Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Value of diffusion layer thickness during increasing the hardening of precision parts by laser method

Alakbar Huseynov
Azerbaijan Technical University
Farid Huseynli
farid.huseynli@aztu.edu.az

Azerbaijan Technical University
Mirzabay Safarov
Azerbaijan National Aerospace Agency

Article

Keywords:

Posted Date: November 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11552310/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Value of diffusion layer thickness during increasing the hardening of precision parts by laser method

Alakbar Huseynov[1], Farid Huseynli[1*], Mirzabay Safarov[2]

[1*]Azerbaijan Technical University, Baku, Azerbaijan Republic.
[2]National Aerospace Agency, Baku, Azerbaijan Republic.

*Corresponding author(s). E-mail(s): farid.huseynli@aztu.edu.az;
Contributing authors: h_alakbar@aztu.edu.az;
ali.rahman.7534@gmail.com;

Abstract

This paper addresses the thickness of the diffusion layer formed during laser surface hardening of precision parts of machines and apparatuses, which must be known in order to assign the machining allowance for subsequent finishing. During saturation, the outer and inner boundaries of the diffusion layer shift relative to the initial surface; this displacement depends on the thermodynamic properties of the system, the type of diffusion process and the material of the part. The process is considered as a sequence of stages in which the rate at which atoms arrive at the surface greatly exceeds their rate of diffusion into the part, so that layer growth is controlled by diffusion in depth. Diffusion saturation of precision parts forms a ternary system of simultaneously interacting elements, which can be described by considering the behaviour of two of them. Using Fick's laws with direct and cross-diffusion coefficients, analytical expressions are derived for the velocity of the outer boundary, the change in the linear dimensions of the part and the total thickness of the diffusion layer, showing a parabolic dependence on saturation time. The curves were calculated for chromium and nitrogen using concentration, diffusion coefficient and rate constant values taken from the literature. The results show that the required quality and thickness of the layer, and hence the machining allowance, are governed by the diffusion coefficients and the thermodynamic reaction rate constant.

Keywords: diffusion layer, laser surface hardening, precision parts, machining allowance, cross-diffusion, Fick's laws

1 Introduction

Laser surface hardening is widely used to increase the hardness and wear resistance of steel parts, because heating is local and fast and the core of the part remains largely unaffected [1, 13–15]. Combined with diffusion saturation (laser alloying and laser-assisted chemical-thermal treatment), it makes it possible to form a hardened layer enriched with alloying elements such as chromium, nitrogen or boron [4, 5, 11, 12, 20]. For precision parts, such as the plunger–barrel pairs of fuel pumps, the hardened layer must not only have the required properties but must also remain on the part after finishing, since the final dimensions are obtained by grinding or lapping [6, 8].

During laser surface hardening, the geometric parameters of the diffusion layer of precision parts change [1, 7, 11, 12, 15]. This change must be taken into account when assigning the machining allowance for finishing [2, 6, 16]. At the same time, the diffusion layer has to be thick enough to compensate for the deformation (warping) of the part, so that a minimum machining allowance can be maintained in subsequent machining [8, 21].

The present work continues the authors' earlier studies on laser hardening of precision parts. The reliability of fuel-pump precision parts with laser-enhanced surface hardness was predicted in [6], and the inheritance of properties along the technological chain of processing such parts was analysed in [7]. The deformation of laser-hardened precision parts and the corresponding minimum machining allowance were determined in [8], where the calculated allowance agreed with the experimentally established range for a fuel-pump plunger. Vacuum laser diffusion boron-chromizing of precision parts was studied in [5], and the thermo-deformation behaviour of a laser-hardened plunger–barrel pair with wear was modelled in [9]. However, these studies did not describe how the thickness of the diffusion layer itself and the position of its boundaries change with saturation time, which is the input required for allowance calculation.

Diffusion processes in the surface layers of precision parts are associated with the formation and growth of new phases. The boundaries of the diffusion layer, relative to the initial surface before saturation, therefore move in two directions: inwards, owing to diffusion of the saturating elements into the part, and outwards, owing to the formation and growth of new phases [10].

The displacement of the outer and inner boundaries depends on the thermodynamic properties of the system, the type of diffusion process and the material of the part. The ratio between the inner and outer parts of the layer thickness varies between 20 and 80% [6, 16]. As the layer thickness increases, the minimum machining allowance usually increases as well [8]. The thickest diffusion layers are formed in laser surface hardening combined with diffusion saturation [3, 6, 16, 18, 21, 22].

In laser surface hardening with diffusion saturation, the diffusion process of the part includes the following stages: (a) formation of a halogen-containing carrier gas of the saturating element(s); (b) transport of the atoms of the element(s) to the surface; (c) decomposition of the carrier gas and adsorption of the saturating atoms on the surface of the precision part; (d) distribution of the atoms over the surface of the part. The main conditions are the absence of oxygen, which is an active oxidizer, and a high temperature, which increases the vibration of atoms and their jumps to other lattice sites with the formation of vacancies.

Studies of laser surface hardening have mainly addressed the temperature field, the hardened depth, and the microstructure and properties of the hardened zone [1, 13–15], whereas kinetic models of multicomponent diffusion layers have mostly been developed for conventional chemical-thermal treatment [10]. Analytical relations that link the thickness of a laser-formed diffusion layer, the displacement of its boundaries and the resulting change in part dimensions to the diffusion coefficients and reaction rate constants are still lacking, although they are needed to assign the machining allowance of precision parts.

Purpose of the study. The aim of this work is to determine the thickness of the diffusion layer formed during laser surface hardening and the factors that govern it, so that a sufficient hardened layer remains after machining. To this end, the formation and growth of a new phase and the displacement of the outer and inner boundaries of the diffusion layer are described on the basis of Fick's laws with direct and cross-diffusion coefficients.

2 Methodology

According to the diffusion theory, the amount of substance that diffuses per unit time is proportional to the difference in concentration [2]:

$$\frac{\partial m}{\partial t} = DF\frac{\partial c}{\partial x}, \tag{1}$$

where ∂m is the amount of diffusing substance; D is the diffusion coefficient; $\partial c/\partial x$ is the concentration gradient along the x direction; F is the cross-sectional area; and ∂t is the diffusion time.

The change in concentration per unit time at a given intersection point is equal:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right). \tag{2}$$

Eq. 1 and Eq. 2 correspond to Fick's first and second laws, respectively. Due to these dependencies, it creates conditions for accelerating the diffusion process in the x direction and increasing the layer and diffusion coefficient with the maximum concentration of saturated elements necessary for the formation of a diffusion layer on the surface of the part in a short time.

During the nanodiffusion processes carried out by the laser technological method, the speed of atoms reaching the surface greatly exceeds the diffusion speed [2, 10]. Therefore, the formation of a nanodiffusion layer is limited by the depth diffusion rate of atoms. It is partially characterized by nanodiffusion coefficients. Nanodiffusion coefficients in precision parts are (partially) determined by the rate of diffusion of saturation elements from core to carbon. When saturated by diffusion in alloyed parts, the diffusion coefficient can be reduced or increased by alloying elements. The most effective method of increasing the diffusion rate is laser technology, because in the technological process high temperature is obtained instantaneously [1–3, 6, 7, 11, 12, 15, 16, 18, 21].

The laser hardening of the surface of precision parts is accompanied by the formation of complex phases on the surface. It is known from the theory of diffusion processes [1, 2, 6, 7, 11, 12, 15, 16] that the number of atoms diffused to the surface as a result of nanodiffusion is directly proportional to the difference in its concentration in the zone near the surface:

$$\begin{aligned} \Delta m_1(t) &= k_1\left(c_1^n - c_1\right), \\ \Delta m_2(t) &= k_2\left(c_2^n - c_2\right), \end{aligned} \tag{3}$$

where $\Delta m_{1,2}$ are the alloying elements in parts 1 and 2 that diffuse to the surface of the part during time t; k_1, k_2 are the thermodynamic reaction rate constants; $c_{1,2}^n$ and $c_{1,2}$ are the concentrations of substances on the surface of the part and in the diffusion layer, respectively.

The laser technological process will tend to bring the material of the precision part to thermodynamic equilibrium due to diffusion. According to Eq. 3, the rates of diffusion reactions will be disturbed as the concentration of saturated elements in the nanodiffusion layer increases.

The diffusion process of precision parts leads to the formation of a triple system of simultaneously interacting elements, for the mathematical description of which it is enough to consider the behavior of two of them (Fig. 1).

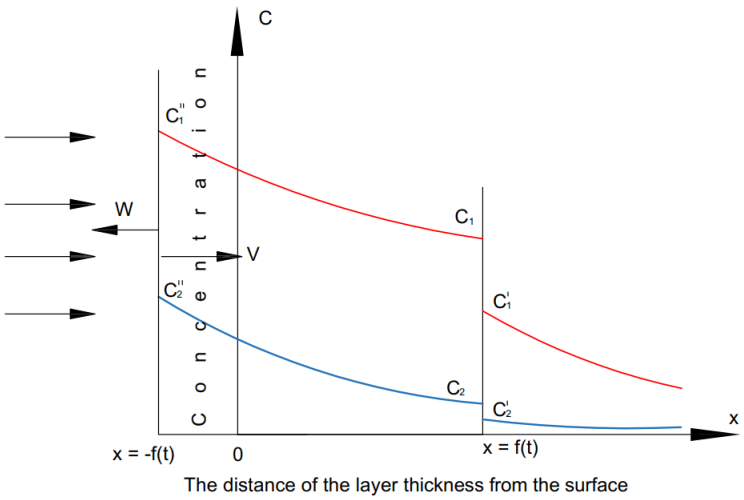

Fig. 1 Scheme of phase growth in the diffusion layer

When considering the laser technological process, the following assumptions are made: the thickness of the nanodiffusion layer is significantly less than the thickness of the whole part; during saturation, the outer and inner boundaries of the nanodiffusion layer move parallel to the initial ones; the kinetics of the reactions is determined only

by the nanodiffusion process; absorption reactions at the surface and phase transformation at the boundary of the nanodiffusion layer; partial coefficients do not change during saturation; the nanodiffusion process is considered in an uniform area.

Since the nanodiffusion process is considered in the coordinates related to the surface of the finite-sized part, at the initial moment of time, the outer boundary of the surface of the part will be at the origin of the coordinates ($x = 0$). During the diffusion process, the inner boundary of the layer moves with the speed $V(t)$, and the outer boundary moves with the speed $W(t)$.

The increase in the thickness of the diffusion layer occurs according to the law $L(t) = V(t) + W(t)$.

The rate of diffusion of saturated elements, which determines the formation and growth of a new phase, and the change of the outer and inner boundaries of the diffusion layer in connection with this, will be determined from Fick's first law [2, 3, 19, 20, 22]:

$$\Delta m_1 = \left(D_{11} \frac{\partial C_1}{\partial x} + D_{12} \frac{\partial C_2}{\partial x} \right) + (V_1 - W_1)\, c_1, \tag{4}$$

$$\Delta m_2 = \left(D_{22} \frac{\partial C_2}{\partial x} + D_{21} \frac{\partial C_1}{\partial x} \right) + (V_2 - W_2)\, c_2, \tag{5}$$

where D_{11}, D_{12} are the direct diffusion coefficients of the 1st and 2nd elements; D_{22}, D_{21} are the cross-diffusion coefficients of the 1st and 2nd elements; $W = W_1 + W_2$ is the movement speed of the outer border during the propagation of the 1st and 2nd elements; $V = V_1 + V_2$ is the velocity of lattice flow near the saturation surface; and c_1, c_2 are the concentrations of saturated elements at the internal phase boundary.

3 Discussion of the results

Taking into account that the concentrations of saturated elements in the diffusion layer satisfy $c_1 + c_2 = 1$ (100%), as well as the expression (Eq. 3): $k_1 = ak$ and $k_2 = bk$, we obtain:

$$-\left(D_{11} \frac{\partial C_1}{\partial x} + D_{12} \frac{\partial C_2}{\partial x} \right) = ak\big(c_1^n - c_1\big) + (V_1 - W_1)\, c_1, \tag{6}$$

$$-\left(D_{22} \frac{\partial C_2}{\partial x} + D_{21} \frac{\partial C_1}{\partial x} \right) = bk\big(c_2^n - c_2\big) + (V_2 - W_2)\, c_2. \tag{7}$$

Adding Eq. 6 and Eq. 7 gives the velocity of the outer boundary of the diffusion layer relative to its initial position:

$$W = -k\big[a\big(c_1^n - c_1\big) + b\big(c_2^n - c_2\big)\big] + \left[\left(D_{11} \frac{\partial C_1}{\partial x} + D_{12} \frac{\partial C_2}{\partial x} \right) + \left(D_{22} \frac{\partial C_2}{\partial x} + D_{21} \frac{\partial C_1}{\partial x} \right) - V \right]. \tag{8}$$

If the boundary concentrations are equal, Eq. 8 takes the form:

$$W = k(b - a)\big(c_1^n - c_1\big) + \left[(D_{11} + D_{12} + D_{21} + D_{22}) \frac{\partial C_1}{\partial x} - V \right]. \tag{9}$$

The change in the geometric parameters over time t is then:

$$X(t) = \left\{ k(b-a)\left(c_1^n - c_1\right) + \left[(D_{11} + D_{12} + D_{21} + D_{22}) \frac{\partial C_1}{\partial x} - V \right] \right\} t. \tag{10}$$

According to Eq. 10, the change in the geometric parameters during diffusion treatment depends on the concentration difference at the inner and outer boundaries of the newly formed phase, the concentration gradient of the saturating elements across the layer, the direct and cross-diffusion coefficients (in complex saturation), the thermodynamic reaction rate constant and the treatment time. If the lattice flow velocity V is numerically equal to the Kirkendall flow velocity given by the Darken relation $V = V_0(D_{11} - D_{22})\partial C_{1,2}/\partial x$, the change in the linear dimensions of the part is caused only by the second term, i.e., by the cross-diffusion coefficients.

Solving Eq. 10 requires the choice of boundary conditions and integration of the partial derivatives. After integration, the total thickness of the diffusion layer is expressed as:

$$L(t) = (m^2 + nt)^{1/2} - m, \tag{11}$$

where the displacement of the outer boundary of the diffusion layer, i.e. the change in the dimensions of the part, is given by:

$$X(t) = \frac{\mu}{\mu - 1} \left(\sqrt{m^2 + nt} - m \right), \tag{12}$$

and the following notation is used:

$$\begin{aligned}
\mu &= (b-a)(bc_1 - ac_2)(c_1 - c_2), \\
m &= \left(c_1 D_{22} + c_1 D_{21}/c_2 + c_2 D_{12}/c_1 + c_2 D_{11}\right) \Big/ \left[k(bc_1 + c_1 a/b + c_2 b/a + c_2 a)\right], \\
n &= 2\left(c_1 D_{22} + c_1 D_{21}/c_2 + c_2 D_{12}/c_1 + c_2 D_{11}\right) \\
&\quad \times \left[1 - (b-a)(bc_1 - ac_2)(c_1 - c_2)\right] \cdot (c_1^n - c_1)/(c_1 - c_2).
\end{aligned}$$

N.S. Gorbunov proposed an empirical expression for the total thickness of the diffusion layer based on experimental data [17]:

$$L(t) = 2\left(\sqrt{Atl}\right)^{-B/(2T)}, \tag{13}$$

where A and B are empirical coefficients and T is the temperature of the diffusion process.

Eq. 12 and Eq. 13 both show a parabolic dependence of the layer thickness and of the change in linear dimensions on saturation time. The agreement in form between the theoretical relation (Eq. 12) and the empirical relation (Eq. 13) is consistent with the assumption that layer growth is controlled by diffusion in depth rather than by the supply of atoms to the surface.

Eq. 12 makes it possible to determine the change in the geometric parameters of the diffusion layer from the partial diffusion coefficients, the concentrations and the reaction rate constant for laser surface hardening of precision parts.

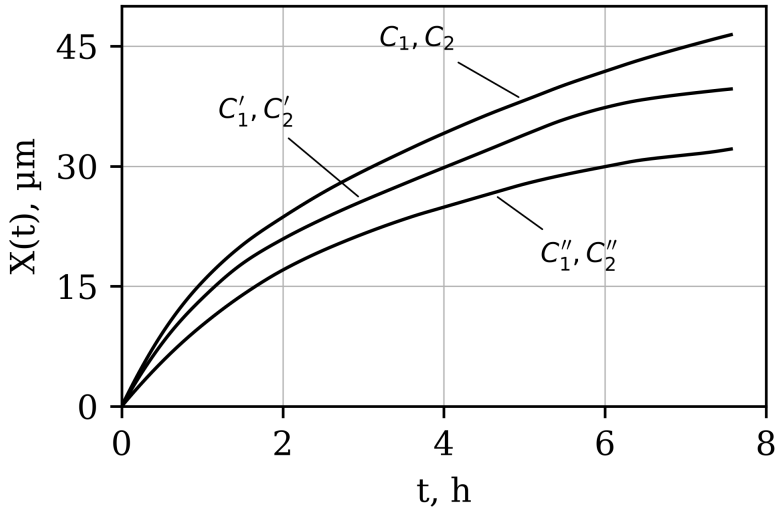

Fig. 2 Displacement of the outer boundary of the diffusion layer of the precision part versus diffusion time t, h (vertical axis: $X(t)$, µm)

Figure 2 shows the displacement of the outer boundary of the part as a function of diffusion time. The curves were constructed for the alloying elements chromium and nitrogen using concentration, diffusion coefficient and thermodynamic coefficient values reported in the literature for precision parts subjected to laser surface hardening [3, 11, 12, 19, 21]. Intermediate values were obtained by interpolation. The following values were adopted:

$$
\begin{aligned}
&c_1'' = 7.19 \times 10^{-3}\,\mathrm{g/mm^3}, && c_1 = 0.78 \times 10^{-4}\,\mathrm{g/mm^3}, && c_1' = 6.8 \times 10^{-4}\,\mathrm{g/mm^3},\\
&c_1'' = 5 \times 10^{-4}\,\mathrm{g/mm^3}, && c_2 = 19.5 \times 10^{-4}\,\mathrm{g/mm^3}, && c_2' = 23 \times 10^{-6}\,\mathrm{g/mm^3},\\
&c_2'' = 30 \times 10^{-6}\,\mathrm{g/mm^3}, && D_{11} = 1.55 \times 10^{-10}\,\mathrm{mm^2/s}, && D_{12} = 4 \times 10^{-8}\,\mathrm{mm^2/s},\\
&D_{21} = 10^{-10}\,\mathrm{mm^2/s}, && D_{22} = 10^{-12}\,\mathrm{mm^2/s}, && k = 1.45 \times 10^{-6}\,\mathrm{mm^3/s},\\
&k_1 = 1.75 \times 10^{-6}\,\mathrm{mm^3/s}, && a = 0.1b. &&
\end{aligned}
$$

Substituting these values into Eq. 12 gives $X(t)$ for each value of t.

The curves in Fig. 2 show that the growth rate is highest at the beginning of saturation and decreases with time, as expected for parabolic, diffusion-controlled growth (Eq. 12 and Eq. 13). The curves are labelled with the concentration pairs at the characteristic boundaries shown in Fig. 1 (C_1, C_2; C_1', C_2'; C_1'', C_2''), and the noticeable spread between them shows that the boundary concentrations of the saturating elements strongly influence the displacement of the outer boundary. Consequently, the machining allowance cannot be assigned from the saturation time alone: the boundary concentrations, which are set by the saturating medium and the alloying of the part, must also be taken into account. Since the allowance must not exceed the part of the

layer that can be removed without losing the hardened zone, $X(t)$ and $L(t)$ together determine the admissible allowance range [8].

From a practical point of view, laser surface hardening of nitrided parts containing chromium is promising [3, 11, 12, 21], since it allows the diffusion coefficient to be increased by a factor of 2–3. The authors' earlier work [8] showed that the minimum machining allowance calculated from the layer thickness and the part deformation agreed with the experimentally established range for a fuel-pump plunger; the relations for $X(t)$ and $L(t)$ obtained here provide the layer-thickness input for such calculations. Further study of laser surface hardening requires multifactorial experiments that take the input and output parameters of the process into account.

The model is based on the assumptions listed in Section 2: constant partial diffusion coefficients, parallel movement of the layer boundaries, kinetics controlled by diffusion only, and a layer much thinner than the part. In laser processing, heating and cooling are rapid and non-isothermal, and diffusion coefficients depend strongly on temperature; the coefficients used here should therefore be regarded as effective values for the treatment cycle. Experimental determination of these coefficients for specific laser regimes and direct comparison of the calculated $X(t)$ and $L(t)$ with metallographic measurements of the layer are the subject of further work.

4 Results

Thus, the required quality and thickness of the diffusion layer in laser surface hardening of precision parts are determined by the diffusion coefficients and the thermodynamic reaction rate constant. The derived relations (Eqs. 10–12) allow the displacement of the layer boundaries and the change in part dimensions to be estimated and used in assigning the machining allowance. Research in this direction is being continued at the Department of Special Technologies and Equipment, Azerbaijan Technical University.

Declarations

- Funding: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.
- Conflict of interest/Competing interests: The authors declare that they have no competing interests.
- Ethics approval and consent to participate: Not applicable.
- Consent for publication: Not applicable.
- Data availability: The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.
- Materials availability: Not applicable.
- Code availability: Not applicable.
- Author contribution: Not applicable.

Corresponding author: Farid Huseynli, farid.huseynli@aztu.edu.az, ORCID: 0009-0007-5393-9440.

References

[1] Castro Cerda FM, Goulas C, Jones D, et al (2024) Modelling the laser surface hardening process in a steel with a spheroidized initial microstructure. J Manuf Process 125:364–373. https://doi.org/10.1016/j.jmapro.2024.07.052

[2] Chen J, Li B, Zhou Y (2022) Modelling of diffusion-driven microstructural evolution during laser heat treatment of steels. Materials & Design 223:111150

[3] Cholkar A, Chatterjee S, Kumar S, et al (2024) Combining ultrafast laser texturing and laser hardening to enhance surface durability by improving hardness and wear performance. Adv Eng Mater 26(20):2401183. https://doi.org/10.1002/adem.202401183

[4] Dudek A, Lisiecka B, Radek N, et al (2022) Laser surface alloying of sintered stainless steel. Materials 15(17):6061. https://doi.org/10.3390/ma15176061

[5] Huseynov A, Huseynli F (2025) Enhancing processing capacity of precision parts via vacuum laser diffusion boron-chromizing. Finnish J Tribol 42(3–4):31–39. https://doi.org/10.30678/fjt.162698

[6] Huseynov A, Huseynli F, Safarov M (2025) Reliability prediction of precision parts of fuel pumps with enhanced surface hardness achieved through laser technology. Finnish J Tribol 42(1–2):64–71. https://doi.org/10.30678/fjt.152491

[7] Huseynov A, Nazarov I, Huseynli F, et al (2025) Challenges of property inheritance during the technological processing of fuel pump precision parts. Finnish J Tribol 42(1–2):72–79. https://doi.org/10.30678/fjt.160975

[8] Huseynov A, Nazarov I, Huseynli F, et al (2025) Determination of deformation and machining allowance of precision parts hardened by laser method. Reliab Theory Appl 20(7):379–385. https://doi.org/10.24412/1932-2321-2025-783-379-385

[9] Huseynov AG, Asadov ShN, Huseynli FS, et al (2025) Modeling of the thermodeformation behavior in a laser-hardened plunger–barrel pair considering wear effects. Herald Azerb Eng Acad 17(4):42–50. https://doi.org/10.52171/herald.325

[10] Jurči P, Hudáková M (2011) Diffusion boronizing of H11 hot work tool steel. J Mater Eng Perform 20(7):1180–1187. https://doi.org/10.1007/s11665-010-9750-x

[11] Kumar A, Singh R, Prakash S (2021) Development of multicomponent diffusion coatings for high-temperature tribological applications. J Mater Eng Perform 30:5140–5152

[12] Li X, Wang S, Zhang Y (2022) Laser-induced diffusion-based chromium enrichment for improving wear resistance of tool steels. Surface & Coatings Technology 449:128994

[13] Li Z, Zhang J, Dai B, et al (2020) Microstructure and corrosion resistance property of laser transformation hardening pre-hardened AISI P20 plastic die steel. Opt Laser Technol 122:105852. https://doi.org/10.1016/j.optlastec.2019.105852

[14] Maharjan N, Wu N, Zhou W (2021) Hardening efficiency and microstructural changes during laser surface hardening of 50CrMo4 steel. Metals 11(12):2015. https://doi.org/10.3390/met11122015

[15] Nath AK, Sarkar S (2018) Laser transformation hardening of steel. In: Advances in Laser Materials Processing, 2nd edn. Woodhead Publishing, pp 257–298. https://doi.org/10.1016/B978-0-08-101252-9.00011-X

[16] Pan X, Zhou L, Hu D, et al (2023) Superior wear resistance in cast aluminum alloy via femtosecond laser induced periodic surface structures and surface hardening layer. Appl Surf Sci 636:157866. https://doi.org/10.1016/j.apsusc.2023.157866

[17] Wang H, Zhao P, Lin J (2025) Laser-based texturing and diffusion-assisted hardening technologies for next-generation tribological surfaces—A review. Coatings 15:1142

[18] Wang Y, Wang X, Hou F, et al (2025) Optimization of laser surface texturing parameters for improving friction and wear resistance of GCr15 bearing steel sliding pairs. Lubricants 13(12):536. https://doi.org/10.3390/lubricants13120536

[19] Xiao N, Tang J, Zhou S, et al (2025) Current research on the design, properties and applications of tribological materials: a review. RSC Adv 15(41):34669–34717. https://doi.org/10.1039/D5RA02780B

[20] Xu W, Liu Q, Chen Z (2023) Laser-induced diffusion mechanisms in multicomponent surface alloying of steels. Surface Engineering 39:152–162

[21] Zhang J, Shen S, Wu Q, et al (2025) Effect of laser energy density on microstructural evolution and wear resistance of pre-hardened DC53 steel by laser transformation hardening. J Mater Res Technol 39:7174–7186. https://doi.org/10.1016/j.jmrt.2025.10.078

[22] Zheng K, Lin Y, Cai J, et al (2022) Corrosion resistance and tribological properties of laser cladding layer of H13 die steel strengthened by ultrasonic rolling. Chin J Mech Eng 35:137. https://doi.org/10.1186/s10033-022-00810-4