Mech. Adv. Technol. Vol. 6, No. 3, 2022, pp. 317–327

DOI: 10.20535/2521-1943.2022.6.3.269900

UDC 621.54.25

Using the functional approach in the development of hybrid processes in engineering: practical aspects

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Received: 23 September 2022 / Accepted: 14 November 2022

Abstract. *The principles of creating hybrid processing processes based on the functional approach are given. The base of this approach, its theoretical aspects are given in the first part of the article. The practical application of the approaches is reflected in specific scientific and technical problems in the problem of high-quality cleaning of the surface from various adhesive coatings, the use of methods for obtaining holes and perforations in workpieces from metals and composite materials, as well as in the problem of contour cutting of plates from super hard sintered materials. It is shown that the use of a functionally oriented approach makes it possible to identify such combinations of force and energy effects that make it possible to process even those materials that are considered difficult to process or not machinable.*

The combination of actions that are heterogeneous in nature into one instrumental effect also allows for a new way of shaping the performed holes. At the same time, the properties of the workpiece have a much smaller effect on the parameters of the obtained surfaces than with traditional processing

Samples of cleaned surfaces, cuts of super hard materials, holes in honeycomb systems of aerospace engineering are presented.

Keywords: *hybrid tool, functional approach, processing of composites, laser processing, jet-laser cutting, cryogenic ice generation.*

Introduction

Traditionally, when creating new products, the range of tasks invested in ensuring the minimum costs for the implementation of the production cycle, ensuring the specified parameters of quality, durability, and reliability. Another block is the issue of ergonomics, environmental friendliness, and recyclability of the product. Somewhat less often the issues of marketing, active promotion of the usefulness and necessity of the product, highlighting its most important competitive advantages are considered.

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The experience of recent decades shows that sometimes success in the market is provided by such approaches, which are fundamentally new, non-standard, forcing to attract the attention of consumers. Thus, the manufacturer often encourages the consumer to purchase products; the so-called concept of “activation” or “formation of the need” to purchase this product is implemented, even if the consumer has no obvious need for it.

In the first part of our work, we formulated the main generalizations based on the works [1–9], which resulted in generalizations reflected in [8, 12, 14, 16, 17]. The practical aspect of the application of such approaches is no less interesting, since it allows one to transform theoretical provisions into scientific and engineering techniques that allow one to effectively solve many problems of modern production. Here are some simulation results for solving problems of practical importance.

The purpose of the work

Is to confirm the expediency of using a functional approach to solving applied problems of mechanics from the point of view of substantiating new technical means and processing methods.

Problem solving methods

Theoretical prerequisites for using the functional approach are considered in detail by us in the previous part of the work. However, practical application required the use of a number of experimental methods for studying the behavior of a solid body, the features of the outflow of liquid from nozzles and nozzles, optics, the theory of heat and mass transfer, as well as statistical processing of the results of direct and indirect measurements.

The study of the cut surfaces, as well as the surfaces obtained after processing, was carried out by the methods of electron and optical microscopy, with the selection of topographic and phase contrast. Obtaining equations relating technological regimes with controlled parameters (geometry of the resulting holes, microgeometry of the surface layer, cut parameters, etc.) was carried out by regression analysis methods.

Obtained Results

Task 1. Cleaning

This task is the most difficult. As a rule, the properties of the surface layer (for example, paint, dirt, etc.) are comparable to the properties of the base – the material of the product.

From the point of view of energy transformations and formation of the function of effective surface cleaning, the processes can be represented as follows (Fig. 1). Here it is marked E_e – energy from the power supply, which in the form of mechanical work is transformed into the potential energy of the compressed fluid E_n; E_m – energy, which involves energy transformations in the multiplier (in particular, the kinetic motion of the mechanical part of the multiplier and the potential of the compressed fluid); E_k– kinetic energy of flow (jet) motion E_p – the energy of destruction of the surface film; E_d- the energy of deformation of the base (the deformation of the film is neglected because we consider it quasi-brittle undeformed due to its small thickness).

When performing jet cleaning (Fig. 1, *a*), electric energy, after a four-stage transformation, consumes elastic deformation of the base E_d and destruction of the surface film E_p. The destruction of the film material is mainly due to deformation of the microvolumes of the material with the emergence of compressive in the center of influence and tensile outside the stress stresses, leading to active development of initial defects with the formation of macrocracks (macrodamages) with separation of sludge particles. Insignificant film thickness h_p and the influence of the mechanical properties of the base, E_o Young modulus, δ, relative extension, [σ], strength, causes low deformability of the surface layer and, therefore, low efficiency of the process. The introduction into the flow of abrasive leads to changes in energy conversions the kinetic energy of the flow is spent on the acceleration of abrasive particles by mass m_i to speeds v_a and to create a vacuum in the supply channel capable of moving particles to the flow, resulting in the energy of the flow E_k decreases with increasing kinetic energy E_k' moving abrasive particles. Part of the supplied energy E_r additionally spent on cutting work, because the abrasive particles not only deform and strengthen the barrier, but also moving in contact, perform micro-cutting work. This actively destroys the adhesive adhesion of the contaminant layer, but the surface of the substrate is also affected, because the microhardness of the abrasive particles σ_a exceeds σ_T base, and the presence of many faces and a sufficient supply of kinetic energy $m_i v_{ai}^2/2$ allows to carry out microcutting of elements of a surface layer.

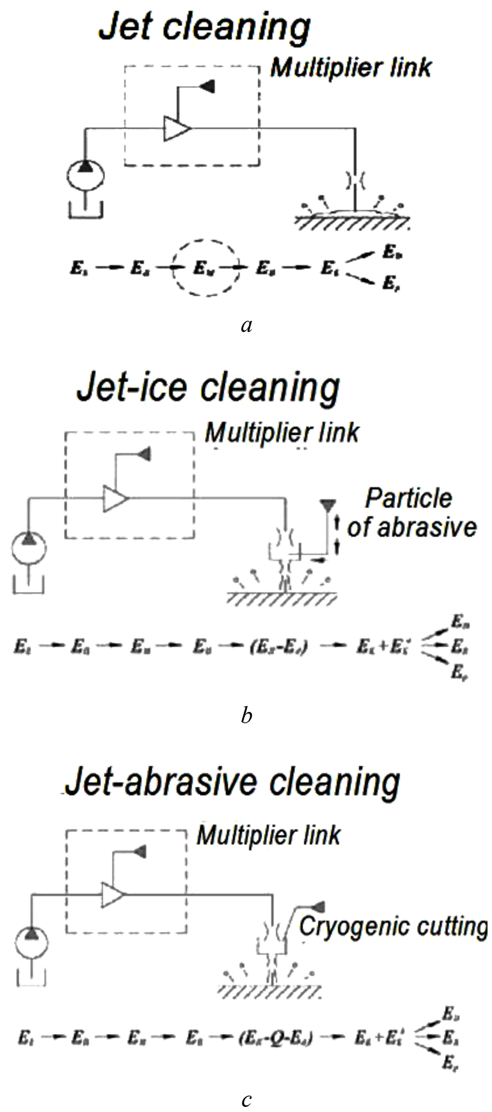


Fig. 1. Formation of a useful function (jet cleaning) because of energy transformations in the system

Cleaning the surface with ice water (Fig. 1, *c*) is almost identical to the above method, but here $\sigma_a < \sigma_T$ and changes in the state of the surface of the base does not occur. The formation of ice cubes is due to the phenomena of heat transfer between the cryogenic fluid (liquid N_2) and transient flow, which leads to the loss of additional heat *Q*. Processes on the surface are like the case of Fig. 1, *b*. However, the component E_r is much smaller.

A table of beneficial and harmful factors of the cleaning process is compiled (Table 1), taking into account the energy transformations in the system and the results of cleaning. The decomposition of the hydroabrasive effect was performed: $E_d \cap E_r \rightarrow E_d + E_r$ (shock and abrasive action→ impact + abrasive); the condition of combination of cryogenic and water flows due to inversion of elements of jet formation is also changed.

The lack of parallel connections, fewer elements allows not only to reduce the overall size of the device (in particular, L_g) and get a number of benefits, table. 1 (3, 4): smaller size L_g, enlarged D_p. Impact action on the surface of the treatment can be carried out by concentrated masses in the form of metal balls of mass m_i, located at the end of the tool and fixed on the suspensions with elasticity c, and which will receive the energy of oscillations from the action of the flow, Fig. 2 *a*. The result of interaction modeling is presented next to it (Fig. 2, *b*).

A description of such a tubeless system, but additionally equipped with a conical annular nozzle, capable of providing a controlled change in the geometry of the shell part of the jet and its core, is given in [16], and is presented in [18].

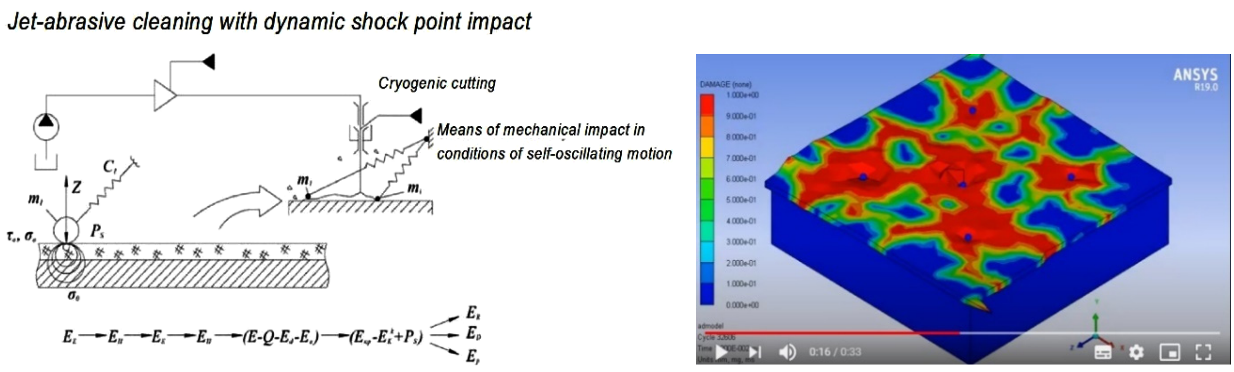
The simulation found that on thin shells, stresses that can cause a significant reduction in adhesive adhesion to the substrate, propagate from the point of action of the concentrated mass to a distance up to 10 d_m at angles 25°–35° relative to the line of action of the impact of the body, which generally corresponds to the provisions of the linear mechanics of the destruction of elastic bodies.

Receiving energy from the flow, the initiators, performing self-oscillating motion, encounter the treated surface having a layer of strong contamination, and create a multipoint shock-cyclic loading of the surface, which leads to active development of initial defects of the contamination film. It is given better and more productive cleaning. It is shown that the local stresses generated based on Hertz contact problems reach 15–20 MPa, do not have a significant effect on the base surface, which is a thin curved shell, do not change the state of its surface in the plane of adhe-

Table 1. Beneficial and harmful factors of the cleaning process

№	Formation of energy influence	The results of the process				Consequences for the basis
		Useful		Harmful		
		E_p	E_r	E_d	Q_d	R_z, R_a
1	Fluid flow	↓	–	↓	↑	–
2	Water abrasive jet	↑	↑	↑	↓	↑
3	Water ice stream (traditional device)	↑	↓	↓	<↑	–
4	Water ice stream (tubeless device)	↑	↑↓	↓	↑↓	–
5	Hybrid influence	↑	↑	↑	↓	–

- Marking: ↓ - low; ↑ - high; ↑↓ - middle; <↑ - reduced



a *b*

Fig. 2. Combination of mechanical and hydro-mechanical influences (*a*) and simulation result (*b*)

sion, but lead to defects in surface film in the form of cracks and exfoliation. In this case, the extraction of the film by water-ice flow is more dynamic.

It should be noted that, in contrast to known technical solutions, cleaning efficiency (and accordingly the area of the cleaned surface per unit time $\Delta\tau$) the use of the proposed hybrid tool is more effective if the axis is located at angles greater than $\pi/4$, Fig. 3.

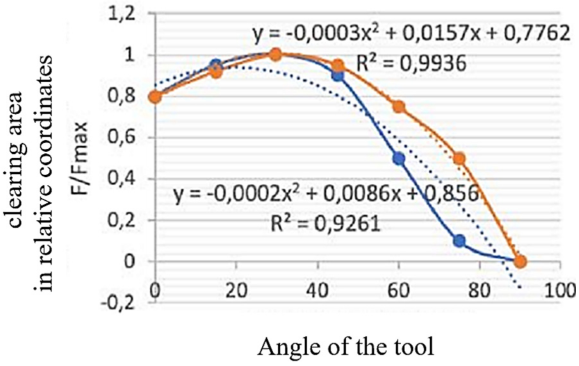


Fig. 3. Changing the cleaning area F/F_{max} at different angles of the axis of the device for typical and proposed technical solutions: –●– – traditional flow; –●– – proposed solution; ········ – polynomial (traditional flow)

Task 2. Drilling

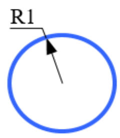
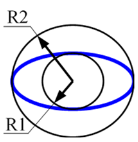
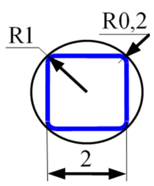
The combination of pulsed laser radiation with the action of jet flux proves that the localization of the impact is more pronounced, and the penetration of the instrument is greater (according to Table 1. – up to 5...6 levels of separation, [18]). In addition, it is possible to perform the profiling of high-energy flux: for example, changing the shape of the jet with the introduced laser beam allowed to obtain a change in the shape of the hole, which in this case is obtained. It was found that the channel profile and the cross section of the cut determine the shape of the flow flowing into the barrier; however, this shape is a function of the p_b pressure at the nozzle inlet and the distance from the cut to the inflow surface h_s, ie a, $b = f(p_b, h_s)$. Simulation in the FlowVision environment allowed to build the appropriate cross sections of the jet (Table 2) and to establish patterns of change in the size of the spot.

The following processes were investigated: *M* – mechanical puncture; *HA* – hydroabrasive cutting (WJ); *LC* – laser cutting in the traditional way (with blowing the impact zone with inert gas); *LCC* – laser cutting with liquid (water) cooling - hybrid process *G-LCC*; *WJGL* is a hybrid process of laser jet cutting *G-WJGL*. Some hybridization process given oh Fig. 4.

Conducting experimental studies allowed to obtain several curves of change in intensity *I* as a function of the Reynolds number Re and to obtain the corresponding regression equations for the controlled sections (Table 2). In the surface layer of the workpiece there are phenomena associated with changes in the structure of the layer and its chemical composition, because at the time of the pulse of radiation on the surface there is a cavity of supersaturated liquid, the size of which changes cyclically when changing modes of energy. Therefore, it is established that there is an equalization of the radiation intensity over the cross section of the jet, and the rational distance from the nozzle cut to the treatment surface should be $l = (15\ldots25)\,D_{max}$.

Another important conclusion is that the regularities of the distribution of the radiation intensity in the flux are identical and such that for numbers Re over 2800 do not depend on the cross-sectional shape of the jet in the flow plane.

Table 2. Change in intensity in the fluid flow from the shape of the nozzle hole

№	Nozzle cross section shape	Minimum intensity at the edge	Reynolds number range
1		$I_{min} = 0{,}2255 - 0{,}0107\cdot A - 0{,}0171\cdot B + 0{,}0022\cdot S - 1{,}42\cdot 10^{-5}\cdot \mathrm{Re}$	2000...5000
2		$I_{min} = 0{,}3854 - 0{,}0161\cdot A - 0{,}0307\cdot B + 0{,}0038\cdot S - 2{,}97\cdot 10^{-5}\cdot \mathrm{Re}$	2000...5000
3		$I_{min} = 0{,}4398 - 0{,}0204\cdot A - 0{,}0322\cdot B + 0{,}0045\cdot S - 1{,}42\cdot 10^{-5}\cdot \mathrm{Re}$	2000...5000

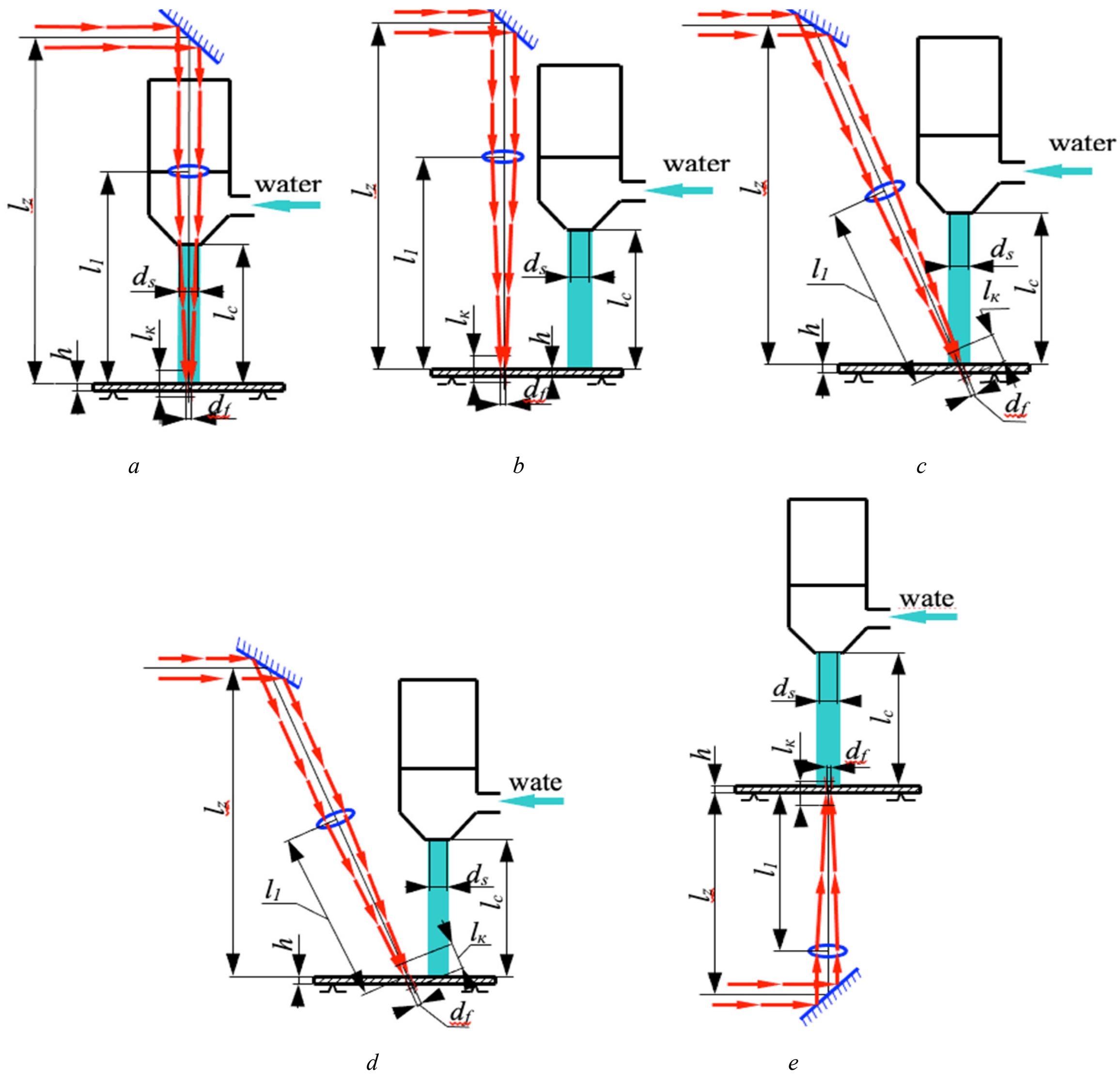


Fig. 4. Variants of combination of a water jet and a laser beam for performance of LCC or WJGL

The time of stitching the hole in the sheet blanks is determined by the intensity of the pulses, and the development of the funnel has a pronounced slow nature with increasing depth of immersion.

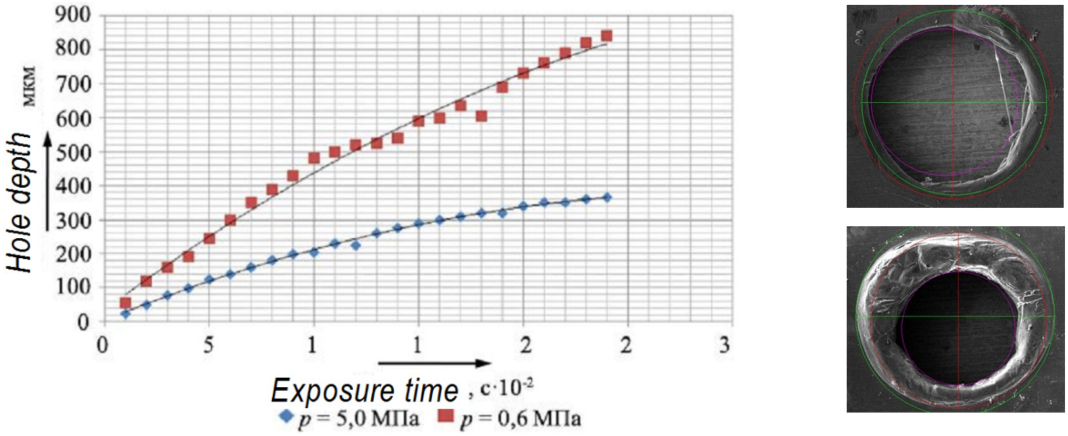
The result of development of the hole during jet-laser stitching in a plate with a thickness of 1.2 mm (12X18H10T) given on fig.5, a and some example of hole in AMG-2H thickness of 55 μm present of fig.5, *b*

Microelectronic study of the accuracy of the hole shape, the size of the zones of thermal destruction and the presence of stress concentrators showed the following. The most accurate holes were made by the jet-laser method: at a given diameter of 0.070 mm, the actual size ranged from 0.067 to 0.071 mm, which is a fairly accurate and reproducible result. Other methods of obtaining holes show that the holes are obtained with a wide range of values in the range of 0.63–0.75 mm. The most inaccurate can be considered holes obtained by mechanical puncture – the average diameter varies from 0.64 mm to 0.97 mm.

It was also found that mechanically obtained (M) holes have significant gaps, often exceeding the diameter of the hole, and the edges are deformed. Thus, when mechanically punching holes, the width of the destructive zone can reach 0.45–0.55 mm.

The holes obtained by the laser with the purge of the processing zone (LC) have a different configuration and are characterized by the presence of a molten zone up to 0.25 mm wide (Table 3). Such configuration and dimensions depended of distance between surface and laser optic systems.

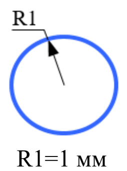
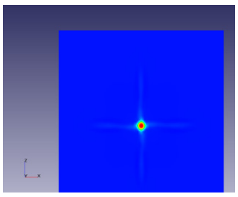
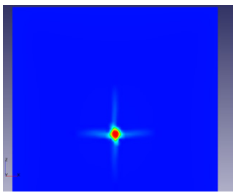
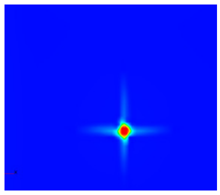
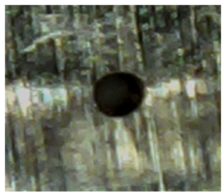
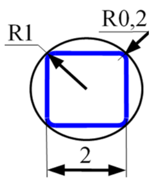
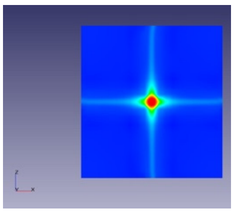
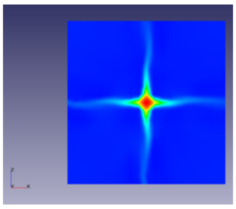
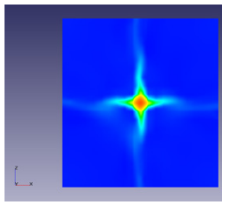
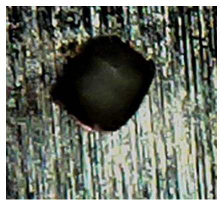
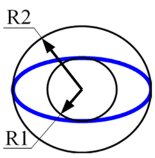
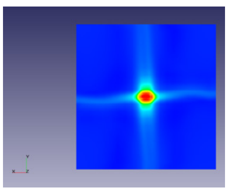
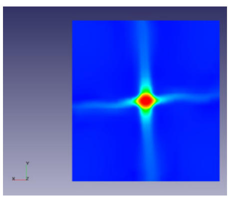
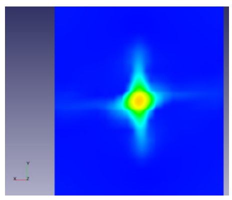
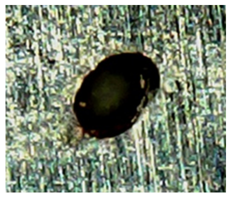
The melting zone has clearly separated microcracks in the radial direction. The use of water to cool the area of the firmware (in the implementation of laser perforation with purge and cooling (LCC)) does not significantly reduce the diameter of the hole, and in some cases contributes to its increase, while distorting the shape of the hole. The resulting holes have different semi-axes – with a nominal diameter of 0,7 mm, the difference can be up to 0,32 mm.



a *b*

Fig. 5. Development of the hole during jet-laser stitching (*a*) in a plate with a thickness of 1.2 mm (12X18H10T) and the obtained holes in the foil AMG-2H with a thickness of 55 μm (*b*)

Table 3. Hole different configuration and dimensions in function of distance

№	Nozzle cross section shape	At a distance from the end of the nozzle 10 mm	At a distance from the end of the nozzle 25 mm	At a distance from the end of the nozzle 50 mm	Holes in the plate with h = 1.2 mm
1					
2					
3					

The melting of the end face is minimal, no more than 0.085 mm, but with little heating of the end face. Laser pulse (LC) firmware is also characterized by low quality, small diameter, and significant melting zone.

Task 3. Cutting

The hybrid tool in the form of a laser beam connected to the jet allowed the processing of materials that are quite difficult to process in the usual way. Thus, for hard alloys and high-strength materials, cutting in the traditional way (for example, hydroabrasive) does not give the desired results. The skeleton of such composites is quite resistant to abrasive wear and can withstand shock and cyclic loading from abrasive particles with almost no problems. The laser also has a limited effect, making it impossible to achieve significant depths of the slot.

Experimental verification proves the following. For hard alloys and high-strength materials, cutting in the traditional way (e.i. hydroabrasive) does not give the desired results. The skeleton of such composites is quite resistant to abrasive wear and can withstand shock and cyclic loading from abrasive particles with almost no problems. The laser also has a limited effect, making it impossible to achieve significant depths of the groove.

At the same time, the hybrid tool has certain advantages. So, in Table 4, 5 variants of hybrid cutting for different superhard materials are given.

Based on Table 4. technological action for obtaining of a particular element can be presented as

$$W_{2i}(t_k) = W_1^{Fp1}(t_k) \cap W_1^{Fv1}(t_k) \cap W_1^{Fv2}(t_k) \cap W_1^{n1}(t_k).$$

Corresponding transformations for LB for different materials are to include four equations now (according to the number of components):

$$h|_{W^{Fp}} = b_0 + b_1 s_k + b_2 T + b_3 Q_v + \ldots;$$

$$\delta|_{W^{Fv}} = b_0 + b_1 s_k + b_2 T + b_3 Q_v + b_4 h_l + \ldots,$$

$$l|_{W^{Fv}} = b_0 + b_1 s_k + b_2 T + b_3 Q_v + b_4 h_l + \ldots$$

$$P|_{W^{Fv}} = b_0 + b_1 s_k + b_2 T + b_3 Q_v + b_4 h_l + \ldots$$

where T– impulse energy, Q_v– liquid discharge out of the nozzle, h_l – depth of the groove in the worked piece.

Microscopic analysis of the cut performed with such modes showed the following. When feeding 300 mm/min (and other parameters determines on result of simulations) we can get a groove 0.13–0.14 mm wide and 2.5–2.6 mm deep; the inclination of the cut did not exceed a few angular degrees, and the surface roughness was at level R_a 6.3 µm. (Fig. 6).

At the ends of the sample formed quite deep grooves of the spray, which can be explained by the action of liquid droplets formed because of air flow into the liquid bath, over which the sample was located. The destruction of the surface occurred due to several processes due to the presence of water on the surface activated by the laser beam. The increase in the depth of the groove is obviously due to the action of the liquid, which not only cools the surface, but also creates a kind of multi-refractive focusing system – an additional “translucent mirror” that precedes radiation scattering and increases the absorption capacity of the material. It can also be assumed that it is water, which under the action of a concentrated heat source, dissociated on H^+ and OH^- participates in chemical transformations and promotes the formation of low-temperature plasma.

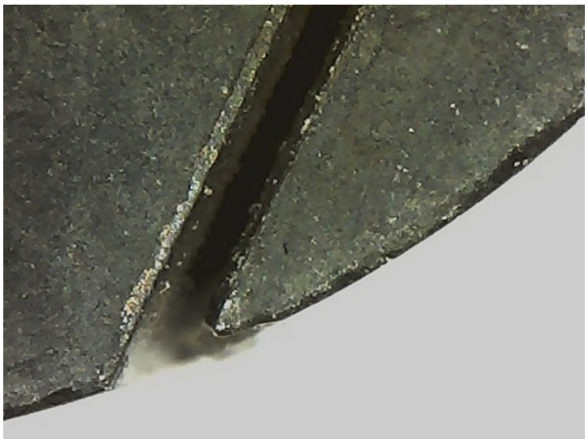
A more detailed study of photomicrographs of the end face of the cut from the side of the beam and from the

Table 4. Provision of the product function by creation of element E_i by a technological action $W_{ij}(t_k)$ – WJGL

Worked material	Functions *F’*			
	Useful F_{pi}	Harmful F_{vk}		Neutral F_{nj}
	Obtaining of orthogonal edge of the product (depth *h*, mm)	Thermodestruction δ, µm	Cracking *l*, mm	Variation of porosity *P*
HA(lower (supporting) layer from hard alloy based on tungsten carbide)	Intensive, linearly depending on *t* (number of cuts *N*)	Minimum	Exists	Absent
PSHM(polycrystal superhard materials)	Intensive, decreasing with increase of groove depth h_l	Minimum	Minimum	Is observed in destructed zone
PCD(polycrystal superhard composite on the basis of synthetic diamond)	Nonlinear medium-intensive	Essential	Absent	Is observed in destructed zone

Table 5. Change in the rate of penetration of energy flow into the material depending on its thickness

Types of working		HAC	LC	LCC	WJGL
Modes of working		100 mm/min, 350 MPa, 0,5 kg/min	30 mm/min, 400 W, 100 Hz	30 mm/min, 400 W, 100 Hz, 0,5 MPa	
		–		2,8 mm	1,05 mm
HA	R_a, µm	12,5	6,3	6,3	3,2
	h, mm/cycle	6,4	5,95	3,5	3,0
	δ, mm/5,0 mm	0,3–0,9	0,02–0,1	0,02–0,09	0,02–0,04
PSHM	R_a, µm	–	6,3–3,2	3,2	2,5–3,2
	h, mm/cycle	< 0,01	3,0–3,2	2,4	1,5–1,75
	δ, mm/5,0 mm	0,8	0,05–0,10	0,02–0,05	



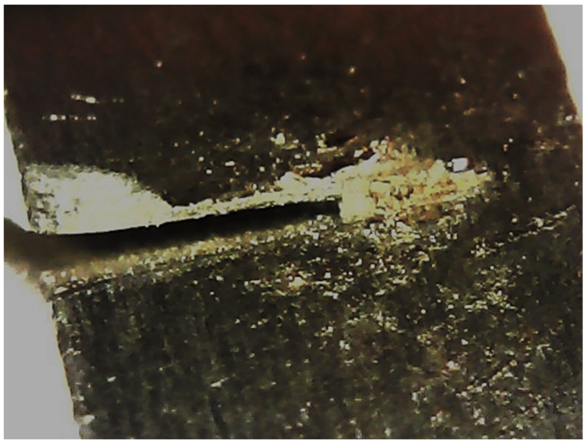


Fig. 6. Groove obtained at a working feed rate of 300 mm/min. Nd: YAG laser: photo from the machining plane and from the end face; grooves from liquid droplets that hit the end of the air stream and were activated by laser

opposite side showed that the cut is heterogeneous in structure and number of surface defects. At the same time, no significant defects and surface damage were detected.

Thus, the use of water supplied as a refrigerant to the low-pressure laser zone significantly enhances the cutting effects, provides a better cut edge, and reduces the thickness of the destructive layer. Differences in the calculated depth of the groove with the obtained experimentally should be considered by introducing additional coefficients in simple empirical equations, which can be obtained by known means of experiment planning and obtaining multifactorial regression equations.

It is established that the increase in the intensity of heat dissipation leads to a greater drop in temperature, and, consequently, to a decrease in the size of the area covered by thermal exposure. Thus, the jet-laser destruction of the material will occur in the local (not more than 0.1–0.15 mm) zone, which is much less than the zone of both hydrodynamic and thermal effects [17].

Discussion

The use of a functionally oriented approach made it possible to obtain new or significantly improved effects in many processes focused on the synergy of the impact of energy flows or mechanical impacts on the treated surface.

Thus, according the ***task 1*** the hybridization of a jet-cryogenic flow with mechanical cyclic action made it possible to significantly increase the productivity of the surface cleaning process, including in closed cavities (for example, in the combustion chambers of turbine units), as we indicated in [18].

It was established that the energy E_Σ, that enters the cutting zone from the flow of icicles E_k, the liquid component E_p and the mechanical impact E_m of concentrated masses suspended on elastic links is spent on the useful work of destruction of A_r in the amount of 5–7% of E_Σ. Such an increase can be seen in the synergetic effect that takes place in the processing zone, as well as the conditions of formation of icicles, their shape (and, accordingly, cutting properties), conditions of impact-cyclic loading of the surface by concentrated masses.

Using the proposed hybrid jet tool with additional small masses on elastic suspensions, capable of performing oscillating movements and impact-cyclic loading of the surface, it is possible to efficiently clean complex surfaces at angles in the range of π/3–π/6. At the same time, the maximum pressure of the liquid does not exceed 90–110 MPa, and the consumption of cryogenic liquid for the formation of the flow of icicles is 40–50 g/s.

This was proved based on energy dispersive microanalysis of the surface layer (Fig. 7), which was subjected to cleaning, as well as construction of the surface profile based on the topographic contrast from the electron microphotograph (Fig. 8).

Analysis of the spectra proves that the most salt and oxide contamination residues are observed based on Fe with low alloying, while on the basis of Ni + Cr + Fe the residues are on average 40–45% less. The verification of its adequacy proved that this linearized model satisfactorily describes the cleanliness parameter for removing surface films from curved surfaces, although we have certain nonlinearities, and the parameter σ_a has the greatest influence on the peeling of adhesive and high-strength contaminants.

According to ***task 3*** the simultaneous action of the laser-jet flux localizes the destruction zone more, but the effect of cutting with the immersion of the groove in the body of the material gradually decreases. At the same time it is possible to achieve 6 levels of localization (according to table 1). These considerations allowed us to propose an original technology for cutting a composite plate, which is a layered system with a layer of polycrystalline cubic boron nitride thick on a carbide base. 2.8 mm. The total thickness of the plate is 4.5 mm.

A sector with a diameter of 3.5 mm was cut out by a hybrid process (Fig. 9).

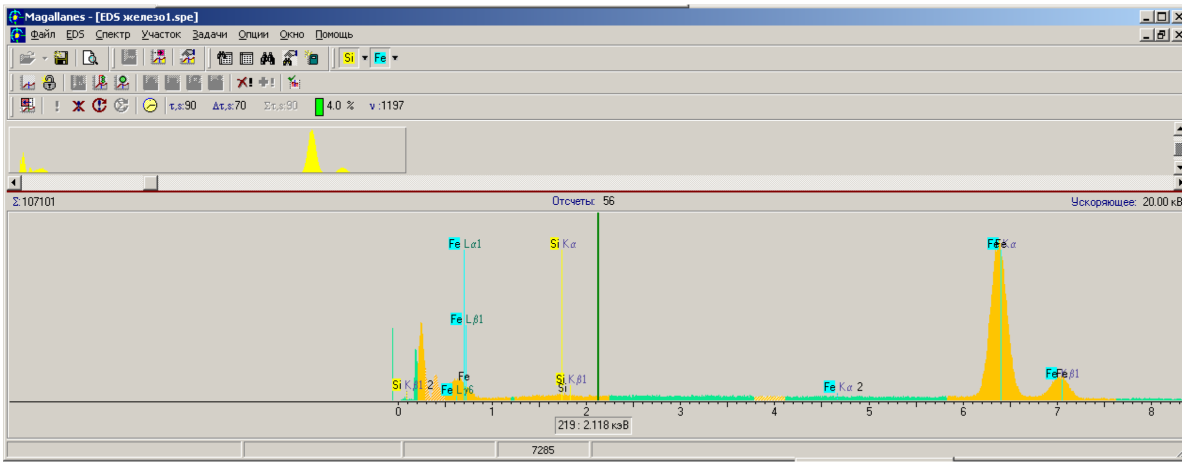
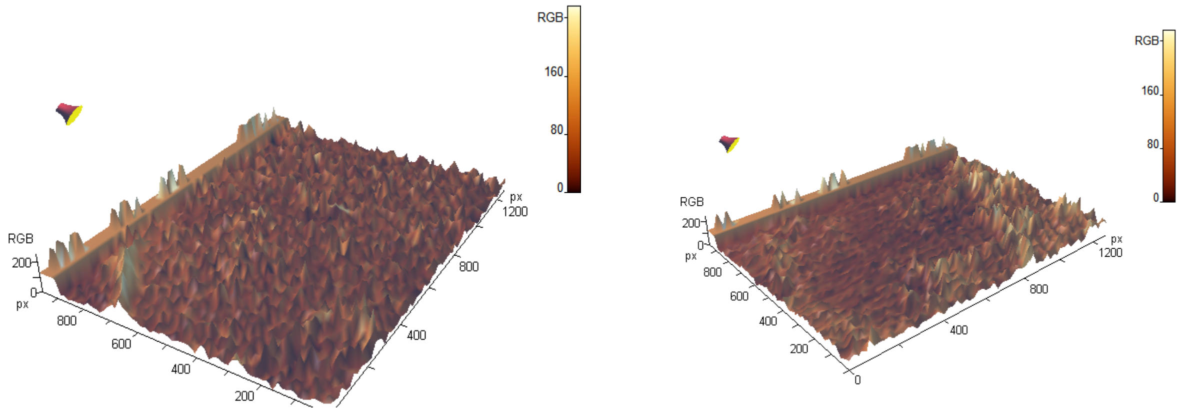


Fig. 7. Obtained spectra of the surface layer of the studied samples



a *b*

Fig. 8. Surface Reproductions with contamination (*a*) according to the obtained electron micrograph of the examined surface and the surface on which the damage initiator acted (*b*)

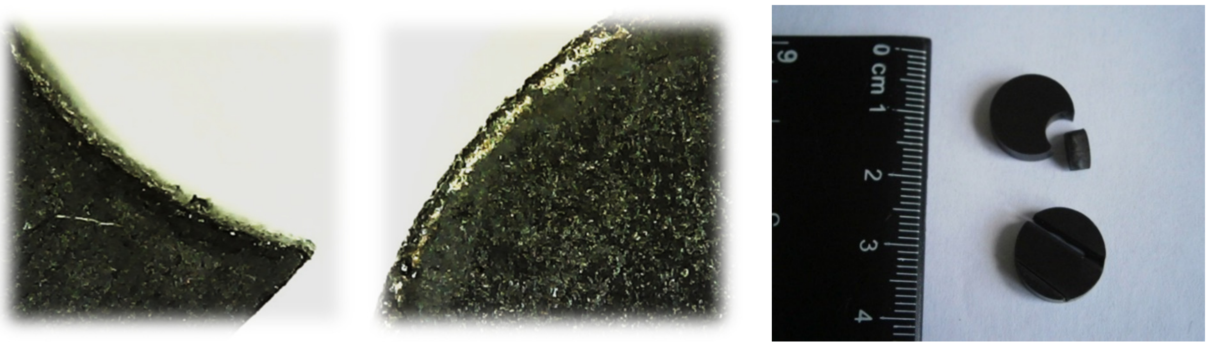


Fig. 9. Sector cut from the experimental composite plate CBN + WC (TiS) and enlarged photos of the obtained surfaces

Thus, the use of a hybrid tool allowed to obtain a high-quality cut (end roughness – 3.2 μm, slot width – 0.12 mm, while the time to perform the cutting operation on the specified contour is only 1.8 minutes. Attempts to cut plates in another way had no result, because the plate was cohesive and adhesive damage, which made impossible to continue its work.

The hybridization of the influence as well as its adaptation to the problems of forming holes (***task 2***) also gives a good result, allowing to change the shape of the hole, while this need can only be partially provided by other methods of impact.

Thus, the functional approach, focused on ensuring the final parameters of products by combining, supple menting, or synergizing the actions of individual components, appears as a universal tool for finding, justifying and adopting such combinations of instrumental influence that will maximally satisfy the desired result with minimal energy or material costs.

Conclusions

The methodology and bases of creation of hybrid highly effective tools for processing of composite materials are developed. It is shown that the application of principles and approaches to identify rational methods of action on the processed material can significantly change the depth of penetration of technological action from the macro level to the microlevels, and in some circumstances – to the nanozones of influence.

The practical application of the approaches is reflected in specific scientific and technical problems in the problem of high-quality cleaning of the surface from various adhesive coatings, the use of methods for obtaining holes and perforations in workpieces from metals and composite materials, as well as in the problem of contour cutting of plates from superhard sintered materials. It is shown that the use of a functionally oriented approach makes it possible to identify such combinations of force and energy effects that make it possible to process even those materials that are considered difficult to process or not machinable.

It is shown that cleaning with a hybrid tool that combines water-ice impact with mechanical initiation of initial defects of non-rigid hollow base surfaces is 25–40% higher compared to typical technical solutions. Cutting composite materials by laser-jet method is expedient in the treatment of high-strength compounds. The greatest expediency is seen in the treatment of multilayer compositions, for which it is possible to perform curved cuts with a roughness level of R_a 6.3 μm to a depth of 10 mm.

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Використання функціонального підходу при розробці гібридних процесів у машинобудуванні: прикладний аспект

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Анотація. *Створення нових високоефективних методів обробки матеріалів, у тому числі, композиційних, є сучасною актуальною науково-технічною задачею. У цьому аспекті використання гібридних процесів вбачається обґрунтованим і доцільним. Доповнення принципами функціонального підходу дозволяє значно скоротити час на розробку процесів і отримати нові ефекти, неможливі при традиційних методах обробки.*

Оскільки теоретичні засади авторами було розроблено раніше, метою роботи є аналіз практичного аспекту використання даного підходу.

Так, показано практичне застосування функціонально-орієнтованого підходу у розв'язанні конкретних науково-технічних проблем, зокрема в проблемі якісного очищення поверхні від різноманітних клейових покриттів, при отриманні отворів і перфорацій у заготовках з металів і композиційних матеріалів, а також у задачі контурного різання пластин із надтвердих спечених матеріалів. Показано, що використання функціонально орієнтованого підходу дає змогу виявити такі комбінації силових та енергетичних ефектів, які дозволяють обробляти навіть ті матеріали, які вважаються важкооброблюваними або необроблюваними. Сполучення різнорідних за природною сутністю дій в один інструментальний вплив дозволяє також по-новому здійснювати формоутворення виконуваних отворів. При цьому властивості заготовки мають значно менший вплив на параметри отримуваних поверхонь, ніж при традиційній обробці.

Представлені зразки очищених поверхонь, зрізів надтвердих матеріалів, отворів у стільникових системах аерокосмічної техніки.

Ключові слова: *гібридний інструмент, функціональний підхід, обробка композитів, лазерна обробка, струменево-лазерне різання, кріогенна кригогенерація.*