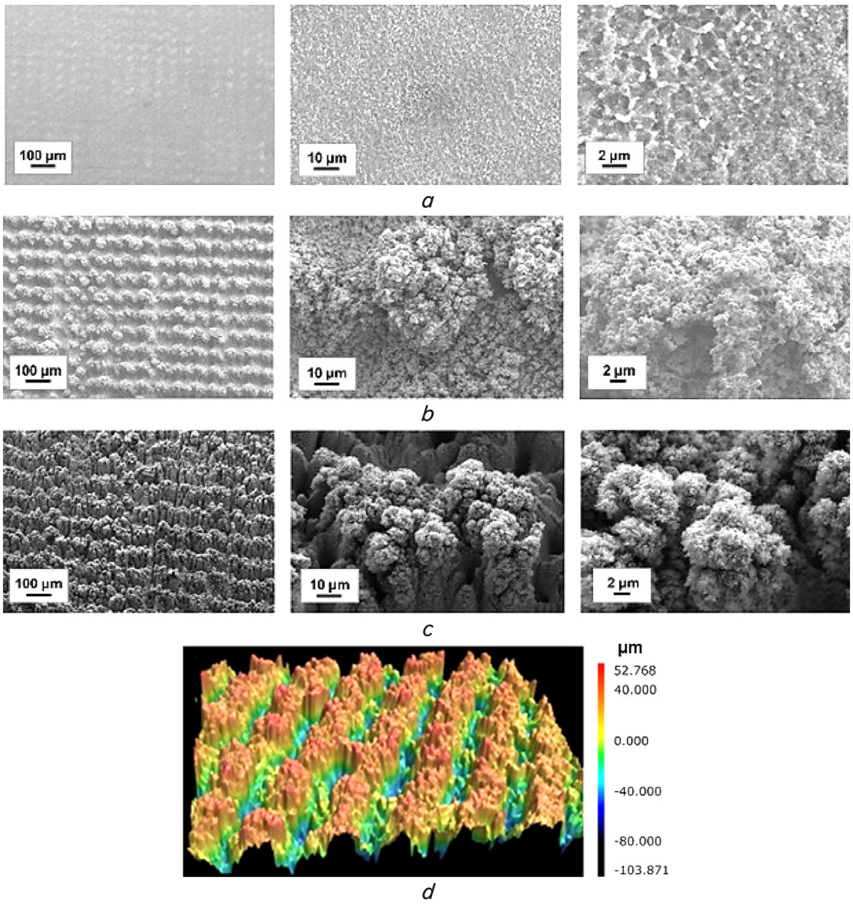

Fig. 3. Microstructure of laser-treated surfaces and their elemental composition at different magnifications (100X, 1000X and 2500X): *a* — moderately structured; *b* — strongly structured; *c* — strongly structured; *d* — laser scanning microscopy of a highly structured sample [26]

The results of mathematical processing of experimental data on the depth of the destructive layer in the power range (30 ... 80) Ws are approximated with sufficient accuracy by second-order equations.

The results of the study of CLASSICO Laserrubber and ECO Laserrubber rubber showed the non-standard nature of the dependence of the depth of the destructive layer on the power of the CO_2-laser (Fig. 4). Unlike the previous materials, the intensive growth of the depth of the destructive layer begins only with (60 ... 65) W and tends to accelerate.

At 80 W, the depth of the destructive layer reaches (12.7 ... 12.9) µm, and individual measurements indicate significant instability of the structure: both dips and depth peaks were detected. The explanation lies in the internal structure of the materials. CLASSICO Laserrubber rubber probably contains mineral fillers, and ECO Laserrubber rubber has a microporous surface that affects local thermal conductivity and heat capacity.

Just like for other rubbers, the forecast of the depth of the destructive layer at a CO_2-laser power of 85 W gives values exceeding 15 microns. Thus, the recommended operating power range of the CO_2-laser can be (45 ... 60) W with multi-pass mode to avoid thermal degradation [20].

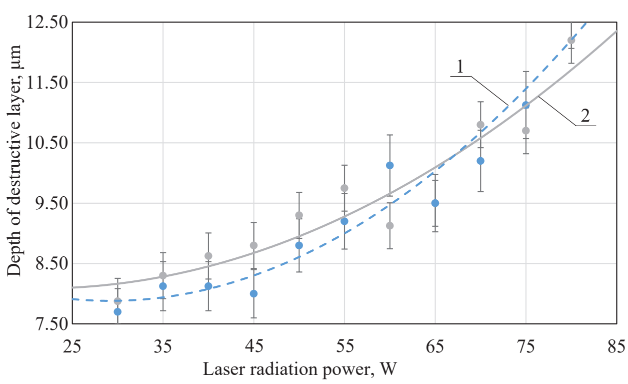

Fig. 4. Dependence of the depth of the destructive layer (µm) on the power of the CO_2-laser (W) for CLASSICO Laserrubber (1) and ECO Laserrubber (2) rubber

Table 7

Approximating the dependencies of the depth of the destructive layer on the power of the CO_2 laser for CLASSICO Laserrubber and ECO Laserrubber rubbers

Rubber	Dependence for determining the depth of the destructive layer Y, µm, on the power of the CO_2 laser x, W	Coefficient of determination
CLASSICO Laserrubber	$Y = 0.0017x^2 - 0.0974x + 9.3011$	0.9369
ECO Laserrubber	$Y = 0.0011x^2 - 0.0449x + 8.5662$	0.9014

6. Discussion of the results of the study of the depth of the destructive layer of special rubbers from the power of the CO_2-laser

Unlike the data [4–19], where linear polymers are studied, specialized rubbers have a cross-linked mesh structure. Therefore, direct comparative data on the depth of the destructive layer in rubber samples were not found.

With the help of RDWorks software, a sample matrix was created to study the effect of CO_2-laser power (30–80) W on the depth of the destructive layer when engraving rubber of various types. It has been established that for AERO, OLIO and TEMPO tires, the optimal power range is (35 ... 50) W, where the depth of the layer increases in proportion to the power that is (1 ... 1.2) µm for every 5 W (Fig. 2), without defects. At powers above 60 W, surface defects (darkening, carbonation, microcracks) are observed, which worsens the quality of the finish. Unlike the previous cases, for CLASSICO and ECO rubbers, the nature of the dependence is non-standard: intensive depth growth starts from 60–65 W (Fig. 3), but at the same time the structure shows instability due to intensive destruction of adjacent layers. It is recommended to work in the range (45 ... 60) W using multi-pass mode to achieve machining accuracy without thermal degradation and defects. Cooling of the samples and washing with distilled water after engraving ensure the stability of the results [22].

If to limit ourselves to the depth of the destructive layer up to 12 microns, then for AERO Laserrubber, OLIO Laserrubber and TEMPO Laserrubber rubber, the experimentally established acceptable power of the CO_2-laser lies within (35 ... 50) W. This simultaneously ensures consistent sample quality without microcracks or local remelting. This is facilitated by the vulcanization homogeneous mesh structure and the presence of titanium dioxide, which contributes to uniform energy absorption over the entire plane of exposure to CO_2-laser radiation. When setting up the technological process of CO_2-laser treatment of these materials according to the criterion of acceptable depth of the destructive layer, it is appropriate to use the dependencies given in Table 7.

Limitations for CLASSICO Laserrubber and ECO Laserrubber tires. These types of materials have an uneven microstructure and, probably, the inclusion of mineral fillers or a microporous structure, which causes heterogeneous absorption of thermal energy. Therefore, CO_2-laser radiation powers of more than 60 W can lead to local overheating of the material, carbonization of the top layer, or even microcracks. The reaction of such materials during processing can be non-linear. In this regard, it is advisable to use a multi-pass processing mode, for example, two passes at the power of a CO_2-laser (40 ... 45) W, or intermediate cooling mode. At the same time, at each stage of processing, it is possible to predict the size of the destructive layer according to the formulas of Table 7.

Regardless of the type of material, when the power of the CO_2-laser exceeds 60 W, the following risks are recorded: excessive local heating, carbonization and blackening of the edges, loss of geometric stability of the groove, deterioration of the accuracy of the product. Such effects are especially dangerous in the production of elements where high repeatability and stability of the profile is required.

Each type of rubber has its own power range to obtain a stable quality result, since it depends on the heat resistance, structure, crosslinking density and formulation. Therefore, before introducing laser engraving of a new material in the production process, it makes sense to conduct preliminary testing and analyze the graphs of the dependence of the depth of the destructive layer on the laser processing mode. Especially when extreme modes are assumed when the power limit is exceeded CO_2-laser 60 W.

The studies are limited by the spectrum of rubbers considered (AERO Laserrubber, CLASSICO Laserrubber, ECO Laserrubber, OLIO Laserrubber, TEMPO Laserrubber), the CO_2-laser modes applied, in particular the level of radiation power (30 ... 80) W.

The disadvantages of the study include the fact that the work does not consider the influence of a number of technological parameters on the size of the destruction zone: the speed of movement of the laser beam, the wavelength of radiation, methods and modes of cooling, and others. These studies require separate experiments.

In further research, it is planned to investigate a wider range of rubber produced by Trodat GmbH in order to determine the power modes of the CO_2-laser to obtain products of the desired quality.

7. Results

1. Complied experimental investigations made it possible to obtain data on the depth of the destructive layer of most common specialized rubbers AERO Laserrubber (gray color), CLASSICO Laserrubber (gray color), ECO Laserrubber (green), OLIO Laserrubber (black), TEMPO Laserrubber (orange) at different levels of CO_2-laser power.

2. Experimental data processing results the dependence of the destructive layer depth on the power of the CO_2-laser for five types of investigated specialized rubbers. The hypothesis regarding the direct dependence of the destructive layer depth on the power of the CO_2-laser has been confirmed. Approximating relationships of the second level with enough for engineering level calculations accuracy provide to forecast the sample quality by the destructive layer depth taken as a criterion.

For practical implementation an important feature was discovered that stateted a sustainable increasing the depth of the destructive layer on average by (1.0 ... 1.2) μm every 5 W of power. It has been experimentally established if the depth of the destructive layer is limited by 12 μm the acceptable power of the CO_2-laser should be within (35 ... 50) W. For CLASSICO Laserrubber and ECO Laserrubber rubber, the intensive growth of the destructive layer depth starts only with (60 ... 65) W and tends to accelerate.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal nature, authorship or other nature, which could affect the study and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence tools

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

References

1. Verhun, O., Oleksiienko, O. (2023). Effect of actual adhesive strength on determination of application conditions for sealing polymer materials. Science and Construction, 35 (1). https://doi.org/10.33644/2313-6679-1-2023-5
2. Mitsyk, A. V. (2022). Mathematical simulation of the deformation of the part material surface layer during its finishing and grinding processing with metal balls in the vibration polishing operation. Visnik of the Volodymyr Dahl East Ukrainian National University, 2 (272), 46–51. https://doi.org/10.33216/1998-7927-2022-272-2-46-51
3. Dobrotvorskyi, S. S., Khavin, H. L., Basova, Ye. V., Aleksenko, B. O., Prykhodko, V. O. (2024). Shorstkist poverkhni pry lazerniy obrobtsi nerzhaviyuchoi stali. Kharkiv: NTU "KhPI", 167. https://doi.org/10.20998/978-617-05-0513-2

4. Mushtaq, R. T., Wang, Y., Rehman, M., Khan, A. M., Mia, M. (2020). State-Of-The-Art and Trends in CO_2 Laser Cutting of Polymeric Materials – A Review. Materials, 13 (17), 3839. https://doi.org/10.3390/ma13173839
5. Kameyama, N., Yoshida, H., Fukagawa, H., Yamada, K., Fukuda, M. (2021). Thin-Film Processing of Polypropylene and Polystyrene Sheets by a Continuous Wave CO_2 Laser with the Cu Cooling Base. Polymers, 13 (9), 1448. https://doi.org/10.3390/polym13091448
6. Kameyama, N., Yoshida, H. (2022). Thermal Effect on Thin-Film Formation of the Polymer Sheets by the CO2 Laser with the Copper Base. Polymers, 14 (17), 3508. https://doi.org/10.3390/polym14173508
7. Lieber, S. C., Varghese, A. P., Tarantino, R., Tafuni, A. (2023). Additive manufacturing for plastic extrusion die tooling: A numerical investigation. CIRP Journal of Manufacturing Science and Technology, 41, 401–412. https://doi.org/10.1016/j.cirpj.2023.01.003
8. Schmidt, B., Rose, M., Zimmermann, M., Kästner, M. (2021). Analysis of process-induced damage in remote laser cut carbon fibre reinforced polymers. Journal of Materials Processing Technology, 295, 117162. https://doi.org/10.1016/j.jmatprotec.2021.117162
9. Karamimoghadam, M., Dezaki, M. L., Zolfagharian, A., Bodaghi, M. (2023). Influence of post-processing CO2 laser cutting and FFF 3D printing parameters on the surface morphology of PLAs: Statistical modelling and RSM optimisation. International Journal of Lightweight Materials and Manufacture, 6 (2), 285–295. https://doi.org/10.1016/j.ijlmm.2023.01.004
10. Munoz, A., Schmidt, J., Suffet, I. H. M., Tsai, C. S.-J. (2023). Characterization of Emissions from Carbon Dioxide Laser Cutting Acrylic Plastics. ACS Chemical Health & Safety, 30 (4), 182–192. https://doi.org/10.1021/acs.chas.3c00013
11. Ham, S. S., Lee, H. (2020). Surface Characteristics of Polymers with Different Absorbance after UV Picosecond Pulsed Laser Processing Using Various Repetition Rates. Polymers, 12 (9), 2018. https://doi.org/10.3390/polym12092018
12. Riveiro, A., Maçon, A. L. B., del Val, J., Comesaña, R., Pou, J. (2018). Laser Surface Texturing of Polymers for Biomedical Applications. Frontiers in Physics, 6. https://doi.org/10.3389/fphy.2018.00016
13. Ruan, X., Wang, R., Luo, J., Yao, Y., Liu, T. (2018). Experimental and modeling study of CO_2 laser writing induced polyimide carbonization process. Materials & Design, 160, 1168–1177. https://doi.org/10.1016/j.matdes.2018.10.050
14. Anjum, A., Azharuddin Ali, M., Shaikh, A. A., Akhtar, S. S. (2024). A numerical and experimental analysis of CO_2 laser micro-milling on PMMA sheet considering a multipass approach for microfluidic devices. Optics & Laser Technology, 176, 110860. https://doi.org/10.1016/j.optlastec.2024.110860
15. Volova, T. G., Golubev, A. I., Nemtsev, I. V., Lukyanenko, A. V., Dudaev, A. E., Shishatskaya, E. I. (2021). Laser Processing of Polymer Films Fabricated from PHAs Differing in Their Monomer Composition. Polymers, 13 (10), 1553. https://doi.org/10.3390/polym13101553
16. Ahmad Sobri, S., Chow, T. P., Tatt, T. K., Nordin, M. H., Hermawan, A., Mohamad Amini, M. H. et al. (2025). Optimization and Validation of CO_2 Laser-Machining Parameters for Wood–Plastic Composites (WPCs). Polymers, 17 (16), 2216. https://doi.org/10.3390/polym17162216
17. Kashihara, K., Uto, Y., Nakajima, T. (2018). Rapid in situ synthesis of polymer-metal nanocomposite films in several seconds using a CO_2 laser. Scientific Reports, 8 (1). https://doi.org/10.1038/s41598-018-33006-9
18. Chen, X., Hu, Z. (2018). Study aspect ratio of microchannel on different polymer substrates with CO_2 laser and hot bonding for microfluidic chip. AIP Advances, 8 (1). https://doi.org/10.1063/1.5012772
19. Ravi-Kumar, S., Lies, B., Lyu, H., Qin, H. (2019). Laser Ablation of Polymers: A Review. Procedia Manufacturing, 34, 316–327. https://doi.org/10.1016/j.promfg.2019.06.155
20. LaserBot-900. Available at: https://bot-ua.com/shop/co2/laserbot-900/?v=d41d8cd98f00
21. LightBurn. Available at: https://lightburnsoftware.com/
22. RUIDA RDWorks Software. Available at: https://www.ruidacontroller.com/ruida-rdworks-software/
23. MT Pro Single/Multi-Channel Integrated Interferometer. Available at: https://en.dimension-tech.com/productdetail/6.html
24. Classico. Laser rubber for text plate production, 60 Shore-A. Available at: https://www.trodat.net/int/en/shop/product/Products-International/Production-Materials/Laser-Rubber/Classico
25. Pukhalska, H. V., Porvin, I. E. (2020). Lazerne markuvannia. TYZhDEN NAUKY-2020. Zaporizhzhia, 21–22. Available at: https://zp.edu.ua/uploads/dept_s&r/2020/conf/4.1/TN_2020-MF.pdf
26. Munirathinam, B., Lerch, L., Hüne, D., Lentz, L., Lenk, T., Görke, M. et al. (2022). Enhanced Performance of Laser-Structured Copper Electrodes Towards Electrocatalytic Hydrogenation of Furfural. ChemElectroChem, 9 (22). https://doi.org/10.1002/celc.202200885