Improving the effects of laser hardening of steels by applying a longitudinally torsional ultrasonic field

Andrey Kochetov¹, Valentin Minakov¹, Elena Fisunova¹, Ivan Kochetov¹, Olga Baryshnikova¹

¹Don State Technical University, sq. Gagarina, 1, Rostov-on-Don, 344010, Russia

E-mail: fis62@mail.ru

Abstract. The paper is devoted to the expediency of using ultrasonic treatment in combination with laser hardening for U8, U10, X12M steels and the study of the effect of ultrasonic longitudinal and torsional acoustic vibrations on the intensification of an increase in the concentration of point defects in the crystal structure. The introduction of a longitudinal and torsional ultrasonic field by transforming longitudinal ultrasonic vibrations made it possible to form a highly concentrated effect, which led to an increase in the effects of laser hardening.

1. Introduction

Hardening of metallic materials with concentrated energy flows (which include ultrasonic exposure) in various combinations allows intensifying the existing technological processes of their processing and makes it possible to obtain results not achievable with traditional technology.

The interconnection between the quality characteristics of the surface layer and the properties of the products indicates that the optimal surface should be sufficiently solid, have compressive residual stresses, a finely dispersed structure, a smoothed shape of microroughness with a significant area of the supporting surface [1].

These requirements are achievable in various ways, including a combination of laser processing and surface plastic deformation. The successful use of combined methods of surface hardening of steels is possible only if the optimal structure of the contacting surfaces is formed, which determines the required performance properties.

Since ultrasonic vibrations are capable of causing plastic deformation of metallic materials, in certain cases it makes sense to compare the effects obtained with effects similar to machining with mechanical action, which lead to hardening. At the same time, the fact that there is no change in the size and shape of the workpiece in contrast to surface plastic deformation (SPD) is important. This allows you to use the acoustic effect in the processing of complex instruments and designs. In the present work, the question of the expediency of using ultrasonic treatment in combination with laser hardening for steels U8, U10, X12M and others was investigated, and ultrasonic treatment was performed both before and after laser processing. In the first case, strain hardening of the surface layers of the samples was achieved, in the second, ultrasonic treatment was carried out in order to reduce the roughness and some additional hardening of the surface layers of steels, and also, under certain laser treatment conditions, to form oil pockets that hold the lubricant during friction pairs operation.
2. Research methods

Pulsed laser surface treatment was carried out on a Kvant-16 technological unit with a change in the radiation power density in the range of 80-100 MW/m². The degree of beam defocusing (3-6 mm) and the radiation duration ($3 \times 10^{-3}$ s - $6 \times 10^{-3}$ s) made it possible to vary the radiation power density in wide limits.

Ultrasonic vibrations with a frequency of 21.2 kHz and an amplitude of 10 μm were continuously supplied to the sample perpendicular to the surface under study. The processing process was carried out through a thin layer of mineral oil, which acts as an acoustic lens in places where there is no mechanical contact of the waveguide with the surface of the sample due to the roughness of the latter.

Parameters of ultrasonic vibrations were set by an ultrasonic generator UZG 1-1, a magnetostrictive transducer PMS 1-1, and a longitudinal ultrasonic waveguide, at the end of which a sample was fixed. It should be noted that such a waveguide design, made on the basis of a titanium alloy, provides intensification of the ultrasonic control interaction, due to the good properties of the acoustic transparency of the material and contributes to a more pronounced manifestation of the effects of exposure. No less than 7 samples with dimensions of $10 \times 10 \times 15$ mm were subjected to surface treatment for each hardening option. When measuring various quantities, their mean values, standard deviations and confidence intervals were determined at a reliability level of $P = 0.95$ (Student's criteria was 2.447).

Microstructures were examined on transverse and longitudinal sections using MIM-7 and Neophot-21 microscopes. The fine structure of the treated layers was studied using an EM-MA-4 electron microscope at magnifications of 15000-20000 using the foil method, which is based on imaging by diffraction contrast.

Microhardness measurements were carried out on a PMT-3 device with a load of 0.49 N. At the same time, the standard rules for placing prints were followed, according to which the minimum allowable distance between the centers of adjacent prints was 30 μm, from the center of the print to the edge of the sample - 20 μm.

The phase composition in the heat-affected zones was identified by the method of depth X-ray diffraction analysis, after electrolytic polishing of the samples and metallographic control of the structure of the studied surface. The studies were carried out on a DRON-0.5 diffractometer in filtered $F_{Kα}$-radiation with intensity recording by scintillation counters. X-ray line profiles were taken in continuous recording mode at a speed of 1 deg/min.

3. Theoretical foundations of the dynamics of the transformation of ultrasonic vibrations

The problem of the efficient and widespread use in energy of energy of complex ultrasonic testing can be solved by developing a theory of transformation of this type of vibrations, which would make it possible to state the dynamics of vibrations in a form convenient for their analysis and engineering calculation, and in addition to the basic formulas, to give a general calculation method.

In the case under consideration, longitudinal ultrasonic vibrations are transformed into complex ones by attaching to the last stage of the concentrator of a longitudinal acoustic system a naturally twisted (spiral) waveguide. The interpretation of a twisted waveguide as a naturally twisted rod subjected to the action of a system of forces arising in the course of one or another type of processing leads to some dynamic three-dimensional problem, the solution of which, even in special cases, is absent in the literature. Nevertheless, the known results of the corresponding statistical problems [1,2,3,4] will be used below.

As a first step in developing the dynamics of a naturally twisted waveguide, we construct such a mathematical model of it that, on the one hand, would make it possible to simplify the study significantly, and on the other, would accurately reflect its actual behavior in any cross section [2].

In the common case, any waveguide cross section is flat in the natural (unloaded) state, undergoes complex deformation during operation and does not remain flat. However, the determining factor affecting the process of a particular type of processing is the nature of the movement of each cross section of the waveguide as a whole, i.e. some averaged movement of this section. This means that
instead of the actual non-planar section, we can consider a certain plane section having an averaged motion of the real section [3].

In addition, the following facts, based on the experiment and solving the corresponding static problems, are the basis for constructing a mathematical model of an oscillating waveguide:
- tensile-compression of the waveguide with a longitudinal force in the absence of external torque is accompanied by its torsional deformation;
- twisting of the waveguide by external torque in the absence of longitudinal force is accompanied by its elongation or shortening;
- the magnitude and direction associated with the deformation of the waveguide, i.e. torsion in the absence of torque and tension (compression) in the absence of tensile (compressive) force is determined by the waveguide material and its geometric characteristics (twisted length, twist angle, cross-sectional area, etc.).

We now consider a waveguide in a fixed coordinate system X, Y, Z, choosing a plane of one of the normal sections of an unloaded waveguide from the coordinate plane (Y, Z) and directing the X axis along the axis of the waveguide.

The position of any section of the unloaded waveguide will be characterized by the coordinate X counted from the beginning of the section X = 0. Any such section will be called the section X.

According to the assumptions introduced above, the waveguide motion will be determined if the movement of any of its cross sections is known. In the absence of bending of the waveguide, the motion of any of its cross sections will be a helical motion consisting of translational motion along the OX axis and rotational around this axis. In accordance with this, we introduce two quantities — the longitudinal displacement U of section X and the angle of its rotation \( \phi \) relative to the natural (undeformed) state [4].

We now consider the cross section of the waveguide lying to the right of the cross section X (Figure 1); to maintain the previous state, the force \( T(x, t) \) directed along the OX axis and the torque relative to this axis equal to \( M(x, t) \) must be applied to the cross section X.

![Figure 1. Diagram of the forces applied to the cross section X.](image)

To obtain differential equations of waveguide motion, we consider the time t; section bounded by two infinitely close sections x and \( x + \Delta x \). Applying the main theorems of the dynamics of the system on the momentum and the kinematic moment relative to the OX axis to this section, taking into account the above assumptions, we find that at the \( \Delta x \to 0 \) they will take the following expression.

\[
\rho \cdot \Omega \frac{\partial^2 U}{\partial t^2} = \frac{\partial}{\partial x} \left( T \right), \quad \rho \cdot J \cdot \frac{\partial^2 \phi}{\partial t^2} = \frac{\partial}{\partial x} \left( M \right)
\]  

\( (1) \)
where: \( \rho \) - waveguide material density;
\( \Omega \) - waveguide cross-sectional area;
\( J_\Omega \) - moment of inertia of the cross-sectional area relative to its center.

Equations (2) are converted to more specific, given the elastic nature of the deformation of the waveguide.

\[
T = \alpha_{11} \cdot \varepsilon + \alpha_{12} \cdot \theta, \quad M = \alpha_{21} \cdot \varepsilon + \alpha_{22} \cdot \theta
\]

(2)

\[
\alpha_{11} = E \cdot \Omega, \quad \alpha_{12} = \alpha_{21} = \tau_0 \cdot E \cdot (J_\Omega - T_0), \quad \alpha_{22} = G \cdot T_0.
\]

(3)

where: \( E \)- elastic modulus;
\( \tau_0=\text{const} \) - the relative angle of twist of the waveguide;

\[
T = \alpha_{11} \cdot \varepsilon + \alpha_{12} \cdot \theta, \quad M = \alpha_{21} \cdot \varepsilon + \alpha_{22} \cdot \theta
\]

(4)

\[
\alpha_{11} = E \cdot \Omega; \quad \alpha_{12} = \alpha_{21} = \tau_0 \cdot E \cdot (J_\Omega - T_0); \quad \alpha_{22} = G \cdot T_0.
\]

(5)

where: \( E \)- elastic modulus;
\( \tau_0=\text{const} \) - the relative angle of twist of the waveguide;
\( J_\Omega = \int R^2 d\Omega \) - moment of inertia of the cross-sectional area relative to its center;
\( T_0 = \int (R^2 + \varphi_\varphi^2) d\Omega \) - geometric torsional rigidity of the untwisted waveguide;
\( G \)- shear modulus;

\[
T = T_0 + 2 \cdot (1 + \nu) \cdot \theta_0^2 \cdot (J_r^0 - T_r^0)
\]

(6)

where: \( \nu \) - Poisson's ratio;

\[
J_r^0 = \int R^4 d\Omega, \quad T_r^0 = \int \left( R^4 - (\varphi_\varphi^2) \right) d\Omega; \quad \varphi_\varphi = y \frac{\partial \varphi}{\partial z} - z \frac{\partial \varphi}{\partial y}.
\]

(7)

\( \varphi \) - torsion function of the corresponding untwisted waveguide.

Expressing the strain components \( \varepsilon \) and \( \theta \) through movement \( U \) and \( \varphi \) angle according to known Cauchy formulas [5]

\[
\varepsilon = \frac{\partial U}{\partial x}; \quad \theta = \frac{\partial \varphi}{\partial x},
\]

(8)

and then using equality (7), we transform the equation (1.8) to the expression

\[
\begin{align*}
\frac{\partial^2 U}{\partial t^2} &= \beta_{11} \frac{\partial^2 U}{\partial x^2} + \beta_{12} \frac{\partial^2 \varphi}{\partial x^2} \\
\frac{\partial^2 \varphi}{\partial t^2} &= \beta_{21} \frac{\partial^2 U}{\partial x^2} + \beta_{22} \frac{\partial^2 \varphi}{\partial x^2}
\end{align*}
\]

(9)

where:

\[
i_0^2 = \frac{J_\Omega}{\Omega}; \quad \beta_{kj} = \frac{\alpha_{kj}}{\rho \cdot \Omega}, \quad (k = 1,2), (j = 1,2).
\]

(10)
Finally, we note that the system (9) can be converted into two separate wave equations if new unknown functions \( V_1(x,t) \) and \( V_2(x,t) \), related to the subjects \( U(x,t) \) and \( \varphi(x,t) \) according to the formulas [6]:

\[
\begin{align*}
U &= a_1 \cdot V_1 + a_2 \cdot V_2 \\
\varphi &= V_1 + V_2
\end{align*}
\]  

(11)

As a result of such a transformation, we find that

\[
\frac{\partial^2 V_m}{\partial t^2} = c_m^2 \cdot \frac{\partial^2 V_m}{\partial x^2}, \quad (m = 1, 2),
\]

(12)

where:

\[
c_m^2 = 0.5 \cdot \beta_{11} + \frac{\beta_{22} + (-1)^{m-1} \cdot R}{2 \cdot i_0^2},
\]

(13)

\[
R = \sqrt{\left( \frac{i_0^2 \cdot \beta_{11} - \beta_{22}}{2} \right)^2 + 4 \cdot i_0^2 \cdot \beta_{11} \cdot \beta_{21}},
\]

and the coefficients \( a_m \) (m=1,2), included in (2.8), are expressed by the formulas

\[
a_m = \frac{i_0^2 \cdot \beta_{11} - \beta_{22} + (-1)^{m-1} \cdot R}{2 \cdot \beta_{21}},
\]

(14)

i.e. are the roots of the quadratic equation

\[
\beta_{21} \cdot a^2 - \left( i_0^2 \cdot \beta_{11} - \beta_{22} \right) \cdot a - i_0^2 \cdot \beta_{12} = 0.
\]

(15)

Using equality (1.8) we transform the (1.11) and (1.12) formulas into the form

\[
c_m^2 = \frac{1}{2 \cdot \rho \cdot \Omega} \cdot \left[ \alpha_{11} + \frac{\alpha_{22} + (-1)^{m-1} \cdot Ro}{i_0^2} \right],
\]

\[
a_m = \frac{1}{2 \cdot \alpha_{11}} \cdot \left[ i_0^2 \cdot \alpha_{11} - \alpha_{22} + (-1)^{m-1} \cdot Ro \right],
\]

(16)

where:

\[
Ro = \sqrt{\left( i_0^2 \cdot \alpha_{11} - \alpha_{22} \right)^2 + 4 \cdot i_0^2 \cdot \alpha_{12} \cdot \alpha_{21}}.
\]

(17)

The equation (1.17), whose roots are the values \( a_m \) (m=1,2), goes into equation

\[
\alpha_{21} \cdot a^2 - \left( i_0^2 \cdot \alpha_{11} - \alpha_{22} \right) \cdot a - i_0^2 \cdot \alpha_{12} = 0.
\]

(18)

4. Discussion of the results

From literature it follows that surface plastic deformation (SPD) causes significant changes in the fine crystalline structure of the main phases of steel, which is manifested in a change in the width of the X-ray lines [2]. During deformation, an increase in the density of defects responsible for the increase in the line width occurs. The created imperfections of the crystalline structure largely determine the mechanism and kinetics of phase and structural transformations during heat treatment.
Moreover, in a number of papers it is indicated that ultrasonic vibrations intensify the increase in the concentration of point defects in the crystal structure, and also contribute to an increase in the dislocation density by an average of 1-2 orders of magnitude [7.8]. Experimental studies have confirmed similar statements. Figure 1 shows that there is a broadening of X-ray reflexes on X12M steel after ultrasonic treatment implementation.

Thus, the formation of the final structure of the alloy, and, consequently, its properties, in the case of laser treatment after acoustic exposure occurs under conditions of increased density of imperfections in the crystal structure of the main phases of the metal [9]. One of the advantages of ultrasonic treatment before laser processing is that with this hardening scheme, an oriented arrangement of the main phases and structural imperfections is created (texture is formed) [10], which manifests itself in an anomalous ratio of austenite reflex intensities. If the type of texture formed in the surface layers of materials is consistent with the nature of the stress state of the processed products, such combined processing leads to a decrease in the coefficient of friction and increase wear resistance. It should be noted that the combination of ultrasonic treatment with laser exposure does not always have a positive effect on strength indicators. However, in this case, a more equilibrium microstructure is formed (compared, for example, with that formed from static stress) with denser cell boundaries, from which the dislocation exit is more difficult [11].

Experiments have shown that in the case of such a treatment, a structure is formed in the surface layers of the material, characterized by the optimal combination of the saturation of the solid solutions with carbon and alloying elements, as well as the structural inhomogeneity that occurs when the initial alloy carbides are partially dissolved.

Figure 2. Fragments of X-ray diffraction patterns of the surface layers of samples of steel X12M before- (1) and after ultrasonic treatment.

There is also an increase in the effect of dispersion hardening and the formation of texture in the surface layers of the metal, which manifests itself in an anomalous increase in the intensity of (200) and (311) austenite reflections. This is confirmed by the X-ray diffraction pattern of U8 steel after ultrasonic treatment and laser hardening (Figure 2).

The hardening effects observed after ultrasonic treatment and playing a certain role in obtaining positive results after subsequent laser treatment are explained by the preparedness of the structure for high-temperature heat treatment: the degree of dispersion of martensitic crystals increases, which is associated with the inheritance of austenite substructure formed during ultrasonic treatment; the states and degree of decomposition of austenite and martensite solid solutions change during quenching cooling; the process of precipitation of finely dispersed carbides is intensified.
As shown by the results of metallographic analysis and durometric studies of samples of various steels, conducting an ultrasonic treatment before laser heat treatment allows to increase the depth of the hardened layer by 15-25%, increase the hardness of the surface layers by 25-30% compared with hardened layers on an unprepared surface.

It should be noted that for steels with a carbon content of more than 1%, in addition to a positive effect on the depth of the hardened layer, ultrasonic treatment does not lead to a significant increase in hardness compared to laser processing without ultrasonic treatment.

Figure 3. Fragments of X-ray diffraction patterns of the surface layers of U8 steel before treatment (1), after ultrasonic treatment (2), laser hardening after ultrasonic treatment (3).

Thus, conducting an ultrasonic treatment before laser hardening causes changes in X-ray diffraction patterns that are similar to those observed during low-temperature tempering. The accelerated two-phase decomposition of martensite after laser treatment is also facilitated by the increased density of defects introduced by ultrasonic treatment into the structure of the main phases of the surface layers of the metal.

The use of ultrasonic treatment in the process of the laser hardening technological cycle of machine parts and tools allows to refuse the preliminary preparation of the irradiated surface (cleaning from technological pollution), which increases the productivity of the process by reducing the time of auxiliary operations before laser processing.

It was also established that the use of the proposed method of hardening processing of materials provides the following advantages over existing ones:

- the ability to increase reliability and tighten operating modes of machine parts and tools by achieving higher values of the basic properties on their working surfaces [12];
- reduction of processing time due to the combination of cleaning operations from technological pollution, deburring, etc. and additional strain hardening.

A variant of combined surface treatment was also investigated, in which ultrasonic vibrations were introduced into the material after laser hardening.

It was found that under the influence of ultrasonic action, laser quenching of martensite needles occurs, and the size of coherent scattering blocks decreases, which manifests itself in a shift of phase reflections towards large reflection angles (Figure 3).

The ultrasonic treatment promotes a uniform and more dispersed distribution of structural components [7]. As indicated above, the ultrasonic treatment leads to an increase in the density of dislocations and a decrease in the content of residual austenite, which ensures an increase in the
strength and plastic characteristics of the layer. This fact is clearly confirmed by the results of X-ray diffraction studies presented in Figure 3.

Figure 4. Fragments of roentgenograms of the surface of U10 steel after sequential carrying out standard volumetric heat treatment (1), laser radiation (2), ultrasonic treatment (3).

A feature of the described variant of hardening is the transition of the unstable structural state of the surface layer after laser irradiation to a stable heat-resistant one with residual compressive stresses using high-speed deformation by an ultrasonic tool [13]. In the reflow zone, this is achieved due to the migration of vacancies and newly emerging dislocations with the formation of new volumes limited by ordered dislocation structures, leading to relaxation of peak stresses and the creation of a finely dispersed structure. In addition, surface deformation by acoustic waves inevitably creates compression stresses in the metal. Such effects have a positive effect on the performance of materials. The use of ultrasonic treatment in the combined method of hardening as a finishing operation provides an improvement in the microgeometric characteristics of the layer.

5. Conclusions

It should be noted that in both cases of combined use, acoustic activation leads to an increase in the rate of solid-state processes limited by diffusion. It should be taken into account that such activation causes a significant increase in the interaction rate at the initial stages of the process, and with an increase in the duration of ultrasonic exposure, the process speed decreases slightly [14]. Thus, there is an optimal (the own for each alloy) ultrasonic processing period of the material, contributing to the maximum efficiency of the process. It was experimentally found that this period should be chosen empirically, despite the fact that there are models (Tamman-Wagner, Yandera, Zhuravlev-Lesokhin-Tempelman) that describe the dependence of the degree of conversion on the duration of treatment.

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