Modeling of laser surface modification processes of tool steel to predict the temperature distribution and modification zone

E D Ishkinyaev1,2, E V Khriptovich1,3, V D Voronov2, V N Petrovskiy3, I N Shiganov1, A S Shchekin1,2 and A A Gavrikov4

1 Scientific and Technical Association "IRE-Polyus" LLC, Vvedenskogo Sq. 3, p. 5, Fryazino, Russia
2 National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 31 Kashirskoe shosse, Moscow, Russia
3 Bauman Moscow State Technical University, ul. Baumanskaya 2-ya, 5, Moscow, Russia

E-mail: elshkinyaev@ntoire-polus.ru

Abstract. Process of metal surface modification during laser treatment requires a long search and control of the treatment technological parameters, depending on the technical requirements imposed on it. The article proposes a method of mathematical modeling of heat transfer during laser processing of the high carbon steel 9HS (equivalent to DIN 150Cr14). The dimensions of the hardening are calculated with high accuracy by the isotherm of the critical temperature Ac3. The influence of the main technological parameters (radiation power, laser spot diameter, processing speed) on the depth and width of the hardening zone is shown. The paper also presents the use of the build model for the selection of multitrack processing modes to harden high-carbon steel 9HS to the required depth without surface melting.

1. Introduction
Laser surface modification is an effective technology for changing the properties of materials in accordance with technical requirements. Laser modification includes surface hardening and alloying processes. The process of laser hardening can be carried out both from the solid and from the liquid phase, and the process of laser alloying only from the liquid phase. In this work, as the first stage, hardening from the solid phase is considered.
Steels and cast irons are the main materials for laser heat treatment due to their good hardenability. With rapid heating of the processing area to temperatures above the critical point Ac3, the transformation of the initial phase into austenite, followed by rapid cooling into martensite, lead to significant increase in hardness in the affected zone [1].
Experimental selection of laser treatment parameters is usually a very resource-intensive process due to the different sensitivity of materials to the incident radiation [2]. Even if the single-track treatment process has already been worked out, the parameters of multi-track processing for obtaining the uniformly hardened subsurface layer may differ and depend, in particular, on the workpiece geometry. Primary mathematical modeling of the temperature fields induced by laser irradiation can significantly fasten the selection of the required technological parameters. Knowing the temperature at each workpiece area at any time it is possible to estimate its final microstructure after processing.
Quenching is possible when material is heated to temperatures between the values of transformation into the austenite phase ($A_{c3}$) and melting ($T_m$). To increase the hardness of the surface domain two conditions need to be satisfied: (1) the time duration above the $A_{c3}$ temperature must be long enough for carbon to fully diffuse in austenite and (2) cooling should occur fast enough to generate the martensitic phase [3].

To simplify the calculation, it can be assumed that the cooling rate during laser hardening is high enough to completely transform austenite into martensite [3–5]. In this case, it is sufficient to determine the boundary of the hardening region as the isotherm corresponding to the temperature $A_{c3}$.

The temperatures $A_{c1}$ at which austenite begins to form and $A_{c3}$ at which ferrite completes its transformation into austenite generally depend on the heating rate. It is shown that during fast laser heating these temperatures are higher than when material is slowly heated in a furnace [6]. However, in this research the stationary value of $A_{c3}$ determined from the iron-carbon phase diagram was used, since the modeling was carried out in several iterations with a slight correction of the material properties, which indirectly took into account the non-stationary dependence of critical temperatures on the heating rate.

The limiting factor of laser hardening is the softening of hard areas during the multi-track processing. The authors [7] simulated the effect of the hardness decreasing in the overlapped area when scanning with two tracks. Although they noted the fact that in order to obtain uniform hardening area with a given depth, it is necessary to vary the technological parameters to maintain steady heating, no techniques have been demonstrated.

This article shows the use of the verified model of the laser treatment in order to select technological parameters for obtaining a uniform depth of hardening area of high-carbon steel 9HS during the multi-track processing.

2. Materials and methods

2.1. Materials and experimental equipment

The experimental part was carried out on a setup equipped with a high-power fiber laser up to 10 kW at a wavelength of 1.07 μm by IPG. The laser hardening of a normalized ground 9HS steel substrate with dimensions 134×83×17 mm was conducted by processing single tracks at three values of scanning speed $V$ corresponding to different degrees of productivity – 10 mm/s, 20 mm/s and 30 mm/s. The change in the laser beam diameter was carried out by going into a greater defocus. In this work, the diameter $D$ was varied in range of 5–11 mm with a step of 1 mm. For each combination of $V$ and $D$ 7–8 values of radiation power $P$ were set, which were selected empirically to obtain hardening without significant surface melting and changing its morphology.

| Material | C, % | Si, % | Mn, % | Ni, % | Cr, % | W, % | V, % |
|----------|------|-------|-------|-------|-------|------|------|
| 9HS      | 0.85-| 1.20- | 0.30- | <0.4  | 0.95- | <0.2 | <0.15|
|          | 0.95 | 1.65  | 0.60  |       | 1.25  |      |      |

2.2. Modeling

The simulation of the laser treatment process was carried out in the COMSOL Multiphysics environment using the finite element method. The substrate geometry was 134×83×17 mm. A coarse mesh with element size of 0.5–7 mm was refined in the processing area to sizes of 0.1–0.5 mm. As a result of calculating heat transfer equations with given boundary conditions, a solution is derived for temperature fields with the isotherm corresponding to the temperature $A_{c3}$, according to which the dimensions of the hardening zone are estimated.
The volume distribution of temperature fields, induced by laser irradiation is determined by solving the Fourier equation:

\[ C_p(T) \rho(T) \frac{\partial T}{\partial t} - \nabla (k \nabla T) = Q(x, y), \]

where \( C_p \) is the specific heat capacity (J/kg.K), \( \rho \) – material density (kg/m\(^3\)), \( k \) – thermal conductivity (W/m.K), \( Q(x,y) \) – laser intensity profile.

The boundary conditions are set by convection with air and thermal radiation, described by the Stefan-Boltzmann law:

\[ k(\nabla T \cdot n) = h(T_{amb} - T) + \varepsilon \sigma (T_{amb}^4 - T^4), \]

where \( T_{amb} \) is the ambient temperature, \( h \) – convection coefficient, \( \varepsilon \) – emissivity coefficient of the body surface, \( \sigma \) – Stefan-Boltzmann constant (5.67 \times 10^{-8} \, \text{W/m}^2\text{K}^4).

Laser heating was modeled as a surface heat source moving with a velocity \( V \) (mm/s) with a Gaussian power density distribution \( Q_L(x,y) \) centered at the initial point \((x_0,y_0)\):

\[ Q_L = A(\lambda, T) \cdot \frac{2P}{\pi D^2} \exp \left( -8 \left( \frac{x-x_0-Vt}{D} \right)^2 + \left( \frac{y-y_0}{D} \right)^2 \right), \]

where \( A(\lambda, T) \) shows the absorbed fraction of the energy from the laser source, \( P \) - radiation power, \( D \) – laser beam diameter.

3. Results and discussions

3.1. Temperature fields

When solving the Fourier equation, temperature distribution induced by the laser irradiation was calculated over the entire volume of the body. The obtained temperature fields were used to determine the isotherms corresponding to the melting point \( T_m = 1450 \, ^\circ\text{C} \) and the critical temperature \( A_{C3} = 850 \, ^\circ\text{C} \) of steel 9HS. They show the boundaries of the melting and hardening zones, respectively (Figure 1).

Also the temperature dependences were calculated at the points on the peripheral area of influence (spaced 5-10 mm from the center of laser beam, depending on the processing parameters) for subsequent comparison of the calculated and experimentally measured using an IR camera data.

![Figure 1](image)

**Figure 1.** Cross section after processing using following parameters - \( P = 1800 \, \text{W}, V = 10 \, \text{mm/s}, D = 11 \, \text{mm} \). a) – modeling result with the isotherm of the temperature \( A_{C3} \), b) – real hardened zone.

3.2. Experimental verification

Experimental verification of the model was carried out by comparison with calculated data of: (1) the temperature dependencies of heating and cooling of the substrate at selected points, taken using an IR camera and (2) the characteristic dimensions of the hardening zone (width and depth). For correct temperature measurements, a Kapton tape with the emissivity coefficient close to 1 was applied to the substrate. Thus, the possibility of temperature measurements errors due to the low emissivity of the ground steel surface and its change due to oxidation during processing was excluded. The dimensions
of the hardening zones were determined by direct observation under an optical microscope of the polished and etched in 20% nitric acid cross sections. An example of temperature plots is shown in Figure 2.

![Figure 2](image.jpg)

**Figure 2.** Calculated (C) and Experimental (E) temperatures at points located at different distance from the laser beam trajectory ($P = 1800$ W, $D = 11$ mm, $V = 10$ mm/s).

Comparison of the experimental and calculated values of the hardening depth is conveniently presented as a dependence on the parameter $P/(VD)$ [J/mm$^2$], which has the dimension of energy density (Figure 2). Such a representation allows combining all varying technological parameters into one variable. Analyzing the results of processing at different speeds $V$, it was found that the hardening depth is linearly proportional to the $P/VD$ at a fixed scanning speed $V$. The change in $V$ introduces a non-linear character to the dependence, which can be seen in Figure 3a. The model with high accuracy describes the hardening depths at scanning speed $V = 10$ mm/s (Figure 3b), calculation errors at $P/VD < 11$ J/mm$^2$ are associated with a significant change in the absorption coefficient of the radiation with a low power density. Errors at $P/VD > 20$ J/mm$^2$ are associated with the appearance of surface melting, which abruptly changes the properties of the liquid phase and is not accurately considered in the model. Improving the accuracy of calculations in these ranges is of no interest when considering laser hardening process, but will be useful for modeling laser alloying process in the future research. With an increase in the $P/VD$ value at $V = 20$ mm/s (Figure 3c) the errors increase, the experimental depth turns out to be less than predicted by the model. This is due to a change in the absorbivity with a change in the processing speed (a smaller part of the energy is absorbed by the material with an increase in the scanning speed due to the shorter exposure time). This phenomenon is especially noticeable in Figure 3d. Although the errors of the simulated results are high, the straight lines of the experimental and calculated dependences are parallel, which indicates the possibility of correcting the model by decreasing the absorption coefficient by a constant value. The hardening depth in the model is largely determined by the laser energy absorption coefficient. It can be concluded that absorbivity of the material actually decreases with decreasing time of radiation exposure per unit area. To simulate fast laser hardening process, it is necessary to consider this factor and select the absorption coefficient for a specific scanning speed. The second reason may be a different hardening mechanism at low exposure times.
3.3. Multi-track hardening

To harden the surface of a part with dimensions larger than the laser beam diameter, scanning of a given area with several overlapping tracks is used. In multi-track processing, there is a need to vary the technological parameters to obtain a hardened layer with a constant depth. If the energy supply is not reduced, the HAZ will increase and ultimately the surface will begin to melt. The values of the parameters variations depend on the processing mode, part geometry and external conditions. The verified model helps to select the technological parameters and their change over time to obtain hardening of a given depth on a specific part, significantly reducing the amount of required experimental work.

Based on the built model, the processing parameters were calculated to obtain uniform hardening area by scanning of 15 tracks. The decrease in the supplied laser energy was carried out decreasing the radiation power. On the first attempt, uniform hardened zone to a depth of 0.6-0.7 mm was obtained. Figure 4 shows the results of processing the substrate surface with $V = 10$ mm/s and laser beam diameter of 11 mm with 33% overlapping.

Figure 3. Dependence of the hardening depth on the $P/VD$. a) All scanning velocities (10, 20 and 30 mm/s), b) $V = 10$ mm/s, c) $V = 20$ mm/s, d) $V = 30$ mm/s.

Figure 4. Results of laser hardening with variable radiation power.
4. Conclusions
A mathematical model of heat transfer during laser modification of the metal surface is proposed. Using the example of hardening high-carbon steel 9HS, the depth and width of the hardened layer are calculated with high accuracy from the isotherm of critical temperature Ac₃ in a wide range of technological parameters of the laser processing.

The possibility of using the model for calculating the values of the decrease in the supplied laser energy for obtaining a uniform hardening depth during multi-track processing is shown. Experimental hardening of the workpiece with 15 tracks to a depth of 0.6-0.7 mm using the calculated processing parameters is in excellent agreement with the model.

References
[1] Babu P D and Marimuthu P 2019. Emerg. Mater. Res. 8(2) 188–205
[2] Barka N, Karganroudi S S, Fakir R, Thibeault P and Kemda V B F 2020 Coatings 10(4)
[3] Ki H and So S 2012 Opt. Laser Technol. 44(7) 2106–14
[4] Patwa R and Shin Y C 2007 Int. J. Mach. Tools. Manuf. 47(2) 307–20
[5] Orazi L, Rota A and Reggiani B 2021 Int. J. Mech. Mater. Eng. 16(1)
[6] Bojinović M, Mole N and Štok B 2015 Surf. Coatings Technol. 273(1) 60–76
[7] Lakhkar R S, Shin Y C and Krane M J M 2008 Mater. Sci. Eng. A 480(1–2) 209–17