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Influence of the parameters of deforming cutting on the features of the resulting slotted filter structures

Dmitry Buzaev [a,*], *Nikolay Zubkov* [b]

Bauman Moscow State Technical University, 5 2nd Baumanskaya str., Moscow, 105005, Russian Federation

[a] https://orcid.org/0000-0002-7258-7379, dm.buzaev@bmstu.ru, [b] https://orcid.org/0000-0003-3757-1299, zoubkovn@bmstu.ru

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ABSTRACT

Introduction. Slot filters are in demand in petrochemical, machine-building, food, mining and other industries. *DC* is an edge cutting machining method based on undercutting and plastic deformation of the workpiece's surface layer without its removal in the form of chip. *DC* stands out from the other slot structure forming methods for its capability of obtaining fine filters (slot width upwards of 20 µm) while maintaining relatively high productivity rate and being waste-free. Nevertheless, patterns of through slots cutting by means of *DC* had virtually not been investigated previously. **The purpose of the work** is to establish the influence of the main parameters of deformational cutting, namely feed and depth of cut, on features of through slots obtained, as well as identifying combinations of parameters that ensure the production of structures suitable for filtration. **Method of investigation** consisted of experiments on through-cutting of corrugations stamped on copper strips and a visual analysis of the structures obtained. Cutting through the corrugations by *DC* was conducted on a lathe while using a special attachment – a barrel which workpiece corrugated strips were wrapped around and fixed on with tension. **Results and discussion**. The resulting typical structures obtained under different combinations of depth of cut and feed are systemized and divided into the following groups: "0" – the absence of the through cut; "1" – uniform slots; "2" – "twinning" (pairwise convergence of slot walls), "3" – stripping of every second slot wall; "4" – non-regular or complete stripping of slot walls; "5" – uniform slots with a continuous burr ("skirt") formed along the slot row on the internal side of the corrugation; "6" – uniform slots with a "skirt" opened incompletely. In the range of feeds 0.2 ... 0.4 mm/rev with increasing cutting depth, there is a transition from structures of group "1" to structures of group "2", and the greater the feed, the greater the maximum depth of cut, at which uniform slots remain. Group "1" is assigned to the area of structures suitable for filtration applications, although it is characterized by the formation of individual burrs on the inner side of each slot. At lower feeds (up to 0.2 mm/rev) with further increase of the depth of cut another group of structures potentially suitable for filtering purposes is reached: groups "5" and "6". With the "skirt" formed, individual burrs next to each slots are absent, and the shape of slots is cleaner. With a decrease in feed, the width of the resulting slots decreases. The least tool feed value, at which uniform slots are obtained, is 0.05 mm/rev which corresponds to 19 µm slot width. Establishing the causes of "twinning" and the formation of "skirts" requires further investigation.

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Introduction

The need for filtration of liquids and gases arises in many industries, such as petrochemical, mechanical engineering, food, mining and processing and others, as well as in the organization of various water supply systems [1].

The most widespread among metal filter elements are mesh [2], as well as those obtained by the method of powder metallurgy and made from metal foam with a pore diameter of 50 µm [3], etc.

*** Corresponding author**
Buzaev Dmitry A., Assistant
Bauman Moscow State Technical University,
5 2nd Baumanskaya Str.,
105005, Moscow, Russian Federation
Tel.: +7 (903) 679-96-59, **e-mail:** dm.buzaev@bmstu.ru

In most cases, when the filter element becomes dirty, it is necessary to stop the filtration process to replace it [2], which requires significant costs. The most promising are regenerable filter designs, which provide the possibility of cleaning it by the countercurrent flow of the filter medium [4]. The slotted structure of the filter in such designs is preferable since it provides both a relatively low hydraulic resistance and a high efficiency of backflow cleaning [5]. Counterflow cleaning is carried out without disassembling the filter and increases the service life of the filter element by 20 or more times [6].

Among the slot filters, the most common are prefabricated elements and those obtained by mechanical or physical and technical processing [7, 8].

On the basis of the wire, meshes are obtained, including those with non-square cells, as well as spring and wire-frame filter elements. Belt and plate filters also belong to prefabricated elements and are not characterized by high manufacturability and productivity of their production. In terms of a set of operational parameters, the most promising are wire-frame meshes with the ability to obtain slotted gaps from 20 μm, however, the high cost limits their widespread use [9].

Mechanical methods for obtaining through slots are based on milling the pipe wall with disc mills and pressure treatment methods. A wide range of slotted grids is obtained by pressure treatment, both by punching slots and by the method of simultaneous punching and drawing [10].

A promising direction in the manufacture of slotted filter partitions is the use of laser and electrical discharge piercing or wire processing [11, 12]. As a blank, sheets or pipes of various profiles can be used. The limitation of use is the high cost of equipment and relatively low productivity.

The listed methods of obtaining metal slotted filtering partitions have limitations either on the minimum width of the slots obtained or on the productivity of their production, which affects the limitation of the operational characteristics and the high cost of their manufacture.

In this paper, the preparation of filter structures by the deforming cutting (*DC*) method is considered.

Deforming cutting is a patented type of blade cutting using a special tool [13] and is based on undercutting and plastic deformation of undercut layers with the formation of a macrorelief in the form of ribbing (Fig. 1). The peculiarities of this method are wastelessness, as well as the possibility of obtaining narrow (up to tens of micrometers) interfin gaps with a depth of gaps of up to a few millimeters.

Earlier, the possibility of obtaining filtering titanium meshes by the *DC* method from thin sheet blanks was considered, with a minimum size of filtering slots obtained from 20 μm with the possibility of increasing the size of the cell by stretching to a few millimeters [14].

Also, earlier, a research was carried out to study the process of obtaining slotted structures by the *DC* method on polymer pipes, in which the expediency of using the method for obtaining adjustable slotted

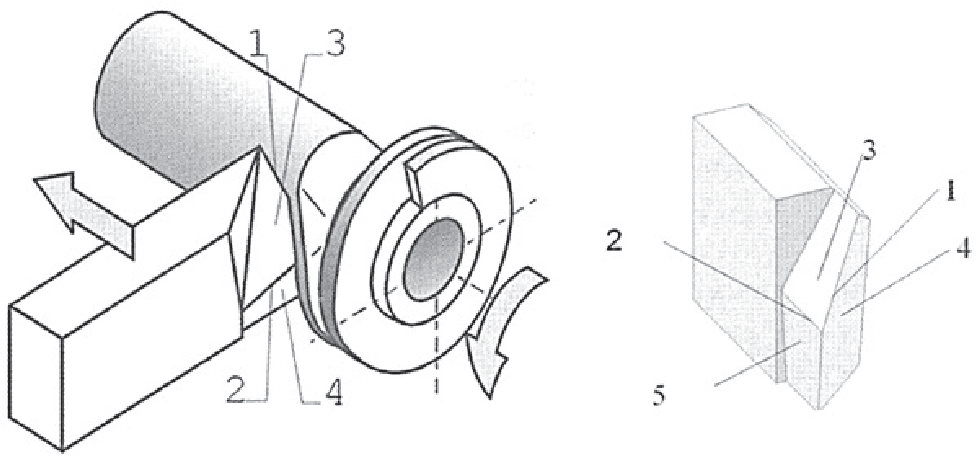


Fig. 1. Scheme of pipe finning by the *DR* method (*a*) and the tool for its implementation (*b*):

1 – cutting edge; *2* – deforming edge; *3* – front surface; *4* and *5* – main back and auxiliary back surfaces filter tubes was established, processing schemes were proposed, the features and key dependencies of the process were identified, recommendations for the implementation of the method were given, and tests of the operational characteristics of the obtained filters were carried out [15, 16]. The physicomechanical properties of polymer materials and their low heat resistance significantly limit the scope of their application. Metal filter elements with a slotted structure obtained by *DC* do not have these disadvantages. The principle of obtaining filtering slotted metal pipes through cutting of sections of special profiles was published earlier [17]. However, for the through-cutting of a metal workpiece by the *DC* method, the influence of the technological parameters on the shape and geometric parameters of the resulting slots has not been studied. The purpose of this work was to establish the influence of the parameters of the *DC*, namely the feed and the depth of cut, on the character and shape of the slotted structures obtained by full-depth *DC* method on copper samples.

Research methodology

At the previous stages of the research, it was tested and recognized as expedient to use longitudinally corrugated (star-shaped) pipes (Fig. 2), obtained using ball dies [18], as blanks for metal filters.

Longitudinally corrugated pipes are available for production on an industrial scale using special equipment [19] and are of interest as blanks in the serial production of filter pipes. However, their production in itself is a rather complex technological task that should be solved for each standard size and workpiece material.

To study the process of full-depth cutting by the *DC* method and obtain an array of experimental data, processing single corrugations obtained on a metal strip using a special device (Fig. 3) installed on a screw-cutting lathe model *16B16KA* was recognized as a more expedient scheme.

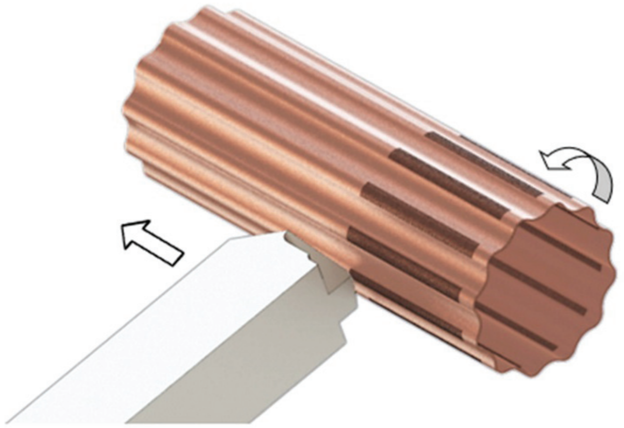


Fig. 2. Cutting slots on a longitudinally corrugated pipe using the *DC* method

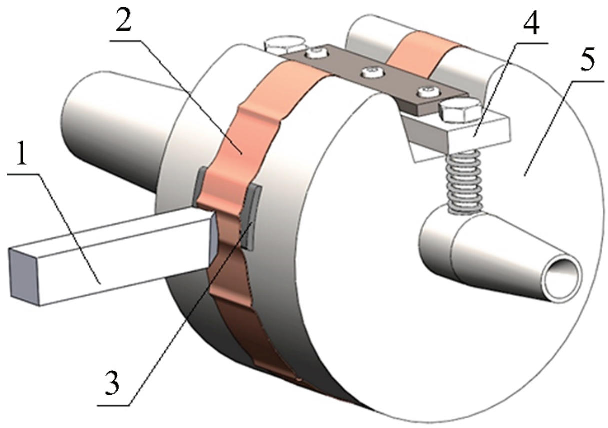


Fig. 3. Scheme of cutting through a single corrugation using a barrel attachment

Corrugated strip *2* is wrapped around a drum *5* mounted on a screw-cutting lathe. The tight fit of the strip to the drum is ensured by the radial movement of the spring-loaded tensioner *4*, in which both ends of the strip are clamped. As an assumption, it was assumed that the tension of the strip did not lead to a change in the geometrical parameters of the strip. In the framework of each experiment, the tool *1* cuts only one of the corrugations of the strip because of pad *3* made of low-pressure polyethylene.

In comparison with the processing of corrugated pipes directly, this scheme allows neutralizing the influence of the different heights of the corrugations and radial runout of the pipe on the cutting of slot and simplifies control over the process. For each corrugation, the depth of cut is set individually from the touch of the surface of the corrugation with the tip of the cutter, which allows obtaining more accurate experimental results.

The corrugations were obtained by stamping with an elastic medium, as which solid polyurethane was chosen (Fig. 4).

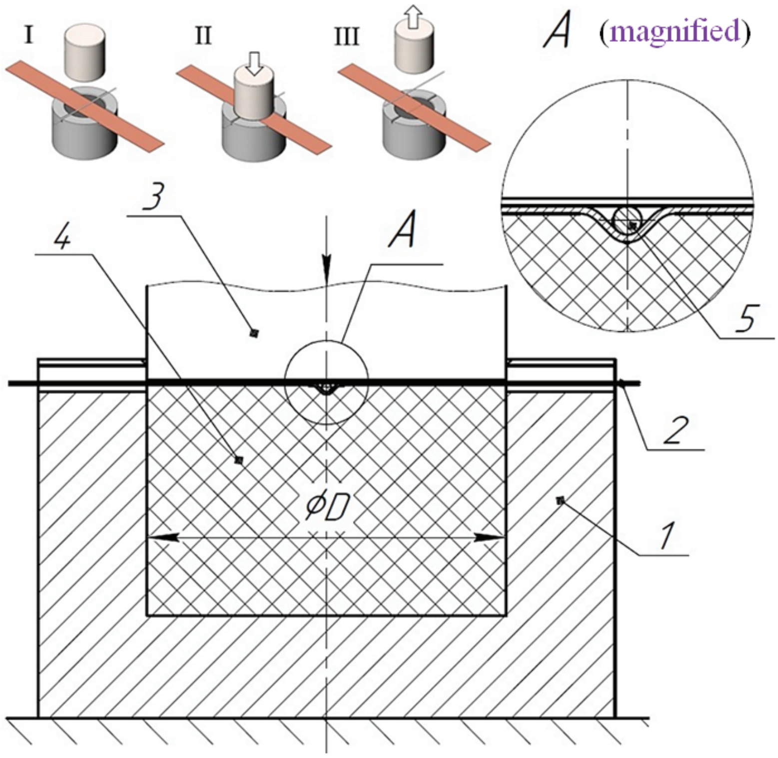


Fig. 4. Stamping corrugations with polyurethane

A steel molding bar *5* with a diameter of 1.5 mm was placed between the strip *2* and the steel punch *3*, after which the strip and the bar were pressed with a punch into a polyurethane pillow *4*, placed in the hollow of the holder *1*, as a result of which the strip partially bent around the bar, forming a corrugation. For mutual positioning of the bar and the strip in the cage, guide grooves are provided.

The geometric parameters of the corrugation (Fig. 5) are determined by the diameter of the bar, the thickness, and material of the strip, as well as the pressing force, and were t = 0.4 mm; r = 0.75 mm; R = 3.6 mm, h = 1.9 mm.

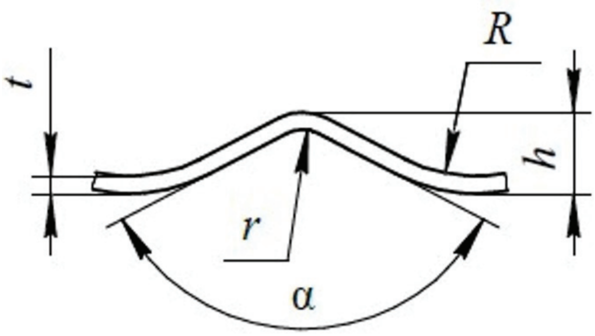


Fig. 5. Parameters of corrugation obtained

When obtaining slots by the deforming cutting method, the dependence of their width b on the feed S_o, the tool cutting edge angles φ and φ_1 has the form [20]:

$$b = S_0 (\sin\varphi_1 - \sin \varphi).$$

By this relationship, the width of the slots theoretically takes zero value when the major φ and minor φ_1 tool cutting edge angles are equal. However, for filtration, it is desirable to have a slotted gap perpendicular to the axis of the pipe blank, which requires the designation of the minor tool cutting edge angle φ_1 close to 90°. Thus, the width of the slotted gap will be determined by the major angle of the tool φ and the value of the feed S_0. The dependence of the theoretical width of the slotted gap on the tool feed at different angles φ is shown in Fig. 6. The influence of the angle φ_1 on the width of the slotted gap is not significant and is shown in Fig. 7.

The length of the slots l depends on the profile of the corrugations and the depth of cut. After the beginning of the full-depth cutting, the length of the slots increases sharply until the cutting depth t_r = 0.45 mm is

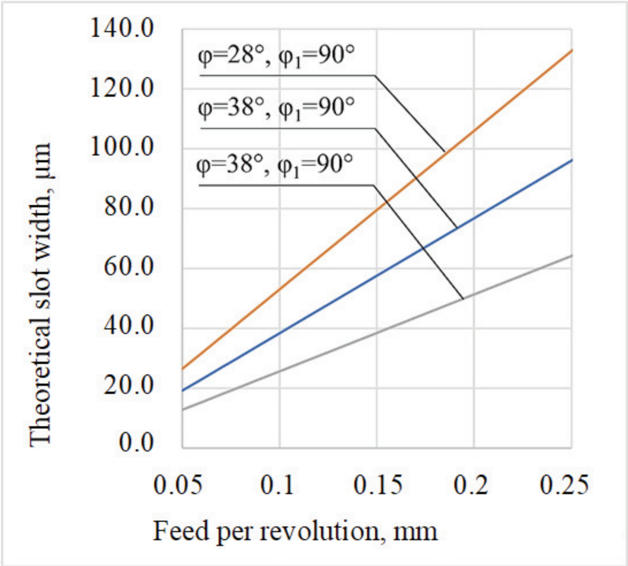


Fig. 6. Theoretical slot width vs tool feed for various values of major cutting edge angle φ

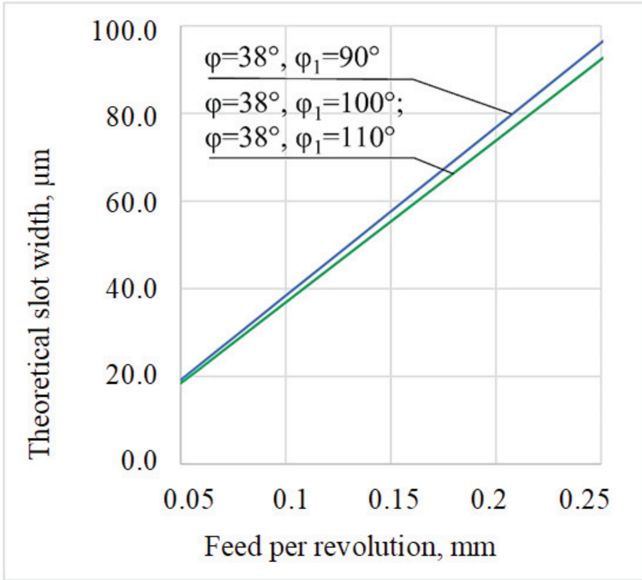


Fig. 7. Theoretical slot width b vs tool feed S for various values of minor cutting edge angle φ_1

reached, which corresponds to the end of the radius region r (see Fig. 5) at the top of the corrugation and the transition to the side regions. Since the cross-section of the lateral regions of the corrugation profile is close to a straight line, with a further increase in the cutting depth, the length of the slots increases linearly (Fig. 8).

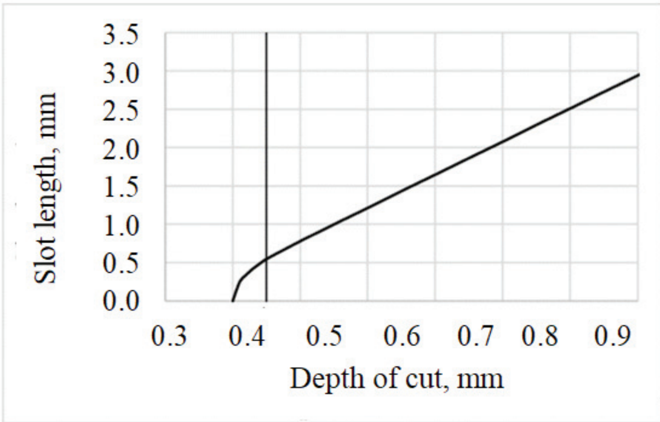


Fig. 8. Theoretical slot length l vs depth of cut t

From the above, we can conclude that to ensure the highest throughput of the filter element with the same filtration fineness, one should strive for a depth of cut not less than the depth t_r, which ensures complete cutting of the radius region r.

The *H10F* carbide (*Sandvik Coromant*) was used as a tool material for full-depth cutting corrugations by the *DC* method. The parameters of the instrument used in the experiments are presented in Table. The error of the angular parameters was ± 1°.

The choice of the geometry of the tool for the experiment was made based on the experience of using cutters for deforming cutting [21]: the rake, side and end relief angles are selected as typical for cutters intended for obtaining ribbing by the *DC* method. The minor tool cutting edge angle φ_1 is set close to 90° to ensure the perpendicularity of the slot gap. The lead angle was assigned 38° to obtain the smallest interfin gap while maintaining a satisfactory structural strength of the tool.

The value of the cutting speed in the framework of this study was taken as a constant and was chosen equal to 207 m/min based on the convenience of observing the experiment.

Material and geometrical parameters of the *DC* cutter

φ	φ_1	γ	γ_1^*	λ	λ_1^*	α	α_1
38.4°	87.6°	47°	–60°	54.4°	0°	3°	3°

* – for reference.

The range of cutting depth was chosen so that it included the boundaries, on the one hand, of the beginning of the full-depth cutting of the material, and on the other hand, the beginning of the destabilization of the process of obtaining slots (irregular or continuous stripping of slot walls). In the absence of slot wall stripping, the depth of cut was increased until the tip of the tool touched the lower point of the corrugation.

At the selected major and minor tool cutting edge angles, the feed 0.4 mm/rev, according to formula, corresponds to a slot width of 151 μm. With a further increase in the feed, the stability of the process, according to the general patterns of the *DC*, will only increase, up to the reaching the feeds at which a mere squeeze of the material is observed instead of the *DC*. Therefore, the feed value 0.4 mm/rev was taken as the upper boundary and the main attention was paid to obtaining structures with a smaller interfin gap (and greater filtration fineness). The lower limit of the considered feeds (0.05 mm/rev.) is due to the technological capabilities of the equipment used.

Results and discussion

According to the results of 167 experiments at various values of feed and depth of cut, among all the results obtained, 6 groups were identified, based on which the entire set of considered combinations of *DC* parameters – feed and depth of cut – was divided into several areas (Fig. 9) depending on the degree of suitability of the resulting structures for filtration. The diagram shows the most frequent result for each combination of parameters for several experiments. Each of the result groups is described below.

Group "0" – absence of the full-depth cutting. Absence of *the full-depth cutting* of the corrugation was noted at cutting depths exceeding the nominal thickness of the belt, which is explained by the error in the thickness of the belt and elastic deformations of the corrugated profile.

Group "1" – uniform slots (Fig. 10). This group forms on the diagram (Fig. 9) the area "*A*" (highlighted in green), which is the target for the manufacture of filter elements. The *DC* process is stable; the slots have

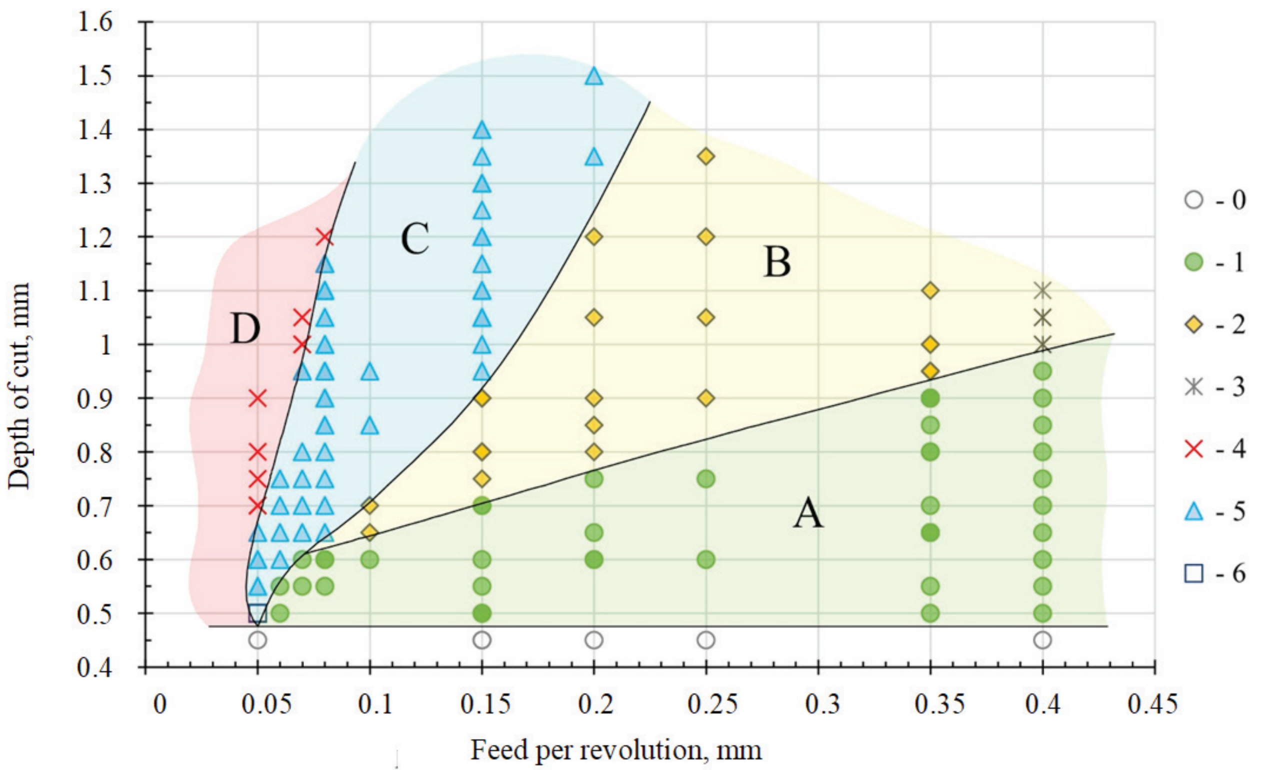


Fig. 9. Diagram of typical structures obtained under different combinations of tool feed and depth of cut: *0* – Absence of the through cut; *1* – Uniform slots; *2* – "Twinning"; *3* – Stripping of every second slot wall; *4* – Non-regular or complete stripping of slot walls; *5* – Uniform slots with a formed "skirt"; *6* – Uniform slots with a "skirt" opened incompletely

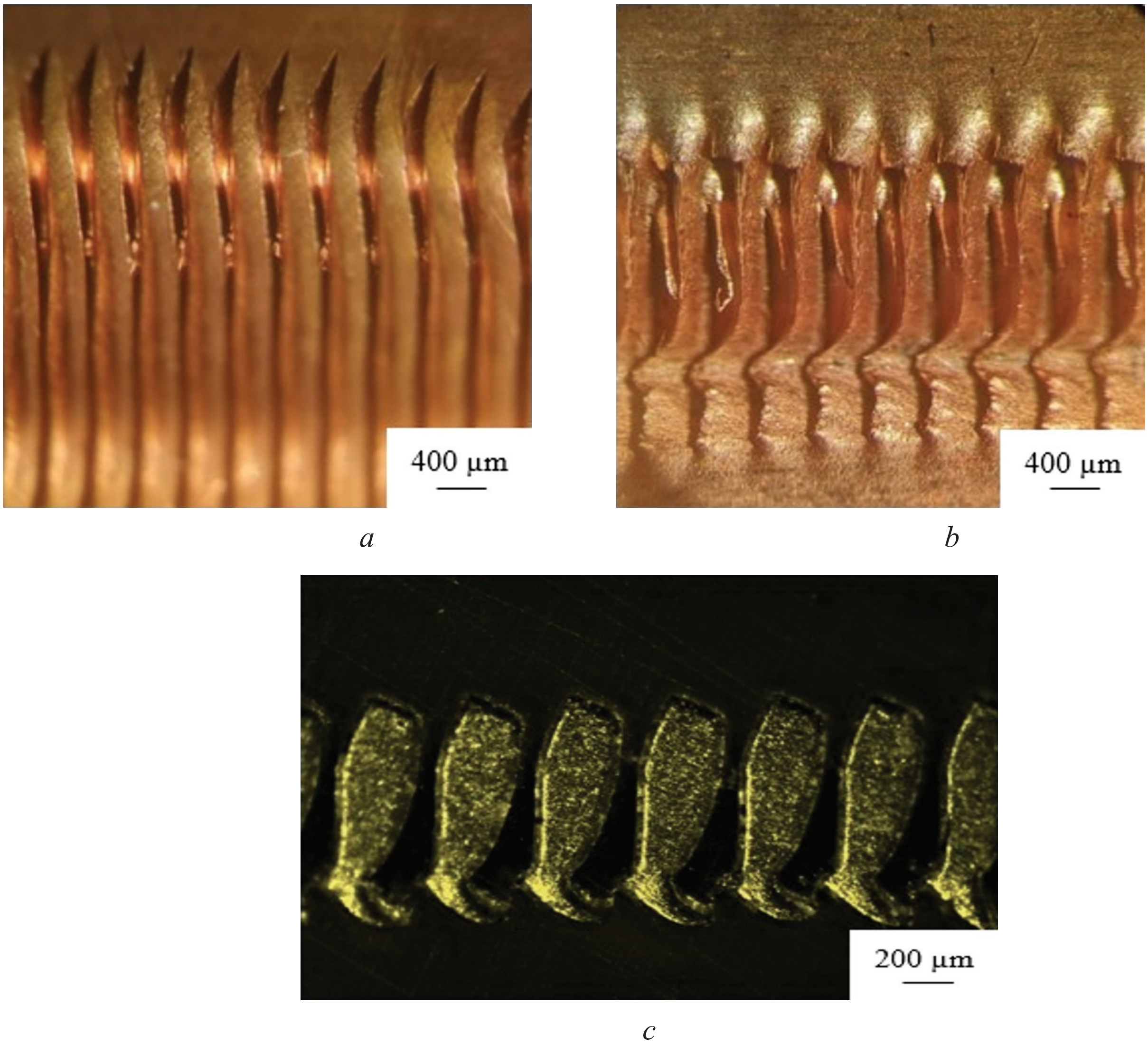


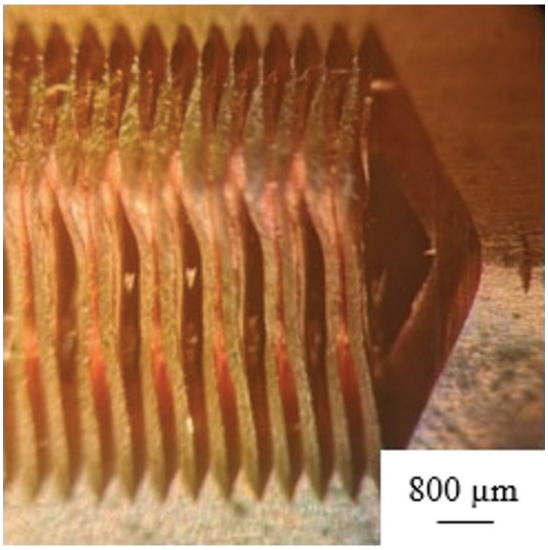
Fig. 10. Uniform slots:

a – outer side; *b* – inner side; *c* – slots cross section

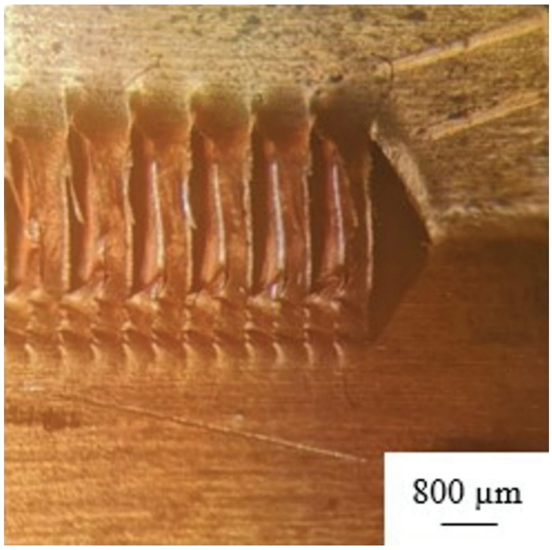
a visually uniform width. By the dependences known for *DC*, the maximum depth of cut at which the stability of the process is maintained increases with an increase in feed. The minimum feed at which, in the course of the experiments, it was possible to obtain uniform slots of this type is 0.06 mm/rev at a depth of cut of 0.55 mm, which corresponds to the theoretical width and length of the slots of 23 μm and 1 mm, respectively. On the inner side of the corrugations, the formation of burrs is noted at each point where the cutter exits the material. This should be taken into account later in the practical implementation of the method.

Group "2" – twinning (Fig. 11). At cutting depths beyond the upper boundary of the region "*A*", a pairwise convergence of the edges bounding the slots was noted, conventionally called twinning, leading to the "collapse" of every second slot, which, with the same thickness of the edges, increases the width of the uncollapsed slots. In some cases, with a further increase in the depth of cut, a transition from pairwise grouping of edges (doublets) to grouping of 3 pieces was also observed (in triplets). These cases were also conditionally assigned to group "2". Despite the fact that such structures have regularity, as of now they have not been found to have potential useful applications for filtering tasks, and therefore they belong to the area of conditional reject – area "*B*" in the diagram (Fig. 9).

Group "3" – stripping of every second slot wall (Fig. 12). At a feed rate of 0.4 mm/rev and a cutting depth of 1 mm or more, a pairwise convergence of the slot walls was noted, accompanied by the breakdown of one of the slot walls in each pair. This effect is also attributed to the area of conditional reject "*B*".



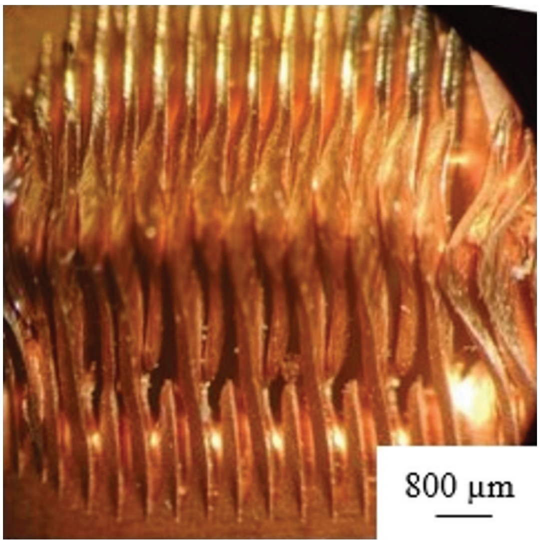
a



b

c

Fig. 11. “Twinning” – pairwise convergence of slot walls:
a – outer side; *b*– inner side; *c* – slots cross section



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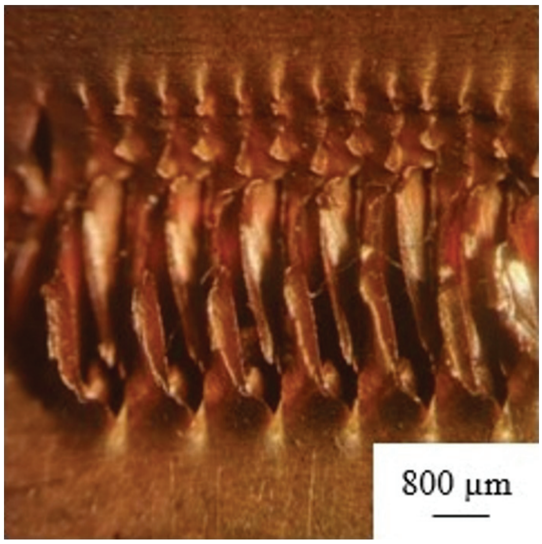


b

Fig. 12. Stripping of every second slot wall:
a – outer side; *b* – inner side

Group "4" – non-regular stripping (Fig. 13). As in conventional deforming cutting, at low feed rates in relation to the depth of cut, the process instability is noted, characterized by the breakdown of some or all of the slot walls upon an excess of the ultimate strength of the slot wall material under the action of the *DC* tool. This group is referred to the area "*D*" on the diagram (Fig. 9) – "reject".

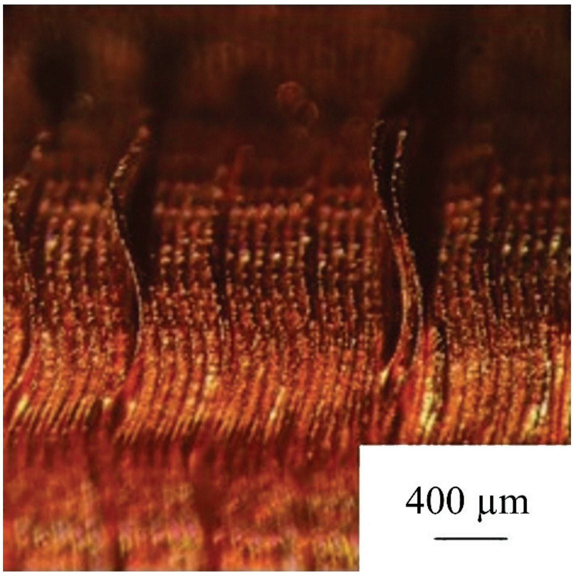
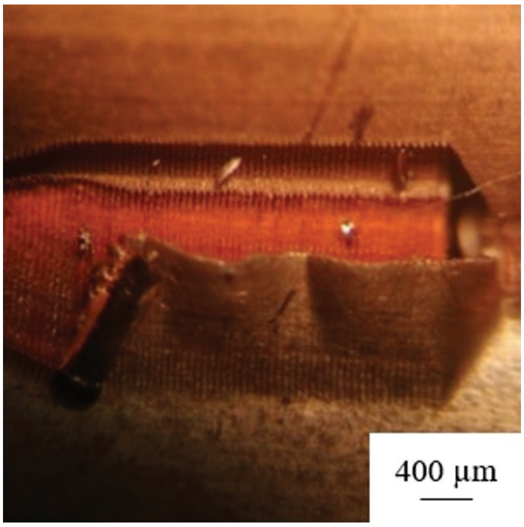


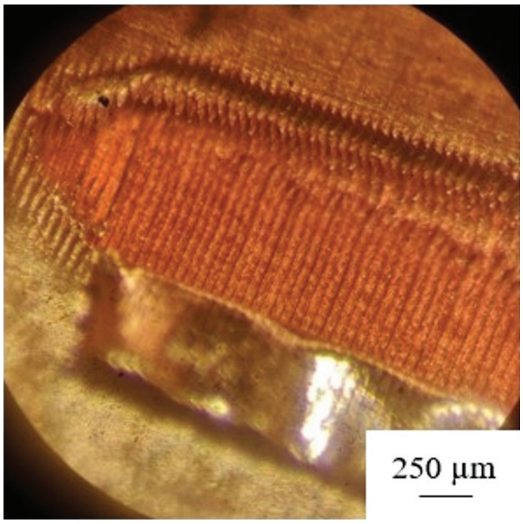
Fig. 13. Non-regular stripping of slot walls (outer side)

Group "5" – Uniform slots with the formation of a skirt (Fig. 14). With a feed rate of 0.2 mm/rev and less, the following effect was noted: when the tool leaves the material on the inner side of the corrugations, burrs are not formed at each edge separately, but in the form of a single foil tape, bent from the material by the tool and hanging over a row of slots. This tape will be conventionally referred to as "skirt" below. The formation of a skirt may be due to the properties of the surface layer of the material and requires further study.

When a skirt is formed, no twinning effects are observed; the slots have a visually uniform width. In addition, upon bending (Fig. 14) and removing the skirt mechanically, a slot structure is found, which is cleaner and free of burrs compared to group "*1*", where uniform slots were also obtained, but without the formation of a skirt. As a consequence, the group of results "*5*" is assigned to the area "*C*" on the diagram (Fig. 9), which can be characterized as the area of potentially suitable structures for filtering tasks along with the area "*A*".



a



b

Fig. 14. Uniform slots with a continuous burr ("skirt") formed:

a – view on the skirt after cutting through slits, *b* – the skirt is bent aside

Group "6" – Slots with a skirt opened incompletely (Fig. 15). At the smallest of the considered feed rates – 0.05 mm/rev – the formation of a "skirt" was noted immediately upon reaching the minimum cutting depth sufficient for cutting the corrugation. At such shallow cutting depths, the "skirt" partially retains its connection with the material on both sides of the corrugation, which makes it difficult to remove it and for the the filtered medium to pass through the slots. However, since the structure of the slots is uniform and the theoretical possibility of removing the skirt is retained, this group is also assigned to area "*C*" in the diagram.

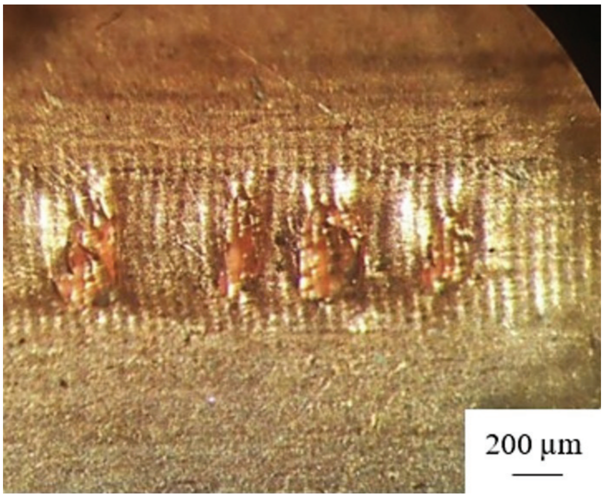


Fig. 15. Slots with a skirt opened incompletely

The distribution of the results obtained showed that in the feed range of 0.25...0.4 mm/rev, the dependancy known for deforming cutting remains: with an increase in the depth of cut when a certain ratio *t/S* is reached, destabilization of the *DC* process is observed with the manifestation of undesirable effects (doublets, triplets, strippings), and the larger the feed rate *S*, the greater the maximum depth of cut t_{max}, at which the stability of the process is maintained. However, the strippings noted at the feed rate of 0.4 mm/rev are regular, in pairs. This can be considered as a limiting case of the pairwise grouping of slot walls, which is observed at lower feeds.

At feed rates of 0.1...0.2 mm/rev with an increase in the depth of cut (see diagram in Fig. 9 and Fig. 16), there is a transition from uniform slots (group "*1*") to the grouping of slot walls without strippings (group "*2*"), and then, with the beginning of the "skirt" formation, the slots again acquire a uniform structure (group "*5*").

Such dependancy was discovered for the first time and can be explained by the peculiarities of the formation of burrs under different angles of exit of the tooltip from the material, which is directly affected by the depth of cut. In particular, the presence of a burr on only one of two slot walls in doublets and on one of three slot walls in triplets (see Fig. 12 and Fig. 16) may be the result of neighboring slot walls being attracted to each other by a common burr and subsequent stripping of the burr off of all slot walls except one.

In the feed interval 0.06 ... 0.08 mm/rev, there is no "twinning" region; with increasing depth, there is a direct transition from uniform slots (group "*1*") to uniform slots with the formation of a "skirt" (group "*5*"),

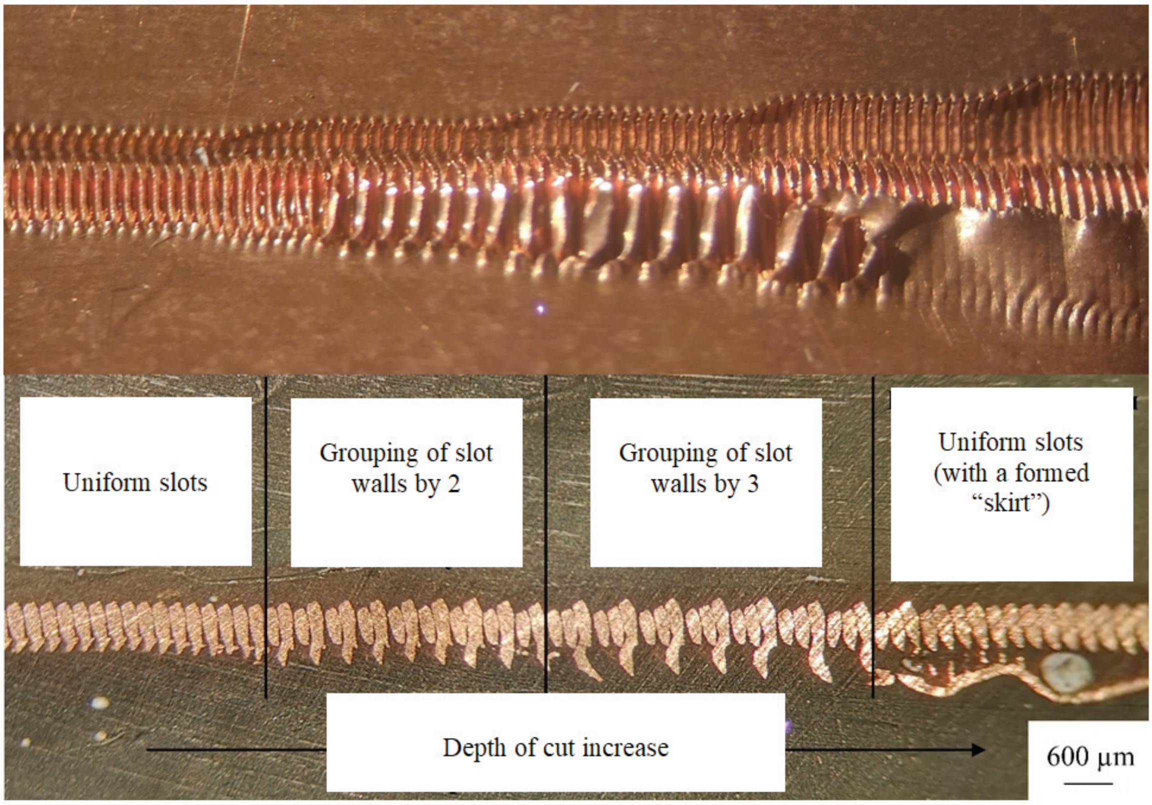


Fig. 16. Evolution of the structures obtained with the depth of cut increase

and at the feed of 0.05 mm/rev, there is no region of group "*1*" either. This indicates that lower feed rates contribute to the formation of a common burr for the entire row of slots – the "skirt".

This circumstance may turn out to be extremely favorable for obtaining structures of high filtration fineness since lower values of the feed rate correspond to smaller values of the width of the slotted gap (see formula (1)). In addition, as noted above, the slots under the "skirt" are distinguished by high cleanliness and the absence of individual burrs; a simpler task than removing individual burrs.

In the future, it is planned to check these assumptions by simulating the process of cutting slots and additional experiments with various corrugation profiles, as well as to investigate the possibility of removing "skirt", in particular, by means of bypassing a powerful flow of filtering medium or tumbling.

The smallest feed rate at which uniform slots (with the formation of a skirt) were obtained is 0.05 mm/rev. This feed, according to formula (1), corresponds to a slot width of 19 μm.

Conclusion

In the feed rate interval 0.2...0.4 mm/rev, with an increase in the depth of cut, there is a transition from uniform slotted structures (area "*A*") to the area of the undesirable grouping of slot walls with an increase in every second or every third slot (area "*B*"), and the higher the feed rate, the greater the maximum depth of cut at which uniform slots are maintained. In each of these groups, the formation of burrs on the inner side of the slots was noted. Burrs in the slotted gap potentially degrade the performance of the filters and create the risk of plugging the filtrate when the burrs are stripped off. At lower feeds (up to 0.2 mm/rev inclusive) with a further increase in the depth of cut, the second region of structures potentially suitable for filtering tasks is reached – the region "*C*", corresponding to the formation of a continuous burr ("skirt") being formed along the slot row on the internal side of the corrugation, upon which the slot structure becomes uniform again. When a "skirt" is formed there are no individual burrs for each slot, the shape of the slots is cleaner. With a feed decrease, the width of the resulting slots decreases. In this study, the smallest feed at which uniform slots are obtained, was 0.05 mm/rev, which corresponds to a slot width of 19 μm. In the future, it is planned to carry out similar experiments with various materials while changing the geometric parameters of the *DC* tool. Establishing the reasons for the formation of "skirts", the choice of the method for their removal, as well as the observed effect of the grouping of slot walls require additional research.

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Conflicts of Interest

The authors declare no conflict of interest.