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On Energy Efficiency Characteristics of Laser Erosion on Oxidic Surfaces of Carbon Steels, Cast Iron and Low-alloy Non-ferrous Alloys During Deoxidizing Cleaning

Part II

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Abstract. An analysis of the energy efficiency characteristics was performed for laser erosion cleaning (LC) processes developed last period for the application in metalworking sector for the wide group of carbon steels, cast iron and non-ferrous metal alloys to remove surface oxidic layers. The consideration of some characteristics of the LC-processes (energy consumption, energy criterion K_{en1s} et al.) gives the opportunity for the evaluation of the effects of different mechanisms of the surface deoxidizing during the pulsed laser cleaning of MeO_x-layers. Analysis of LC-processes taking into account the efficiency characteristics was based on the massive of parameters of typical (in the field of LC of oxides) regimes of processing of samples of carbon steels with surface oxide layers (including using data from our experiments) with use of various pulsed lasers, as well as some samples of aluminum, copper and titanium alloys and cast iron with surface oxides. Our comparison of estimated values of the parameters for a number of recent LC-variants demonstrates that it can be supposed with a sufficient reliability that for the most typical LC-processing cases (preliminary studied in our experiments with cleaning steel samples from mill scale and also described for LC-processes with removal of oxides from some non-ferrous alloys), the first, i.e. the most energy-consuming (thermal ablation with heating to the melting temperature or even higher) of the cleaning mechanisms is more probable. For this processing group the level of the energy criterion values achieved in our experimental series with the LC of FeO_x-scale ($K_{en1s} \approx 4.4$ and corresponding approximate value can, according to our kinetic estimates, be considered close to the threshold level, below which not only the LC thermal ablation will be realized in parallel, but also partially the other two deoxidizing mechanisms (not so high energy consumed ones). At the same time active realization of other, i.e. non-ablative mechanisms is feasible in a rarer group of LC-operating cases (e.g. in the laser removal of TiO_x-film from the titanium alloy, and also, possibly, in the regime of alumina removal from aluminium alloy for which the K_{en1s} level is probably equivalent to the “transition zone” with substantial contribution of both non-ablative mechanisms and thermal ablation).

Keywords: laser erosion, cleaning of metal parts, oxidated surface, steels, non-ferrous metal alloys, energy efficiency characteristics, mechanisms of layer removal, oxides, surface deoxidizing, energy/power consumption

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О характеристиках энергоэффективности лазерной эрозии при очистке от оксидов поверхностей углеродистых сталей, чугуна и низколегированных сплавов металлов

Часть 2

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Реферат. Проведен анализ показателей энергоэффективности процессов лазерной эрозионной очистки (ЛО), разрабатываемых в последнее время для применения в технологиях металлообработки многих углеродистых сталей, чугунов и сплавов цветных металлов, с целью удаления с них поверхностных оксидных слоев. Учет некоторых характеристик данных ЛО-процессов (энергозатраты, энергетический критерий K_{en1s}, и др.) дает возможность оценить влияние различных механизмов поверхностного деоксидирования при импульсной лазерной очистке MeO_x-слоев. Анализ LC-процессов с учетом характеристик эффективности проводился на основе массива параметров типичных (в области ЛО от оксидов) режимов обработки образцов углеродистых сталей с поверхностными оксидными слоями (в том числе с использованием данных наших экспериментов) с применением различных импульсных лазеров, а также некоторых образцов алюминиевых, медных и титановых сплавов и чугуна с поверхностными оксидами. Проведенное нами сравнение расчетных значений параметров для ряда современных вариантов ЛО показывает, что с достаточной степенью надежности можно предположить, что для наиболее типичных случаев ЛО-обработки (предварительно изученных в наших экспериментах по очистке стальных образцов от прокатной окалины, а также описанных для ЛО-процессов по удалению оксидов с поверхности некоторых сплавов цветных сплавов) более вероятен первый, т.е. наиболее энергозатратный (термическая абляция с нагревом до температуры плавления и даже выше) из механизмов очистки. Для этой группы процессов уровень значений энергетического критерия, достигнутый в нашей серии экспериментов с ЛО FeO_x-окалины со стали ($K_{en1s} \approx 4,4$) и соответствующее ему приближенное значение можно, согласно нашим кинетическим оценкам, считать близким к пороговому уровню, ниже которого будет параллельно реализовываться не только ЛО-термоабляция, но и частично два других (менее энергозатратных) механизма деоксидирования. В то же время в более редкой группе случаев процессов ЛО (например, при лазерном удалении пленки TiO_x с титанового сплава, а также, возможно, в режиме удаления оксида алюминия с алюминиевого сплава, для которого уровень K_{en1s}, вероятно, эквивалентен «переходной зоне» с существенным вкладом как неабляционных механизмов, так и термоабляции) возможна активная реализация иных, т. е. не термоабляционных механизмов.

Ключевые слова: лазерная эрозия, очистка металлоизделий, окисленная поверхность, стали, сплавы цветных металлов, характеристики энергоэффективности, механизмы удаления слоя, оксиды, деоксидирование поверхности, энергозатраты

Для цитирования: О характеристиках энергоэффективности лазерной эрозии при очистке от оксидов поверхности углеродистых сталей, чугуна и низколегированных сплавов металлов. Часть 2 / О. Г. Девойно [и др.] // *Наука и техника.* 2025. Т. 24, № 4. С. 261–269. https://doi.org/10.21122/2227-1031-2025-24-4-261-269

Introduction and research objective

An important trend in current metalworking sector is a modernization of outdated mechanical and other processes for surface deoxidizing cleaning of various metal parts and structures from unwanted oxide layers (products of low-temperature or hot corrosion degradation), such as rust and scale on structural steels and oxidic layers (up to ≥1 mm thickness) on different non-ferrous metal alloys, especially based on Al and Ti [1–9]. For these objective a number of groups of advanced technologies, such as laser-erosion ones (in pulse or continuous wave variants) and some others, can be applied, and these are actively designed last period for different grades of steels, cast iron and alloys (to remove the layers of FeO_x, Al_2O_3, TiO_2, CuO, ZnO, MgO, WO_x, PbO, Ag_2O, etc.) [1–21] and even partially commercialized for some industrial facilities, especially in China.

Consideration of some efficiency characteristics (energy consumption, energy criterion, etc.) gives the opportunity for the evaluation of potential of different mechanisms of the surface deoxidizing during the pulsed laser cleaning (LC). Corresponding analysis of the LC-processes based on this approach has recently been initiated using the characteristics mentioned for the empirical data massive of typical LC-regimes of processing of structural steels, measured in the experiments with the use of pulsed laser systems, as well as some cast iron and non-ferrous metal alloy surfaces with oxidic layers (including of iron oxides, alumina, titania, copper oxides) [22]. The K_{en1s} criterion (or some other similar dimensionless parameters used typically for engineering analysis of high temperature systems), in accordance with some estimations (with use of experience of this criterion application in thermal plasma engineering for inorganic materials production, as was demonstrated before [23, 24]), in some cases can be suitable for modeling and technical scaling of the LC-processes with phase transitions in the condensed surface phase [22]. For the objective of our current research, the special comparison of the efficiency characteristics was chosen to estimate the effect of main possible physical mechanisms of surface deoxidizing of different layers during the analyzed group of LC-processes.

Research approach for the laser deoxidizing erosion of surface layers and data obtained

In our analysis of the LC-regimes for different oxides such special variant of energy criterion K_{en1s} was used, which takes into account not only the conductive heating of the oxidic surface in the axial direction with laser beam, but also other mechanisms of heat transfer which occur in all directions in the laser removal/cleaning systems under consideration [22]. For this case the simplified expression can be used, by analogy with the energy efficiency parameter (the energy efficiency) of plasma-chemical systems [25, 26]:

$$K_{en1s} = \frac{E_{1w}}{Q_{1w-ox}}. \tag{1}$$

Here E_{1w} – total value of energy consumption of the LC-processing (for such case of the process as laser heating to melting point of the surface layer) in units of J/(kg of removed material).

Additionally, the Peclet number Pe, characterized the surface rate of the laser cleaning of the oxidic surfaces, can be used for estimations of energy performance level of LC-processes [22]; in this the thermal diffusivity is used: $a = \kappa/(\rho \cdot c_p)$ (where ρ и c_p are the density and specific heat capacity for oxidic layer, averaged for specified temperature range).

For the determination of K_{en1s} criterion the enthalpy difference ΔH can be obtained for the analyzed oxidic layer with the use for the case of LC-process with thermal ablation (heating to the level of evaporation or melting/fusion temperatures – T_b or T_m) standard expression:

$$\Delta H_1 = \int_{T_0}^{T_m} c_{p,s}\mathrm{d}T + \int_{T_m}^{T_b} c_{p,l}\mathrm{d}T + \Delta H_m + \Delta H_v \tag{2}$$

(the variant for the heating with the oxidic layer melting and next vaporization (ΔH_v – is the heat of vaporization)).

It is also significant that when calculating the values of the specific heating power and the energy criterion for various laser processing regimes, the value of the energy of the laser irradiation absorbed by the surface in general case should be determined using an expression of the following type [27]:

$$Q = (1 - R)\cdot I_o(x, y, t)\Lambda, \tag{3}$$

here R – the coefficient of the radiation reflection from the heated surface, $I_o(x, y, t)$ – the distribution of the laser beam energy (before contact with the surface) in a 2D coordinate system (x, y) and in time (t), coefficient Λ (it is equal to 0.9 when modeling LC with a LI-pulse duration in different modes from 0.050 to 10.0 ms [27]) is the shielding coefficient of the surface from the beam in zone of near-surface laser-induced plasma (it is usually considered a quasi-spherical formation [28] and has a characteristic size of 0.14–1.8 mm on our estimations for the conditions of experimental LC-regimes with various oxide layers (with thickness of up to 330 μm), including those given below in Table 1), and thus this value is the degree of conservation of the laser beam energy during its propagation/motion through the near-surface plasma.

The complete group of parameters that was selected to characterize the main physical mechanisms of removing oxide layers during LC of the steels and alloys was presented before in the paper [22], including the removing mechanisms with shock wave generation in laser-induced plasma zone near the irradiated oxidic surface. As shown in [29], under LC conditions with pulsed lasers, the "shock wave ejection mechanism" prevails at high intensive laser plasma (in terms of the dynamic effect on solid surfaces) rather than the mechanism of photon pressure from the beam of LI.

A comparative description of the obtained experimental data, including energy consumption parameters, for a number of typical variants of laser removal of oxidic corrosion products from steels and some alloys is briefly presented in [10], including the case of the results of a series of our experiments on lab-scale 30W LC-system from mill scale layers (30–50 μm thickness (δ)) on carbon steel samples. Figure 1 shows, as an example, a micrograph of the cross-section of carbon steel sample with oxidic scale layer before the scale removal with the laser processing. In this case, the LC-processing was carried out on experimental setup using the laser with high-frequency nanosecond pulses (HFNP) with single pulse energy ≤1 mJ and the pulse duration t_P = 120–150 ns [10]. The rate of LC-removal of the layer (containing mainly the magnetite phase Fe_3O_4 with an admixture of hematite Fe_2O_3 (and small impurities of other phases) in accordance with X-ray diffraction analysis performed for samples with mill scale in the OIM of NASB (laboratory of nanostructured and superhard materials), using the diffractometer from Bruker D8 ADVANCE (Germany) with CuK_α-radiation (the wavelength 0.15418 nm)) in the optimal regime is at the level of no less than 0.005 dm^2 of the scale surface per second (at operating time-averaged thermal power of the beam $P_0 \approx 28$ W, emitting in IR-region of spectrum, and at five passes of the beam δ ≈ 32 μm). Carbon steel of St3 grade (with 0.14–0.22 wt. % C, 0.15–0.3% Si, 0.4–0.65 % Mn, ~97 % Fe) was used as the sample material in our experiments on LC. The size of the plate samples was 90×70 mm, thickness δ = 4 mm.

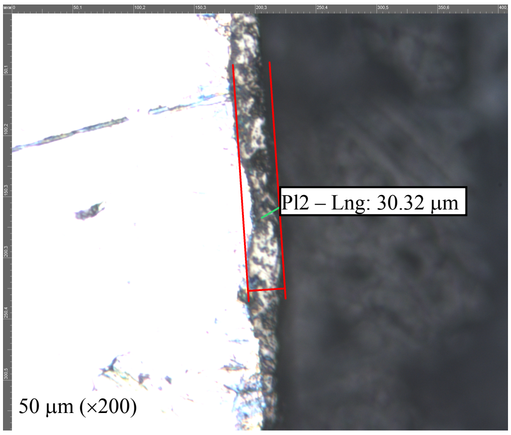

Fig. 1. Micrograph of a cross-section of the sample made of St3 carbon steel (light (left) part of the photo) with a layer of oxidic mill scale with ≤ 30.5 μm thickness, taken before the start of our experiment for laser cleaning. The scale bar (bottom left) in this micrograph represents 50 μm

The micrographs of the cross-sections of carbon steel samples with oxidic mill scale layer were obtained with the use of the metallographic optical inverted microscope ADF I350 (ADF Co. (China), with a digital camera of Aksalit Soft Co. (Russia)) with a magnification of up to 2000 times.

A special analysis of the experimental results obtained for laser surface deoxidizing [10] and other published empirical data for the LC-processes on different metal samples (oxidated steels, cast iron, alloys, – see the data for typical examples of the surface cleaning processes in Table 1) was carried out, using systematized data on the number of thermophysical and optical properties of important group of metal oxides, which were generalized by us in [22].

The obtained results on the parameters of laser cleaning in different regimes. In general, as we found, for comparative analysis of the efficiency of different (by the composition of the layers) laser processes it is advisable to use a group of parameters affecting energy consumption of LC processing: a) the criterion K_{en1s}; b) surface absorbed power N_0 of irradiation from the laser beam or/and the ratio of N_0 to the thermal conductivity of layer; c) the amplitude of the shock wave (SW) pressure in the laser plasma near the surface ($P_{sw\text{-}p}$). In accordance with our preliminary data, it is possible to estimate the effect of main mechanisms for removal of the irradiated layers during the pulsed LC: 1) thermal ablation; 2) low temperature thermoelastic stress in the oxidic layer or at the "layer/substrate" interface ("exfoliation" or "spallation" mechanism); 3) effect of the pressure front of the laser induced SW on the oxidic surface. Our approximated estimation of the LC processes taking into account the data of the efficiency characteristics (some of the analyzed LC parameters are given below in a form of Table 1) was based on the parameters of a number of regimes of LC with pulsed lasers (with different laser power and pulse energies up to E_p = 100 mJ) of samples from carbon steels, cast iron, and some aluminum, copper, titanium and other alloys containing surface oxides. Collation of levels of these special characteristics for different variants of LC allows us to select energy efficient regimes for the removal surface oxides from various metal substrates. It is also important, that for the regimes of removing oxide layers from carbon steel, the found value of such additional parameter characterizing the power efficiency of the LC-process as Peclet number (in the surface variant of the number) is at the level of Pe ≥ 1500–2000 when optimal interval of the operating modes was used.

Table 1

Comparison of parameters and energy consumption for recent technologies for laser surface deoxidizing of some steels and low-alloy metal alloys

No	Material of processed metal products	Application area of the processed products, objective of laser processing	Composition of the layer removed during deoxidizing/ cleaning; cleaning rate G	Type of laser processing system, operating and energy consumption parameters (radiation wavelength λ, etc.); value of the energy criterion for LC (assuming oxidic layer heating to the point of complete melting of irradiated layer); estimated parameter of possible laser induced shock wave (SW)	Technological features of the deoxidizing process (gas environment, etc.), auxiliary effects
1	2	3	4	5	6
1.	Structural carbon steel (SCS), plate-type samples [1]	Metalworking industry; the purpose of LC is to clean hot rolled parts/products before further mechanical processing (metalworking) operations	Removal of oxidic scale (FeO_x) from the steel surface; G – from 0.0023 $cm^2/(s·W)$ (for SM-L with power P = = 0.5 kW) to 0.0043 (for MM-L with P = 1.0 kW) and 0.0048 $cm^2/(s·W)$ (for MM-L with P = 2.0 kW)	Pilot system for pulsed laser processing (with single-mode (SM-L) and multimode (MM-L) lasers with λ ≈ 1064 nm with averaged thermal power of laser beam P = 0.1–0.5 kW (SM-L) and 1.0–2.0 kW (MM-L). For the processing system with MM-L in the used operating regime: laser pulse duration t_P = 85 ns, pulse repetition frequency f = 10 kHz, diameter of laser beam spot d_s = 0.85 mm, beam scanning speed v = 0.506 m/s; individual pulse' energy E_p = 100.0 mJ, total energy consumptions – E' ≈ 38.1 MJ/(kg of the layer) and E^* ≈ 2.33 MJ/(m^2 of the layer). Maximal pressure of a front of SW $P_{sw\text{-}p}$ ≤ ≤ 21.0 MPa. Criterion (approximate value) K_{en1s} ≈ 20.25 (††) (^)	Thickness of the removed (by ablation with melting and partial (or complete) vaporization) film of the oxidic mill scale δ = 15.0 μm (with porosity on our estimation P ≈ 0.20)
2.	SCS of Q235 grade, plate-type samples [4]	Metalworking industry; the purpose of LC – a cleaning of rusted parts/ products (mainly sheets) before further mechanical processing (metalworking)	Rust films/layers (composed of FeO_x-phases) from piped/municipal water and natural soil; no data for G presented	Pulsed laser cleaning unit with P = 350 W at λ ≈ 1064 nm, maximal E_p = 30–50 mJ, d_s = 0.7 mm, f = 7–15 kHz, t_P = 6 ns; E^* ≈ 0.04 kWh per 1 m^2 of the oxidic layer (assuming a single dose of the laser radiation per surface area unit)	There is no data on the thickness of the layer removed from the surface
3.	SCS of St3 grade, plate-type samples (authors' experi-	Metalworking industry; the purpose of LC is to clean hot rolled parts/products before further	Removal of oxidic mill scale (based on Fe_3O_4) from the steel surface; G – up to 0.0045 dm^2/s	Processing system with Ytterbium pulsed fiber laser RFL-P30QB (China) with λ ≈ 1070 nm. In used operating regime: f = 37 kHz, t_P = 120–150 ns; d_s = 0.050 mm, v = 2.0 m/s; pulse energy E_p = 0.81 mJ, E' ≈ 11.3 MJ/kg of the layer, E^* ≈ 0.300 MJ/m^2.	Thickness of the removed (by ablation with melting) part of the scale layer δ ≈ 6.5 μm (porosity p ≈ 0.20), here total thickness

Continuation of Table 1

1	2	3	4	5	6
	mental data)	mechanical processing		Pressure of the shock wave front $P_{sw\text{-}p} \leq 2.01$ MPa. Criterion $K_{en1s} = (6.02)\cdot 0.815\cdot 0.9 = 4.41$ (accurate value) (††) (^)	of the layer was measured to be δ ≤ 30–50 μm
4.	Gray cast iron (with content of 3.5 wt. % C and with Cr fraction up to 0.45 %) [5]	Maintenance and repair of automotive equipment; the purpose of the LC-process is to remove rust from brake discs while rising the strength characteristics of the cleaned metal surface	Rust layer formed during an operation of transport equipment in humid air; $G \approx 0.065$ dm^2/s	Continuous wave (i.e. non pulsed) CO_2-type laser (λ = 10.6 μm) with maximal P = 85 W; d_s = 0.71–1.69 mm; transverse moving speed of laser beam v = 0.030–3.0 m/s; $E^* \geq 0.033$ kWh/m^2 (at the values of operating parameters P = 60 W, d_s = 0.72 mm and v = 0.9 m/s)	The thickness of the removed rust layer δ ≤ 330 μm, the final roughness of cleaned cast iron surface $R_a \approx 1$ μm, its final microhardness is up to 235–306 on the HV scale (while the hardness of the original rusty parts is 93 on the HV scale)
5.	Aluminium alloy 5754 (with Mg content 2.6 –3.6 wt. %), plate samples [11]	Metalworking; the process objective is to clean the surface of aluminium sheet before welding to improve a quality of the welding joints	Removal of Al_2O_3-based oxide film from the alloy plate surface; $G \leq 0.06$ dm^2/s	Solid-state pulsed laser with λ = 1064 nm with P = 40–100 W, laser beam scanning speed v = 0–12 m/s. In used optimal regime: f = 120 kHz, t_P = 100 ns; d_s = 0.050 mm, v = 12.0 m/s; pulse energy E_p = 0.833 mJ, $E' \approx 20.9$ MJ/kg of the layer, $E^* \approx 0.1667$ MJ/m^2. Pressure of the shock wave front $P_{sw\text{-}p} \leq 3.2$ MPa. Criterion (approximate value) $K_{en1s} \approx$ ≈ 6.13 (††) (^)	Thickness of the removed (probably due to ablation and at least partly due to other mechanisms (i.e. spallation, SW)) part of the oxidic layer δ ≈ 2.0 μm
6.	Near-alpha titanium alloy TA15 (Ti–6Al–2Zr–1Mo–1V), sheet form samples with δ = 2 mm [7]	Preparation of oxidized surfaces of parts for aerospace and medicine applications for subsequent processing, including welding; the cleaned metal surface has better corrosion resistance	Removal of oxide film (from a mixture of phases of anatase and other oxides) and traces of oil stains from the surface of the alloy samples. At the LC-process G = 0,0008 dm^2/s	Solid-state YAG:Nd pulsed laser (IPG Photonics, USA) with λ = 1064 nm at beam scanning speed 0–12 m/s. In optimal used operating regime: f = 10 kHz, t_P = 100 ns; d_s = 0.800 mm, v = 0.01 m/s; pulse energy E_p = 40.01 mJ, $E' \approx 232.6$ MJ/kg of the layer, $E^* \approx 50.01$ MJ/m^2. Pressure of the shock wave front $P_{sw\text{-}p} \geq 12.0$ MPa. Criterion (approximate value) $K_{en1s} \approx$ ≈ 108.2 (††) (^)	The best surface properties were obtained in the optimal LC-regime with ablative removal of the oxide film (at laser beam speed of 0.005 m/s): the degree of oxidation and roughness of resulted surface were 2.08 wt. % and 37 μm, respectively. For removed (most likely with thermal ablstion) film δ ≈ 50 μm
7.	Alpha-beta titanium alloy TC4 (i.e. T–6Al–4V) plate samples with δ = 4 mm [33]	Metalworking; the purpose is to clean the surface of the alloy parts before welding and other technological operations.	Removal of TiO_x film to avoid such undesirable effects as porosity in the weld on products manufactured from the alloy, reduced mechanical properties, conductivity and weakened bonding of the plating with TC4-substrate. At the LC-process $G \leq 0.045$ dm^2/s	Solid-state pulsed laser with λ = 1064 nm with average P = 30 W, beam scanning speed 0.5–10.0 m/s. In used optimal operating regime: $f \approx 500$ kHz, $t_P \approx 5.0$ ns; d_s = 0.050 mm, v = 9.0 m/s; pulse energy E_p = 0.06 mJ, $E' \approx 5.19 \pm 1.04$ MJ/kg of the layer, $E^* \approx 0.067$ MJ/m^2. Pressure of the shock wave front $P_{sw\text{-}p} \leq 32$ MPa. Criterion (approximate value) $K_{en1s} \approx 2.41$ (††) (^)	When the scanning speed at the LC is 9.0 m/s, oxygen content reaches its lowest value of 4.54 wt. % (i.e. the transformation of TiO_2-phases to ~$TiO_{0.25}$ was carried out). The oxide film was removed, and substrate is exposed. LC-process can improve the hardness and corrosion resistance of metal surface. Exfoliated TiO_x-fragments were found after the LC at regimes with $v \geq 9$ m/s. For the removed (at parallel thermal ablation and other deoxodizing mechanisms realization) film δ ≈ 2–4 μm
8.	Copper alloy (plate samples of museum storage,	Restoration of monuments containing elements of copper and its alloys, as well as cleaning	Oxidized layer of increased thickness, which contains cuprite (Cu_2O) and tenorite (CuO) phas	The following systems were used for LC-process: 1) pulsed YAG:Nd laser Smart Clean 2, and 2) ytterbium pulsed fiber laser Mini-Marker2 M20 with maximum output power 20 W, both lasers with λ = 1064 nm. In the optimal	The problem of undesirable changes in the oxidized copper surface layer with the transition of the Cu_2O phase to the CuO phase of black or gray color

End of Table 1

1	2	3	4	5	6
	consisting of Cu with admixtures of As, Pb, Fe (~0.1 %)) [14]	of oxidized surfaces of industrial copper-based metal products/parts	es; G = 0.003 dm^2/s	LC-regime (with use of the Mini-Marker2 M20 laser) the energy consumption was: $E^* \approx 0.132$ MJ/m^2 in the mode with f = 20 kHz, t_P = 100 ns; d_s = 0.050 mm, v = 0.60 m/s and E_p = 0.20 mJ. Pressure of the shock wave front $P_{sw\text{-}p} \leq 1.6$ MPa	(it is a by-effect during LC of the copper surfaces) is eliminated using LC-processing in the conditions with protective nitrogen environment
9.	Thermally oxidized (in air) copper (99.99 % pure), plate samples [3]	Cleaning the surface of copper layers of components of semiconductor microelectronic products	Oxidic layer (CuO and Cu_2O phases) with thickness ~1 μm; $G = 10^{-4}$ cm^2/s (at the LC with femtosecond pulse laser)	System based on solid-state femtosecond-pulsed laser with λ = 800 nm; range of Q = 1.7–4 kJ/m^2 (optimal level – 3.1 kJ/m^2 (it is threshold value for complete removal of the oxidic layer)) in pulsed regime with f = 1 kHz, t_P = 50 fs, square laser spot area of 100 $μm^2$; $E^* \approx 3.10$ MJ/m^2 (at the optimal total number of pulses (n = 1000) per unit surface area)	Femtosecond LC is preferable because it reduced the thickness of the oxide layer by 99 % to ~20 nm without by-effects. LC-variant with nanosecond laser either does not remove the entire layer or has a negative effect (formation of secondary oxidic layer of ~0.15 μm)

Nomenclature: K_{en1s} values are determined taking into account an absorptance value for the oxidic surface A; (^) – the values are obtained with taking into account the degree of conservation of the laser beam energy during its propagation/motion through the near-surface plasma Λ (≈0.90) [27]; †† – calculated with the use of the enthalpy difference value ΔH_2 (at ΔH_2 = 1.88 MJ/kg – on energy consumption for heating of the Fe_3O_4 phase (and 3.41 MJ/kg – on energy consumption for heating of α-Al_2O_3 phase and ~2.15 MJ/kg (for TiO_2 phases (at the titania oxidic material with ρ ≈ 4300 kg/m^3 [27])) – up to melting temperature (including the phase transition).

Our comparison of estimated values of operating parameters (including the values of cleaning rate G during the LC-process) and the energy consumption levels for a number of recent technologies for laser surface deoxidizing of a few steels and low-alloy metal alloys (based on the data of Table 1) demonstrates that it can be supposed with a sufficient reliability that for the most typical LC-processing cases (preliminary studied in our laser experiments with cleaning steel samples from mill scale and also described for LC-processes with different oxides removal from metals, for example in the data [1, 4, 5, 7, 8]), the first, i.e. the most energy-consuming (ablation with heating to the melting temperature or even higher) of the cleaning mechanisms is more probable. For this processing group the level of the energy criterion values achieved in our experimental series with the LC of FeO_x-scale ($K_{en1s} \approx 4.4$ (accurate vale) and corresponding approximate value (without taking into account the effect of the A and Λ coefficients) can, according to our kinetic estimates (based on the approach [30–32]), be considered close to the threshold level, below which (according to the values of K_{en1s}) not only the LC thermal ablation will be realized in parallel, but also the other two deoxidizing mechanisms with comparable intensity. At the same time active realization of other, i.e. non-ablative mechanisms is feasible in a rarer group of LC-operating cases (for example, in the published study of the authors [33] on laser removal of TiO_x-film from the corresponding alloy, and also, possibly, in the regime of alumina removal from aluminium alloy 5754 [11] for which the K_{en1s} level is probably equivalent to the "transition zone" with substantial contribution of both non-ablative mechanism(s) and thermal ablation during laser cleaning process).

CONCLUSIONS

1. The values found for the specified group of the efficiency parameters of laser erosion deoxidizing of the analyzed group of surface oxidic layers on the commercial grades of carbon steels and low-alloy non-ferrous alloys gave an opportunity to estimate the degree of prevalence of one of the possible mechanisms of MeO_x-layer removal during LC.

2. A comparison of estimated values of operating parameters (including the values of cleaning rate during the LC-process) and the energy consumption levels (K_{en1s}, etc.) for a number of recent technologies for laser surface deoxidizing of a few steels and low-alloy metal alloys shows that it can

be supposed with a sufficient reliability that for the most typical LC-processing cases (investigated in our laser experiments with cleaning steel samples from mill scale and also described for LC-processes with different oxides removal from metals, for example in the published data for LC of the steels, cast iron, Ti- and Cu-based alloys), the ablative, i.e. the most energy-consuming of the cleaning mechanisms is more probable.

3. The realization of the non-ablative physical mechanisms is probable in rarer cases of technological regimes, such as laser removal of some TiO_x- and Al_2O_3-films [33, 11]. It is shown that a collation of the levels of these special characteristics for different LC variants allows to select approximately the most energy-efficient processing regimes for oxidized layer removal from metal substrates, and there is some potential for decreasing energy consumption for a number of LC modes with decomposition of zones with iron- and other metal oxides.

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