Analysis of the process of laser ablation of marble surfaces

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Abstract. Over the last decade, laser surface treatment of stones has gained increasing scientific interest. New technologies and processes based on different types of laser sources and processing modes are being studied. This report examines the process of laser ablation of a marble surface using a fiber laser. Three factors influencing the process of laser marking and engraving were studied: laser power, processing speed and step between raster lines. The functional dependencies between these factors and the contrast of the obtained graphic image are established. The optimal operating intervals for this group of technological parameters are analyzed.

Thanks to the very-high-definition laser ablation, inscriptions, drawings and images can be re-created and processed with unique accuracy. In addition, the reduction of manufacturing time and resources used in the process makes this technology an environmentally-friendly and extremely cost-efficient solution.

1. Introduction

In the last few years, laser technology has developed extremely rapidly. Lasers are used in various fields – in science, industry, medicine, electronics, etc., due to their specific properties.

Over the last decade, laser surface treatment of stones has gained increasing development in various applications in the design and jewelry industry, in the manufacture of monuments and memorial plaques, cleaning of sculptural figures, among many others. [1–5].

A number of research laboratories are developing new technologies based on different types of laser sources and modes of processing by laser ablation on different types of natural stones. The physical process of laser radiation interaction with the stone is one of the areas that has not been sufficiently researched.

A major part of the technology developed so far has been based on the use of CO₂ lasers. Various types of laser technology for stone surface treatment have been offered on the market mainly with a CO₂ laser source. Marking of natural stones, such as granite, marble or slate, with dark spots is indicated as successful solutions.

In recent years, due to the needs of the market for automated decipherment of information and protection of intellectual property of the manufacturer, the need for laser marking as barcodes and QR codes has increased significantly. In this type of marking, it is important to achieve the necessary contrast and to preserve the applied information throughout the working life of the detail [6–9]. This requires mandatory preliminary research of the type of technology in order to achieve the required quality of the marking in relation to the factors that affect the physics of the process [10–12].
The aim of the present study is to analyze the influence of specific technological parameters, such as power, processing speed and step between raster lines on the process of marking by a fiber laser with wavelength $\lambda = 1640$ nm on samples of polished black marble.

2. Laboratory setup and materials used
In the experiments, a scanning system with a fiber laser emitting the wavelength $\lambda = 1640$ nm was used to mark polished black marble and to study the dependence of the contrast on the technological processing parameters.

The change in the mode of operation of the laser system is performed with the help of the specialized EZCAD software [13], which varies the technological parameters studied.

Figure 1 presents a general view and a schematic diagram of an experimental installation for marking with a fiber laser and a scanner. Table 1 provides some technical characteristics of the technological system.

![Figure 1. Scheme and general view of the experimental system for marking marble samples.](image)

Table 1. The technical parameters of the fiber laser marking system – RFL-P30Q.

| Laser type   | Fiber laser               |
|--------------|---------------------------|
| Laser source | Raycus 30W Pulsed Fiber   |
| Operating mode | Pulsed                   |
| Wavelength   | 1060 – 1085 nm            |
| Maximum power | 30 W                     |
| Frequency    | 20 ÷ 200 kHz              |

| Scanner     |               |
|-------------|---------------|
| Scanning head | GalvoScan     |
| Work area   | 200 mm × 200 mm|
| Focal length | 290 mm        |
| Scan speed  | 0 ÷ 3000 mm/s  |
| Positioning accuracy | 0.02 mm |

Marble is a metamorphic rock that consists of at least 50 percent by volume of the minerals calcite, dolomite or aragonite. Chlorite, epidote, mica, limonite, garnet, pyrite, quartz and serpentine are possible secondary parts. The characteristic feature of the marble is the so-called marbling, which can be present in the form of light and dark stripes running through the rock, grains, spots or veins and are an expression of the mineral admixtures. The grains in the marble are connected by direct adhesion of the crystals without a cementing substance (figure 2). As a result, marble has a high density $\rho_o = 2.60 – 2.75$ g/cm$^3$. 
Marble is soft with a hardness of 3 – 10 degrees Mohs scale and has a relatively high wear resistance, as well as low water absorption $W = 0.1 – 0.7\%$.

![Figure 2. Structure of marble samples.](image)

3. Factors affecting the process

The laser marking process is affected by a number of factors [12, 14–17]. They can be summarized in several groups related to:

- material properties – optical characteristics (reflection coefficient, absorption ability, absorption coefficient) and thermophysical characteristics (coefficient of thermal conductivity, coefficient of thermal diffusivity, thermal diffusion length);
- laser source – power, power density, pulse repetition rate and pulse duration, beam quality;
- technological process - speed, defocus, marking step, number of repetitions.

In our specific case of study, the factors most significantly influencing the laser marking of black marble specimens are presented in figure 3: power density $q_s$, marking speed $v$, focusing $f$, raster step $\Delta x$, color, number of repetitions $N$ in the processing area.

![Figure 3. Factors affecting the laser marking.](image)

4. Methodology

According to the experimental plan, the present study analyzes the influence of the power $P$, processing speed $\nu$ and step $\Delta x$ between raster lines on the contrast $k$, and hence, on the quality of the marking. The marking was performed by using the raster method shown in figure 4 (a). The used
methodology makes it possible to study the following dependences for the contrast $k$ on the technological parameters:

- $k = k(v)$ at constant power $P = \text{const}$
- $k = k(P)$ at constant speed $v = \text{const}$
- $k = k(\Delta x)$ at constant speed $v = \text{const}$ and power $P = \text{const}$

A marking matrix was used, i.e., the treated areas are squares with a side of 10 mm, with a distance between the squares of 2 mm (figure 4 (b)). The processing speed $v$ changes in the interval $v \in [100 \div 1000]$ mm/s with a step of 100 mm/s; the power changes with a step 10% in the interval $P \in [10 \div 100]$% (the values of $P$ as a percentage of the nominal maximum power 30 W). In each square, a single processing of the area is performed. A series of experiments to study the influence of the step between the raster lines $\Delta x$ was performed for three values $\Delta x = (0.02; 0.04; 0.06)$ mm at constant power $P = 70\%$ and speed $v$ varying in the interval $v \in [100 \div 1000]$ mm/s.

Due to its granular structure, marble is inhomogeneous and the resulting image after laser marking is also inhomogeneous. Therefore, when examining the contrast $k$, averaging is performed for each marked area. Every part of the processed area is analyzed with Photoshop graphics software. A method for averaging the value (Filter - Blur - Average) is applied. As a result, a homogeneous area is obtained, after which the level on the gray scale is taken into account. This is performed for each area studied within the entire range of experimental research.

The contrast $k$ in percent is determined by a reference scale, which is integrated into the raster processing software. With the help of this software, we read the values of the gray hue of the raster image of each zone, which can be represented as a number between 0 (black) and 255 (white).

The contrast $k$ is determined by linear interpolation from the expression

$$k = \frac{N_f - N_x}{N_f} \cdot 100\%.$$  

(1)

The values $N_f$ of the reflection from the untreated surface (base / background) and $N_x$ of each area treated with different technological parameters are evaluated.

5. Results

The results of the first series of experimental results are summarized in figure 5 graphically representing the dependencies of the contrast on the power $k = k(P)$ for the three different marking speeds: $v_1 = 300$ mm/s, $v_2 = 600$ mm/s and $v_3 = 900$ mm/s. The analysis of the graphs shows that:

- As the power increases, the contrast of the marking for the three tested speeds increases;
✓ For powers in the range $P \in [10, 50] \%$ the curves are very steep, which shows a high rate of contrast change;
✓ For powers in the range $P \in [50, 100] \%$, the dependence is linear and the contrast increases very slowly;

![Graph showing contrast as a function of laser power](image1)

**Figure 5.** Investigation of the laser power effect on the contrast $k$ of laser marking.

The results of the second series are summarized in figure 6 presenting graphically the dependences $k = k(v)$ for the three different powers: $P_1 = 20\%$, $P_2 = 30\%$ and $P_3 = 60\%$.

![Graph showing contrast as a function of marking speed](image2)

**Figure 6.** Investigation of the effect of the marking speed on the contrast $k$ of laser marking.

The analysis shows:
✓ When the speed increases, a nonlinear decrease in contrast is observed for all three speeds used;
For power \( P = 20\% \), the contrast has a very small value and is not suitable for marking;

- Power \( P = 30\% \) is suitable for distinguishing the marking by means of readers in the interval \( v \in [100, 290] \) mm/s;

- At power \( P = 60\% \) the marking is distinguished visually and by readers in a very wide interval – \( v \in [100 – 900] \) mm/s.

Figure 7 presents graphs of the dependence \( k = k(\Delta x) \) for black marble with polished surface and power \( P = 70\% \).

After analyzing the graphs obtained, the following conclusions can be made:

- As the step increases, a decrease in contrast is observed for all examined marking speeds;
- For a step \( \Delta x = 0.04 \) mm, the contrast is about 10% higher than that for a step \( \Delta x = 0.06 \) mm;
- For a step \( \Delta x = 0.02 \) mm, the contrast is about 11% higher than that for a step \( \Delta x = 0.04 \) mm;
- A step \( \Delta x = 0.10 \) mm, a threshold value at which no change in the treatment area is observed. This is the reason why the graph of the dependence of the contrast on the speed in this step is not presented.

6. Conclusions

The following conclusions can be drawn from the experimental studies for laser marking of black polished marble by means of a fiber laser:

- The granular inhomogeneous structure of the marble creates an inhomogeneous area in the places of laser marking. Thus, the laser marking parameters must be optimized for each specific sample treated.
- The optimal ranges for marking with good contrast samples of polished black marble are: speed in the in the interval \( v \in [500, 1000] \) mm/s and powers \( P \in [50, 80]\% \). These were used to produce the graphic images in figure 8 (b).
Figure 8. Four characteristic zones of laser action in the studied matrix as a function of processing speed and power (a).

- As a result of the laser light impact on the surface of the material in the studied intervals of speed and power, five zones were clearly outlined (figure 8 (a)):
  - **zone 0** – no changes in the surface structure.
  - **zone 1** – interaction threshold (the ablation process starts in the power interval \( P = 10 – 20\% \) and speed interval \( \nu \in [200 – 700] \text{ mm/s} \).)
  - **zone 2** – of gray tint on the processed area (in intervals \( P \in [30–40]\% \) and \( \nu \in [200 – 900] \text{ mm/s} \).)
  - **zone 3** – area of maximum contrast. It is suitable for laser marking with speed \( \nu \in [500 – 1000] \text{ mm/s} \) and power \( P \in [50 – 80]\% \). As a result of the laser interaction and ablation of the surface of the samples, white engraving is created with a very good contrast \( k = 50\% – 60\% \) to the dark background of the black marble samples.
  - **zone 4** – melting threshold. Areas of melting and partial boiling on the surface are observed in this zone. After cooling, foaming of the processed area of marble is observed, a clear relief is obtained.

In the future, research is planned to study the effect on marble marking of the focal length, defocusing, color of the marking, number of repetitions, and addition of inert gas.

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