Development of the technology of 0NBC code formation on a metal surface by laser marking

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Abstract. In this work, the formation of a two-dimensional code, NBC, using laser marking is considered. A complete factorial analysis was carried out to determine the optimal laser irradiation parameters for obtaining the most contrasting image of code cells on a metal surface (steel AISI 321) using laser marking. The regression equation is obtained, the coefficients of the equation are checked for significance, and the equation is checked for adequacy, an interpretation of the equation coefficients is given, the optimal laser marking parameters are obtained.

1. Introduction
The methods for metal product marking of current usage are mainly based on the application of marks on intermediate carriers such as labels, tags, and packages. However, due to the lack of protection against falsification and inability to carry a large amount of information, these methods are not effective. To provide a higher level of product protection, a barcode mark can be applied with laser irradiation directly to the surface of the finished product. The application of barcodes directly on the product surface allows solving such important issues as placing information with the information of its manufacturing and operation conditions on the product [1]. Nevertheless, until now direct labeling of products using laser marking has not been widely used.

This can be explained by the following reasons:
- the technology of laser marking of finished products using barcodes is considerably complex, requiring highly qualified engineering personnel who can put “readable” barcodes on products. Only a high-quality printed barcode can be read by a scanner;
- encoding a sufficiently large amount of information in a barcode increases the overall dimensions of barcodes themselves, including two-dimensional matrix barcodes (PDF417, DataMatrix, QR Code, etc.) [2][3][4]. Accordingly, for a great number of products, that do not have large dimensions, using such barcodes is impossible.

Based on the analysis of the disadvantages of existing barcodes technologies for finished products, a technological process was developed for applying new barcodes with a high recording density of bit-coded information directly on the surface of products made of metal materials. NBC was chosen as such a barcode with a high recording density.

2. Materials and methods
Steel plates AISI 321 were used for the experiments, 50x50 mm in size and 0.5 mm thick. The samples were marked with a laser setup based on a ytterbium pulsed fiber laser with a wavelength of 1.06 μm. Photofixing was carried out on an optical installation (Figure 1). The optical setup contains a ring
illuminator (KONIG), a macro lens (AF MICRO NIKKOR 60 mm 1:2.8D with an adapter for EOS mount), a digital camera (Canon EOS 50D), rider [5].

![Figure 1. Experimental installation of photofixation of objects on metal: 1 – object of study; 2 – adjustment unit; 3 – ring illuminator; 4 – macro lens; 5 – digital camera; 6 – rider.](image)

Color measurement in the RGB system on the resulting image was performed in the graphics editor CorelDraw X3.

Processing of the obtained experimental data was carried out using a complete factorial experiment with the determination of the optimal laser irradiation parameters by the path-of-steepest-ascent method along the response surface of the system. The regression model was described by the following linear equation [6]:

\[ y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ij} x_i x_j. \]  

The calculation of the regression coefficients was carried out according to the formula:

\[ b_i = \frac{\sum_{l=1}^{n} x_{ij}x_l}{n}, \text{ гдe } j = 0,1, \ldots k. \]  

The significance of the coefficients of the regression equation was tested according to the Student criterion:

\[ S_{(y)}^2 = \frac{1}{n} \sum_{j=1}^{n} S_j^2. \]  

The adequacy of the model was evaluated by the Fisher criterion [6]:

\[ F_{\text{calc}} = \frac{s_y^2}{s_{(y)}^2}. \]  

The search for the optimum was carried out using the path-of-steepest-ascent method along the response surface of the system [7].

3. Results and discussion

To apply the code to the protected product, the following technology was proposed.

The NBC is applied directly to the product using a ytterbium fiber laser, which can create a contrasting barcode on various metals. To determine the optimal laser irradiation parameters, a multivariate analysis was carried out to define the color value in the RGB system as close to black as
possible. Multivariate analysis is widely used in modern scientific researches and it is an effective means of processing and planning experimental research [8].

For factors influencing the experiment progression (the color value in the RGB system), the parameters of laser radiation are taken:
- pulse duration, ns - x₁;
- pulse repetition rate, kHz - x₂;
- scanning speed, m/s - x₃;
- pulse Power, W- x₄.

The number of factors k = 4, which implies that the number of experiments N that must be carried out is 16. The factors and their products cover all possible combinations x₁, x₂, x₃, x₄, x₁x₂, x₁x₃, x₁x₄, x₂x₃, x₂x₄, x₃x₄.

The first thing to be determined is the limits of variation of factors.

All factors and their limits, as well as the complete matrix for the four-factor experiment, are presented in Tables 1, 2.

### Table 1. Factors and their limits

| Factor | Minimum | Main | Maximum |
|--------|---------|------|---------|
| x₁     | Pulse duration τ, ns | 100  | -1      | 150     | 0       | 200     | +1       |
| x₂     | Pulse repetition rate f, kHz | 85   | -1      | 92      | 0       | 99      | +1       |
| x₃     | Scanning speed S, m/s | 1    | -1      | 90      | 0       | 179     | +1       |
| x₄     | Pulse Power P, W | 85   | -1      | 92,5    | 0       | 100     | +1       |

### Table 2. The full matrix of the four-factor experiment

| №   | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| x₀  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |
| x₁  | 1  | -1 | 1  | -1 | 1  | -1 | 1  | -1 | 1  | -1 | 1  | -1 | 1  | -1 | 1  | -1 |
| x₂  | 1  | 1  | -1 | -1 | 1  | 1  | -1 | -1 | 1  | 1  | -1 | -1 | 1  | -1 | -1 | 1  |
| x₃  | 1  | 1  | 1  | 1  | -1 | -1 | 1  | 1  | -1 | 1  | 1  | -1 | -1 | 1  | 1  | -1 |
| x₄  | 1  | -1 | -1 | 1  | 1  | -1 | -1 | 1  | -1 | 1  | 1  | -1 | -1 | 1  | 1  | -1 |
| x₁x₂| 1  | -1 | -1 | 1  | -1 | 1  | -1 | -1 | 1  | -1 | 1  | 1  | -1 | 1  | 1  | -1 |
| x₁x₃| 1  | -1 | 1  | -1 | -1 | 1  | 1  | -1 | 1  | -1 | 1  | 1  | -1 | 1  | 1  | -1 |
| x₁x₄| 1  | -1 | -1 | -1 | 1  | -1 | -1 | -1 | 1  | -1 | 1  | 1  | -1 | 1  | 1  | -1 |
| x₂x₃| 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |
| x₂x₄| 1  | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| x₃x₄| 1  | 1  | 1  | 1  | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| x₁x₂x₃| 1  | -1 | -1 | 1  | -1 | 1  | -1 | -1 | 1  | -1 | 1  | 1  | -1 | 1  | 1  | -1 | 1  |
| x₁x₂x₄| 1  | -1 | -1 | 1  | 1  | -1 | -1 | -1 | 1  | 1  | 1  | 1  | -1 | 1  | 1  | -1 | 1  |
| x₁x₃x₄| 1  | -1 | 1  | -1 | 1  | -1 | -1 | -1 | 1  | 1  | 1  | 1  | -1 | 1  | 1  | -1 | 1  |
| x₂x₃x₄| 1  | 1  | -1 | 1  | 1  | -1 | -1 | -1 | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |
| x₁x₂x₃x₄| 1  | -1 | -1 | 1  | -1 | 1  | -1 | -1 | 1  | -1 | 1  | 1  | -1 | 1  | 1  | -1 | 1  |

Results:

| 1  | 14 | 13 | 11 | 12 | 11 | 14 | 13 | 14 | 13 | 14 | 13 | 14 | 13 | 14 | 13 | 12 |
| 2  | 13 | 12 | 14 | 11 | 14 | 14 | 11 | 12 | 14 | 13 | 13 | 13 | 13 | 13 | 13 | 11 |
| 3  | 11 | 14 | 13 | 12 | 14 | 11 | 14 | 14 | 11 | 12 | 14 | 13 | 11 | 14 | 15 | 13 |
| 4  | 12 | 12 | 13 | 12 | 12 | 13 | 12 | 13 | 11 | 13 | 14 | 11 | 13 | 14 | 13 | 13 |
| 5  | 14 | 11 | 14 | 13 | 12 | 12 | 13 | 14 | 14 | 13 | 12 | 12 | 11 | 14 | 14 | 14 |
| A  | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| v  | 8  | 6  | 4  | 4  | 4  | 2  | 6  | 8  | 8  | 8  | 4  | 8  | 4  | 8  | 4  | 13 | 8 |
The coefficients of the regression equation are presented in a general form:

\[ Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{34}x_3x_4 + b_{123}x_1x_2x_3 + b_{124}x_1x_2x_4 + b_{134}x_1x_3x_4 + b_{1234}. \]

The regression coefficients are calculated using the average value of \( Y \) (the result of 5 measurements) and the matrix of coefficients of factors variation. The obtained results of the sums of the products are the coefficients of the equation.

Thus, the regression equation takes the following form:

\[ Y = 11.84 + 0.84x_1 + 0.79x_2 + 0.79x_3 + 0.71x_4 - 0.81x_1x_2 - 0.76x_1x_3 - 0.89x_1x_4 - 0.66x_2x_3 - 0.79x_2x_4 - 0.79x_3x_4 + 0.79x_1x_2x_3 + 0.81x_1x_2x_4 + 0.81x_1x_3x_4 + 0.86x_2x_3x_4 - 0.73x_1x_2x_3x_4. \]

Then, the significance of the regression coefficients is evaluated by the Student’s criterion.

The reproducibility variance equals \( S_{2r}^2 = 0.274. \)

Then the obtained value is compared with the coefficients of the regression equation presented in Table 3.

| \( b_0 \) | \( b_1 \) | \( b_2 \) | \( b_3 \) | \( b_4 \) | \( b_{12} \) | \( b_{13} \) | \( b_{14} \) | \( b_{23} \) | \( b_{24} \) | \( b_{34} \) | \( b_{123} \) | \( b_{124} \) | \( b_{134} \) | \( b_{1234} \) |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 11.84 | 0.84  | 0.79  | 0.79  | 0.71  | -0.81 | -0.76 | -0.89 | -0.66 | -0.79 | 0.79  | 0.81  | 0.81  | 0.86  | -0.73 |

It can be seen that all the coefficients are larger in absolute value than 0.274. Therefore, all coefficients of the equation are significant. Thus, the regression equation will in the end have the same form as given earlier.

Next, the equation for adequacy according to the Fisher criterion is studied. To determine the calculated value of the criterion \( F_{calc} \), it is necessary to estimate the residual variance \( S_{2r}^2 \). To do this, the values of the studied parameter are found according to the obtained regression equation \( \hat{y}_j (j = 1, ..., 16) \), substitute +1 or -1 instead of \( x_i \) in accordance with the number \( j \) of the experiment.

The residual dispersion is \( S_{2r}^2 = 2.3582. \)

The calculated value of the Fisher criterion is \( F_{calc} = 1.56. \)

The table value of the Fisher criterion can be found from the table of critical points of the Fisher distribution with a significance level of \( \alpha = 0.05 \) and the corresponding degrees of freedom \( k_1 = 1 \), \( k_2 = 64 \). The table value of the Fisher criterion equals \( F_{table} = 3.98 \). Since \( F_{calc} < F_{table} \) the regression equation is adequate. Then, the interpretation of the obtained regression coefficients is carried out:

\[ Y = 11.84 + 0.84x_1 + 0.79x_2 + 0.79x_3 + 0.71x_4 - 0.81x_1x_2 - 0.76x_1x_3 - 0.89x_1x_4 - 0.66x_2x_3 - 0.79x_2x_4 - 0.79x_3x_4 + 0.79x_1x_2x_3 + 0.81x_1x_2x_4 + 0.81x_1x_3x_4 + 0.86x_2x_3x_4 - 0.73x_1x_2x_3x_4. \]

Interpreting the coefficients of the equation, it becomes apparent that the function has the greatest response with a combination of factors \( x_1x_4 \), since they have the largest coefficient in absolute value. Further, according to the strength of the influence on the response, there is a triple interaction \( x_2x_3x_4 \), as well as interactions \( x_1x_2x_4 \) and \( x_1x_3x_4 \) and double interaction \( x_1x_2x_4 \); other factors and their combinations play a smaller role.

Since all 4 single factors \( x_1, x_2, x_3, x_4 \) are positive, the response increases with these factors. The coefficients at \( x_1x_2, x_1x_3, x_1x_4, x_2x_3, x_2x_4, x_3x_4 \) are negative, which means that with a decrease in interacting factors, the response value will increase and, with the increase, it will decrease.

All 4 single factors \( x_1, x_2, x_3, x_4 \) are positive, therefore, with an increase in these factors, the response increases, that is, the color value in the RGB system approaches black. The coefficients at \( x_1x_2, x_1x_3, x_1x_4, x_2x_3, x_2x_4, x_3x_4 \) are negative, which means that with a decrease in interacting factors, the response value will increase, and with increase, decrease.

Thus, factors and their combinations that have the greatest influence on the color value in the RGB system as close to black as possible are determined.

To determine the optimal laser irradiation parameters from the range of variation of factors, the path-of-steepest-ascent method along the response surface was applied (Table 4).
In this case, it is taken into account that the derivative of the objective function in a certain direction of the starting point in multifactorial space characterizes the rate of change of this function in the selected direction. The derivative for the objective function towards the constant level surface of this function is equal to the algebraic quantity of the vector, which is called the gradient of the objective function at the point in question.

Table 4. The path-of-steepest-ascent along the response surface

| Factors | x₀ | x₁ | x₂ | x₃ | x₄ | Estimated Function Response | RGB value |
|---------|----|----|----|----|----|-----------------------------|----------|
| Regression coefficients, bᵢ | 11,84 | 0,84 | 0,79 | 0,79 | 0,71 | | |
| Range of variation, e | 0 | 100 | 14 | 178 | 15 | | |
| bᵢ*e | 83,75 | 11,03 | 140,18 | 10,69 | | | |
| Step acc. to change | 20,00 | 2,63 | 33,47 | 2,55 | | | |
| Rounded step | 20 | 5 | 50 | 5 | | | |
| Parameters | 17 | 100 | 85 | 1 | 85 | 11,84 | 12 |
| | 18 | 200 | 90 | 51 | 90 | 13,41 | 13 |
| | 19 | 200 | 95 | 101 | 95 | 12,58 | 13 |
| | 20 | 200 | 99 | 151 | 100 | 12,52 | 13 |

Thus, two optimal laser radiation regimes are determined.
- Parameter 17: pulse duration is 100 ns, pulse repetition rate is 85 kHz, scanning speed is 1 mm/s, pulse power is 17 W.
- Parameter 21: pulse duration is 200 ns, pulse repetition rate is 99 kHz, scanning speed is 179 mm/s, pulse power is 20 W.

When these parameters are implemented, the color of the cells in the RGB system will have the coordinates 12.12.12. The optimization of the modes allowed the color value to be brought closer to black by 5%.

4. Conclusion
Thereby, in this paper, the parameters of laser radiation for applying a color NBC code were determined. However, when applying laser marked NBC code, a number of important parameters of laser technology, such as the linearity of the code, the number of laser passes, the size of the code module, and other parameters, affect the image quality of the code and its readability. Therefore, after a full factorial experiment using four factors, it would be logical to study all the important factors together, but in this case it would be necessary to conduct not a complete factorial, but a fractional factorial experiment in order to reduce the total number of experiments.

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