*Environment. Technology. Resources. Rezekne, Latvia*
*Proceedings of the 15th International Scientific and Practical Conference. Volume III, 449-455*

# *Multi-criteria Research of Geometric, Mechanical, Energetic and Temporal Indicators Depending on Laser Hardening Parameters*

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***Abstract.*** **In the paper, using experimental data, models for geometric, mechanical, energetic, and temporal indicators of surface laser hardening are derived. A single-criteria and multi-criteria research was performed using DEFMOT. On this basis, three compromise solutions were obtained, which were rated in terms of performance and energy intensity. From them, a mode for the most rational use is recommended. It consists of *V* = 3.5 mm/s; *P* = 1450 W; *FPP* = 60 mm. The controlled indicators calculated according to the models are specified for it.**

***Keywords: surface laser, hardening process, energy intensity, multi-criteria research, optimization models,***

## I. INTRODUCTION

In the paper, using experimental data of laser hardening of AISI 4130 steel published by authors Mahmoud Moradi, Mojtaba Karami Moghadam [1]. The solution of modern technical problems is associated with the removal of a given technical or physical contradiction of the factors describing the problem [2 - 7]. In the field of surface laser hardening, multi-criteria problems are defined with criteria depending on the technological parameters of the equipment used. For the composed multi-criteria tasks in laser surface strengthening, the DEFMOT approach can be useful, facilitating the Decision Maker (DM) in the analyses he/she makes. The approved software can be defined as a multifunctional tool, with the help of which the desired solution is reached. In control theory, independent variables are defined as input factors varying within a certain range, and dependent variables are defined as output parameters. The method, which is built into the software, is extremely suitable for systems where these two groups of parameters are not optimized. Optimization of the system (object) process can be done for several output parameters with pre-set requirements for them. The software determines all efficient combinations of the input factors that fulfill the desired preferences for the output parameters. This approach was founded by the authors of the present paper and is described in detail in the monographs [8, 9]. When applying it, sustainable effective solutions are obtained with a sufficiently large number of the examined goal functions to determine the input data of non-optimized or undetermined technological processes. If acceptable energy-saving solutions are determined for the obtained effective solutions in terms of a complex of mechanical, energetic, temporal indicators and other investigated parameters, this is defined as innovation by all rules. The latter involves the convergence of laser surface-structured materials together with decision-supporting systems (DSS) so that the proposed technological modes of structuring are proven, as reliable as possible and less energy intensive.

In laser hardening of steels, the surface of the workpiece is heat treated by a laser beam that heats the workpiece locally while the rest of the workpiece acts as a heat sink with respect to the core of the workpiece. The movement of the laser along the surface creates the hardened traces. The complex of properties of a hard wear-resistant surface and a soft and tough core, resistant to brittle failure and impact cracks, is useful in a number

*Print ISSN 1691-5402*
*Online ISSN 2256-070X*
*https://doi.org/10.17770/etr2024vol3.8183*

of elements and details of machine and instrument construction. Surface strengthening techniques include coatings, diffusion methods, and hardening processes. Hardening processes can be performed by flame, induction heating, electron beams and laser beams. Laser hardening of steel offers significant advantages over conventional hardening processes.

Efficient technological modes bring benefits to the production process. To discover these modes, however, it is necessary that the process under consideration be fully defined in terms of the set objectives. This seemingly elementary formulation of the problem inevitably becomes more complicated when examining real problems, characterized by more than two governing factors that simultaneously affect the various investigated quality indicators. Modern means of automating engineering work create good conditions for intelligently solving such problems.

The surface integrity during processing is summarized in [10], [11], which describes the main advances in the research of contact strength after chemical heat treatment. Tribological issues, and in particular those related to wear resistance, need to be identified before the process of designing treatment modes when it comes to thermal treatment. Similar research is described in the monograph [12], [13], where the relationship between the goal parameters and the technological factors of the modes for processing are defined.

The brief overview of this research can determine the characteristics of the chosen topic, which is associated with complexity and nonlinearity, in properties of materials in depth of the examined surfaces. These new surface conditions are formed by a desired set of properties, which is determined by solving multicriteria problems [14]. The latter guarantee certain benefits of the research, most often expressed in increased longevity (extended life) of contact products [15]. All this is related to the resource for production, characterization and applications in the field of hard coatings and wear-resistant surfaces. This review would be more targeted if a methodology could be analytically or numerically created to establish the influence of different modes equally affecting an entire class of steels. In this way, the particular influence of one or another alloying element as a concentration and in combination with other elements will be ignored.

## II. MATERIALS AND METHODS

In [1], a planned DOE research of laser surface hardening of AISI 4130 carbon steel performed with a high-power diode laser was conducted. In this paper, the authors of the DEFMOT computational methodology use data from the research [1] to demonstrate the advantages of the methodology in process identification. This adaptation is necessary because in the future they intend to examine the same steel with a fiber laser with which the present results will be compared. The schematic diagram of the parameters of the laser hardening process is shown in Fig.1.

In Fig.1 and in Table 1 the input parameters of the technological process are indicated. They are, respectively, the scanning speed $X_1$ (mm/s), the laser power $X_2$ (W) and the position of the focal plane $X_3$ (mm). These quantities are parameters controlling the surface hardening process. These variables significantly influence the cross-sectional geometry of the hardened zone (width $Y_1$ and length $Y_2$ of the hardened zone (mm), entrance angle of the quench bath $Y_3$ (°)), average microhardness of the hardened layer $Y_4$ (HV), percentage of soft phase (the ferrite phase) $Y_7$ (%), the power density $Y_5$ (W/mm$^2$), the duration of the process between two cycles $Y_6$ (s).The structure of manuscripts:

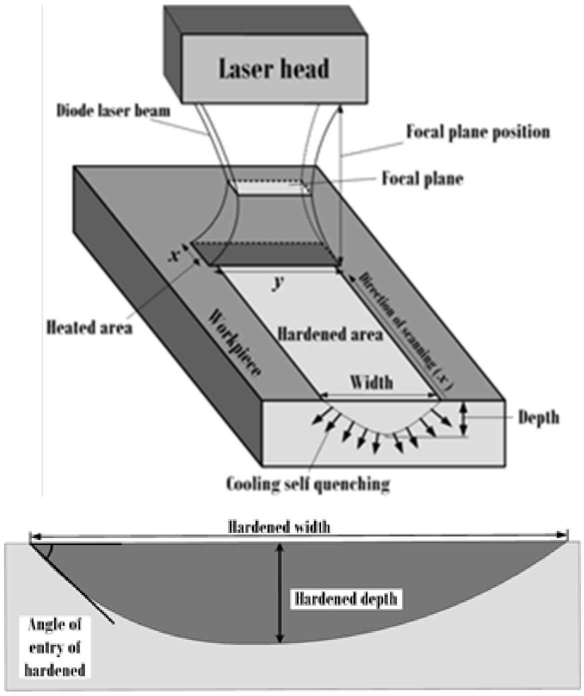


Fig. 1. Schematic of the surface laser hardening process.

TABLE 1 RANGE OF VARIATION OF INPUT PARAMETERS OF THE TECHNOLOGICAL PROCESS OF SURFACE LASER HARDENING

| Independent process parameters with design levels | Variable, Symbol | | |
|---|---|---|---|
| | ***Scanning speed V [mm/s]*** | ***Laser power P [W]*** | ***Focal plane position FPP [mm]*** |
| Zero level – [0] | 5 | 1400 | 70 |
| Amendment step – *S* | 2 | 100 | 10 |
| Lower level – [–1] | 3 | 1300 | 60 |
| Upper level – [+1] | 7 | 1500 | 80 |

## III. RESULTS AND DISCUSSION

### A) RESULTS OF THE SINGLE-CRITERIA

The change of the interval of variation, as a range of change of the values of the technological input parameters is indicated in Table 1, and Table 2 shows the results of the experimental research defined in [1]. The authors of this research wish to perform a side-by-side comparison between a diode laser and a fiber laser, applying their proprietary methodology. That is why the experimental data from [1] were used as the basis for the research. The aim of the research is to determine the effective solutions for a diode laser of geometric, mechanical, energetic and temporal indicators depending on the parameters of the surface laser hardening. The obtained results are part of a comprehensive analysis for research on carbon steel AISI 4130. The approach can define one or more sets of process parameters to be experimentally tested in specifying the technology for the test item. The desired complex of properties depends on one or several certain combinations of technological parameters. This set of properties will be determined using the author's DEFMOT approach.

One of the main directions for the creation of highly efficient competitive products is the formation, at the stage of their design, of such a set/combination of their parameters and characteristics, which ensure the satisfaction of a set of conflicting requirements for the different operative modes during work. With this task, our approach will be applied for the first time to the simultaneous optimization of geometric, mechanical and indirectly economic metrics. Increasingly, there is a significant reorientation of the research and design parts of the work from physical CAE simulation of products and their modes of operation to the use of models for optimization purposes. Such approaches, along with their inherent tools, have procedures for optimizing the parameters (static properties) of simulated systems based on nonlinear programming methods and the mathematical theory of experimental design. The formation of characteristics of the developed engineering products (dynamic properties) with the help of such tools is not provided in the existing virtual modeling systems, which reduces their instrumental potential. At the same time, it is possible to solve specific problems with the calculation of characteristics when setting fixed values for the parameters of the simulated product.

Classical regression analysis is based on processing the results of active experiments, as described in Table 2. At the same time, in connection with the engineering problem, the researcher draws up an experimental plan, choosing experimental points based, for example, on intuition or own experience. After running the experiment, using a standard statistical procedure described in [16], adequate models are derived. After checking the adequacy of the models, the specific results of the identification are determined.

Geometrical criteria are defined in Table 3, and mechanical, energetic and temporal criteria are defined in Table 4, and on this basis the features of the considered proposal are reflected. In this case, it is about the defined statistical models of a qualitative and quantitative kind.

The derivation of the models in this case is done with the use of our own DSTAT system, which automatically performs the adequacy check.

Fig.2 shows the indicator of the entry angle of the stiffened zone, which is directly proportional to the depth of the stiffened zone. These two indicators, together with the width of the bath, are directly related to the efficiency of the technological operation.

TABLE 2 NUMERICAL VALUES OF THE EXPERIMENTAL DATA FOR THE RELATIONSHIP BETWEEN ALL PARAMETERS [1]

| № | Scanning speed | | Laser power | | Focal plane position | | h | b | α | HV | qs | τ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $V$, [mm/s] | $X_1$, kod | $P$, [W] | $X_2$, kod | FPP, [mm] | $X_3$, kod | $Y_1$, [mm] | $Y_2$, [mm] | $Y_3$, [o] | $Y_4$, [/] | $Y_5$, [W/mm$^2$] | $Y_5$, [s] |
| 1 | 4 | -0,5 | 1500 | 0,5 | 65 | -0,5 | 0.94 | 9.30 | 10.82 | 586.0 | 59.2 | 0.64 |
| 2 | 7 | 1 | 1400 | 0 | 70 | 0 | 0.22 | 8.86 | 3.04 | 342.0 | 32.7 | 0.50 |
| 3 | 5 | 0 | 1400 | 0 | 70 | 0 | 0.47 | 8.82 | 5.95 | 489.0 | 32.7 | 0.70 |
| 4 | 5 | 0 | 1400 | 0 | 70 | 0 | 0.44 | 9.84 | 5.89 | 480.0 | 32.7 | 0.70 |
| 5 | 5 | 0 | 1400 | 0 | 60 | -1 | 1.22 | 9.78 | 13.02 | 577.0 | 117.0 | 0.30 |
| 6 | 5 | 0 | 1400 | 0 | 80 | 1 | 0.30 | 9.97 | 4.29 | 370.0 | 15.70 | 1.13 |
| 7 | 6 | 0,5 | 1300 | -0,5 | 75 | 0,5 | 0.27 | 8.73 | 4.06 | 338.0 | 20.20 | 0.80 |
| 8 | 6 | 0,5 | 1300 | -0,5 | 65 | -0,5 | 0.42 | 9.03 | 7.02 | 424.0 | 51.30 | 0.40 |
| 9 | 4 | -0,5 | 1300 | -0,5 | 75 | 0,5 | 0.39 | 9.24 | 5.24 | 386.0 | 20.20 | 1.16 |
| 10 | 4 | -0,5 | 1300 | -0,5 | 65 | -0,5 | 0.52 | 9.10 | 6.78 | 549.0 | 51.30 | 0.60 |
| 11 | 6 | 0,5 | 1500 | 0,5 | 65 | -0,5 | 0.50 | 9.27 | 6.57 | 544.0 | 59.20 | 0.40 |
| 12 | 5 | 0 | 1400 | 0 | 70 | 0 | 0.43 | 9.85 | 5.70 | 400.0 | 32.70 | 0.70 |
| 13 | 5 | 0 | 1600 | 1 | 70 | 0 | 0.52 | 10.10 | 6.47 | 342.0 | 37.40 | 0.70 |
| 14 | 6 | 0,5 | 1500 | 0,5 | 75 | 0,5 | 0.34 | 9.24 | 4.47 | 350.0 | 23.30 | 0.80 |
| 15 | 3 | -1 | 1400 | 0 | 70 | 0 | 0.48 | 9.27 | 6.02 | 496.0 | 32.70 | 1.20 |
| 16 | 5 | 0 | 1200 | -1 | 70 | 0 | 0.23 | 8.58 | 3.72 | 330.0 | 28.10 | 0.70 |
| 17 | 5 | 0 | 1500 | 0,5 | 75 | 0,5 | 0.62 | 9.86 | 8.21 | 474.0 | 23.30 | 1.16 |

TABLE 3 COEFFICIENTS OF THE REGRESSION MODELS OF THE GEOMETRIC PARAMETERS OF THE STIFFENED ZONE

| | Depth | Width | Angle |
|---|---|---|---|
| $b_0$ | 0.461304 | 9.72522 | 6.06130 |
| $b_1 \times x_1$ | -0.18250 | -0.281250 | -1.8125 |
| $b_2 \times x_2$ | 0.17250 | 0.576250 | 1.55875 |
| $b_3 \times x_3$ | -0.2750 | 0.0937496 | -3.32875 |
| $b_{11} \times x_1^2$ | -0.0893477 | -0.777393 | -1.2095 |
| $b_{12} \times x_1 \times x_2$ | -0.250 | -0.0349984 | -3.52500 |
| $b_{13} \times x_1 \times x_3$ | 0.0700001 | -0.5150 | -0.4550 |
| $b_{22} \times x_2^2$ | -0.0643477 | -0.552394 | -0.644348 |
| $B_{23} \times x_2 \times x_3$ | -0.10 | 0 .345001 | -0.104999 |
| $b_{33} \times x_3^2$ | 0.220652 | -0.0173925 | 2.90565 |
| R =0 .9634<br>F = 10.0370<br>F (a=0.05, 9, 7)= 3.6767 | | \`R= 0.9140<br>F= 3.9481<br>F(a=0.05, 9,7)=3.6767 | R= 0 .9649<br>F - 10.5036<br>F= (a=0.05, 9, 7) = 3.6767 |

TABLE 4 COEFFICIENTS OF THE REGRESSION MODELSOF THE MECHANICAL, ENERGY AND TIME INDICATORS

| | hardnes | % Ferit | Dentisity | Time iteraction |
|---|---|---|---|---|
| $b_0$ | 474.217 | -0.494783 | 45.7632 | 0.701579 |
| $**b_1 \times x_1$ | -61.6250 | 9.520 | $-0.953674*10^{-06}$ | -0.640000 |
| $b_2 \times x_2$ | 77.1250 | -7.470 | 10.1500 | 0 .00999 |
| $b_3 \times x_3$ | -111.375 | 7.180 | -84.1500 | 0.8850 |
| $b_{11} \times x_1{}^2$ | -7.89126 | 25.3104 | -54.2369 | 0 .601580 |
| $b_{12} \times x_1x_2$ | -51.5000 | - | - | -0.0799999 |
| $b_{13} \times x_1x_3$ | -65.5000 | 19.040 | - | -0.560 |
| $b_{22} \times x_2{}^2$ | 4.10874 | 17.9704 | -54.0369 | - |
| R =0.9222 F - 4.4206 F -(a=0.05, 9, 7) = 3.6767 | | R= 0.8633 F =3.7631 F (a=0.05, 7,9) = 3.2927 | R .9061 F =7.6479 F -(a=0.05, 6,10)=3.2172 | R = 0.9972 F= 177.0720 F -(a=0.05, 8, 8) = 3.4381 |

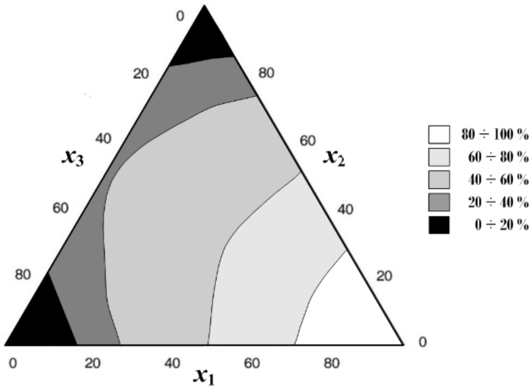


Fig. 2. A standard three-variable representation of constant-level lines.

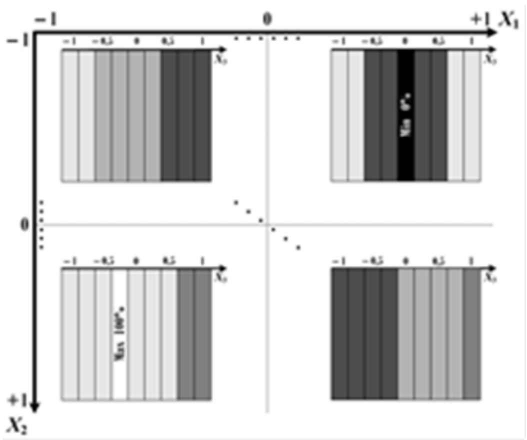


Fig. 3. A three-factor representation using on the principle of - local embedded in the global.

The model of the examined indicator is obtained using the results of experiments. The task of planning an experiment is to establish the minimal number of experiments required.

B) OPTIMIZATION WITH DEFMOT

DEFMOT identifies the goals of using experiments for the research indicator and specifies the practical considerations that drive the design. The conducted physical experiment helps to make decisions, to implement and discuss concepts that serve as a basis for all conclusions.

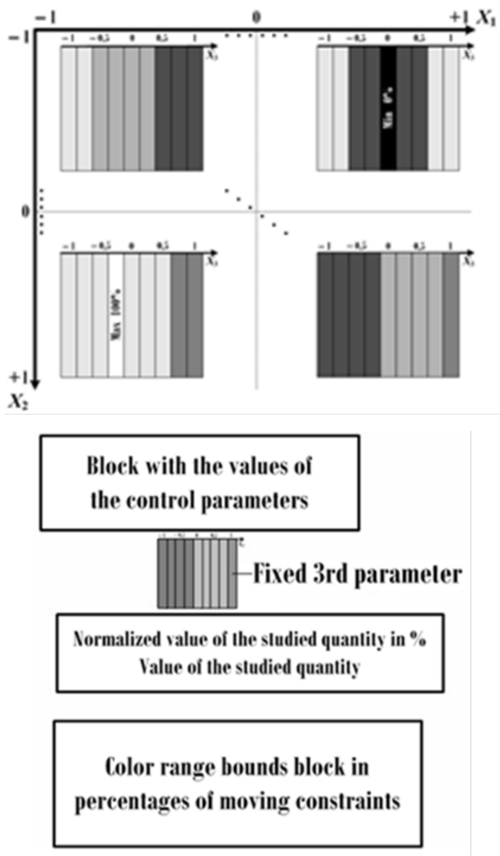


Fig. 4. The organization of information when deciding with the DEFMOT system.

In the field of materials science, the above outlined topic is used both in the synthesis and modeling, and to specify the modes in their processing [10].

A common three-factor representation is shown in Fig.4. However, it violates the “local embedded in the global” principle, a principle adopted by our team in the analysis of multifactorial processes. The image in Fig.5 is a solution to the graphical representation used by DEFMOT. The advantage of implementing this principle is its essential importance in the development of the decision support system.

Fig.4 shows the organization of information when deciding with the DEFMOT system. More useful for the decision-maker in the analysis of the corresponding response surface may be the image of a contour diagram with lines at a constant level (Fig.2 and Fig.3), in which the value of the examined quantity is already set with a given color in a certain interval.

The analysis can be performed for several iterations of the moving constraints (Fig.5 and Fig.6 – as the different input angle images are constructed). Initially, these constraints can be located around the minimum and the influences determined and then judged as to whether they are confirmed when the moving constraints are located around the maximum.

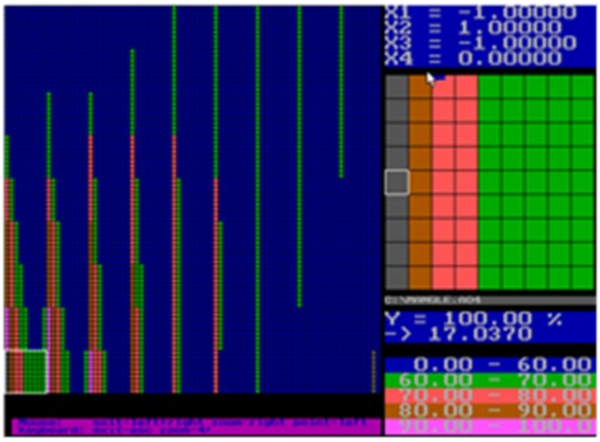


Fig. 5. Input parameters of the maximal angle

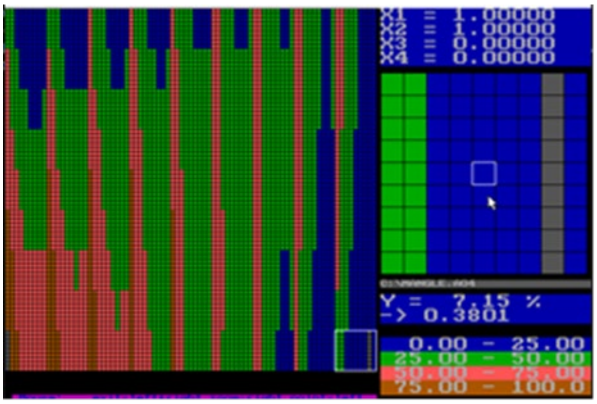


Fig. 6. Input parameters of the minimal angle

The results of the experiment are used to obtain the mathematical model of the examined process. A mathematical model is a system of mathematical dependencies that describe the investigated process.
When planning an experiment, a mathematical model is often understood as an equation that relates an optimization parameter to factors. The criterion equation is also called the response function.
The results of the one-criterion optimization based on the data shown in Fig. 6 – Fig. 10 are shown in Table 5.

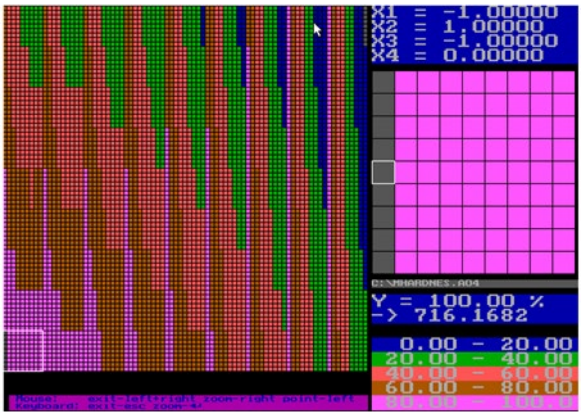


Fig. 7. Input parameters of the maximum hardness

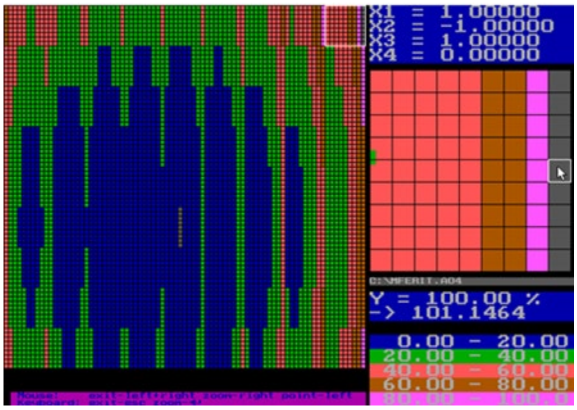


Fig. 8. Input parameters of the maximum hardness

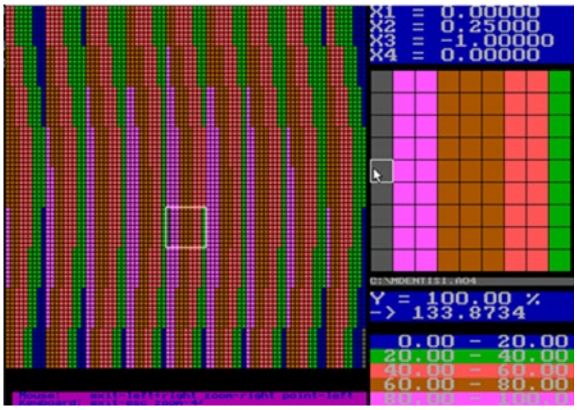


Fig. 9. Input parameters of the maximum power density

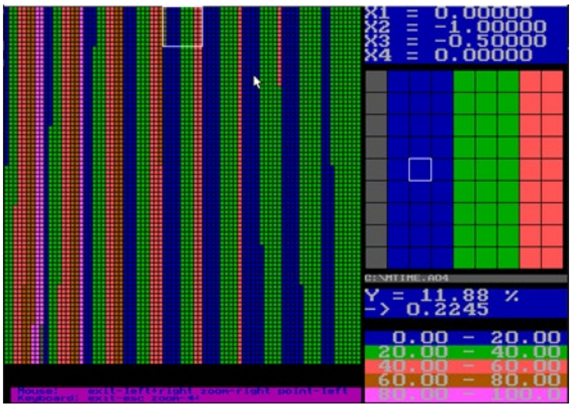


Fig. 10. . Input parameters of the minimum time of one cycle during laser hardening

The indicated in Table 5 results are due to the research of each model separately from Table 3 and Table 4. Despite some differences in the values between the experimental research and the model-derived values, the results can be accepted due to the adequacy of the models. Apart from this, the DEFMOT system works with a normalized percentage – an approach that smooths out the observed inaccuracies. This normalized percentage will play an important role in the next section on multi-criteria optimization

TABLE 5 RESULTS OF THE SINGLE-CRITERIA OPTIMIZATION OF THE CONTROLLED INDICATORS OF THE STUDY OF SURFACE LASER HARDENING

| **Examined values** | **Min** | **A combination in which the relevant extremum occurs** | | | **Max** | **A combination in which the relevant extremum occurs** | | |
|---|---|---|---|---|---|---|---|---|
| | | **[X1] *V*, (mm/s)** | **[X2] *P*,(W)** | **[X3] *FPP*, (mm)** | | **[X1] *V*, (mm/s)** | **[X2] *P*, (W)** | **[X3] *FPP*, (mm** |
| Angle | 0.38 | [1] 7 | [1] 1500 | [0] 70 | 17.03 | [-1] 3 | [1] 1500 | [-1] 60 |
| Hardness | 216 | [1] 7 | [-1] 1300 | [1] 80 | 716.1 | [-1] 3 | [1] 1500 | [-1] 60 |
| Ferit [%] | 1.89 | [0] 5 | [0] 1400 | [0.25] 72 | 101 | [1] 7 | [-1] 1300 | [1] 80 |
| Denticity | 0.68 | [1] 7 | [1] 1500 | [-0.5] 65 | 133.8 | [0] 5 | [0.25] 1425 | [-1] 60 |
| Time iteractio n | 0.2 | [0] 5 | [-1] 1300 | [-0.5] 65 | 3.45 | [-1] 3 | [1] 1500 | [1] 80 |

### C) Results of the Multi-Criteria Optimization with DEFMOT

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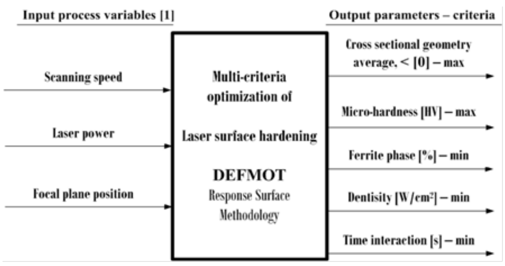


Fig. 11. Statement of the problem for the multi-criteria research

The results of this research are shown in Table 6 based on the derived equations in Table 3 and Table 4, after setting the identifiers of the criteria from Fig.11.

From the analysis of the results indicated in Table 6, decisions (1) and (2) stand out. In terms of performance, both modes are suitable for industrial application. However, the authors recommend mode (1) because not only is the stiffness higher, but of the two modes, mode (1) is less energy intensive. This mode is with V = 3.5 mm/s; P = 1450 W; FPP = 60 mm. The specific values of the controlled indicators are as follows: width – 9.40 mm; entrance angle to the strengthened zone – 15.5 °; average microhardness – 685 HV; percentage of ferrite in the strengthening zone – 33.35 %; power density – 91 W/mm$^2$, time between two cycles – 0.38 s. Mode (3) is the least energy-intensive, but from the one cited in Table 6, the indicators have the most unsatisfactory characteristics. Solution (4) is ranked third among all compromise solutions in applicability. Only with it the interaction time is the greatest. However, the latter is compensated by the low power density value.

TABLE 6 RESULTS OF FOUR COMPROMISE SOLUTIONS WITH CALCULATIONS FOR ALL CONTROLLED INDICATORS OF THE SURFACE LASER HARDENING PROCESS

| **Parameters / Values** | **Combinations of the solution complex from the multi-criteria optimization determined by DEFMOT** | | | |
|---|---|---|---|---|
| | **[$X_1$] = -0.75 [$X_2$] = 0.75 [$X_3$] = -1** | **[$X_1$] = -0.25 [$X_2$] = 0.5 [$X_3$] = -1** | **[$X_1$] = 1 [$X_2$] = -1 [$X_3$] = -0.75** | **[$X_1$] = -0.5 [$X_2$] = 1 [$X_3$] = 0.** |
| Solution | (1) | (2) | (3) | (4) |
| Angle – max | [91.65] % | [81.30] % | [53.56] % | [57.24] % |
| Width – max | [78.51] % | [93.23] % | [17.90] % | [89.11] % |
| Hardnes – max | [93.84] % | [88.08] % | [69.82] % | [78.79] % |
| Ferrite [%] – min | [34.34] % | [13.83] % | [49.13] % | [13.23] % |
| Denticity – min | [85.2] % | [97.86] % | [45.5] % | [49.74] % |
| Time iteraction – min | [16.37] % | [10.88] % | [18.41] % | [39.05] % |

### Conclusion

After deriving models of the geometric, mechanical, energetic and temporal indicators for surface laser hardening, multi-criteria research was conducted. Based on it, three compromise solutions were obtained, which were rated according to performance and energy consumption. It is determined by the values V = 3.5 mm/s; P = 1450 W; FPP = 60 mm. The controlled indicators calculated according to the models are specified for it.

### Acknowledgment:

The authors gratefully acknowledge financial support by the European Regional Development Fund, Postdoctoral research aid Nr. 1.1.1.2/16/I/001 research application "Analysis of the parameters of the process of laser marking of new industrial materials for high-tech applications, Nr. 1.1.1.2/VIAA/3/19/474".

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