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Combined Ultrasonic–Mechanical Treatment

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It is demonstrated that the application of combined processing, specifically, the simultaneous use of ultrasound and mechanical action (friction), is an effective method for surface treatment. Optimal parameters of influence are identified, which are leading to an increase in hardness, a favourable redistribution of stresses, and a reduction in surface roughness. This approach integrates the benefits of ultrasonic energy to modify the materials' subsurface structure with the mechanical smoothing effects of friction. This synergy enhances material properties by refining the microstructure, promoting homogenous distribution of alloying elements, and inducing beneficial compressive stresses, all of which contribute significantly to improving the wear resistance and longevity of treated surfaces.

Key words: steel, ultrasonic–mechanical treatment, combined processing, 'white layer', plastic deformation.

Доведено, що застосування комбінованого оброблення, зокрема одночасне використання ультразвуку та механічної дії (тертя), є ефективною методою оброблення поверхні. Визначено оптимальні параметри впливу, що приводить до підвищення твердости, сприятливого перерозподілу напружень і пониження шерсткости поверхні. Цей підхід інтеґрує переваги ультразвукової енергії для модифікування підповерхневої структури матеріялу з механічними вирівнювальними ефектами тертя. Така синергія поліпшує властивості матеріялу шляхом удосконалення мікроструктури, сприяння однорідному розподілу леґувальних елементів та індукції корисних стискальних напружень. Всі ці чинники істотно сприяють підвищенню зносостійкости та тривалости експлуатації оброблених поверхонь.

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Ключові слова: криця, ультразвукове механічне оброблення, комбіноване оброблення, «білий шар», пластична деформація.

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1. INTRODUCTION

The durability and operational robustness of most machine components depend on the condition and physical-mechanical properties of their working surfaces, where wear processes originate and develop. A relatively minor (5–20%) wear of the working surface, such as in the friction pairs of conjugated parts, leads to their rejection, even though the remaining mass-dimensional characteristics of the parts overall are still close to nominal. Furthermore, the wear resistance of the working surface often limits not only the operational life of individual parts but also the maintenance interval of the machine as a whole. The costs associated with its downtime, along with expenses on renovation, far exceed the cost of new parts. Thus, the task of strengthening working surfaces is extremely relevant for mechanical engineering, as is the choice of technological methods for hardening treatment. Alongside this, the requirements for the quality of machine parts' surfaces for various purposes, such as laser mirrors, machine disks, *etc.*, have demanded a more refined yet deeper impact on their treated surfaces. Lately, the treatment of the surface and subsurface layers of material, providing them with functional properties distinct from those required from the bulk material, has been defined as 'engineering' of the surface [1–3]. One category of surface engineering methods is the technology of modifying existing surfaces by changing their topography, chemical composition, and microstructure. Analysis of existing methods for forming and treating surface layers of parts has shown their insufficient effectiveness with high material and energy costs. This reduces the competitiveness of modern mechanical engineering products as a whole. Therefore, researching and developing new ways of impact that can radically change the state of working surfaces of machine parts and extend their service life is important and timely.

2. EXPERIMENTAL/THEORETICAL DETAILS

Significant advancements in quantum electronics (lasers), electron and ion beams, electrohydroimpulse processes, ultrasound, explosion techniques, and other areas of physics have led to the creation and increasingly practical application of new pulse methods for the treatment of metals and alloys. These methods are characterized by the application of high specific energy, its impulse impact on relatively small volumes of a solid body followed by rapid cooling. Such extreme conditions, primarily heating and cooling, lead to the intensification of many physicochemical processes, which significantly affect the formation of the structure, physical-mechanical properties, and stressed state of the metal, shaping the quality of the treated surface [3].

Currently, ultrasonic vibrations are increasingly used in technology: low-energy ultrasonic vibrations (tenths of watts) are used in measuring techniques, defectoscopy, signalling, *etc.*; high-energy vibrations (several hundreds of thousands of watts per square meter) are used for metal treatment.

The impact of ultrasound on a solid body generates mechanical elastic waves within it. A vibrating sound source periodically compresses the metal particles directly adjacent to it, which then transmit this compression to the next layer. Compression waves alternate with rarefaction waves. A distinctive feature of ultrasound is that, unlike thermal energy, which is distributed quite evenly throughout the volume of the deformed metal, acoustic energy is mainly absorbed by grain boundaries, defects in the crystal lattice, *i.e.*, selectively. It is almost not absorbed in defect-free zones of the crystal. Thus, heating under the influence of ultrasound can occur locally. Ultrasound, especially high-energy, can also affect the electronic structure (electronic levels) of the material, as evidenced by the ‘acoustomagnetoelectric effect’ [4–6].

The proposed method combines two processing techniques, namely, ultrasound and mechanical (friction) ones, which occur simultaneously.

The challenge lies in transferring maximum ultrasonic vibrations to the processing zone (where the waveguide tool presses against the workpiece). The method of transferring ultrasonic vibrations from a solid body (waveguide) to another solid body (the workpiece) is an important factor, as too strong a pressure of the tool on the part can disrupt acoustic connection, while too weak does not allow achieving the necessary structure, as almost all the energy disperses into the air when ultrasonic waves propagate from the material of the magnetostriction vibrator or tool.

The delivery of ultrasonic energy to the hardening zone was carried out using a fork-shaped waveguide tool (tip) in a radial direction. The converter with the waveguide was mounted horizontally in a special bracket installed in movable slides, the base of which was fixed on the support of the lathe 1K62 (Fig. 1). The waveguide was pressed against the workpiece by a freely hanging weight (P1), suspended via a pulley to the bracket. This scheme allows for the hardening of parts of various shapes (during the processing, the tool traced the profile of the part).

The waveguide tool was made of 40H steel in a fork shape, fitted with carbide plates soldered to the internal (working) cavities of the prongs. The profile of the plate (in cross-section) had a radius of 5 mm. The tip and the converter were connected with a tight thread. The fork

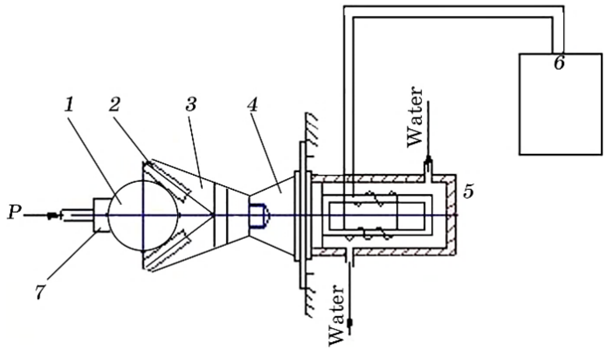

Fig. 1. Schematic diagram of the setup for processing by combined ultrasonic-mechanical method: *1*—sample; *2*—carbide plate; *3*—technological waveguide (tip); *4*—ultrasonic vibration concentrator (waveguide); *5*—magnetostrictive converter; *6*—ultrasonic generator; *7*—clamp.

angle was chosen based on the diameter of the parts, not exceeding 50 mm.

For hardening, magnetostrictive converters of the type PMS-15A-18 were used. They are powerful and reliable, not requiring stability of amplitude and allowing the use of higher P1 pressures. The main technical specifications of PMS-15A-18 include: power of 5 kW, resonant frequency of 17.5–19.3 kHz, amplitude at 15 microns. When processing with the PMS-15A-18 converter, the ultrasound intensity (energy density) reached approximately $146 \cdot 10^4$ W/m^2. An ultrasonic generator of type UZG-10-22 was used to convert electrical energy of industrial frequency (50 Hz) into ultrasonic waves. Table 1 presents the processing modes.

The mechanical processing involved a friction process that occurred between the workpiece and the clamp-segment. The clamp was brought to the workpiece from the side opposite the ultrasonic generator, with pressing force P2, which was regulated similarly to P1.

The chemical composition of the clamp matched that of the workpiece being processed.

Spectra were recorded photographically (ISP-30 spectrograph). Layer grinding was performed on a special machine with a high-hardness stone, namely, Arkansas stone, which provided minimal changes in element concentration during layer removal.

TABLE 1. Pulse hardening modes.

Geometry of the hardening tool				P_1, kN	P_2, kN	Notes
α_0	ϕ	R_p, mm	D_1, mm			
60	–	5.0	–	0.6–1.0	5	$\omega_0 = 20$ kHz

X-ray spectral analysis was conducted using a CAMECA microanalyzer with an electron beam diameter of 1 micron, on the polished section both on the surface of the sample and the depth of the white layer (cross-sectional polish).

3. RESULTS AND DISCUSSION

The combined treatment resulted in the formation of a 'white layer' of increased hardness on almost all hardenable steels and high-strength cast irons, regardless of their structural state. Ultrasound significantly reduces the metals' resistance to plastic deformation, thus the depth of the deformed layer (when treating unhardened steels) sharply increases, and beneath the white layer, a hardened zone is observed, often exceeding the thickness of the white layer itself.

A common characteristic of all white layers is their decreased etchability and increased hardness compared to the martensite formed through conventional quenching. The reduced etchability is attributed to the formation of a specific structureless martensite in the white layer, coherence of interphase boundaries, 'specific centration heterogeneity of the structure', its high dispersion, and the presence of carbides and oxides.

The increased hardness of the white layer, compared to the hardness of conventional martensite, despite a higher residual austenite content, can be explained by the structures' significant dispersion, considerable distortions of the austenite crystalline lattice, and the martensite concentration heterogeneity.

The proposed combined method involves rapid heating to high temperatures (above A_{c3}), simultaneous deformation, and subsequent quenching under extreme conditions occurring during pulse hardening. This process induces a unique phase, structural, stress state, and properties of the metal in the surface layers of parts, resulting in the formation of a 'white layer'.

During the combined treatment, a sharp increase in the mobility of metal atoms is observed. Despite the short duration of the process, many chemical elements manage to migrate over relatively large distances. High diffusion rates and an increase in the number of elements in the white layer have been established. For instance, the carbon content in some cases can increase by more than twice, primarily due to carbon diffusion from the sublayer. In some cases, the possibility of transferring carbon and other elements from the tool to the workpiece is not excluded. It is noteworthy that the chemical composition of the steel surface layers of samples changes to a significant depth, with the peak of element content increase (C, Cr, Mn, *etc.*) shifted deeper into the part. Such distribution of components in the white layer is explained by the influence of ultrasonic vibrations on heating, defor-

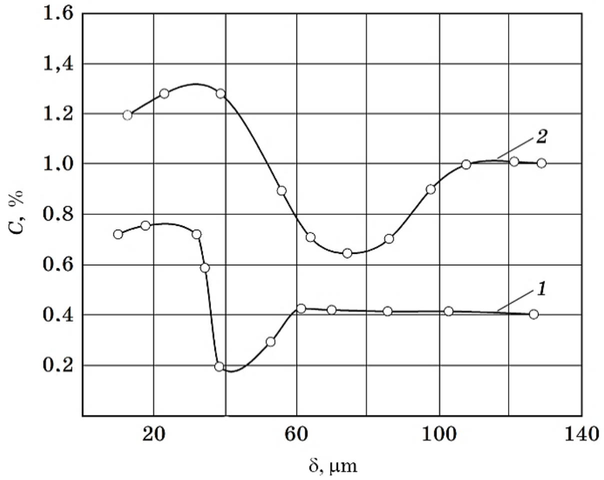

Fig. 2. Carbon distribution in the surface layers of 9X (*1*) and 40X (*2*) steel samples with a ‘white layer’.

mation, and diffusion processes. The stress state of the metal changes too: tensile stresses in the surface layers of the part decrease, and their maximum shifts deeper into the metal. Ultrasound facilitates plastic deformation during friction, accelerating the diffusion and other physicochemical processes. Layer-by-layer local spectral (Fig. 2 and Table 2) and micro-x-ray spectral analyses (Fig. 3) were conducted, showing the redistribution of other chemical elements (C, Mn, Si, Cr, Cu) in the white layers.

To enhance accuracy, reproducibility, eliminate the effects of heat treatment on analysis results, and achieve minimal sample damage depth (0.01–0.02 mm), a double-circuit high-frequency generator of condensed spark was used as the excitation source for the spectrum.

In analysing high-alloy steels, a high-frequency generator of condensed spark with impact excitation was used as the spectrum excitation source. This generator ensured minimal erosive impact of the light source on the metal (layer depth from 5 to 10 micrometers), high stability, and accuracy of results while simultaneously determining the content of all alloying elements. It also allowed for the practical elimination of the metal structure’s influence on the analysis outcomes. The coefficient of variation did not exceed 1%.

Changes in concentration and diffusion of components in the white layer compared to the base metal could be caused by several factors, among which the main ones include: heating due to friction, creating a high temperature gradient; significant specific pressures causing deformation at high speeds and a high stress gradient; increased density of dislocations and other defects in the crystal structure; electrotran-

TABLE 2. Content of chemical elements (%) in the surface layers of samples of alloyed steels after ultrasonic–mechanical treatment.

Steel	Element	White layer	Raw material	β_e, %
38HBA	C	0.69	0.48	114
	Ni	0.18	0.16	112
	Cr	1.25	0.99	126
	Mn	0.44	0.35	125
	Si	0.25	0.15	167
	W	0.51	0.51	100
H12M	C	1.95	1.70	112
	Ni	0.32	0.21	152
	Cu	0.17	0.12	142
	Cr	14.0	11.0	127
	Mn	0.35	0.25	140
	Si	0.45	0.22	204
	V	0.15	0.15	100
	Mo	0.46	0.46	100

sport, phase transformations, *etc*.

As a result of the tool rubbing against the workpiece, high temperatures are generated in comparatively thin surface layers of the parts, leading to a large temperature gradient. Such conditions facilitate the directed transfer of elements from cooler to hotter layers of metal during hardening, as well as their redistribution after hardening.

Tensile stresses can increase the diffusion coefficient by 2–3 orders of magnitude. It should be emphasized that the effect of tensile stresses on accelerating diffusion is stronger at lower temperatures. During the combined treatment process, individual volumes of metal in the contact zone of the tool with the part are subjected to significant tensile stresses. Thermomechanical stresses can precede the contact zone. Stretched zones act as acceptors of electrons or individual atoms (negatively charged), while compressed zones are donors (positively charged). Consequently, during stretching, diffusion flows occur from compressed to stretched zones, where, depending on the diffusion coefficient of the substrate and the concentration of elements, their mass transfer takes place.

The maximum increase in carbon content in the white layer compared to other elements is explained by the fact that carbon is a light element with a smaller atomic radius than iron, forming an interstitial solid solution with it. Chromium, manganese, silicon, and other elements forming substitutional solutions and having a larger atomic radius than iron migrate to the white layer less intensely than carbon. Refractory heavy elements with a larger atomic radius such as V, Mo,

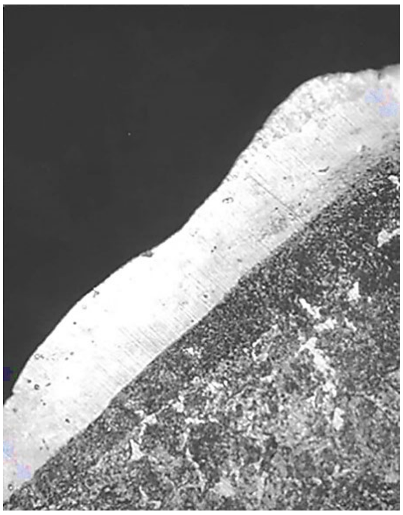

Fig. 3. Microstructure of a 'white layer' obtained by combined treatment; ×63.

W (Table 3) are the least mobile, and under these conditions, there appears to be insufficient time and energy for their transfer. The dependency of the activation energy for the transfer of elements forming substitutional solutions in iron from the physical properties of iron and these elements is quite complex. This issue becomes even more complicated with the additional impact of ultrasound.

During the combined treatment, the nickel content in the white layer increases (Table 2). Ultrasonic vibrations, by altering the stressed and deformed state of the metal, affect significantly the diffusion process.

Nickel acts as a donor of elements in ferrous-carbon alloys and increases the diffusion coefficient of carbon in austenite, facilitating the formation of the white layer. An increase in the chromium content in steel by more than 2–3% decreases the carbon diffusion coefficient in austenite and worsens the conditions for the formation of these structures, as well as contributes to reducing the heat capacity of steel. For example, it is significantly easier to obtain a quality white layer on 40H steel than on 4H13 steel under otherwise identical conditions.

A similar pattern is also observed with an increase in the content of silicon and manganese in the presence of chromium (to obtain a white layer on steels like 30HGSA, 35HGSA, higher energies are required). This behaviour of chromium and silicon is explained by the fact that chromium, by increasing the charge of carbon ions, strengthens their bond with the austenite lattice. Silicon, having a similar electronic structure to carbon, can easily donate electrons to complete the $3d$ levels of iron atoms and, in solution, can exist as a positively charged ion

TABLE 3. Physical properties of the elements considered in Table 2.

Element	Melting point, K	Valence	Ion radius, nm	Ionization potential, eV	Change in ion radius relative to iron, nm		Crystal cell
					α-Fe	γ-Fe	
C	4173	4	0.0550	64.47	–0.0689	–0.0736	diamond, graphite, face-centred cubic (f.c.c.) (in metal)
Ni	1726	2	0.1243	18.15	–0.0004	–0.0043	f.c.c.
Fe	1812	2	0.1239	16.18	–	–	body-centred cubic (b.c.c.)
		2	0.1286	–	–	–	f.c.c.
Cu	1356	1	0.1275	7.72	+0.0036	–0.0011	f.c.c.
Cr	2193	3	0.1246	30.95	+0.0007	–0.0040	b.c.c.
Mn	1517	1	0.1365	7.73	+0.0126	+0.0079	complex cubic, f.c.c.
		2	0.1332	15.64	+0.0093	0.0046	b.c.c.
Si	1683	4	0.1290	45.13	+0.0051	+0.0004	diamond, b.c.c. (in metal)
V	2173	5	0.1314	65.00	+0.0075	+0.0028	b.c.c.
Mo	2883	6	0.1360	68.00	+0.0121	+0.0074	b.c.c.
W	3683	6	0.1367	61.00	+0.0128	+0.0081	b.c.c.

like carbon. As a result of electrostatic repulsion, silicon displaces carbon. Through such a mechanism, silicon increases the thermodynamic activity of carbon and its tendency towards graphitization in cast irons.

Despite the significant acceleration of diffusion influenced by the factors discussed above, explaining the diffusion process of individual (especially light) elements across such large distances in such a short time (10^{-3} to 10^{-2} seconds) using classical diffusion mechanisms is challenging. A distinctive feature of the diffusion process during such treatment is its weak dependence on temperature and the method of loading; the rate of deformation has a significant impact on diffusion, occurring both through the volume and along grain boundaries, and is more intense in metals with a dense crystalline lattice than in those with a less dense b.c.c. lattice.

Experiments have shown that the microstructure of the white layer obtained by the investigated methods of treating steels and cast irons (Fig. 3) consists of fine-needle (fine-plate) martensite, residual austenite, and in most cases, much dispersed carbides.

4. CONCLUSION

The results obtained demonstrate that ultrasound significantly reduces the resistance of metal to plastic deformation. As a result of the combined treatment, a 'white layer' was formed on the surface, a marked increase in the mobility of metal atoms was observed, and the content of elements such as Ni, Si, and Mn in the white layer doubled.

In the contact zone on the surface, tensile stresses were generated that, in our opinion, accelerated the diffusion and increased the mass transfer.

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