

**О РЕЗУЛЬТАТАХ ИССЛЕДОВАНИЯ ЛАЗЕРНО-СТРУЙНОГО
ВОЗДЕЙСТВИЯ НА ПОВЕРХНОСТИ ТВЕРДЫХ ТЕЛ****ABOUT SOME RESULTS OF EXPLORATION OF WATER JET GUIDED
LASER ONTO THE SOLIDS'SURFACE**

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The summary

In this article results of some exploration of jet-ray engraving on solids with the help of Nd:YAG laser up to the capacity 400 W with wide diapason of regulating of impulse duration and it's energy are displayed. It has been being analyzed in details the condition of this theme, displayed the influence of high-speed liquid stream of the small diameter onto the condition of cooling in the engraving zone. The scheme of technological adjustment with the exception of expensive jet-ray arrangements is offered, and the efficiency of this method for accomplishing of cutting operation of sheet procurements.

Keywords: *water jet guided laser, a thermal problem, parameters of an edge, property of processed materials*

INTRODUCTION

The laser-jet processing (that named *water jet guided laser*) of materials is comparatively young, unexplored enough, but perspective method of local guided thermal hydro-dynamical influence, with the help of which in surface levels of procurement which is being processed high-speed processes of thermo-mechanical destruction are taking place. In the fragile and quasi-fragile materials destruction is accompanied by the development of inner defects and appearing of area with active development of micro cracks, what allows to implement of the processes of thermal removal of surface layer of the material and thermal cut off of sheet procurements; in resilient and resilient-plastic materials the destruction is displayed in appearing of areas of high temperature with high-speed drawing aside of heat, what makes the material to dispersion in the shape of microgranules, (for metals with the same time phase conversion of dispersion of the sludge); destruction of high-flexible materials is expressed as sublimation with following formation of firm phase and partial dissolving of it in the cooling liquid.

**REVIEW OF WORKS IN THE SPHERE
OF JET-RAY TECHNOLOGIES**

By this time there are no systematic information and the unified theory in the sphere of the water jet guiding laser processing. Various information is present in several printed works: [1-3], where the problem of laser-jet processing's principle is displayed, [7]- processing of silicon plates, [9-12]- various aspects of usage of method while radio-electronic metals' engraving, [14] – possibilities of unsteady materials' cutting, including cubic boron nitride, [16]- principles and machines, in which this principles are fulfilled. This works do not carry out the fundamental character and do not present satisfactory descriptions about effects while such a processing. Nevertheless the results, mentioned in [4], [8] give reasons to confirm the displayed type of processing is the most perspective while cutting and superficial processing of series of materials, where other means are not effective or unacceptable at all. Researches of laser-jet processing of new constructive and instrumental materials such as composites, for example, where functional orientation needs the elaboration of corresponding effective

functionally oriented methods. The Science Research company Synova (Synova S.A., Switzerland) [1,2],[14] actively explores the problem of laser-jet processing. Before the first laser-jet system was invented, the results of experiment with so-called “fountain of light” had been displayed in Paris in 1841.

This experiment proved by visual demonstration the possibility of light's stir in laminar liquid flow (to be more exact - close to the laminar) while it's deflection which is caused by terrestrial gravity of the Earth. Mentioned experiment was quite simple (fig. 1). In light-tight cell fulfilled with liquid (water), which was slowly flowing out the nozzle set in the bottom part of the cell. On the opposite side of the cell the slot with set glass, through which the light was coming into the cell, was made.

In overshadowed room the spectators had an opportunity to watch clearly that in spite the principle of linearity of light rays' spreading, light spot was exactly on the screen of cuvette, liquid was flowing down to, so the ray was bending and directing coaxial to the liquid spurt. In other words, the liquid spurt, mentioned before, was the first optical waveguide, where the diffusion of light took place under the frequent fracture and reflection from the jacket of the light.

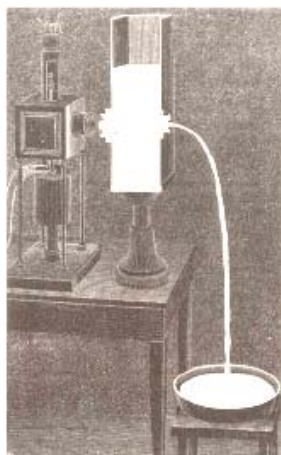


Fig. 1. *Fountain of light, having been demonstrated in Paris in 1841*

Coming back to this idea, creators of laser-jet cutting equipment have suggested the system composed with such elements [5] (fig.2,a): focusing system, spurt cell with window to let the laser ray come in, nozzle, generator of coherent laser emission and system of working feeding of the procurement.

Laser emission focusing on the nozzle shear allows to avoid the lugging of caustic surface in focused ray, so instead few millimeters of working area in existing laser system we are speaking about much larger working area (fig.2,b). Consequently, cutting the materials with sizeable thickness will not confront with difficulties so as there won't appear the paring of the ray and other violations of stability of thermal cutting processes.

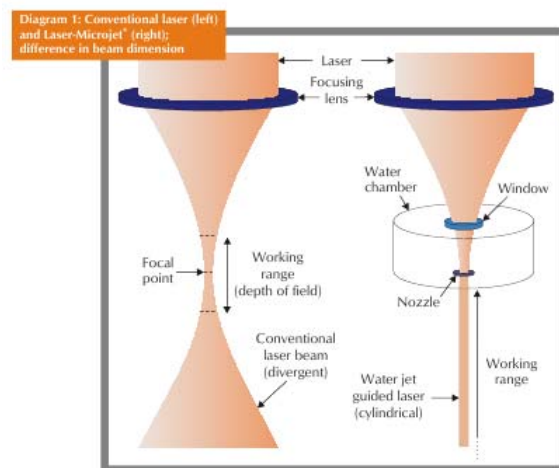


Fig. 2. *Differences of the traditional laser ray from water jet guiding laser spurt. Liquid spurt is the waveguide, which also supports the function of the refrigerant (according to the [5]).*

Grave disadvantage of this method is that the jet cell is supposed to possess clear glass, connected with laser emission. From one side, it limits to the liquid pressure, but from another-diminishes energetic effectiveness of the system by itself, so as any window partially reflects the emission and hydrodynamic effect in the system “water jet cell-nozzle” bring ray capacity losses even larger.

Nowadays, Synova S.A., Switzerland propose for the consumers few dimension-types of equipment for water jet laser cutting (fig.3), [6]: with working area from 50*50 mm to 250*250mm. Major part of such machines are destined to accomplishing of precious cutting plates of glass, silicon, selenium, solid and over-solid materials. The company actively applies the given method into the radio-electronic branch; also makes efforts to cope with other sector of action-aerospace industry, which needs materials' cutting and processing of the thermal protection of the spaceship (of various filled heat screens).

According to the data [16], the method of laser-jet influence is successfully used for operations of precision buffing, metals' welding. Though, we have not found any detail information according modes of processing operations. Also the theoretical underground main calculated dependences and mathematical patterns, which would allow to continue researches in this direction are absent too.

Hence, to sum up, it becomes possible to establish that laser-jet processing is high effective method of operated work with materials of any structure and mixture; high-gradient local thermal load, depending on scheme of influence what is able to implement phase chemical transformation as well as dispersion of the material, located in microvolume of the body which is being processed.



Fig. 3. Line of machines for laser-jet cutting semi-conducting plates [6]

But now any systematic information about rational conditions of processing of various metals, limits of effective usage of given method and effects which lead to creation of modern integrated technologies. Besides, there are questions about searches of rational schemes of technological tooling, elements of jetray equipment, which would provide similar effects while usage of other elements (according to the results of our researches displayed in work [18], where we propose individual variants of realization of joining of the liquid and laser ray).

THE AIM OF THE RESEARCH: to evaluate the effects of guided laser-jet influence upon solids' surface while the spurt of liquid under the

high pressure joins with laser ray without complicated optical-spurt devices, to discover possibilities of mentioned effects for realization of industrial technologies of cutting.

MAINTENANCE OF THE WORK

Now the chair of processes and equipment of mechanical and physico-technical processing of Kremenchuk Mykhaylo Ostrogradskiy State University in cooperation with National Technical university of Ukraine (NTU) have started systematical researches of the mentioned method on five-coordinate laser-jet complex LSK-400-5, created on the native base, which allows to conduct operations of hydro-engraving, hydro-abrasive and laser cutting, and also to do laser-jet processing by original laser-jet nozzles.

While elaboration of principles of water jet-ray influence we have based our researches on aspect that the effectiveness of laser-jet cutting and thickness of the surface of active absorption of emission with further destruction depends on the pressure and conditions of liquid outlet. In fact, let's examine equation of thermal sum for the case of liquid with leakage emission onto the normally-oriented surface while leading refrigerant directly to the zone of laser influence accordingly to the scheme, fig.4. Equation, found in [17] it is possible to determine the temperature fields in case, when the cooler-the liquid of overhigh pressure is not given to:

$$T(x, y, z, t) = \frac{P}{\pi^{\frac{3}{2}} \rho c} \int_0^l \frac{e^{-\frac{(x-v(t-\tau))^2}{4a\tau+A^2}} e^{-\frac{y^2}{4a\tau+B^2}}}{[(4a\tau+A^2)(4a\tau+B^2)a\tau]^{\frac{1}{2}}} \cdot \left[e^{-\frac{z^2}{4a\tau}} - h(\pi a \tau)^{\frac{1}{2}} \operatorname{erfc} \left(\frac{z}{2(a\tau)^{\frac{1}{2}}} + h(a\tau)^{\frac{1}{2}} \right) \cdot e^{hz+h^2 a \tau} \right] d\tau \quad (1)$$

where ρ , c , λ - density, specific thermal capacity and coefficient of heat conduction of the material; $a = \frac{\lambda}{c\rho}$ - material's termoconduction;

h - coefficient of heat irradiation from the surface; A and B - larger and smaller half-axes of the elliptic ray; $P = q\pi AB$ - capacity of laser emission.

Feeding of the liquid with over-high pressure needs considering of extreme conditions

$$c\rho \frac{dT}{dt} - \lambda \Delta T = \frac{(1-R_0)kP}{\pi AB} \exp \left[-2 \left(\frac{(x-vt)^2}{a^2} + \left(\frac{y}{b} \right)^2 \right) \right] \cdot \exp(-kz);$$

$$\lambda \frac{dT}{dz} \Big|_{z=0} = \alpha(T)(T - T_p); \quad T(x, y, z, t) = T_0 \quad \text{while}$$

approximation of coefficient increase of heat irradiation with dependence of type [18]

$$h(T) = h_m \exp\left(-\frac{(T - T_m)^2}{\Delta T^2}\right), \quad \text{what according to the}$$

results of numerical solution of equations gives zones (I) of abrupt temperature recession in the admission place of cooling liquid. Besides, depending from expense of cooler and the effectiveness of heat deflection, distribution of temperature fields might possess significant differences (fig. 5, (II)). The given illustration gives obvious picture of differences in the division of isotherms of the intersection, which is parallel with the one to cross the rays' axis in the direction of working supply.

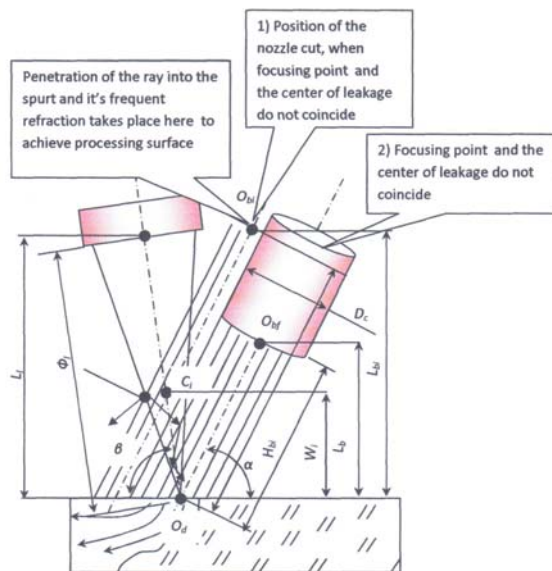


Fig. 4. Laser-jet spurt's interaction with pre-production model while lateral inlet of the ray

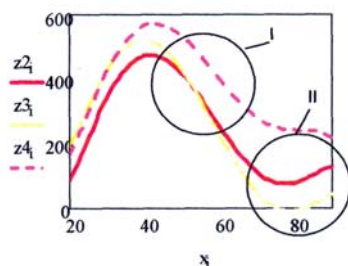
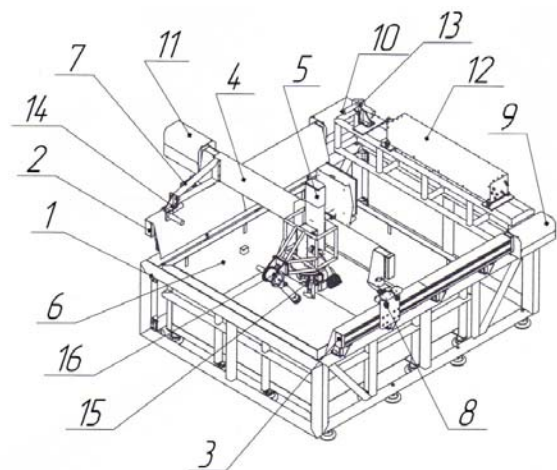
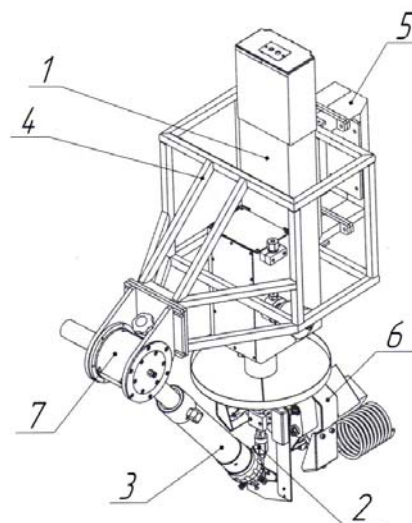


Fig. 5. Hypothetical division of the temperature $T(x, z)$ by intersection, parallel to the laser axis, which is on the distance $l=1,5d_c z_2$ - work with the pressure up to 50MPa; z_3 - increasing of the pressure of liquid outlet up to 100 MPa, indirect spurt leakage; z_4 - without supply of the refrigerant

Inasmuch as the step of construction is 0,005mm localization of the temperature (on the isotherm $T=600^{\circ}\text{C}$) might be within limits 0,04mm, what for overfull $\Delta T=1500^{\circ}\text{C}$ will cover zone not larger than 0,1mm. Besides, the increase of heat deflection causes temperature fall, and as well as diminution of sizes of the area, spanned with thermal influence. Consequently, laser-jet destruction of the material is taking place in local (not larger from 0,1-0,15mm) zone, what is much smaller from the hydrodynamic and thermal influences[18].



1.Carrying system; 2,3- girder of the transverse transference (X-coordinates); 5- girder of vertical transference (Z-coordinates); 6-receiving waters; 7-sistem of so-called "flying optics" of solid state laser; 8-carriage of power drive; 9,10,11-drive casing; 12-laser oscillator; 13, 14, 16-components of ray turn; 15-rotating head (with additional rotating coordinates B and C)



1-Girder of vertical transference of working organ; 2- jet appliance; 3-focusing laser tube with system of automatic self- regulation in focal area in vertical coordinate direction (Z coordinate); 4-carrying tube system; 5- carriage of the

transverse transference (X-coordinates); 6-high pressure hinge for providing of revolving transferences of jet-forming organ; 7-tube's turning hinge for inlet of ray to the fleeting flow.

Fig.6. Elements of research equipment LSK-400-5(a) and working body (b)

If lateral inlet of the ray into fleeting spurt is the simplest and do not need special expensive equipment, and several works [20,21] display that cycles of thermal load of the surface on the length $3...5 d$ are guided, on the phase of preceding researches exactly this scheme has been chosen as the base. At the same time with the aim to examine the level of influence of technological system onto the parameters of cut furrow, the direction was assigned athwart to the area created with of ray and water jet. Definitely, the lateral ray inlet into the spurt results in some changes in intensity distribution of radiation behind intersection [19], but it is not important for study of separate effects. It is assumed, that laser ray can be given into the spurt to the point of it's contact with surface as well as to the arbitrary point on the axis of the spurt. Taking to consideration thoughts, mentioned in [9], ray reflection in the casing of the spurt (at the angle approximately 47 for coherent beam with the wave length 1062nm) allows to provide directing of the ray inside of spurt casing. It is quite easy to implement it constructively, so as the complex LSK-400-5, fig.6) allows to complete technological tuning without considerable complications.

Testing cut was implemented on the steel plate 40X with the thickness 3,5mm on such conditions (see the table): capacity-300 W, impulse frequency 75 Hz, insufflation of cut zone with compressed air under the pressure 0,35 MPa, velocity of working feed- 12mm/sec. As the result it has been received common roughness under the roughness Ra 3,2 mkm, with the zone of thermal influence about 1,2-1,5 mm. Detailed electronic-microscopical examination demonstrated presence of separate phase transformations in adjacent to the edge of the section with dimensions' changes of grains model' body.

Further, under the angle of $\alpha=15^\circ$ the nozzle was set and combining of focused laser beam with theoretical center of leakage of the spurt

onto the surface was accomplished. At the same time, combination on the focus and spurt axis was provided under the conditions, that the spurt remains compact, i.e. $L_{bi} < H_{bi} \cos(\alpha)$. Also it was assumed, lugging of caustic in existing optical system is small, and the condition of combination laser ray with spurt ray is fulfilled, when $W_i = L_{ii} - \hat{O} \sin(\beta) = 0$ (fig. 4.), Φ - focusing length of optical laser system's object-glass.

With regard to usage of nozzle with aperture on the cut 0,25 mm, the one, which is provided by compact nucleus with length 20-25 mm, made of constructive parameters, the slope of tube laser is set $\beta=30^\circ$, accordingly it has been received the lengths $L_i=52$ mm, $L_b=21$ mm. Carrying out specimen cut on the speed of the supply $s=12$ mm/sec showed, that the process of laser-jet erosion is more productive in the comparison with traditional and it is complicated enough to receive the picture of the cut by itself. That is why the speed of supply is increased to $s=35$ mm/sec, having received groove with depth 2,1-2,2mm. The comparison of pictures of cutting (fig. 7) is displayed below:

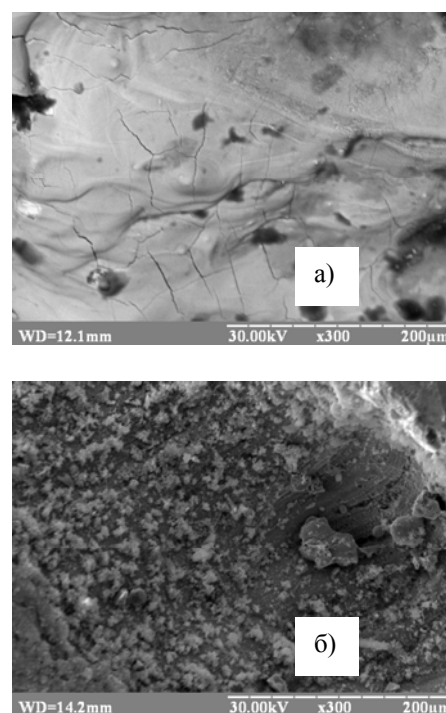


Fig. 7. Examples of the cut on the procurement made of steel 40X, received with laser (a) and jet-laser (b) cutting

Using the most simple scheme of getting the ray into the spurt it became possible to receive scribe of high quality on the surface of metal plate made of steel 40X. In comparison

with traditional methods of hydro-abrasive engraving or laser influence groove happened to be more deep, with even edges, and without layer of thermo-destructions. In cross-section, it's groove is asymmetrical, it's axis is approximating to the axis of the spurt, that is increasing of the angle α leads to proportional increasing of asymmetry. The direction of supply is also influences this asymmetry, what is obvious, just as the approximation of the direction of the movement to the area on which axes of ray and spurt are set influences only the shape groove's cut front, and edges of groove are becoming practically symmetrical.

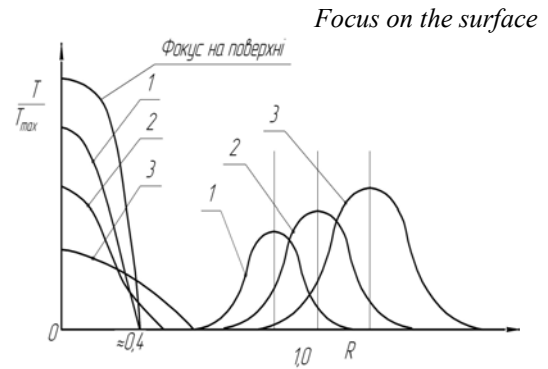
The change of inlet of the ray while increasing of length L_{bi} lead to formation of adjacent groove (pict. 8, see the last line of the table) on the definite length from the previous one. Obviously, appearance of this groove is the result of smelt of surface by the ray, which got through the casing of the spurt or passed over it because of inaccuracy of alignment and after showing through with refraction got to the surface. Changing the controlled length L_{bi} , it has been determined the series of diagrams of temperature changes on the surface (in dimensionless form) depending on the

parameter $\Phi = \frac{W_i}{d_c}$, W_i – displacement of focusing point on the surface, (fig. 7).

Though, in the process of combining of the high pressure liquid with the laser ray it became possible to get results, equivalent to those, displayed in work [7] with the quite simple realization of the process. Lateral inlet of the ray into the spurt causes asymmetrical cut in case when the system is oriented transversely or under sizeable angles to the supply direction and practically symmetrical when all axes of the ray, spurt and supply direction create the single area. Tolerance to the size of groove's width is not worth from IT8-IT9.

Also, it has been studied the influence of nozzle D_c diameter (and, as the result, liquid expenses q_p while constant pressure p_b) onto the production of the process, which is expressed through the depth of the cut groove. Nozzles with diameters D_c 0,1

mm, 0,22 mm, 0,3 mm, 0,38 mm та 0,5 mm. were used.



Groove, received in liquid flow, $h=2,4$ mm

Adjacent groove, appeared on the surface $H=0,8$ mm

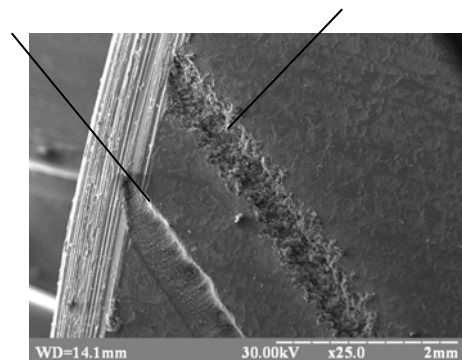
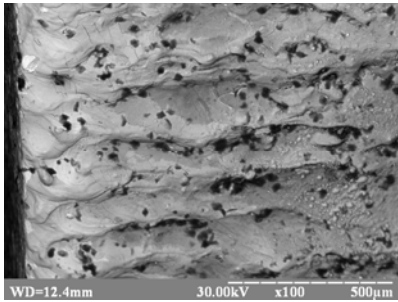
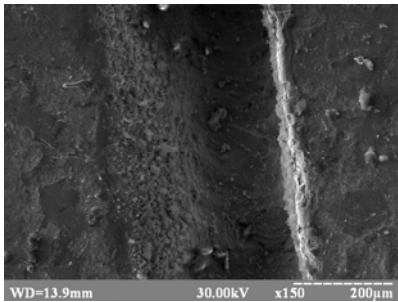
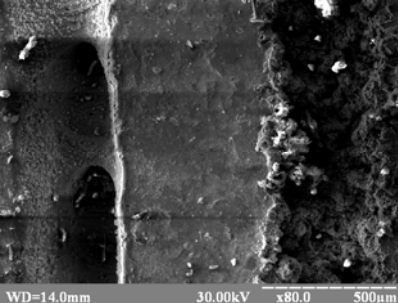


Fig. 8. Distribution of comparative temperature (T/T_{max}) on the surface in the function of parameter W : 1 – $W=0,2$; 2 – $W=0,4$; 3 – $W=0,6$

The results of measurement of the depth of the cut groove with the supply $s=35$ mm/sec and other parameters, displayed in the table. It w with largamente of outlet of the nozzle w w synchronous outstripping increase of groove's width. Intersection by itself becomes more rounded. While re-calculation of omitted metal volume q_w during time t , which is determined by cross cut of the groove f_b as $q_w = f_b \cdot s \cdot t$, it is received that this data increases pro rata. While comparison of groove's depth, received by authors [7], we have the increase of liquid pressure from 50 to 100 MPa under other even conditions would cause depth increase in 1,8 times. So it is correct to assume that the further increase of the diameter of

Table - Electronic micro photos of models , received while invesyigation (material: Steel 40X)

Procedure of processing	Electronic microphotos	Commentary
1. Laser cutting $p_a=0,35$ MPa; $S=12$ mm/sec; $P=300$ W; $F=75$ Hz		Surface microsplits can be noted, surface has expressed grooves of running-off liquid melt of metal, which is being processed
2. Laser-jet processing with focusing on the surface $p_a=0,35$ MPa; $S=35$ mm/sec; $P=300$ W; $F=75$ Hz $P_p=100$ MPa; $D_c=0,25$ mm, the angle of spurt tilt $\alpha=15^\circ$, optical system focus– 80 mm		Surface is homogeneous, roughness according to parameters $Ra=1,6-0,8$ мкм, Bath of the melt has remains of metal particals in the shape of balls $d_k=10-50$ мкм. Cut is asymmetrical, tilt angle is hypothetical centre corresponds to spurt tilt.
3. Laser-jet processing with focusing in the body of spurt $p_a=0,35$ MPa; $S=35$ mm/sec; $P=300$ W; $F=75$ Hz $P_p=100$ MPa; $D_c=0,25$ mm, the angle of spurt tilt $\alpha=15^\circ$, optical system focus – 80 mm		One groove received from laser-jet influence is observed, and another one on the length 500-600 мкм, received as a consequence of shining through the liquid spurt by laser ray. Irregularity of liquid supply leads to formation of caverns of larger depth.

nozzle outlet is going to cause considerable dimension of the depth of groove cut, which means it is possible to reach the effect of surface polishing (taking off of microdefects) under certain conditions, the information about which is mentioned in work [1]

CONCLUSIONS

Making the conclusion, it is permissible to notice, the process of laser-jet cutting is perspective, sufficiently effective and universal while the processing of wide range of metals. The process is

fulfilled by various schemes of combination of the laser with liquid spurt of high pressure, and proposed method of putting in the ray allows receiving the same effect as world producing leader suggests in the sphere of laser-jet technologies. Accordingly to the displayed in this work scheme it becomes possible to receive linear cuts. Usage of more high pressure allows to increase productive of the process of expected dimension of the destructive area, nevertheless this problem requires further investigation.

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