Effect of laser radiation parameters on surface modification of critical engineering part

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Abstract. In this work, computational experiments were carried out using the MatLab Laser ToolBox package to determine the power range of a radiation source for realizing nanomodification of the C45 grade steel surface without melting. The dependences of the sample maximum temperature are determined depending on the power of the laser radiation source, beam diameter, and scanning speed. It has been found that for a steel plate, a power of more than 3.7 kW in the case of a slowly moving source (10 mm/s) and more than 4.9 kW in the case of a fast-moving source (20 mm/s) are required for melting. Moreover, an increase in power of a slow source by 0.2-0.3 W is accompanied by an increase in the maximum temperature by 200 K at the beginning and will increase towards the end of the heating process, which goes into melting stage.

1. Introduction
Lasers can be used in various technical applications. While specific spatial and temporal characteristics of the radiation type are important in measuring technologies, the extremely high energy density in production processes makes it possible to create a wide-profile technology that can be used for laser laying of thermoplastic prepregs [1], laser cutting, surface structuring, etc.

Martensitic laser hardening was one of the first industrial laser processes and compared with other types of laser surface treatment, it requires a relatively low intensity of electromagnetic radiation. The intensity between 10 and 100 W/mm² [2, 3] is sufficient to ensure the technological process, laser sources with an average power of 2 kW to 5 kW are necessary to cover a larger area of the workpiece with a focal spot. When lasers were first introduced into industry, CO₂ lasers were the only laser sources available that provided sufficient power. The main disadvantage of CO₂ lasers, in addition to their high cost of maintenance, is the wavelength in the far infrared zone, which is 10.6 μm. The absorption of electromagnetic radiation of this wavelength in steel is very low (<15%), and therefore it was necessary to use carbon coatings to increase absorption [4].

Advances in semiconductor technology have allowed the creation of high-power diode lasers (HPDL) [5]. They are usually associated with low beam quality and, therefore, with low intensity. However, the intensity level is high enough not only for hardening, but also for the implementation of other processes. In combination with the ability to inject radiation into the optical fiber and low
maintenance, HPDL has now become a common laser source for hardening. To achieve the required power density, most HPDLs require a superposition of several laser beams provided by so-called diode arrays. Current studies show that in the future, direct-emitting laser diodes will achieve a high enough power density to actually emit light directly to the surface [6]. Among other advantages, the intensity distribution of these sources can be easily adjusted by turning on and off individual diode arrays/stacks.

While this technology is not available, it is necessary to use optical elements, such as mirrors, lenses or fibers, which can direct light from laser sources to the workpiece. The easiest way to achieve this is to use one or two lenses between the laser source and the workpiece. Most systems have complex optics, which not only projects a laser spot on the workpiece, but also changes the shape or even the distribution of power density [7, 8, 9].

To harden the surface, the laser must heat the material above the austenite temperature, then withstand such a temperature long enough so that carbon can diffuse, then the surface must cool down quickly.

Laser hardening has been used in industry for over 40 years, but nonetheless, unresolved problems still remain. Research is ongoing to optimize the microstructure, as well as thermal stress and strain. One of the main tasks is to reduce the effect of tempering that occurs when several quenching tracks are located next to each other. The temperature field [9], which is described by the distribution of laser intensity, scanning speed, and spot diameter, has the ability to consider all these factors. A lot of research has been done to predict the outcome of these parameters by modeling [10, 11, 12]. Kunc et al. [13], for example, predicted the multi-track hardening of the 42CrMo4 studied (AISI 4140). Bailey et al. [10] added a diffusion model to thermal finite element analysis (FEM) to predict hardness as well as laser quenching stress 42CrMo4 (AISI 4140). Mikovich et al. [14] investigated the influence of the austenization process, as well as martensitic kinetics. Tobar et al. In [13], an even more complex model of metallurgical impact during laser hardening was implemented. Leung et al. [15] described the effect of the optimized intensity distribution. An analytical model was used to illustrate the resulting temperature field in the workpiece.

The aim of this work is to determine the range of powers of a radiation source for implementing nanomodification of the C45 grade steel surface without melting.

2. Methods

There are a number of theoretical methods that allow us to describe the temperature field for a model of heating a plate by a laser radiation source. They are mainly divided into simulation, numerical, analytical and their complexes. Analytical methods give the most general results in absolute units, but when using them it is difficult to take into account the features of the simulated system, for example, boundary conditions. Simulation methods are applicable in the case of a difficult formalized problem and the presence of uncertain parameters. In addition, these methods give results that need post-processing, for example, conversion from relative units to absolute ones. Numerical methods make it possible to obtain a solution to the model in a particular case, taking into account its features, which in most cases is a satisfactory result. In our case, the problem is well formalized and the parameters are known and have exact values, and the temperature field can be obtained as a first approximation through the analytical model, taking into account the initial conditions, therefore it is convenient to use the numerical-analytical model implemented in LASER TOOLBOX. This environment was chosen because of its openness, usability, and high enough speed for calculating models. In addition, it implements various models of laser beams used by us with variable parameters, and the calculation results are presented in absolute units.

The calculations were carried out for a plate of steel C40x13 with the parameters:

- A (absorption capacity): 0.4
- Lambda (wavelength): 0.80e-6
- K (thermal conductivity): 0.25
- Rho (density): 7630
The computational domain was 140 x 70 mm. The initial temperature was chosen equal to room temperature 293 K. The increment of temperature on the surface of the sample relative to the initial one in the quasistationary case was calculated.

For laser hardening, there are four widely used distributions of the intensity of laser radiation, two of which can be obtained using static optical elements. Using scanning mirrors, the intensity profile can be specified by harmonic oscillations or optimized intensity distributions, which were calculated by Burger in [9]. In order to show the effect of these intensity distributions on the thermal field on the workpiece, thermal modeling was performed. The initial data for the implementation of these simulations were measured and intensity distributions were preliminary calculated.

3. Results and discussion

Intensity distribution profiles can be seen in Fig. 1, while the simulation of the thermal field caused by these profiles is shown in Fig. 2 and Fig. 3. Thermal modeling was tuned using a semi-analytical approach.

Based on the Green's function, one can summarize the thermal profiles of individual heat sources [16]. Compared to FEM, it is beneficial that the solution does not depend on the size of the calculated grid, but only on the size of the intensity data. In addition, the calculation of high resolution on the plane is much faster than using the finite element method. The temperature range can be changed by

- Cp (heat capacity): 482
- Tm (melting point): 1793
linear conversion. The main disadvantage of this method is that the solution is valid only for certain boundary conditions on which the analytical solution is based. These conditions are an infinite body and a stationary state. The dependence of specific temperature values cannot be taken into account. Therefore, it is necessary to take into account a certain error [17]. In this introduction, modeling should not be used for a numerical approach, but for visualizing the effect of various intensity distributions.

The thermal fields caused by these intensity distributions are calculated based on the superposition of a point source described by formula (1). Formula (2) shows the superposition at a certain point, and formula (3) shows the radius that must be calculated for each element of the intensity matrix:

\[
T(x, y, z) - T_{\text{Environment}} = 2 \frac{P_L}{\rho_0 c_p} \times \frac{1}{\pi \nu k} e^{\frac{-v(x+y)}{2k}}, \quad (1)
\]

\[
T(x, y, z) - T_{\text{Environment}} = \frac{P_L}{\rho_0 c_p} \times \frac{2}{\pi \nu k} \sum_{k_y=1}^{n_y} \sum_{k_x=1}^{n_x} \frac{1}{\nu \Delta x \Delta y} e^{\frac{-v(\Delta x_{k_x}+\Delta y_{k_y})}{2k}}, \quad (2)
\]

\[
r_{x,y,z} = \sqrt{\left(\Delta x_{k_x}\right)^2 + \left(\Delta y_{k_y}\right)^2 + (z)^2}. \quad (3)
\]

According to the formulas, the temperature \( T \) at the point \( x, y, z \) is determined by the laser power \( (P_L) \), the material parameters \((\rho_0, c_p, k)\), the displacement velocity \((\nu)\) and the distance to the center of an individual point source \((\Delta x_{k_x}, \Delta y_{k_y}, z)\). The intensity distribution can be described by the normalized coefficient \((\mu_{k_xk_y})\) and the number of elements in the intensity matrix \((n_x, n_y)\). The mesh size was set to 10x10 \( \mu \text{m}^2 \), and the depth of the plane shown was 100 \( \mu \text{m} \). The temperature was normalized to 1225 °C at the hottest point.

Laser radiation profile in Fig. 2a represents a beam of a defocused diode laser source of 4.5 kW with a divergence of 33 mm rad. In the focal plane, the laser beam had a spot diameter of the order of 1 mm, and in the defocused plane about 40 mm. While the density distribution in the focal plane can be characterized as a narrow cylinder, defocusing in turn leads to a super-Gaussian profile. As can be seen from the thermal simulation in Fig. 2a, the properties of such a beam are far from optimal. The temperature reaches the highest value in the center. Through the process, they are limited to 1225 °C, so the temperature of exposure is clearly controlled. To the edges of the treatment zone, the temperature drops. For better visualization, the temperature of 850 °C, at which the material is austenitized, is highlighted in Fig. 2 by dashed line. If look in depth, the heating and quenching zone will be characterized by an undesirable circular cross section. The main advantage is that the high energy density in the center of the laser source beam is lost due to defocused exposure. Although this negative effect of defocusing is well known, in practice this procedure is still common, since there is no need for complex and, therefore, expensive optical elements, and the spot size can be easily adapted. Especially with CO\(_2\) lasers, it is usually preferable to defocus, because transparent optics are problematic for a wavelength of 10.6 microns.

The most commonly used beam shape is the uniform intensity distribution of a rectangular laser beam. A beam-shaper is often used, which typically projects a laser spot onto multiple spots, but other methods are also common. By combining several spots, the intensity distribution is homogenized, and the external shape can be changed, for example, to a rectangle. As optical elements can be used a matrix of cylindrical lenses, various optics and kaleidoscopes. The intensity distribution shown in Fig. 2b is created by optics, which converts a round laser spot into a rectangular 16x4 mm\(^2\). Despite the fact that such a density distribution is usually used in technological processes, the resulting temperature field in Fig. 2b indicates some limitations. The center of the laser spot overheats, and the effect of a thermal lens occurs due to higher thermal conductivity on the side of the hardened zone. The spot size in most cases is fixed, but it can be adapted by changing lenses in a modular system. Interactive zoom adjustment is also possible.
Figure 2. Modeling the temperature field of the beam of a defocused diode laser (a) and a rectangular laser (b)

The first two intensity distributions were obtained using static optics. Laser scanners can provide greater flexibility. High feed rates of the laser spot to the surface can be achieved using mirrors on precision piezoactuators. The rate of heat conduction to the workpiece is limited, so a laser scanner is used to generate a local intensity distribution scheme. The main method of precision supply of laser radiation to the processing area is the positioning of the axis of the robot or the portal coordinate system. If the speed of the spot on the surface is much higher than the thermal conductivity, it can be assumed that the distribution of intensity transmitted to the workpiece is equal to the integration of movement in one period of time.

Figure 3. The simulated temperature field of a harmonic oscillating scanner (a) and the Burger intensity distribution (b) at 0.1 mm

The intensity profiles that were created using the laser scanner head (Fig. 1c, d) were calculated as the sums of the measured round laser beam.

For the first calculated distribution, it was assumed that the scanner mirror moved only in harmonic oscillation. This oscillation mode allows you to realize the highest frequencies. However, it has a
significant drawback: due to deceleration at turning points, the distribution shows (Fig. 3a) thermal overheating along the edges of the track. The entire heat affected zone in the direction of movement is very thin, and in the middle of the track, the temperature does not reach the austenite temperature.

When scanning with two mirrors, it becomes possible to generate more complex intensity distributions. To overcome the limitation of the harmonic oscillator, Burger examined the laser intensity profile for effective hardening. The profile that he developed is often called the “chair” profile after its recognizable shape. Distribution is done by adding a triangular motion to harmonic oscillation. The peaks at the beginning of the intensity profile and slightly higher edge peaks can compensate for the higher thermal conductivity on the sides of the laser spot. Using this distribution, a uniform temperature field can be obtained.

**Figure 4.** The optimal calculated intensity distribution for the generation of a top-hat temperature field during movement

Temperature field on Fig. 3b shows the temperature distribution if the scanning technology is not properly adapted to material properties (e.g., thermal conductivity). The edges are overheated; it still seems to be the best among the discussed profiles, since it generates sharp edges and a zone in the middle of the beam, where the temperature is above the austenite temperature for a sufficiently long time to start the diffusion process. Adaptation to create a uniform temperature distribution and profile optimization can be realized either by calculating the inverse heat conduction problem, or by trial and error.

For laser hardening, the energy conversion efficiency can be defined as the ratio between the hardened volume and the laser power multiplied by the unit time of the process. This factor includes optical loss and heat transferred to the workpiece. Another factor may be the geometric coefficient of efficiency for surface hardening, and it should be defined as the ratio of the area over which the hardened depth reaches the calculated value and the total area of heat hardening. This factor describes the local part of the track being processed. The calculation of the temperature field distribution was based on the simulations shown in Fig. 4.
Figure 5. Gaussian source type (top-hat) with a beam diameter of 12 mm, speed 10 mm/s, power 2.8 kW. Maximum temperature $1.3791 \times 10^3$ K

Figure 6. Gaussian source type with a beam diameter of 12 mm, speed 10 mm/s, power 3 kW. Maximum temperature $1.4776 \times 10^3$ K
Figure 7. Gaussian source type with a beam diameter of 12 mm, speed 10 mm/s, power 3.3 kW. Maximum temperature $1.6254 \times 10^3$ K

Starting from a power of 3.7 kW, a melting is observed at a laser beam velocity of 10 mm/s. For the following computational experiments, the speed of the laser beam was increased to 20 mm/s. The obtained calculation results are presented in Table 1.

Table 1. The results of computational experiments

| No. | Type of radiation source | Diameter, mm | Radiation power, kW | Scanning speed, mm/s | Maximum temperature, K |
|-----|--------------------------|--------------|---------------------|----------------------|------------------------|
| 1.  | Gaussian                 | 12           | 2.8                 | 20                   | 1032.5                 |
| 2.  |                         |              | 2.9                 |                      | 1069.3                 |
| 3.  |                         |              | 3                   |                      | 1106.2                 |
| 4.  |                         |              | 3.7                 |                      | 1364.3                 |
| 5.  |                         |              | 4                   |                      | 1474.9                 |
| 6.  |                         |              | 4.3                 |                      | 1585.6                 |
| 7.  |                         |              | 4.6                 |                      | 1696.2                 |
| 8.  |                         |              | 4.9                 |                      | 1806.8                 |

Under these conditions, melting was observed starting from power 4.9 kW.

Based on the obtained results of computational experiments, the dependences of the maximum temperature on the radiation power were constructed at a speed of 10 mm/s (Fig. 8) and 20 mm/s (Fig. 9).
Figure 8. Dependence of maximum temperature on radiation power, speed 10 mm/s

Figure 9. Dependence of maximum temperature on radiation power, speed 20 mm/s

The shape of the temperature field is elongated in the direction of movement of the laser beam, and over time, it stretches more horizontally than vertically, especially in the case of fast moving sources.
4. Conclusions

Analyzing the calculations, it can be concluded that for a steel plate for melting, a power of more than 3.7 kW in the case of a slowly moving source (10 mm/s) and more than 4.9 kW in the case of a fast-moving source (20 mm/s) are required. Moreover, an increase in power in the case of a slow source by 0.2–0.3 W is accompanied by an increase in the maximum temperature by 200 K at the beginning and will increase towards the end of the heating process, which goes into melting.

The dependence of the maximum temperature on power for this case is on average quite smooth. In the case of a fast-moving source for power up to 3 kW, the maximum temperature increases by 10–30 K when the power changes by 0.3 W. For powers above 3 kW, the maximum temperature increases more, already by 200–300 K with a change in power by 0.1 kW. Up to 4 kW, the process of increasing the maximum temperature slows down 0.1 kW - 100 K and then to 4.9 kW.

Thus, the calculations show that in the considered range of powers of the radiation source, surface nanomodification without melting can be realized.

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