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CUTS OF THE WORKPIECES OF HARD AND SUPERHARD SINTERED MATERIALS BY JET METHODS

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РІЗАННЯ ПЛАСТИН З ТВЕРДИХ ТА НАДТВЕРДИХ МАТЕРІАЛІВ СТРУМИННИМИ МЕТОДАМИ

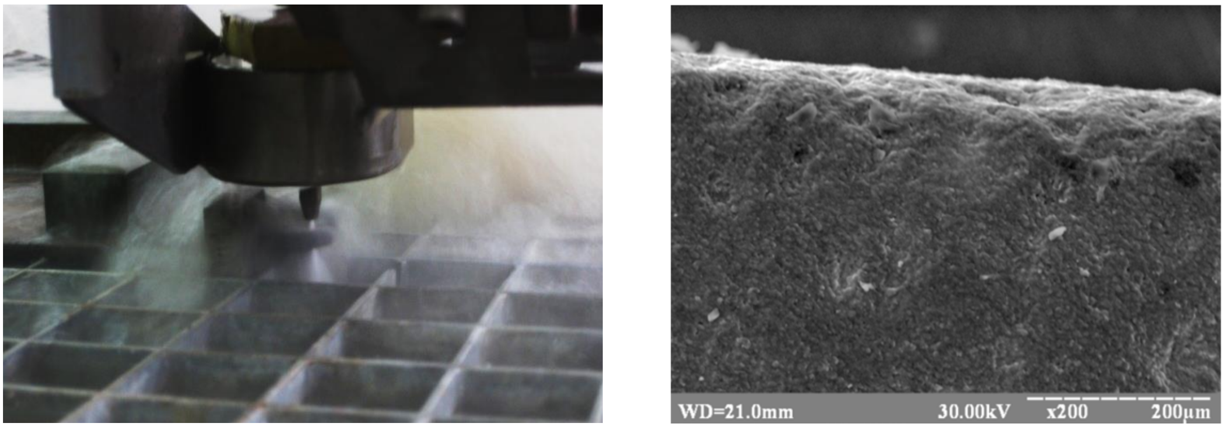
The paper deals with cutting workpieces of Carbide and Superhard Materials Chip by the abrasive water jet of small diameter, give are some aspects of the stress state of the material under the action of the jet. It is shown that cutting superhard materials multi pass processing leads to an increase in the width of the cut and the emergence of some spatial errors. To improve the accuracy of performance slots, edges, holes in the slab is proposed to use a functional approach, based on the partition of the process into separate stages and to find appropriate methods of their execution. Thus, the change in the angle and speed of leakage bypass circuit can significantly improve the accuracy of processing. Found that the decrease in speed around the contour should be proportional to the thickness of the processed material and its physical and mechanical characteristics.
Keywords: hydro-abrasive cutting, water jet, functional approach, hard and super hard materials

High-quality and productive cutting the plates of hard and super hard materials is an actual scientific and practical task. It allows to obtain precision surfaces of arbitrary shape. The same time the areas of use this technology are wide enough – ranging from the electronic industry to the tool production and manufacture of medical devices.

The complex of works aimed at identifying approaches and principles, as well as the formulation of scientific foundations of the high-performance jetting (cold) of hard and super hard materials are made at the Department of processes and equipment for mechanical and physical-technical processing, Kremenchuk Mykhailo Ostrohradskyi National University, Ukraine.

Phenomena and basic regularities of hole propagation through the hydro-abrasive impact with high-strength and hard materials cutting were the object of research. The opportunity of applying of the functional approach to improve processing efficiency and accuracy also was the object of research.

Essence of the hydro-abrasive cutting is that to the jet flow of small-diameter (mostly 0,25…0,5 mm) the finely dispersed abrasive with graininess of 50/100 microns is injected. Then the flow is rectifying by the gauge tube with diameter of 0,9 – 1,1 mm. After that the flow inleaked on the processed surface (Fig. 1). The abrasive particles with high-speed impact perform the work of microfracture by different mechanisms: polydeformation, wearout, microcutting. And the mechanism of destruction depends on the direction of the particle motion relative to the processed surface and may vary during this processing.



а *б*

Fig. 1. Hydro-abrasive cutting process of the CBN plate (a) and microphotograph of the surface layer (b)

Feature of the cutting of hard and super hard materials is that the physical and mechanical properties of the abrasive and processed materials are comparable. Furthermore, flexural strength of the cutting particles is less than 1,5–2 times in comparison with the processed material. At the same time the particles inleaked on the surface can cause local high-intensity loads, which lead to some elastoplastic macrodeformation of compression in local volumes of the surface layer. The carbide skeleton mostly perceives these loads in hard alloys (alloys with a cobalt content of ≈ 10% by weight). Further swoop up of abrasive particle by fluid flow leads to the removal of compression load and to the partial elastic recovery of the deformed volume of the surface layer, i.e. to appearing the tensile stresses in this local volume. This leads to the redistribution of stresses between the components of the hard alloy structure. In this case the grains boundary carbides destroy first. It leads to the appearance of microcracks in the grains of hard alloy carbides and to the plastic deformation by dislocation mechanism of the cobalt binder [1]. Next is the boundary destruction of the cobalt binder and binder itself (Fig. 2,a). Such a mechanism can explain the appearance of initial holes during broaching of the test samples.

Displacements components $U(t)$ and $H(t)$ at a certain point by making the calculation scheme (Fig. 2,b) were identified to evaluate the stress-strain state of the processed surface during jet inleakage. These displacements easily obtained from the equations relating stresses and strains:

$$\sigma_r = 2G\left(\frac{\partial U}{\partial r} + \frac{\mu\varepsilon}{1-2\mu}\right);$$
$$\sigma_t = 2G\left(\frac{U}{r} + \frac{\mu\varepsilon}{1-2\mu}\right);$$
$$\sigma_z = 2G\left(\frac{\partial H}{\partial z} + \frac{\mu\varepsilon}{1-2\mu}\right);$$
$$\tau = 2G\left(\frac{\partial H}{\partial z} + \frac{\partial H}{\partial r}\right). \tag{1}$$

Then

$$U(t) = -\frac{(1-2\nu)\,p_в(t)\left[\frac{D_к}{2}\right]^2}{4G}, 0 < \frac{D_i}{2} < \frac{D_к}{2}; \tag{2}$$

$$H(t) = -\frac{(1-2\nu)\,p_в(t)D_к}{2G} \tag{3}$$

provided that

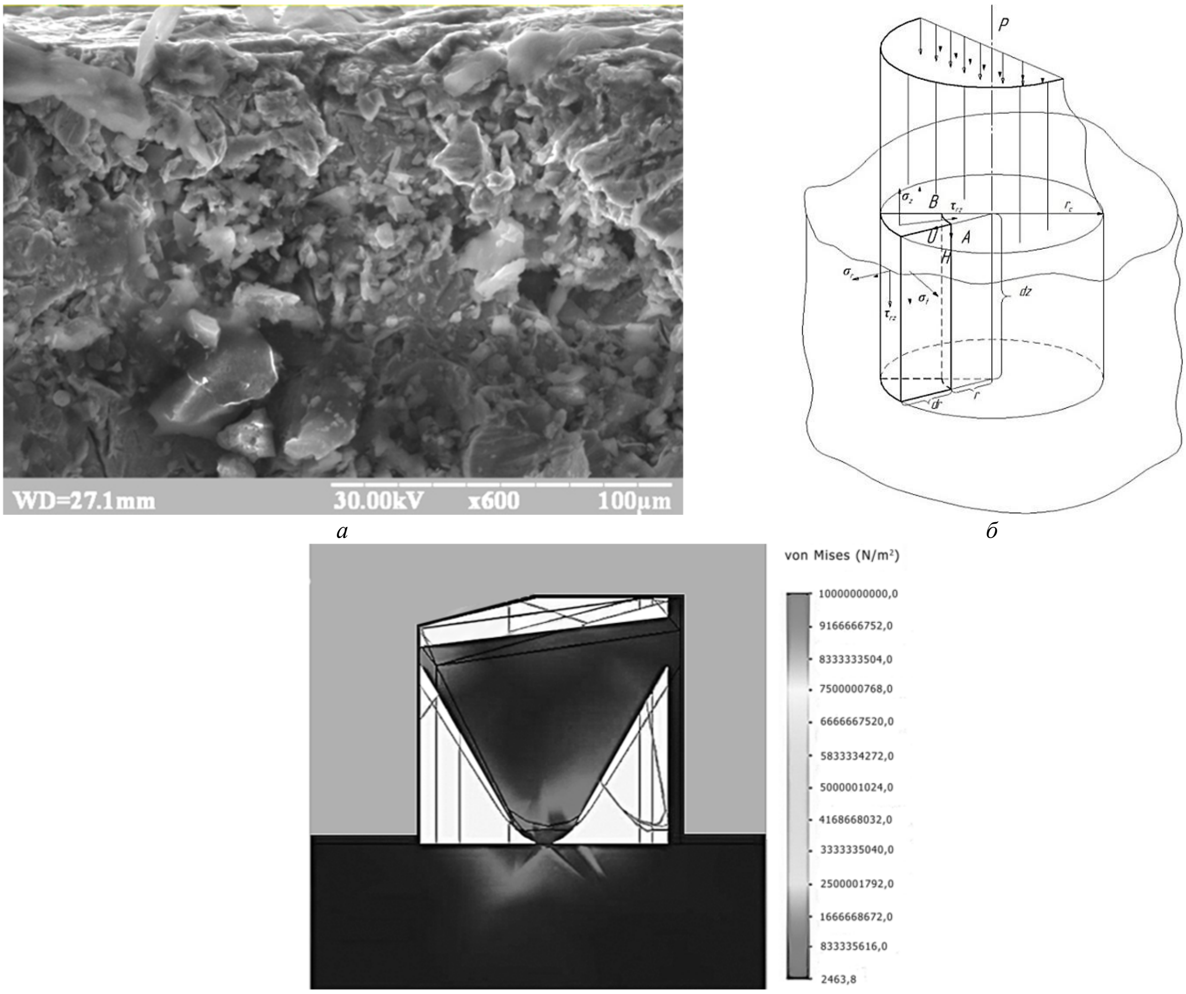
$$\varepsilon = \varepsilon_r + \varepsilon_t + \varepsilon_z = \frac{\partial U}{\partial r} + \frac{U}{r}\frac{\partial H}{\partial z},\ \varepsilon = \frac{1-2\nu}{2(1-\nu)G}\left(\sigma_r + \sigma_t + \sigma_z\right) = \frac{1-2\nu}{E}\left(\sigma_r + \sigma_t + \sigma_z\right)$$

and

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

G – shear modulus of the processed materials; μ – its Poisson's ratio; ε – volumetric deformation; $\Delta = \frac{d^2}{dr^2} + \frac{d}{r\partial r} + \frac{d^2}{\partial z^2}$ – Laplace operator, $D_к$ – gauge tube diameter.

By virtual experiment results (Fig. 2c), carried out in the computer laboratory of the Department found that the magnitudes of stresses arising in the contact zone of the jet with the surface of the hard alloy and super hard synthetic materials during hydro-abrasive cutting are significant. They reach their maximum at the points of contact with the abrasive grains and during interaction should occur the destruction of the grains with polydeformational damage of surface. This phenomenon is typical to conditions of water jet leakage at angles close to normal (i.e. in the case where there is no through procutting and particles bombard the surface causing some microstrain, and activating origin and growth of the initial microdefects). Material destruction, origin and growth of the jet hole is also possible by microcutting. But in this case the surface defects, caused by initial elastic deformation at the impact point of the particle, are possible only when particle motion vector is changes, i.e. when it's moving tangent.



a *б* *c*

Fig. 2. Photo microelectronic surface exposed hydro-abrasive impact (*a*), the scheme of the jet-abrasive flow impact on a processed area *D* (*b*) and result of the modeling of the interaction of particles with the surface (*c*)

Then volume remote in time t of the material at first approximation will be microgrooves profile close to cylindrical, rounded at the beginning and end of groove (provided that the particles move at the small angle of attack by stream which determined). It will be

$$W_p = \left(\frac{\pi \delta_г^2 \left(3r - \delta_г\right)}{3} + \sqrt{r^2 - \left(r - \delta_г\right)^2}\, \delta_д \delta_г \right) \frac{M_c}{m}, \tag{4}$$

r – radius of the abrasive particle, m – its weight.

Depth of the hole $\delta_г$ and the length $\delta_д$ as a function of processing parameters can be determined on the basis of regularities proposed by Strutinskiy V. B. and Manuel E. F. and refined in the microscopic research by Fomovska A. [2]:

$$\delta_г = \frac{m \left(C \left(\frac{L}{X_c} \right)^{\frac{4}{3}} \frac{2\mu p_в}{\sqrt{2 p_в \rho} + \dfrac{M_a}{f_к}} \right)^2 \sin\varepsilon}{2} \frac{R_a}{k_n z_a H_V};$$

$$\delta_д = \frac{m \left(C \left(\frac{L}{X_c} \right)^{\frac{4}{3}} \frac{2\mu p_в}{\sqrt{2 p_в \rho} + \dfrac{M_a}{f_к}} \right)^2 \cos\varepsilon}{2} \frac{z_a}{k_a \sigma_b} - \frac{k_a T_p^2 \sigma_b R_a}{2 m z_a}, \tag{5}$$

R_a, H_V ,σ_b – roughness, hardness and the surface strength of the processed material; z_n – graininess of the abrasive particle; T_p – constant, taking into account the inertia of the microcutting process; k_n,k_a – constant coefficients; ε – striking angle onto the processed surface of the particle.

However, the calculations showed that the intensity of destruction, determined by the last formulas corresponds to the experimental values only at angles of inleakage not exceeding $\pi/12$. The error of calculations increases and reaches 60 % for large angles of $\pi/3$. The reason for this is that more expedient to use an indicator of stress intensity K_{Ic} during processing of hard alloys to evaluate the influence of the strength characteristics on the process productivity. The principal advantage of K_{Ic} in comparison with other characteristics of ultimate strength is that the fracture toughness also considers the crack length. Any fracture criterion expressed in terms of stress, suggests that, in achieving this stress the fracture occurs instantaneously. In fact, all the destruction is the result of crack growth, and therefore characteristic of the limiting ability to brake the destruction should include not only the stress but the crack length.

We have shown that the critical stress σ_b will be:

$$\sigma_b = \frac{K_{Ic}}{\sqrt{\pi l_m}}, \qquad (6)$$

l_m – critical crack length.

Minimum critical crack length is related to the particle size, which can accommodate this crack, i.e.

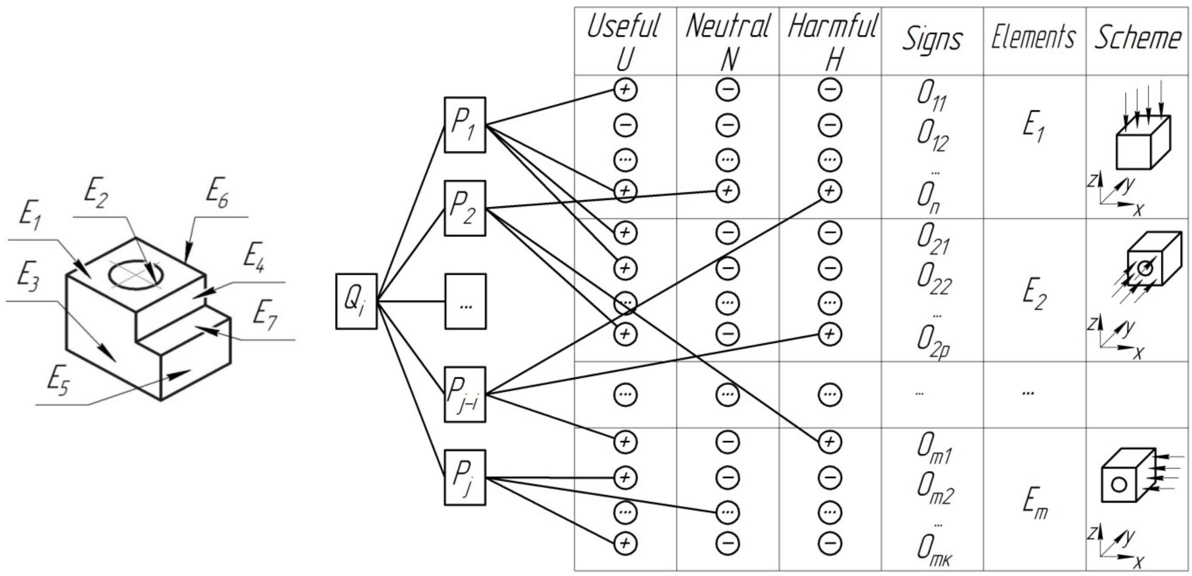
$$l_m = \frac{0,06bE^2}{\sigma_t^2(1-\mu)\left\{1+0,4(1+\mu)\ln\left[\frac{76(1-\mu^2)\sigma_t}{E}\right]\right\}}, \qquad (7)$$

E – elastic modulus, b – Burgers vector, σ_t – yield strength at angles of attack close to $\pi/3$ and the smaller. Formula (4) of the hole size as a function of processing parameters and physical and mechanical characteristics of the processed material will acquire the following form

$$W_{pm} = \left(\frac{\pi\delta_e^{\,2}\left(3r-\delta_e\right)}{3} + \sqrt{r^2-\left(r-\delta_e\right)^2}\,\delta_e l_m\right)\frac{M_c}{m}, \quad \sigma_r > \sigma_b .$$

Cutting hard and superhard materials occurs with a change the conditions of interaction the flow with the workpiece leading to a change in the mechanism of material removal. Design of the effective process of the jet cutting can be carried out using the functional approach. Its essence lies in the differentiation of obtained surface and occurred processes by individual features [3].

It is known (Fig. 3) that technological process is a set of operations and transitions aimed at changing the size of the production object, state or parameters of machined surfaces. Technological process of the part consists of several operations Q_i, each of which is implemented on individual transitions P_{ij}. Consistent their implementation will lead to the formation a number of elements E_i on the workpiece and adoption the form expressed by qualitative and quantitative attributes of functions. At the same time the implementation of individual transitions (P_{ij}) leads to the appearance not only useful, but also neutral and harmful functions created by processing elements as material carriers, Fig. 3.



a *b*

Fig. 3. Elements of the product obtained by implementation of technological operations (a) and the forming functions by operations (b)

The scheme presented here allows to postulate graph of the functions conditionality by product elements and transitions of the technological process, due to which these elements are formed (Fig. 4).

Accept that output signs constitute an array of values **B**. Divide the signs B_{ij} by a number of elements L_k formed during the processing a workpiece. These elements jointly will uniquely identify the signs of the processed part.

Denote useful properties as K_m, neutral – N_p, harmful – S_u. Of all the possible alternatives of technological transitions will be the best one that does not provide for the occurrence the harmful properties of the product, or has a minimum number of such properties. At the same time formation of the useful properties should be done with minimal material expenses and the harmful properties should be excluded on the following transitions. Possibly these transitions should be combined with transitions of generate the basic functions of the product.

For this purpose, the most expedient drawing up tables of states and use of morphological analysis and graph theory. An example of such a table is shown on Fig. 4.

Conditionality functions of the product by processing elements

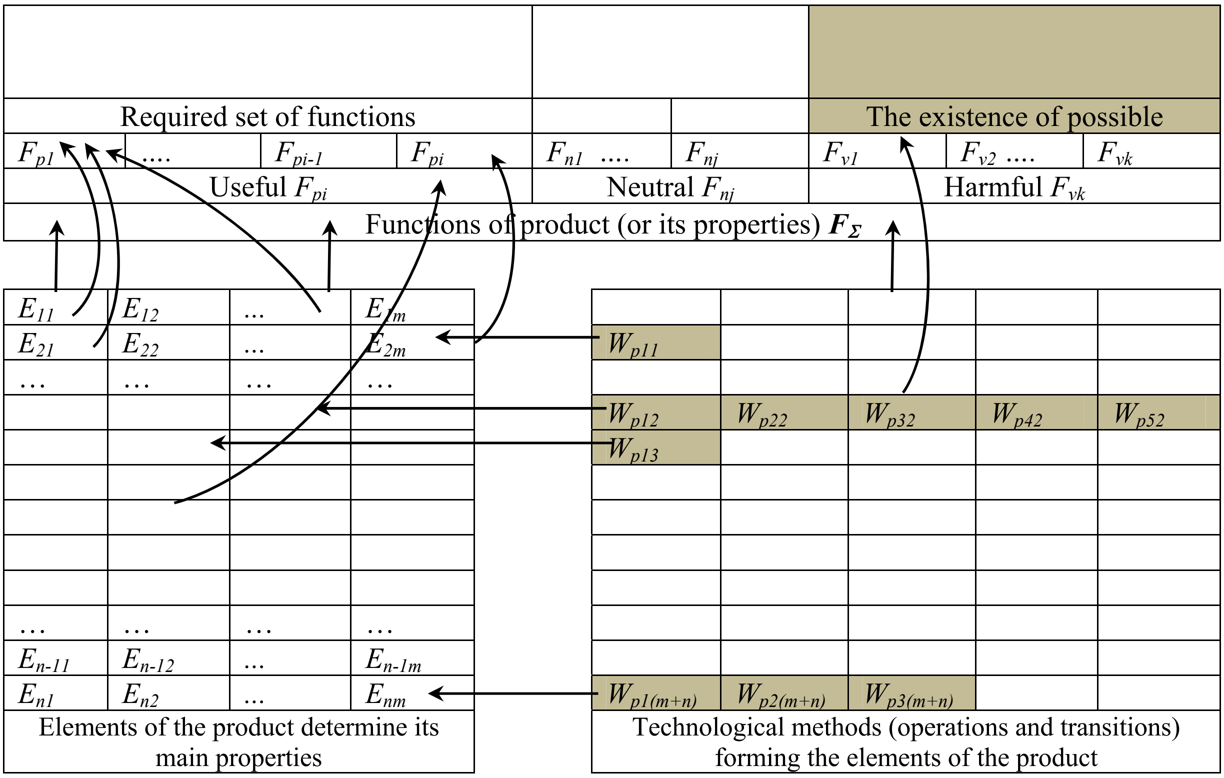


Fig. 4. Ensuring functions (properties) of the product F_{pi} by its individual elements and their formation by technological transitions W_{ij}

Process was differentiated to perform operations of hydroabrasive cutting: T_1 – obtaining the initial strokes on the surface; T_2 – formation of the initial hole and bottom microrelief; T_3 – growth of the hole; T_4 – work with the feed movement; T_5 – ensuring a predetermined surface microgeometry after procutting ("smoothing"). Set of functions of the finished product is represented as a matrix of properties including micro- and macrogeometrical indicators and parameters of the defect layer (possible cracking near the place of receipt of the cut).

This made it possible to propose a new technical solution of the device to perform the cutting and consider options for processing as at a minimum infeed with full procutting of the workpiece, so at multipass cutting with formation of neutral functions of the product – grooves to exit the waste liquid. Process modelling showed greater expediency of the second method of processing.

The above considerations have been checked making the openings in the workpiece of the TC group hard alloy. The hole was performed on the laser-jet complex LSK-400-5, equipped with jet-head with water nozzle $d_с$ = 0,22 mm and gauge tube $D_к$= 1,05 mm. Was processed the T5C10 plate with thickness of 7 mm; was performed the hole D_0 = 5,0±0,025 mm. As an abrasive was used garnet with fraction of 50/100 microns. Abrasive consuption – 0,5 kg/min, liquid pressure $p_в$ = 250 MPa.

As a result was obtained several holes, as with the constant velocity around the contour ($s_к$=300 mm/min), so with variable velocity (from $s_{к0}$ = 300 mm/min to $s_{к1}$= 100 mm/min), Fig. 5.

Measuring of obtained hole have shown that multipass holes obtaining is not only more efficient but also prevents the formation of a number of defects, first of all the macrogeometric character. Work with the constant velocity led to a significant distortion of the contour at jet output (i.e. to the incorrigible marriage). While speed variation, despite an increase in the processing time allowed to obtain deviation from circularity on the outlet within 0.4 mm for the plates with thickness of 7 mm; in a sample as a sphere was obtained through hole.

Thus we have shown the feasibility of using multipass processing to produce precise cuts in a hard-alloy materials using variable cutting feed leading to a significant reduction in deviations from the intended form of jet. Found that decreasing of velocity around the contour should be proportional to the thickness of processed material and to its physical and mechanical characteristics.

Was researched the process of obtaining through and blind cuts in CBN and SiC material. The blind cuts subjected to cutting with already applied metallization and element base.

a *b*

Fig. 5. Obtaining quality holes (a) and defective holes (b) in hard-alloy workpieces

Found that traditional processing of super hard materials and hard alloys with translational feed and with jet formation in the jet-blender chamber nor performance nor quality has not given: when using PCBN plates with hardness of 38–40 GPa, with diameter of 12,7–25,4 mm, with thickness of 3,97–5,56 mm, with the outflow of the stream up to 350 m/s resulting cut was low-quality and has charging in the surface layer of the abrasive particles. Processing was carried out with such regimes: p = 320 MPa; contouring feed rate v_s = 100–1,0 mm/min, mass flow of abrasive m_a = = 0,5–1,5 kg/min; diameter of the gauge tube $d_{тр}$ = 1,1 mm. As an abrasive used the natural material – garnet brand «garnet mesh 80» with average grain size of 0,180 mm, with hardness of 8 Moh's which is supplied from the abrasive feed hopper.

Research of the processed surface of the polycrystalline samples showed the presence of grooves formed by water jet stream closer to the output of the jet with satisfactory quality of the leakage plane. At the same time the evaluation of the surface state (using energy dispersive X-ray microanalyzer) showed the presence in a surface layer of abrasive particles remaining after water jet cutting (Fig. 6). Sufficiently large number of particles observed with the naked eye: inner part of the groove had a characteristic reddish hue and the attempt to remove these particles mechanically yielded no result. Obviously, at the moment of contact with processed surface and abrasive particles moving practically perpendicular to the surface in which they are introduced. At the moment of the collision the kinetic energy almost expended on destruction of the material was converted into heat. It has been proposed that the local heat emission may change the conditions of the contact and instead elastic contact became a viscoelastic with the manifestation of the plasticity.

The denser stream of abrasive particles than more heat is generated. Reducing the flow of abrasive led to that glow partially eased. However, cutting depth per one pass is not significantly changed. The conclusion is obvious that the destruction of material with carryover micro swarf possible with tangential impact of abrasive particles. Consequently the task of improving effectiveness of the processing was introduced as the task of ensuring the corresponding direction of the particles motion.

Study damage of the material and the formation of the hole of microcutting showed the following:

– velocity of jet penetration into the material is unstable. It first has a tendency to increase and then to decrease. Upon receipt of deep (several jet diameters $D_к$) blind holes may complete cessation of the cutting process due to reduced $U(t)$ and $H(t)$ and a sharp increase in losses e_c;

– significant increases the volumetric material removal during transmission the feed movement to the jet the formation of initial groove to drain fluid and does not lead to a reduction of this parameter in obtaining of the groove.

Obviously, this contributes to the fact that destruction of material is performed not only by stream which flows down across the surface but the peripheral portion of the jet in which the velocity of particles is much higher. Thus, multipass cutting is an effective and be more satisfactory than a single pass;

– presence of zones of high hardness on the processed surface (caused, for example, an abnormal amount of cobalt binder leads to a deflection of the jet from the hypothetical direction of movement under given conditions of its moving). The more linear feed velocity than the larger the deviation of jet. Reducing of energy parameters of the jet with increasing groove depth causes larger deviation. obvious conclusion: feedrate of multipass cutting should be variable, higher at the initial process and decreasing with growth of the hole.

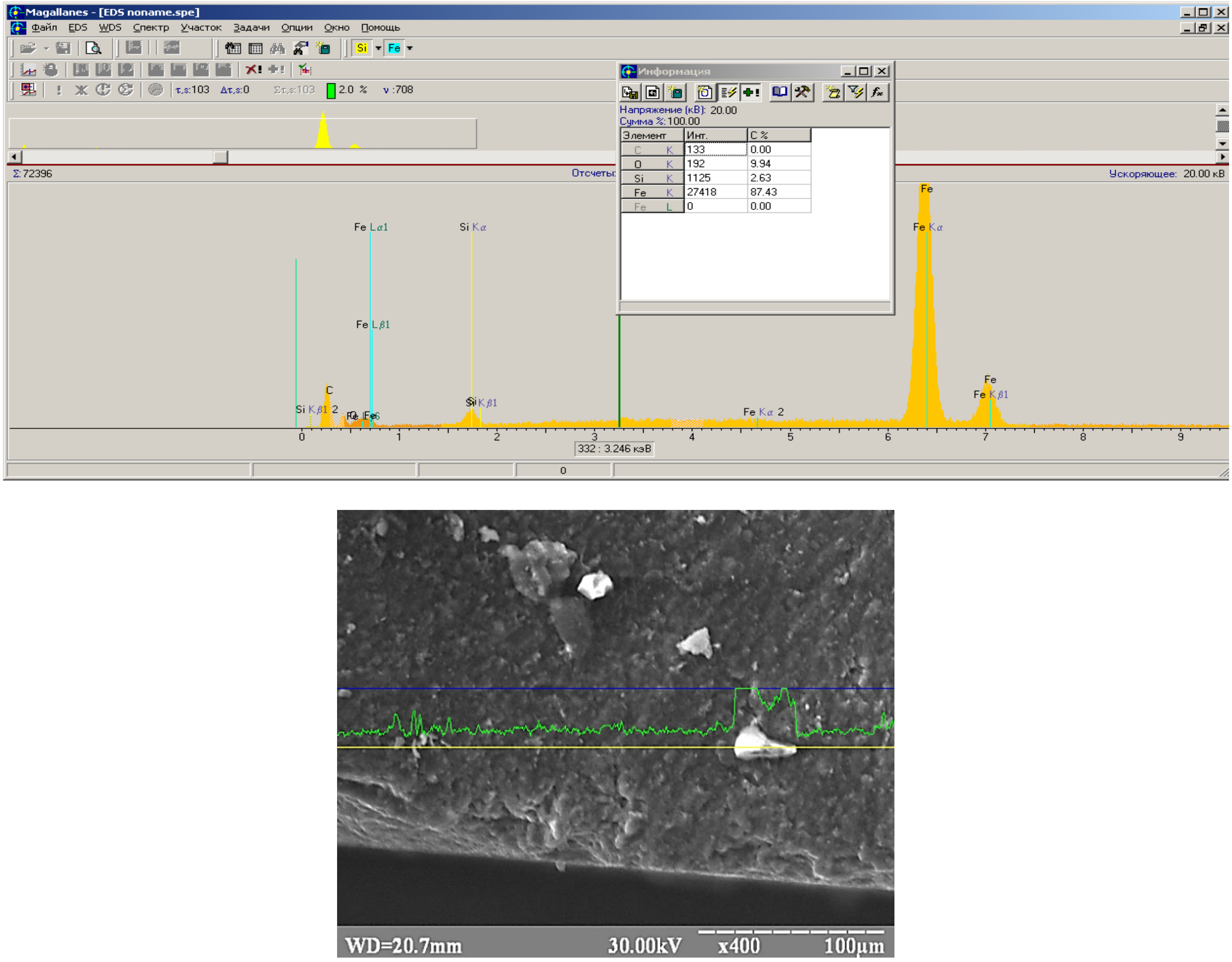


Fig. 6. The result of energy dispersive microanalysis sample surface with a determination of the presence of silicon oxide (abrasive residues) on the surface

Therefore a high surface quality (as the normal efficiency of the overall process) conditioned by the functional approach to the implementation of processing: the creation of certain conditions to eliminate unwanted effects and maximum ensuring the small angles of attack of the abrasive particles; performing multipass cutting, while maintaining a speed at which the in the cutting zone provides optimum microgeometry of interaction.

Implementation of these prerequisites for cutting SiC micro plates allowed us to obtain high-quality almost flawless cut with minimal material and labor costs (Fig. 7).

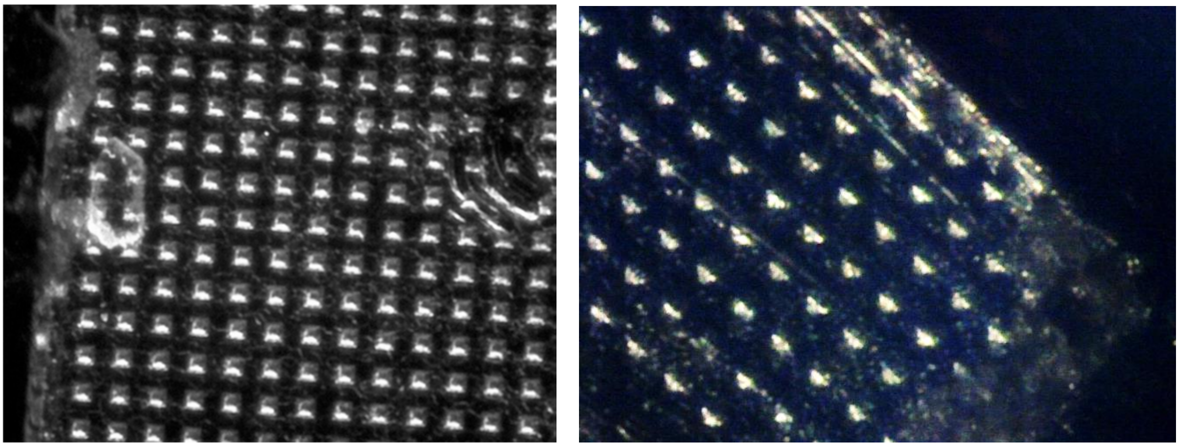


Fig. 7. Optical micrograph of the silicon wafer with inflicted metallization after cutting by precision hydroabrasive jet (x500)

Thus, we have shown the feasibility of using multipass processing for obtaining precision profile cuts of hard-alloys material using the changable cutting feed that leads to significant reduction in deviations from intended form of jet. Found that the decrease in speed around the contour should be proportional to the thickness of the processed material and its physical and mechanical characteristics.

Further research should be aimed at getting regularities of quality of the obtained surface depending on the processing regimes and on the type of abrasive used. The construction of such model will allow us to offer efficient methods of jet processing as a universal and effective method for forming finished products.

Анотація. *Проілюстрована можливість використання багатопрохідної обробки для отримання складнопрофільних високоякісних крайок у заготовках із твердих сплавів та надтвердих матеріалів із використанням багато прохідного різання, яка веде до значного зниження відхилень від правильної геометричної форми. Встановлено, що зменшення швидкості обходу контуру має бути пропорційним товщині оброблюваного матеріалу та його фізико-механічним властивостями.*

Ключові слова: гідроабразивне різання, водоструминні пристрої, функціональний підхід, тверді сплави та надтверді матеріали

Аннотация. *Показана возможность использования многопроходной обработки для получения сложнопрофильных высококачественных кромок в заготовках из твердых сплавов и сверхтвердых материалов с использованием многопроходного резания, что приводит к значительному снижению отклонений от правильной геометрической формы. Установлено, что уменьшение скорости обхода контура должно быть пропорционально толщине обрабатываемого материала и его физико-механическим характеристикам.*

Ключевые слова: гидроабразивная резка, водоструйные устройства, функциональный подход, твердые сплавы и сверхтвердые материалы

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