Laser marking and engraving of household and industrial plastic products

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Abstract. Laser marking and engraving has developed in many ways into an attractive process for identifications of consumer goods made of plastic. It is a quick and inexpensive process that offers a variety of flexible options for designing identification products (barcodes, security information, codes). This report examines the possibility of marking PVC products used in the electronics industry with different colors using a CO$_2$ laser technological system. The functional dependences of the width and depth of the marking lines on the main technological parameters – average power and processing speed, are analyzed. The analysis aims to help determine the optimal working intervals for marking and engraving by the bar coding method, as well as for the coding and reading of information on household PVC products used by visually impaired people. The analysis further aims to help determine the optimal operating intervals of speed and power when choosing a given geometry of the ablation zone in marking and engraving products for different users.

Keywords: laser marking, plastic products, CO$_2$ laser, PVC products, cable marking

1. Introduction
PVC is now one of the world’s major polymers and a large amount of PVC is produced worldwide because of its superior mechanical and physical properties [1]. PVCs have a relatively low intrinsic thermal stability; however, its amorphous nature allow it to mix easily with many different substances that can be used to tailor the properties of the PVC products within certain limits [2, 3]. The poor thermal stability of PVC is attributed to structural defects formed during polymerization [4].

Laser marking can be used in various technological processes. A laser marking device can be readily integrated into a production line. The marking is easily legible, abrasion-resistant and can be applied to areas which are difficult to access by conventional marking methods [5]. In many branches of industry, the direct marking on the product method (DPM) is used to allow identification of the final industrial product [6, 7].

Bitay has researched the markability of PVC-coated automotive insulation cables by 1064 nm and 532 nm laser beams [8]. Blazevska-Gilev et al. has studied the effects of IR laser ablation of PVC [9].

Laser systems of different wavelengths can be used to create markings on PVC. UV lasers (such as excimer lasers) cause a color change through pigmentation, but IR lasers produce ablation and carbonization of thermoplastic materials. A laser mark is created by the insulation absorbing the electromagnetic energy and the subsequent alteration of the polymer to create a visible and contrastable
The quality of a mark is assessed by the mark contrast – the width and depth of its characters [11, 12]. The material's color affects the amount of energy absorbed by PVC. In cases where it is not possible to create a contrasting mark, it is possible to create a legible mark by selectively melting the PVC surface. This can be carried out by a CO\textsubscript{2} laser system [10].

CO\textsubscript{2} lasers emit electromagnetic radiation in mid-IR range (\(\lambda = 10620\) nm), which interacts with polyvinyl chloride by causing thermal degradation and sublimation or vaporization of the material [13]. Many organic polymers (including PVC) are strongly absorbing this wavelength. The main process occurring during laser light interaction with PVC is dehydrochlorization. In the initial stages of degradation, HCl starts “zipping off” from the polymer backbone, resulting in the formation of polyene sequences [13].

The aim of this study is to find the method and optimal parameters of applying information on the surface of different colored types of PVC cables by a CO\textsubscript{2} laser, so that it meets the conditions for both visual and automated reading of the recorded information. Two of the most important factors that affect the quality of the marking are the depth and width of the characters marked/engraved on the sample PVC channel, which is the subject of this study.

2. Technologies of cable marking

The range of offered types of cables and wires, differing in purpose, parameters, design, etc., is quite large. They provide useful information and are easily recognizable thanks to the special marking of each type of cable.

Cable marking usually refers to the application of various characters, labels and symbols that allow the parameters of the cable or wire to be determined. This information includes technical information on the thickness of the section, the number of cores, their cross section, the type of core insulation, the type and material of insulation used and its intended purpose. This information may correspond to national, international or industry standards. Usually it includes a combination of letters and numbers and is applied by the manufacturers of the external insulation of the cable (figure 1).

One of the most commonly used identifiers of cable or wire is the color of its insulation. For example, in the case of multi-core cables, the insulation of the individual cores is of a different color, which allows one to quickly determine the purpose of each core.

![Figure 1](image.png)

**Figure 1.** Examples of manufacturer’s marking on cables with different purposes.

Cables and wires can be used in different climatic conditions. Combinations of alphanumeric or numeric designations are also often used to distinguish different embodiments. The numbers often indicate under what environmental conditions it is appropriate to use a cable or wire, for example outdoors, indoors, in high humidity, etc. The class of resistance to high temperatures is also indicated.

In the marking of symmetrical cables, in addition to letters, numbers are placed, which show the number and type of groups of cable conductors, as well as the diameter of the conductors. In the case of main coaxial communication cables, figures are also affixed which are related either to the diameters of
the inner and outer diameters of their coaxial pairs or to the number of the same type of coaxial pairs in the cable.

Markings can be applied to the cable by various methods or by using special equipment. One of the most common ways of marking is through the application of color or embossed printing; usually the embossed markings are colorless. The application of such marking is often implemented by means of rotating marking discs.

Inkjet and laser printers are also used for marking. They are suitable for marking cable insulation of the most commonly used materials. An advantage of using printers for marking is the ability to freely program the text that will be marked on the cable.

3. Equipment and materials

Laser System:
An ST-CC9060 CO₂ laser marking system was used in the experiments on marking the samples. It is specially designed for marking non-metallic materials. It is equipped with an original CO₂ laser with a unique fully sealed cavity design and a high-speed X-Y coordinate table, (figure 3).

Principle of operation: the laser tube is filled with CO₂ gas as the laser gain medium; when a high voltage is applied to the electrodes, a glow discharge is generated in the tube, which causes the gas molecules to emit a laser radiation. After amplification, the laser beam leaves the resonator through the output mirror to be used for material processing. The X-Y coordinate table is controlled by a specialized computer program to perform the samples marking.

An OLS-5000 SAF laser microscope (figure 2) was used for measuring the width and depth of the laser affected zone. The magnification used is ×2000 with a repeatability of 0.03 μm.

Figure 2. OLS-5000 SAF confocal laser microscope.

Table 1. Technical parameters of the CO₂ laser marking machine.

| Model          | ST-CC9060 |
|----------------|-----------|
| Laser power    | 100 W     |
| Laser wavelength | 10640 nm |
| Marking area   | 900 mm × 600 mm |
| Marking speed  | 0 – 1000 mm/s |
| Repetition accuracy | ±0.02 mm |
| Power consumption | 1.5 kW   |
| Power supply   | 220 V/50 Hz/10 A |
| Cooling system | water cooling & protection system |
| Focal Length   | 65 mm     |
Figure 3. Scheme of the experimental setup for marking PVC by CO₂ laser.

4. Materials / Experimental samples

PVC is a thermoplastic that can range from soft, flexible materials to hard, rigid plastics. Rigid PVC is easily machined, heat formed, welded, and even solvent cemented. PVC can also be machined using standard metal working tools and “unplasticized,” because it is less flexible than the plasticized formulations. PVC has a broad range of applications, from high-volume construction-related products to simple electric wire insulation and coatings [14, 15]. The differences between flexible and rigid PVC are shown in table 2.

Table 2. Characteristics of flexible and rigid PVC.

|                          | Plasticised (Flexible) PVC | Unplasticised (Rigid) PVC |
|--------------------------|-----------------------------|---------------------------|
| Density                  | 1.3 – 1.7 g/cm³             | 1.35 – 1.5 g/cm³          |
| Thermal Insulation       | 0.16 W/m K                  | 0.16 W/m K                |
| Conductivity             |                             |                           |
| Young Modulus            | 0.001 – 1.8 GPa             | 2.4-4 GPa                 |
| Flexural Modulus         | 0.001 – 1.8 GPa             | 2.1 – 3.5 GPa             |
| Elongation at Break      | 100 – 400%                  | 25 – 80%                  |
| Fire Resistance (LOI)    | 20 – 40%                    | 40 – 45%                  |
| Transparency (% Visible Light Transmission) | 75 – 85% | 80.00% |

Polyvinyl chloride can be obtained by chain polymerization of its monomer produced from chlorine (57 wt.%, manufactured by chlorine alkali electrolysis of brine yielding chlorine, sodium hydroxide, and hydrogen as co-products) and ethylene (43 wt.%) via 1,2-dichloroethane [16].

There are three broad classifications for rigid PVC compounds: Type I, Type II, and CPVC. Type II differs from Type I by its greater impact values, but lower chemical resistance. CPVC has a greater high temperature resistance. PVC has a broad range of applications, from high-volume construction-related products to simple electric wire insulation and coatings [17].

Samples of colored cables with a PVC sheath were prepared for the experimental studies. The dimensions of the samples were 30 mm×150 mm. The following types of cable colors were used in the experiments: white, blue, turquoise, red, orange, green, pink and black.
5. Methodology
We analyzed the width $b$ and depth $h$ of the marked channel as a function of the power $P$ of the laser radiation and of the processing speed. The experiments were grouped into two series of measurements. Samples of the following types of colors PVC cables were prepared for the whole research: white, blue, turquoise, red, orange, green, pink and black. The methodology of the experiment followed the scheme below:

**The first series** of experiments examined the dependencies:

\[ b = b(v) \text{ and } h = h(v) \text{ at } P = \text{const} = 10 \text{ W} \]

The laser processing speed $v$ was varied in the range from 20 mm/s to 380 mm/s in increments of 40 mm/s.

**The second series** examined the dependencies:

\[ b = b(P) \text{ and } h = h(P) \text{ at } v = \text{const} = 200 \text{ mm/s} \]

Ten different $P$ values were used, namely (1, 1.5, 2.2, 3.5, 4.1, 5.1, 7.3, 8.9 and 10 W). The focal length $f$ and the diameter $d$ of the working spot on the surface of the cables were maintained constant for the entire period of the study ($d = 92.7 \mu m$).

6. Results

![Figure 4](image4.png) ![Figure 5](image5.png)

**Figure 4.** Depth $h$ as a function of speed $v$.  
**Figure 5.** Width $b$ as a function of speed $v$.

Figure 4 shows the dependence of the depth $h$ as a function of the speed $h = h(v)$ in the studied speed intervals from 20 – 380 mm/s. The analysis of the graphs for all three types of cables (white, red and black) shows that the interaction with laser radiation leads to a non-linear nature of the changes in the material.

Two characteristic zones (first zone from 20 – 140 mm/s and second from 140 – 380 mm/s) of interaction with different speed of change of the impact on the material are clearly outlined. The rate of depth change $\Delta h/\Delta v$ in the interval between 20 mm and 140 mm/s is 23 times higher than that in the speed interval 140 – 380 mm/s.

The experimental studies of the dependence of the width on the speed $b = b(v)$ for samples of white, red and black cables are presented in figure 5. Again, two intervals with different steepness of the slope of the graphs are outlined – from 20 mm/s to 140 mm/s and from 140 mm/s to 380 m/s. The rate of width change $\Delta b/\Delta v$ between 20 mm/s and 140 mm/s is 2.73 times higher than between 140 mm/s and 380 mm/s.

Tables 3 and 4 show in absolute values how many times the width $b$ and the depth $h$ increased at the end of the two intervals, compared to the values at the beginning of these intervals. In table 3, $h_{20}$, $h_{140}$, $h_{380}$ indicate the depth values $h$ of the treated area at speeds of 20 mm/s, 140 mm/s and 380 mm/s. In table 4, the values for $b_{20}$, $b_{140}$, $b_{380}$ are the channel widths at 20 mm/s, 140 mm/s and 380 mm/s, respectively.
Table 3. Comparison of the change in the width $b$ of the laser ablation zone for two separate speed intervals (20 mm/s – 140 mm/s and 140 mm/s – 380 mm/s).

| Color | $b_{20}/b_{140}$ | $b_{140}/b_{380}$ |
|-------|------------------|------------------|
| White | 1.25             | 1.38             |
| Red   | 1.26             | 1.22             |
| Black | 1.24             | 1.25             |

As can be seen in table 3 for the three selected color samples, the average percentage of the ratio $b_{20}/b_{140}$ is 125%; for $b_{140}/b_{380}$ it is 128%. Therefore, there is no major difference between the width change in the two intervals.

Table 4. Comparison of the change in the depth $h$ of the laser ablation zone in the two separate speed intervals (20 mm/s – 140 mm/s and 140 mm/s – 380 mm/s).

| Color | $h_{20}/h_{140}$ | $h_{140}/h_{380}$ |
|-------|------------------|------------------|
| Red   | 7.14             | 2.77             |
| Blue  | 8.98             | 2.14             |
| Green | 7.69             | 2.95             |

For the three selected color samples, the $h_{20}$ values in table 4 are in average 7.94 times larger than those of $h_{140}$; and the $h_{140}$ values are 2.62 times larger than $h_{380}$ values. It is seen that the depth change in the first interval is much sharper than that between 140 mm/s and 380 mm/s.

Figure 6. Width $b$ as a function of the power.  
Figure 7. Depth $h$ as a function of the power.

The results of the second series of experiments were summarized and presented in figure 6 and figure 7, namely, graphs for the width $b$ and the depth $h$ as depending on the power $P$. The results of the yellow, green and blue samples were selected from the tested samples, with the aim to check the effect of the color, or more precisely, the absorption for the laser wavelength by the color of the treated surface.

To analyze the changes in the width and the depth in the processing area (marking area) as a function of the laser power, we divided the graphs in figures 6 and 7 into two intervals – from 1.5 W to 5.1 W, and from 5.1 W to 10 W.

The rate of width change $\Delta b/\Delta P$ between 1.5 W and 5.1 W is 11.6 times greater than that between 5.1 W and 10 W. The rate of depth change $\Delta h/\Delta P$ between 5.1 W and 10 W is 1.56 times greater than that between 1.5 W and 5.1 W.

Tables 5 and 6 show in absolute values how many times the width $b$ and the depth $h$ increased at the end of the two intervals, compared to the values at the beginning of these intervals. In table 5, $h_{1.5}$, $h_{5.1}$,
$h_{10}$ indicate the values of the depth $h$ of the treated area at powers of 1.5 W, 5.1 W and 10 W. In table 6, the values for $b_{1.5}$, $b_{5.1}$, $b_{10}$ are the channel widths $b$ at powers 1.5 W, 5.1 W and 10 W, respectively.

Table 5. Comparison of the change in the depth $h$ of the laser ablation zone for two separate power intervals (1.5 W – 5.1 W and 5.1 W – 10 W).

| Color | $h_{1.5}$/$h_{5.1}$ | $h_{5.1}$/$h_{10}$ |
|-------|---------------------|-------------------|
| Yellow | 0.14                | 0.37              |
| Green  | 0.17                | 0.41              |
| Blue   | 0.17                | 0.46              |

As seen in table 5., for the three selected color samples the values $h_{1.5}$ are in average 15% of those of $h_{5.1}$; and the $h_{5.1}$ values are 41.3% of those of $h_{10}$ values. The increase of the depth is noticeably larger between 1.5 W and 5.1 W than between 5.1 W and 10 W.

Table 6. Comparison of the change in the width $b$ of the laser ablation zone, for two separate power intervals (1.5W - 5.1W and 5.1W - 10W).

| Color | $b_{1.5}$/$b_{5.1}$ | $b_{5.1}$/$b_{10}$ |
|-------|---------------------|-------------------|
| Yellow | 0.42                | 0.95              |
| Green  | 0.65                | 0.96              |
| Blue   | 0.5                 | 0.97              |

For the three selected color samples, the $b_{1.5}$ values in table 6 are on average 53% of those of $b_{5.1}$ values; and $b_{5.1}$ values are 96% of those of $b_{10}$. The width increases linearly between 1.5 W – 5.1 W, it increases minimally between 5.1 W and 10 W.

7. Summary
The recommended depth $h$ of the marked area depends on the area of application of the cables and the thickness of the material. For insulating materials, it is recommended that the marking depth does not exceed 10% of the total thickness. Preferably, the width of the marking is to be well perceived visually. The optimal marking speed $v$ obtained is from 140 mm/s to 340 mm/s, and the optimal power $P$ of the laser radiation is in the range from 5.1 W to 10 W. The color of the PVC sample does not play a considerable role in the process of marking by a CO$_2$ laser. For the colors studied, the difference in the depth and width of the marked areas is insignificant.

However, one could notice that the graphs of the darker cables lie above those of the lighter ones, although the difference is minor. This can be explained by the higher absorption of laser radiation by dark colors than light ones.

8. Conclusion
This study is based on the real needs of PVC manufacturers of electrical and optical cables, but may also be of interest to other companies that manufacture PVC products for the automotive and aerospace industries. For such products, it is necessary to mark a relatively large amount of information on a small limited area of the product. The aim is, on the one hand, to achieve a maximum resistance to external influences of the marking, and on the other, to ensure a high degree of automation of the process of decoding information from QR or barcodes during its reading.

The present study examines the geometry of the marked area as a function of the average power and processing speed, which is directly related to the resistance to external influences.

In the second stage of our research we plan to focus on the contrast and readability of the marker information when applying QR codes as a function of the laser parameters and the exposure time during...
processing. Another important parameter that is planned to be studied is the influence of defocusing, as a large part of the marked PVC products have a spherical, conical or cylindrical shape, which in turn affects the choice of the optimal area in which the marking should be located.

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