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SURFACE QUALITY IMPROVEMENT OF STEEL PARTS BY COMBINED LASER-ULTRASONIC TREATMENT: DETERMINATION ALGORITHM OF TECHNOLOGICAL PARAMETERS

Dmytro Lesyk
Corresponding author
PhD, Associate Professor*, Senior Researcher**, Research Scholar***
E-mail: lesyk_d@ukr.net
Vitaliy Dzhemelinskyi
PhD, Professor*
Bohdan Mordyuk
Doctor of Physical and Mathematical Sciences, Senior Researcher**
Silvia Martinez
PhD, Researcher
Advanced Manufacturing Centre for Aeronautics
University of the Basque Country
Bizkaia Science and Technology Park, 202, Zamudio, Spain, 48170
Pavlo Kondrashev
PhD, Associate Professor*
Dariusz Grzesiak
PhD, Lecturer***
Yurii Klyuchnikov
PhD, Associate Professor*
Aitzol Lamikiz
PhD, Professor
Advanced Manufacturing Centre for Aeronautics
University of the Basque Country
Bizkaia Science and Technology Park, 202, Zamudio, Spain, 48170
*Department of Laser Systems and Advanced Technologies
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
Peremohy ave., 37, Kyiv, Ukraine, 03056
**Department of Physical Principles for Surface Engineering
G. V. Kurdyumov Institute for Metal Physics
of the National Academy of Sciences of Ukraine
Academician Vernadsky blvd., 142, Kyiv, Ukraine, 03142
***Department of Mechanical Engineering and Mechatronics
West Pomeranian University of Technology
Piastow al., 17, Szczecin, Poland, 70310

To provide the quality of the surface layer and improve operational properties, a combined laser-ultrasonic surface hardening and finishing technology of steel products is proposed. This work is devoted to determining the range of rational parameters of laser heat treatment and ultrasonic impact treatment for enhancing the complex hardening process of AISI 1045 steel and AISI D2 steel. Laser surface transformation hardening was carried out with a constant temperature strategy using a fiber laser and scanning optics at a heating temperature of 1200–1,300 °C and a processing speed of 40–140 mm/min. Ultrasonic surface hardening and finishing were performed on technological equipment with an amplitude of ultrasonic vibration of 18 μm and a load of the ultrasonic tool of 50 N. The ultrasonic treatment duration varied from 60 to 180 s. The results showed that laser-ultrasonic treatment leads to an increase in the hardening intensity by more than 200 %, forming a hardening depth of 200–440 μm. Combined treatment leads to a significant increase in wear resistance due to the formation of ultrafine-grained martensitic microstructure with hardness (58–60 HRC$_5$) in the near-surface layer. The combined laser-ultrasonic hardening process control algorithm for surface treatment of structural and tool steels is proposed, limiting the heating temperature, the duration of laser (ultrasonic) exposure, and the vibration amplitudes of the ultrasonic horn. Laser-ultrasonic treatment will allow the formation of a surface layer with a given set of properties, providing increased wear and corrosion resistance. The developed technology can be used for surface hardening and finishing of large-sized steel products in the mechanical engineering industry

***Keywords:** laser-ultrasonic treatment, AISI 1045 steel, AISI D2 steel, surface hardening*

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1. Introduction

Complex assurance of reliability and quality of the surface layer using advanced production technologies that provide the necessary operational properties of metal products and reduce energy consumption is a priority task of mechanical engineering companies. The use of traditional surface modification technologies does not fully allow for obtaining the necessary quality parameters of the surface layer, and the use of high-strength materials does not always ensure surface integrity and satisfy the operational properties.

To improve the operational properties of steel parts, combined/hybrid thermomechanical processes of surface hardening and finishing using highly concentrated energy sources are promising. The combined surface hardening technology using laser heat treatment (LHT) and ultrasonic impact treatment (UIT) is an effective technological solution to improve the surface layer quality and ensure the surface integrity of iron-carbon alloys. In particular, LHT+UIT promotes the structural particle (grain) refinement and the increase in the dislocation density in the near-surface layer, as well as the transition of the unstable structural state of the surface layer to a heat-resistant one with higher/deeper residual compressive stresses. UIT using equipment with computer numerical control (CNC) allows forming a regular microrelief on the surface.

However, the use of the combined LHT+UIT method as a finishing treatment of steel parts is hindered by the lack of systematic studies of the influence of processing parameters/modes. Therefore, the study of the effect of combined laser-ultrasonic treatment on the operational properties of hardened steel surfaces is an urgent scientific problem and has great practical importance in the field of surface engineering.

2. Literature review and problem statement

Laser surface hardening, laser alloying, or laser cladding (spraying) are advanced methods of modifying and restoring the surface layer in metal products to increase fatigue strength, wear resistance, and corrosion resistance. It is known that laser surface hardening consists in the formation of fine-sized martensite in a thin surface layer due to the absorption and transfer of high-concentration energy [1]. The power density of the laser beam and its interaction time with the processed material determine the heating/cooling cycle of the surface [2]. At the same time, the heating and cooling rates of the processed material reach 10^8 to 10^{10} °C/s. The depth of hardening is 0.2–1.0 mm after LHT without surface melting (10^3–10^4 W/cm^2) [3] and 1.2–3.0 mm after LHT with surface melting (10^4–10^5 W/cm^2) [4]. Laser surface hardening increases the surface hardness of structural steels by about 2 times due to the formation of a highly dispersed microstructure in the near-surface layer, without changing the chemical composition and properties of the base material [5]. The disadvantage of this method is the impossibility to perform hardening of low-carbon iron-carbon alloys without partial surface melting.

In contrast to laser hardening, the process of laser alloying and laser cladding of materials on the base of the processed product leads to changes in the chemical composition and surface quality, forming a purposeful structure of the surface layer with a given set of properties. In particular, laser surface alloying consists in saturating the material with alloying elements by the diffusion of a pre-applied layer under the influence of a laser beam (10^5–10^6 W/cm^2) [6]. It is shown that the laser surface alloying technology contributes to an increase in the wear resistance of iron-carbon alloys by 1.5–3.0 times [7]. Laser surface cladding consists in applying a layer of another material (10^4–10^6 W/cm^2) to the surface, melting the base of the processed material [8]. In [9], laser deposition of a nickel alloy on the base of an iron-carbon alloy leads to a decrease in corrosion resistance. However, the laser alloying (cladding) process is not without drawbacks. This is primarily because the formed surface is rough with significant waviness. At the same time, there is an uneven distribution of residual tensile stresses in the near-surface layers, which can initiate cracks.

To comprehensively improve the quality of the surface layer of steel parts, one of the effective solutions is to use laser surface transformation hardening in combination with surface plastic deformation (SPD) using ultrasonic tools [10]. Compared to traditional thermal methods of surface hardening, the advantages of selective laser transformation hardening technology are high processing speed, the ability to process hard-to-reach surfaces of complex geometry [11], and the possibility to combine them with SPD methods. In particular, hybrid laser thermal and strain alloying guarantees the formation of residual compressive stresses (–1000 MPa) and an increase in hardness by more than 30 % in the near-surface layer compared to post-processed SPD material [12]. Hybrid laser thermal and strain hardening without surface melting leads to low surface roughness (Ra~0.2–0.3 μm) using a deformation tool in the form of a roller [13]. The thermo-deformation hardening process according to the combined treatment scheme is more effective due to the SPD of the heated surface [14]. However, it should also be noted that hybrid laser thermo-deformation alloying/hardening has limitations for post-processing small-sized metal products due to the significant forces involved in static surface deformation.

The combination of LHT and UIT makes it possible to obtain a much greater effect in increasing the strength, reliability, and durability of the surface layer in steels and alloys [15]. The results show that the most common technologies of ultrasonic surface hardening and finishing of metal products are ultrasonic burnishing [16] and ultrasonic impact peening [17].

In [18], ultrasonic treatment with a ball-shaped tool after discrete LHT is proposed to increase the fatigue strength of an iron-carbon alloy. It is shown that compared to LHT, the combined treatment reduced the surface roughness by ~50 % and increased the hardness by ~15 %, forming residual compressive stresses of about –900 MPa instead of tensile stresses of about 325 MPa. The proposed method of ultrasonic burnishing is not effective for hardening and finishing large-sized products made of structural/tool alloy steels. In addition, this UIT method requires significant static loads of the ultrasonic tool ($1.88 \cdot 10^3$ N), which can cause rapid wear of the burnishing ball when processing high-strength steels.

To increase the efficiency of laser-ultrasonic surface hardening of large-sized steel products, a combined LHT+UIT method using a heating temperature control system for a laser scanning beam and an ultrasonic multi-pin impact head was recently developed [19]. It was found that the programmed UIT with the multi-pin head leads to the formation of nanostructuring in the near-surface layer and a special microrelief on the surface, significantly increasing the wear resistance of the treated surface of structural and tool steel samples [20]. However, it should be noted that due to the large number of technological parameters in both LHT and UIT, the relationship between LHT+UIT parameters and quality parameters of the surface layer has not been studied. All this gives reason to assert that it is advisable to conduct a study devoted to determining the range of rational parameters of LHT with a scanning laser beam and UIT with a multi-pin impact head for controlling the combined LHT+UIT hardening process of high-strength steels.

3. The aim and objectives of the study

The study aims to determine the relationship between the technological modes of the combined LHT+UIT treatment of AISI 1045 steel and AISI D2 steel and the quality/operational parameters of the surface-modified layer. This will make it possible to purposefully control the geometric surface parameters and the physical and mechanical properties of the surface layer, narrowing the range of rational/optimal parameters of the combined LHT+UIT treatment of structural and tool steels. As a result, the use of combined laser-ultrasonic surface hardening and finishing will allow you to form a favorable microrelief on the surface and a structure with a given set of properties, guaranteeing an increase in wear resistance, corrosion resistance, and fatigue strength.

To achieve the aim, the following objectives were set:

– to perform an analysis of the quality parameters of the surface layer of AISI 1045 steel and AISI D2 steel, obtained under optimal modes of LHT+UIT treatment;

– to determine the wear resistance of AISI 1045 steel and AISI D2 steel after combined laser-ultrasonic treatment under quasi-static and dynamic load modes;

– to evaluate the corrosion resistance of AISI 1045 steel;

– to develop an algorithm for determining technological parameters to control the combined LHT+UIT hardening process of structural and tool steels.

4. Materials and methods

The long-term use of parts made of AISI 1045 structural steel and AISI D2 tool steel depends on the strength indicators and surface roughness (microrelief), which can be improved by additional surface hardening and finishing.

Application of laser heat treatment and ultrasonic impact treatment under optimal modes and sequence will allow obtaining better surface properties of the studied steels and parts from them.

The combined laser-ultrasonic surface hardening and finishing process was implemented according to a separate scheme [20]. The research was carried out on flat samples of AISI 1045 structural steel (~0.45 % C) and AISI D2 stool steel with increased chromium content (1.45–1.65 %) and inclusions of molybdenum (0.5 %) and vanadium (0.2 %).

Laser surface transformation hardening of the steel specimens was carried out using a technological laser complex, which included a Rofin Sinar FL010 fiber laser (radiation wavelength 1.07 μm) with a maximum output power of 1 kW [19]. The Scanlab Hurryscan25 optical system was placed in a Kondia Aktinos B500 machine with numerical control for moving the test samples (40–140 mm/min) along the XY axes. Laser beam scanning was set at a constant speed of 1000 mm/s and a scanning amplitude of 10 mm, while the heating temperature was varied at 1200–1300 °C. The heating temperature was 1200 °C (LHT5/LHT6/LHT7 modes) and 1300 °C (LHT8/LHT9/LHT10 modes) for hardening AISI 1045 steel and 1270 °C for AISI D2 steel. Thus, the following modes were performed for AISI 1045 steel: T=1200 °C, S=40 mm/min (LHT1 mode); T=1200 °C, S=90 mm/min (LHT2 mode); T=1300 °C, S=40 mm/min (LHT3 mode); T=1300 °C, S=90 mm/min (LHT4 mode). The sample feed rate was 40 mm/min, 90 mm/min, and 140 mm/min at a heating temperature of 1270 °C (LHT5, LHT6, and LHT7 modes) for AISI D2 steel, respectively.

Ultrasonic surface strain hardening of the LHT-processed steel specimens was carried out using technological equipment (an ultrasonic generator with a frequency of 21.6 kHz and a power of 0.3 kW), which is mounted on a CNC machine [10]. The UIT tests were performed with a vibration amplitude of the ultrasonic horn of 18 μm, a load of the ultrasonic tool to the treated surface of 50 N, and a specimen feed rate of 600 mm/min. The treatment duration was 60 s (UIT1 mode), 120 s (UIT2 mode), and 180 s (UIT3 mode).

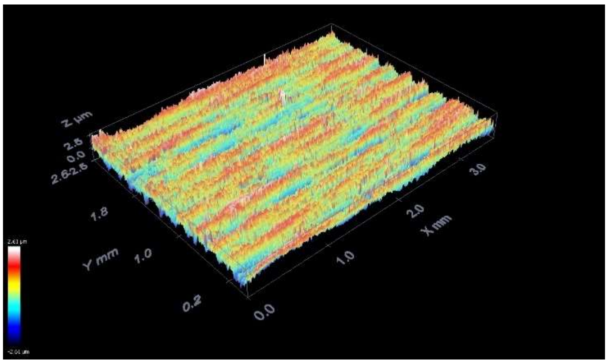
The study of the surface topography (2.5×3 mm) of the samples was performed on a Leica DCM3D optical profilometer. The roughness and waviness parameters of the surface profile were evaluated along the sampling length of 0.8 mm under the international standard ISO 4287. The values of the arithmetic mean roughness/waviness (Ra/Wa) and the total profile height (Rt/Wt) along the evaluation length were chosen to evaluate the state of the untreated and hardened surfaces. The surface hardness and microhardness in the near-surface layer of the samples were measured respectively using the Computest SC hardness tester with an indenter load of 5 kg and the FM800 microhardness tester with an indenter load of 50 g. The surface hardness (HRC) of the specimens was measured 5–7 times. The intensity of hardening (u_h) of the specimen surface was estimated by the ratio of the difference between the hardness values of the hardened LHT+UIT (HRC_h) and the untreated (HRC_{in}) surface by the formula $u_h = \left(HRC_h - HRC_{in}\right) / HRC_{in} \cdot 100\,\%$. Measurement of the microhardness of the LHT+UIT hardened zones was performed at a distance of ~25 μm from the surface in the center of the laser track in the transverse direction of the heat-affected zone, which allowed estimating the hardening depth (h_h). In addition, the hardening depth was evaluated by the analysis of optical micrographs. The specimens were tested for wear resistance for 15 and 45 minutes with a silicon nitride indenter on an automated tribological complex under static and dynamic loading [15]. The wear values of the friction tracks were estimated using an Alicona Infinite Focus G5 optical profilometer. Experimental studies of hardened surfaces of AISI 1045 steel samples for corrosion resistance were carried out in a 3 % NaCl solution at room temperature. The external observation of the samples was carried out using a Bresser Biolux LCD microscope.

5. Results of studies of the quality and operational parameters of AISI 1045 steel and AISI D2 steel under laser-ultrasonic treatment

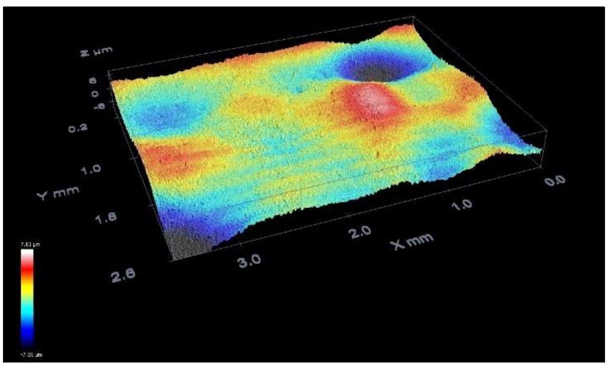
5. 1. Analysis of the quality parameters of the surface layer

Parameters of surface roughness (Ra, Rt) and waviness (Wa, Wt) and surface hardness HRC_5, hardening intensity u_h, microhardness $HV_{0.05}$, and hardening depth h_h) of the LHT+UIT-processed steel parts are given in Table 1. The surface topography of the samples before and after combined treatment is presented in Fig. 1, 2.

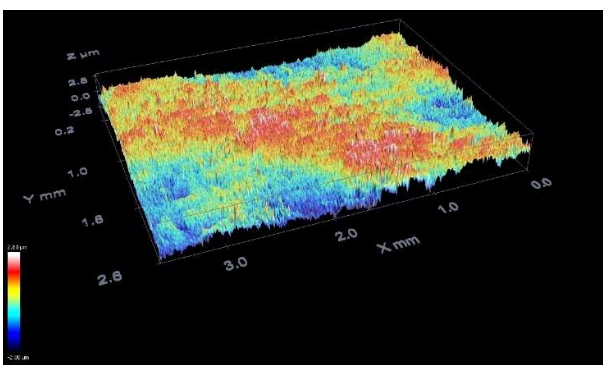
Compared to the untreated specimen, the surface roughness parameters (Table 1) decreased after LHT+UIT regardless of the initial surface state (Fig. 1, *a* and Fig. 2, *a*). In contrast to AISI D2 steel specimens (Ra=2.6 μm), AISI 1045 steel specimens (Ra=0.65 μm) were subjected to a grinding process.



a



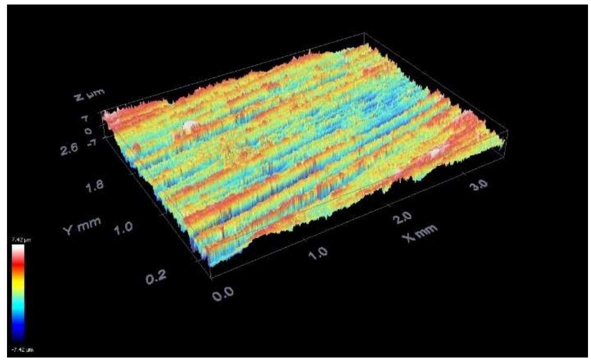
b



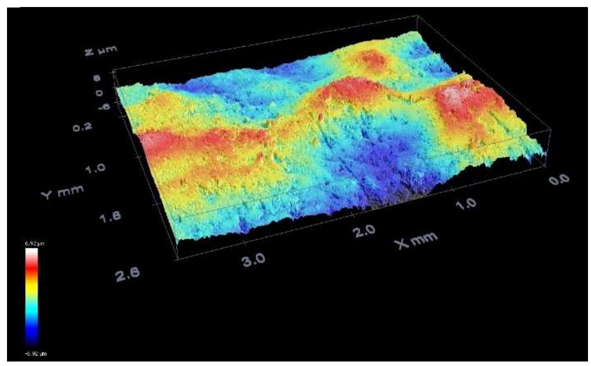
c

Fig. 1. Surface topography of AISI 1045 steel: *a* – initial state; *b* – LHT1+UIT2; *c* – LHT4+UIT2

UIT after LHT led to a decrease in surface roughness parameters, but at the same time to an increase in surface waviness parameters in the pre-polished AISI 1045 steel specimens (Table 1). The roughness parameter Ra ranged from 0.26 to 0.33 μm after combined LHT+UIT processing. Compared to AISI 1045 steel samples, UIT provided a decrease in both surface roughness and waviness parameters in the unpolished AISI D2 steel samples (Table 1, Fig. 2). An increase in the UIT duration (t_{UIT}>120 s) leads to an increase in the total height of the roughness and waviness profile of the surface hardened by the LHT. It can be seen that the LHT-hardened specimens with a higher hardness contribute to the enhanced surface finishing by the multi-pin UIT (Fig. 1, *c*). It is known that UIT using rotating multi-pin heads promotes sliding with multiple high-frequency impacts of the pins, which causes flatteening of microirregularities on the treated surface [19]. As a consequence, both lower roughness and waviness of the surface can be achieved.



a



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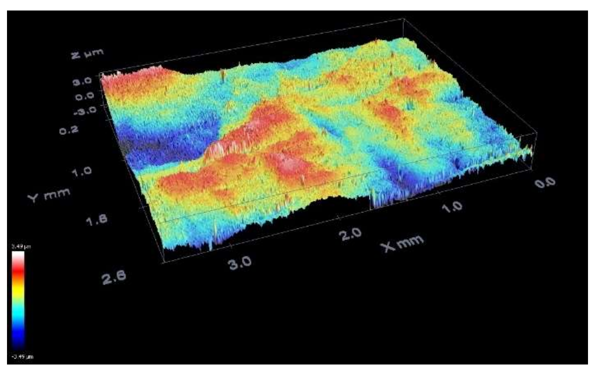
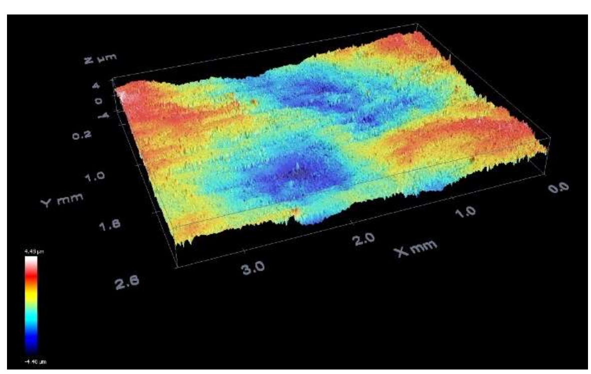


c



d

Fig. 2. Surface topography of AISI D2 steel: *a* – initial state; *b* – LHT5+UIT2; *c* – LHT6+UIT2; *d* – LHT7+UIT2

Table 1

Surface microrelief parameters and physical and mechanical parameters after combined laser-ultrasonic treatment

Mode	Surface microrelief parameters				Physical and mechanical parameters			
	Ra, μm	*Rt*, μm	*Wa*, μm	*Wt*, μm	HRC	u_h, %	HV, MPa	h_h, μm
AISI 1045 steel								
Initial	0.65	6.08	0.15	0.57	18.6	0	300	0
LHT1+UIT1	0.33	3.02	0.93	3.99	59.7	220	970	290
LHT2+UIT1	0.27	2.95	1.38	3.27	60.7	226	1,100	200
LHT3+UIT1	0.39	3.17	0.18	1.09	61.5	230	1,120	440
LHT4+UIT1	0.28	2.25	0.36	1.60	62.3	234	1,200	340
LHT1+UIT2	0.33	4.82	0.63	1.90	60.9	227	990	290
LHT2+UIT2	0.26	2.02	1.03	2.38	62.1	233	1,100	200
LHT3+UIT2	0.33	2.34	0.57	1.39	59.7	220	980	440
LHT4+UIT2	0.26	2.31	0.47	1.61	61.8	232	1,070	340
AISI D2 steel								
Initial	2.60	16.0	1.66	15.4	19.6	0	320	0
LHT5+UIT2	0.38	4.17	0.18	0.56	58.4	197	710	380
LHT6+UIT2	0.28	3.31	0.32	1.60	58.5	198	780	310
LHT7+UIT2	0.29	4.47	1.14	3.22	58.8	200	840	240
LHT5+UIT3	0.36	4.99	1.81	5.62	57.2	191	750	380
LHT6+UIT3	0.55	8.38	0.97	5.80	58.2	196	800	310
LHT7+UIT3	0.42	6.44	1.44	5.53	58.9	200	830	240

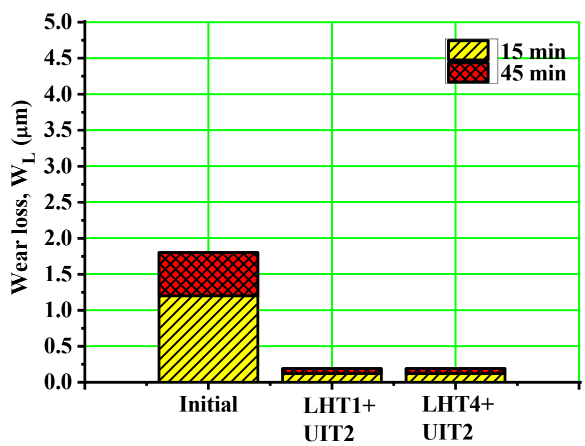
Note: Ra and Wa are the average variation of the roughness and waviness profile from the mean line; Rt and Wt are the height difference between the highest and lowest point of the roughness and waviness profile; HRC is the surface hardness; u_h *is hardening intensity; HV is the microhardness in the near-surface layer;* h_h *is the hardening depth*

It is worth mentioning that both surface macrohardness (HRC) and near-surface microhardness (HV) of AISI D2 steel increase with increasing laser processing speed (LHT5+UIT2, LHT6+UIT2, LHT7+UIT2 modes). This is due to the fact that the higher the cooling rate, the lower the grain/crystallite size in the formed structure. Further UIT after LHT contributes to the refinement and more uniform distribution of martensitic grains, as well as to an increase in the dislocation density and a decrease in residual austenite in the near-surface layer [10, 20]. As a result, the hardness values in the near-surface layer are increased 3–4 times after LHT+UIT (Table 1), nanostructuring the subsurface layer [19]. The hardening depth after combined LHT+UIT treatment is 200–440 μm for AISI 1045 structural steel and 240–380 μm for AISI D2 tool steel, respectively. The UIT finishing induced structural changes at a depth of up to ~50 μm [18, 19].

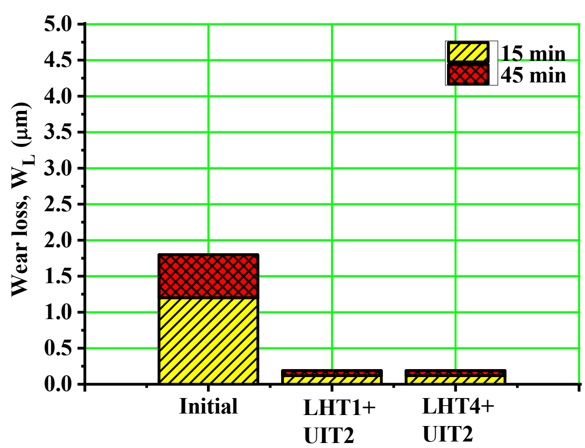
5. 2. Determination of wear resistance of AISI 1045 steel and AISI D2 steel

The wear loss magnitudes under the quasi-static (Fig. 3) and dynamic (Fig. 4) load modes were obtained during the reciprocating sliding of an indenter with a diameter of 8 mm with a frequency of 1 Hz along a track of 4 mm. The tribological tester is described in detail elsewhere [15].

It can be seen that the wear loss values are lower for AISI 1045 steel than for AISI D2 steel regardless of wear test conditions. This may be related to the different surface hardness of the LHT+UIT-processed near-surface layer and initial surface roughness of the studied steels (Table 1). The rougher surface in AISI D2 steel (*Rt*=16 μm) is about 2 times less wear-resistant for 45 min compared to AISI 1045 steel. This correlates well with the roughness parameter *Rt* (Table 1). This trend is expected to change slightly with a further increase in the wear test duration due to a more wear-resistant structural-phase composition of the tool steel.

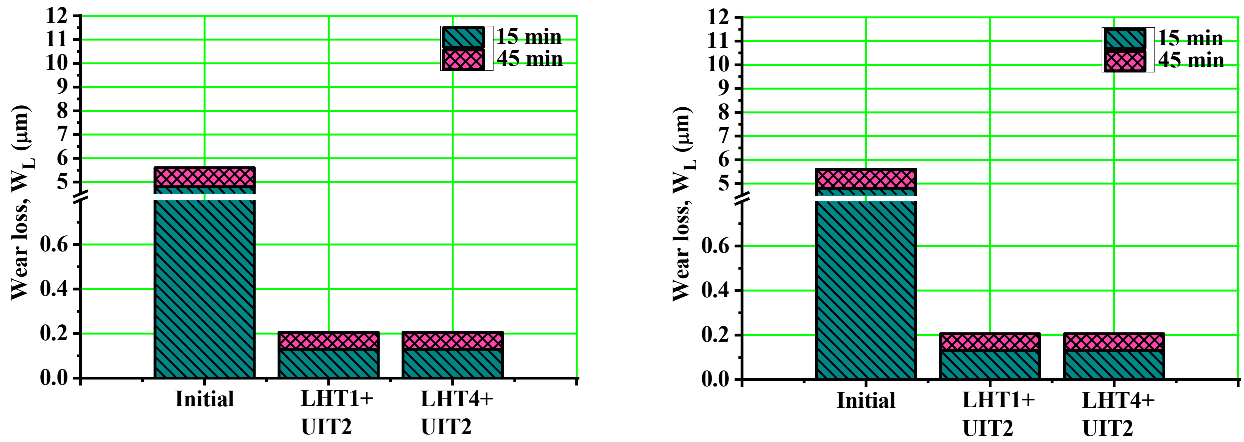


a



b

Fig. 3. Wear loss values under quasi-static load: *a* – AISI 1045 steel; *b* – AISI D2 steel



a *b*

Fig. 4. Wear loss values under dynamic load: *a* – AISI 1045 steel; *b* – AISI D2 steel

Compared to the untreated sample, the surfaces hardened by LHT followed by UIT of AISI 1045 steel are significantly resistant to wear irrespective of the wear test conditions (Fig. 3, 4, *a*). At the same time, different values of the heating temperature (1200–1300 °C) practically did not change the wear loss magnitudes both for 15 min and 45 min compared to the initial state. The wear loss values of AISI 1045 steel decreased from 1.8 μm to 0.19 μm (quasi-static load mode) and from 5.6 μm to 0.2 μm (dynamic load mode) after combined LHT+UIT treatment. In contrast to AISI 1045 carbon steel, the wear loss magnitudes of AISI D2 tool steel (Fig. 3, 4, *b*) are much larger due to the high peaks of surface microrelief irregularities, which are quickly destroyed during the run-in process. Additionally, this may also be due to the additional probability of abrasive wear by oxide particles [15]. In particular, the combined treatment leads to an increase in wear resistance by about 4 times in the dynamic load mode for 45 minutes (Fig. 4, *b*).

Thus, combined LHT+UIT treatment leads to a significant increase in the wear resistance of both AISI 1045 steel and AISI D2 steel due to the formation of a fine-sized martensitic structure of high density [10, 19] and hardness in the near-surface layer (Table 1). In addition, the UIT-formed microrelief on the surface with a low roughness contributes to wear resistance.

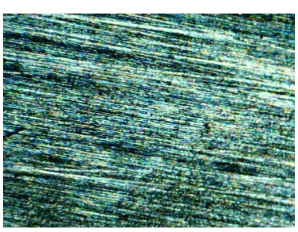
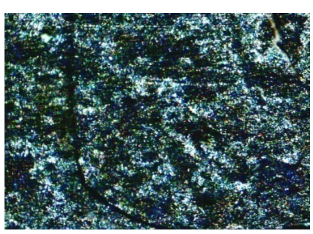
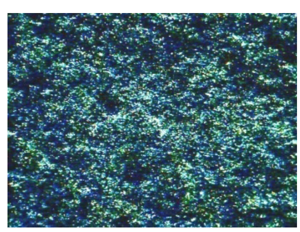
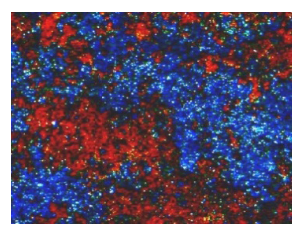
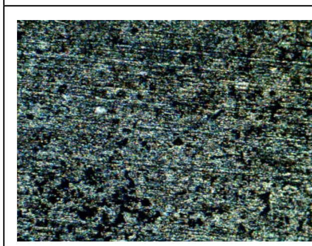
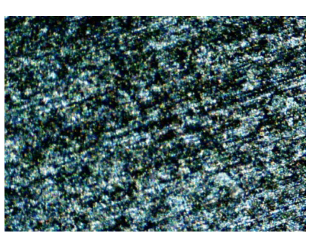
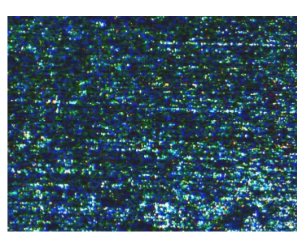
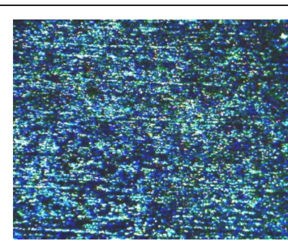
5. 3. Evaluation of corrosion resistance of AISI 1045 steel

Testing of AISI 1045 steel surface parts for corrosion resistance in a 3 % NaCl solution was performed on specimens processed by the optimized LHT+UIT parameters (Table 2).

The results of experimental studies of corrosion behaviors showed that the corrosion areas (iron hydroxide) were observed on the original sample after 146 hours, while no surface corrosion signs were found after the combined treatment. This is due to the formation of a flattened/smoothed microrelief profile with low surface roughness (Table 1) and nano-sized equiaxed grains in the near-surface layer [18]. The results of corrosion behavior agree with the data given in [21]. It is shown that severe plastic deformation of the martensitic structure formed by LHT causes accelerated formation of a passive film in a corrosive medium, which further protects the surface.

Table 2

Optical images of the untreated and LHT+UIT-treated surfaces (magnification x40) after corrosion tests of AISI 1045 steel

Before the test	50 hours	100 hours	146 hours
Initial state			
			
LHT2+UIT2			
			

5. 4. Combined laser-ultrasonic surface hardening process control algorithm

Based on the results of experimental and theoretical studies [19, 20], an algorithm for determining the technological parameters/modes of combined laser-ultrasonic treatment of iron-carbon alloys according to a separate processing scheme was developed (Fig. 5). It should be noted that a laser surface transformation hardening process (fiber laser in combination with scanning optics) of the studied steels with maintaining a constant heating temperature is offered in this work [20]. Laser beam dimensions, heating temperature (T_H), specimen feed rate (S), as well as scanning speed (V_{sc}) and amplitude (h_{sc}) of the laser beam, are the most influential parameters in LHT.

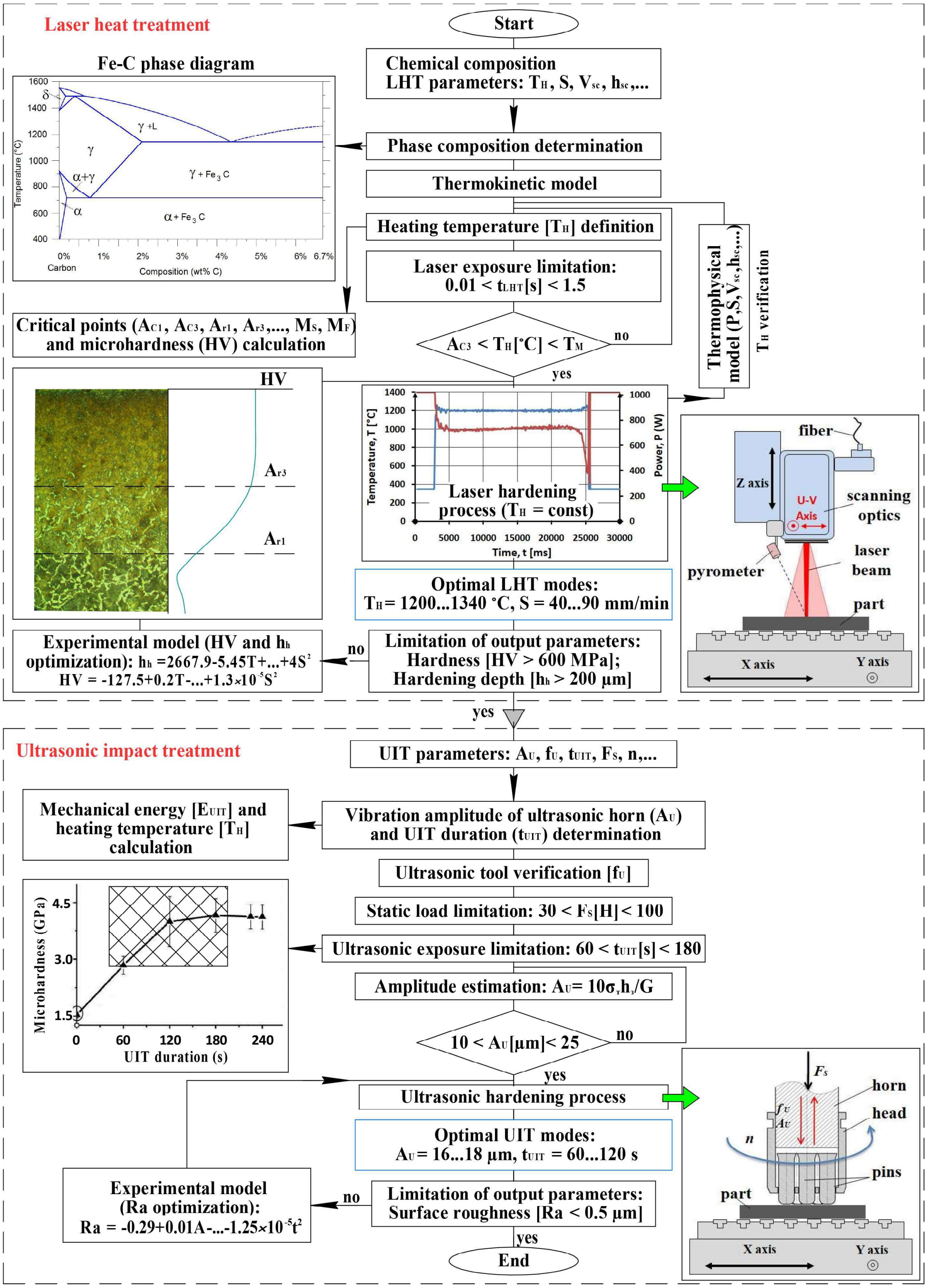


Fig. 5. Determination algorithm of technological parameters of combined laser-ultrasonic treatment of structural and tool steels

Preliminary determination of the heating temperature in LHT is carried out taking into account the phase and chemical composition of the treated steel according to the Fe–C phase diagram (Fe–C–Cr phase diagram for AISI D2 steel), limiting the temperature range of excessive heating ($A_{C3}<T_H<T_M$). To narrow the temperature range of complete austenization of the studied steels, critical temperature points of structural and phase transformations during heating (cooling) are determined according to the thermokinetic model, limiting the duration of laser exposure (0.01 s$<t_{LHT}<$1.5 s) [14]. At this stage, volume fractions of structural components and microhardness in the near-surface layer of iron-carbon alloys are also determined using an experimental model [22]. The measured surface heating temperature of the laser pyrometer is consistent with the temperature determined by the thermophysical model [14].

The subsequent ultrasonic hardening and finishing process can be applied if the surface layer parameters (hardening depth, hardness) meet the required values (Fig. 5). The vibration amplitude of the ultrasonic horn (10 μm$<A_U<$25 μm) and treatment duration (60 s$<t_{UIT}<$180 s) are the most influential parameters in UIT. The range of UIT duration of the studied steels is determined taking into account previous studies (Fig. 5), limiting the static load of the ultrasonic tool (30 H$<F_S<$100 H).

To obtain the maximum depth of hardening and hardness, and minimum surface roughness, it is recommended to use the LHT speed of 40–90 mm/min and a heating temperature of 1200–1300 °C for AISI 1045 steel and 1270–1340 °C for AISI D2 steel. At the same time, the laser beam scanning speed of 1000 mm/s and scanning amplitude of 10 mm should be chosen as constant. Optimal UIT modes are as follows: the static load of the ultrasonic vibration system (UVS) – 50 N, the rotation speed of the multi-pin impact head – 76 rpm, the vibration amplitude of the ultrasonic horn – 16–18 μm, and the UIT duration – 60–120 s.

6. Discussion of the results of studying the quality and operational parameters in iron-carbon alloys formed by thermomechanical treatment

The results of the research allow concluding that the severe SPD methods have proven to be effective in combined/hybrid thermomechanical surface treatment of iron-carbon alloys. In particular, shot peening significantly improved the surface roughness of the laser-melted low-carbon steel [23], while LHT without surface melting reduced the ability of shot peening to reduce the roughness [24]. At the same time, increasing the intensity of peening resulted in a rougher surface than in the initial and laser-melted states [23]. The surface roughness can be slightly reduced using a shot of small diameter after intermediate shot peening of specimens hardened by LHT without surface melting [24]. The results of the combined LHT+UIT treatment also show that surface roughness can be essentially minimized under the optimum laser-ultrasonic conditions observed in this study. The roughness parameter *Ra* is less than 0.5 μm regardless of the UIT modes used (Table 1). In [18], the ultrasonic burnishing process of surfaces hardened by LHT reached the roughness parameter *Ra* ~0.35 μm instead of *Ra* ~0.53 μm. The surface roughness after UIT is 2 times lower as compared to the shot peening treatment of the LHT-hardened surface [23]. In addition, it should be noted that the use of shot peening before LHT allows increasing the depth of the hardened layer due to the formation of a rough microrelief, which improves the absorption capacity of laser radiation [25]. Unlike shot peening, the UIT-formed microrelief on the surface is characterized by slight waviness (Fig. 1, 2).

On the other hand, severe SPD with ultrasonic tools before/after LHT leads to an increase in surface hardness due to the structural particle refinement and an increase in the dislocation density in the near-surface layer [14, 18, 19]. The strain-affected zone is located at a depth of about 50 microns with combined LHT+UIT according to a separate processing scheme. The determined values of the strain-affected zone in the heat-affected zone correlate with the values obtained after ultrasonic burnishing [18].

Taking into account the wear loss values under different test conditions, it is confirmed that compared to AISI 1045 steel, the LHT+UIT-hardened AISI D2 steel samples have lower wear resistance due to a rougher surface (Fig. 3, 4) and the presence of a larger amount of residual austenite in the near-surface layer and a thicker oxide film on the surface [15]. The combined LHT+UIT treatment leads to an increase in the wear resistance of the studied steels by more than 4 times due to the complex improvement of the surface layer quality. In addition, it should also be noted that the surface layer with equiaxed nano-sized grains formed by the combined treatment increases the corrosion resistance of AISI 1045 steel (Table 2). It is known that the application of severe plastic deformation of iron-carbon alloys leads to the formation of a white layer on the surface, which protects the surface in corrosive media [21, 26]. The work [27] shows that UIT is an effective method of increasing resistance to stress corrosion cracking.

It should also be noted that the use of a 1 kW fiber laser in combination with scanning optics limits obtaining the hardening depth in iron-carbon alloys of more than 500 μm without melting the surface. On the other hand, the use of a CNC machine tool center (3 linear, 2 rotary axes) with a total working area of 500×300 mm has limitations in the LHT treatment of large-sized or complex-shaped products. At the same time, the scanning area of the laser beam in the focal plane (defocusing size 50 mm) is 120×120 mm. In addition, the performance of ultrasonic surface hardening and finishing with multi-pin heads has limitations for processing small-sized or complex-shaped products.

It is promising to search for new methods of combined laser-ultrasonic treatment of complex-shaped products, including lasers of other types in combination with surface plastic deformation by balls in an ultrasonic vibration chamber.

7. Conclusions

1. To provide the surface integrity and the quality of the surface layer, the thermal and strain hardening and finishing technique was used with laser heat treatment followed by ultrasonic impact treatment of AISI 1045 steel and AISI D2 steel. The roughness parameter *Ra* decreased from 0.65 μm to 0.26–0.33 μm (AISI 1045 steel)

and from 2.60 μm to 0.28–0.38 μm (AISI D2 steel) after combined treatment. The microhardness in the near-surface layer is ~1.000 $HV_{0.05}$ (AISI 1045 steel) and ~800 $HV_{0.05}$ (AISI D2 steel), respectively, forming a hardening depth of 200–440 μm.

2. Complex improvement of the surface layer quality through thermal and deformation effects made it possible to reduce the wear loss values for AISI D2 steel by 2 times under quasi-static loading and 4 times under dynamic loading. In contrast to AISI D2 steel, the wear resistance of AISI 1045 steel increased more than 4 times under both quasi-static and dynamic load modes.

3. It was confirmed that the combined laser-ultrasonic hardening led to an increase in the corrosion resistance of the hardened AISI 1045 steel samples. The results of experimental studies showed that corrosion areas were found on the untreated surface specimen after 146 hours in a 3 % sodium chloride solution.

4. Based on the experimental studies, an algorithm was developed for determining technological parameters of combined LHT+UIT treatment of structural and tool steels, limiting the heating temperature, the duration of laser (ultrasonic) exposure, and the vibration amplitude of the ultrasonic horn. The specified LHT+UIT parameters provide a surface hardness of more than 600 HV, a hardening depth of at least 200 μm, and an average surface roughness (parameter *Ra*) of less than 0.5 μm.

Conflicts of interest

The authors declare that they have no conflict of interest in relation to the current study, whether financial, personal, authorship, or any other, which could affect the study and the results reported in this paper.

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Data availability

The manuscript has no associated data.

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