

New reinforcing technique of alumina coatings on steel substrates

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Alumina protective coatings were made on steel samples by pulsed laser deposition. Improvement of the thermal shock resistance of the steel is the main purpose of such a steel coating. The adhesion of the aluminum oxide thin layer on the steel base was increased by a whole new technique. Thus, microdimensional holes were done in the coating by a pulsed Nd:YAG laser. The characteristics of the laser and the geometry of the experiment were analyzed and they were chosen and used in order to have a cylindrical shape of the holes and also with the purpose that the laser spot would reach the steel substrate. Thus, small columns of steel emerged through the holes, reinforcing the coatings.

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1. Introduction

Nowadays materials are continuously being developed and improved, blending a wide spectrum of technologies. Steel continues to be the most appropriate choice for many fields in Industry. Still, there are many improvements necessary to be made in order to comply with the specific requirements of each particular industrial application. Along the years, specialists tried to improve steel by using different alloying methods, different composition and/or post-preparation treatments.

One of the most exciting evolutions of all materials happens in ceramics engineering. Ceramic materials and ceramic coatings take advantage of their wear and corrosion resistance, which is beneficial in pumps, valve parts or nozzles, while their thermal shock resistance is useful when making engine parts.

In a previous paper [1] we reported on structural characterization of nickel /alumina nano-particles composite coatings.

Steel coating is an alternative method for steel alloying that can be used to make steel and also other metallic alloys better for different goals, such as mechanical, thermal and/or corrosion resistance, which would allow them to be better used and for a longer time duration.

Thus, double and multi-layer ceramic coatings deposited by PLD - *pulsed laser deposition* or other techniques represent the objective of many national and international research groups, including our group of authors.

The aluminum oxide (alumina) is the most widely used type of ceramic, because it represents a material with superior properties compared with the ones of other oxidic

ceramics, due to its composition, phase structure and texture of the ceramic body (shape, size and distribution of grains).

One significant difference between ceramics and metals is that in ceramics bonding is ionic and/or covalent. As a result, there are no free electrons in ceramics. So, they are generally poor conductors of electricity, but are frequently used as insulators in electrical applications. Because ionic and covalent bonds are extremely strong, ceramic materials are intrinsically stronger than metals. Because of their more complex structure, the ions/atoms in a ceramic material cannot be easily displaced under the action of external forces. This rigid bond structure confers high temperature stability, resistance to chemical attack and resistance to absorption of foreign substances. However, as a consequence of this rigidity, rather than bending to accommodate external forces, ceramics tend to fracture in a brittle manner. This brittleness generally limits their use as structural materials, but efforts are under way to improve this feature by several innovative ideas, such as the ones presented in this paper.

If a steel sample is covered with an aluminum oxide layer, then this coating acts as a very stable barrier, because the aluminum oxide is insoluble in a variety of external media or environments, thus ensuring to the steel substrate a long lasting corrosion resistance. Alumina also exhibits a very good adhesion on metals and alloys. This means that it bonds strongly to the substrate that it is protecting. Thus, for the α -Al₂O₃ coating, stud pull tensile tests have determined that the cohesive strength of this coating and the adhesive strength of the α -Al₂O₃/substrate bond are each greater than for other oxides [2, 3].

There are also other advantages of the alumina layer deposited onto steel surfaces, such as: 1. being shining; 2. having a good abrasion resistance; 3. electric insulation – since the aluminum oxide is a dielectric, having the breakout voltage ranging from several Volts till thousands of Volts, as a function of its thickness; 4. increases the wear resistance of the substrate material.

In order to build fast and high-quality coatings on steel, with good adhesion and improved thermal and corrosion resistance, a technique is proposed here consisting in PLD-coating with alumina of steel workpieces, followed by their laser drilling in such a manner that columns of the basis material, namely the ferritic phase from the steel substrate would melt and emerge through these holes. This columnar structure is thought to reinforce the alumina coating on steel. Following the results and the study of the performances attained with such a technique, another alumina coating will be electrodeposited on top of the first one. This final multilayer, sandwich-like, interiorly porous structure is intended to improve the corrosion resistance not only for the OLC 45 steel workpieces that were used, but also for other types of steel, in view of their multiple industrial applications. Alumina coatings were performed by PLD, by means of a Nd: YAG laser device. Also, the drilling of the structure was done by another properly chosen Nd: YAG laser.

2. Theoretical approach – review

Thermal stress appears after sudden temperature changes of a material that would induce mechanical deformations leading finally to cracks and destruction of that material. There can be many causes of thermal stress, such as the conditions of the heat exchange between the sample and the environment, the stopping of dilatation or contraction of the ceramic body submitted to temperature changes due to other factors, the mismatch between the thermal dilatation coefficients of the phases contained by the ceramic materials, etc. The thermal shock resistance is considered good enough whenever the coating resists to a definite number of thermal cycles (heatings and subsequent coolings) without being significantly deteriorated.

Alumina coating of steel samples offers a good alternative to other techniques used in order to improve the thermal shock resistance of steel and PLD is one of the best choices. Furthermore, steel-filled holes drilled by laser pulses into the alumina coating improve the adherence and reinforces the coating.

Since Maiman invented it in 1960, laser has been used for multiple applications in Industry and Science. Lasers proved to be especially effective for high speed material processing and material removal. A focused laser beam can be easily concentrated onto small targets even of micronic dimensions. The interaction between the material and the laser can be controlled by some of the laser's parameters, such as its pulse energy, wavelength and pulse duration, which determines the peak power density. Proper

choice of the previously enumerated parameters can make the laser pulses suitable as a very useful tool for ablating, cutting, drilling, shaping, annealing, hardening, etc of various materials [3].

The physical processes in laser - material interaction is very important for understanding the capabilities and the limitations of laser machining processes. When a laser beam strikes on a target material, part of its energy is reflected and part of it is absorbed. The absorbed energy heats up the target. The absorption and the reflection of the laser radiation have resonant features, such as the laser's wavelength, due to the microstructure of the materials and its electromagnetic properties.

The first step in modeling laser machining is the description of the laser energy and its temporal and spatial distribution in a pulse. The laser parameters that should be known in this modeling are: wavelength, intensity, power, pulse energy, divergence, depth of focus, profile of the unfocused laser beam, profile of the focused laser beam, polarization and minimum focus spot size.

2.1 Laser ablation

Laser ablation is a materials-processing technique that was born soon after laser's invention. *Pulsed laser deposition* (PLD) is an application of laser ablation consisting in thin films deposition based on the removal effect of an intense laser radiation focused onto targets of interest, in order to evaporate small amounts of material.

The experimental principle of coating a substrate by the material ablated from a target by a proper laser radiation is presented in Fig. 1. The experimental device contains a laser, a reaction chamber, a target and a substrate. The pulsed-laser deposition contains 3 big stages: 1. the laser-target interaction; 2. the formation of typically-shaped laser plasma, known as plume; 3. the condensation of the film on the substrate.

Thus, PLD happens as follows. High energy laser pulses focused on a target are absorbed in the target surface in a small volume. The absorbed energy density is sufficient to break any chemical bonds of the molecules within the volume. Thus, a high-pressure gas is produced in the surface layer. As a result of the pressure gradient, a supersonic jet of particles is ejected normal to the target surface, forming plasma known by the name of *plume*, after its plume-like typical shape, at approximately 50 microns from the target. This plasma is completely ionized and its brightness is due to the fluorescence and the recombination processes that take place within it. Even that the characteristic lifetimes of the atomic transitions are around a few nanoseconds, the collisions within the plasma can re-excite the atoms, such as their emission lines can be observed even after many microseconds after

the incidence of the initial laser pulse. The particle cloud absorbs a large amount of energy from the laser beam producing an expansion of the hot plasma (plume) through the deposition chamber [4-7].

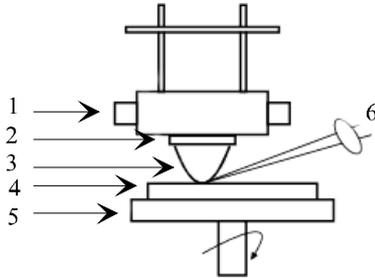


Fig. 1. Scheme of the principle of laser ablation (1-substrate heater; 2 – substrate; 3-plume laser plasma; 4-ablation target; 5-rotatable target holder; 6-laser radiation).

The material ablated from the target is transported to the substrate by the expanding plasma either in vacuum or in an inert or reactive atmosphere. The ablated atoms or molecules condense on the substrate placed opposite to the target, thus forming a thin film after some hundreds or thousands of laser pulses [5-8].

In the particular case of the oxides, the oxygen atmosphere is preferable, because it allows for compensation of the possible sub-stoichiometry of the deposition. What it is necessary to be considered is that the plume plasma has different behavior with respect to vacuum as compared to an ambient gas present in the ablation chamber. Thus, in vacuum the plasma doesn't expand unidimensionally and the atomic species ejected from the target diffuse in the plasma, collide between them, which leads to a fast thermalization of the cloud of particles [8].

The density energy in J/cm^2 of the laser pulses, known as *fluence*, the wavelength, pulses repetition frequency or duration of the laser pulse influence the ablation process and the subsequent thin film deposition and thus, they are chosen as a function of the physical properties of the target and of the desired properties of the films to be deposited. The essential condition is that the target has to be able to absorb the laser radiation. Also, the substrate's temperature strongly influences the morphology, the microstructure and the crystallinity of the deposited films [5-8].

2.2 Drilling holes with laser radiation

Besides ablation, the possibility to produce high-energy laser radiation made laser devices also useful for welding, drilling, cutting, heat treatment, medical surgery, etc. One of the main advantages of laser cutting is its ability to cut easily even very hard materials, such as ceramics, since they are among the most difficult materials to process by conventional machining techniques, because of their hardness and brittleness. Laser drilling is also one

of the oldest applications of laser machining processes. Some of the best motives to choose a laser to drill holes are the precision that can be easily controlled in drilling holes, the edge quality of the material's surface, the quality of the inner holes walls and the high reproducibility in the micrometer range. Thus, laser drilling proves to be an inexpensive alternative to mechanical holes drilling methods for various industries as semiconductor manufacturing, nanotechnologies and medical device industry [9-11].

The sizes of the laser drilled holes vary depending on the laser power, motion control, etc. It also allows for dynamic, "on-the-fly" changing of the parameters of the holes (sizes, shape, etc.). Depending on the laser drilling application, there are 5 methods that can be used: single pulse, percussion, trepanning, helical drilling and laser-micromachining [9-11]. Each method depends on depth requirement, diameter of the holes, number of holes to be drilled, edge quality and production quantity.

Percussion laser drilling uses a "rapid-fire burst-of-pulses" micromachining method. By properly adjusting the laser pulse duration, its spot size, optics and beam characteristics, high-quality holes can be drilled, with minimum residue and consistent edge quality from entry to exit point. Percussion laser drilling evaporates the target material layer by layer. Percussion is particularly suitable for metals and ceramics. Instead, trepanned laser drilling is a method used to remove a cylindrical core or a circular disc from the target.

Usually, Nd: YAG lasers with pulse lengths of several tenths of milliseconds are used to drill holes when a certain degree of inaccuracy of diameter and shape, as well as thin recast layer can be tolerated. Means to increase precision include reduction of pulse length and improved machining techniques. Laser intensity distribution has influence on the shape of the holes, but also a lot of other factors are involved, especially the properties of the target material and their change during the drilling process.

In laser drilling, material is removed from the target as a mixture of melt and vapor, whose distribution depends both on the properties of the material and on the laser intensity and its spatial and temporal distribution. A large amount of melt is advantageous for the efficiency of the process, but, on the other hand, if the layer of melt is thicker, then the geometry of the holes has to suffer for lack of precise shape and/or reshaping.

Given the laser pulse duration, one can estimate the depth L of heat penetration (i. e. the distance that heat can be transferred to during the laser pulse), which is proportional to the quantity of material melted from the target, from the next formula [11]:

$$L = 2 \cdot \sqrt{\kappa \cdot t_p} \quad (1),$$

where κ is the thermal diffusivity (m^2/s as SI unit) and t_p is the pulse duration, which has to be greater than 10 ps in order to have a correct formula. The thermal diffusivity is a measure of transient heat flow and is defined as the

thermal conductivity divided by the product of specific heat times density [12]:

$$\kappa = \frac{k}{c_p \cdot \rho} \quad (2),$$

with: k - [thermal conductivity](#) (in W/(m K)); ρ - [mass density](#) (in kg/(m³)) and c_p - [specific heat capacity](#) (in J/(kg K)).

Thus, thermal conductivity, density, heat capacity and thermal diffusivity are the parameters that mainly influence the heat conduction into a target material and, subsequently influence the laser pulse penetration when drilling holes or cutting the material. Since laser machining involves strong phase changes, the property variations with temperature should also be considered. Other influencing properties are the melting and the vaporization temperatures, melting latent heat and vaporization latent heat, respectively.

In detail, it happens as follows. Under the action of proper laser irradiation, the surface quickly rises up to the melting temperature. This melting expands through heat conduction. For welding, maximum melting without vaporization is desired, but this happens in a very narrow range of laser intensity and pulse durations. If the laser intensity is too high then the surface starts vaporizing before a significant melting depth of molten material is formed. However, in laser machining vaporization is preferred. Thus, higher intensities of laser radiation than the ones used for welding are focused on the targets such that both melting and vaporization coexist and the material is removed from the target through ablation. The most common regime for laser drilling and cutting is ranging from 100 μ s to 10 ms. This time scale allows the surface to heat to the vaporization temperature and to remain there for some time. When vaporization occurs, it generates a pressure called recoil pressure [9]. Temperature gradients are also present in the molten material, the center being hotter than the outer part of the hole because of the intensity profile of the laser beam. The recoil pressure and the temperature gradient drive the molten material out from the target.

The laser energy transmitted to the material at depth z is given by the next formula [9]:

$$I(x, y, z, t) = A \cdot I_0(t) \cdot e^{-\alpha \cdot z} \cdot SP(x, y) \quad (3)$$

where A is a coefficient considering surface reflection and plasma absorption, $I_0(t)$ is the temporal distribution of laser intensity, α is the absorption coefficient and $SP(x, y)$ is the spatial distribution of the laser intensity.

The best holes are drilled when the right choice of combination of pulse energy, wavelength, pulse duration and pulse repetition frequency is selected. In order to remove bigger amounts of material from the target, a high peak power is recommended to create the required vapor pressure, but with a very short pulse duration. As it is known, the peak power P_p is related to the pulse energy E

and the pulse duration t , according to the following formula [13]:

$$P_p = \frac{E}{t} \quad (4)$$

The irradiance I_0 , i. e. the concentration of the laser power on the surface of the target material can be calculated according to:

$$I_0 = \frac{P_p}{A} = \frac{E}{t \cdot A} \quad (5)$$

where A is the area of the focused spot, formula from which one can determine many laser settings required to drill holes with the help of laser pulses [13].

The required value for drilling purposes of laser pulse energy is determined by the composition and the thickness of the target material and by the diameter of the holes to be drilled. Higher pulse energy implies faster drilling rates, but this would also imply a lower quality of the obtained holes.

The spot size is directly related to the diameter of the holes to be drilled. For thin materials the size of the hole is equal to the laser spot size, but if holes are to be drilled in thicker targets, then the range of the diameters of the holes that can be percussion drilled decreases. The focusing lens determines the spot size for a given laser setup. Thus, for larger holes and thicker target materials imply the use of longer focal length lenses.

Laser focus control is a key figure along with other characteristics of the laser pulses with respect to the shape of the laser-drilled holes [14, 15]. The shape of the holes is strongly influenced by the focal position of the laser beam that can be optimal either above, below or on the surface of the target, depending on the result to be obtained, as one can notice from the next figure. Most often focus lies between 5 and 15 % of the metal's thickness, below its surface. Best focus for a desired result will most often be determined empirically following the evaluation of the quality of the holes (i. e. roundness, taper, recast and microcracks).

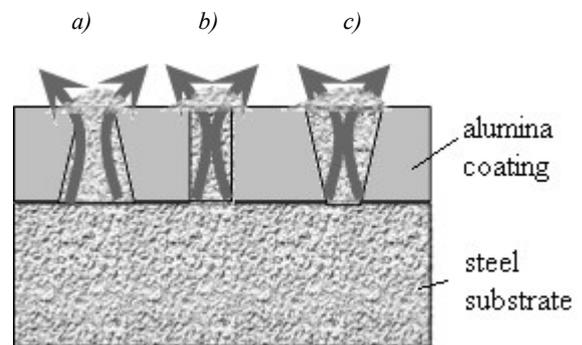


Fig. 2. Possible shapes of holes as a function of the distance between the target to be laser drilled and the focus point of the laser beam: a) too far; b) medium distance; c) too close.

The drilling process was investigated for different ceramic materials. The energy density at the focal position influences the diameter of the drilled holes, the removal depth per laser pulse, the time for drilling through the material and the maximum depth of a hole. The energy density can be easily varied by changing the pulse repetition rate. At higher pulse repetition rates the pulse energy decreases.

Similar to ablation, the removal depth per pulse has a maximum value at a material's specific energy density. The best results are obtained at lower intensities, because higher intensity causes a damage of the surrounding material. Microcracks formation near the drilled holes is another problem encountered in laser drilling of ceramics. Cracks are induced by rapid heating during laser processing, which causes large temperature gradients near the surface of the hole. Microcracking can be minimized by preheating the target material to an elevated temperature prior to laser drilling or cutting, such that the temperature gradients achieved during machining will be significantly lower compared to the ones appearing when a cold target is laser machined [15].

3. Experimental – proper choice of devices and results

As we mentioned before, the proposed technology consists in building up a vertical sandwich-like structure at the surface of some OLC 45 steel bar (10X10X3 mm³). This overlapped structure is obtained by PLD alumina coating of the steel workpieces followed by drilling nanodimensional holes into the structure. Then, another alumina coating will be electrodeposited onto the previously-described structure.

3.1 Laser ablation - experimental

First part of the research project consisted in PLD (pulsed laser deposition) of alumina coatings onto steel samples.

The proper choice of the laser system capable to perform this action was a preliminary source of analysis. The laser we used for ablation-deposited thin film was a Q-switched high power Nd:YAG laser, with 266 nm laser wavelength.

This kind of laser has applications in a wide range of fields, from Medicine to Military technique, from environmental science to process control, for scientific and applicative research.

This laser's typical emission wavelength is in the infrared domain, at 1064 nm; it also has other weaker emission spectral lines, at 940 nm, 1123 nm, 1320 nm and at 1440 nm, respectively. Since shorter wavelengths are to be desired when using a laser for ablation, by using the SHG – second harmonic generation technique in one or even two successive steps, one can get from 1064 nm to 532 nm and 266 nm, respectively. This last value was the one we used in our research to deposit the alumina by PLD onto steel samples.

The typical bloc diagram for a device delivering 266 nm laser radiation with the help of a Nd:YAG laser is presented in Fig.3, containing two SHG devices and an acousto-optical modulator AOM, in order to operate the laser in the Q-switched mode, which determines an important increase of the laser's peak power. The scheme also contains a pre-amplifier before the first SHG stage. Frequency selectors are, also, generally used to precisely select only the wavelength to be further used [17].

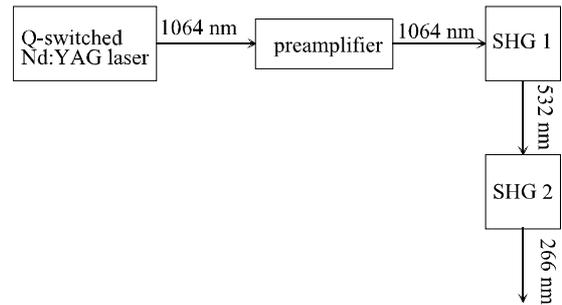


Fig. 3. Bloc scheme of a device delivering 266 nm laser radiation from an initial Nd:YAG laser.

The scheme of the experimental device used for alumina deposition onto steel substrates by laser ablation is presented in Fig. 4, where: 1-laser device; 2-pulsed laser beam; 3-focusing lens system; 4-quartz window; 5-rotatable substrate holder; 6-laser ablation plume; 7-target; 8-vacuum chamber; 9-rotatable target holder ; 10-towards vacuum pumps [5, 8]. As it can be noticed, this experimental arrangement is of the static laser beam type. Both the target holder and the substrate holder can be rotated around an axis perpendicular to their surfaces. The uniform ablation of the target is ensured by its rotation and by movements of the substrate with respect to the plume plasma (e. g. by eccentrically rotating the substrate holder). The angle θ between the direction of the incident laser beam and the target can be also adjusted. Also, the substrate can be brought closer or further relative to the target. The distance between the target and the substrate is, generally in the centimeters range.

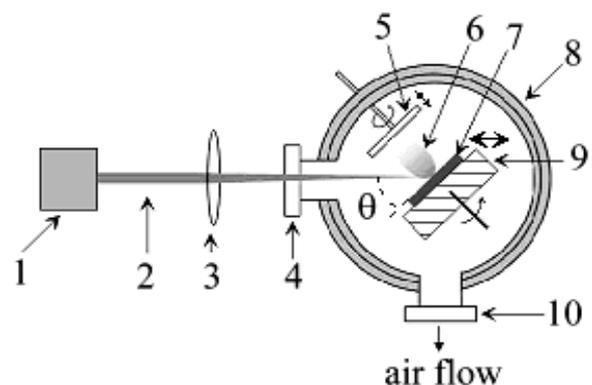


Fig. 4. Schematic diagram of a pulsed laser ablation of a solid target onto a substrate.

Fig. 5 a) and b) show the images of a steel sample mounted on the special device of the ablation chamber before and after the alumina deposition, respectively.



Fig. 5. Steel sample on the holder of the PLD device: a) before and b) after the alumina PLD deposition.

Table 1 contains the main experimental data of the alumina coating of OLC 45 steel samples performed by laser ablation, in an oxygen atmosphere. The targets consisted in alumina Al_2O_3 and steel specimen as collecting substrates. A distance of 4 cm between the target and the substrate was found as optimum. The repetition frequency of the laser pulses was set at 10 Hz, at laser radiation energy of 25 mJ and an energy density of 3.3 J/cm^2 . The working value U_{flash} of the tension for the flash lamp used to pump the Nd: YAG laser ablation source was of 1.5 kV. The area of the focused laser spot was set at 0.75 mm^2 on the alumina targets. The duration of each deposition was one hour; thus, 36,000 pulses were used for each alumina coating of the steel samples, in an oxygen atmosphere [13, 18-20].

Table 1. PLD coating experimental data.

Target	p (mbar)	$p_{p \text{ oxygen}}$ (mbar)	t ($^{\circ}\text{C}$)	Oxygen flow capacity (sccm)
367 Al_2O_3	$2 \cdot 10^{-5}$	$1.3 \cdot 10^{-3}$	500	10
368 Al_2O_3	$3.7 \cdot 10^{-5}$	$1.1 \cdot 10^{-3}$	500	10
369 Al_2O_3	$6 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	500	10
370 Al_2O_3	$1.6 \cdot 10^{-5}$	$9 \cdot 10^{-3}$	300	30

The meanings of the terms from the table are: p (mbar) – pressure in the laser ablation chamber, after vacuuming; $p_{p \text{ oxygen}}$ – oxygen partial pressure (oxygen is introduced as surrounding gas into the chamber); t (500°C) is the temperature maintained for the steel samples used as substrates; Oxygen flow rate is expressed in the vacuum chamber in sccm (standard cubic centimeters per minute - cm^3/min); standard conditions imply zero degrees Celsius and 760 torr pressure.

3. 2 Laser holes drilling - experimental

Comparisons made between the capacities of several laser devices used for micromachining applications showed that the pulsed YAG laser is one of the best choices for laser thick layers drilling or cutting metallic or non-metallic materials.

In order to obtain a porous structure into the alumina coating, whose thickness was around 1000 nm, another laser device type Nd:YAG was used, namely the KVANT 17 laser device, which is destined for cutting and welding. Figures 6 a) and b) present on the whole and close-up pictures, respectively, of this laser device, where: 1-optical resonator; 2 – glass rod as active medium; 3 – metallic pumping cavity, water cooled; 4 – flash lamp for laser pumping.

The scheme of the experimental device with the KVANT 17 laser is given in fig. 7, where the numbers signify: 1 - command and controls unit; 2 – power and frequency adjustment unit; 3 - YAG:Nd active medium; 4 – unfocused laser radiation; 5 – objective lens; 6 – deviation mirror; 7 – cable for laser pulses command; 8 – PC display; 9 – PC central unit and work program; 10 – cable for step by step motor movement command; 11 – protection interface (galvanic separation); 12 – xy mass contact cable; 13 – sample; 14 – xy mass; 15 – xy mass holder; 16 – lasers unit; 17 – energy supply of the pumping lamp; 18- direct current energy supply.

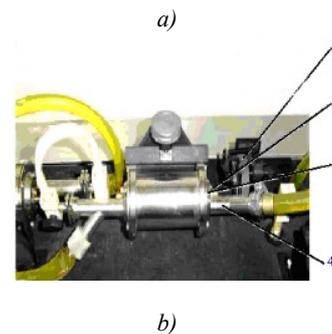


Fig. 6. a) On the whole-view and b) Close-up view of the KVANT 17 laser device.

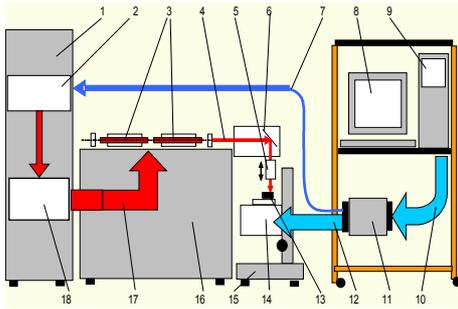


Fig. 7. The scheme of the experimental device with the KVANT 17 laser.

The laser used for drilling holes into the alumina coating of steel samples has the following characteristics, that make it suitable for our purpose: 1) a solid active medium of YAG:Nd ($Y_3Al_5O_{12}$ - yttrium and aluminum granate), with 6.3 mm diameter and 100 mm length; 2) 1060 nm wavelength (in the Infrared); 3) 2-5 ms pulse duration; 4) 1 - 20 Hz pulse frequency; 5) 50 mm focal distance of the objective lens; 6) 0.3 – 1.3 mm diameter of the focusing spot; 7) 8 J pulse energy; 8) 600 mm /minute cutting speed. Since the pulse durations are shorter than normally-used this implies the use of higher laser energy, as the value of 8 J it was mentioned.

The sample with the alumina coating was placed on a horizontal table with 3 freedom degrees – see fig. 8. Two of them allow for the table to be horizontally displaced, by means of a booster, controlled by dedicated computer software, while the third one, which is vertical (after Oz axis) allows to establish the optimum position of the alumina coating with respect to the laser beam used for drilling. The displacement step p could be changed according to the formula:

$$p = n \cdot 0.06 \text{ (mm)} \quad (n = 1, 2 \dots) \quad (6)$$



Fig. 8. Close-up picture of the experimental arrangement for laser drilling.

After each laser irradiation a crater resulted in the coating. The laser power was set such as the laser beam would perforate the alumina coating and would melt a small enough quantity of the ferrite phase from the steel substrate that would fill the crater. Thus, columns-like structure was performed into the alumina coating, whose role is to reinforce the coating.

One important consideration in laser drilling of ceramics is the energy required to initiate drilling. The threshold energy density value is defined as the energy density level below which material removal is not

possible. This threshold for energy density has different ranges according to literature, any of them being rather low for ceramics as compared to the maximum possible fluences of the laser source which is used. The fluency of the KVANT 17 laser used in the present research for drilling holes can be calculated from the values of the working parameters presented above and it ranges from 600 till 11320 J/cm² [4, 12, 14-16].

Laser power is determined by the employed pulse frequency and pulse energy. Power is limited by the duty cycle at which a laser can operate without important performance lowering. Maximum usable laser power is also limited by the power supply and the resonator design of the laser device. Percussion drilling is accomplished using average power ranging from less than 100 Watts to 400 Watts. The pulse length strongly influences the quality of the drilled holes. The most common values of the drilling-used laser pulse length range from 0.5 to 2 μ s. In the presented data, this figure is significantly higher, from 2 up to 5 ms [4, 12, 14-16].

Pulse frequency is chosen in order to reach an optimal balance between the laser throughput and the quality requirements. The pulse frequencies used for percussion drilling range from 5 to 20 Hz for Nd: YAG lasers. They are much higher, till 1000 Hz when using CO₂ lasers. As it can be noticed, the 1-20 Hz frequency range was used for alumina drilling with the KVANT 17 device.

Usually, focal length of the objective lens used to focus the laser beam onto the target ranges from 10 to 25 cm, but in the presented case was of only 50 mm.

The schematic representation of the sandwich structure that we propose is given into the next figure, where the numbers signify: 1 – steel basis (substrate); 2 – 1st alumina coating; 3 – 2nd coating, probably also alumina; 4 – laser-drilled holes; 5 – steel columns with peaks emerging from alumina.

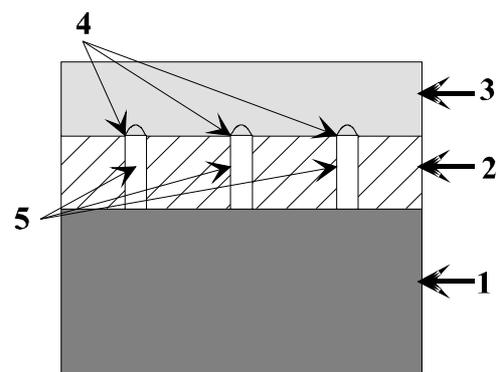


Fig. 9. Schematic representation of the proposed sandwich-like columnar structure, laser-drilled.

The SEM investigations done before and after laser drilling were performed in order to observe the shape of the obtained crater, aspect which allows adjusting the laser power in such a range that would allow for a small enough quantity of molten material to emerge through the holes from the basis substrate, namely the ferrite. Thus, Fig. 10 contains the SEM image of the PLD alumina coating.

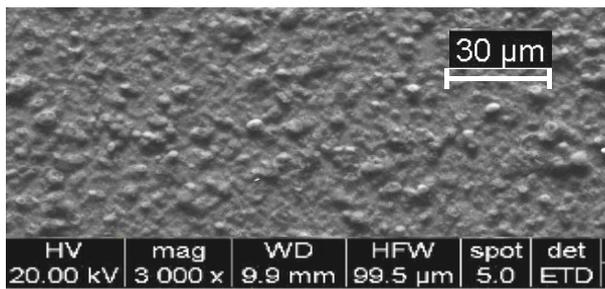


Fig. 10. SEM image of the surface of the alumina coating.

The grain sizes also influence the quality of the machined ceramic. This is because during the material removal process, not only vaporization of the material takes place, but also removal of whole grains, due to the high pressure of the vaporized material. Single grains can be detected in the area surrounding the moulds, as we obtained with SEM micrographs. Fig. 11 presents the SEM image of a crater made in the alumina coating, with several dimensional details (see also Fig. 2).

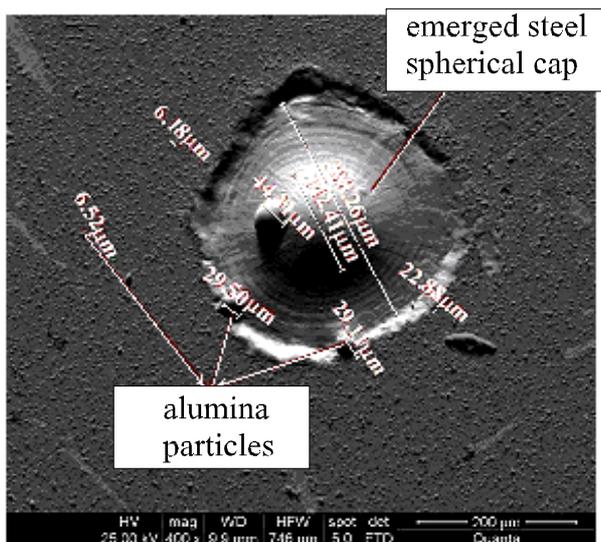


Fig. 11. SEM image of the top of a hole made in the alumina coating of an OLC 45 steel sample.

4. Conclusions and further projects

A new technique is proposed here to cover steel samples with alumina layers in order to obtain columns of steel emerging from the basis substrate, which would reinforce the structure, conferring it better thermal shock and corrosion resistance.

Initially the research assumed that the perforated net would have been realized by controlled electrocorrosion. The laser drilling finally used is much better than the initial intention. Still, electrocorrosion perforation of the

alumina coatings will be also done and the results of both methods will be compared, such as the best technique would be chosen to obtain porous structures. Then, the vertical sandwich structure will be electrochemically coated with a ceramic layer type Me_xO_y (probably also alumina). Hopefully, the final structure would have a higher structural solidity, acting both as thermal and as corrosion barrier for the steel substrate. Research will be done on the behavior of the complex structure at thermal fatigue strain up to 700⁰ Celsius, at mechanical fatigue and at corrosion stress. Special attention will be paid to study the adherence degree of the coating relative to the steel substrate, by performing scratch tests.

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