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Cutting of Complex-Contour Parts Made From Cellular Thin-Walled Honeycomb Structures and Determination of Their Optimal Tool Parameters and Processing Conditions

Iakov Iu. Pikalov,
Maksim V. Brungardt*, Mikhail V. Saramud,
Alexandr V. Tololo and Maksim V. Kubrikov
Reshetnev Siberian State University
of Science and Technology
Krasnoyarsk, Russian Federation

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Abstract. The article presents the results of the research of the cutting process of complex contour products from cellular honeycomb structures based on aluminum alloys, with a cutting tool in the form of a thin narrow blade with double-sided sharpening, reciprocating perpendicular to the wall of the honeycomb structure. The functional dependence of the cutting force and speed on the sharpening angle of the cutting tool blade and its thickness has been established. The optimal distance of the cut plane from the nodal points of the honeycomb structure is determined. The results of numerical simulation and experimental research to determine the optimal processing parameters that ensure the maximum cutting quality are presented. The reliability of the results obtained at the stage of analytical calculations and numerical simulation was confirmed experimentally by full-scale tests. As a result of the research, the optimal parameters and conditions of the cutting process were established: the thickness of the cutting tool is 0.4 mm, the sharpening angle is 20°, the speed of the tool is 5 m/s, the distance of the cut plane from the nodal point is 0.4 of the length of the cell wall. The results of the research can be used in the creation of a fundamentally new technological equipment for processing honeycomb cellular fillers, which have low manufacturability with traditional types of processing, which has found wide application in aviation and space production and makes it possible to produce complex-contour products from cellular honeycomb structures based on aluminum alloys. without additional processing, which increases its speed and reduces the cost.

Keywords: honeycomb blocks, plastic deformation, stress intensity, cutting, cellular structure, cutting force.

* Corresponding author E-mail address: mbrungardt@sfu-kras.ru

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Резание сложно-контурных изделий из ячеистых тонкостенных сотовых структур и определение оптимальных параметров инструмента и режимов процесса обработки

Я. Ю. Пикалов, М. В. Брунгардт, М.В Сарамуд, А. В. Тололо, М. В. Кубриков

Сибирский государственный университет науки и технологий имени академика М. Ф. Решетнёва

Российская Федерация, Красноярск

Аннотация. В статье приводятся результаты исследования процесса резания сложно-контурных изделий из ячеистых сотовых структур на основе алюминиевых сплавов, режущим инструментом в виде тонкого узкого лезвия с двухсторонней заточкой, совершающим возвратно-поступательные движения перпендикулярно стенке сотовой структуры. Установлена функциональная зависимость силы и скорости резания от угла заточки лезвия режущего инструмента и его толщины. Определено оптимальное расстояние плоскости реза от узловых точек сотовой структуры. Приводятся результаты численного моделирования и экспериментального исследования по определению оптимальных параметров обработки, обеспечивающих максимальное качество резания. Достоверность результатов, полученных на этапе аналитических вычислений и численного моделирования, была подтверждена экспериментально натурными испытаниями. В результате исследований установлены оптимальные параметры и режимы процесса резания: толщина режущего инструмента 0,4 мм, угол заточки 20°, скорость движения инструмента 5 м/с, расстояние плоскости реза от узловой точки – 0,4 от длины стенки ячейки. Полученные результаты исследования могут найти свое применение при создании принципиально нового технологического оборудования для обработки сотовых ячеистых наполнителей, обладающих низкой технологичностью при традиционных видах обработки, в авиационном и космическом производстве и позволяющих производить из ячеистых сотовых структур на основе алюминиевых сплавов сложно-контурные изделия без дополнительной обработки, что увеличивает ее скорость и снижает себестоимость.

Ключевые слова: сотовые блоки, пластическая деформация, интенсивность напряжений, резание, ячеистая структура, сила резания.

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Introduction

The improvement of space and aircraft apparatus involves the development of ultralight structures possessing high strength and low weight, for example, composite components used for hulls and other structural elements of the designed load.

One of the types of such materials is honeycomb blocks. Honeycomb blocks with hexagonal cells (Fig. 1) have the most common cellular structure, which is made of various materials, including aluminum alloys. The honeycomb blocks of interest to us consist of plates or sheets that form the edges of elementary cells, ranging in size from tens of micrometers to tens of millimeters. Most honeycomb structures are closed cell structures. These unit cells are repeated in two dimensions to create a cellular solid. This topology is effective under the action of external loads on the structure, especially shear due to bending of the panel [1].

Currently, there are several methods for processing honeycomb blocks. Among them, machining with end and disk mill [2] and tangential cutting of walls with a specially shaped tool that performs ultrasonic vibrations [3], [4] are the most widely used.

However, the milling of honeycomb blocks has the following disadvantages: firstly, it is impossible to provide sharp internal corners on the contours being machined (the minimum internal radius corresponds to the radius of the cutter), and secondly, the radial component of the cutting force bends the thin walls of the honeycombs, as a result, the perimeter of the processing contour turns out to be of poor quality, thirdly, it is difficult to fix the workpiece on the machine due to the low rigidity of the honeycomb block in the plane of the table, fourthly, after processing, it becomes necessary to remove small chips from the honeycombs.

The shape and methods of cutting honeycomb blocks with an optimal trajectory by the method of vertical cutting involves the process [5] in which the cutting edge of the knife is directed perpendicularly to the surface of the face of the honeycomb cell, bypassing the nodal faces.

This method is quite promising, however, ultrasonic treatment involves a complex selection of parameters of both the geometry of the tool itself and the source of ultrasonic vibrations, while the values of the optimal parameters may vary depending on the change in the parameters of the tool itself (mass, geometry, sharpening angle, speed, etc.).

This article presents the results of a research of the cutting process of complex-contour products from cellular honeycomb structures based on aluminum alloys, with a cutting tool in the form of a thin narrow blade with double-sided sharpening, which reciprocates perpendicular to the wall of the honeycomb structure.

Honeycomb block (Fig. 1) is a cellular structure, each cell of which has a hexagonal shape in cross section.

To take into account the effect on adjacent faces when modeling the cutting process of a honeycomb block, the computational model took into account eight cells located along the perimeter of the cut face, the dimensions of each were: height 20 mm, width 2.5 mm and the thickness of a single wall was 0.1 mm. Cells that were located more than two faces away from the cut were not considered, since they did not have a significant effect on the cutting process Figure 1.

The well-known works [6–7] investigated the deformation of cutting pipes of square or circular cross-section. An analysis of the works by the authors Woisin [8] and Jones et al. [9] showed that in the above empirical formulas, the left and right sides turned out to be incorrect for the expression they

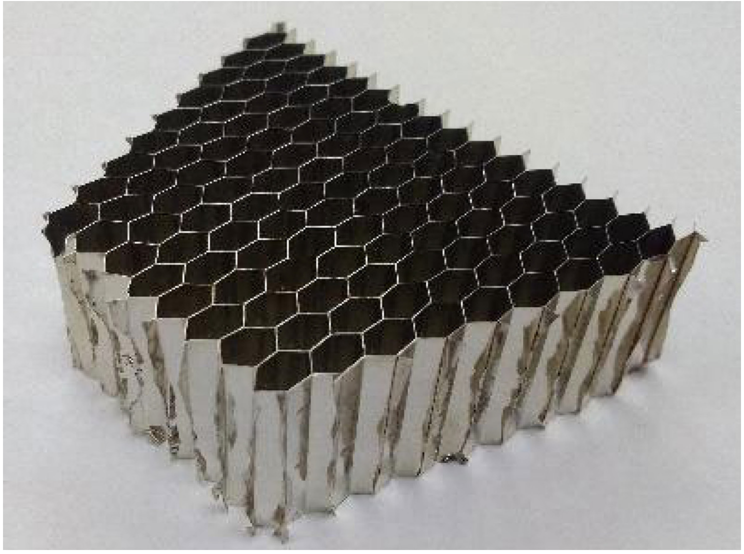


Fig. 1. Cellular structure of a honeycomb block

proposed. To correct this problem, Lu et al. [10] derived an empirical relationship, but based on an analysis of dimensions, and this showed that the cutting energy was proportional to 1.3 and 1.7 degrees of the depth of cut and wall thickness, respectively. Cutting metal plates in the work of Zheng et al. [11] showed that the deformation zones can be divided into three parts: the plastic deformation zone at the top of the wedge, the transitional ramps and straight transitions, and even proposed a simple model of the cutting process. Simonsen et al. [12] analyzed ductility, fracture and the effect of friction when cutting a metal plate with a sharpened steel knife.

Gene and Altenhof et al. [13–15], after making experiments on cutting a round and square pipe, made of aluminum alloy 6061-T6, obtained a nonlinear, while increasing, relationship between the cutting force and the number of cutting edges.

Ip-Hoi et al. [16], when testing for cutting honeycomb structures, divided the cutting process into three components, such as bezels, honeycombs, and their combination. Local destruction of the honeycomb structure was investigated by Zhou et al. [17], where a knife was pressed into the honeycomb wall and concluded that the cutting conditions are associated with delamination of the glued honeycomb walls, stretching and rupturing with subsequent destruction. Askhab et al. [18–19] proposed an empirical relationship between rupture energy and strain rate in honeycombs. To study the bursting energy of the honeycomb, experimental and numerical quasi-static and dynamic tests for indentation and compression were carried out. A similar result was obtained by Liu et al. [20], simulating the effect of rupture in an equivalent honeycomb model using elastoplastic beam elements with fracture criteria. All of the above studies were aimed at cutting a separate thin plate with a fixed support, as well as square or circular pipes with a wedge-shaped tool. However, studies of the reaction from cutting forces of more complex sections have not been carried out. A study by Xiangcheng Li et al. [21] showed that cutting a honeycomb structure with a vertical knife at several points is a difficult task, in which the influence of the effect of cell size on the cutting ability of hexagonal thin-walled aluminum honeycombs cut by die blades under quasi-static compression is considered as the effect of plastic flow of the cells, and the relationship between the cutting force and the depth of cut for vertical cutting of honeycomb is the same as for cutting a single thin plate. The present study involves cutting a single cell wall with a complex-contour trajectory and finding the optimal position of the knife plane relative to the nodal points [22].

1. Force and speed when cutting a single wall of a honeycomb cell

The method for determining the cutting force used by empirical coefficients [23] is not always convenient and accurate, therefore, the principle of cutting the material of the honeycomb wall was considered as an impact cutting of the knife edge and the cutting force was determined through inequality, provided that it did not break, taking into account the friction forces and the angle of sharpening of the cutting edge knife, determined from the designed diagram in Fig. 2.

The proposed method for cutting the wall of the honeycomb cell was considered according to the scheme (Fig. 2) of the action of forces between the side edges of the knife blade and the surface of the wall being cut. Due to the wedge-shaped form, the tool penetrates into the workpiece material and, under the action of a vertically directed external force F_{cut}, normal forces N arise on the side surfaces of the cutting edges, generating friction forces F_{fr} along the boundaries of the edge contact with the wall material. In this case, if the cutting force F_{cut} is greater than or equal to the resulting friction force ΣF_{fr}, as the vector addition of the friction forces on both sides of the cutting edges of the knife, then the honeycomb wall is cut. Failure to fulfill this condition only leads to deformation of the honeycomb wall at the point where the cutting edge of the knife touches the upper edge of the wall. The friction force on one side of the knife edge from the design scheme is determined as the ratio:

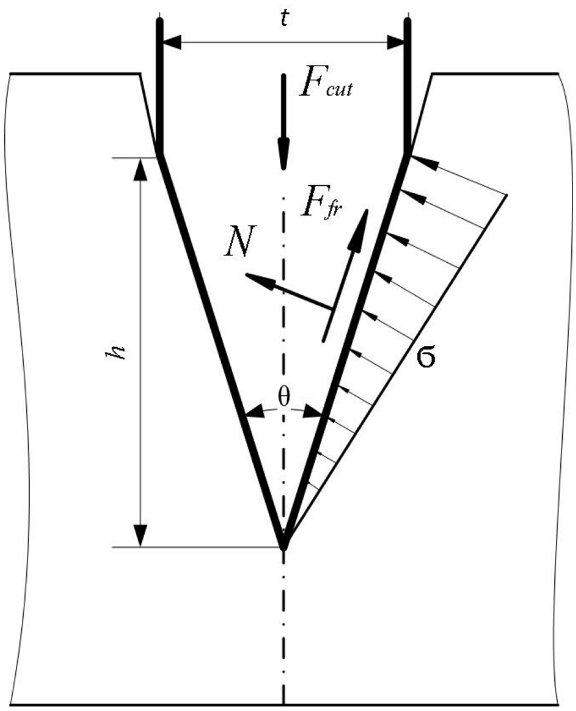


Fig. 2. Design scheme to determine the optimal angle of knife sharpening

$$F_{fr} = N \cdot \mu = \frac{F_{cut}}{sin\left(\frac{\theta}{2}\right)} \cdot \mu$$

where σ_0 is the stress intensity of the honeycomb material, for AMg6 σ_0 = 296.4 MPa; θ – knife sharpening angle; t_1 – single cell wall thickness; t – is the thickness of the knife; μ – coefficient of friction.

$$F_{cut} = 2 \cdot \sigma_0 \cdot S$$

where the area of the contact surface of the cutting edge of the knife and the upper edge of the honeycomb wall $S = \frac{t \cdot t_1}{sin\left(\frac{\theta}{2}\right)}$,

then:

$$\sum F_{fr} = \frac{\sigma_0 \cdot t \cdot t_1 \cdot \mu}{sin\left(\frac{\theta}{2}\right)} \cdot cos\ \left(\frac{\theta}{2}\right)\ = \frac{\sigma_0 \cdot t \cdot t_1 \cdot \mu}{tg\left(\frac{\theta}{2}\right)}$$

provided that: $F_{cut} \geq \sum F_{fr}$:

$$F_{cut} \geq \frac{\sigma_0 \cdot t \cdot t_1 \cdot \mu}{tg\left(\frac{\theta}{2}\ \right)}$$

In [22], the cutting speed was no more than 2 mm/min, in contrast to the method with the high-speed nature of the movement of the cutting edge of the knife, which contributes to the appearance of the effect of cutting the honeycomb wall.

In this case, the cutting speed ϑ_{cut}:

$$\vartheta_{cut} = \frac{P}{F_{cut}},$$

where P is the power of the knife drive.

The sharpening angle, the cutting force and the speed of the cutting tool movement determine the course of the cutting process. Graphical dependencies $F_{cut}(\theta)$ and V_{cut} (θ) are shown in Fig. 3. It can be seen that the cutting force F_{cut} is inversely proportional to the sharpening angle θ, and the cutting speed V_{cut} is directly proportional to the angle θ.

The values of the characteristics when constructing the graph are taken for a sample of a honeycomb block: the material of the honeycomb structure was AMg6, t_1=0.1 mm, μ=0.3.

The graph in Fig. 3 shows the change in cutting force and speed with a honeycomb wall thickness of t_1=0.1 mm and a cutting tool thickness of t=0.2; 0.3; 0.4 mm when changing the angle of sharpening of the cutting tool θ=15°…35°. The analysis of the obtained data showed that the mechanical properties of the honeycomb block material and the thickness of a single wall allow cutting under the action of an applied force of 20 N in the vertical direction and an optimal sharpening angle of the cutting edge of 20° without deformation of the adjacent walls of the honeycomb. Obviously, when the speed of the knife is 5 m/s, the nature of the process is the cutting of the wall of the honeycomb block.

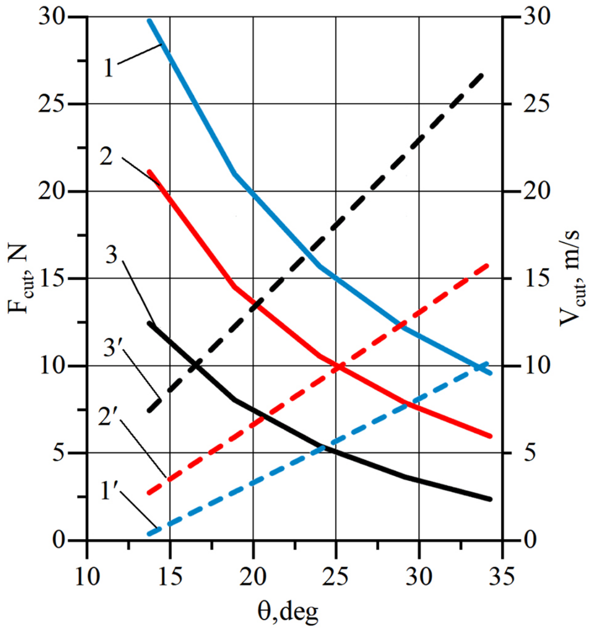


Fig. 3. Graph of dependence of force and cutting speed from the sharpening angle with a cell wall thickness of 0.1 mm; 1, 2, 3 – cutting force at knife thickness at t=0.2, t=0.3, t=0.4 mm; 1′, 2′, 3′ – cutting speed at knife thickness at t=0.2, t=0.3, t=0.4 mm

Thus, in order to facilitate cutting, it is necessary to reduce the taper angle of the cutting edge, which in turn led to the increase in its height h (Fig. 2) and, as a consequence, to a decrease in strength, since this contributes to an increase in the contact area of the cutting edge. This limits the possibility of reducing the sharpening angle. The choice of its size was determined by the material to be processed: the harder the metal, the greater the angle of taper; the softer the metal, the smaller the taper angle.

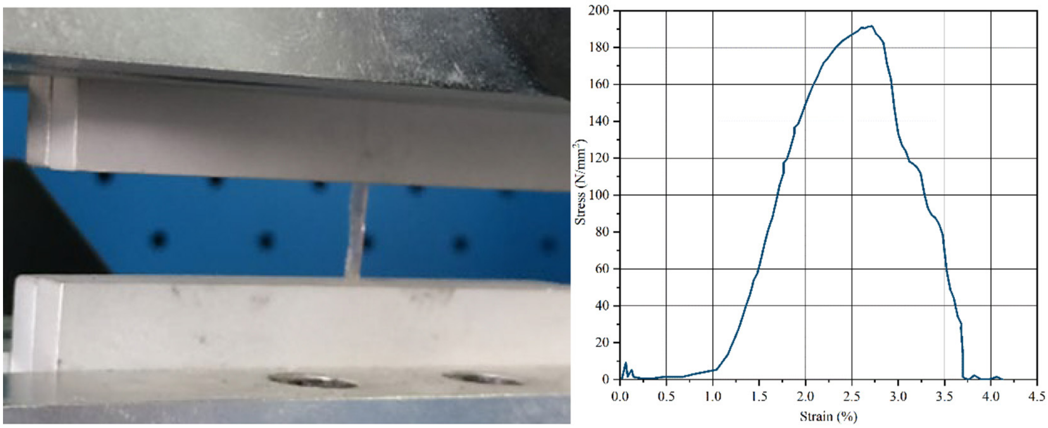
The material from which the honeycomb structure was made, namely a fragment of the wall, was subjected to tensile tests, experiments were carried out on an electromechanical machine TiniusOlsen 10ST for testing materials with a range of 10 kN and a graduation value of 3.5 N. The loading rate 5 mm/min. was chosen, as it is shown in Fig. 4a. A 0.07 mm thick AMg6 aluminum foil specimen was tested and used to make a honeycomb block. An experimental tensile diagram is shown in Fig. 4b, based on which the yield stress (σ_y) of the honeycomb material is approximately 190 MPa.

The thermal factor of cutting was not taken into account due to the small cutting area, and the friction between the cut part of the wall and the surface of the knife tended to zero due to the expanding cut during the process of deepening the knife.

2. Numerical modeling

Deformation and stress distribution in honeycomb structures are difficult to determine in analytical calculations. Therefore, the cutting process was analyzed using numerical simulation.

Numerical modeling of the cutting processes of hexagonal honeycombs was carried out in the software for calculating the explicit dynamics ANSYS Explicit Dynamics. The full- size finite element model is shown in Fig. 5. The size of the elements ranges from 0.05 mm in the wall being cut to 0.2 mm



a) b)

Fig. 4. Tensile test of honeycomb material: a) method of fxing during tests; (b) the relationship between stress and strain of the materia

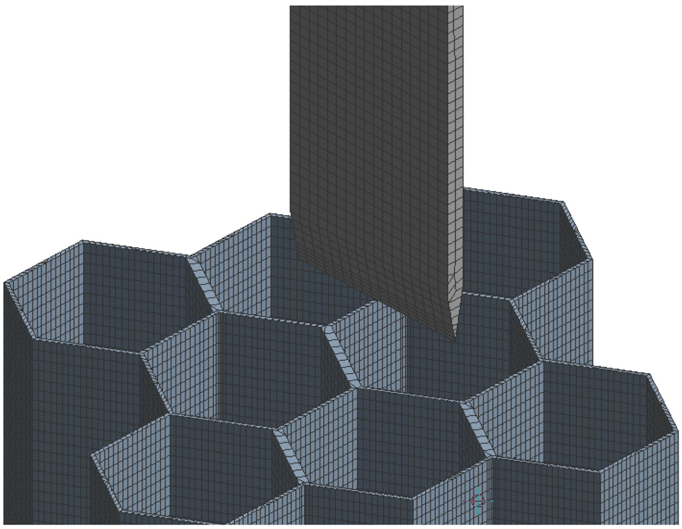


Fig. 5. Finite element model of the honeycomb block and the position of the knife blade relative to the wall

in adjacent walls as they move away from the cutting zone. The numerical model has 73398 nodes and 53357 finite elements.

To identify the influence of neighboring cells on the cutting process and deformation of the honeycomb, four cases of cutting placement were considered: at a distance of 0.5 mm and 1 mm from the double edge and at a distance of 0.5 mm and 1 mm on the single edge from the nodal point as shown in Fig. 6. The rest of the options were not considered due to the symmetry of the location. Aluminum alloy AMg6 was chosen as the material for the honeycomb blocks, and chromium steel grade 50H14MF was chosen for the blade. The physical and mechanical characteristics of the materials were taken into account in the calculation model.

When modeling the cutting process in the finite element model of the knife, a solid element with constant stress was used, and an elastic-plastic model was used for the honeycomb structure. The

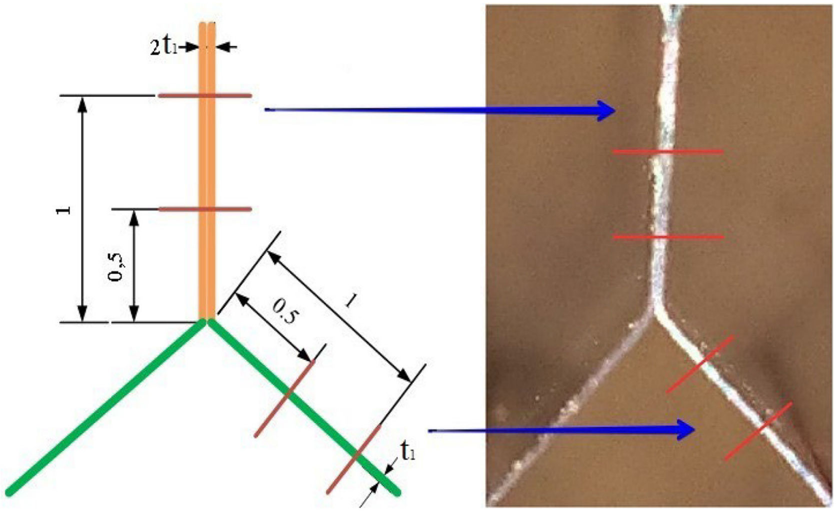


Fig. 6. The position of the cut relative to the nodal point on double and single walls

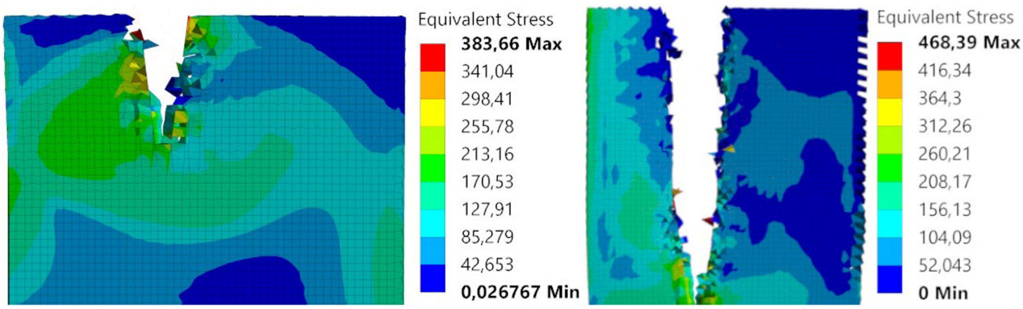
Table 1. Characteristics of the material of the honeycomb and the knife used for numerical simulation

Element	$\sigma_{в}$, MPa	E, MPa	ρ, kg / m^3
Knife	650	2,1x10^{-5}	7850
Cellular structure	200	0,71 x10^{-5}	2640

mechanical characteristics of the knife model and the honeycomb structure are shown in Table 1. The contact between the cutting edge of the knife and the honeycomb wall, as well as between the honeycomb and the fixed base of the structure, was assigned as automatic. The friction coefficient was taken to be 0.3, which corresponds to the approximate value of the sliding friction coefficient of smoothly machined non-lubricated surfaces for friction pairs of chromium steel on aluminum. The value of the relative elongation ε = 3 %, which was determined experimentally in Section 1 of this article, which was taken as the beginning of cutting the wall of the honeycomb structure. The cutting process was modeled as a vertical movement of the knife at a speed of 5 m/s and was limited by the direction along the honeycomb wall, while the force applied to the knife was taken equal to 20 N.

Analysis of the process of cutting the honeycomb wall with the help of a cutting tool with a cutting-edge sharpening angle of 15°. At the beginning of the cutting process, stresses arise in the contact zone of the blade edge with the edge of the honeycomb, the intensity of which in the honeycomb (Fig. 7a) and in the tool (Fig. 8) increases as it deepens by 0.5 mm to 3 mm (Fig. 7b). With further penetration of the blade into the wall of the honeycomb block, the stress intensity in the tool practically does not change, which means that this value does not depend on the depth of cut. Simulation of cutting with sharpening angles of the cutting edge of the tool of 20° and 25° indicates that similar processes take place (Fig. 9–12).

Comparing the calculated data, we built graphs of dependence of stress intensity (Fig. 13a) and plastic deformation (Fig. 13b) on the depth of cut of the honeycomb at sharpening angles of 15°, 20° and 25°.



a) b)

Fig. 7. Stress intensity in a honeycomb with a cutting tool sharpening angle of 15 ° cutting depth (MPa): a) 1 mm; b) 3 mm

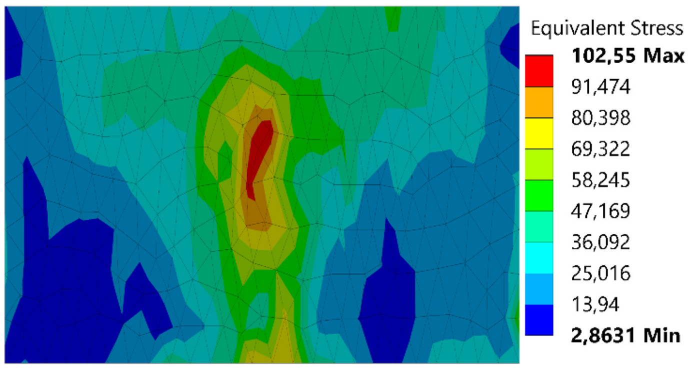
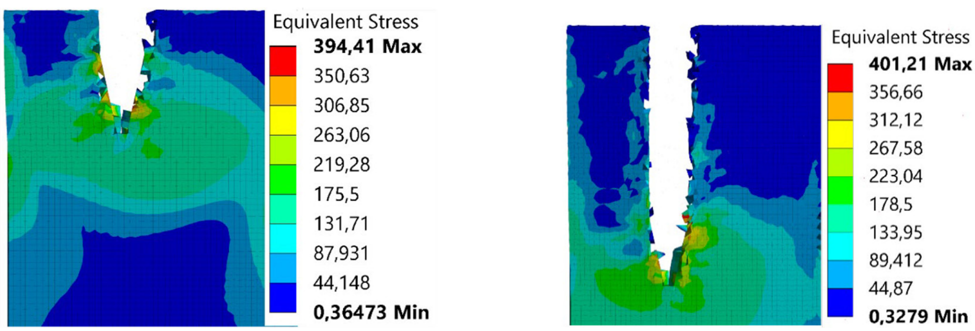


Fig. 8. Stress intensity in a cutting tool with a sharpening angle of 15° (MPa)



a) b)

Fig. 9. Stress intensity in a honeycomb with a cutting tool sharpening angle of 20° cutting depth (MPa): a) 1 mm; b) 3 mm

The optimal condition for cutting a honeycomb panel, as can be seen from the graphs, is obtained with a sharpening angle of the cutting edge of the knife of 20 °, since at this parameter there is a decrease in the stress intensity at the point of contact on the knife blade with an increase in the stress intensity on the honeycomb wall, and plastic deformations in the knife and the honeycomb wall are minimal.

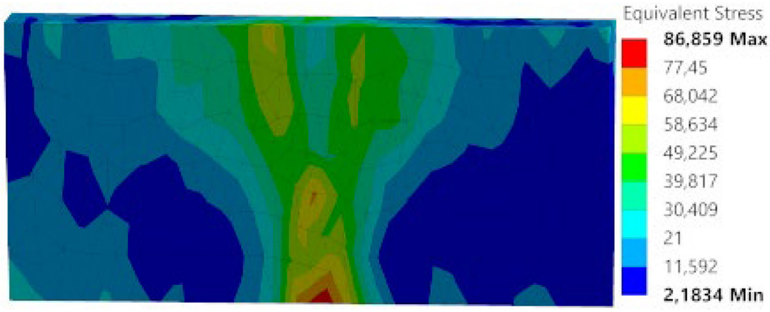


Fig. 10. Stress intensity in a cutting tool with a sharpening angle of 20°(MPa) at a distance of 0.5 mm from the nodal point, the neighboring walls of the honeycomb are deformed, and the maximum effective deformation in the cutting zone was 0.3

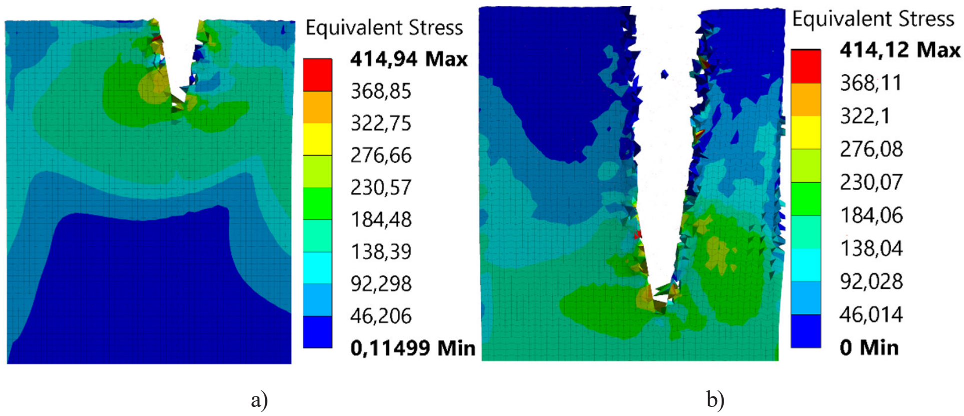


Fig. 11. Stress intensity in a honeycomb with a cutting tool sharpening angle of 25° cutting depth (MPa): a) 0.5 mm; b) 3 mm

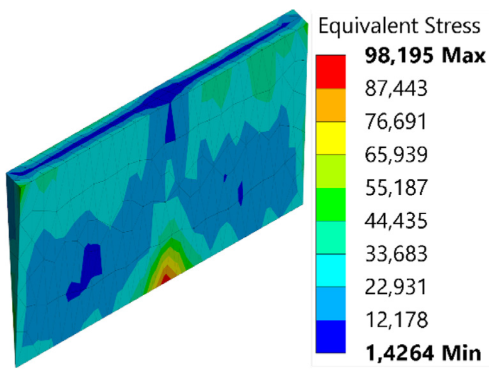
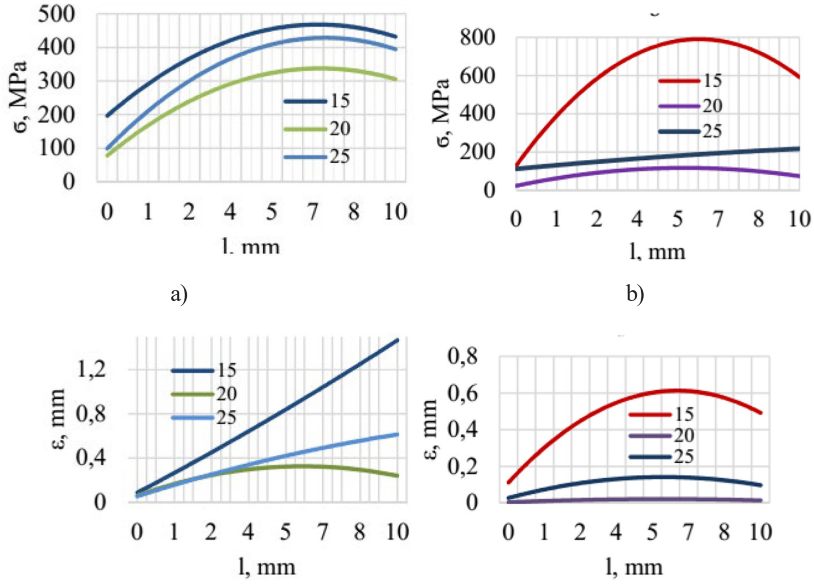


Fig. 12. Stress intensity in a cutting tool with a sharpening angle of 25°(MPa)

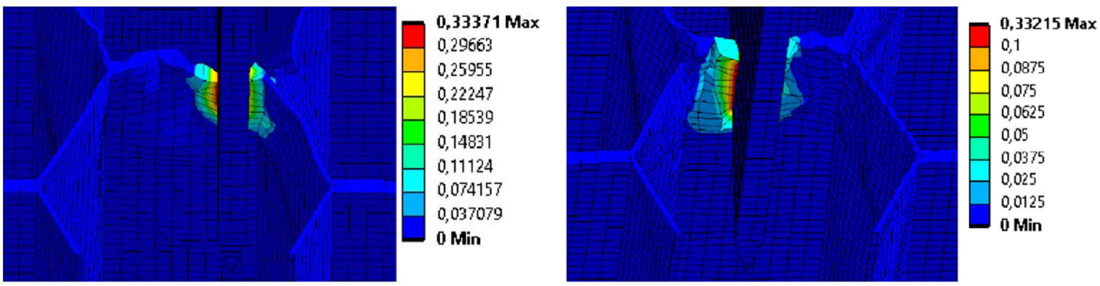
Studies of the process of cutting double (Fig. 14) and single (Fig. 15) honeycomb walls with a cutting tool with a sharpening angle of 20° show that when cutting at a distance of 0.5 mm from the nodal point, the neighboring walls of the honeycomb are deformed, and the maximum effective deformation in the cutting zone was 0.3. When the cut line was removed up to 1 mm from the nodal point, the effective deformation was 0.1 and, at the same time, as can be seen from Fig. 20b and 21b, the



a) b)

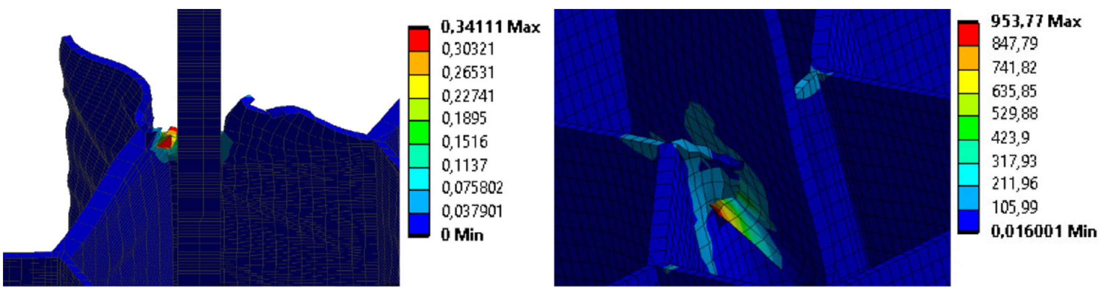
c) d)

Fig. 13. Graphs of dependencies: a) stress intensity in the cell; b) intensity of stresses in the knife; c) plastic deformation in the honeycomb; d) plastic deformation in the knife



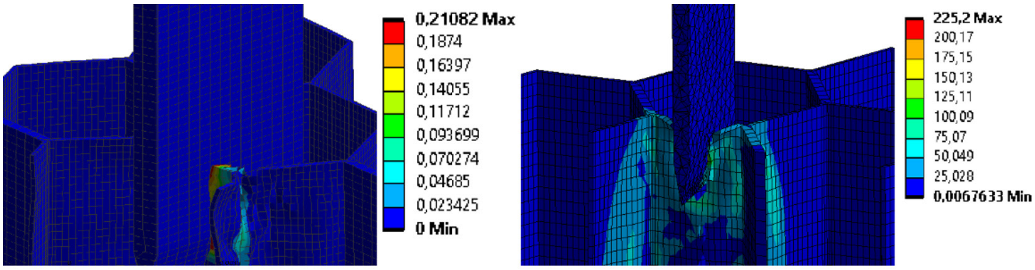
a) b)

Fig. 14. Plastic deformations when cutting with a knife the double edge of a honeycomb block at a distance of 0.5 mm (a) and 1 mm (b) from the nodal point with a knife sharpening angle of 20°



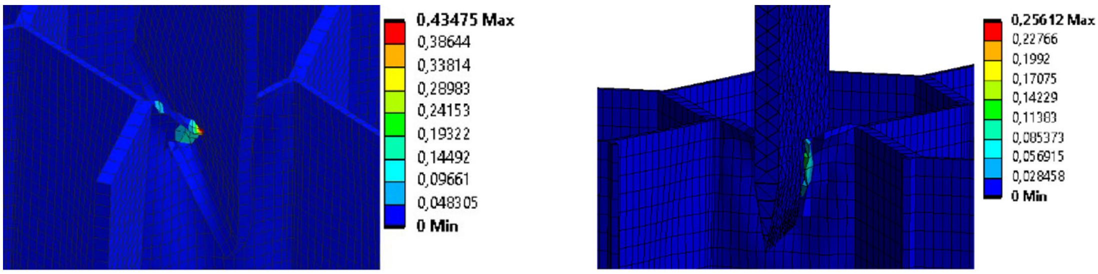
a) b)

Fig. 15 Plastic deformations, m/m when cutting a single edge of a honeycomb block with a knife at a distance of 0.5 mm (a) and 1 mm (b) from the nodal point with a knife sharpening angle of 20°



a) b)

Fig. 16. Distribution of stress intensity with a knife sharpening angle of 20°, MPa a) knife thickness of 0.2 mm and b) with a thickness of 0.4 mm



a) b)

Fig. 17. Distribution of plastic deformation with a knife sharpening angle of 20° a) knife thickness of 0.2 mm and b) knife thickness of 0.4 mm

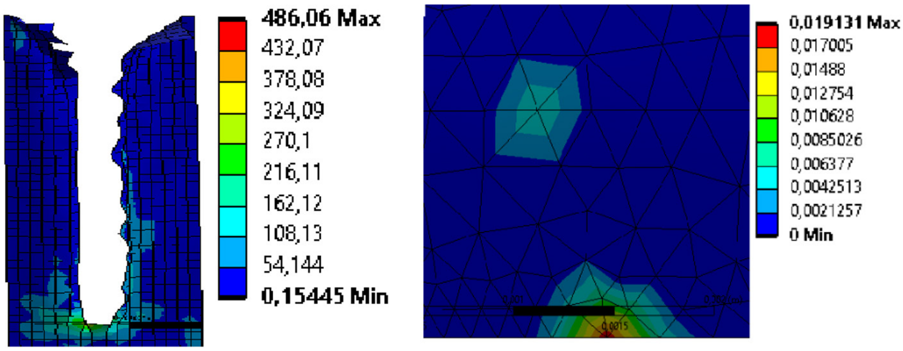
walls of neighboring cells were not deformed, which indicates a rational arrangement of the cut plane at a distance 0.4L, where L is the wall length of a honeycomb block.

3. Determination of the optimal knife geometry

The task of finding the optimal blade thickness at the optimal knife sharpening angle of 20°, as it was mentioned earlier, was to fulfill the following conditions: implementation of a «clean» cut (no ragged cut edges and plastic deformations on adjacent sides of the honeycomb block) along the entire height of the honeycomb block face and minimal plastic deformations of knife. At the first stage, a series of solutions was carried out with knives thickness of 0.2 mm and 0.4 mm. Calculations with blades 0.2 mm and 0.4 mm thick with a sharpening angle of 20° (Table 2) showed that in all cases a fairly clean cut was observed without ragged edges and deformation of the adjacent faces of the honeycomb block (Fig. 12, 13).

Table 2. Calculation results for different knife thicknesses at the sharpening angle of 20°

Calculated parameter	*t*=0,2mm	*t*=0,4mm
Stress intensity in the blade, MPa	210	36
Plastic deformation, mm	0,048	0,00095



a) b)

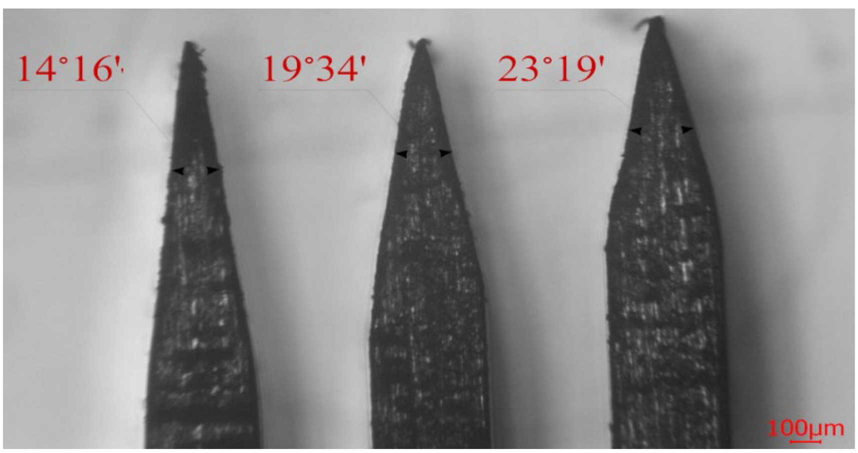
Fig. 18. Distribution with a knife thickness of 0.4 mm: a) stress intensity at the cut edge, MPa and b) plastic deformation in the knife blade, m/m

4. Field tests

The analysis of cutting a cellular structure using a narrow knife with a sharpened cutting edge is complicated by a small cell size, but in comparison with cutting several cellular structures with an extended wedge [20], it is one of the possible ways to obtain a complexly contoured required geometry of a cellular panel. Studying the behavior of the material when cutting the wall of the honeycomb block, experiments were carried out with a set of knives (three for each angle), having average sharpening angles of the cutting edge of 15°, 20°, and 25°, made of steel DIN C 70W2 and wall thickness of the honeycomb block 0.07 mm. Images of the cutting edges of a sample batch of knives obtained with a Neophot-32 microscope with a resolution of 100 μm are shown in Fig. 19.

To move the knives at a given speed, an electromechanical machine TiniusOlsen 10ST (Fig. 20) was used with the ability to register the cutting force in the form of graphs when cutting the wall of the honeycomb block.

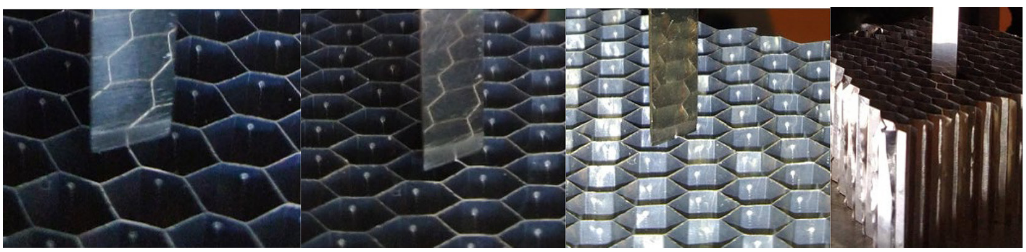
According to Fig. 22–24, the averaged values of the cutting forces for 15 °, 20 ° and 25 ° are presented in Table 3. Fig. 25 shows samples with the results of cutting the walls of a honeycomb block



a) b) c)

Fig. 19. Valid cutting tool sharpening angles for: a) 15°; b) 20°; c) 25°

Fig. 20. Equipment for experimental cutting of honeycomb block



a) b) c) d)

Fig. 21. The process of cutting a knife into the cell wall of a honeycomb block a) touch; b) beginning of plastic deformation; c) excess of σy,; d) cutting

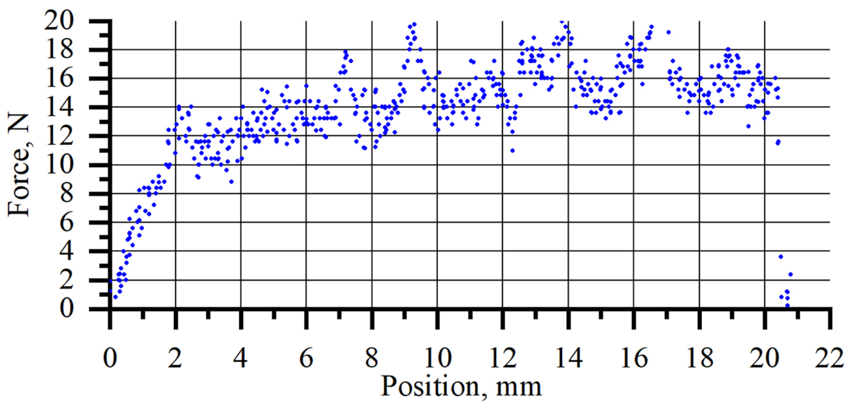


Fig. 22. Graphs of dependence of cutting force on the depth at a sharpening angle of 15°

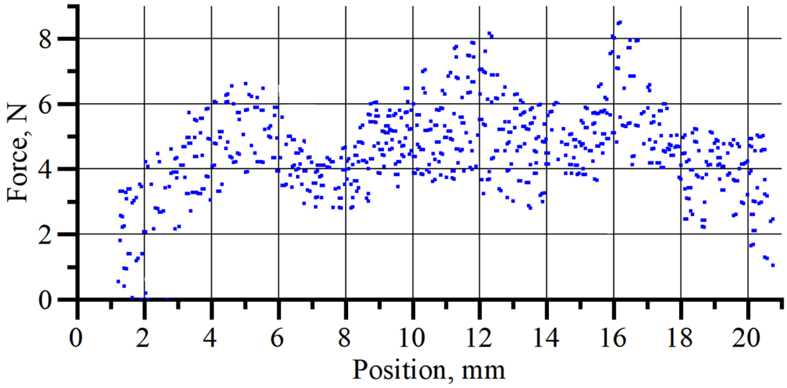


Fig. 23. Graphs of dependence of the cutting force on the depth at a sharpening angle of 20°

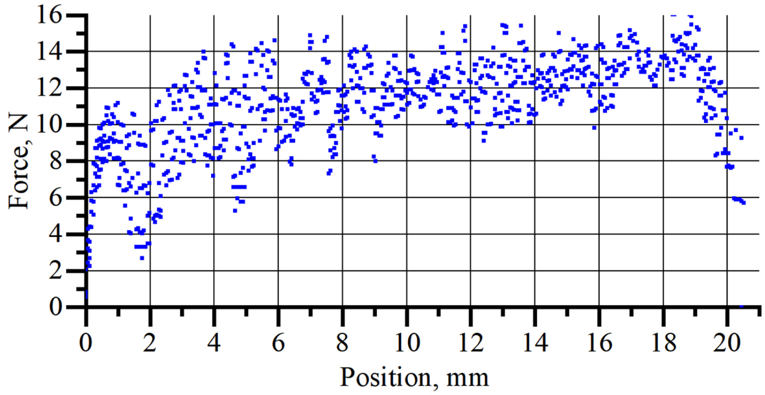


Fig. 24. Graphs of dependence of cutting force on the depth at a sharpening angle of 25°

Table 3. Average experimental values of cutting forces

Knife sharpening angle, deg	15°(14°16′)	20°(19°34′)	25°(23°19′)
Experimental cutting force Fcut, N	24,45	8,96	16,3

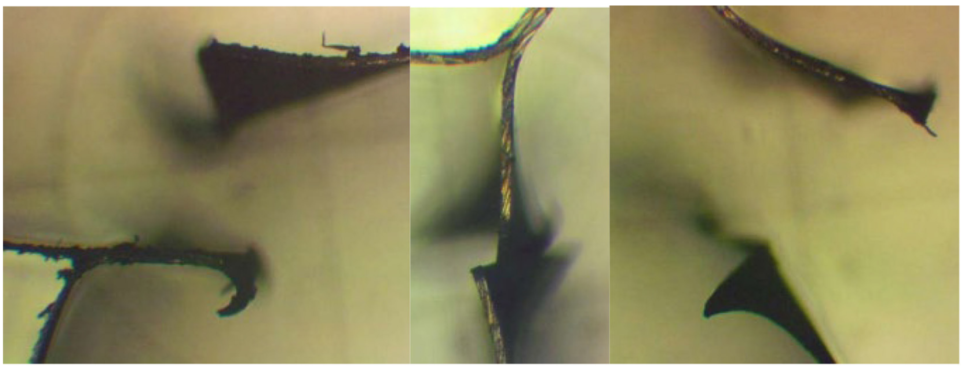
for knives with cutting edge sharpening angles of 15°, 20° and 25°. It was found that the cleanest cut without plastic deformation of edges of the cell walls of the honeycomb block had the samples when cutting with a knife which had a sharpening angle of the cutting edge of 20°, Fig.25b. A detailed study from the frontal view along the direction of movement of the knife, Fig. 26 revealed a qualitative picture of the state of cut wall of the honeycomb block, which, similarly, showed the best result of cutting with a knife having cutting edge sharpening angle of 20°.

5. Analysis based on the results of field tests

The result of the impact of cutting edge of knife on the honeycomb wall at sharpening angles of 15°, 20° and 25° is shown in Fig. 25. It was revealed that the samples had the cleanest cut with minimal

a) b) c)

Fig. 25. The structure of the honeycomb walls when cutting with a knife with sharpening angles: 15°; b) 20°; c) 25°



a) b) c)

Fig. 26. View of the contacting face of the cell with the cutting edge of the knife at sharpening angles a) 15°; b) 20°; c) 25°

plastic deformation of the edges of the honeycomb block cell walls when cutting with a knife with a sharpening angle of the cutting edge of 20° (Fig. 25b).

A detailed study from the frontal view along the direction of movement of the knife revealed a qualitative picture of the state of the cut wall of the honeycomb block, which, similarly, showed the best result of cutting with a knife with a sharpening angle of the cutting edge of 20°, which is observed in Fig. 26b. The remaining images: 26a and 26c reveal significant deformations of the cut walls.

(Fig. 25c) Then, with further cutting with a knife along the cell wall of the honeycomb block, a friction force component is added and the cutting force increases to a maximum value. At 25°, the cell wall is touched by a tool with a double-sided sharpening of the cutting edge, which leads to wall collapse at the initial stage of cutting. The cutting process changes into chopping with more effort to keep the cut straight. The optimal cutting angle in this case is a tool with a sharpening of 20°, which is intermediate between 15° and 25°, i.e., has a minimum value of the friction force when the tool blade enters the honeycomb wall and a smaller, compared to 25°, area of contact between the surface of the cutting edges of the tool and the cell edge of the honeycomb block, which once again confirms the theoretical description of the cutting process presented in this article. As the experiment shows, the combination of the following values of the considered parameters is optimal: cutting speed 5 m/s; tool thickness 0.4 mm, sharpening angle of the cutting edge of the tool 20° and cutting force of approximately 20 N.

Conclusion

The result of the work carried out on cutting the cell wall of a honeycomb block with a knife moving perpendicular to a single face in the cell proved that this method is an effective way to make complex-contoured products from honeycomb blocks. The location of the cut plane at a distance of 1 mm from the nodal point for the honeycomb block under study does not cause plastic deformations leading to jamming of the adjacent cell walls. The choice of honeycomb blocks with cells of other standard sizes assumes the location of this plane at a distance of 0.4 from the length of the cell wall. The sharpening angle of the knife has a similar effect on the quality when cutting the cell wall. Experimental and theoretical studies have shown the efficiency of the cutting process for a tool with a thickness of 0.4 mm, with a tool sharpening angle of 20°, a cutting speed of 5 m/s and a cutting force of 20 N.

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