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The advantage of composite materials used in downhole cutting tools

Zalety materiałów kompozytowych stosowanych w otworowych narzędziach skrawających

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ABSTRACT: One of the important reserves for the growth of oil and gas production is the acceleration of emergency recovery work in production and exploration wells at minimal cost. A significant amount of work in downhole conditions is performed using downhole destructive and cutting tools. Each oil and gas producing country annually uses more than 100 standard sizes, thousands of cutting tool sets: downhole, annular, combined, pilot, internal and external pipe cutters, as well as reamers for cutting side "windows" in production strings. Therefore, the need for them is growing significantly every year. The conducted experiments show that during the operation of cutting tools, the working abrasive-cutting part of the tool wears out and collapses, but the body, other elements and the connecting thread remain suitable for further operation. Therefore, the restoration of working bodies, consisting of crushed particles of used borehole cutting tools, is an urgent scientific and technical task for the oil and gas industry. When repairing oil and gas wells, as well as eliminating the most complex accidents, more than a hundred standard sizes of downhole cutting and destructive tools are used. Currently, an acute shortage of this equipment in oilfield facilities makes it necessary to reconsider the technologies for restoring downhole cutting and destructive tools and introduce them into production. The conducted studies show that there is not enough information about the thickness and height of the layers of the material applied to the damaged area of the cutting and destructive tool, as well as the information necessary for the optimal mode of its operation and its effectiveness after restoration. Composite materials are widely used in the preparation of cutting-chopping and destructive elements of oil-field tools and equipment used in the drilling, operation and repair of wells. In order to increase the cutting capacity of the cutting part of the tool, it is necessary to investigate the advantages of tungsten-carbide (TC) type composite materials compared to other materials and ensure their resistance to high temperatures. As a result of theoretical studies, the stress-deformation state of the contact areas of the composite elements, where the working areas of the cutting and destructive tools are reinforced, and the dependence of the productivity of the composite materials on the speed of transition to metal and the sizes of the composite grains were determined by using the finite element method (two-dimensional simplex elements).

Key words: composite material, finite elements, stress-deformation state, cutting-chopping destructive tools.

STRESZCZENIE: Jedną z ważnych kwestii wpływających na wzrost wydobycia ropy naftowej i gazu ziemnego jest przyspieszenie awaryjnych prac naprawczych w odwiertach eksploatacyjnych przy minimalnych kosztach. Znacząca ilość pracy w warunkach wgłębnych w otworach wykonywana jest z zastosowaniem otworowych narzędzi niszczących i skrawających. Każdy kraj produkujący ropę i gaz rocznie stosuje ponad sto standardowych rozmiarów zestawów tysięcy narzędzi skrawających: otworowych, pierścieniowych, łączonych, pilotażowych, wewnętrznych i zewnętrznych przecinaków do rur, jak również rozwiertaki do wycinania „okien" bocznych w rurach eksploatacyjnych. Tym samym każdego roku zapotrzebowanie na te narzędzia znacząco wzrasta. Przeprowadzone doświadczenia pokazują, że podczas pracy narzędzi skrawających część robocza ścierająco-tnąca narzędzia zużywa sie i zapada, lecz korpus, inne elementy i gwint łączący pozostają odpowiednie do dalszej pracy. Tym samym, odbudowa korpusów roboczych, składających się ze zmiażdżonych cząstek zużytych otworowych narzędzi skrawających, jest pilnym zadaniem badawczym i technicznym dla przemysłu ropno-gazowego. Podczas naprawy odwiertów ropnych i gazowych oraz likwidacji najbardziej skomplikowanych awarii stosuje się ponad sto standardowych rozmiarów otworowych narzędzi skrawających i niszczących. Obecnie poważny niedobór tego sprzętu na złożach ropy naftowej wymusza konieczność ponownego rozważenia technologii dla naprawy otworowych narzędzi skrawających i niszczących oraz wprowadzania ich do produkcji. Przeprowadzone badania pokazują, że brak jest wystarczających informacji o grubości i wysokości warstw materiału nakładanych na uszkodzoną powierzchnię narzędzia skrawającego i niszczącego, oraz informacji koniecznych dla optymalnego trybu jego pracy i jej skuteczności po renowacji. Materiały kompozytowe są szeroko stosowane w przygotowywaniu elementów tnąco-skrawających i niszczących dla narzędzi naftowych i sprzętu stosowanego przy wierceniu, pracy i naprawie odwiertów. W celu zwiększenia wydajności cięcia części tnącej narzędzia konieczne jest zbadanie zalet materiałów kompozytowych typu węglik wolframu (TC) w porównaniu z innymi materiałami, oraz zapewnienie ich odporności na wysokie temperatury. W wyniku badań

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teoretycznych określono stan naprężeniowo-odkształceniowy obszarów styku elementów kompozytowych, w których wzmocnione są obszary robocze narzędzi skrawających i niszczących oraz zależność wydajności materiałów kompozytowych od prędkości przejścia w metal i rozmiarów ziaren kompozytowych metodą elementów skończonych (dwuwymiarowe elementy sympleksowe).

Słowa kluczowe: materiał kompozytowy, elementy skończone, stan naprężenie-odkształcenie, tnąco-skrawające narzędzia niszczące.

Introduction

Global practice shows that composite materials are widely used both abroad and in the CIS countries in the preparation of cutting-chopping and destructive elements of oilfield tools and equipment in the drilling, operation and repair of wells. The results of numerous studies show that composite materials containing tungsten-carbide (TC) composite alloys, which increase the cutting capacity of the tool, are widely used in the formation of the cutting parts of cutting-chopping and destructive tools. The significant application of composite materials has been reflected in scientific works (Mustafayev et al., 2021a; Mustafayev and Nasirov, 2021).

Technological leadership on the world stage is inextricably linked with the development of new technologies and materials. Increasing the operating temperature of composite materials is one of the main tasks in the creation of promising materials and products obtained from them. As a result of technological progress, it became clear that complex alloying, combined with optimal heat treatment and improvement in the technology of obtaining materials, contributed to an increase in their heat resistance. This requirement is met by high-temperature materials created on the basis of composite materials with an increased operating temperature (Kablov, 2015, 2016; Kablov et al, 2017a, 2017b).

Eliminating the discrepancy between the requirements of new technology for structural materials and the capabilities of classical alloys is achieved by creating and using composite materials (Portnoy and Babich, 1974).

In engineering a wide range can be attributed to composite materials, but it is difficult to consider them all within the framework of one article. Therefore, matrix-based materials created for use in wells with elevated temperatures are considered.

Composite materials are heterogeneous in nature and often their structure is oriented in a certain way. They are divided into two groups: fibrous-layered and dispersion-strengthened. This division is convenient for getting acquainted with metal composite materials (MCM). However, there are cases when a mixed material is created. Pseudo-alloys can be singled out as a separate group of composite materials.

Fibrous compositions consist of reinforcing components such as threadlike wire crystals; layered – from alternating reinforcing components in the form of sheets, plates or foils, firmly interconnected along the entire contact surface and dispersion-strengthened – from those materials, in the matrix of which fine particles are evenly distributed, which do not interact with it and do not dissolve in it. The load-bearing elements in fibrous and layered materials are reinforcing fibre, wire and foil, and in dispersed reinforced materials – the matrix. The reinforcing elements are presented with high strength, a modulus of elasticity and low density. It has been experimentally established that the mechanical properties of the matrix depend on the behaviour of the composition under shear, compression, and fatigue failure (Portnoy et al, 1979; Kostikov and Varenkov, 2003).

In dispersion-strengthened materials intended for operation at elevated temperatures, the components of the composite material are selected from the standpoint of minimal interaction. At high temperatures, in dispersion-strengthened materials, the grain shape (length and diameter) is of particular importance. Dispersed materials as fibrous composites are strengthened with ultradispersed particles, in connection with which the redistribution of loads and stresses between the fibres is carried out due to the boundaries and adjacent areas. In such a situation, the strength at elevated temperature can be increased by changing the boundaries in the direction of increasing stress. This situation is achieved by increasing the ratio of the grain length to its diameter, which is called the coefficient of unequal alignment of the grain. For such composites, a directional structure with highly elongated grains is formed during deformation-heat treatment. A linear dependence of most of the strength characteristics of dispersed compositions on the coefficient of grain unequal alignment has been determined. This coefficient depends on the temperature and strain rate. It should be noted that the strengthening effect due to the unevenness of the grain is most pronounced at a low strain rate and high temperature. However, the coefficient of unevenness of the grain is not always a structural characteristic that controls the high-temperature strength. When assessing the influence of structural factors on the high-temperature properties of dispersion-hardened materials, one should take into account the shape and size of grains, as well as the density, size of dispersed particles, distances between particles, and stability of the structure of elements during deformation-heat treatment.

The structural inhomogeneity formed as a result of deformation and subsequent high-temperature annealing is retained in dispersion-hardened materials in all temperature ranges (up to 0.97 T_{mt} (melting temperature)) and is a typical structure for these materials. The good creep resistance of dispersion-strengthened materials at elevated temperatures is due to a fairly stable substructure and provides a significant advantage in heat resistance at (0.8–0.9 T_{mt}) compared to traditional materials. The temperature of superalloys prepared on the basis of nickel and titanium must exceed the operating temperature at the fracture surface. These alloys exhibit high strength, fatigue resistance and creep resistance. Along with corrosion resistance, they are also able to maintain their properties for extended periods of time at higher temperatures. About half of the total mass of a jet engine falls on nickel or nickel-iron superalloys (Structural applications of mechanical alloying, 1990; Campbell, 2006).

Due to the high strength and hardness at elevated temperatures, as well as good thermal properties, the use of molybdenum-based composite materials as tool materials is possible while the treatment of steels and alloys is at high temperatures under the pressure. Recently, a possible and important area of application of molybdenum alloys has been their use in the form of a thin high-strength wire as a reinforcing fibre in composite materials. In terms of specific strength, such a wire at temperatures up to 1100°C is superior to wires made of other refractory metals and alloys (Emelyanov et al., 1977).

The levels and anisotropy of strength properties in the longitudinal and transverse directions in deformed bars of composite materials based on tungsten, molybdenum and niobium are also studied. It has been determined that with an increase in the content of tungsten in the composition of the material, the anisotropy of properties will be higher than in molybdenum-based compositions (Ershova, 1997).

The high efficiency of hardening of extruded powdered molybdenum with zirconium diboride (ZrB_2), which is achieved in the region of temperature-active recrystallization (1400–1600°C), has been determined. Efficient temperature ranges for hardening compositions based on molybdenum and tungsten with nitride additives have been defined (Ershova, 2003).

Other researchers also pay attention to obtaining composite materials based on refractory metals and alloys. Using electrospark plasma sintering and subsequent annealing, a molybdenum-based composite material with TiC particles was obtained. As a result, the authors obtained a material with a density close to the theoretical one (Ohser-Wiedemann et al., 2012).

Using the technology of powder metallurgy, the La–TZM composite material was obtained and studied. Solid state La_2O_3 was added to the TZM molybdenum composition powder. The operations of sintering, hot, warm and cold rolling were carried out. This makes it possible to increase the ultimate strength and relative elongation of the material (Hu et al., 2013).

The thermal stability and mechanical properties of a tungsten-based composite material have been studied using dispersion-strengthened HfC (*Hafnium carbide*) particles. The methods of electric pulse plasma sintering and forging were used for completing the material. As a result of the research, it was found that the forged composite material based on tungsten has better thermal stability, thermal conductivity and higher mechanical properties compared to the composition obtained by electropulse plasma sintering (Wang et al., 2017).

A natural composite material based on the Nb–Si system is one promising material for operation in the temperature range of 1200–1400°C. Titanium and hafnium have proven themselves well for additional alloying of the Nb–Si composite, which contribute to an increase in oxidation resistance, impact strength, and hardness. To suppress pitting at moderate temperatures (800–900°C), these materials are alloyed with small amounts of tin and germanium.

The microstructure and phase composition of the composite of the Nb–Si–Ti system were also studied; the effect of the technological impurity of iron on the hardness and density of the samples was evaluated, and the optimal duration of the mechanical alloying process was determined (Grashchenkov et al., 2011a, 2011b, 2016; Efimochkin et al., 2018).

Various technologies for the production of composite materials have been developed as a result of attempts to optimise their structure and mechanical properties. One of these methods is the method of directed crystallisation of a liquid melt of a eutectic composite material. In this case, the structure of the material is created naturally in the process of crystallisation of the eutectic melt, and not due to the artificial introduction of the second phase. A distinctive feature of this method is that the material is formed in one operation (Balasubramanian, 2014).

Gas-phase methods for obtaining composite materials are based on gas-thermal spraying and deposition of metal from the gas phase, which is intended for coating (Kovtunov et al., 2017).

A technology based on powder metallurgy for the production of parts with dimensions close to those specified and with a special microstructure is also considered. Some of these technological schemes were investigated at a European level in the HYSOP project with the development of effective coating systems based on multilayer EBC coatings (*Environmental Barrier Coatings*) (Seemüller, 2016).

For parts manufactured from various materials using powder injection molding (PIM) technology, fine powders with sizes of <5 µm are used with high accuracy. Spherical powders are preferred rather than powders of a fragmented shape (Goulon, 2010).

An analysis of existing works in the field of mechanical processing of metal objects revealed that the best cutting properties for processed materials are obtained by the tungsten group of hard alloys (HA) and titanium-tantalum-tungsten (TTT) (Kablov, 2015; Kablov et al., 2017b).

A common feature of hard alloys is high hardness (HRA 86-92) and heat resistance (700–1000°C), which determine the advantages over high-speed steels, such as increased wear resistance and the ability to process at high cutting speeds (Portnoy and Babich, 1974; Kablov, 2016; Kablov et al., 2017a).

Hard alloys are characterised by a relatively low flexural strength σ = 90–165 kgf/mm^2, significantly yielding in this respect to high-speed steels. The low flexural strength of hard alloys causes brittle fracture of the cutting part of hard alloy tools during interrupted cutting with sudden changes in load. Hard alloys in the same and different groups are notable for their physical and mechanical properties, which must be taken into account when choosing the carbide component of the cutting edge of the tool.

Foreign firms indicate that when reinforcing the cutting part of the tool, the ultimate strength of hard alloys in bending is significantly affected by the carbon content, residual porosity, surface condition and strain rate of hard alloys (Portnoy et al., 1979; Structural applications of mechanical alloying, 1990; Kostikov and Varenkov, 2003; Campbell, 2006).

Practice shows that technical hard alloys made from fine-grained low-temperature carbide powder are less strong than medium-grained TC (*Tungsten Carbide*) alloys, which, in turn, are inferior in strength to group alloys made from high-temperature carbide powder (Kostikov and Varenkov, 2003; Kablov, 2015; Kablov et al., 2017b).

The most effective way to destroy metal objects left in the wellbore is a mechanical method based on the destruction of objects by milling them.

This process is a continuous removal of thin metal layers in the form of chips and its successive removal to the bottom surface with a flushing-cooling agent.

The following requirements are imposed on the design of the cutting edge of a downhole milling tool: ensuring high rates of the milling process (penetration through metal), resistance of the cutting edge of the tool to impact loads, hydroabrasive wear, high temperatures and aggressive components contained in the formation, manufacturability of the tool design, optimal distribution specific contact loads over the entire contact surface of the cutting edge, ensuring a rational route and the amount of flushing and cooling agent supplied directly to the cutting zone.

The creation of a design of the cutting part of the tool that meets these requirements will significantly reduce the duration of the milling process in the event of accidents in the wellbore.

The task set in the article is the selection and justification of the study to determine the effectiveness of the hard-alloy component of the cutting edge of the downhole destructive tool.

Discussion

In the works under study, various technologies for obtaining composite materials, as well as the formation of an attempt to optimise their structure and mechanical properties, were carefully studied. The technologies based on powder metallurgy for the production of parts with different sizes with a given microstructure are considered. The restoration of the working body of used downhole destructive and cutting tools by modern methods was also studied, taking into account the factors affecting the composition of the formation of composite materials. However, in the works under consideration, the deformed stress state affecting the further operation of the downhole cutting and destructive tool after the restoration of its cutting edge was not taken into account. The stress deformation state that occurs in the shear zone depends on the resistance of the metal subjected to dissolution to plastic deformation. The higher the shear strength of metals, the higher their viscosity and malleability.

An increase in the deformation-stress state and temperatures in the cutting zone affects the ductility of the material; as the cutting zone hardens, the cutting forces increase, and as a result, the cutting elements are disconnected during the operation, the tool becomes blunt, loses its ability to work, and fails prematurely. These negative factors force one to reconsider the various parameters that affect the operation of downhole cutting and destructive tools.

Scientific novelty

Based on the results of numerous studies, it was determined that the cutting composite elements of the milling cutter the hardness of which is reinforced with the HB70 matrix material have a relatively low wear rate, and the specific productivity is higher. It was therefore recommended to adopt this matrix material as the main base material in the design of the cutting parts of the tool. The proposed matrix material is close to the physico-mechanical properties of other objects subjected to breakage when it is reinforced in the failure area of the tool, and allows adjusting the stress deformation state in the breakage area. According to the results of the conducted studies, the productivity of the proposed composite alloy matrix grains in milling changes in the range of q = 9.5–200 grams.

Case study

Study of the effect of geometrical dimensions of composite alloys on tool performance with emphasis on tribotechnical properties in the analysis of composite materials.

Methods of solving the problem

In order to determine the stress-deformation state created on the contact surfaces of the tool, the problem posed in the article is to solve the stresses created in the unit area of a grain due to the compressive force using the finite element method (two-dimensional simplex elements), which is considered a suitable method in modern calculation methods, to determine the dependence of the productivity of cutting-chopping and destructive tools on the physical and mechanical properties of composite matrix materials and to simulate the obtained results in the MS-EXCEL-2016.

Solution of the problem

The advantage of tungsten-carbide (TC) type composite materials for the cutting part of chopping and destructive tools compared to other materials is their increased cutting ability and resistance to high temperatures. High productivity can be achieved in milling objects subjected to disintegration with TC type composite materials resistant to temperatures of 950–1000°C.

When the components of composite materials with electrical conductivity interact with metals, the electric charge caused by friction on the contacting surfaces of the tool causes an increase in temperature on the contacting surfaces and the overheating of the composite elements and the failure of the tool in a short time.

It is necessary to create new types of composite materials that meet modern requirements based on the materials obtained to increase the cutting capacity of the cutting-chopping and destructive tools.

Due to the uneven distribution of the load on the contact surfaces of the cutting-chopping and destruction tools used in the drilling and repair of wells, the cutting part of the tool is periodically affected by shocks. When cutting elements are damaged by friction, corrosion occurs, temperatures on the contact surfaces increase, heat exchange weakens, cracks appear in a set of composite elements, cutting elements fall apart, and the force in the cutting-disintegration zone increases. As a result, riveting occurs and the tool ends its intended service life prematurely (Mustafayev et al., 2021a; Mustafayev and Nasirov, 2022).

The efficiency of cutting-chopping and destructive tools depends on the stress-deformation state of composite elements, the physical-mechanical properties of composite alloy joints, the value of impact forces and other factors.

Depending on the construction of the cutting-chopping and destructive tools, the effect of impact forces is more typical for the two extreme cases. In the first case, it is assumed that the forces act on the cutting elements in the first layer (after the failure of the first layer) in the contact area of the composite material assembly, and in the second case, the force acts on the composite alloy particles in the entire assembly.

The stress state created on the surface of cutting and destructive tools can be considered as a plane stress state.

The finite element method, which is considered a more appropriate and advanced method, can be used to determine the stress-deformation state that occurs on the contact surfaces of the tool (Mustafayev, 2017b; Mustafayev and Amirova, 2017; Mustafayev et al., 2021b). Two-dimensional simplex elements are used for it.

The main essence of the finite element method is to conduct searches using discrete models in solving physical-mathematical problems. Each of the discrete models is formulated as a set of continuous cross-sectional functions defined in a given interval of subfields. Each of the subfields is called a finite element. Discrete fields allow solving a system of differential equations to solve a simpler system of mathematical equations.

Using the finite element method, it is possible to determine the discrete values of the function at the given nodes. The finite element method is performed in the following order:

1. The area under consideration is divided into a finite number of elementary subareas. Elementary areas have nodal points, which in general approximate the shape of the area.
2. The continuous function at the nodal points is not known in advance; it is determined only later.
3. The unknown quantities in each element are approximated by the collection of certain functions. These functions are used depending on the type of element and the number of nodes included in the element. The polynomials should be chosen in such a way that the functions along the boundary of the element keep their continuity.
4. The solution is performed with the help of enabling a certain functional related to the given differential equations. In this case, the functional is discretised using the approximating function and its derivative in the given finite elementary set.
5. As a result of discretization and minimization of the transformed functional, a system of mathematical equations is obtained. The solution of these equations determines the value of the function at the given nodes.

Force vector for the element $[\bar{F}]$:

$$\left[\bar{F}\right]=\left[\bar{F}_R\right]^e+\left[\bar{F}_P\right]^e \tag{1}$$

If the calculated area is divided into n number of elements, then the solving mathematical equations of the finite element method are expressed as follows:

$$\left[K\right]\cdot\left[f\right]=\left[F\right] \tag{2}$$

$\left[K\right]=\sum_{e=1}^{n}\left[K\right]^e$ is the consumption matrix

$$[F]=\sum_{e=1}^{n}[F_R]^e+\sum_{e=1}^{n}[F_P]^e \quad \text{is a vector of forces} \qquad (3)$$

where:

F_R – discrete function,

F_p – minimization function,

$[f]$ – is the displacement vector of the nodes and determined from the solution of the system of mathematical equations (2).

After determining the displacement of the nodes, the stress and deformation at any point of the element can be determined.

In solving the system of mathematical equations (2), it is necessary to take into account that the stiffness matrix is drag and positive. Therefore, the solution of the considered system of mathematical equations should be done by the method of adding square roots. This allows both reducing the calculation time and storing only the non-zero elements of the matrix.

The block diagram of the computational program that determines the plane stress state of the cutting elements using the finite element method is shown in Figure 1. The obtained results were simulated in MS-EXCEL-2016.

On the basis of theoretical studies, the main and tangential stresses caused by the compressive force falling on the hollow surface of a grain of the composite element included into relationship (grain size 2.5 mm) were determined, and based on the obtained results, graphs of the dependence of the main and tangential stresses along the contact area of this grain were constructed (Figures 2 and 3).

It can be seen from the stress distribution graphs that the intensity of the tangential stress in a grain entering the solid connection in the area where the compressive force is applied is $\sigma = 1.91 \cdot 10^{-1}$ MPa, and the intensity of the principal stresses is $\sigma = 0.182 \cdot 10^{-1}$ MPa. The analysis of the graphs shows that the tangential stresses caused by the composite elements under the influence of the compressive force falling on the unit area close

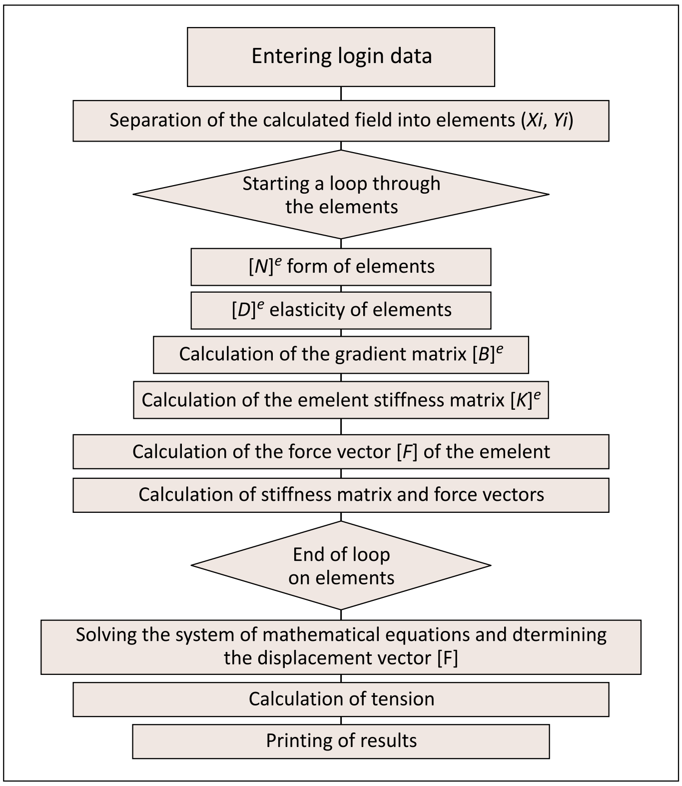

Figure 1. A block diagram constructed to study the plane stress state on the contact surfaces of a cutting-chopping and destructive tool

Rysunek 1. Schemat blokowy skonstruowany do badania stanu naprężeń płaskich na powierzchniach kontaktu narzędzia tnąco-skrawającego i niszczącego

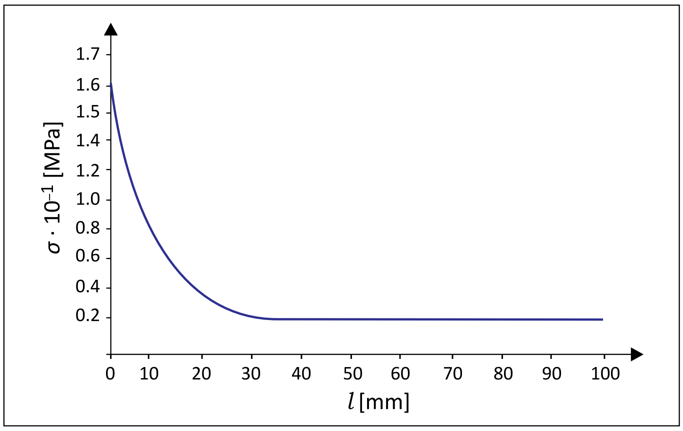

Figure 2. The distribution scheme of the principal stresses generated in the contact area of this grain due to the compressive force applied to one grain of the cutting-chopping and destructive tool

Rysunek 2. Schemat dystrybucji głównych naprężeń generowanych w obszarze kontaktu danego ziarna ze względu na siłę ściskającą wywieraną na jedno ziarno narzędzia tnąco-skrawającego i niszczącego

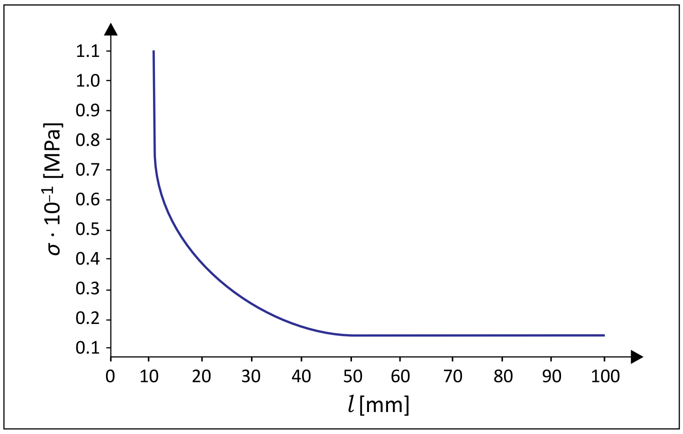

Figure 3. . Distribution scheme of tangential stresses generated in the contact area of this grain due to the compressive force applied to one grain of the cutting-chopping and destructive tool

Rysunek 3. Schemat dystrybucji naprężeń stycznych generowanych w obszarze kontaktu danego ziarna ze względu na siłę ściskającą wywieraną na jedno ziarno narzędzia tnąco-skrawającego i niszczącego to the centre of rotation of the tool (at the minimum values of pressure and temperatures) take minimal values. And this is one of the main properties characterizing the strength of the particles included in the relationship.

Using the results of theoretical studies, the effect of cutting-chopping and destructive composite elements on the destruction of metals was examined experimentally.

Unlike other areas of mechanical engineering, in the milling works performed in well conditions, since the cutting elements are not affected by radial forces, the deformation during cutting reaches a high level, so the cutting elements slide and tangential forces affect the sliding plane.

Shear forces in metal cutting are determined according to the "shear" theorem under the conditions that ensure the special work of plastic deformation in shear and compression:

$$F = \frac{\frac{n}{1.5}\frac{\xi^2 - 2\xi\sin\gamma}{\xi\cos\gamma} - 1}{1 - \frac{\sin\eta}{\xi\cos(\eta - \gamma)}} st\frac{\sigma_0}{n} \tag{4}$$

where:

F – is the force acting in the direction of cutting speed,

n – the polytropic indicator of tension,

s – the width of the cut,

t – the cutting depth,

σ_0 – the conditional flow limit,

ξ – shavings compression,

γ – the position occupied by the front angle of the cutting element,

η – the friction angle.

In order to simplify the solution of the problem, the tangential stresses in the sliding zone can be taken as a constant quantity ($\tau = 2/3\,\sigma_0 = \text{const}$, $n = 0$) and this expression can be considered in (4) and the shear force (F_1) is determined as follows:

$$F_1 = \frac{2}{3}\sigma_0 s \cdot t \, \frac{\xi^2 - 2\xi\sin\gamma + 1}{\cos\gamma\left[\xi - \sin\gamma - \cos\gamma\,\mathrm{tg}(\eta - \gamma)\right]} \tag{5}$$

Formula (5) shows that the cutting force depends on the physical properties of the material being cut (σ_0, n), the dimensions of the cutting area (t, s), the front side (γ), friction (η), angles of the cutting element, the compression of shavings (ξ), etc.

The front angle of the cutting element (γ) depends on the main parameters that accelerate the cutting and affect its force.

The distribution of normal stresses generated on the contact surfaces of the tool during contact with the object of the accident is characterised by the abc curve in the scheme (Figure 4).

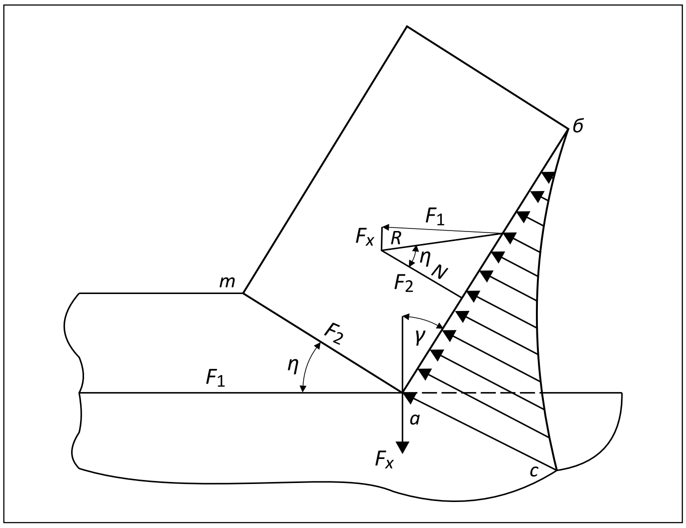

Figure 4. Distribution scheme of the forces affecting the front angle of the cutting elements in the milling process (explanations in the text)

Rysunek 4. Schemat dystrybucji sił działających na kąt czołowy elementów tnących w procesie frezowania (objaśnienia w tekście)

The normal force (N) is a substitute for the internal forces generated in the cross-section of the shear element and consists of only normal stresses with a regular distribution along the cross-sectional area of the shear element. The sum of the tangential stresses generated in the area of friction of the front surface of the cutting element against shavings is equal to the friction force (F). The reciprocal of the frictional force and the normal force (R) equals the force that creates the shavings.

According to the "Theory of Metal Cutting" and "Distribution Schemes of Forces Arising in the Front of Cutting Elements", the force consists of the forces acting on each grain of the cutting element in the direction of the trajectory of the grain (F_z) and the axial force determined from the mass of the drill pipes (F_x).

As can be seen from the graph, the cutting elements slide along the *am* plane, where the deformation reaches its maximum, and the tangential force (F_τ) acts on the sliding plane.

If the forces acting in the radial direction are not taken into account, then the forces generated in the other two directions can be expressed as follows (Figure 4):

$$F_z = \sigma_0 t s \xi^n (\cos\gamma + \mu\sin\gamma) \tag{6}$$

$$F_x = \sigma_0 t s \xi^n (\mu\cos\gamma - \sin\gamma) \tag{7}$$

μ – is the coefficient of friction, defined as follows:

$$\mu = \frac{F}{N} = \mathrm{tg}\eta \tag{8}$$

here:

$$\eta = 90° - (2\rho - \gamma) \tag{9}$$

Then pressing shavings:

$$\xi = \frac{\cos(p - \gamma)}{\sin p} \tag{10}$$

From (10), we define p as follows:

$$p = \mathrm{arctg}\frac{\xi - \sin\gamma}{\cos\gamma} \tag{11}$$

Based on the results of the experiment, the compression ratio of shavings was taken as $\xi = 2$.

The relationship between the distance of each intersecting cutting elements and the volume concentration of the particles characterised the strength of the composite material.

The free distance between the particles entering the relationship is found as follows:

$$\lambda = \frac{2a_{av}}{3V_p}(1 - V_p) \tag{12}$$

where:

λ – is the free distance between the particles in contact,

a_{av} – is the size of the particles,

V_p – is the volume concentration.

We define the distance between particles as follows:

$$L_p = \sqrt{\frac{2(a_{av})^2}{3V_p}(1 - V_p)} \tag{13}$$

As the distance between particles (L_p) increases, the volume concentration of dispersed particles (V_p), the normal modulus of elasticity and the temporary resistance to fracture of composite elements decrease.

The mathematical relationship between the strength characteristics of the particles entering the relationship and the size of the shavings to be milled is determined as follows:

$$\sigma_{\max} = \frac{6\sigma_0 a\left[0.5\left(a - \sqrt{a^2 - d^2} + 1.77K_2\sqrt[3]{\frac{F_1}{0.5a(K_2 + K_3)}}\right)\right]\left(L^{\frac{n}{1.5}\frac{\xi^2 - 2\xi\sin\gamma + 1}{\xi\cos\gamma}} - 1\right)(3x - h)}{\left[1 - \frac{\sin\eta}{\xi\cos(\eta - \gamma)}\right](3a^3 + 0.6h^3)n} + \frac{Q}{a^2K_1\pi(R^2 - r^2)n_p} \tag{14}$$

where:

F_1 – is the axial force acting on the milling cutter,

Q – the axial load given to the milling machine under the weight of the drilling pipelines,

$\sigma_{\max}$ – the maximum stress that characterised the stability of composite particles in contact,

σ_0 – the conditional flow limit of the object to be milled,

x, a – the major and minor axes of the ellipsoid of the rotating grain,

h – the depth of formation of the grain in the connection,

d – a trace that characterised the depth of the grain after the release of the load,

K_1, K_2, K_3 – the ratio indicators of the area of the working surface of the milling machine and the washing channels,

$\pi(R_2 - r_2)$ – the area of the milling object,

n_p – the number of working particles falling on a unit surface, determined experimentally or analytically.

$$K_2 = \frac{1 - \mu_1^2}{\pi E_1} \tag{15}$$

$$K_3 = \frac{1 - \mu_2^2}{\pi E_2} \tag{16}$$

where:

μ_1 and μ_2 – are the Poisson coefficients of the object and material under study,

E_1 and E_2 – the modulus of elasticity of the studied object and material.

Experiments were carried out in order to adjust the composition of composite materials to the composition of objects subjected to disintegration (Mustafayev, 2017a; Mustafayev and Pashayeva, 2017; Mustafayev and Nasirov, 2021; 2022).

During the tests, milling cutters (milling model samples) reinforced with composite alloy matrix materials with different physical-mechanical characteristics and grain sizes were used. Physical-mechanical properties of matrix materials are given in Table 1.

During the research, samples of D-grade pipes made of steel 40, which is close to the assortment of oil pipes, were used.

The absolute efficiency of composite alloy matrix materials is evaluated after matching the physical-mechanical properties of the objects destroyed by the matrix material.

Since the physical-mechanical properties of the composite alloy matrix grains change, the performance of the cutting elements will depend on the sliding friction generated along the cross-sectional area of the object to be destroyed and the mode parameters of milling.

Experiments were carried out with 1; 2; 2; 3; 4; 5 mm matrix material granules in the following mode parameters (Table 2).

In order to achieve high productivity in milling, it is considered more appropriate to reinforce the working surface of the tool with composite alloy grains from 0.5 mm to 5 mm. (Figures 5 and 6). Reinforcement of the cutting surface of the milling cutter by this method has been confirmed in the conducted experiments.

A matrix with yield strength σ_{fl} = 380–500 MPa, temporary resistance $\sigma_{m.m}$ = 95–140 MPa, impact viscosity α = 7–9, Brinell hardness 70 HB as a research object for determining the degree of influence of the resistance force against the matrix grains of the objects subjected to disintegration material was selected.

Table 1. Physical-mechanical properties of matrix materials

Tabela 1. Właściwości fizykomechaniczne materiałów matrycowych

Physical-mechanical properties	Milling model number				
	1	2	3	4	5
Matrix hardness [HB]	80	70	100	110	115
σ_{com} [MPa]	26.6	31.8	19.3	11.7	13.5
σ_{fl} [MPa]	650	380	950	500	750
Relative elongation [%]	97	61	82	33	22
Impact viscosity [kgm/cm^2]	9	8	8	6	7
Melting temperature, T_{mt} [°C]	900–1050	1000–1100	850–900	825–915	836–885

Table 2. Mode parameters of the milling machine (model)

Tabela 2. Parametry trybu maszyny frezującej (model)

Factors studied	Mode settings				
Specific load [kN]	3.7	1.7	6.4	2.8	4.9
Rotational frequency [rad/sec]	52.3	26.0	104.6	37.0	74.3

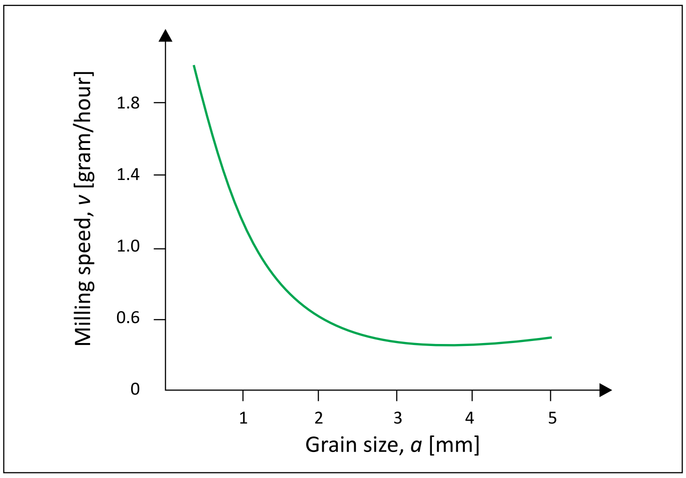

Figure 5. Graph showing the dependence of milling speed (v) on grain size (a)

Rysunek 5. Wykres przedstawiający zależność prędkości frezowania (v) od rozmiaru ziaren (a)

Axial load 1.7–2.8 kN, rotation frequency 26–37 rad/sec were adopted as mode parameters of the experiment.

Based on the results obtained from the experiment, graphs were constructed showing the dependence of milling speed (v) on grain sizes (a) (Figure 5) and specific productivity (q) of the mill on grain sizes (a) (Figure 6).

Analysis of the graphs shows that the increase in the specific gravity of the milling yield and the corrosion resistance of the composite materials depend more on the strength of the grains in contact. The low productivity of dispersed particles of large size (3–5 mm) is related to the strength characteristics of the particles in the relationship.

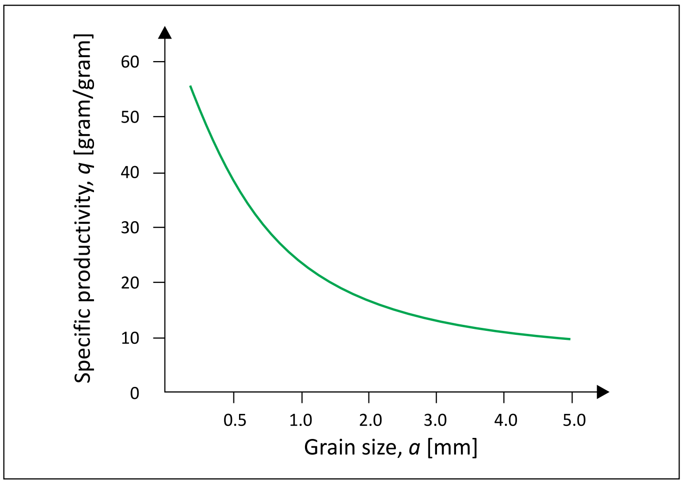

Figure 6. The graph showing the dependence of the specific productivity of the milling machine (q) on the grain size (a)

Rysunek 6. Wykres przedstawiający zależność wydajności właściwej maszyny frezującej (q) od rozmiaru ziaren (a)

The dependence of the size of the parts separated from the metal on the shape and size of the grains allows making a decision on the strength of the grains in contact.

As the dimensions of composite alloy materials and the grains in close contact with each other on the metal during milling increase, the stresses between the grains also increase. If the grain tears off the shavings from the metal up to 2 mm thick, then the tension in the zone where the grain is strengthened in the connection will gradually increase; if the grain tears off the shavings from the metal with a thickness of 3 mm and more, then the compressive stress in the connection will increase and exceed the allowable limit.

The yield of composite alloy grains with large sizes (3–5 mm) is very low. Although the thickness of the shavings that these grains tear from the metal is large, the forces spent on sawing exceed the required forces, which reduces the strength of the grains in the matrix. As a result, the large grains in the bond begin to break and the specific productivity in milling decreases. Due to the small distance between the small grains in the relationship and the large participation in milling, the volume of shavings they remove from the metal is greater.

Research results show that the efficiency of composite elements depends more on the mechanical properties of the material of the elements, the impact forces and the stress state of the elements. By applying the simplex method, the analysis of the stress state of composite elements shows that the stress intensity in the area where the force is applied takes values of $\sigma = 1.89 \cdot 10^{-1}$ MPa.

Conclusion and suggestions

1. According to the research results, the efficiency of the composite elements was determined depending on the mechanical properties of the material, the impact force and the stress state of the elements.
2. By using the simplex method, the stress distribution intensity was determined between the composite elements included in the area where the force is applied.
3. The dependence of the shaving speed of the milling machine on the size of the grain and the specific productivity on the size of the grain was determined.

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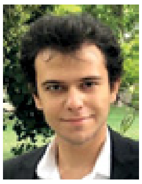

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OFERTA BADAWCZA ZAKŁADU TECHNOLOGII WIERCENIA

- opracowywanie składów i technologii sporządzania wodnodyspersyjnych i olejowodyspersyjnych płuczek wiertniczych, cieczy specjalnych (roboczych, nadpakerowych, buforowych, przemywających) i zaczynów cementowych do wiercenia otworów i rekonstrukcji odwiertów w warunkach normalnej i wysokiej temperatury oraz występowania różnych ciśnień złożowych i skażeń chemicznych;
- dobór właściwości płuczek wiertniczych, zaczynów cementowych, cieczy buforowych oraz oprcowanie metod usuwania osadów filtracyjnych w celu poprawy skuteczności cementowania otworów wiertniczych;
- badania serwisowe płuczek wiertniczych podczas wiercenia otworu oraz zaczynów cementowych w trakcie zabiegu cementowania;
- specjalistyczne badania laboratoryjne dotyczące oznaczania: wpływu cieczy wiertniczych na przewiercane skały, napięcia powierzchniowego na granicy faz, współczynnika tarcia w warunkach HPHT, sedymentacji materiału obciążającego, wynoszenia zwiercin w otworach kierunkowych i poziomych, doboru materiałów uszczelniających do zapobiegania ucieczkom płuczki wiertniczej i zaczynu cementowego w warstwy szczelinowate, odporności na migrację gazu w wiążącym zaczynie cementowym w warunkach otworopodobnych, odporności korozyjnej kamienia cementowego, związków chemicznych w cieczach wiertniczych i ich toksyczności przy użyciu bakterii jako bioindykatorów;

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