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Influence of Deformational Cutting Data on Parameters of Polymer Slotted Screen Pipes

A method for manufacturing polymer slotted screen pipes by the use of deformational cutting (DC) technology is presented in this paper. The slotted macrostructure is created by cutting through the pipe wall without chip removal. These screen pipes can be made from thermoplastic tubular workpieces which can either be standard pipes or have internal longitudinal grooves. Descriptions of the manufacturing method, process kinematics, required equipment, and tool for making slotted screen pipes are given. The influence of tool angles and process parameters on dimensions and accuracy of manufactured through slots is analyzed. The theoretical equations are verified by experimental results. [DOI: 10.1115/1.4030827]

Keywords: filtration, deformational cutting, machining, screen pipe, filter tube

Introduction

Slot screen pipes are widely used in different filtration applications in the oil and gas, water, chemical, and agricultural industries. They have low hydraulic resistance, large open area, and relatively high strength. These screens can be produced with slots having specific size and this feature is very important for filtration applications. Another common feature of slot screens is high capacity for efficient backwash cleaning.

Polymer materials, such as polyethylene (PE), polypropylene, polytetrafluoroethylene, polyvinyl chloride (PVC), are gaining in popularity in the modern filtration applications. Polymer screens have light weight, low cost, high-corrosion resistance, and longer life time compare to metal screens.

Slot screen pipes can be manufactured by using different methods. Pipes with slots produced by saw-cutting (slotted liners) or punching usually have a slot width not less than 0.12 mm [1]. Slotted liners are made of different materials, such as steel, stainless steel, or polymers. The main disadvantage of slotted liners is the small open area (2–3%), which causes high-pressure drops [2].

Another alternative for manufacturing slotted screen pipes is wrapping and welding of a wedge-shaped wire to a perforated pipe or longitudinal rods. The wire-wrapped screens are available with slot widths upward from 0.075 mm. The open area is 6% or larger depending on the slot width. These screens are commonly made of stainless steel, but special metals, such as Hastelloy, can also be used. PVC wrapped screens are manufactured by ultrasonic welding technique [3]. The main disadvantage of this technology is high cost due to the low productivity. In this article, an application of DC technology for polymer slotted screen pipe manufacturing is presented. The main principle of DC slotting has been partially described by Zubkov and Sleptsov [4]. The slots are formed by cutting through the pipe wall without chip removal. The main problem when slotting by DC is that the machined slots have nonuniform width which is important for filtration applications. The main goal of this article is to determine the influence of DC cutting data on geometrical parameters of polymer slotted pipes including the slot width nonuniformity.

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DC technology was invented by Zoubkov (now Nikolay Zubkov) and Ovtchinnikov [5]. A DC tool cut plastically deforms the surface layers of the workpiece forming a finned macrostructure since the cut layers are connected to the workpiece material (Fig. 1).

The main difference between the traditional cutting process and DC is that the chips become fins and remain as a functional part of the workpiece. Table 1 represents the typical macrostructure parameters that can be manufactured by DC.

The DC machining can increase the surface area up to 12 times for copper and up to 6 times for steel. The main limiting factors for DC are workpiece ductility and hardness. A stable DC process can be achieved in materials with hardness smaller than HB220 and elongation larger than 18%.

There are a number of different application areas of DC technology. The main application area is the heat exchange intensification, for example, finning of tubes for heat exchangers [6] including internal finning [7]. DC can be used for making boiling surfaces and capillary structures for heat pipes [8]. Another DC application areas are electrical joints manufacturing [9,10] and surface quench hardening [11].

Use of DC Technology for Making Polymer Slotted Screens

Polymer pipes having internal longitudinal grooves (Fig. 2(*a*)) or standard pipe (Fig. 2(*b*)) can be used as workpieces for DC slotting. When using pipes having internal longitudinal grooves, the process kinematics are the same as for pipe finning shown in Fig. 1(*b*). The authors used this principle and succeeded in obtaining the first samples of copper-slotted pipes with controlled slot

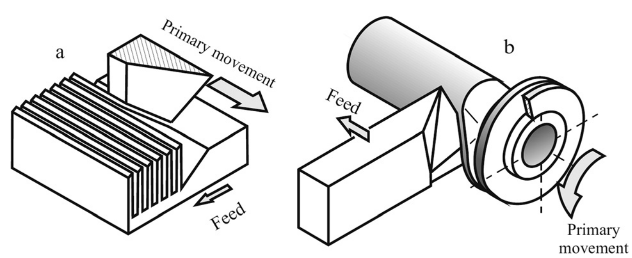

Fig. 1 Concept of DC: shaping of flat surfaces (*a*) and turning of cylindrical surfaces (*b*)

Table 1 Typical macrostructure parameters available for DC on metals

Fin pitch (p)	mm	0.05–2.0
Fin height	mm	$\leq 7 \times p$ for copper $\leq 5 \times p$ for steel
Slot width	μm	10–2000
Fin angle	deg	45–90

width in the range from 20 to 100 μm. These experiments showed a possibility to use DC technology for making metallic-slotted screens and this should be a subject for further research.

Synchronous rotations of the tool and the workpiece provide through wall slotting of standard pipe. If rotational speeds of the tool and the workpiece are equal, one row of slots will be achieved. A multiple increase of the tool rotational speed gives increased number of slot rows. For example, if the ratio is 3, the number of rows also will be 3. Several DC tools can be used as well. In that case, the number of slot rows parallel to the pipe axis is calculated according to the following equation:

$$i = n_t \times z / n_w \tag{1}$$

where i is the number of slot rows, n_t is the tool rotational speed, n_w is the workpiece rotational speed, and z is the number of DC tools.

If the ratio between tool and workpiece rotational speeds is desynchronized and is not an integer, the slot rows become helical (Fig. 3(*a*)). In that case, the value of i calculated by using Eq. (1) should be rounded to the nearest integer. The pipe having helical slot rows can have a significant elastic deformation in the axial direction like a spring (Fig. 3(*b*)). This provides the possibility for changing the width of through wall slots from zero to several millimeters by compressing or stretching the slotted pipe. The slot width change caused by the pipe length elongation (compression) ΔL is calculated according to the equation

$$\Delta b = \Delta L \times p / L \tag{2}$$

where Δb is the slot width change, ΔL is the pipe length change, p is the slot pitch, and L is the length of slotted area.

The slot width adjustment by compressing/stretching is characterized by high precision. For example, if a pipe having a 300 mm length of slotted area and a 0.5 mm slot pitch is stretched by 3 mm, the width change for all slots will be equal to 5 μm.

It is important to mention that the process kinematics has no significant effect on effective tool angles. The lead angle of the tool trajectory is negligible for the relatively large pipe outer diameters typical for this application.

These adjustable pipes can also be stretched when backwashing to increase the cleaning efficiency.

Experimental Setup for Slotting Pipes With Helical Rows of Slots

Through slots were made on the 16K20 lathe according to the scheme shown in Fig. 2(*a*). The lathe was equipped with a follow rest mounted on the carriage to support the flexible polymer workpiece (Fig. 4).

The detailed description of the machinery for making slot rows according to the scheme shown in Fig. 2(*b*) is presented by Zubkov and Sleptsov [4]. Figure 5 shows the 16K20 lathe equipped with a follow rest and an additional tool spindle mounted on the cross slide. The tool spindle was driven by an AC motor which was controlled by the Mitsubishi A700 inverter drive. The rotating tool block of a diameter 190 mm allows the mounting of 1–4 DC inserts (Fig. 6).

The workpiece used for the machining experiments was a standard pipe with outer diameter 50 mm made of high-density PE 80. Pipes with wall thicknesses 2.5 mm and 3.7 mm were used. The experiments were performed with one cutting insert having tool major and minor cutting edge angles $\kappa_r = 70$ deg and $\kappa_{r1} = 75$ deg, respectively.

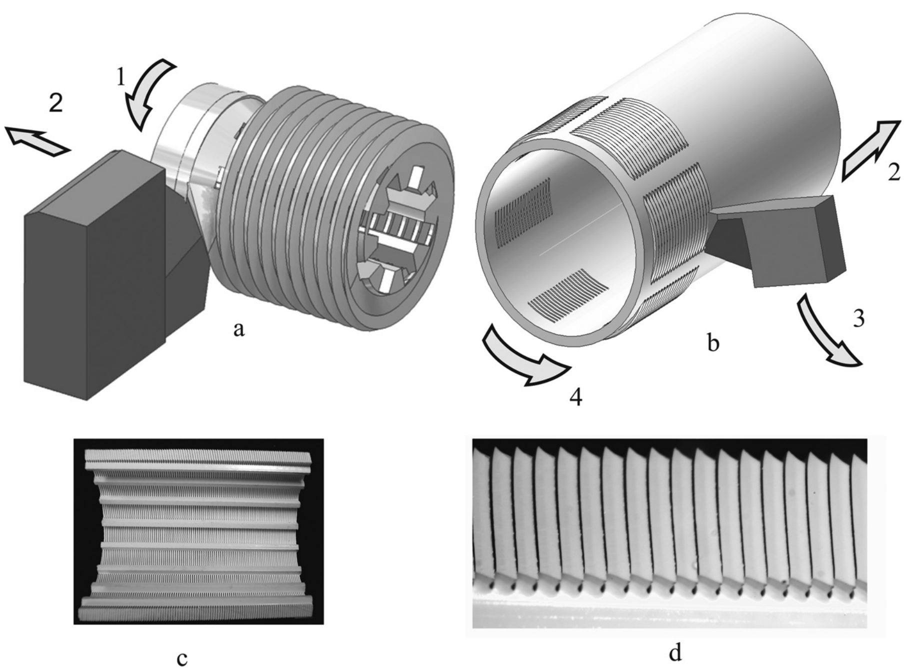

Fig. 2 Process kinematics of slotting pipe having internal longitudinal grooves (*a*) and for slotting conventional pipe (*b*), half-section of pipe with internal grooves (*c*), and cross-cut of filtering slots (*d*). 1—primary rotational movement of the workpiece, 2—tool feed movement, 3—primary rotational movement of the tool, and 4—circular feed movement of the workpiece

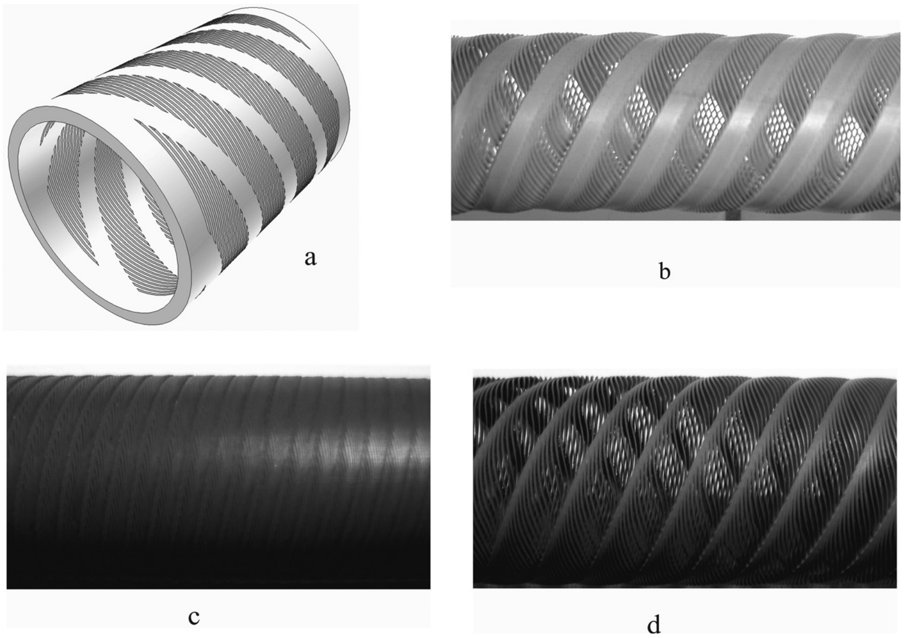

Fig. 3 Computer-aided design model (*a*) and photo (*b*) of screen pipe with helical rows of through wall slots. Photos of compressed (*c*) and stretched (*d*) screen pipes.

Helix Angle of Slot Rows and Tool/Workpiece rpm Ratio. The axial pipe stiffness is inversely proportional to the helix angle which is calculated according to the following equation:

$$\omega = \arctan\left[\frac{\pi \cdot D}{f_a} \cdot \left(1 - \frac{z \cdot n_t}{i \cdot n_w}\right)\right] \tag{3}$$

where ω is the helix angle, D is the pipe outer diameter, f_a is the axial feed, and i is the number of helical slot rows.

Positive values of ω correspond to the right-handed helical rows while negative values match the left-handed rows.

Figure 7 depicts a theoretical graph showing the influence of tool rotational speed n_t on helix angle ω when $n_w = 100$ rev/min, $i = 6$, $z = 1$, $D = 50$ mm, and $f_a = 0.5$ mm/rev. Thus, accuracy of the tool and workpiece rotational speed ratio is a crucial factor influencing the helix angle precision dramatically.

Table 2 represents the received slot rows helix angle and confirms the abovementioned equations for a pipe with six rows of slots, outer diameter 50 mm, rotational speed of the tool block with one DC tool adjusted around 750 rpm, and tube rotation 125 rpm.

Dependence of the Slot Size on the Machining Parameters. The slot width is the main parameter which limits the filter rating of slotted screen pipes. The slot width depends on DC tool angles and axial feed and can be determined from a scheme of DC slotting. Figure 8 shows the plan view of the DC zone when slotting a pipe with internal longitudinal grooves. The initial and final positions of the DC tool within one spindle revolution are marked as *I* and *II*, respectively. The cross section of undeformed fin *ABCD* is cut by the cutting edge and moves on the tool rake surface. Basing on the work material conservation principle, the tool deforming

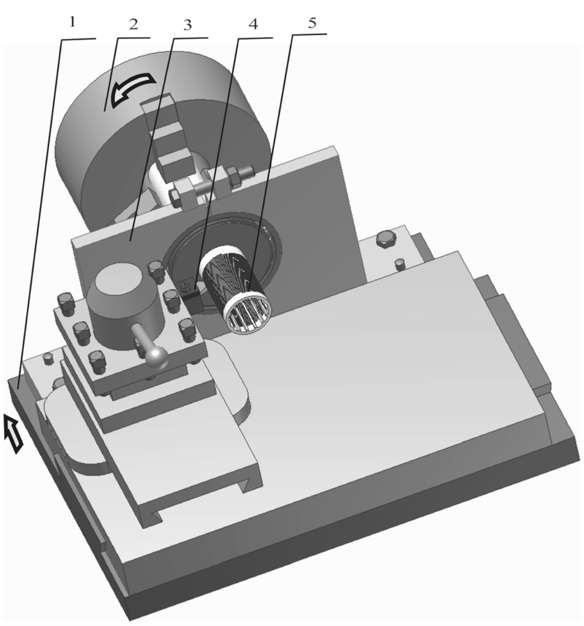

Fig. 4 Slotting of pipe having internal grooves on lathe: 1—carriage, 2—chuck, 3—follow rest with ball bearing and reducing bushing, 4—DC tool, and 5—workpiece

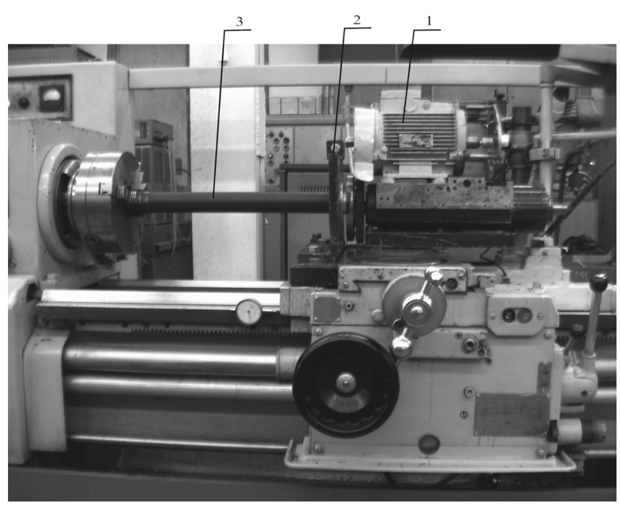

Fig. 5 Lathe modernized for slotting by DC technology: 1—tool spindle, 2—follow rest, and 3—workpiece

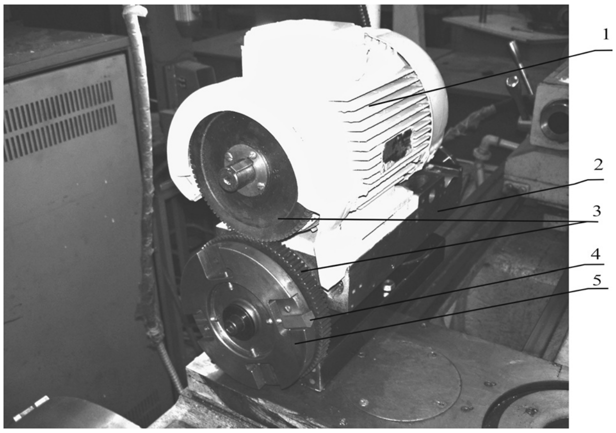

Fig. 6 Tool spindle for slotting: 1—AC motor, 2—spindle housing, 3—gears transmitting torque from the AC motor to the spindle, 4—DC insert, and 5—tool block

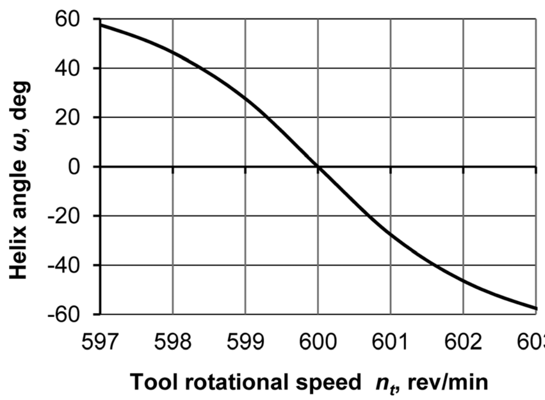

Fig. 7 Theoretical graph for influence of tool rotational speed on helix angle of slot rows

edge determines the final position of the fin marked as $A_1B_1C_1D_1$. The slot width b depends on the tool major cutting edge angle κ_r, tool minor cutting edge angle κ_{r1}, and axial feed f_a

$$b = f_a \times (\sin\kappa_{r1} - \sin\kappa_r) \tag{4}$$

As can be seen from Eq. (4), if κ_r and κ_{r1} are equal, the slot width b will theoretically be zero. This means that the minimal slot width is not theoretically limited when slotting by DC.

The slot inclination angle τ equals κ_{r1} when machining metals. Elastic properties of polymers cause partial fin retraction after formation. The fin tends to have a residual deformation in the direction of the initial position *ABCD* when the tool is not in contact with the fin, i.e., the slot inclination angle τ is larger than κ_{r1} by the fin retraction angle ψ

$$\tau = \kappa_{r1} + \psi \tag{5}$$

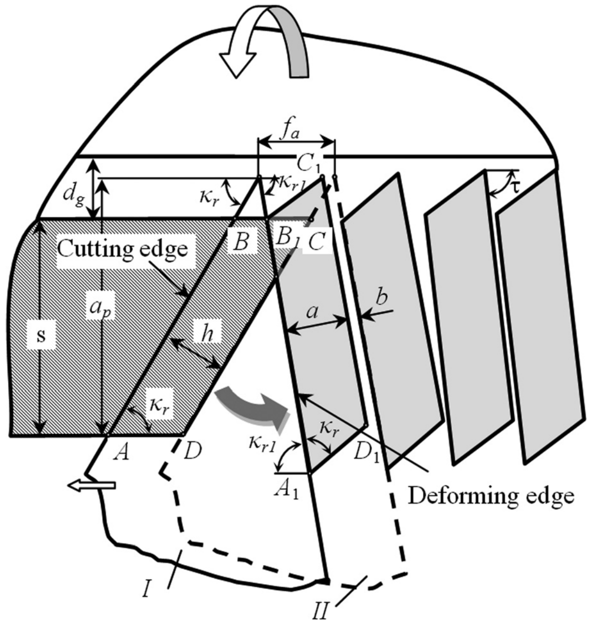

Fig. 8 Scheme of DC slotting of pipe having internal longitudinal grooves: *I*—initial DC tool position, *II*—final DC tool position, *s*—pipe wall thickness, d_g—depth of internal longitudinal groove, a_p—depth of cut, f_a—axial feed, *h*—fin thickness, *b*—slot width, κ_r—tool major cutting edge angle, κ_{r1}—tool minor cutting edge angle, and τ—slot inclination angle

Hence, the slot width can be expressed as

$$b = f_a \times (\sin(\kappa_{r1} + \psi) - \sin\kappa_r) \tag{6}$$

The fin retraction angle should be experimentally determined for particular polymer material and conditions. The experimental research of fin retraction angle when slotting high-density PE was performed. The results show that the fin retraction angle is influenced mainly by feed per revolution while the effect of penetration depth is negligible (Fig. 9). In fact, higher feed causes higher fin stiffness which tends to increase the retraction angle due to elastic properties of polymer materials. According to Eq. (6), the slot width decrease is less than or equal to 2.3% when the retraction angle varies from 13 deg to 18 deg, and the tool major and minor cutting edge angles equal 70 deg and 75 deg, respectively. Thus, the value of fin retraction angle ψ can be taken equal to 15 deg for DC machining of high-density PE. In that case, the minor cutting edge angle κ_{r1} providing slots and fins perpendicular to the pipe axis equals 75 deg. If needed, a more precise compensation of fin retraction can be done by changing the κ_{r1} by the real fin retraction angle value.

The fin thickness h depends on the axial feed and major cutting edge angle

$$h = f_a \times \sin\kappa_r \tag{7}$$

However, deformation occurs when fin formation causes a slight increase of the real fin thickness h_r compared with the

Table 2 Influence of ratio between the tool and workpiece rotational speeds on the helix angle and hand of slot rows (rotational speed of the tool block with one DC insert was adjusted around 750 rpm)

Feed	f_a	mm/rev	Pipe #1 0.64	Pipe #2 0.64	Pipe #3 1.1	Pipe #4 1.1
Tool and workpiece rotational speed ratio	n_t/n_w		6.018	6.034	6.058	5.935
Calculated helix angle of slot rows in accordance with Eq. (3)	ω	deg	−36.365	−54.284	−54.079	57.121
Measured helix angle of slot rows	ω	deg	−37	−54	−54	57
Hand of helical slot rows			Left	Left	Left	Right

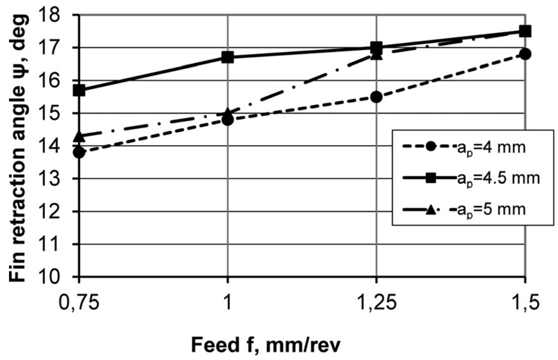

Fig. 9 Fin retraction angle for different feeds and penetration depths

theoretical value calculated according to Eq. (7). Figure 10 shows the graphs of the measured fin thickness and values calculated using Eq. (7) for different feed values and penetration depths (PE pipe wall thickness $s = 3.7$ mm and $D = 50$ mm). The fins were cut out from every pipe and the fin thickness was measured along the fin with an optical microscope. The fin thickness increase grows over the feed while the penetration depth a_p has no significant influence on the fin deformation. The measured fin thickness, slot width, and the fin deformation coefficient $\xi = h_r/h$ for $a_p = 5$ mm are shown in Table 3. The fin deformation coefficient ξ varies from 1.008 to 1.052 depending on the feed. Despite the fact that the fin deformation is relatively small, the ξ has a great influence on the slot width. For example, when the ξ increases from 1 to 1.052 the slot width b decreases from 0.09 mm to 0.017 mm. Hence, the fin deformation coefficient should be taken into consideration to provide the required slot width. It is possible to compensate the fin deformation by diminishing the major cutting edge angle κ_r. This coefficient can be evaluated experimentally for every combination of workpiece material, DC tool angles, and cutting data.

Analysis of the Slot Width Nonuniformity in the Areas of Tool Penetration and Exit

Screen pipes should have unslotted areas at the ends to provide connection to other pipes, fittings, caps, or plugs. Thus, the slotting process comprises three steps (Fig. 11): the tool penetrates into the workpiece with radial f_{rp} and axial feeds f_{ap} to reach the required depth a_{pmax}, the tool makes slotting with regular axial feed f_a, and the tool exits the work piece with radial f_{re} and axial feeds f_{ae}.

The additional radial feed in the penetration areas causes a change of the fin thickness Δh

$$\Delta h = \Delta a_p \times \cos\kappa_r = f_{rp} \times \cos\kappa_r \quad (8)$$

So, the fin thickness h_p and the slot width b_p in the penetration area change by this value

$$h_p = f_{ap} \times \sin\kappa_r + \Delta h \quad (9)$$

$$\begin{aligned} b_p &= f_{ap} \times (\sin\kappa_{r1} - \sin\kappa_r) - \Delta h \\ &= f_{ap} \times (\sin\kappa_{r1} - \sin\kappa_r) - f_{rp} \times \cos\kappa_r \end{aligned} \quad (10)$$

The slot width in the exit area increases in the similar way

$$b_p = f_{ae} \times (\sin\kappa_{r1} - \sin\kappa_r) + f_{re} \times \cos\kappa_r \quad (11)$$

The slot width increase is not acceptable, because it affects the filtration rating. Slot width uniformity can be provided by changing the axial feed in the penetration and exit areas compare to the regular axial feed. The axial feed should be increased in the penetration area and decreased in the exit area, respectively. The axial feed values f_{ap} and f_{ae} that provide the slot width uniformity can be calculated using the radial feeds f_{rp} and f_{re}, respectively, or the lengths L_p and L_e, respectively.

$$f_{ap} = f_a + \frac{f_{rp} \cdot \cos\kappa_r}{\sin\kappa_{r1} - \sin\kappa_r} = \frac{f_a \cdot L_p \cdot (\sin\kappa_{r1} - \sin\kappa_r)}{L_p \cdot (\sin\kappa_{r1} - \sin\kappa_r) - a_{p\max} \cdot \cos\kappa_r} \quad (12)$$

$$f_{ae} = f_a - \frac{f_{re} \cdot \cos\kappa_r}{\sin\kappa_{r1} - \sin\kappa_r} = \frac{f_a \cdot L_e \cdot (\sin\kappa_{r1} - \sin\kappa_r)}{L_e \cdot (\sin\kappa_{r1} - \sin\kappa_r) + a_{p\max} \cdot \cos\kappa_r} \quad (13)$$

Equations (8)–(13) are correct for the DC slotting with rotating tool as well.

Analysis of the Slot Width Nonuniformity for Adjustable Screen Pipes

Pipes with helical rows of slots manufactured by rotating tool have fin thickness varying along the fin and, therefore, the slots have variable width (Fig. 12). When slotting the left-handed rows, the fin thickness is decreasing while the cutting edge is moving in the workpiece material. When the slot rows are right-handed, the fin thickness is increasing along the cutting edge trajectory.

The slot width nonuniformity is caused by variability of cutting depth Δa_p while the cutting tool is moving in the workpiece material. Figure 13 shows the tool motion when machining a helix slot row. The tool trajectory relative to the workpiece was approximated by arcs of radius equal to the tool radius. The polar coordinate system with pole O was used to calculate the cutting depth difference Δa_p

$$\begin{aligned} \Delta a_p(\vartheta) = R_t - A\sqrt{2 - \cos\frac{720\,\text{deg} \cdot f_a \cdot \tan\omega}{\pi D}}\cos\left(\vartheta - 90\,\text{deg} - \frac{180\,\text{deg} \cdot f_a \cdot \tan\omega}{\pi D}\right) \\ - \sqrt{R_t^2 - A^2 \cdot \left(2 - \cos\frac{720\,\text{deg} \cdot f_a \cdot \tan\omega}{\pi D} \cdot \sin^2\left(\vartheta - 90\,\text{deg} - \frac{180\,\text{deg} \cdot f_a \cdot \tan\omega}{\pi D}\right)\right)} \end{aligned} \quad (14)$$

where ϑ is the tool angular coordinate, R_t is the tool radius, and A is the distance between tool and workpiece axes.

Hence, the actual fin thickness at any point can be calculated by using Eqs. (8), (9), and (14). The actual slot width at any point is calculated by using the following equation:

$$b(\vartheta) = f_a \cdot (\sin\kappa_{r1} - \sin\kappa_r) - \Delta a_p(\vartheta) \cdot \cos\kappa_r \quad (15)$$

Figure 14 shows graphs of the measured and calculated fin thickness values. The parameters of manufactured pipes are represented in Table 2. Analysis of the experimental results revealed

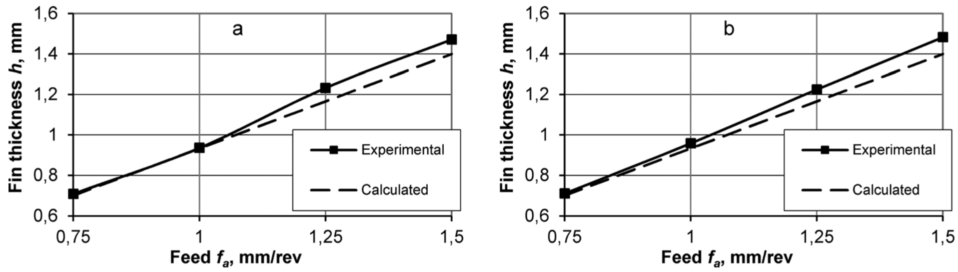

Fig. 10 Comparison of experimental and calculated values of fin thickness versus feed for $a_p = 4$ mm (*a*) and $a_p = 5$ mm (*b*)

Table 3 Measured fin thickness, fin deformation coefficient, and slot width for $a_p = 5$ mm

Feed, f_a (mm/rev)	Fin thickness, h_r (mm)	Fin deformation coefficient, ξ	Slot width, b (mm)
0.75	0.71	1.008	0.04
1	0.959	1.021	0.041
1.25	1.225	1.043	0.025
1.5	1.483	1.052	0.017

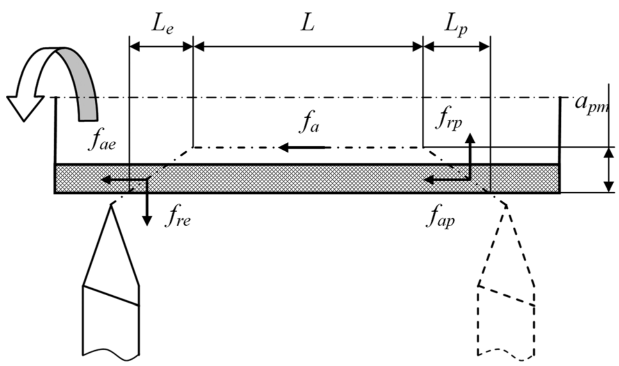

Fig. 11 Tool trajectory when slotting in lathe

Fig. 12 Nonuniformity of slot width for adjustable screen pipes (bright-field photo)

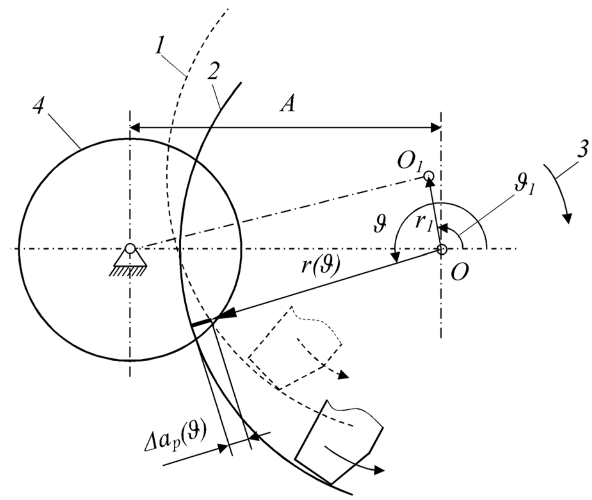

Fig. 13 Relative motion of the tool when cutting a helical slot row. All motions are applied to the tool. 1—relative tool trajectory when making previous slot, 2—relative tool trajectory when making considered slot, 3—relative tool motion caused by circular feed, and 4—workpiece outer surface.

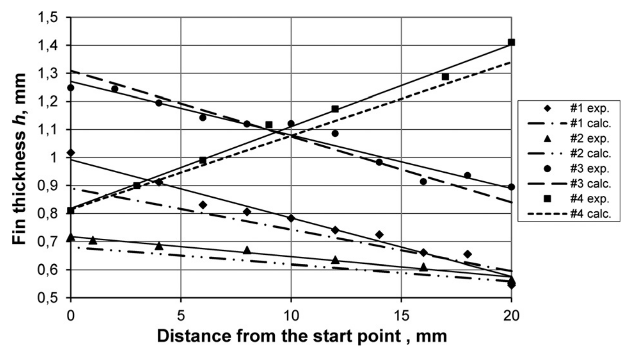

Fig. 14 Comparison of experimental and calculated values of fin thickness along the fin for different pipes with helical rows of slots. The parameters of the pipes are shown in Table 2.

that the major influencing factor on the fin thickness nonuniformity was given by the helix angle of slot rows ω. This has a direct influence on the slot width and should be taken into consideration on slot pipe design stage. However, the slot width nonuniformity decreases if the pipe is adjusted by compressing. This is caused by variable stiffness of fins having variable thickness.

Conclusion

(1) The DC technology can be used for manufacturing polymer slotted screen pipes from standard tubular workpieces or

tubular workpieces having internal longitudinal grooves. Making slotted screens from workpieces with internal grooves is more manufacturable and ensures slot width uniformity. In that case, no complicated equipment for a lathe is needed but workpieces are not standard.

(2) When using a standard tubular pipe as a workpiece, the slotted structure is made by cutting the rows of through slots. These slot rows can be helical or parallel to the pipe axis.

(3) The helical slot rows provide the slot width adjustment by compressing or stretching the pipe.

(4) The pipes with helical slot rows are characterized by the slot width nonuniformity. When slotting the left-handed rows, the slot width is increasing along the slot. The situation for the right-handed slot rows is opposite.

(5) The radial feed of the DC tool in the penetration and exit areas leads to the difference between the slot width in these areas and in the main section. Compensation of the slot width change in the penetration and exit areas can be done by changing the axial feed according to the equations described in this article.

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