LASER PERCUSSIVE STRENGTHENING OF THE ALUMINUM ALLOYS

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Abstract

The matter of laser percussive strengthening by shock wave generated from laser pulse (LSP – Laser Shock Peening or LPS - Laser Percussive Strengthening) is presented. The building of the investigative position to making the quick photo of the laser influence with the subject was described. The idea of the registration of fast changing physical processes kinetics setting near the influence of short laser impulses with the aluminum alloys (ENAW-2017A and ENAW-2618A) was introduced. Variants were applied for enlargement of the process efficiency of laser strengthening in laboratory experiments from thin absorbing coat and inert layer (water). The tests results of the surface layer strengthening of ENAW-2017A and ENAW-2618A aluminum alloys are described. Those investigations enclose selection of strengthening parameters above named materials, measurement of: the surface topography, microstructure, micro-hardness and also fatigue investigations in restricted range for σ =180 i 350 MPa. It was confirmed essential influence of surface topography as well as created subsoil microstructure on the fatigue life of strengthening samples. Obtained research results were confirmed very beneficial influence of used surface strengthening processing on the fatigue life.

***Keywords**: laser radiation, aluminum alloys, laser percussive strengthening*

1. Introduction

As distinct from non laser radiation, laser radiation: light (ultraviolet UV, visible VUS, infrared IR), X-radiation and gamma radiation characterizes very small divergence of beam (even decimal parts of μrad), district monochromatic (emanated to 10^{-6} μm as well as coherence (compatible in phase and in the space) [2].

Thanks those properties, which do not possess light non laser radiation, laser radiation in touch with medium (material) stands out series properties, which are not possible to receipt at using another radiation. The most important property is gigantic power density, which is supplied to work material, its income up to 10^6 W/cm^2 for continuous radiation and – uniquely to 10^{11} W/cm^2 (and even more) for pulse radiation.

That power density might be supplied to zone about small and very small surface (diameter of laser spot may amount to a few of μm in the teens of millimetres) [6, 8]. In aerology laser radiation beam finds applications more or less from moment, when it was used to technological targets in machine industry for example to: cutting and welding. Opposite of laser integration and disintegration of metal materials, a laser beam was started to use also to space forming of metal materials.

Typical applications of laser beam in aerology are different technologies of the surface layers modifications: hardening (with tempering) with joint penetration and without joint penetration, alloying, pitting. Notably seldom are used technologies of laser calking of coatings and surface smoothing.

In all those Technologies is used heat influence of laser beam on material: heating to temperature of phase changes in solid state, state of aggregation change with solid to liquid state with presumptive letting out of alloying elements – and thereafter self-cooling of heating material.

The medium, which directly influence on a material is consistent photons beam, which is comprehend as work tool.

Initially in aerology to laser modification of the surface has not used of gas medium, more directly of shock wave has been formed as result of creating by photons bream of plasma cloud and its expansions. This cloud mainly was formed by ablative evaporation of work material particles (in solid state) and gas ionization.

Gas medium was started to use, with while of generating of high power lasers with pulsed action, which were applied to perforation of thin materials, holes drilling, marking, and to percussive strengthening of resilent- plastic materials.

In this case is used also heat of laser radiation action, but in indirect way: to local evaporating of material and plasma cloud generating, which already directly strengths by gas shock wave of work material and next creates shock wave , which propagates in the material.

This way of influence of laser beam on a material may call as ablative influence.

2. Pulsed influence of laser beam with a material

The laser beam influence with material depends on mutual relations of laser radiation properties and properties of work material.

Laser radiation mainly characterizes wale length λ, power density q and quantity as well as shape of laser spot d.

Pulsed radiation moreover characterizes energy value or power density in pulse $g_{e,}$

duration, frequency of pulses repetition f and number of pulses. It is important also distribution of power density in laser spot.

To laser percussive strengthening absolutely are applied lasers about pulsed work, in the main Nd –YAG laser (which generates beam about wave length λ = 1,064 μm in the infrared range as well as harmonic 0,532; 0,355 i 0,266 μm about pulse length τ = 0,1÷100 ns and pulses frequency f = 50 kHz) or excimer ultraviolet range. Energy in the pulse touches 200 J [1].

Material properties evidently depend on kind of material. For specific kind of material, the most important are temperatures of phase changes, melting point, evaporation, also radiation absorption coefficient (surface roughness, oxidation, and absorptive coating), thermal conductivity.

Close mutual overall relations between radiation properties and material properties are not known. There are known qualitative dependence between reliable properties. For example is known, that [6]:

- with increase of radiation absorption coefficient trough the surface layer of material, grows degree of material heating, but absorption of radiation depends on wave length λ and material temperature.
- with increase of power density q and duration its influence, grows degree of material heating (till evaporation inclusive);
- Gaussian distribution of power density in cross section of laser beam, especially in laser spot is advantageous for laser cutting, welding, holes drilling, but is less advantageous for aerological applications, where is required more uniform distribution.

Still it is not accurately known, how to influence on forming of pulsed plasma cloud and how it to use to strengthening different materials.

Generally is known, that condition of forming of laser percussive strengthening is ultra fast heating, which be able to get only at pulsed heating [11].

Laser pulse goes on repeatedly more curtly then typical mechanical pulse (body's collision with high speeds).

3. Laser forming of shock wave

3.1. Power density

Single laser pulse absorbed by work material can cause effects in dependence on power density or energy and pulse duration, which are named in Table 1 [4, 6]

Tab. 1. Power ranges of typical laser aerological processings

Power density [W/cm^2]	Influence on work material	Heating of work material to temperature	Zone of heat influence	Kind of laser processing
$10^3 – 10^5$	thermal	Phase changes in solid state	occurred	Hardening without joint penetration
$10^6 – 10^7$	ablative	Melting and even evaporation	occurred	Joint penetration hardening Alloying Packing Cleaning
10^8 - 10^9	Ablative (intensive)	Intensive ablation	lack	Percussive strengthening Cleaning
10^9 - 10^{10}	Ablative (very intensive)	ionization	lack	Percussive strengthening

A few or more laser pulses directed in the some place of work material cause intensification of thermal effect and none always foreseeable effects.

3.2. Pulse duration

Influence of laser pulses on the material depends not only on transferred power density (or energy density), but also on pulse duration– time of influence laser radiation on the material.

At influence of laser radiation about power density to 10^8 W/cm^2 and duration considerably, which exceeds relaxation times, (average of 10^{-9}÷10^{-11} s), heat energy, which is released at touching of beam with material, is caring away in the depth of material: its heating, melting and evaporation - depends on density of supplied energy (or power) – it runs in accordance with traditional rights of energy transition [9].

Whereas at 10^{-8}÷10^{-10} s laser pulse duration and power densities of 10^{10}÷10^{12} W/cm^2 and baggers, the pulse duration influence on the material approach relaxation time, in connection with this carry out of energy in depth of material is failed.

Very big power density in micro-area of the surface layer causes transition of material into plasma state. Heated plasma widens, are formed very big – similarly like at explosion – pressures and might arise shock wave, that is wave of strong discontinuity of gas flow parameters, which propagates in the material with bigger speed than local speed of sound. However, it forms only then, when the pulse duration is shorter than duration of propagation of shock wave in micro-area [2]. Than pressure in superficial layer of material is very big, and in the depth of material fast decreases. Non-uniform of pressures propagation is reason of shock wave formation [9].

For majority of solid bodies duration of shock wave propagation amount to10^{-5} s (at thickness of body about of 10 mm). In this cause laser pulses already about duration of 10^{-6} ÷10^{-7} s might cause formation of shock wave in the material.

At power density of 10^9 W/cm^2 and pulse duration of 10^{-8} s at absorption coefficient of incident radiations of 0,1 – values of pressures for CO_2 laser radiation amount to: 0,212·10^5 MPa for copper, 0,121·10^5 MPa for aluminum and 0,060·10^5 MPa for beryllium.

The influence of ruby laser radiation is twice more strong [10]. Nd:YAG lasers emit radiation about energy density in pulse of 100÷300 J/cm^2 and 3·10^{-9} s pulse duration and can generate percussive pressure to 10^4 MPa, so 4÷20 times higher then pressures at cold rolling (600÷7500 MPa) and 10÷100 times higher then amounts to pressure of powders die stamping compaction (100÷1250 MPa).

So high pressures bring about influence on material of mechanical stroke, which deforms surface layer and hardens of material.

Additionally next to of mechanical strengthening zone might also occur zone of heat influence (therefore zone of presumptive heat strengthening), but only at smaller power density.

At material transition in plasma state and evaporation in ambient micro-area, ionized cloud (plasma) brings about screening of work piece against laser beam. Formed plasma comes up to the surface of work material, in place of beam incidence is formed crater about shape, which is dependent on power density distribution in cross section of beam. After walls of this carter, plasma comes up to the surface and its material is strengthening by plasma pressure [15].

3.3. Emitted and absorptive radiation

Not all energy of emitted radiation by laser is absorbed by work material, but only its part, which is dependent on absorption coefficient. For metals, especially about smooth and non-oxidized surface, the absorption of radiation is small. In order to increase its – is covered a material by absorptive coating (for example: paint, gouache, soot), directly saying absorptive-protective coating or seldom – material surface is made as abrasive.

In this case absorptive coating should be enough thick and is distinguished by small thermal conductivity in the depth of material, in order to reduce material heating, but not so fat, in order that does not force of pressure pulse before reach to the surface of work material [6, 12].

As result of heating metal surface (with coating) to evaporation temperature – material of absorptive coating and the surface of external surface layer rapidly evaporates (thickness of evaporated layer brings about 0,1÷10 μm), it is formed plasma cloud and increased pressure in the cloud (figure1). In order to limit propagation of pressure wave in perpendicular direction, but from surface, before coating is located inert coating, for example in form of several-millimetres or fatter layer of water or glass, or water and glass .

Both functional elements of laser system transmit Nd-YAG laser radiation, also and deflexed from metal surface, but do not transmit of plasma cloud, which can not freely expands.

It is increased pressure in its and is formed strong shock wave, which propagates from all sides, also to work material side [3, 4, 5, 7, 12, 13, 14, 16]. Pressure wave hitting in material, deforms plastically and strengthens, additionally it propagates trough work material, comes to back wall of material, reflexes from its, comes back to work material surface, reflexes from its and again. The amplitude of wave pressure reduces until decay.

Laser radiation does not penetrate in depth of material yet, because plasma cloud screens its. The propagation of pressure wave in material accompanies formation of negative and compressive stresses.

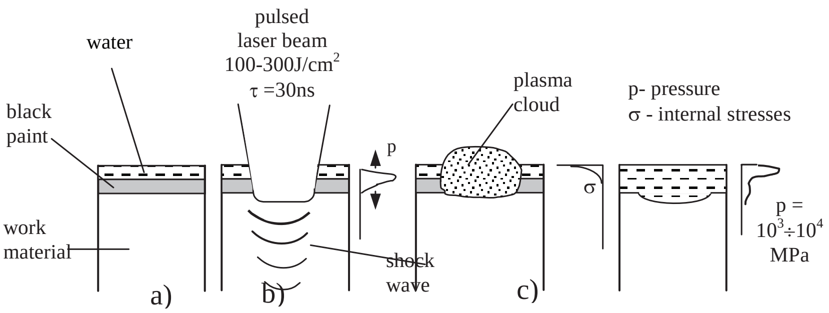


Fig. 1. Ideological diagram of percussive laser strengthening [1]: a – before laser pulse, b – during laser pulse, c – after laser pulse

At correctly lead process after laser processing in the core fall into arrears negative stresses, and in the surface layer compressive stresses, which distribution is close to distribution of stresses at classical mechanical shot peening [13].

Pulse of modern Nd –YAG laser might form plasma in gas or solid medium about temperature of $10^4 \div 10^6$ K, 1÷100 GPa pressure and duration of 5÷100 ms [12]. Application of inert layers enlarges value of maximal pressure several-times (table 2) [12].

Tab. 2. Pressure [bariums] after 100 ns from beginning of Nd -YAG laser pulse (λ = 1,064 μm) in aluminum foil about thickness of 0,6 mm (on the basic data from work [12])

Power density [J/cm^2]	Without inert layer	With inert layer / Increase multiplicity	
		Water	Rigid barrier
1	1000	3000/3	9000/9
10	4000	10000/2,5	17000/4

Absorbed laser pulses about energy density of 100÷300 J/cm^2 and duration of 300 ns, can form percussive pressure about value of $10^3 \div 10^4$ MPa [12].

4. Photographing process of interaction of laser radiation from a surface layer of aluminum alloys

The laboratory process of for photographing interaction of laser radiation with matter consisted of a V12 camera with optics, semiconductor laser 810 nm from supply system and synchronize backlight , laser Nd^{3+} YAG 1.06 μm affecting energy 400 mJ for 4 ns in the test material and mobile PC the supervising process recording. Semi- conductor laser light was brought to the blade through the fibber optics with a field observation of surface shapes with a diameter of about 5 cm. The functional pattern of the measuring position was shown on drawings 2 and 3 to making „the quick” photo together with the units of the pulling into the step of the experiment and his photo.

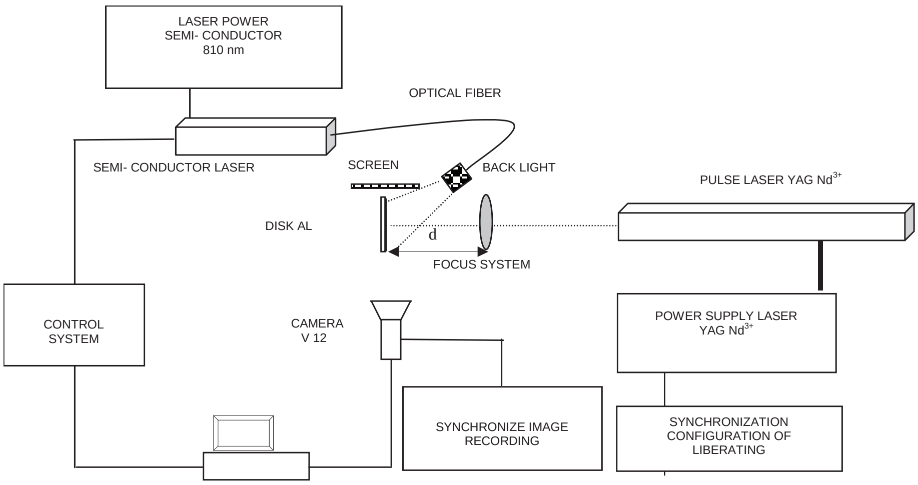


Fig. 2. Functional diagram of measuring stand to perform a "fast" photographs interaction of laser radiation with aluminum alloys, atmosphere - air, absorptive coating layer, inertial (water)

Automated measurement system is designed to capture the selected phase during the experiment, when we are dealing from a single event running in a very short time. Picture of the moulded shape and moving plasma cloud as a result of interaction of laser radiation from matter was recorded on the CCD camera followed by the Phantom V12 controlling transmitted to the onboard data acquisition system. The measuring system was working in a synchronous regime from dedicated illumination. Synchronization of shooting the next phases process of control system ensures the semiconductor laser. Results of registration have been archived in electronic form with the possibility of further processing using specialized software.

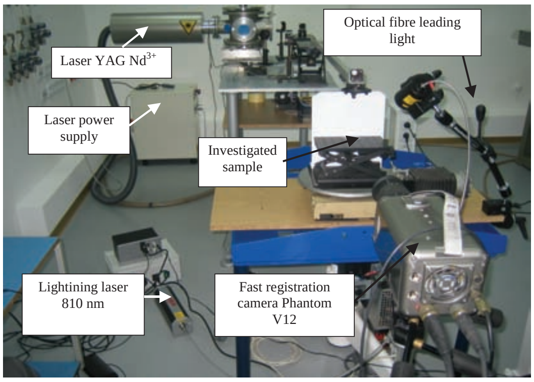


Fig. 3. Photo measuring stand to perform a "fast" photographs interaction of laser radiation from matter-coated absorber and with out absorber

The results of the experiments, a pattern observed in illustrating the duration of process of. For samples of aluminum alloy with high purity at the surface, the exposure duration of the laser plasma is three times shorter in comparison to the process observed in samples coated with varnish (Figure 4). This is probably due to the prolonged maintenance of plasma coating products, rising off the surface of the thermally loadable samples. These products are likely to be a dynamic process of heating, melting, evaporation (sublimation), which is beneficial to maintaining and extending the ionization process, thus it affects the extension of the phenomenon of generation of laser plasma.

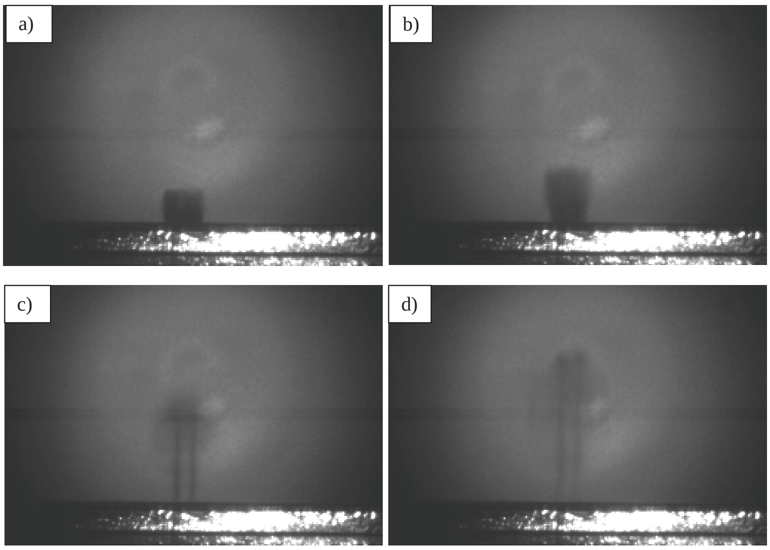


Fig. 4. The effects of the laser radiation influence Nd: YAG 1.064 μ m, 400mJ, 4 ns, the time of the exposition 200 ns, on the superficial layer of the sample from the alloy ENAW-2017A covered the black lacquer coat - the atmosphere of the air, registration after various times from the generation of the laser impulse moment:
a) after 10 μs, b) 20 μs, c) 80 μs, d) 150 μs

When the samples are covered with water the process of the laser radiation influence with the matter additionally lengthens to few hundred µs and runs very intensely (Fig. 5). The high wave of the pressure is generated in this variant from observed registrations.

5. Selected results of laser percussive strengthening

The Basic task of laser percussive strengthening technology is getting of hardness increase and connected with its fatigue life as well as abrasive wear resistance.

At this, it is necessary generation in the surface layer of compressive internal stresses felled into areas if possible deep, however with no sharp gradients of changes.

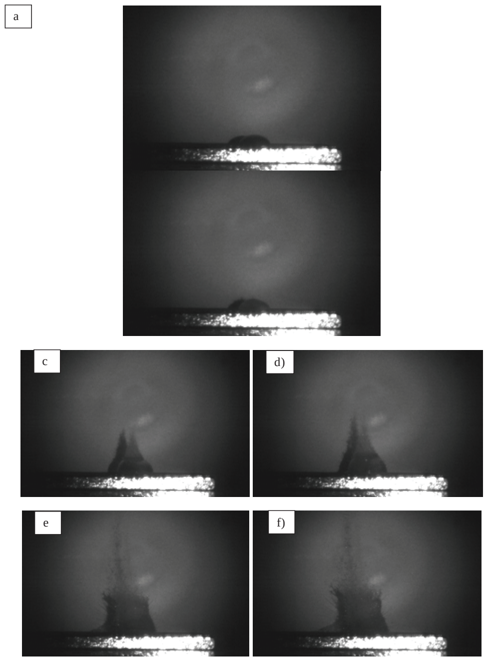


Fig. 5. The effects of the laser radiation influence Nd: YAG 1.064 μ m, 400mJ, 4 ns, the time of the exposition 200 ns, on the superficial layer of the sample from the alloy ENAW-2017A the black lacquer coat covered with water (ca. 3 mm) - the atmosphere of the air, registration after various times from the generation of the laser impulse moment: a) after 0 μs; b) 10 μs; c) 120 μs; d) 180 μs; e) 430 μs; f) 530 μs

Laser percussive strengthening (LPS) shows many analogies with mechanical shot penning.

In the some work material, for the sake of bigger power density in the laser pulse, which is delivered to the surface unit of charge than power density, which is given back to unitary surface of charge through single globule (shot). The plastic influence of laser pulse on the work material surface layer will be more intensive than globule – will be formed bigger (deeper) trace after laser pulse than after globule hit, bigger roughness and bigger internal compressive stresses, but about smaller gradient.

Process economy will be on the side of mechanical peening, but technological benefits seem to be on the side of laser percussive strengthening technology LPS).

Laser peening enables besides soft materials strengthening (for example aluminum), also hard materials strengthening, for example heat-resisting material (turbine blades). Moreover, it lets on the removal of micro-cracks [3].

The roughness after laser peening depends on pulse energy on the surface unit, on number of directed on the one place pulses and pulse duration. On the figure 6 is shown characteristic topography of ENAW-2618A aluminum alloy surface after laser percussive strengthening in two technological variants: at different covering degree of strengthened zones as well as in the different medium (air and water medium).

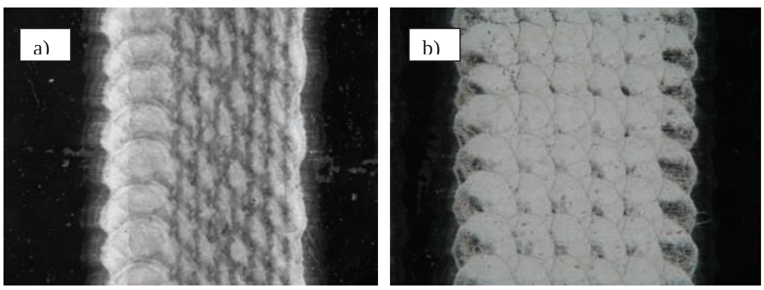
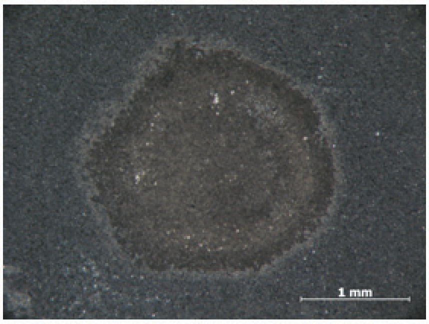


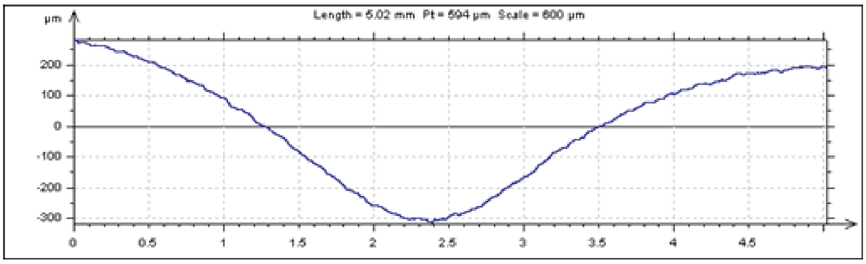
Fig. 6. Characteristic zones of sample surface from ENAW-2618A aluminium alloy after laser percussive strengthening, with make use of strategy of strengthen zones partial covering in following pulses: a) cover degree „0,5", absorption layer - black paint (spray), lack inert coating, medium – air, b) cover degree „0,75", absorption layer - black paint (spray), inert layer (water), processing on the an automated computer control station with table to X -Y liner dislocation

On the Figure 7 is presented topography profilograms of aluminum foil surface (g = 0,11 mm), deflection by laser pulse generated shock wave in different technological variants. (description above figures). These results prove, that very essential influence on the generation of shock wave has not only laser radiation power density, but also absorbent as well as inert layer, which repeatedly increases efficiency of strengthening percussive laser process.

a) A view of real foil with absorptive-protective coating as well as plastic deflection zone in variant with inert layer



b) 2D profilograms from plastic deflection foil (d)



c) 3D profilograms from plastic deflection foil (d)

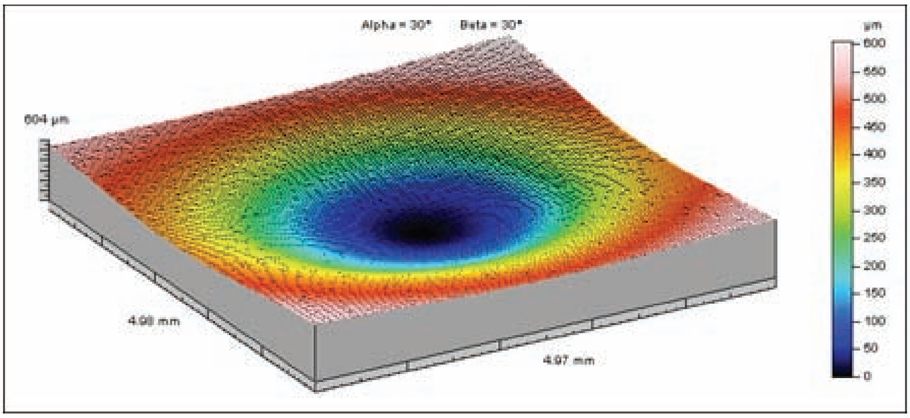


Fig. 7. characteristic profilograms of plastic deflection zones in the foil from aluminum alloy, formed as result of influence of shock wave generated from laser pulse – LSP in the different experimental variants: a) A view of real foil with absorptive-protective coating as well as plastic deflection zone plastically *in variant with inert layer, b,c) 2D profilograms (b) and 3D profilograms (c) from plastic deflection foil (a); Nd:YAG pulse laser, model ReNOWA Laser 5, λ = 1064 nm, E_{imp} = 500 mJ, τ = 25 ns, density q = 14 J/cm^2, one laser pulse*

The topography of the aluminium alloy surface ENAW-2618A after affecting short laser impulses about the large density of the power (q = 20 - 33 J / cm2) was introduced for various technological variants on Fig. 8. It was affirmed that the influence of laser radiation on the unsheltered surface of the aluminium alloy caused her melting what influences the topography of the surface and wearing proprieties unfavourably (Table 3.).

Laser percussive strengthening, which is performed at properly selected parameters, resolute, improves fatigue strength. It is performed with partial melting of superficial layer brings about reciprocal effect – considerably reduces fatigue strength (Table. 3) [12].

The results of wearing investigations prove, that laser strengthening with micromeltings of the layer top worse wearing endurance approx. 25 %. The use of polishing the surface after the process of strengthening laser LSP influences wearing properties very profitably, causing their growth approx. 50%.

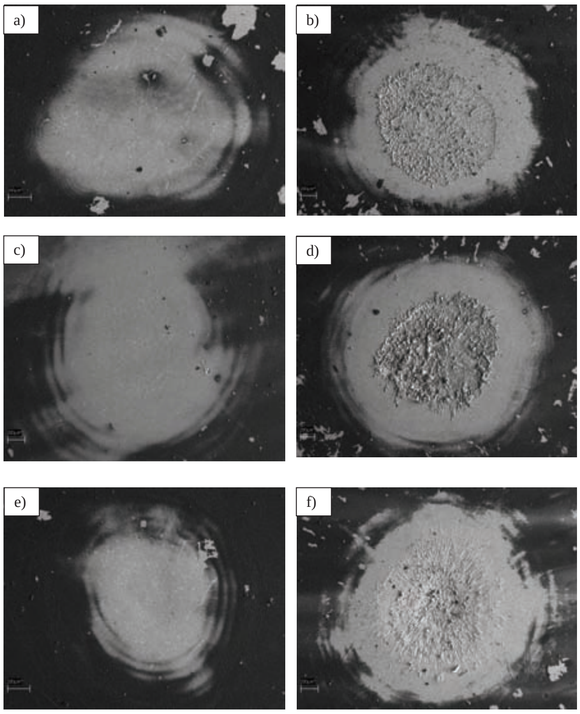


Fig. 8. Topography of aluminum alloy ENAW-2618A surface, polished, covered thin absorption coating (colloidal graphite), limited inert layer (water + glass), after processing by laser Nd laser pulse: YAG at energy density q = 20 - 33 J/cm^2, one or two laser pulses, half time of pulse duration τ=10 ns, different conditions of absorption and percussive strengthening — A general view of laser modificated zones: a) one pulse, q = 20 J/cm^2, b) two pulses, c) one pulse, q = 27 J/cm^2, d), two pulses, e) one pulse, q = 33 J/cm^2, f) two pulses, scanning electron microscope (SEM)

Tab. 3. The results preliminary fatigue investigations of samples made from aluminum alloy ENAW-2618A

Kind of sample	Mean number of fatigue cycles (double-ended bending σ = 180 MPa)	Mean number of fatigue cycles (cyclic tensionσ = 350 MPa)
Material in the initial state	184 923	19 592
Material after laser percussive strengthening with inert layer (water) as well as absorptive (Al_2O_3)	142 125	13 980
Material after laser percussive strengthening with inert layer (water) as well as absorptive (Al_2O_3), polished	292 377	29 046

5. Summary

The results of the experimental diagnostics of the shape of forming and moving the cloud of plasma in the influence of the radiation laser result with the alloys of aluminum were presented in the work. The most modern technique of the digital photo was applied to the registration of these processes using the CCD with short time exposition, and first time in Poland laser pulse highlight shortening the time of the exposition to 100 ns additionally. Using the Cavilux laser highlight new functionalities were reached when it comes to the quick imaging. This system makes possible the image of quicker processes than letting to register the registration possibilities of quick cameras, the pictures also on larger distances from the arrangement recording. Moreover using its parameters (the short pulse time, λ = 810 nm) the possibility of the observation of process surrounded the high temperature exists or the large energy of dazzling enlightened coming from the process itself of the laser ablation.

In the result of laboratory investigations, for samples from the aluminium alloy with high cleanness on the surface, the time of duration of the exposition of laser plasma is three times shorter in the relation to the process observed near samples covered with lacquer coat. This probably is the result of longer supporting plasma through the products of the coat, coming off from the burdened termical surface of samples. These products probably are subjects to dynamic warms, melts, evaporation (sublimation), what influences supportingly and extensions the process of ionization profitably, it has the influence on extension of the phenomenon of the generation of laser plasma

Conducted laboratory investigations in the range of the parameters selection of laser strengthening the top layer of the aluminium alloys ENAW-2017A and ENAW-2618A they enclosed the surface topography measurements, investigations of microstructure, microhardness and also wearing investigations in the limited range for σ = 180 and 350 MPa. The essential influence of the surface topography was affirmed, especially formed micromeltings in the process of generating laser plasma. The results of wearing investigations prove, that strengthening laser with microhardness of the layer top lowers wearing endurance about approx. 25 %. The use of surface polishing after the process of strengthening laser LSP influences wearing proprieties very profitably, causing their growth about approx. 50%. Should apply the protective absorbing layers effectively to protect the surfaces of the strengthened aluminium alloys from micromeltings.

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