

A technique is presented for hardening metal products, in particular, the main tools (hammers) and cases of core drilling bits made of steel 30HGSA, using thermomechanical surface treatment according to a separate scheme. The method of combined laser thermomechanical hardening used in the study consists in the use of shot peening followed by laser heat treatment. Its use makes it possible to increase the operational properties of steel products, in particular, their wear and corrosion resistance. Based on the results of theoretical and experimental studies, the paper substantiates the features of dynamic surface plastic deformation for the analysis of impact during shot peening. The advantages of using laser hardening without surface melting are presented. Experimental research methods are proposed for determining the structural-phase composition, structure of the surface layer, hardness and microhardness of the hardened zones of steel 30HGSA. The range of rational modes of impact shot peening and thermal laser treatment has been determined. A device for testing samples for wear resistance has been developed. Methods of testing for wear and corrosion resistance of the surface of samples are proposed for assessing the tribological properties and contact interaction of materials under quasi-static and dynamic loading conditions. It is concluded that rational technological modes of hardening tools made of steel 30HGSA using combined laser thermomechanical treatment allow increasing the depth of the hardened layer by ~1.5 times compared to laser heat treatment. In addition, they provide the microhardness of the surface layer of ~5400 MPa, which is ~2.5 times higher than the microhardness of the base material

Key words: combined surface hardening, shot peening, laser heat treatment, steel 30HGSA

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INCREASING WEAR AND CORROSION RESISTANCE OF STEEL PRODUCTS BY COMBINED LASER THERMOMECHANICAL TREATMENT

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1. Introduction

With the current high level of technological requirements for industrial products, special attention is paid, above all, to their reliability and durability. The surface layers of parts are exposed to the most intense mechanical, thermal, chemical and other destructive influences, which reduces their performance characteristics. Taking this into account, the production of competitive products in mechanical engineering is impossible without the use of technologies that make it possible to form the surfaces of products with improved performance characteristics, primarily high wear resistance.

Traditional methods no longer meet modern requirements and technological requirements of modern enterprises, therefore, the attention of scientists is focused on the search for new, in particular, combined and hybrid methods of surface hardening. The relevance of the study is determined by a number of factors. Thus, one of the promising modern technologies for increasing the strength of structural steels is a combined thermomechanical hardening using shot peening and laser heat treatment. The use of combined technologies for hardening steel parts allows to increase the service life, because they most often work under shock and alternating loads. For example, these are products made of structural

steels, including steel 30HGSA, such as: aircraft parts (aircraft pylon sheathing), impact tools (crusher hammers), core drill bit bodies, axles and shafts (including camshafts), compressor blades. machines that operate at temperatures up to 200 °C, tools, fasteners, levers, pushers, etc. Of course, the implementation of the method is not limited to one area of production.

In addition, the economic benefits of the combined method of hardening steel products, in particular for enterprises, are decisive. The use of the method allows extending the service life of parts and, thus, reduces the expenditure part for updating and adjusting installations after scheduled replacements.

Therefore, the development of combined methods of hardening, which increase the operational properties of products and at the same time have an economic advantage, is an urgent task that requires detailed study.

2. Literature review and problem statement

The issue of equipment wear as the main reason for a decrease in the service life of mechanical engineering products has repeatedly become the subject of detailed study of surface

engineering. The development of new methods for surface treatment of metal products to increase their service life is a priority in the field of engineering.

Laser surface hardening [1], combined/hybrid laser-mechanical surface hardening [2] and alloying/cladding [3], as well as laser heat treatment combined with heat treatment [4] are advanced methods for modifying metal products.

It is known that combined or hybrid methods of surface modification are more effective than monotechnologies. In particular, work [2] presents the results of studies of the combined laser-ultrasonic process of hardening and finishing large-sized products using laser heat treatment (LHT) followed by ultrasonic shock treatment of 45 structural steel and H12MF tool steel. It is shown that combined laser-ultrasonic treatment leads to a significant increase in rigidity and the formation of a regular microrelief on the surface. In addition, in [3], it was confirmed that the use of a hybrid method of laser-mechanical alloying of steel contributes to an increase in wear and contact stiffness in comparison with separate laser alloying. However, it should be noted that the remaining unresolved issues related to the processing of small-sized products due to the limitation of the use of ultrasonic tools.

An option to overcome the corresponding difficulties can be the use of shot peening (SP) instead of ultrasonic treatment. In work [5], a new method of thermomechanical surface hardening (SP+LHT) is proposed. Its essence lies in the fact that the process of high-speed heating by a laser beam begins after the implementation of a pulsed deformation shock action by a gas-ball flow with spherical small-sized particles, followed by laser hardening. Under this condition, thermal action in the zone of hardening the surface of the part without reflow is carried out to a temperature corresponding to the region of stable austenite $T(A_{C3}+\Delta T)$, followed by intense heat removal at rates of 10^4-10^8 °C/s, which is higher than the critical hardening rate [6]. At the heating stage, an austenitic structure is formed, which, after cooling, turns into martensite [7]. It should be noted that when processing hypoeutectoid steels, both complete and partial austenitization occurs along the depth of the heat-treated sample due to the difference in transformation temperatures ($A_{C1} \rightarrow A_{C3}$) [8]. Surface layers can be heated without reflow [2], and with reflow of a metal surface [9]. Under the action of fusion, microcracks are fused and the surface roughness decreases, since a finely dispersed near-surface structure is formed [10]. Reflow also increases the tedious strength of the items [11].

The $\alpha\beta$ transformation temperature of steels (A_{C1}) decreases after their plastic deformation, which is explained by the possible relaxation of the slander energy particle in the process of phase transformation [12]. As a result, the equality of the thermodynamic potentials of the phases, which determine the temperature of phase equilibrium, is achieved at lower temperatures [13]. Improvement of operational characteristics during hardening by surface plastic deformation (SPD) is associated with the formation of a dislocation structure on the surface of the hardened zone, which prevents the occurrence and development of fatigue cracks [14]. In addition, the SPD process of metal surfaces increases the hardness of the deformed layer, which is due to the formation of residual compressive stresses in the surface layer of the material and an increase in the dislocation density [15]. The technical result of hardening is the formation of a block structure in the grains, which leads to an increase in hardness, strength, prevents the initiation and development

of tiresome cracks, which is the result of the barrier hardening mechanism [16].

In contrast to the combined laser-ultrasonic treatment [17], the combined laser thermomechanical treatment technology can be used to strengthen the main percussion tools for crushing, as well as drill bits for core drilling. Crushing plants are used in 80 % of all technological lines for the preparation of concentrated and compound feed. The main working element of the hammer crusher is the rotor, to which the main installation tools – the hammers are attached.

Since the hammers work in difficult conditions, their service life is ~300 hours. This relative fragility, due to the technical and obsolescence of the main tools, requires a large amount of technical maintenance (about 14 per year). Increasing the service life of hammers, in particular due to the combined laser thermomechanical processing, will extend their life cycle and, accordingly, reduce the number of required maintenance. This will also avoid the mandatory rotor balancing procedure that needs to be done every time you change hammers to eliminate crusher vibration.

An equally important task is to strengthen the surface of drill bits for drilling wells, because they work in difficult conditions of shock loads (sliding friction). When drilling rocks of high rigidity, shock loads act on the bit. The duration of impacts is usually very short and amounts to $10^{-4}-10^{-6}$ C, at which the average pressure on the contact areas is 10^9-10^{10} Pa. As a result of the impact, residual deformations, elastic vibrations occur, the bodies are heated, their mechanical properties change, etc., and at impact velocities exceeding the critical speed, the bodies are destroyed at the impact site. It is noted that 15 % of drilling accidents occur as a result of wear of the steel bit bodies and the formation of cracks on their surface. The crown bodies are especially prone to fracture when working with hard rocks.

As a result, it is important to study the effect of combined SP+LHT processing on the depth of hardening, structure, hardness, grain size and wear and corrosion resistance of steel 30HGSA. Research and practical implementation of the results made it possible to improve the operational properties of machined parts such as hammers and crowns.

3. The aim and objectives of research

The aim of research is to increase the wear and corrosion resistance of steel products by combined laser thermomechanical treatment. This will increase the service life of the main tools (hammers) of impact crushers and core drill bit bodies and help reduce their maintenance by a year. Accordingly, the use of the proposed combined thermomechanical method will reduce the expenditure part, which indicates its economic advantage over other processing methods.

Achieving this aim requires solving the following tasks:

- to determine the rational technological modes of the thermal action of the laser beam and the high-speed deformation action of the tools to increase the wear and corrosion resistance of parts made of steel 30HGSA;
- to investigate changes in the structure and phase composition of the surface layer, hardened by SP and LHT;
- to determine the feasibility of using the developed combined laser thermomechanical method of surface hardening of products from steel 30HGSA by testing samples for wear and corrosion resistance.

4. Materials and methods of research

The material for carrying out the combined laser thermomechanical processing was flat samples (110×50×6 mm) of steel 30HGSA, from which the main percussion tools for hammer crushers, in particular, the A1-DM2R series, as well as drill bit bodies are made. Compared with classical types of steels, steel 30HGSA has an increased resistance to temper brittleness, as well as a relatively low cost.

4.1. Methods for determining the modes of shot peening

SP was carried out at the technological unit (LLC UKRM-INGLASS, Ukraine), taking into account the results of the exploratory research and technological recommendations [5, 18]. For surface hardening, hardened metal balls made of ShKh15 steel with a grain size of 200–500 μm were used.

A number of technological factors influence the results of SPD in SP. First, the air pressure used to cut the fine spherical ball jet should be 0.3 to 0.6 MPa. Second, the angle of attack of the jet α between the direction of the incident jet and the surface to be treated for effective surface hardening should be 90° with a jet length l of 50–200 mm.

Search modes for determining the duration of treatment at SP were carried out on samples of steel 45 at a pressure of 0.6 MPa and a duration of 3 min, 2 min and 1 min. The selection criteria for the modes were: step, damage (deformation) of the surface, depth and hardness of the hardened layer.

Hardening of the surface of samples made of steel 45 and 30HGSA was carried out for 1 min at different values of the pressure of the flow of metal shot – 0.4 MPa, 0.5 MPa and 0.6 MPa.

4.2. Technique for determining the modes of laser heat treatment

LHT experiments on the surface of the samples were carried out on the basis of a three-coordinate manipulator using a DY044 laser from ROFIN-SINAR (Germany) with a radiation wavelength $\lambda=1.06 \mu\text{m}$, on a crystal of yttrium-aluminum garnet doped with ions. The setup used in the study is shown in Fig. 1.

LHT was carried out with a defocused laser beam in the focus area without reflow, ensuring the maximum possible hardening depths, structure homogeneity and hardness. The modes of processing on a laser installa-

tion and measuring the depth of hardened tracks by laser hardening are given in Table 1.

It was found that at a speed of 300 mm/min (track 1) and defocusing $f=50 \text{ mm}$, the sample surface melts (Table 1). For quenching without reflow (track 7), the distance from the lens to the surface of the workpiece is gradually increased to $\Delta f=80 \text{ mm}$ with the diameter of the laser beam in the processing zone $d=10.67 \text{ mm}$ (Table 1). The best modes of laser hardening without reflow were obtained on lanes 6–8 (Table 1).



Fig. 1. Laser technological unit ROFIN SINAR DY 044: 1 – resonator; 2 – laptop

Table 1

Search modes for laser hardening of steel 30HGSA

Scheme of the processed sample	Track No.	Micrographs	Processing speed, mm/min	Depth, mm	Width, mm	Sample temperature, °C	
						before	after
	1		300	1.456	3.959	16	40
	2		900	0.672	2.834	16	38,1
	3		1000	0.621	2.601	16	34
	4		1200	0.514	2.601	16	31
	5		1400	0.427	2.373	16	28
	6		500	0.435	2.149	16	34,8
	7		300	1.060	4.072	16	46
	8		400	0.740	3.088	16	43

During LHT, the temperature of the hardened zone was measured using a GM1350 pyrometer on the sample surface at a distance of 15 mm from the track every 3 s after the action of the laser beam.

4. 3. Equipment and methods for testing samples for wear and corrosion resistance

For testing flat samples 17×17×6 mm in size, an installation was developed for comparative assessment of the wear resistance of materials and coatings under friction under conditions of rigidly fixed abrasive particles (Fig. 2).

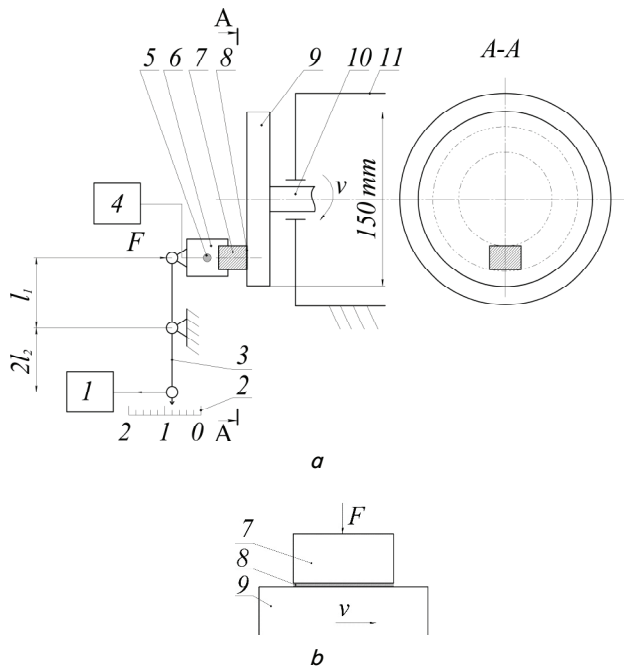


Fig. 2. Scheme: *a* – device for testing for wear resistance; *b* – interaction of the sample with the abrasive wheel: 1 – severity; 2 – linear scale; 3 – two-armed straight lever; 4 – multimeter DT-838 for temperature measurement; 5 – thermocouple TR-01A; 6 – pressure plate; 7 – test sample; 8 – intermediate layer; 9 – abrasive wheel ZAK 14A 150×20×32 mm F60; 10 – electric motor shaft; 11 – electric motor

For a comparative analysis of the mass of samples before and after experiments on wear resistance, an electronic balance for jewelry N1126 was used with a measurement accuracy of up to 0.01 g. With a load mass of 0.875 kg, the pressing force was 17.2 N. 8, which can slow down or accelerate wear (Fig. 2, *b*). The size of the captured surface layer was determined using a linear scale of 2.

The experiment was carried out on samples, the surface of which was hardened in the modes that showed the highest efficiency:

- 1) the original sample (base material);
- 2) SP (gas ball flow feed pressure – 0.5 MPa, processing time – 1 min);
- 3) LHT (processing speed – 300 mm/min, power – 1 kW);
- 4) SP+LHT.

For the reference, the original sample of steel 30HGSA was used.

During the experiment, the samples were continuously cooled with air at a pressure of 2 atm in order to keep the temperature within 78–84 °C.

The degree of wear is determined by measuring the mass of the sample before and after the wear test. Determination of the wear rate was carried out by fixing the time (duration *t*, min), during which the wear depth reached 2 mm – the value of the optimization parameter. The abrasive material was a circle with a diameter of 150 mm made of electrocorundum with a fraction of 0.2–0.4 mm, rotating at a constant speed of 1320 rpm.

For corrosion tests, samples of steel 30HGSA were immersed in a 3 % aqueous solution of sodium chloride (rock salt). The solution covered the sample surface by 5 mm. Under these conditions, the samples were kept for 10 days at room temperature. External review was performed daily and the results were recorded at the same magnification (×40) on an Andonstar AD106S electron microscope at intervals of 24 hours, 48 hours, 96 hours, 240 hours. When processing the results, it was taken into account that forced breaks during accelerated corrosion tests should not exceed 10 % of the total time. The countdown of the beginning of the tests began from the moment the samples were introduced into the vessel.

5. Results of studies of wear and corrosion resistance of steel 30HGSA, hardened by combined laser-mechanical treatment

5. 1. Determination of rational modes of shot peening and laser heat treatment

Experimentally, taking into account the maximum depth of hardening, it was possible to narrow the range of technological modes for surface plastic treatment and LHT and to establish rational modes of combined processing (SP+LHT) for steel 30HGSA. The depth of the hardened layer after LHT was chosen taking into account that it was not less than the thickness of the deformed layer after LHT.

Experimentally, rational modes of combined thermo-mechanical hardening for SP have been determined: supply pressure of the gas-ball flow – 0.5 MPa, SP time – 1 min; laser beam power – 1 kW at a sample movement speed of 300 mm/min. It was found that an increase in the SP pressure to 0.5 MPa at a LHT speed of 500 mm/min increases the microhardness by 360 MPa (5720 MPa) (Fig. 3). At a hardening depth of 950 microns, the microhardness increases by 1040 MPa (3090 MPa), compared with a SP pressure of 0.4 MPa. At a speed of 400 mm/min, the microhardness to a depth of 910 μm decreases by 810 MPa.

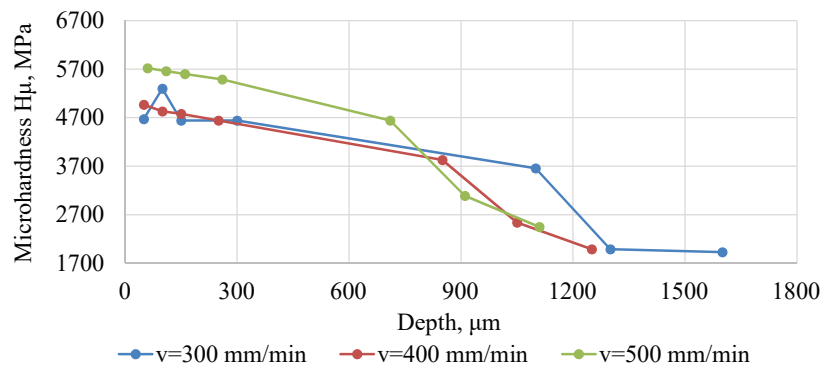


Fig. 3. Dependence of microhardness on the depth of hardening after shot peening (0.5 MPa, *t*=1 min) and laser heat treatment (*P*=1 kW)

The curves of the decrease in microhardness (Fig. 3) at a depth of 150–850 μm ($v_{pr}=400$ mm/min; $v_{pr}=500$ mm/min) are similar to the curve of the dependence of microhardness on depth at SP with a LHT speed of 300 mm/min. Nevertheless, it should be noted that at a depth of 910–1100 μm of the latter, the microhardness is 1210 MPa higher, and at a depth of 50–150 μm, an increase in microhardness up to 5300 MPa is observed. This phenomenon is due to the fact that LHT is short-lived and the processes of dynamic return and recrystallization do not have time to pass.

5. 2. Change in structure and phase composition

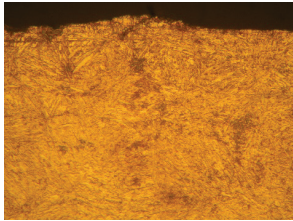
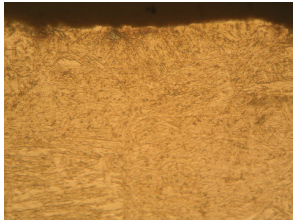
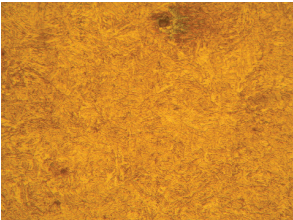
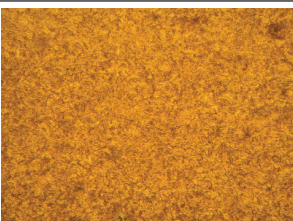
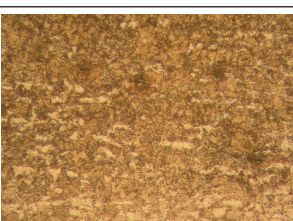
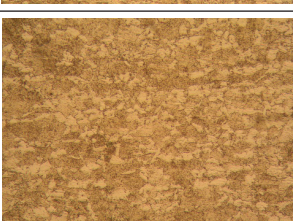
Table 2 shows an image of the microstructure of a sample after hardening with a combined SP (0.5 MPa, $t=1$ min) followed by LHT ($v_{pr}=300$ mm/min, $P=1$ kW), made on a Neophot 32 microscope (Germany). The structure of the hardened zone is dominated by martensite (7 points on a scale of 3 (zone

2, 1000)) [6, 10]. The creation of a martensite structure in the hardening zone is due to both the formation of martensite itself and the mechanism of barrier growth. With an increase in the depth of the heat-affected zone (zone 3, 500), the martensite constituent is 100 % on a scale of 8, and the size of the martensite needles decreases. At the border of the transition to the base material, there is a ferrite-pearlite structure (sorbitol-like pearlite), in which the content of the pearlite component prevails. In the images of microstructures (Table 2), one can see non-metallic inclusions, in particular sulfide ones, which is due to the peculiarities of steel production.

X-ray structural analysis was performed on an Ultima IV diffractometer (Rigaku, Japan). The results of X-ray diffraction analysis of the hardened surface of the SP samples (0.5 MPa, $t=1$ min) followed by LHT ($v_{pr}=300$ mm/min, $P=1$ kW) (Fig. 4) showed an iron content of 6.2 %, oxide iron – 28.5 %, magnetite – 62 % and wustite – 3.3 %.

Table 2

Micrographs of the hardened zones of SP (0.5 MPa; $t=1$ min) and LHT ($v_{pr}=300$ mm/min, $P=1$ kW)

Zone No.	Structure	Magnification	
		×500	×1000
2	Martensitic		
3	Fine-grained martensite		
4	Fine-grained martensite		
5	Sorbitol perlite		
6	Ferrite-perlite		

Scheme



Hardened zone 2 3 4 5 6

1 ○ Base material

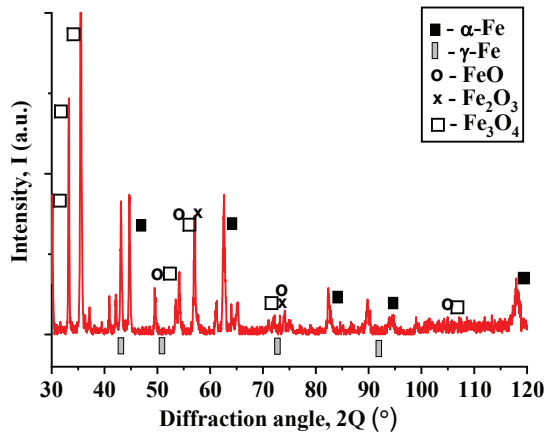


Fig. 4. Diffraction pattern of steel 30HGSA after combined laser thermomechanical treatment

It should be noted that the lattice deformation is insignificant: iron (Fe) – 0.04 %, iron oxide (Fe₂O₃) – 0.14 %, magnetite (Fe₃O₄) – 0.13 %, wustite (FeO) – 0.09 %. In this case, the size of iron crystallites increased to 13.7 nm compared to the results of separate treatments: SP – 15.3 nm, LHT – 8.8 nm, starting material – 20.8 nm.

5. 3. Test of hardened samples for wear and corrosion resistance

Fig. 5 shows the results of experimental studies on wear resistance. The duration of wear of the surface layers of samples made of steel 30HGSA, with a depth of 0.5 mm, 1 mm, 1.5 mm and 2 mm, hardened by different processing methods (SP, LHT, SP+LHT) was empirically determined. Fig. 5 shows the curves of the dependence of the wear depth of the surface of the indicated samples on the time during which the wear

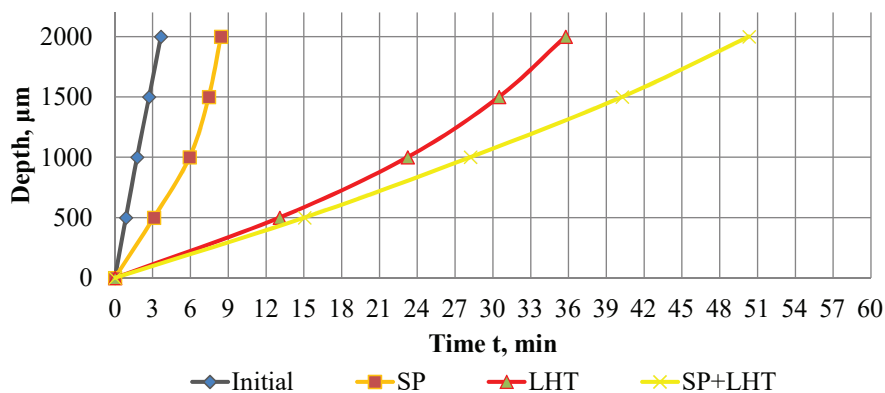


Fig. 5. Dependence of the durability of the wear resistance of steel 30HGSA samples on the depth

depth reached 2 mm. The value was chosen taking into account the maximum depth of hardening achieved by combined laser processing (SP+LHT) – ~1.5 mm. Thus, 4 depth values were obtained for each sample, achieved in time *t*. The curves plotted on the basis of the obtained values show that the achievement of a certain depth of wear for each of the samples, hardened by different processing methods, is different.

The results of experimental studies (Fig. 5, Table 3) show that hardened samples with combined thermomechanical hardening have the best wear resistance – 49.92 min. This is 14.16 min longer compared to separate LHT (*v_{pr}*=300 mm/min, *P*=1 kW), and 42.87 min more compared to SP (gas ball flow feed pressure – 0.5 MPa, *t*=1 min).

Let's also note that for the authenticity of the results, samples of the same geometric dimensions were selected. Checking the weight of the samples before and after the tests for wear resistance by the gravimetric method showed (Table 3) that the deviations of the lost weight of the samples are minimal.

The results of the study showed that the use of the combined method SP+LHT is the most effective and appropriate for hardening parts made of structural steel 30HGSA, in particular tools (hammers) of A1DM2R series crushers and drill bit bodies.

For experiments on corrosion resistance, samples were selected that were hardened by the following modes: LHT (*v_{pr}*=300 mm/min, *P*=1 kW), SP (gas ball flow feed pressure – 0.5 MPa, *t*=1 min), SP+LHT. Images of the surface of the samples (magnification δ40) after testing for corrosion resistance are presented in Table 4.

The results of experimental studies showed that after 240 hours in the sample hardened by SP, places of corrosion appear, but under the action of the combined SP+LHT, the amount of iron hydroxide on the surface is much less.

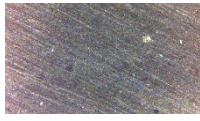


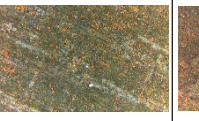
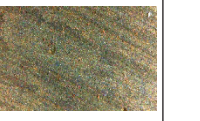
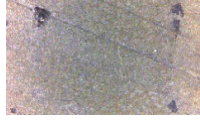



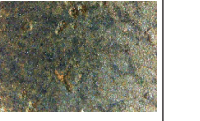
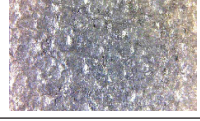
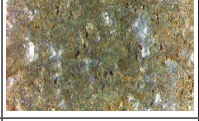
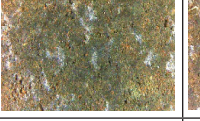
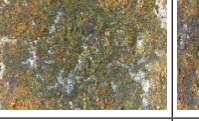

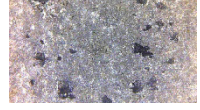



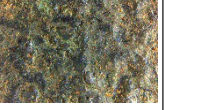
Table 3

Wear resistance of samples from steel 30HGSA

No.	Hardening type	Microhardness, MPa	Removal duration, min				Sample mass, g		Sample temperature, °C	
			Depth, mm				before	after	before	during
			0.5	1.0	1.5	2				
1	Initial	2060	0.883	1.77	2.72	3.65	9.69	6.71	17	82
2	SP	3600	3.1	5.16	6.47	7.05	8.88	6.64	19	76
3	LHT	4640	13.07	23.22	30.48	35.76	8.32	5.77	17	68
4	SP+LHT	4670	15.05	27.8	39.86	49.92	9.31	6.37	23	70

Table 4

Corrosion resistance of samples from steel 30HGSA

No.	Hardening type	Duration, h					T of sample, °C
		Initial	24	48	96	240	
1	Main						22
2	SP						
3	LHT						
4	SP+LHT						

6. Discussion of the results of the study of improving the operational properties of steel parts by combined laser thermomechanical treatment

Crushing tools and core bit bodies require extended service life. The reliability of these tools depends on the quality of the surface layer (geometric parameters of the surface microrelief, structural-phase composition, rigidity, hardening intensity, stress state, etc.). The results of wear and corrosion resistance clearly indicate the favorable effect of the proposed combined SP+LHT treatment, which leads to a significant strengthening of the steel under study.

The results of the study performed indicate that the rigidity and depth of hardening of steel 30HGSA (Fig. 3) can be effectively changed by choosing the modes of SP and LHT, causing various structural and phase transformations (Tables 1, 2, Fig. 4). The experimental wear values shown in Fig. 5, depend on the surface microhardness (Table 3). The combined treatment increases the rigidity by more than two times in comparison with the untreated sample (~200 HV), which is associated with the formation of a fine-grained martensitic structure in the near-surface layers, regardless of the sequence of application of SP and LHT [10, 19]. The obtained values of stiffness in the hardening zone correlate with the values given in works [5, 10, 20]. In these works, a combined treatment using ultrasonic shock hardening and surface laser hardening using scanning optics is investigated.

It has been confirmed that the preliminary intense surface plastic deformation of the SP before the LHT contributes to an increase in both the depth of hardening and the surface rigidity of steel 30HGSA in comparison with a separate LHT. As a result of this combination, the wear resistance of the samples processed by the combined SP+LHT method significantly increases (~14 times). A similar significant wear resistance of the modified surface was found in the case of combined laser-ultrasonic treatment of structural steel 45 [20].

Taking into account the results of X-ray structural analysis (Fig. 4), an oxide layer is formed on the surface after LHT, which can lead to excessive abrasive wear of the steel under

study at the running-in stage [20]. In addition, an increase in the corrosion rate of steel 30HGSA is expected due to the formation of an excessive wavy/coarse microrelief after preliminary SP. Therefore, to ensure low roughness / waviness, high hardness and the formation of guaranteed values of residual compressive stresses in the near-surface layers, it is recommended to apply mechanical surface treatment after preliminary LHT.

Let's note that, in contrast to the combined/hybrid laser-ultrasonic treatment [8], the proposed combined method (SP+LHT) can be used for surface treatment of products of complex shape. The limitations of the study are that only a few parameters were taken into account for studying the hardening of the surface layer of products made of steel 30HGSA, in particular, the parameters of depth and microhardness. It is necessary to assess the quality of the hardened surface layer of the steel 30HGSA samples taking into account other parameters, in particular, the stresses in the subsurface layer and the study of the surface morphology.

Considering that the high surface roughness negatively affects the corrosion resistance, the prospects for further research are to improve the combined strengthening technology in order to improve the quality of the processed surface of the steel 30HGSA samples. In particular, taking into account the optimal modes of combined processing proposed in this work.

7. Conclusions

1. The results of the study made it possible to determine rational technological modes of combined thermomechanical processing of tools made of steel 30HGSA, in particular:

- for SP: supply pressure of the gas-ball flow – 0.5 MPa, processing time – 1 min, distance from the nozzle end to the treated surface – 150 mm, angle of inclination of the jet stream – 85°;
- for LHT: laser beam power – 1 kW, sample movement speed – 300 mm/min.

2. The study of the structure of the surface layer of the cut, hardened by the combined method of laser thermome-

chanical hardening, using X-ray diffraction analysis showed the high efficiency of this type of treatment in comparison with others. The used combined method SP+LHT makes it possible to increase the depth of the hardened layer of the main tools (hammers) of crushing installations and bit bodies for core drilling by 1.5 times compared to LHT. This is due to the fact that after the SP, a microrelief is formed on the surface of the parts, which improves the absorption capacity of laser radiation. It was found that the depth of the hardened layer decreases with an increase in the LHT rate. In addition, as a result of the preliminary action of the SP, a hardened layer with a depth of 105 μm is formed on the surface of the part, which does not disappear with further LHT. Due to the fact that LHT is short-lived, the processes of dynamic return and recrystallization do not have time to pass. Therefore, the microhardness of the surface layer during LHT+LHT is ~ 5400 MPa, which is ~ 2.5 times higher than the value of the microhardness of the base material and ~ 1.5 times greater than the values obtained after LHT.

In addition, studies of the microstructure of the hardened sample showed that the heat-affected zone has a uniform martensitic structure. The size of the martensite needles decreases as it approaches the base material. A ferrite-pearlite structure (sorbitol-like pearlite) is located at the border of the transition, in which the content of the pearlite component prevails. The formation of a uniform martensite structure after laser hardening indicates a significant increase in microhardness.

3. The results of testing the samples for wear resistance showed that when using the combined treatment of SP+LHT, the wear resistance of the sample under sliding friction in an abrasive environment significantly increases (~ 14 times) compared to the original sample. In addition, the results of testing samples for corrosion resistance showed that the combined action of SP+LHT reduces the amount of iron hydroxide on the surface of the material in comparison with a separate SP. Thus, the method of combined laser thermo-mechanical treatment makes it possible to increase the wear and corrosion resistance of the processed samples, which indicates the expediency of its use for hardening products made of steel 30HGSA.

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