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Development and Research of the Laser Engraving Process in Packaging Manufacturing Technology

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1. Introduction

Laser processing of materials used in packaging manufacture mainly includes laser cutting, engraving and marking. In work [1], the possibility of marking PVC products used in the electronics industry by means of a CO_2 laser system is examined. The functional dependencies of the marking-line width and depth on the main technological parameters –average power and processing speed – are analyzed. This analysis helps determine the optimal ranges of speed and power for achieving a desired ablation-zone geometry in marking and engraving for different users.

The variety of materials studied in the packaging industry using this technology is extremely broad. In work [2], the process route for obtaining processing-parameter data is formulated by first performing engraving tests and then using those data for laser engraving. Through experiments on a wide range of materials – such as wood, bamboo, paper, plastic, leather goods, PCBs, acrylic, glass, and paint layers – the changes in laser engraving with respect to laser intensity, engraving speed, and black-and-white contrast are studied. The physical process of laser engraving is analyzed, and successful engraving of different materials is achieved using the optimized parameters obtained experimentally.

Work [3] investigates the effect of CO_2 laser cutting of thin plates made from MEX WPLA filament on mean kerf width (Wm) and mean surface roughness (Ra). Wood powder flour blended with thermoplastic polylactic acid (WPLA) is an eco-friendly composite material used in filament-based extrusion (MEX) additive manufacturing. Paper [4] presents the optimization of wood laser-engraving process parameters based on the Taguchi method and analysis of variance (ANOVA). The main parameters in experimental wood-surface laser engraving include laser power (P), engraving speed (S), number of engraving lines per millimeter (L), and engraving-head focal height (H). The surface geometric dimensions –engraving width (B) and engraving depth (D) – are the key factors that determine line performance and product aesthetics.

A significant number of publications are devoted to laser processing of metals. In work [5], the optimum laser parameters required for Inconel 625 alloy surfaces to exhibit desired properties were determined. Process parameters were optimized to achieve maximum heat-affected-zone depth (HAZ) and width, maximum aspect ratio, and minimal defects outside the spot area, independently. The effect rates of the examined process parameters on each quality characteristic of the treated surface were also determined.

Because of its short processing time and the absence of wastewater or oil, the CO_2 laser is applied as an environmentally friendly thermal treatment for wood materials to improve properties such as appearance, color, and wettability. However, the morphological features of the treated wood surface also change, which can negatively affect product performance. To reveal trends in surface-roughness change during laser irradiation, the common indices of average roughness (Ra) and mean peak-to-valley height (Rz) were chosen for evaluation [6].

Article [7] deals with laser cutting of wood and wood composites. Laser cutting of these materials is widely accepted and used in the wood industry. The goal of this research was to optimize the cutting parameters of spruce wood (Picea abies L.) using a low-power CO_2 laser. The influence of three factors was investigated: laser power (100 and 150 W), cutting speed (3, 6, and 9 mm/s), and the number of annual rings (3–11). Paper [8] discusses the surface properties of beech wood treated by CO_2 laser engraving.

Researchers [9] believe that the assist gas plays a central role in laser cutting. This work examines the aerodynamic interaction between the assist gas and the workpiece, providing insight into the phenomena that impede cutting quality and productivity.

In machining large-sized parts, one of the most important problems is the long processing time. Hence, it is very important to find new methods to save machining time. Research [10] presents the idea of a cooperative laser-engraving system in which a work area is divided into multiple sections, each assigned to a different laser head. The various laser heads process their assigned sections simultaneously, and all finished sections are then integrated to realize the target geometry in a shorter time compared to traditional engraving by a single laser head. This work aims to study the feasibility and industrial applicability of this concept.

Authors of [11] conducted experimental studies on laser engraving of paper packaging. First, they investigated various phenomena occurring during paper engraving—such as plant-fiber combustion, charcoal formation, and edge discoloration; second, they Equally relevant is the study of laser engraving in the manufacture of packaging from wood-fiber materials (HDF, MDF, plywood). Progress in this field is based on further improvement of laser-radiation characteristics: broadening the emission-wavelength range, increasing frequency stability, raising pulse-radiation intensity, improving efficiency, and enhancing spatial coherence, among other advances.

2. Problem Description and Formulation

The task of optimizing laser material processing is largely determined by the physical processes occurring within the material, as the classification of lasers based on the physical characteristics of the active medium is the most widespread. Identifying the nature of thermophysical processes will enable the distribution of laser radiation energy, thereby increasing equipment efficiency and improving product quality.

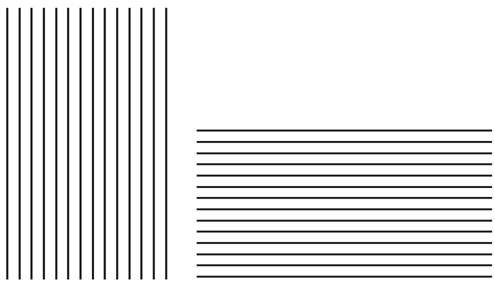
Based on the analysis of material characteristics, the physical essence, and the technological process of laser engraving, experimental studies should be conducted to investigate the influence of CO_2 laser radiation parameters on the engraving process of wood-fiber materials. These materials are widely used in the printing industry for the production of packaging, souvenirs, advertising, and display products, among others.

3. Research methods and equipment

Experimental studies of the laser engraving process were carried out using a carbon dioxide (CO_2) TS1390 laser machine with a wavelength of 10.6 μm. The control panel of the laser machine is equipped with a monitor that displays speed, power, task processing time, file size, and allows real-time adjustment of processing parameters during operation. The image layout was developed using COREL DRAW software.

High Density Fiberboard (HDF), a wood-based product with a modern white-painted surface and a thickness of 3 mm, was chosen as the packaging material.

The engraving process was performed by varying the laser power from 30 to 50 W and the engraving speed from 150 to 300 mm/s, with an engraving step of 0.635 mm. To assess the quality of the laser seam, 14 lines with a thickness of 1 point were engraved on the HDF material in both the longitudinal (Fig. 1, a) and transverse (Fig. 1, b) directions relative to the laser tube axis. Based on the experimental studies, optimal processing parameters were identified to achieve the highest engraving quality on HDF-based packaging materials.



a b

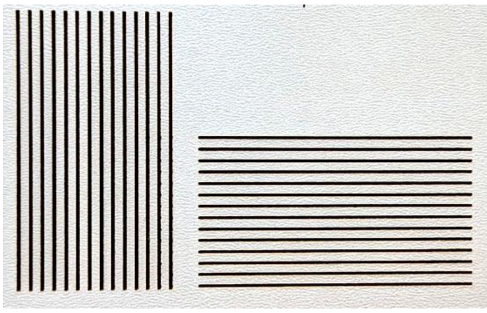
Fig. 1 Scale for assessing the quality of a laser seam in the longitudinal (a) and transverse (b) directions

4. Results and Discussion

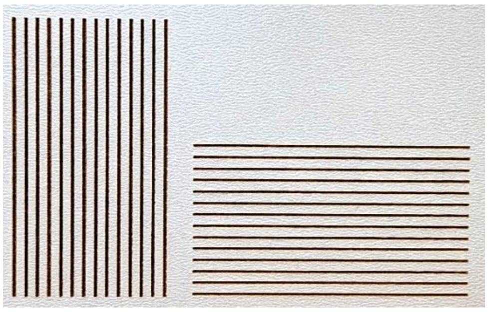
Characterized by outstanding properties such as low beam divergence, high brightness, excellent monochromaticity, and coherence, lasers have taken a significant place in many fields: information and communication, biomedicine, scientific research and military applications, as well as industrial manufacturing. Their areas of application continue to expand, as lasers simplify and reduce the cost of manufacturing processes for small production runs, while enhancing product performance and durability.

The process of laser engraving natural and synthetic materials is used as a technological tool across various ranges and operating modes. In the printing industry, this technology is applied in the production of packaging, personalized products, seals and stamps, printing plates for various printing methods, book covers, postcards, business cards, product marking, and more.

Laser engraving modes are highly adaptable to the surface characteristics of the processed items, allow for automation, and offer excellent mechanical and physicochemical properties in terms of laser-material interaction. With these advantages, laser engraving is recommended for applying text and images to complex-shaped parts and materials with special properties. It also enables the inclusion of additional customer-specific information beyond the standard content block.



a



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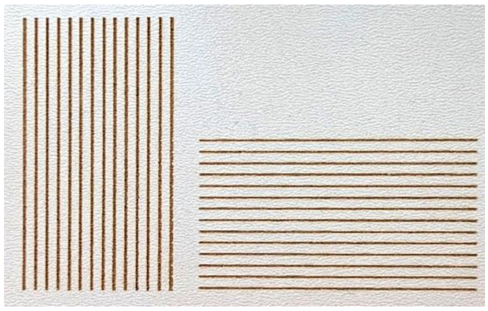


c

Fig. 2 Engraving process with speed: a – 150 mm/s, b – 300 mm/s, c – 500 mm/s and power 40 W

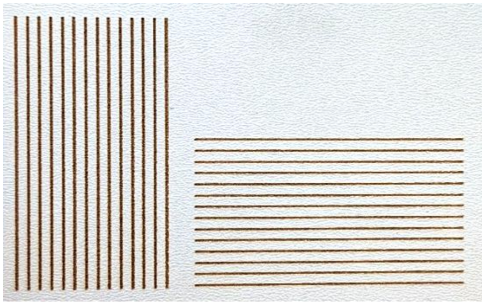
The technological process of laser engraving includes the following operations:

1. Preparation of the computer workstation and the laser system;
2. Creating a design layout for laser engraving using CorelDRAW software and verifying the correctness of all text and elements according to technical specifications;
3. Setting the main technological parameters for engraving;

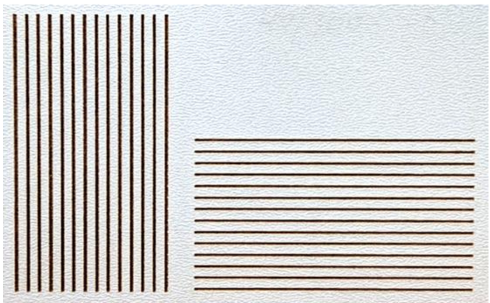
4. Adjusting the focal distance. To do this, place the workpiece on the working table and check the focal distance from the laser system lens to the surface of the workpiece using a template;
5. Optimizing the engraving parameters based on the quality of the applied markings;
6. Performing the engraving process;
7. Visual and electron-microscopic quality control of the engraving.

During laser engraving, the speed of the laser beam movement and the power of radiation are interdependent factors. To determine the optimal beam movement speed, experimental studies were conducted at engraving speeds of 150 mm/s (Fig. 2, a), 300 mm/s (Fig. 2, b), and 500 mm/s (Fig. 2, c), with a power of 40 W. Increasing the engraving speed to 500 mm/s (Fig. 2, c) results in a decrease in image contrast. The lower the speed, the greater the scanning depth at the same energy level, resulting in a thicker engraved line and, consequently, lower resolution. Conversely, the higher the speed, the shallower the engraving depth at the same energy, but the distortion of details increases.

Based on the analysis of the experimental results, the optimal laser engraving quality was achieved at a speed of 300 mm/s. Therefore, subsequent studies were conducted at a constant engraving speed of 300 mm/s in order to determine the optimal laser power: 30 W, 40 W, and 50 W (Fig. 3).



a



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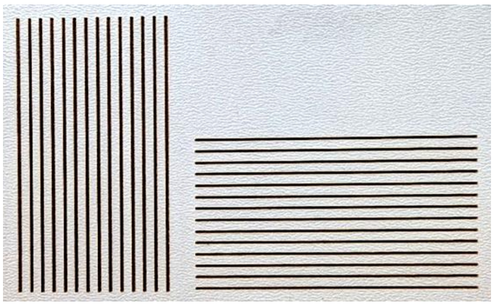

c

Fig. 3 Engraving process at a speed of 300 mm/s and power: a – 30 W, b – 40 W, c – 50 W

An increase in laser power leads to a greater engraving depth and an increase in the width of the engraved line by up to 20%, depending on the power level. To achieve the sharpest image without deviations in linear dimensions relative to the design layout, it is advisable to use the following engraving settings (Fig. 3, b): speed – 300 mm/s and power – 40 W.

If the goal is to obtain an image with maximum contrast, it is recommended to increase the power to 50 W while maintaining the same engraving speed (Fig. 3c). However, this may result in a slight increase in the width of the engraved layer.

According to the images (Fig. 4), the engraved line follows a zigzag pattern, indicating that the oscillation period differs between the longitudinal (Fig. 4, a) and transverse (Fig. 4, b) directions. In Fig. 4, c (longitudinal direction), an increase in the thickness of the laser-engraved line of up to 50% can be observed, along with greater irregularity compared to the transverse direction (Fig. 4, d). Depending on the nature of the image, this should be taken into account when positioning the workpiece either transversely or longitudinally relative to the movement axis of the laser beam.

The low precision of the engraved line when working with fine details in the longitudinal direction is due to the laser not having enough time to reach its full power. Additionally, an uneven edge at high engraving speeds may be caused by belt tension and the play (backlash) between the toothed belt and the gear teeth of the drive mechanism. This play can have both negative and positive values, which are adjusted using the compensation value ***d*** in the laser machine's settings for each speed individually (Fig. 5).

After selecting the appropriate laser processing parameters for HDF material, both contour engraving (where

a b c d

Fig. 4 Result of laser engraving of lines in longitudinal and transverse directions: a – longitudinal direction, b – transverse direction, c – longitudinal (5x magnification), d – transverse (5x magnification)

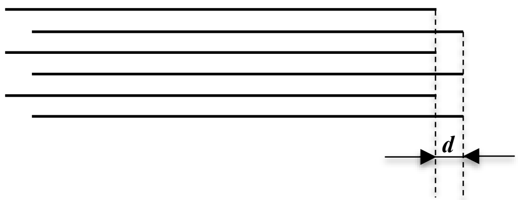

Fig. 5 Compensation value ***d*** for uneven edge during engraving

a b

Fig. 6 Laser engraving at a speed of 300 mm/s and power of 40 W: a – contour engraving, b – solid engraving

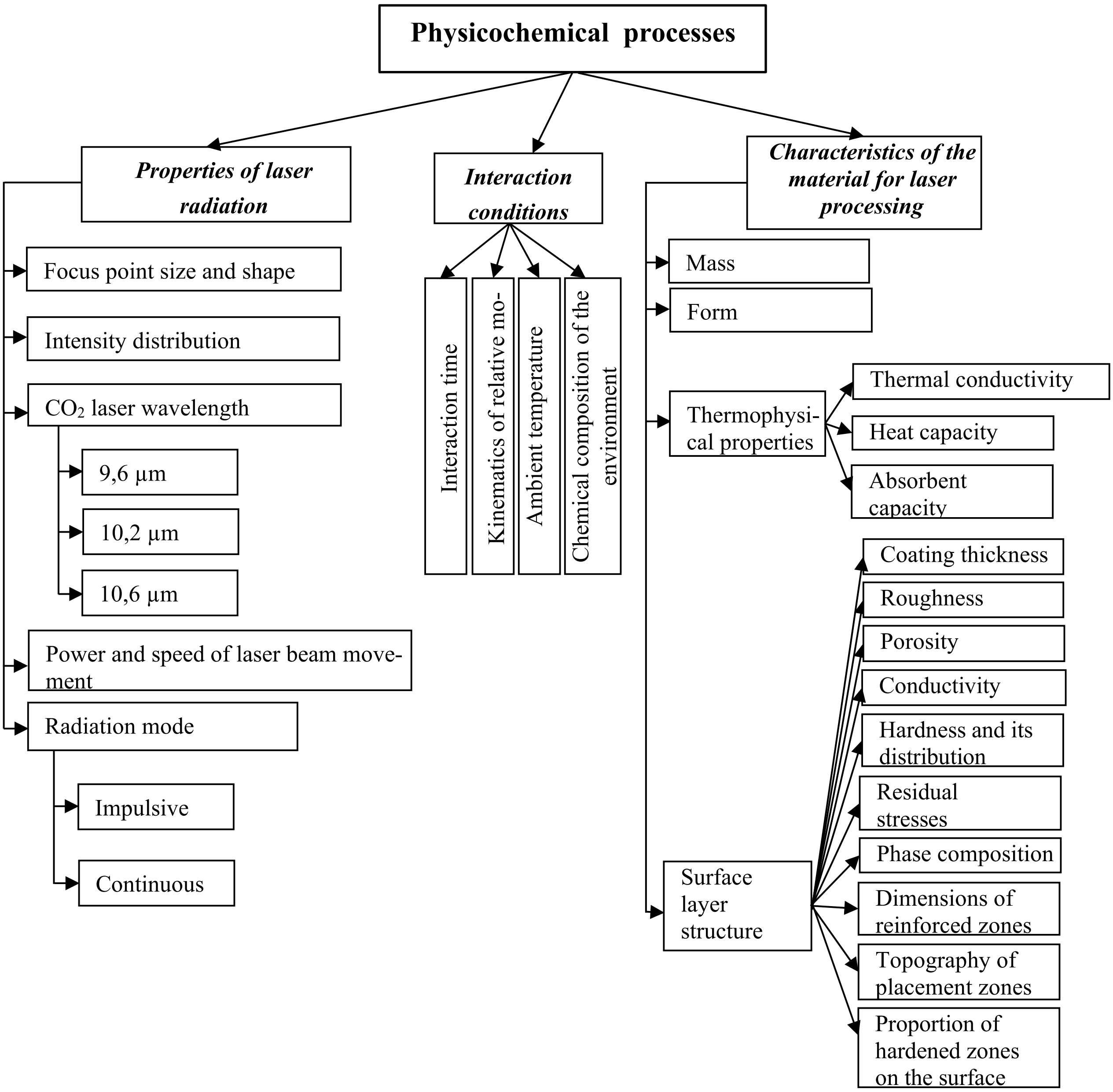

Fig. 7 Laser surface treatment as a technological system

the laser beam engraves only the outlines of the image) (Fig. 6, a) and solid engraving (removal of parts of the image from the material, creating a relief on the surface) (Fig. 6, b) were performed on packaging at a speed of 300 mm/s and a power of 40 W.

Under the influence of high-power laser radiation, various physico-chemical processes occur within materials. The nature and type of these processes are determined by temperature, duration, and the rates of heating and cooling, which in turn depend on the energy and geometric characteristics of the laser beam, the properties of the processed material, the geometric shape and mass of the workpiece, the technological processing scheme, and other factors.

Based on experimental studies, the main characteristic of laser-material interaction is its thermal nature. The wide variety of possible effects can be controlled by manipulating three main parameters:

- laser parameters,
- material properties,
- processing modes.

Thus, by implementing a specific combination of these parameters, it is possible to induce desired physicochemical processes in a particular material and impart the necessary surface properties (structure, phase composition, hardness, stress state, wear resistance, etc.).

However, to achieve the desired result and ensure its reproducibility, it is essential to establish correlations between thermal state parameters (conditions of laser radiation) and the corresponding quality and performance characteristics of the material's surface layer. To this end, laser surface processing should be considered as a comprehensive technological system that includes all relevant factors and parameters, with appropriate—ideally formalized—interrelationships established between them (Fig. 7).

The first group of factors includes the direct characteristics of the laser beam that forms the heat source; the second group includes the characteristics of the processed workpiece; and the third group comprises the characteristics of the interaction conditions between laser radiation and the material.

The most important parameters of the laser beam during surface processing are the wavelength of the radiation, the shape and size of the focal spot, and the distribution pattern of radiation intensity within the focal spot. Depending on the power, both continuous and pulsed radiation modes are possible.

The characteristics of the processed workpiece, which constitute the second group of factors, include the geometric parameters and mass of the product, and its thermophysical properties, such as thermal diffusivity, thermal conductivity, heat capacity, and absorptivity.

The structure of the surface layer is defined by the chemical composition of the material (grain size, roughness, porosity, thickness, hardness, electrical conductivity, dispersity, etc.), all of which influence the process of radiation energy absorption and transfer.

The main characteristics of the third group of factors include the interaction time, kinematics of relative motion, temperature, pressure, and chemical composition of the environment, and the angle of incidence of the laser beam on the surface of the material. All these factors influence the thermal state of the surface layer and must be taken into account when studying, modeling, and developing laser surface treatment processes.

However, in practical terms, only some of these factors are controllable:

- power or energy of the radiation,
- speed of laser beam movement,
- size and shape of the focal spot,
- intensity distribution in the focal spot,
- surface absorptivity.

One of the defining characteristics of different laser types is the generated wavelength. Every material has a characteristic absorption spectrum, meaning that it absorbs certain wavelengths of light more effectively than others. When the laser's wavelength matches the material's absorption spectrum, the processing results are more efficient and the duration of the process is reduced.

CO_2 lasers emit in the infrared region of the spectrum, approximately 9.2–10.6 µm, with 10.6 µm being the most commonly used wavelength. The radiation from CO_2 lasers matches the absorption spectra of polymers, ceramics, textiles, and natural materials such as paper, cardboard, and wood. Light sources that generate shorter wavelengths, such as Nd:YAG or fiber lasers, are better absorbed by metals.

The experimental studies conducted have made it possible to determine the main performance characteristics of laser engraving on workpieces (Fig. 8).

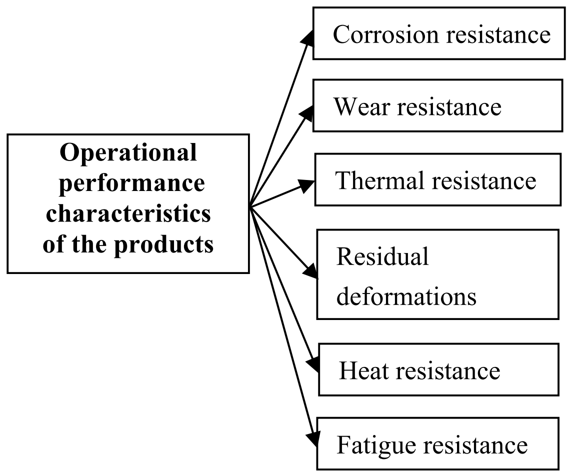

Fig. 8 Operational performance characteristics of the products during laser engraving

Key features of laser engraving are:

- Exceptional precision: The laser beam provides minimal error, which is very important for small details;
- No contact: The laser beam acts locally, without deforming or damaging the material, which is important for complex logos, serial numbers, or decorative elements;
- Speed of operation: Thanks to high productivity, processing costs are reduced;
- Versatility: A wide variety of materials can be engraved;
- Durability: Laser engraving provides stable results, which is important for anti-counterfeiting;
- Cost-effectiveness: Although laser technology might seem more expensive at first, it proves to be more cost-effective in the long term;
- Savings on consumables: Laser systems do not require additional materials such as chemicals or cutting tools;
- Minimal maintenance: Laser systems have a long service life and only require repair in exceptional cases;
- Environmental friendliness: Laser technology does not require the use of chemicals, making it safe for the environment.

Laser engraving is ideal for industrial applications where high-quality standards and compliance with environmental requirements are crucial. This method allows the creation of unique and durable designs without damaging the material, making it the best choice for modern production.

5. Conclusions

Laser engraving, as one of the methods of laser processing, is widely used in the printing and packaging industries for the production of packaging due to the simplification and cost reduction of the technological process for small-batch production, as well as the enhancement of performance characteristics and durability.

In this study, a technological process for both contour and solid laser engraving was developed for 3 mm thick HDF material and tested under various processing modes. The experimental research revealed an interdependence between the laser beam's movement speed and the radiation power.

To achieve the clearest image without deviation in linear dimensions relative to the design layout, optimal parameters were determined: a laser movement speed of 300 mm/s and a power of 40 W.

It was also found that the direction of engraving—longitudinal vs. transverse—affects the accuracy of the engraved line.

Based on experimental studies, a comprehensive technological system was developed that includes all relevant factors and parameters, along with the corresponding, including formalized, interrelations among them. The key performance characteristics of laser-engraved products were also identified.

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DEVELOPMENT AND RESEARCH OF THE LASER ENGRAVING PROCESS IN PACKAGING MANUFACTURING TECHNOLOGY

S u m m a r y

The areas of application of carbon dioxide lasers in the printing industry are given. A technological process for laser engraving of packaging made of wood-fiber materials has been developed. Experimental studies of the influence of the parameters of CO_2 laser radiation on the engraving process of HDF material, which is widely used in the packaging industry, have been conducted. The dependence of the engraving depth on changes in the speed and power of laser radiation has been studied. Based on the experimental studies conducted, the main operating, technological and operational factors affecting the quality of engraving have been identified.

Keywords: laser technologies, engraving, CO_2 laser, laser power, packaging, wood-fiber materials, HDF.

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