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Chapter

Cutting Superhard Materials by Jet Methods (on Functional Approach)

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Abstract

Dimensional processing of products made from hard alloys and superhard materials is of a certain interest for contemporary high-technology production, as it enables creation of half-finished or final products of various geometric shapes from workpieces obtained by sintering. In this case conventional methods, first of all abrasive processing and electroerosion cutting, find limited application, which is caused by special features of the structural condition and physical and mechanical properties of the materials of the processed workpieces. The functional approach can be used in working of composite workpieces from laminated superhard materials. The performed research with the use of hydro-abrasive cutting (HAC), laser cutting (LC), laser cutting with water cooling (LCC), and water jet-guided laser (WJGL) has enabled studying of the intensity of destruction area introduction into the worked piece and finding out the functional features of a particular process that are caused by the working conditions. It has been shown that the hypothesis of quasistationary rate of destruction is unacceptable for such materials, which is caused by the structure and high hardness of the material. It has also been determined that when deepening increases, the rate of jet introduction has a pronounced tendency toward reduction.

Keywords: carbon materials, carbon composite, water-jet-guided laser process, jet methods

1. Introduction

Dimensional processing of products made from hard alloys and superhard materials, in particular, contour cutting prismatic and circular plates and arbitrary shaped flat workpieces, is of a certain interest for contemporary high-technology production, as it enables creation of half-finished or final products of various geometric shapes from workpieces obtained by sintering.

In this case conventional methods, first of all abrasive processing and electroerosion cutting, find limited application, which is caused by special features

of the structural condition and physical and mechanical properties of the materials of the processed workpieces. Processing of products made from laminated compounds is especially complicated as there is a danger of breakage of adhesion bonds in the "base-surface layer" plane. Workpieces made from such products include diamond carbide (DC) composite containing an upper (working) layer of polycrystal superhard composite on the basis of synthetic diamond (PCD) and a lower (supporting) layer from hard alloy based on tungsten carbide (HA), obtained by sintering in high-pressure apparatus [1].

It was demonstrated that, first of all, liquid blasting and laser blasting have good prospects in industrial use for cutting flat workpieces from polycrystal superhard materials (PSHM) and HA, as they allow creation of the cut surface with sufficient efficiency. However, the problems of provision of high quality of the worked surfaces of the products have not yet been solved in full.

So, surfaces of products from HA and PSHM obtained by the mentioned methods are characterized by high roughness and essential deviation of the shape. In Ref. [2], it is shown that hybrid processing methods based on a combination of different ways of power and other flows impact on the material that make it possible to essentially reduce working hours necessary for production and improve the quality of processing. At the same time, analysis of the final product from the point of view of its useful functions enables improvement of the method and scientific substantiation of most rational ways of impact on the workpiece to achieve the maximum quality level.

The solution to these problems can be found in the use of an innovative approach to development of hybrid working methods; its essence consists in provision of useful functions of the product on the basis of morphological analysis of variants of combination of power and energy flows generating a hybrid production process.

The purpose of the chapter consists in development of principles of functional approach to creation of hybrid processes as a morphological combination of various ways of power and energy flows that impact on the worked piece when functions and properties of the final product are formed by totality of results of some technological transitions realized on micro-, meso-, or macro-levels of the product.

2. Approaches to problem solution and research methods

Functional approach to development and creation of new machines, objects, and complex technical systems was studied by many researchers [3]. They state that any material object is characterized by a certain totality (matrix) of functions among which it is possible to single out useful, harmful, and neutral functions (**Figure 1**). Unlike a material approach, a functional approach is based on the fact that the product is made to perform a number of functions provided by corresponding material carriers (the cheapest ones or the ones with the least costly manufacturing steps).

This approach can also be applied to working technologies: the manufacturing process expressed through material carriers is to be minimized according to criteria taken into consideration—working time, cost price, and quality. Systemized data of this approach are presented in a number of papers, for example, [4].

The idea of modularity of technological processes (TP) and their functional orientation can develop in the following direction.

As all types of functions (useful, neutral, and harmful) are available in a final product, manufacturing steps are to be oriented in such a way that harmful
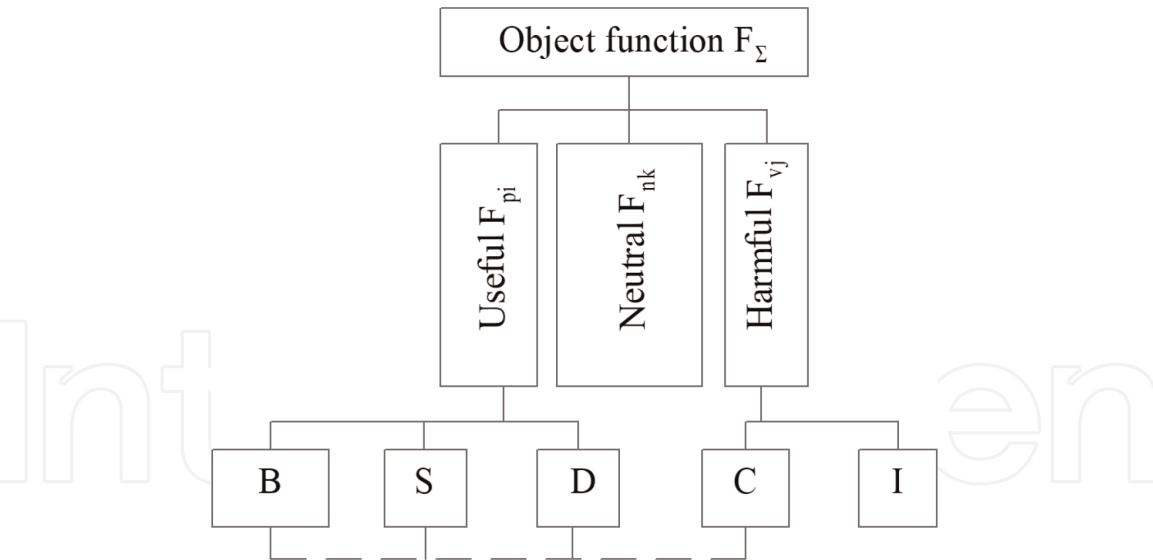
Figure 1.
Classification of the object functions: B, basic; S, secondary; D, derived (obtained without special provision); C, connected (accompany useful functions); I, independent.

functions be weakened and useful ones, in their turn, be obtained in the minimum number of steps. Under these conditions a technological process can be considered prospective if weakening or complete elimination of harmful functions takes place along with creation of useful functions during the steps.

Analysis of typical products of mechanical engineering from the point of view of functional approach reveals that practically always creation of a particular useful consumer function F_p will go together with manifestation of neutral F_n and harmful F_v functions. Then a product having only useful (under certain conditions) functions is ideal from the point of view of operation:

$$F_p = F_{pz}, F_v = 0, F_n \rightarrow \min, \tag{1}$$

where F_{pz} are the product useful functions having the following matrix of consumer properties

$$P = \sum_{i=1}^{l} F_{pi} + \sum_{j=1}^{m} F_{nj} + \sum_{k=1}^{p} F_{vk}. \tag{2}$$

Hence, an equation of restrictions (1) and optimization (2) makes it possible to choose the most rational material carriers of functions on the basis of morphological analysis and then to pass to material carriers in the technological process creating these functions.

As there is a functional interrelation between separate functions, that is,

$$F_v = pF_p, F_n = qF_p. \tag{3}$$

taking into account the fact that a function is created by a separate TP step in the form of transformation element W_p, Eq. (2) can be presented in the following form:

$$P = \sum_{i=1}^{l} W_p F_{pi} + \sum_{j=1}^{m} W_n q F_{pj} + \sum_{k=1}^{p} W_v p F_{pk}. \tag{4}$$

3

Taking into consideration the fact that TP cannot be aimed at creation of harmful functions and properties in the product, minimization of the unnecessary functions is expressed by dependence:

$$P = \sum_{i=1}^{l} W_p F_{pi} + \sum_{j=1}^{m} \overline{W_p} q F_{pj} + \sum_{k=1}^{p} \overline{W_p} p F_{pk},$$ (5)

or after transformation, in the following way

$$P = \sum_{i=1}^{l} F_{pi} \left(W_p + \overline{W_p} q + \overline{W_p} p \right).$$ (6)

Approaching of the totality of the product properties to the ideal implies transformation of summands $\overline{W_n} q$ and $\overline{W_v} p$ into zero, which is possible under the condition of absence of functional relation between useful and harmful properties of the product or under the condition that the process of obtaining useful properties due to a particular TP step is at the same time the inverse one as to the occurring harmful functions. Availability and interrelation of TP separate elements enable presentation of Eq. (6) in the following way:

$$P = \sum_{i=1}^{l} F_{pi} \left(W_p + \overline{W_p} q + \overline{W_p} p + \overline{W_p} (p + q) \right).$$ (7)

For totality of alternative variants of TP, the obtained equality is supplemented by quantitative signs of every function, the integral sum of which is equal to 1, then

$$I = \sum_{i=1}^{l} F_{pi} \left(b_{ki} W_{pi} - b_{vi} \overline{W_{pi}} p - b_{ri} \overline{W_{pi}} (p + q) \right).$$ (8)

under the condition that $\overline{b_{ni} W_{pi}} q = 0$, where b_{ki} and b_{vi} are the corresponding weight coefficients of each of the useful and harmful functions and b_{ri} is the weight coefficient of interaction of independent steps revealing reserves in improvement of output properties of the final product.

Describing the object by setting its initial condition C_n, as a totality of parameters characterizing the form and dimensions of the workpiece, its physical and mechanical properties, and final condition C_k via particular forms (dimensions, relative position of the surfaces, physical and mechanical properties, etc.), the technological transformation function φ_0 is presented as

$$\varphi_0 : \left\{ \begin{array}{c} C_{n1} \\ C_{n2} \\ \vdots \\ C_{nR} \end{array} \right\} \rightarrow \left\{ \begin{array}{c} C_{k1} \\ C_{k2} \\ \vdots \\ C_{kT} \end{array} \right\}$$ (9)

where C_{nR} is r-th elementary property of the workpiece; C_{kT} is t-th elementary property of the product; and R and T are total number of parameters of the workpiece and the product, respectively. The function $\varphi_0 = \Sigma W_i E_j$, where E_j is the product separate elements creating its properties.

As the product separate functions expressed via obtaining parameters of geometric accuracy, condition, structure, etc. can be generated in different ways, it

is expedient to create morphological tables that may provide the basis for search of more rational variants of combination of technological actions.

Let the created product realize some totality of functions $F_1...F_l$. To guarantee them the elements of condition of workpiece, E_{ki} is to be formed in such a way (**Figure 2**) that

$$F_l = C_{ki} = C_{pi}W_{pj} = \Sigma\, E_{ki}W_{pj}.$$

Application of this approach makes it possible to reveal rational sequence of TP steps, find causes of occurrence of harmful functions and eliminate them (or invert), and also determine the possibility for hybridization of the process to meet condition (1).

As generation of assigned functions is a multivariant task (**Figure 2** and **Table 1**), logical relations obtained on the basis of morphological analysis can be simplified according to the known rules of Boolean algebra provided that restrictions be met (7). In this case differentiation or hybridization of operation may have new effects that are to be taken into account by corresponding weight coefficients (8).
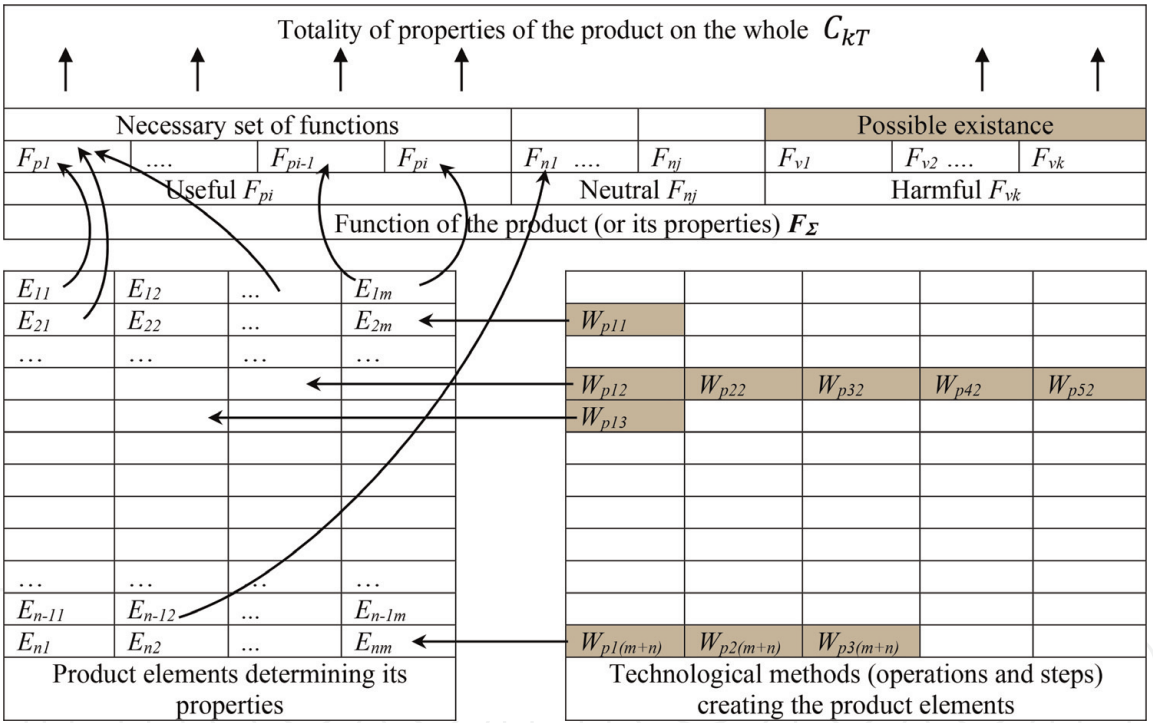

Figure 2.
Provision of the product functions F_{pi} by separate elements when they are generated by TP steps W_{ij}.

No. п/п	Product functions	Element provision	Material carriers—TP steps	Probable harmful functions
1	2	3	4	5
1	F_{p1}	$E_2 \cap E_3 \cap E_4$	$W_{p1} * W_{pj} + W_{p3}$	—
2	F_{p2}	$E_2 \cap E_3 + E_7 \cap E_8$	$W_{p4} * W_{p7} + W_{p3} * W_{p5} + W_{p2}$	F_{v1}
...				
L	F_{pl}			

Table 1.
Components of the product useful functions and their provision by TP.

The product properties are generated as a result of a number of manufacturing steps during which a complete or partial change of the initial properties takes place. Technological transformation of a workpiece into a product is achieved by purposeful total technological impacts $W_{ij}(t_k)$ of material $S_o(t_k)$, energy $E_o(t_k)$, and information $I_o(t_\kappa)$ types which enable presentation of a scheme of output properties generation according to **Figure 3** and write down.

$$W_{ij}(t_k) = S_o(t_k) \cup E_0(t_k) \cup I_o(t_k).$$

Then, on the grounds of the condition that tool technological impacts on the product are to be performed at the levels from nano-areas to the product on the whole, and the product is a 3D object, to realize the totality of variants of technological impacts the morphological matrix will correspond to the following form:

$$A_3^\Pi = \left\| \begin{matrix} \Pi_{11}^S & \Pi_{12}^S\ldots & \Pi_{21}^S & \Pi_{22}^S\ldots & H_{11}^S & H_{12}^S\ldots & H_{21}^S & H_{22}^S\ldots & E_{11}^S & E_{12}^S\ldots & E_{21}^S & E_{22}^S\ldots \\ \Pi_{11}^t & \Pi_{12}^t\ldots & \Pi_{21}^t & \Pi_{22}^t\ldots & H_{11}^t & H_{12}^t\ldots & H_{21}^t & H_{22}^t\ldots & E_{11}^t & E_{12}^t\ldots & E_{21}^t & E_{22}^t\ldots \\ \Pi_{11}^v & \Pi_{12}^v\ldots & \Pi_{21}^v & \Pi_{22}^v & H_{11}^v & H_{12}^v\ldots & H_{21}^v & H_{22}^v\ldots & E_{11}^v & E_{12}^v\ldots & E_{21}^v & E_{21}^v\ldots \end{matrix} \right\|$$

where $\Pi_{11}^s, \Pi_{12}^s, \ldots; \Pi_{21}^s, \Pi_{22}^s, \ldots; \Pi_{11}^t, \Pi_{12}^t, \ldots; \Pi_{21}^t, \Pi_{22}^t, \ldots; \ldots \Pi_{11}^v, \Pi_{12}^v, \ldots; \Pi_{21}^v, \Pi_{22}^v, \ldots;$ ...—variants of discontinuous technological actions along the corresponding axes s, t and v of the coordinate system of s, t, v; $H_{11}^s, H_{12}^s, \ldots; H_{21}^s, H_{22}^s, \ldots;. H_{11}^t, H_{12}^t, \ldots; H_{21}^t, H_{22}^t, \ldots; H_{11}^v, H_{12}^v, \ldots; H_{21}^v, H_{22}^v, \ldots$—different variants of continuous technological actions along the axes s, t and v of the coordinate system of s, t, v; $E_{11}^s, E_{12}^s, \ldots; E_{21}^s, E_{22}^s, \ldots;$—different variants of one-time technological actions.

The presence of variants of discontinuous technological actions makes it possible to consider processing of one element of the product in the form of a successive
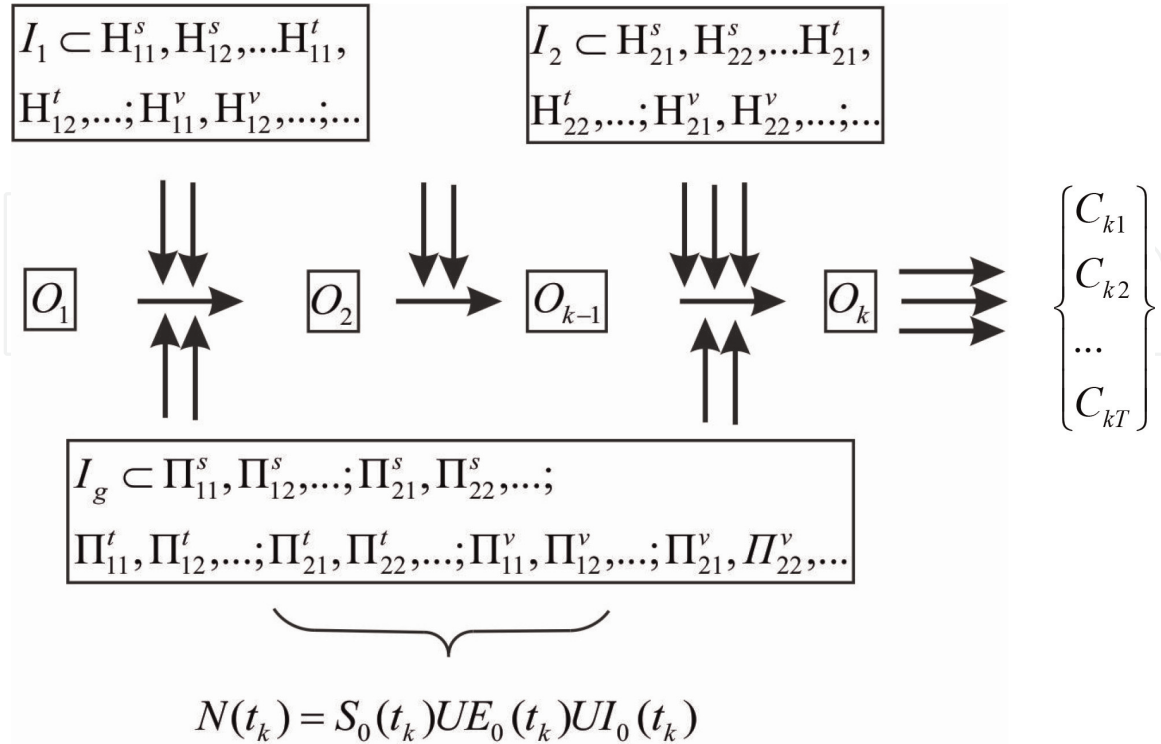
Figure 3.
Generation of the product properties during manufacturing steps by conventional (upper) and hybrid (lower) tools.

totality of different actions. In this case if the element geometric characteristics (e.g., flatness, accuracy of linear dimensions) are its output index, this process can be realized by different types of actions that more completely correspond to the properties of the workpiece elements. As actions providing the conditions for minimum error of the shape are to be taken without reinstallation of the workpiece and change of its position in the fixation and orientation device, such processes should be considered hybrid ones.

Let some element E_m of a product be obtained due to realization of discontinuous technological actions Π_{ij}^t and Π_{ij+k}^t. It can be expected that k tools, accordingly, will be required for the realization. However, if it is taken into account that a new tool is created on the basis of the known ones, that is, expression $R_{nj} = \bigcap_{i=1}^{\rho_i} R_{si}$ takes place, where R_{nj} is the field of creation of new types of tools; R_{si} is the i-th totality of the known engineering solutions; and ρ_i is the weight of the subset of the known engineering solutions, then the newly created tool can combine the means for fundamentally different types of actions (**Figure 3**).

Let totalities of properties of two tools represent expressions

$$I_1 = \left\{ \begin{array}{ccc} \rho_{11}S^1_{11} & \rho_{21}S^1_{21} & \rho_{k1}S^1_{k1} \\ ... & ... & ... \\ \rho_{1j}S^1_{1j} & \rho_{2j}S^1_{2j} & \rho_{kj}S^1_{kj} \end{array} \right\}, \quad I_2 = \left\{ \begin{array}{ccc} \rho_{11}S^2_{11} & \rho_{21}S^2_{21} & \rho_{k1}S^2_{k1} \\ ... & ... & ... \\ \rho_{1j}S^2_{1j} & \rho_{2j}S^2_{2j} & \rho_{kj}S^2_{kj} \end{array} \right\}. \quad (10)$$

Then a hybrid tool obtained on the basis of the principle of morphological search and combination of properties will consist of m elements and $m < k + j$, as some of properties of initial tools can be combined. Thus, the index of hybridization of the created instrument is $k_g = \frac{k+j}{m}$. This index provides the possibility to find rational engineering solutions for a hybrid tool on the grounds of a totality of the required properties of the worked product and also the possibilities to achieve them by available means.

Consider specific features of application of this approach to creation of hybrid processes for working of diamond-bearing products intended to be used as tools. Such products are rather simple, the number of elements E_i, defining functions F_j of the latter is not large and, as a rule represents several surfaces making working surfaces of the tool and a cutting element fastening plane.

Conventionally, these products represent plates of various geometric forms and are made homogeneous or laminated depending on their purpose. They are mainly worked up by an abrasive tool (AT). The use of various abrasive wheels enables obtaining flat elements of surface (during cutting or profile ones during wheel periphery copying (**Figure 4a**).

An alternative consists in application of laser working methods, in particular, laser cutting (LC), laser cutting with water cooling (LCC) or water-jet-guided laser (WJGL), and also a method using loose abrasive accelerated by a supersonic liquid flow—hydro-abrasive cutting (HAC). In this case the obtained surfaces can be of an arbitrary form determined by operational movement of the tool in relation to the worked surface (**Figure 4c**).

Peculiar features of application of these processes are discussed in [1, 3, 5].

As preliminary research has revealed, separate application of these methods is not optimal.

Let us consider specific features of LC, LCC, WJGL, and HAC from the point of view of a functional approach.

HAC is known to generate a stressed condition at the obstacle—the worked surface; this state is described by components
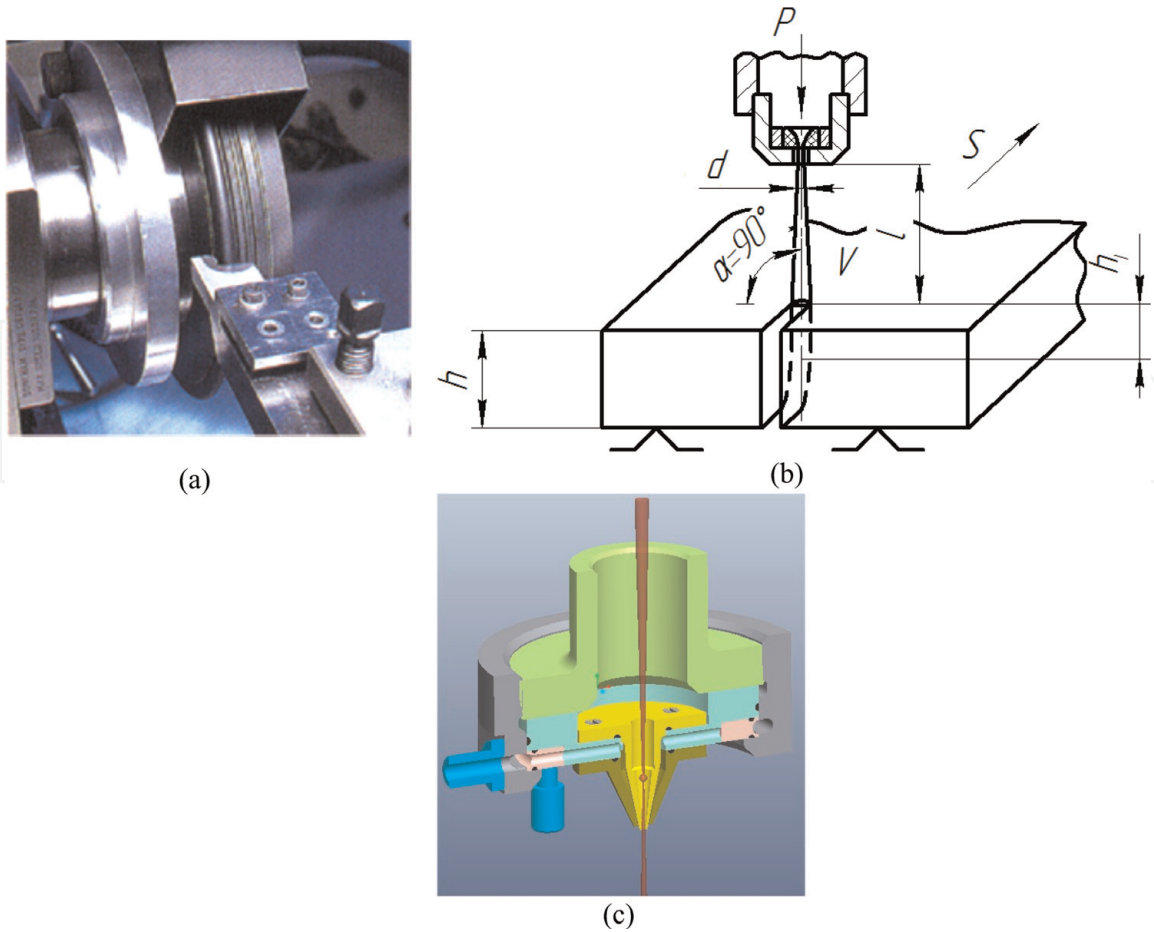
Figure 4.
Processing tool working surface shaped abrasive wheel (a), model of a jet device (b), a laser head for cutting the model (c).

$$\sigma_r = 2G\left(\frac{\partial U}{\partial r} + \frac{\mu\varepsilon}{1 - 2\mu}\right); \sigma_t = 2G\left(\frac{U}{r} + \frac{\mu\varepsilon}{1 - 2\mu}\right);$$

$$\sigma_z = 2G\left(\frac{\partial H}{\partial z} + \frac{\mu\varepsilon}{1 - 2\mu}\right); \tau = 2G\left(\frac{\partial H}{\partial z} + \frac{\mu\varepsilon}{1 - 2\mu}\right);$$

$$\varepsilon = \varepsilon_r + \varepsilon_t + \varepsilon_z = \frac{\partial U}{\partial r} + \frac{U}{r}\frac{\partial H}{\partial z}; \varepsilon = \frac{1 - 2\nu}{2(1 - \nu)G}(\sigma_r + \sigma_t + \sigma_z)$$

$$= \frac{1 - 2\nu}{E}(\sigma_r + \sigma_t + \sigma_z)\begin{cases} (1 - 2\nu)\left[\Delta U - \frac{U}{r^2}\right] + \frac{\partial\varepsilon}{\partial r} = 0 \\ \\ (1 - 2\nu)\Delta U + \frac{\partial\varepsilon}{\partial r} = 0. \end{cases},$$

where $U(t)$ and $H(t)$ are components of movements at a particular point of the surface that are determined as $U(t) = -\frac{(1-2\nu)p_o(t)\left[\frac{D_k}{2}\right]^2}{4G}; 0 < \frac{D_i}{2} < \frac{D_k}{2};$ $H(t) = -\frac{(1-2\nu)p_o(t)D_k}{2G}; G$ and μ are the shift module and Poisson ratio of the worked material, respectively; ε is the volume deformation; $\Delta = \frac{d^2}{dr^2} + \frac{d}{rdr} + \frac{d^2}{dz^2}$ is the Laplace operator; and p_0 is the pressure at the obstacle $p_i = 0, 5\rho v_i^2 + \rho v_i^2 dQ$.

Intensification of the stressed condition contributes to development of initial defects and creation of a grid of microcracks actively joining under the action of abrasive particles when material particles come off the surface. HAC is

characterized by the property to efficiently continue working only till the moment when the loss of jet energy due to friction against the surface of the funnel that appeared is comparable with the energy at which the cutting process ceases.

In particular, in [1, 5] it is shown that during working of carbides (HA), the dimple depth h_l increases due to manifestation of mechanisms of micro-cutting and deformation destruction, that is, the process is described by the expression $h_l = c\sqrt{\frac{m_a v^2}{8\sigma u^2} + \frac{2m_a(1-c)v^2}{\pi u \varepsilon D_j}}$, where c is the process constant; m_a is the abrasive mass flow; v is the velocity of abrasive particles movement, $v = \frac{2p_b f_b}{f_b\sqrt{2p_b/\rho + m_a}}$; σ is the material flow stress; u is the feed rate; ε is the material specific energy; and D_j is the flow diameter corresponding to the diameter of the nozzle section.

On the other hand, due to flow energy losses, the real depth of the obtained dimple will be less and can be taken into account by the relation

$$h_l = c\sqrt{\frac{m_a v^2}{8\sigma u} + \frac{(1-N_1)^2 d_j}{\frac{N_2 N_3}{1-c} + C_f(1-N_1)}}, \qquad (11)$$

where $N_1 = \frac{v_c}{v}$; $N_2 = \frac{\pi}{2}\frac{\varepsilon d_j^2}{m_a v}$; $N_3 = \frac{u}{v}$; v_c is the critical velocity of abrasive particles movement.

A peculiar feature of cutting hard composite workpieces used in tools both separately and in the form of bases for the required layers of other materials consists in the fact that particles flowing on the surface cause local highly intensive loads resulting in some elastoplastic compressive macrodeformations in local volumes of the surface layer. These loads are mainly received by the carbide structure (for alloys containing cobalt ≤10%). Further pickup of the abrasive particle by liquid flow results in removal of compression load and partial elastic restoration of the deformed volume of the surface layer, that is, in occurrence of tensions in this local volume, which causes redistribution of tensions among the components of HA structure. In this case, at first carbide grain boundaries break, which results in appearance of microcracks in HA carbide grains themselves and plastic deformation along the dislocation mechanism of cobalt bundle [2, 3]. After that the boundaries between the carbide grains and the bundle and the bundle itself break.

Hence, movement of the destruction area slows down when the cutting depth increases, and distortion of the jet as a "nonrigid" tool increases.

Much higher rigidity of polycrystal superhard materials, including cubic boron nitride (PSHM, CBN) and diamond-bearing elements (DBE), causes the fact that a moving flow of abrasive grains slightly influences the worked material and the workpiece is not cut at a speed admissible by manufacturing conditions (**Figure 5a**).

Obtaining the initial groove and creation of a cut or a channel result in distortion of the jet and its drift from the theoretic axis to the side opposite to the feed movement. It is facilitated by selectivity of destruction caused by "nonrigidity" of the jet, due to which creation of specific destruction areas takes place (**Figure 5b**); their location and dimension determine the form of hydro-cutting front and deviation of the jet by angle α, whose value is determined by the relation of speed v_z of jet penetration into the worked material and feed rate s. This phenomenon results in appearance of surface defects in the form of waviness and also in cut edge deviation from orthogonality.

The jet ability to selectively go about obstacles results in the fact that heterogeneity of the worked material and specific features of the power scheme may provoke availability of both bumpy elements of the surface and surface cleavages (**Figure 5c**).

Thus, the possibilities of HAC process from the point of view of the functional approach can be presented by elements of **Table 2**. In this case the ability of the jet to destroy the obstacle with creation of vertical edges can be regarded as a useful function only for a restricted number of materials.

Then

$$W_{1i}(t_k) = W_1^{Fp1}(t_k) \cap W_1^{Fv1}(t_k) \tag{12}$$
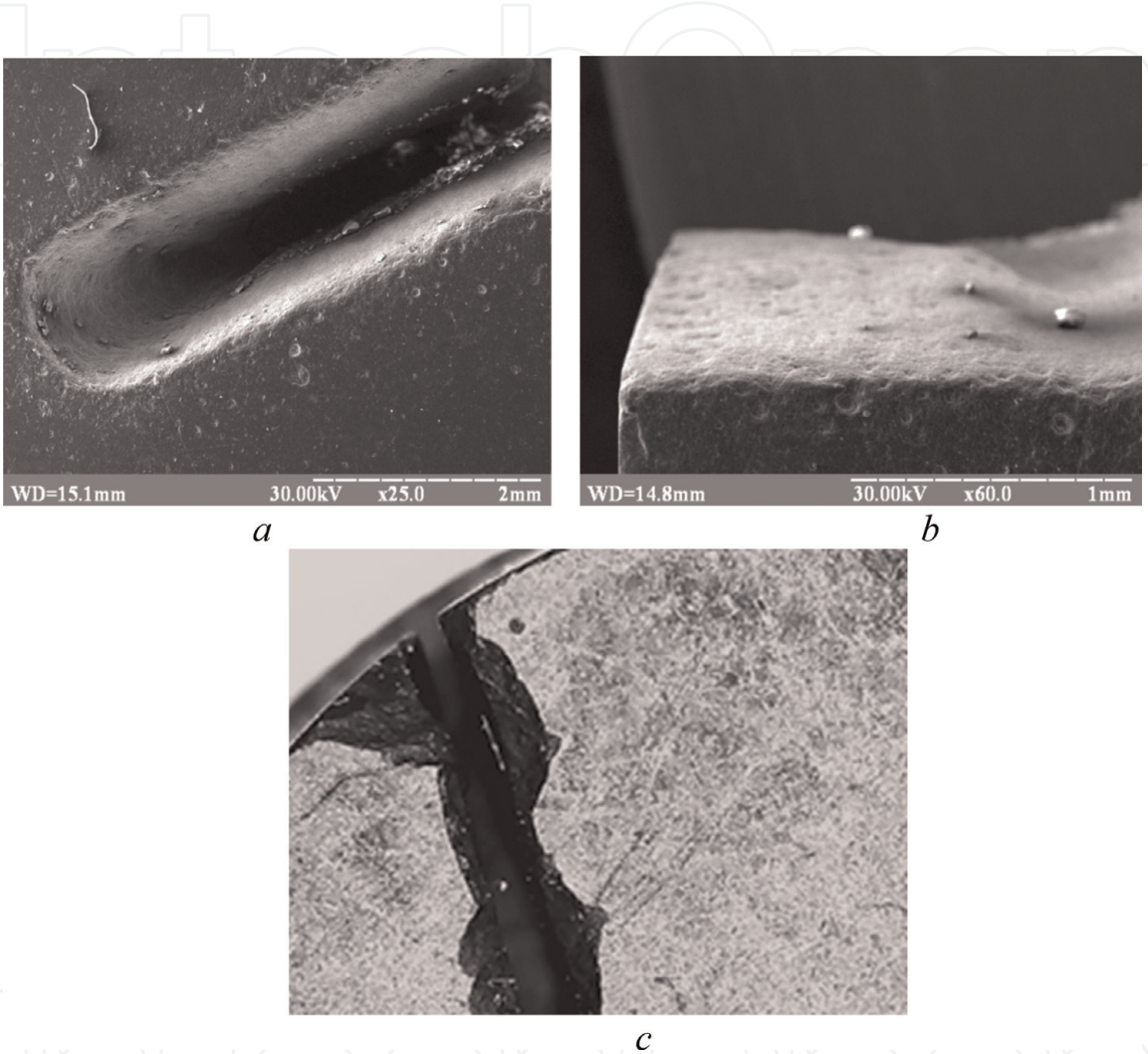
Figure 5.
Surface defects as manifestation of harmful functions of technological actions: (a) incomplete cutting; (b) surface waviness; (c) surface cleavages.

Worked material	Functions F'			
	Useful F_{pi}	Harmful F_{vk}		Neutral F_{nj}
	Obtaining of orthogonal edge of the product h, mm	Waviness δ, μm	Surface cleavage	Workpiece heat, T (°C)
HA	F_{p1} depends on cutting modes	F_{vk} depends on cutting modes	Minimum	Up to 50–60
PSHM	Weak	High	Complete	Up to 50–60
PCD	Absent	Absent	Insignificant	Up to 50–75

Table 2.
Provision of the product function by creation of element E_i by a technological action $W_{ij}(t_k)$ at HAC.

under the condition that F_{v2} and F_{n1} can be neglected and useful and harmful properties (functions) are manifested simultaneously. Corresponding transformations in the form of the process result, for example, depth h (the surface element linear value) for HA, may represent regression equations in the form

$$h|_{W^{Fp}} = b_0 + b_1 s_k + b_2 M_a;$$

$$\delta|_{W^{Fv}} = b_0 + b_1 s_k + b_2 h_m, \tag{13}$$

where M_a is the abrasive grains mass flow, h_m is the thickness of the worked material, and for other materials $h|_{W^{Fp}} = 0$ and $\delta|_{W^{Fv}} = 0$.

It is obvious from the given relations that these two dependences are interconnected and increase of cutting depth h at a higher rate of contour feed s_k results in increase of waviness δ.

More possibilities are provided by combined working of material by wate-jet-guided laser (WJGL). In this case working variants correspond to schemes in **Figure 6**; in this case both WJGL (**Figure 6a**) and LCC (**Figure 6b–e**) can be realized.
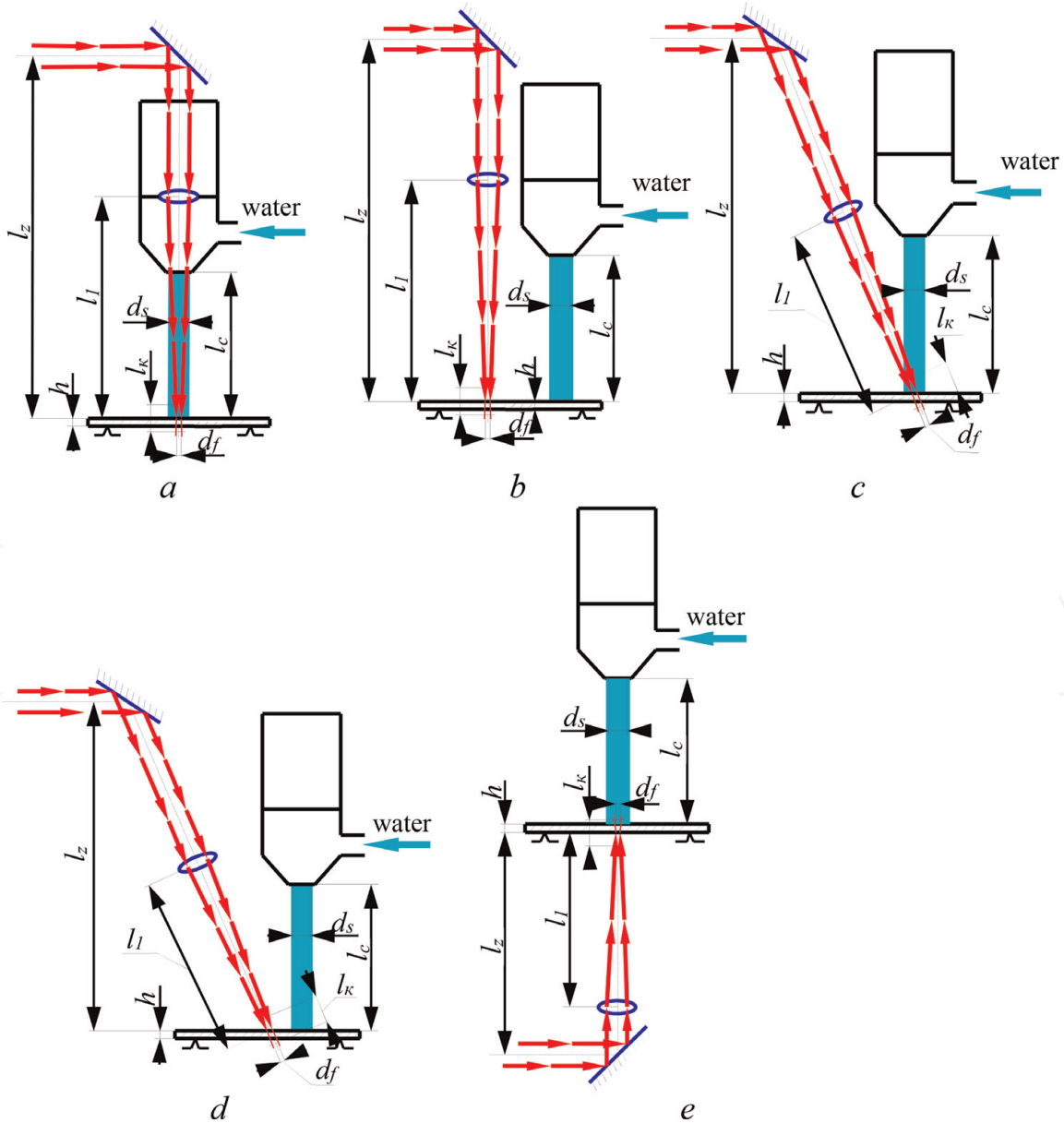
Figure 6.
Variants of combination of a water jet and a laser beam for performance of WJGL (a) or LCC (b–e).

The action of a water jet or a laser beam can be both simultaneous and successive. In this case different variants of laser blasting and possibilities of variation of the form of jet nozzle flow section, as shown in [6], provide good prospects in combination of methods of actions on the worked piece and, consequently, in meeting principle (10).

Application of thermo-hydrodynamic jets typical of WJGL or LCC causes heating of the workpiece whose temperature field can be described by equation [7]

$$
T(x,y,z,t) = \frac{P}{\pi^{\frac{1}{2}}\rho c} \int_0^l \frac{e^{\frac{(x-v(t-z))^2}{4\alpha\tau+A^2}-\frac{y^2}{4\alpha\tau+B^2}}}{\left[(4\alpha\tau+A^2)(4\alpha\tau+B^2)\alpha\tau\right]^{1/2}} \times \\
\times \left[e^{-\frac{z^2}{4\alpha\tau}} - h*(\pi\alpha\tau)^{1/2}erfc\left(\frac{z}{2(\alpha\tau)^{1/2}}+h*(\alpha\tau)^{1/2}\right) \times e^{h*z+h*^2\alpha\tau}\right]dt,
$$

where t is the time from the moment of beginning of thermal impulse action, ρ, c, λ, $\alpha = \frac{\lambda}{cp}$, and h^* are density, specific heat capacity, heat conductivity coefficient, temperature conductivity of the workpiece material, and coefficient of heat transfer from the surface of the workpiece, respectively; $\alpha = \frac{\lambda}{cp}$ A and B are the bigger and smaller half axes of beam elliptic section; and $P = \pi q AB$ is the power of the lasing emitter. Integral equation of heat energy balance in an arbitrary area $\omega \subset \Omega$ according to [4] will take the form $\int_w \frac{\partial e}{\partial t}dv = \int_w gdv - \oint_{\partial w}\left(\vec{q_T} + c_g\rho_g T \vec{v_f}, \vec{n}\right)ds$.

Taking into account the boundary conditions in the cutting zone

$$
c\rho\frac{dT}{dt} - \lambda\Delta T = \frac{(T-R_0)kP}{\pi AB}\exp \times
$$
$$
\times \left[-2\left(\frac{(x-vt)^2}{a^2}+\left(\frac{y}{b}\right)^2\right)\right] \times \exp(-kz) \qquad \lambda\frac{dT}{dz}\bigg|_{z=0} = \alpha(T)(T-T_p),
$$

temperature distribution across the sample section is obtained; its analysis reveals the following (**Figure** 7): temperature distribution across the surface is determined by conditions of coolant outflow and may considerably vary with the change of the flow shape; when the thickness of the sample increases, considerable reduction of the jet's ability to perform the work of destruction can be observed, as at the same amount of rejected heat, the amount of delivered heat constantly decreases.
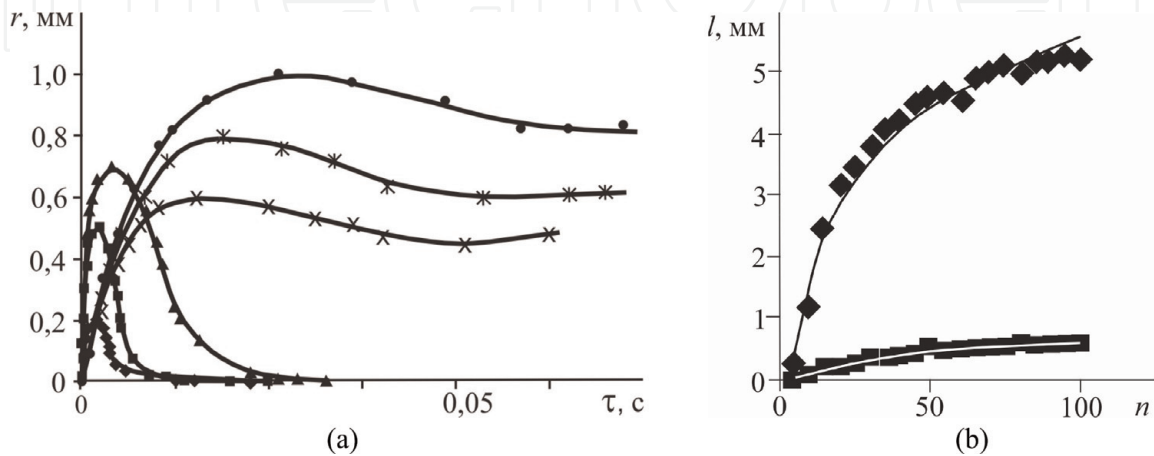
Figure 7.
Changes in border radius zone temperature field (T = 850°C) as a function of time for different processing methods LC (×, Ж, ●), LCC (▲), WJGL (♦, ■) (a) and cutting depth in materials (HA, ♦; PSTM, ■) depending on the number of cuts (b).

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	Intensive, linearly depending on t (number of cuts N)	Minimum	Exists	Absent
PSHM	Intensive, decreasing with increase of groove depth h_l	Minimum	Minimum	Is observed in destructed zone
PCD	Nonlinear medium-intensive	Essential	Absent	Is observed in destructed zone

Table 3.
Provision of the product function by creation of element E_i *by a technological action* $W_{ij}(t_k)$—*WJGL.*

Thus, it is possible to create a table of provision of the product with the function via formation of its separate element or a totality of elements. This table is analogous to the one considered above (e.g., for WJGL; **Table 3**), but it reflects the peculiar feature of each of the variants in **Figure 6**. It should be noted that the given tables just illustrate the approach and draw attention to the most important functions, while a totality of such functions may be much bigger.

On the basis of **Table 3**, technological action for obtaining a particular element can be presented as

$$W_{2i}(t_k) = W_1^{Fp1}(t_k) \cap W_1^{Fv1}(t_k) \cap W_1^{Fv2}(t_k) \cap W_1^{n1}(t_k). \tag{14}$$

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

$$h|_{W^{Fp}} = b_0 + b_1 s_k + b_2 T + b_3 Q_v + ...;$$
$$\delta|_{W^{Fv}} = b_0 + b_1 s_k + b_2 T + b_3 Q_v + b_4 h_l + ...,$$
$$l|_{W^{Fv}} = b_0 + b_1 s_k + b_2 T + b_3 Q_v + b_4 h_l + ...$$
$$P|_{W^{Fv}} = b_0 + b_1 s_k + b_2 T + b_3 Q_v + b_4 h_l + ... \tag{15}$$

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

Analogous tables, including the ones with extended features of functions F', are created for all the types of working.

The obtained dependences (12) and (14) make it possible to determine the totality of variants for carrying out the process of working of a particular element of the surface, and the most optimal method can be searched on the basis of morphological analysis.

This approach is applicable not only to the processing of superhard materials. It can also be successfully used for the treatment of special difficult-to-cut materials, such as carbon-carbon composites, multilayer aircraft panels, etc. [9–11].

3. Used equipment, workpieces, and succession of experimental research

Cut workpieces of HA T5K10, PSHM on the basis of CBN "borsinit" represented plates of the size 12.7 × 12.7 mm, of the thickness up to 3.5 mm, DC workpieces were two-layer composites of the size 12.7 × 12.7 mm with an upper

PCD-layer of the thickness up to 1.0 mm and a hard alloy base of the thickness up to 3.0 mm.

The cuts were performed by methods of hydro-abrasive (HAC), laser (LC) cutting, laser cutting with liquid cooling (LCC), and water-jet-guided laser (WJGL).

Experiments were carried out with the use of laser blasting complex LSK-400-5, equipped with a hydro-abrasive head with water nozzle d_c = 0.22 mm and a metering tube D_k = 1.05 mm.

HAC was performed with abrasive consumption up to 0.5 kg/min and under liquid pressure of 250 MPa. Garnet sand of granularity of 300 meshes was used as abrasive during cutting.

During multi-cut laser blasting, the cuts were performed with feed up to 50 mm/min. Impulse Nd:YAG laser with impulse frequency of 75–150 HZ and power of 400 W was used. For realization of the hybrid process, the unit was equipped with a special laser blasting head enabling working with the use of a ring laser nozzle and a mixing chamber to provide hydro-abrasive cutting without disturbance of the position of basic axes of the tools. The beam was focused according to a method providing centering and ingress of all its modes on the focusing lenses of the tube. Optic elements were blown with purified compressed air through a nozzle of ∅ 2.8 mm under excess pressure of 0.05 MPa. During LB the liquid was fed directly into the center of laser focus under the pressure of 25–50 MPa.

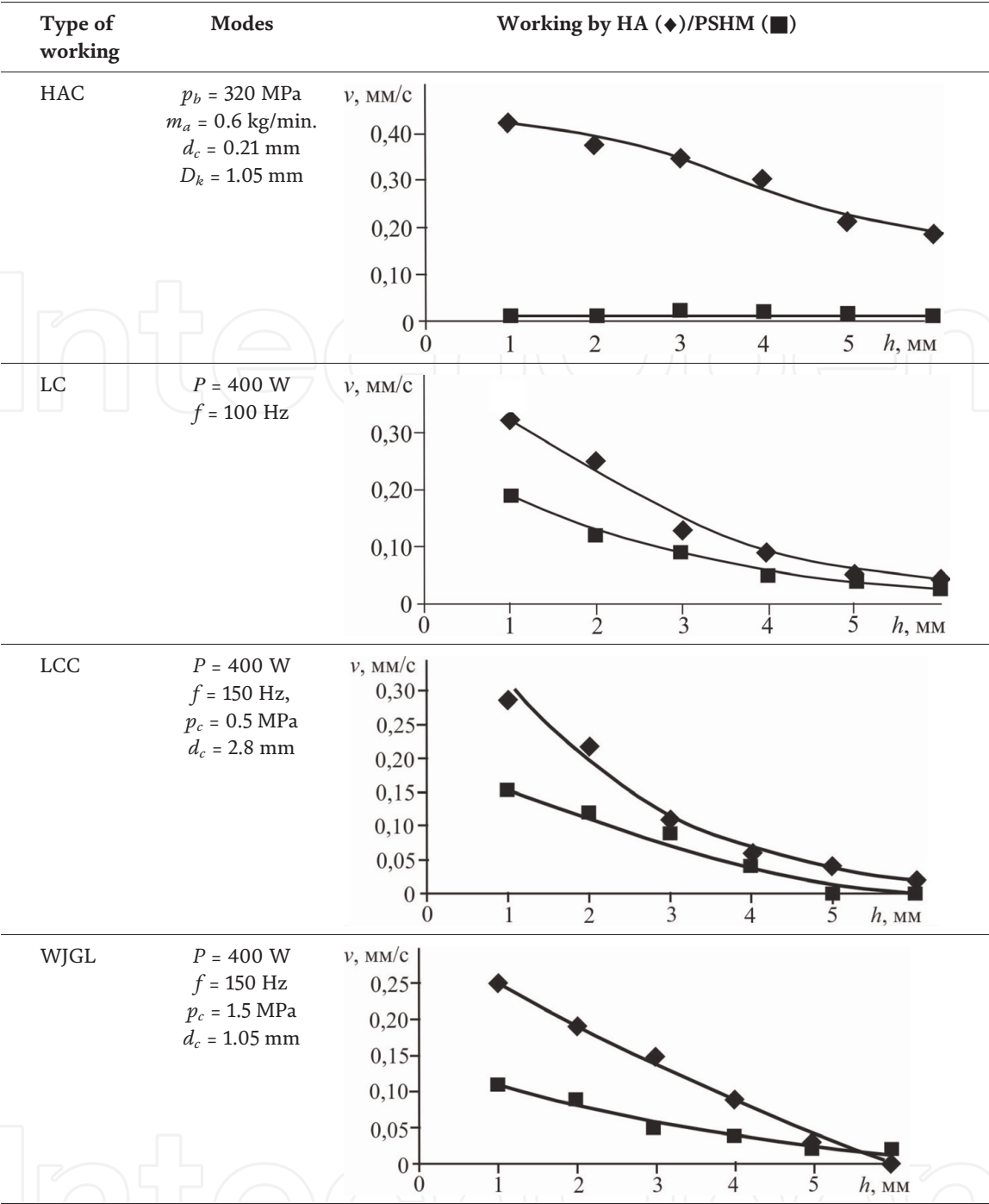A high-temperature carbon-carbon composite weave composite was also used.

4. Discussion of the obtained results

Paper [5] contains comparative results of the research of productivity of different working methods. In the present paper, experiments with workpieces made of HA and PSHM are repeated, but attention is focused on the indices of the quality of the worked surfaces, roughness and accuracy of relative position, and also deviations of their values from theoretically possible ones.

To determine components in **Tables 2** and **3**, the values of separate parameters whose averaged values are given in **Table 4** are determined. Comparison of erosion rates determining the rates of deepening of the cutting dimples is given in **Table 5**. In this case only particular results of the research are shown; they are sufficient for hybridization of the process according to principle (10).

Type 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	
		—		2.80 mm	1.05 mm
HA	R_a, μm	12.5	6.3	6.3	3.2
	h, mm/cycle	6.4	5.9	3.5	3.0
	δ, mm/5.0 mm	0.3–0.9	0.02–0.15	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	0.80	0.05–0.10	0.02–0.05	

Table 4.
Accuracy and roughness of the surfaces of workpieces made from HA and PSHM at different jet working methods.

Type of working	Modes	Working by HA (♦)/PSHM (■)
HAC	p_b = 320 MPa m_a = 0.6 kg/min. d_c = 0.21 mm D_k = 1.05 mm	
LC	P = 400 W f = 100 Hz	
LCC	P = 400 W f = 150 Hz, p_c = 0.5 MPa d_c = 2.8 mm	
WJGL	P = 400 W f = 150 Hz p_c = 1.5 MPa d_c = 1.05 mm	

Table 5.
Material erosion rate at HAC, LC, LCC, and LB depending on the thickness of the plate.

The performed research revealed the following. Any initial deviation of the cut shape, especially during performance of discontinuous working processes, distorts the jet, and further working results only in deterioration of the quality of the product, first of all, due to progressive deviation of the cut shape. It concerns all the types of working. So, **Figure 8** demonstrates a defect of DC cutting in the form of deviation from orthogonality of the edge at partially incomplete cutting of PCD layer.

A peculiar feature of two-layer DC consists in the fact that workability by a certain method changes on the surface obtained at the section, depending on the structure of the material and physical and mechanical properties. A peculiarity of DC consists in the fact that PCD is not practically worked by HAC, while it can be worked by LCC and WJGL. The carbide base is worked by HAC with high efficiency.

Hence, generation of the surface as an element of the product can be presented in the form of logical multiplication of transformations $W_{1i}(t_k)$ and $W_{2i}(t_k)$ and is described by the expression

$$W_p(t_k) = W_1{}^{Fp1}(t_k) \cap W_1{}^{Fv1}(t_k) \cap W_1{}^{Fv2}(t_k) \cap W_1{}^{n1}(t_k) \cdot W_1{}^{Fp1}(t_k) \cap W_1{}^{Fv1}(t_k)$$

Thus, taking into account the condition of provision of initial high-quality formation of a destruction dimple in PCD layer, a hybrid process is to represent a totality of processes of initial WJGL up to the moment of complete cutting of PCD layer and creation of a dimple in WC with further cutting of the plate by HAC (**Figure 9**).

Further research is to be directed to determine rational combinations of hybridization at multi-cut working, at which the number of cuts directly influences the quality of obtained surfaces, and also to the condition of adhesion surfaces in multilayer products.

Comparison of the diagrams of cutting rates of DC and PSHM demonstrates (**Figure 10**) that productivity of the process is determined by obtaining scribe in the superhard layer. HAC cutting of hard alloy base is practically performed in an identical way.

Let the acquisition of an array of properties of a finished product (a sample of a carbon-carbon composite) in the form of sets Fi (l, b, h, r, δ ...) be possible by the implementation of a certain set of technological influences Mj, inherent in one or another method of processing. Each technological effect can be represented as a
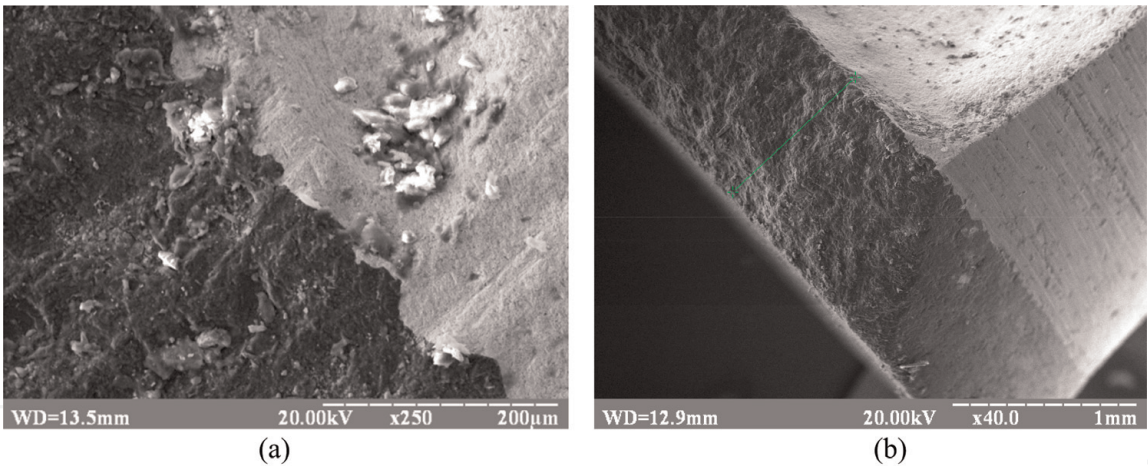

| WD=13.5mm | 20.00kV | x250 | 200μm |

(a)

| WD=12.9mm | 20.00kV | x40.0 | 1mm |

(b)

Figure 8.
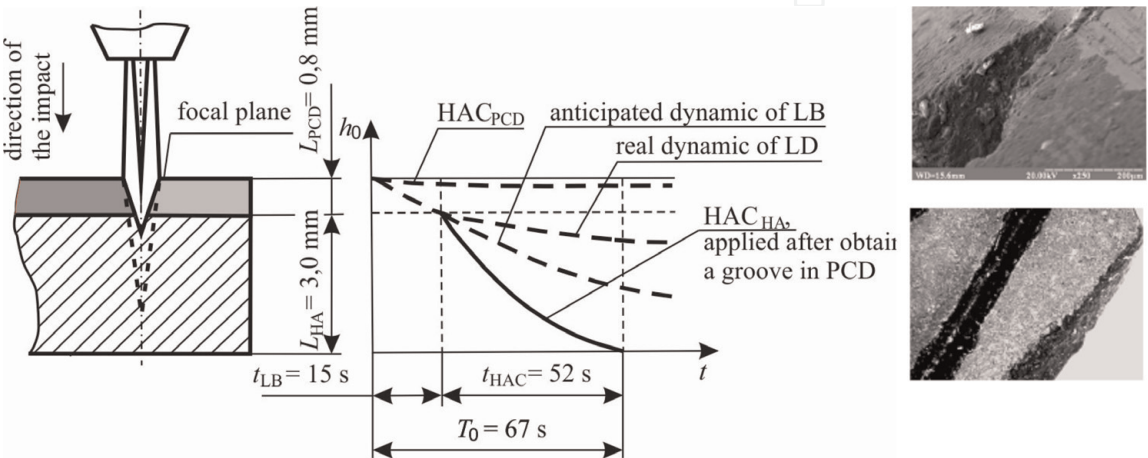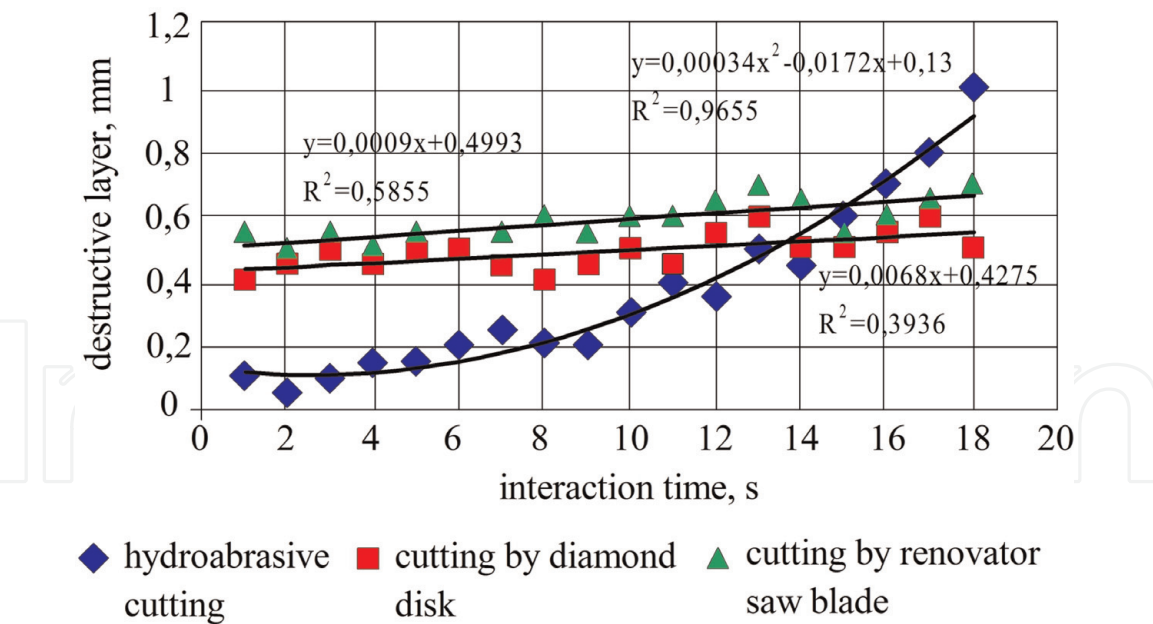*PCD layer after WJGL (a) and a plane of adhesion of PCD with WC (b).*

Figure 9.
Making a cut in PCD and PSHM workpieces.

Figure 10.
Change in the width of the destruction zone depending on the time of the interaction of the cutting surface with the tool.

set of sets of properties of the tool Tj, the dynamic properties of the processing system Wj, the method of power influence Pj, for which (Tj, Wj, Pj) ∈ Mj, which gives the opportunity to perform with the properties of Si, output quality parameters to be presented as:

$$Fi\ (l, b, h, r, \delta...) = M_j \cdot S_i.$$

Based on the provisions reflected in the work [8], we can record the condition for providing output processing parameters as

$$Fi\ (l, b, h, r, \delta...) = T_j \cdot S_i \cap W_j \cdot S_i \cap P_j,$$

which gives a set of variants of processing conversions, the best of which can be selected according to a certain criterion.

Since this material is resistant to temperature effects, the only way to treat it is mechanical abrasive cutting.

Take into account the following processing methods: R1, milling; R2, processing with abrasive disc; R3, processing by the renovator (reciprocating motion); R4, drilling; and R5, hydro-abrasive cutting. For these methods, the maximum stresses and diagrams of stress distribution at the intersection of the cut in the workpieces are determined.

The cutting modes, as well as the parameters of the applied tool, directly determine not only the processing performance but also the thickness of the destruction of the surface layer, which must be taken into account when processing samples for mechanical tests.

On the other hand, in the process of processing, there is wear of the tool: the change of angles on the cutting edge and curing abrasive grains. All this leads to the fact that even in stable cutting modes, the parameters of the surface layer are changed.

The change in the width of the destruction zone (**Figure 10**) measured on the natural samples (shown as separate points in the diagram) shows the following. The "hardness" of the hydro-abrasive jet leads to the fact that the power circuit of the interaction is constantly changing and, consequently, the components are increasing, that is, the flow will then simply blur the machined sample, which requires minimization of the time of finding the jet in a stationary state.
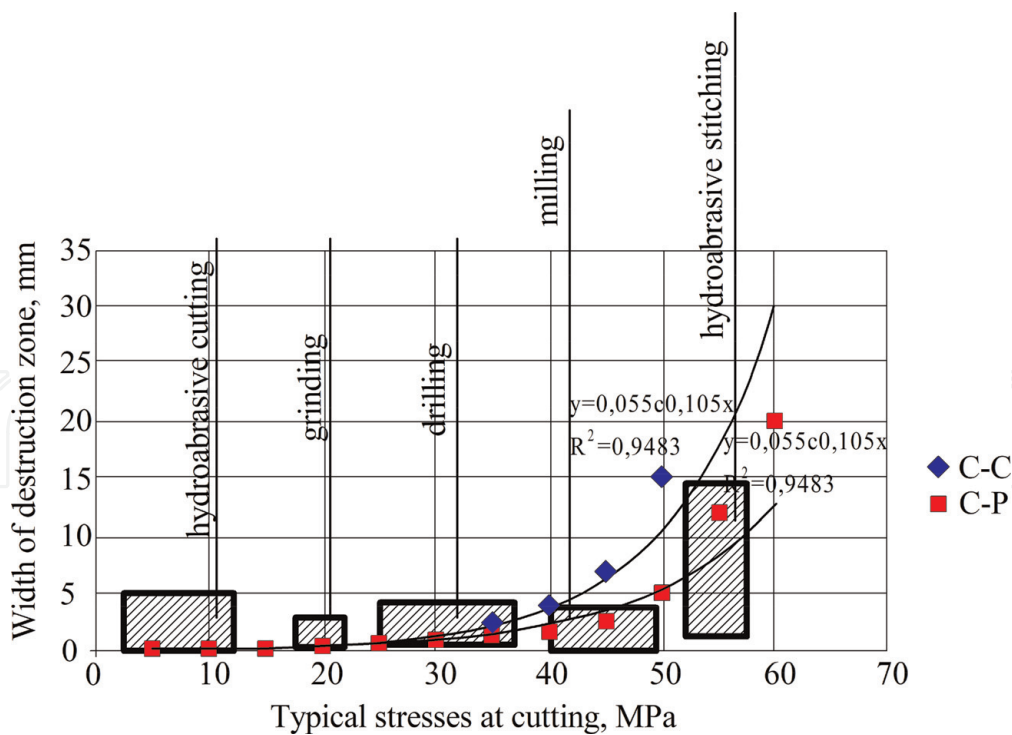
Figure 11.
Emerging stresses under different processing methods and their effect on the width of the destruction zone.

When processing materials with diamond disks or saw blades, there is no significant change in the width of the destructive zone.

We also propose rather simple regressive dependences of the width of the destruction on the function of maximum stresses in the cutting area $\delta = f(\sigma_{max})$:

$$\delta_1 = 0.55 \exp^{0.1\sigma_{max}};$$
$$\delta_2 = 0.74 \exp^{0.08\sigma_{max}}, \tag{16}$$

where δ_1 is the destruction of carbon-carbon material and δ_1 is the destruction of the carbon polymer, which made it possible to construct and compare diagrams of the development of the width of the destructive zone (**Figure 11**) of the processing of carbon composites, which are formed by various methods.

Thus, we have shown that obtaining qualitative samples of a complex configuration is associated with some complexities due to the heterogeneous structure of
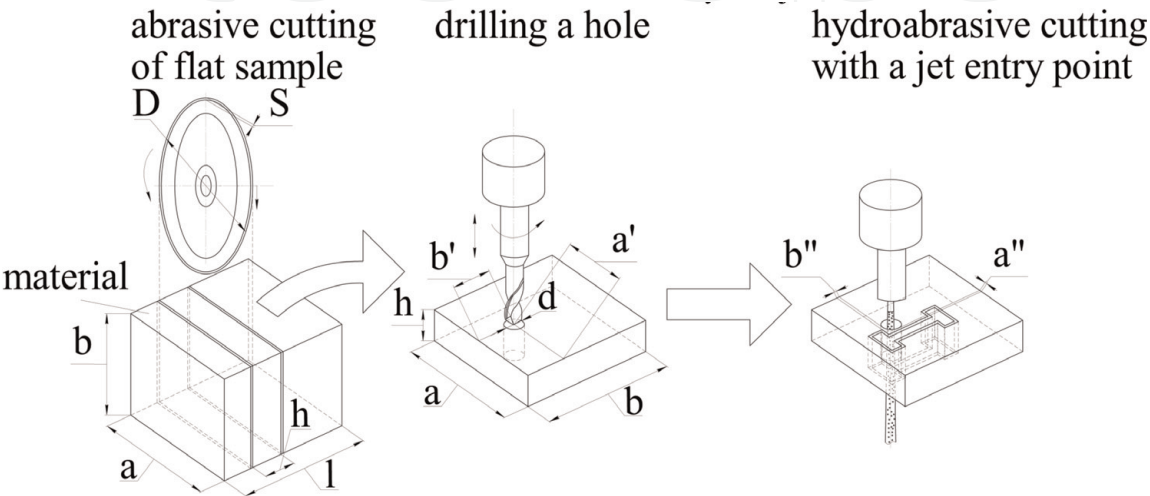
Figure 12.
Sequence of sample preparation from carbon fiber blanket as the result of cutting.

the treated material, as well as the manifestation of quasi-cleaved properties of carbon reinforcing fibers.

In this case, the main condition for obtaining the desired result is the restriction of the thickness of the destructive layer at >2% of the measurement basis.

The application of the proposed approach allows for the task of obtaining a sample $a \times b \times h$ from a cubic blank in $A \times B \times L$ sizes, to offer the following possible technological operations: R2-R1; R2-R5; and R2-R4-R5. When optimizing the process by the criterion of minimizing the processing time for a given level of quality, a variant of the functionally oriented process (R2)-(R4)-(R5) is obtained, the scheme of which is shown in **Figure 12**.

Such a sequence of operations allows us to make full use of all the benefits of hydro-abrasive cutting (a significant reduction in the processing time) and to avoid material destruction at the time of the breakdown by the jet.

5. Conclusions

Application of the functional approach makes it possible to reveal rational succession of TP steps, find optimal conditions and points of occurrence of harmful functions, eliminate them (or invert), and also determine the possibility of hybridization of the process. Such an approach can be used in working of composite workpieces from laminated superhard materials.

The performed research with the use of HAC, LC, LCC, and WJGL has enabled studying of the intensity of destruction area introduction into the worked piece and finding out the functional features of a particular process that are caused by the working conditions. It has been shown that the hypothesis of quasistationary rate of destruction is unacceptable for such materials, which is caused by the structure and high hardness of the material. It has also been determined that when deepening increases, the rate of jet introduction has a pronounced tendency toward reduction.

A peculiar feature of cutting two-layer composites including a PCD layer based on HA has been analyzed, and it has been shown that the use of functional approach principles makes it possible to propose a hybrid process and corresponding hybrid tool (combining WJGL and HAC), enabling efficient and productive cutting of such plates. Besides, conditions for essential improvement of working process efficiency have been demonstrated (**Figures 13** and **14**).

To improve the considered approach, it is necessary to orientate further research to optimization of working conditions and search for ways of improvement of cut

(a)   (b)
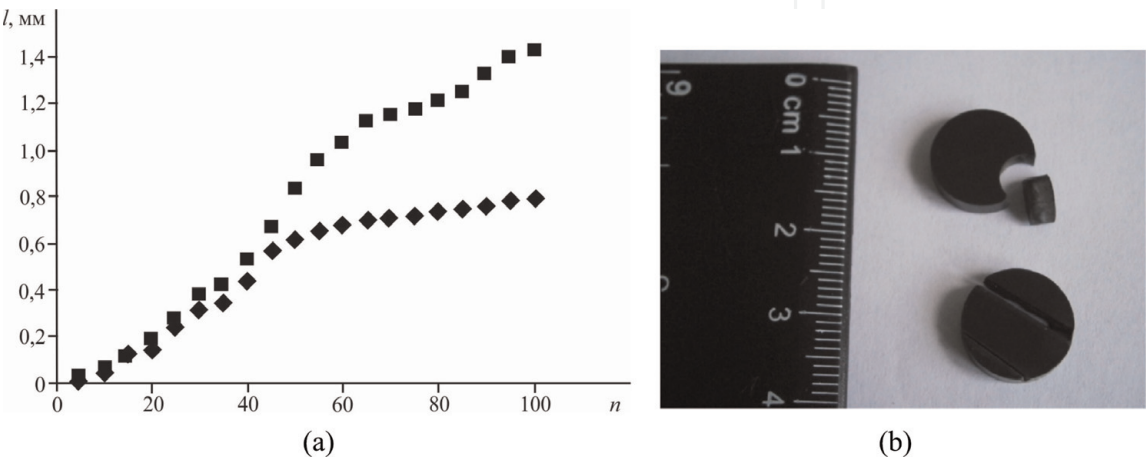
Figure 13.
Intensity of scribe development (a) in workpieces from PCD (◆) and PSHM (■) (linear feed rate, 35 mm/ min; impulse passing frequency, 75 Hz) and a cut product (b).

Figure 14.
The result of cutting carbon-carbon composites.

quality by selection of rational parameters of the process and design solutions for the hybrid tool.

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