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Salenko A., Kholodnyi V.
Kremenchuk Mykhaylo Ostrogradskiy National University, Kremenchuk, Ukraine (salenko2006@ukr.net)

CHANGING THE SPOT OF LOCAL DESTRUCTION OF SAMPLES AT WATER JET GUIDED LASER PROCESSING WITH APPROPRIATE PROFILING JET

Саленко А.Ф. д.т.н., проф., Холодный В.Ю.
Кременчугский национальный университет имени Михаила Остроградского, г. Кременчуг, Украина

ИЗМЕНЕНИЕ ПЯТНА ЛОКАЛЬНОГО РАЗРУШЕНИЯ ОБРАЗЦА ПРИ СТРУЙНО-ЛАЗЕРНОЙ ОБРАБОТКЕ СООТВЕТСТВУЮЩИМ ПРОФИЛИРОВАНИЕМ СТРУИ

The results of studies of laser-jet materials processing technologies, as one of the promising methods for cutting a variety of products are shown. On the basis of current world developments are considered features profiling nozzles (transition region) for optimal formation of laser-jet flow. Optimal nozzle opening of the cavity, satisfying all the stated requirements have been created. Using a simulation program Mathcad propagation of the luminous flux in the nozzle cavity and in the free jet. Mathematical modeling of fluid flow through the nozzle into the cavity built software environment FlowVision was conducted. Research on the simulation installation and laser-jet complex LSK-400-5 was conducted. The diameter of the jet should be greater than the diameter of the laser ray by the amount of its decay.
Keywords: water jet guided laser, hole, power beam effectivity.

Introduction

Development of engineering products is inextricably linked with the expansion and introduction of new technologies for the treatment of various materials with special properties (which are almost impossible to be treated with traditional methods of materials machining) [1]. In recent years, new methods for cutting of various products began to receive the spread, among which the most promising is water jet guided laser processing, based on the simultaneous action on the surface being treated of heat and jet streams [2]. The combination of these streams allows such an impact on the treated surface, in which the high thermal gradient field is localized on only a small part of the surface as a result of a powerful heat sink, which provides with high-speed fluid flow. Water jet guided laser processing of materials, which provides a pulsating thermo-hydrodynamic effect on the treated surface and is able to effectively perform the processing of metals, ceramics, metal and non-metal composites, are now actively developing. In industry these technologies are used for silicon chips cutting [3], but there are certain decisions on the use of this process in aim to perform the processing of heavy-duty materials [4].

Purpose

Other than getting cross-cuts in the specimens, there is a need to perform firmware operations - making holes of small diameter with cylindrical or profile shape. In this case water jet guided laser processing may be especially helpful, as it has high productivity and reproducibility, i.e. stability of the resulting shape of the holes. Currently, there is a need to systematize the developments and approaches to the issue for ensuring stability of the geometric shape of the holes, the required quality and minimal destruction of the processing surrounding areas. This is caused by the relevance of these studies.

Investigations

Existing water jet guided laser systems presented in [5], are built on the principle of a jet chamber with a transparent window through which the laser beam (Fig. 1, [6]) is injected into the jet stream. However such cameras are not enough technological to produce, require frequent replacement of the optical elements - a transparent window; the presence of the window limits the pressure that can be created by hydraulic system. The disadvantages of such a device can also be attributed lack of transition section in the orifice (required for the formation the jet) and as a result:

- necessity of creation "propped up" pressure with neutral gases (eg, helium) at the outlet of the orifice which will held jet from the collapse;
- the need for high precision positioning of the laser beam relative to the formed jet, as caustic hauling in this case should be at the entrance of the formed liquid jet.

- To eliminate mentioned drawbacks and to the expansion of technological capabilities as well as implementing of hybrid processing technologies is proposed to use stream chamber with annular orifices (Fig. 2) in which the optical elements are absent and the introduction of the laser beam into the fluid jet takes place in the annular space.

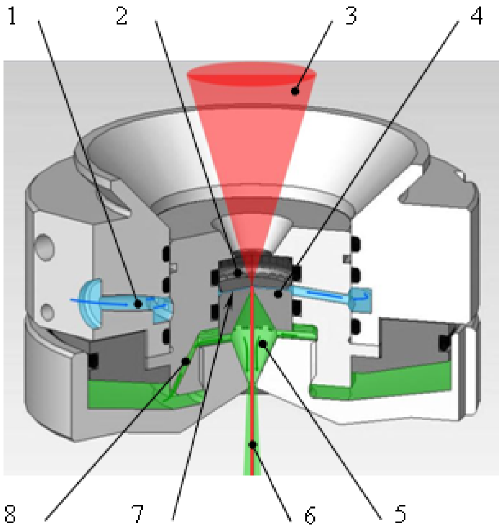


Fig. 1. An apparatus for forming water jet guided laser stream produced by Synova (*Switzerland*)
1 - a channel for supplying a refrigerant into the chamber; 2 - an optical element of window for entering the laser beam into the stream of the refrigerant; 3 - laser beam; 4 – nozzle with a orifice; 5 - chamber for the formation of refrigerant jet by introducing a pressure of neutral gas (*helium*); 6 - refrigerant jet with laser beam and the "shell" of the neutral gas introduced into it; 7 - camera with the supplied refrigerant; 8 - channel for supplying of neutral gases to formed stream

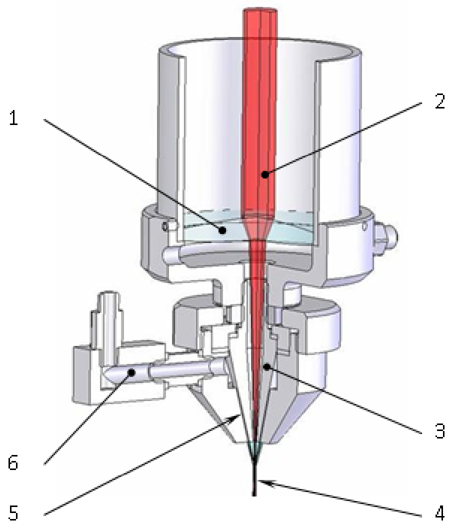


Fig. 2. The apparatus for forming water jet guided laser stream with the ring nozzle:
1 - an optical element for laser beam focusing; 2 - laser beam; 3 - conical insert; 4 - formed water jet guided laser stream; 5 - annular conical channel for refrigerant supplying; 6 - channel for refrigerant supplying

At the same time, considering that research on the development of stream chambers with annular orifices are not yet completed, further laboratory studies of the processes on the formation of water jet guided laser stream were produced using the simulation setup, structurally similar to the installation of Synova.

In order to bring the regime of expiring of the refrigerant flow from the nozzle to laminar, it was decided, in contrast to the design of Synova, to use the profiled of transition section connecting the camera and the orifice nozzle. It is also allowed to create nozzle with the output section of the channel differ from a circle.

For carrying out simulation experiments were created special nozzle, for the following reasons:

- providing compensation of misalignment of the laser beam and the free liquid jet;
- exception of back reflection of the beam towards the optical system;
- providing of total reflection of the laser beam due to the absence of his separation at the interface (liquid - air).

Necessity of misalignment compensation is caused by the remoteness of the laser source from the orifice nozzle and features of the adjustment of their relative position. At the same time the need to use transition sections for the formation of stream is conditioned by the fact that the diameter of the laser beam using orifices with channel profiles, other than circular, should be guaranteed larger then maximum size of the orifice cross section. Thus, through the transition section using the total reflection of the beam from its walls, it is possible to achieve the most effective use of the laser power emission.

In this connection, were analyzed literary sources offering different techniques of orifice modeling [7 - 10]. The result found that practically there are no restrictions in the shape of the channel. However, the specific configuration requires an appropriate transition section (defined by the profile using the formulas by Vitashinskyi, conoidal, conical, etc.). Channels themselves have tapered transition sections, and tangent to any point of the profile (for these curves) have a variable angle of inclination to the axis of the nozzle. Consequently, there is a high probability that in the event of misalignment of the beam with the liquid jet, it will be partial loss of light flow due to its dissipation.

A special interest for the production has the possibility of not only round but also profiled holes, further investigations were directed at determining the conditions for effective distribution of the emitting beam by the cross section of formed jet. Based on the results obtained by previous studies, it can be assumed that the emission distribution in indentation spot inside a cylindrical liquid jet can be described using a Gaussian curve. However, for the liquid jet, the cross section of which differs from circular, considering the turbulence effects, is quite difficult to assume the character of distribution of the emission; modeling is also requires a number of adjustments that can be obtained exceptionally by experiment.

For conducting research it was designed simulation laboratory setup (Fig. 3). Its peculiarity is in interchangeable nozzles with profile channels, allowing forming the refrigerant jet of desired configuration. Designed setup was based on the idea to have minimum cost on its production, using the principles of similarity effects, to achieve the highest possible visualization of research results.

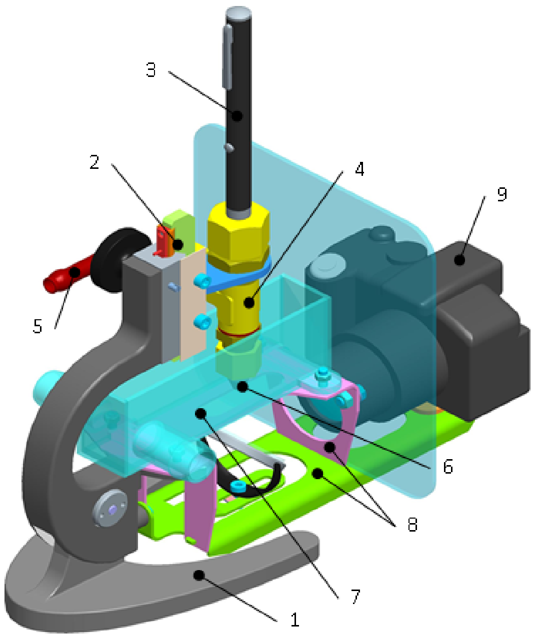


Fig. 3. 3-D model of the device for coaxial input of beam into a liquid stream
1 - base; 2 - the mechanism of vertical movement of the nozzle; 3 - laser source; 4 - chamber of coaxial input of laser beam into the stream of the refrigerant (liquid); 5 - a tube for supplying fluid; 6 - nozzle with the profile gauge channel; 7 - bath; 8 - the camera to fix the beam distribution in the imprint of liquid jet contact with the bottom of the bath; 9 - mounting brackets for bath and camera

Setting allows:

- create the geometrical dimensions of the fluid with the introduced into it laser beam which are sufficient for monitoring without increasing the use of special equipment;
- change the height of the jet;
- use nozzles with different configurations of the channel profile;
- conduct a visual inspection and fixation of configuration of the jet and its imprint, using photographic recording.

One of the major issues in the preparation of studies using the simulation laboratory setup was creation configurations of optimal profiles of channels for nozzles with three different output sections (circular, square, ellipse). In this regard, were analyzed the literature offering various solutions of questions raised and discussed a number of techniques for orifices modeling [7 - 10]. As a result, the design of the transition section of nozzle holes is based on two ideas, namely:

- ensuring of compensation of misalignment of the laser beam and the free liquid jet;
- ensuring of total reflection of the laser beam due to the absence of his separation at the interface (liquid - air).

Necessity of compensation misalignment was due to the remoteness of the laser source from the orifice nozzle and the characteristics of the adjustment of its position. It turned out that this requirement is fulfilled by using almost any of the considered configurations of transitional sections of the nozzle (formulas by Vitashinskyi, conoidal, conical, etc.), which is explained by the presence of walls tilt in all of them.

At the same time at misalignment of the beam with the orifice outlet may be a situation of decrease brightness imprint on the surface being treated. This is explained by the fact that the beam reflected from the transition section surface, after entering the stream of liquid, will expire emission a result of its incomplete reflection at the interface. The analysis showed that, of between all examined longitudinal configurations of the transition section, only conical can provide constancy limit angle of total reflection regardless of magnitude of the displacement of the laser source. Settlement scheme of determining the angle value of generatrix of the cone of the nozzle transition section, which provides complete reflection of the beam in the fluid jet is shown in Fig. 4.

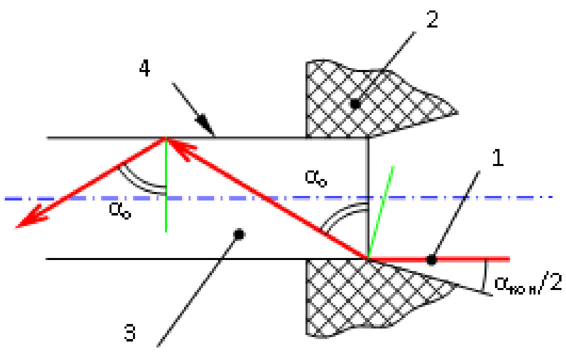


Fig. 4. Settlement scheme determining the value of a half angle of generatrix of the cone of nozzle transition section
1 - laser beam; 2 - nozzle; 3 - jet of liquid; 4 - the interface (water - air)

For produced nozzles angle of inclination of generatrix of the cone of the transition section, depending on the configuration of the output section should not exceed 20.6 degrees.

Considering the complexity of manufacturing the transition section hole, it was decided to make a orifice by using prototyping technology SLS (Selective Laser Sintering - laser sintering of powder materials) (Fig. 5).

Fig. 5. Nozzles created by prototyping

At the same time, questions of emission distribution across the stream remain unexplored. To conduct research is created a measurement system that can detect and evaluate the spatial distribution of emission over the cross section, as well as get his temporal distribution. However, it has been found that such measurements involve a number of errors occurring due to the instability of liquid outflow conditions.

According to the results of the working off of methods for the investigation of jet guided laser processing method were noted and recorded factors, indirectly confirming the existence of different kinds of errors.

Studies were conducted on the simulation experimental setup designed and manufactured earlier (Fig. 6).

Principles of similarity underlying in the design of the setup, had to make occurring processes as close as it possible to processes occurring in industrial equipment. That is why it was used a larger diameter of orifice and a less powerful laser light source having geometric parameters of the beam similar to the orifice size. For the convenience of visualization in setup it was used the laser source with a nominal beam diameter of 1.2 mm (100 mW, 532 nm). Liquid jet was formed with a nozzle with circular outlet of diameter 2 mm. The magnitude of the light emission was recorded using the photoresistor FSD-1. Considering the possible pulsations in the measurement process, for the purpose of fixing the measurement results, it was decided to use the ADC m-DAQ connection scheme which is shown in Fig. 7. In the studies the distance from the end face of the orifice to the work surface varies from 0 to 48 mm in 1 mm increments (the additional distance from the working surface of the photoresistor until the orifice - 8^{+1} mm), the fluid pressure in front of the working chamber - 0.5 kgf/cm^2.

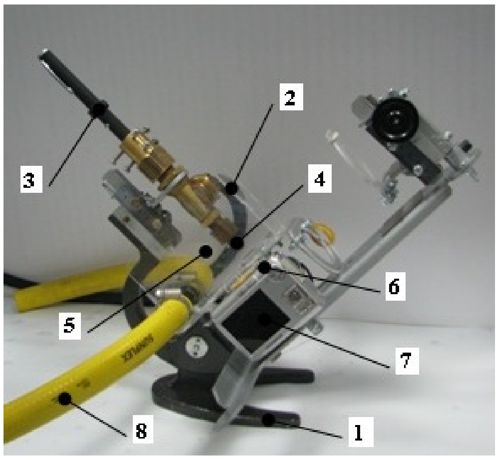


Fig. 6. Experimental setup
1 - base; 2 - feeding liquid tube; 3 - laser source; 4 - nozzle; 5 - working bath;6 - photoresistor; 7 - camera; 8 - drain hose

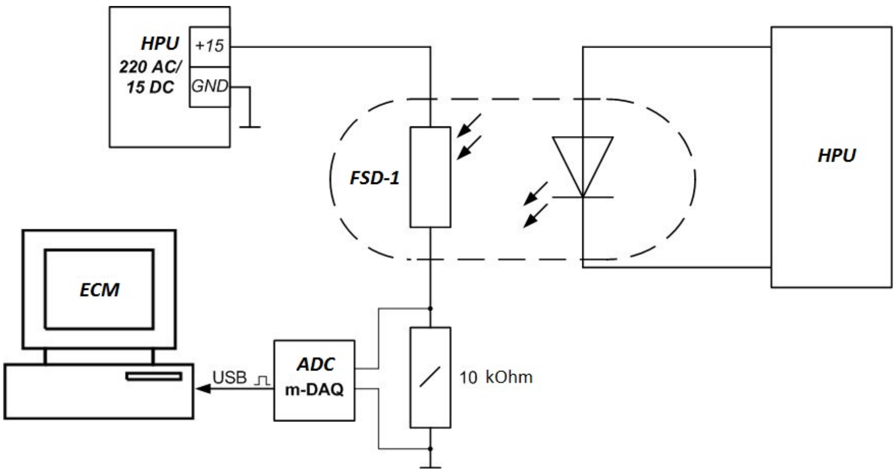


Fig. 7. Schematic diagram of the measuring system based on ADC

Instrumental error used in research settings was caused by low power density of the laser emission source in comparison with industrial lasers. So power of industrial laser on 1 mm^2 can be 1865 W/mm^2, while the specific power of the laser source of the experimental setup is just 0.032 W/mm^2 for the same 1 mm^2.

Based on these, it was made an assumption about the significant impact on the experiment results of the external artificial and natural lighting, which was confirmed experimentally (see curves 1 and 2 in Fig. 8). Excluding the impact of external lighting is offered by placing the setup in a dark room or in a light-tight chamber. It was decided to use that camera, which allows to make experiments regardless of time of day and under any ambient light. Analysis of the research showed that the error introduced by external light sources can reach 4.2-5.5%.

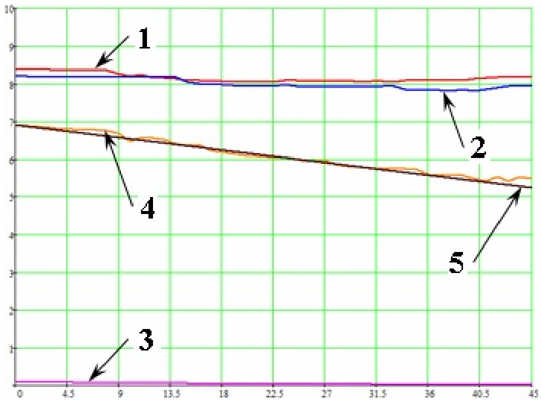


Fig. 8. Experimental results:
1 - without water with external lighting; 2 - without water in the chamber; 3 - with water; 4 – with water and device for removing of turbulence effect; 5 - calculated dependence

After elimination of the instrumental error and a liquid supply in the system luminous flux has strongly fallen, due to the turbulent motion of the liquid in the chamber of setting (see curve 3 in Fig. 8), where the input of laser beam into the liquid is. This was accompanied by a visually perceptible shimmer of nozzle made from translucent plastic, confirming the instability of the existing processes, due to the refraction of the light flux from the laser beam being led away to the side, as well as the partial scattering of the laser beam.

In order to reduce turbulence was made device for removing of turbulence effect shown in Fig. 9. Its purpose is that liquid supplied under constant pressure into the working chamber, where jet collides on the walls of the cylindrical chamber, forming a turbulent flows with lots of vigorously stirred twists in a mode of intensive turbulent mass transfer, passed through device for removing of turbulence effect of stream and transported to the nozzle of the orifice in the laminar flow regime. Shallow grid in device for removing of turbulence effect (pos. 2, Fig. 9) is situated opposite the inlet opening of the working chamber and is designed to protect the laminar moving flow of liquid inside the device for removing of turbulence effect and further flux redistribution in the upper part of the chamber. The larger grid (pos. 1, Fig. 9) designed to form a laminar flow in the upper part of device for removing of turbulence effect and eliminate airing of the working chamber.

The results of the effectiveness of device for removing of turbulence effect using are clearly demonstrated with curve pos. 4 on Fig. 8. The resulting voltage dependence U (V) on photoresistor from the liquid jet length l (mm) can also be described using the following formula (pos. 5 in Fig. 8):

$$U(l) = -0{,}03705 \cdot l + 6{,}915 .$$

In the next step it was evaluated the effect of misalignment of the spot emitting focus and closing point of the liquid jet. While take into account that from all the above configurations of the transition section only conical one can provide a consistent of limit angle of total beam reflection regardless of the displacement of the laser source.

Fig. 9. Versions of devices for removing of turbulence effect
1 - grid with a mesh size of 0.3 mm; 2 - grid with a mesh size of 0.18 mm; 3 - mounting flange

Fig. 10 shows results of simulation visualization of the luminescence intensity of the laser beam on the specimen surface in the event of misalignment of the location of beam and refrigerant jet. Considering sizes of components of previously created simulation setup the following parameters in the calculations were taken: the laser beam diameter of 2.2 mm, the diameter of the liquid jet 2 mm and misalignment in their mutual arrangement of 0.18 mm, the studies were conducted in the medium Mathcad.

From these results it follows that the presence of the conical section of nozzle allows to make more full use of the luminescence energy "forcing" her to the geometry of the jet. At the same time placement of the reflected part of beam relative to the main imprint depends on the height of the liquid jet.

However, flow formed by a annular orifice closes, so there is a possibility of significant violations of the flow in its certain areas that requires additional model experiments aimed at establishing patterns of distribution of pressure and velocity in the stream. Zones, which will have the maximum changes, are likely to be areas of maximum power loss of the laser emitting.

In addition, the evaluation of changes in the velocity gradient at the surface of leakage will allow specifying mechanism of injury and the softening of the material, which will give possibility of predicting during jet guided laser processing.

To study this issue, it was decided to carry out the simulation of the processes, namely its hydraulic component, which runs in the medium FlowVision (Fig. 11).

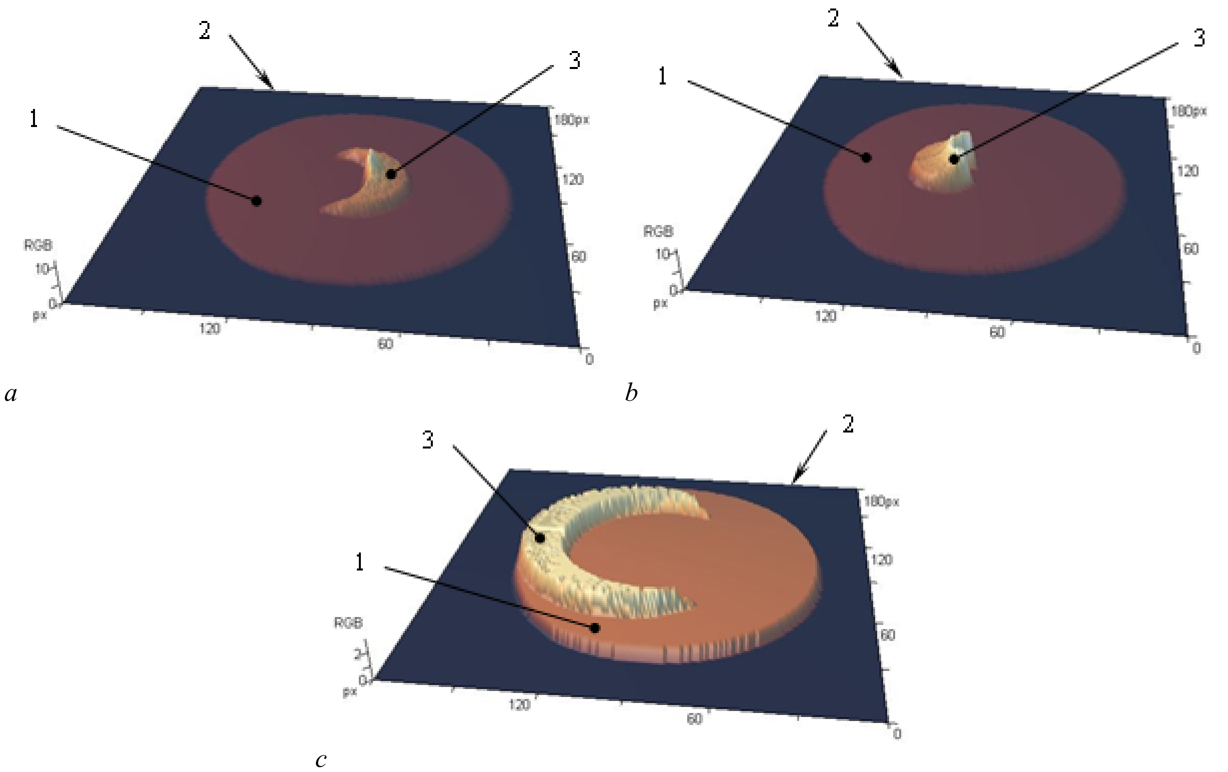


Fig. 10. Simulation visualization of luminous intensity of the laser beam imprint on the surface of the specimen with misalignment of the jet beam and the refrigerant of 0.18 mm. Orifice hole is made in the shape of a circle
a **- the height of refrigerant jet - 5 mm;** ***b*** **- the height of refrigerant jet - 10 mm;** ***c*** **- the height of refrigerant jet - 16 mm;**
1 - the imprint of the luminous flux of the laser beam coming through the refrigerant jet without refraction; 2 - part of the laser beam reflected from the conical section of nozzle and interface "water-air"; 3 - the surface of the specimen

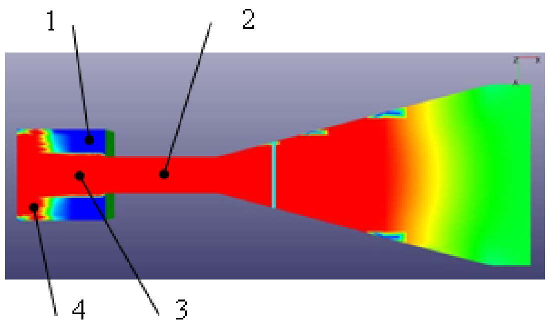


Fig. 11. The result of the simulation of liquid outflow from the orifice nozzle in the software medium FlowVision:
1 - air surrounding free stream; 2 – nozzle plot with a profiled hole; 3 - free liquid jet; 4 - flow diffluented after the collision

It was considered that the jet stream is formed with a orifice with flow passage variable geometry. Depending on the circumstances, the following forms of opening outlet (orifice): round, rectangular with rounded corners, oval. The diameter of the orifice nozzle hole was 2 mm; fluid flow velocity at nozzle inlet - 14 ... 50 m/s. The aim was to evaluate the difference of velocities in free stream (below the orifice) and to identify the zone of maximum instability, which according to earlier results, will consist the maximum possible damage to the transparency and, accordingly, the maximum dissipation of the laser emitting. Performing calculations it was received data array consisting of 5594 lines at coordinates x and y axes, and the velocity values along the x axis (Fig. 12).

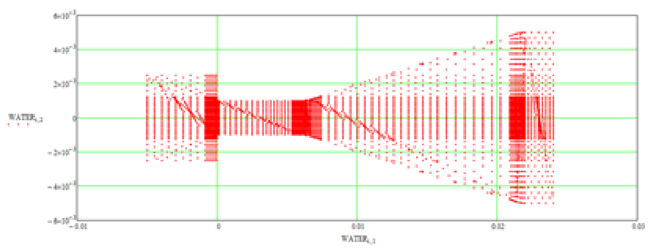


Fig. 12. An array of points resulting in a medium FlowVision, characterizing the high-speed mode of fluid flow

Point visualization of data array derived from the calculation allows to determine the distribution of velocities in flow, and to determine a change in the intensity of the laser emission with the proviso that the intensity distribution at the beam waist of caustic in the plane of the clamping stream corresponds to Gauss law (Fig. 13).

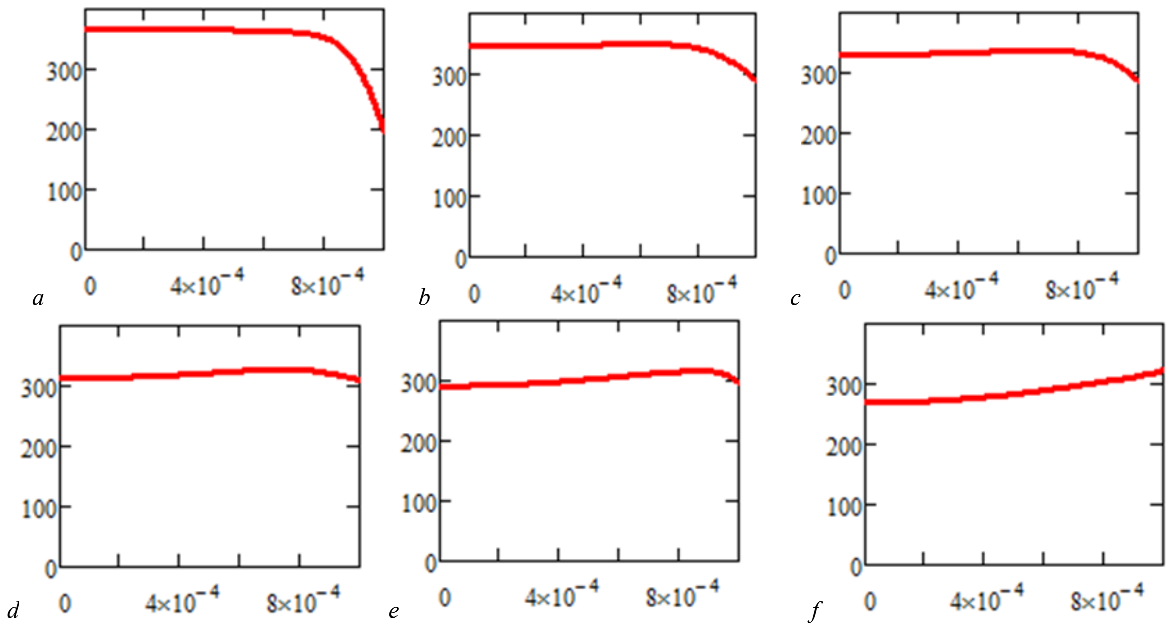


Fig. 13. Reduction of the flow velocity at the nozzle end face and at each next millimeter of free liquid discharge behind the nozzle, which leads to a corresponding reduction in the intensity of the laser emitting. This graphic representation shows from the jet axis (left) to the boundary of the nozzle hole projection (right):
a **- the orifice end face;** ***b-f*** **- distance from the orifice end face with a 1.0 mm pitch, where** ***f*** **- treatment surface**

Thus, it becomes apparent that there is a clear distance from the orifice edge to the treatment surface, where the costs of emission power and, consequently, the possible processing performance is the highest; on this section sharply decrease the contour fidelity and productivity of the process are possible (Fig. 14). Based on simulation data it was made experimental studies which have confirmed these observations and allowed to explore the features of the process of water jet guided laser cutting of materials in which $h/D_c > 1.0$ (ratio of the thickness to the intersection of the jet and the waist of the caustic of the focused beam). We have also established stage process and its quasi-cyclic nature. Cyclicity is manifested in several harmonics and is defined with the conditions of fluid flow, and a pulse repetition rate of the laser; practically does not depend on the structure of the material being processed and the physical and mechanical properties of its components. Experimentally confirmed the existence of peak amplitudes at frequencies $(0.2\text{-}0.25)n_l$ and $(2.4\text{-}3.5)n_l$. Experiments were performed with solid state laser with a wavelength of λ = 1062 nm and orifice device with D_c = 0.25 mm. The decision of thermal problem for the range of materials from the action of concentrated heat source and heat sink with an intensive mass transfer has shown that in the surface layer the transformation taking place associated with changes in the structure of the layer and its chemical composition. The presence of a vapor layer with liquid residues in the cavities of microdefects creates the conditions for the prior development of major cracks and active defects merger, therefore, the conditions for high-mass transfer by midget particles are created.

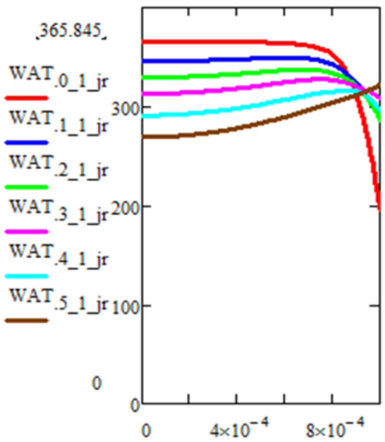
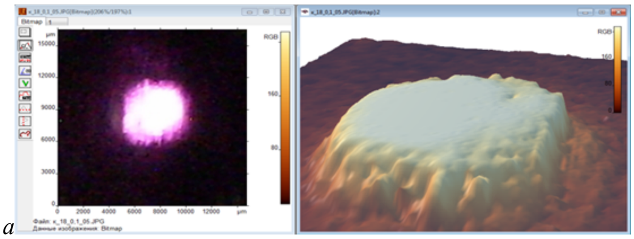


Fig. 14. Reducing the intensity of emitting and its distribution for the expected path: area of emitting propagation is designated with the corresponding curves

The theoretical premise allowed offering an effective means to change the form of manifestation of the water jet guided laser stream, while the effectiveness of such change is quite high. Therefore, after the model experiments it was proceeded to research the formation of profile holes in the specimens from stainless steel 12H17 1.5 mm thick. Investigations were carried out at the facility LSK-400-5 with modes: pressure leakage - 60 MPa, the processing time - 0.2 s. It was checked by means: pulse frequency - 65 Hz, exemplary gauge (5 - 500 MPa), vacuum gauge (0.5 - 10 mm. v. s.), a pressure sensor LNA-300, vacuum sensor LNR-25.

Conclusions

It was established that circular cross section is reproduced most accurately, but other shapes (such as square and ellipse) are sufficiently accurate (Fig. 15 a, b). Thus, further researches should be oriented at improving the accuracy of form reproduction.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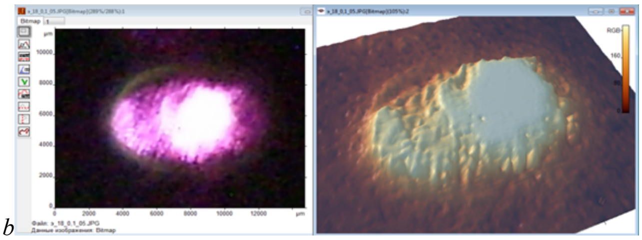
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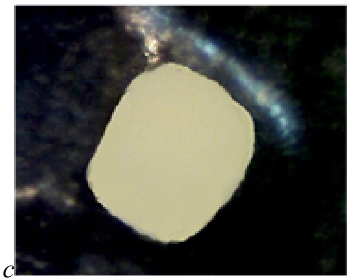
c

Fig. 15. Beam shapes, received by the relevant profiling of the orifice section:
a **- a square with rounded corners;** ***b*** **- photo-real hole ellipse;** ***c*** **- hole obtained during profiling of the flow**

Considering that in a free fluid jet relative to the projection of the edge part of the orifice, there is a velocity change of fluid flow in the direction of its reduction, it can be assumed about similar changes in the optical properties of the jet in the direction of their deterioration. Based on the foregoing, in subsequent studies, we should pay attention to the possibility of increasing the size of the profiled the holes on the thickness of the liquid layer defined by a sharp drop in flow rate.

Аннотация. *Рассмотрены результаты исследований лазерно-струйной технологии обработки материалов, как одного из перспективных методов резки различных изделий. На основании существующих мировых разработок рассмотрены особенности создания профилей насадков (переходного участка) для оптимального формирования лазерно-струйного потока. Создано оптимальное отверстие полости насадка, удовлетворяющее всем заявленным требованиям. С помощью программы Mathcad проведено моделирование распространения светового потока, как в полости насадка, так и в свободной струе. Было проведено математическое моделирование потока жидкости через полости построенных насадков в программной среде FlowVision. Проведены исследования на имитационной установке и на лазерно-струйном комплексе ЛСК-400-5. Диаметр струи должен быть больше диаметра луча лазера на величину ее распада.*
<u>*Ключевые слова:*</u> *лазерно-струйная обработка, отверстия, высокоэнергетический поток.*

Анотація. *Розглянуто результати досліджень лазерно-струменевої технології обробки матеріалів, як одного з перспективних методів різання різних виробів. На підставі існуючих світових розробок розглянуті особливості створення профілів насадків (перехідної ділянки) для оптимального формування лазерно-струминного потоку. Створено оптимальний отвір порожнини насадка, що задовольняє всім заявлені вимоги. За допомогою програми Mathcad проведено моделювання розповсюдження світлового потоку, як в порожнині насадка, так і в вільному струмені. Було проведено математичне моделювання потоку рідини через порожнини побудованих насадків в програмному середовищі FlowVision. Проведено дослідження на імітаційній установці і на лазерно-струменевому комплексі ЛСК-400-5. Діаметр струменя повинен бути більше діаметра променя лазера на величину її розпаду.*
<u>*Ключові слова:*</u> *лазерно-струминна обробка, отверстия, високоенергетичний потік.*

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