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Investigation of the furrow formation by the disc tillage tools

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Abstract

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Tillage operation is one of the most power consuming processes in agriculture. Disc tillage tools due to their numerous advantages are of great importance in agriculture all over the world. In order to minimize the power requirements for the tillage process, it is developed the disc tillage tool by dividing the plain cutting surface into separate elements and turning them at an angle to the plane of rotation. This type of designing provides a condition for the soil sliding on the working surface. However, their furrow formation process differs from the known tillage tools. Hence, the purpose of this research is to improve the work quality, namely smoothness of the furrow bottom, weed destroying, due to the optimization of the furrow formation process based on the modeling of the soil-separate cutting elements of the tillage disc interaction. Mathematical models for determining the parameters of the furrows formed by three types of the disc tillage tools, namely with a plain concave and conical ring working surfaces, with separate cutting blades, mounted obliquely to the plane of rotation were presented. Experiments were carried out with the model of disc with the separate cutting blades under controlled conditions in the soil bin, filled with sand. The disc angle was 20°, 30°, 40° and the kinematic coefficient (ratio of peripheral disc speed to forward speed) was 1.0, 1.33, 1.8 and 2.2. Cutting blades inclined to the plane of rotation form short furrows with the elliptic section, inclined to the travel direction at an angle of 35-90° depending on the disc angle and the kinematical coefficient.

Keywords: disc tillage tool; furrow; width and length of furrow; direction of furrow; cutting blade

Introduction

Agricultural implements equipped with the tillage discs in comparison with the sweep tillage tools have less draught resistance and better tillage performance (Vozka, 2007). They can operate over moist and heavy trash conditions and ride over the high stubble and crop residues. However, the disc tillage tools with the plain concave and conical ring working surfaces have a serious disadvantage. In particular, on the working surface of the tillage discs the soil volume accumulation is occurred and in these zones of working surface the fixed soil body is built up, which increases the power requirements and decreases the quality of work (Gaifullin et al., 2013; Amantayev et al., 2016). Scrappers do not prevent this phenomenon. In doing so, numerous studies have been done to quantify the geometry of furrow, formed by the agricultural disc with the plain concave working surface (Hettiaratchi, 1997a, 1997b; Hettiaratchi and Alam, 1997). Development of disc tillage tools by dividing the plain cutting surface into separate elements and turning them at an angle to the plane of rotation provides a condition for soil sliding on the working surface (Patent 27820 RK). However, issues of the furrow formation by this kind of disc tillage tools are not studied.

Hence, the purpose of this research is the investigation of the furrow formation by the disc tillage tools in order to improve the quality of soil tillage process (smoothness of the furrow bottom, weed destroying).

Materials and Methods

The investigated disc tillage tools

Disc tillage tools due to their numerous advantages are of great importance in agriculture all over the world. Spherical disc tillage tools with the plain concave working surfaces are the most widely used (Figure 1a) (Strelbicki, 1978). They are manufactured with different diameters, radii of curvature of the working surface and the configuration of the cutting blade. During operation, the tillage discs are set at an angle β to the forward travel direction.

In the erosion-prone zones tillage discs with the conical ring working surfaces (conical discs) are used (Figure 1b). They consist of a hub 2 with the attached spokes 3, on which is rigidly fixed the ring cutting blade 4 with a conical form (Nartov, 1972; Bondarenko et al., 2009; Kurach and Amantayev, 2014). Tillage tool is functioned with the angle of β. The soil and crop residues pass through cutouts 5. The crop residues are uniformly distributed over the field surface and protect the soil from wind erosion.

The next disc tillage tool is developed based on the previous one as follows. The ring cutting blade is separated into several blades 6 (Figure 1c). These obtained blades 6 have been inclined from the plane of rotation at an angle α. The cutting blades 6 are rigidly fastened to the spokes 3, which are fixed to the hub 2. The plane of rotation of the spokes 3 is inclined from the forward travel direction OX at an angle β. This angle is actually the disc angle of the tillage tool. Their cutting edges have been configurated the elliptical shape to provide a constant tilling depth. The cutting edges of blades 6 coincide with the cylinder surface with a diameter equaled to the diameter of the disc with the ring working surface. The cylinder axis coincides with the axis of rotation of the mentioned disc (Patent 27820 RK). This type of designing makes an improved soil-disc tillage tool interaction in terms of the soil sliding over the surface of the cutting blades.

All three types of the disc tillage tools can work in passive and active modes (Hoki et al., 1988; Perdok and Kouwenhoven, 1994; Hann and Giessibl, 1998; Nalavade et al., 2010; Nalavade et al., 2011; Gaifullin et al., 2014). In the first case, they rotate due to the interaction with the soil. In the second case, the tillage tools are driven by the energy applied to them from the tractor engine.

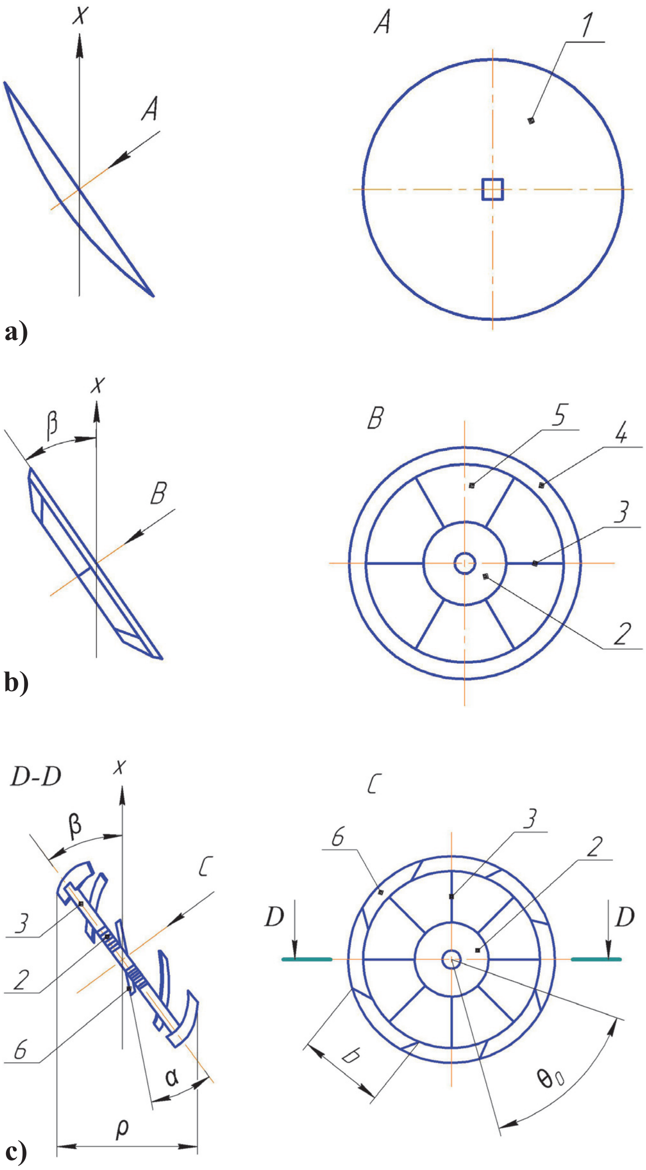


Fig. 1. Investigated disc tillage tools

a – spherical disc with the plain concave working surface;
b – conical disc with the ring working surface;
c – disc with the separate cutting blades mounted obliquely to the plane of rotation
1 – spherical disc; 2 – hub; 3 – spoke; 4 – cutting blade;
5 – cutout; 6 – separate blade

Experimental studies were conducted under controlled conditions of the soil bin filled with the sandy soil. The disc angle of the investigated tillage tools was 20°, 30°, 40° and the kinematic coefficient (ratio of peripheral disc speed to forward speed) was 1.0, 1.33, 1.8 and 2.2.

Results

Furrow formation by the disc tillage tools with the solid and ring working surfaces

The disc tillage tools with the plain concave and conical ring working surfaces form furrow, scheme of which is presented in the Figure 2. In Figure the angle *OX* characterizes the travel direction of the machine.

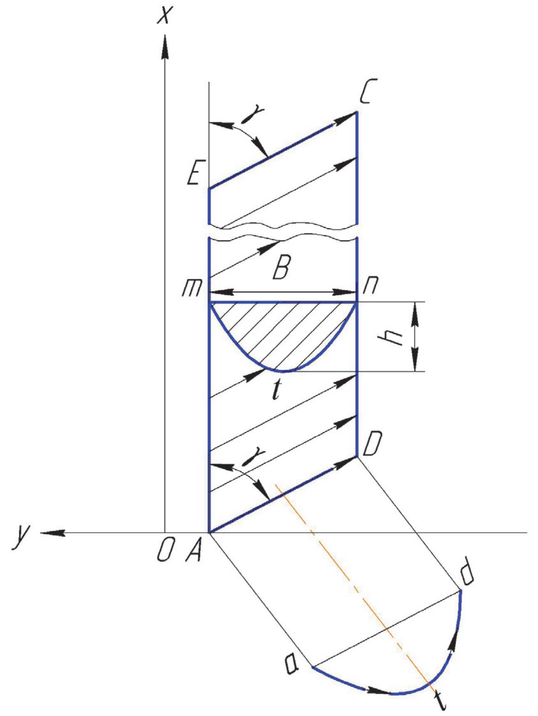


Fig. 2. Scheme of the furrow formed by the disc tillage tools with the plain concave and conical ring working surfaces (top view)

Parallelogram *AECD* schematically represents the top view of the furrow formed by the disc tillage tool with the plain concave and conical ring surfaces. The line segments *AE* and *DC* are the sides of the furrow. They are parallel to the travel direction of the machine and the length equals to the length of the cultivated land run.

During the tillage work the agricultural disc executes simultaneously forward and rotational motions. Due to this, each point on the disc edge is cyclically penetrated into the soil and lifted out from depth through a curvilinear trajectory *afd*. Along the curve *af* occurs the penetration of the point on the disc edge into the soil, and along the curve *fd* occurs the lifting. Each point on the disc edge moves in the soil along such trajectory. All trajectories start at the line *AE* and finish along the line *DC*. The trajectory projections on the horizontal plane (soil surface) are segments of the straight lines. The line segment *AD* is the trajectory projection of the point on the disc edge, which starts to deform the soil at the beginning of the run. The line segment *EC*, respectively, is the trajectory projection of the point on the disc edge, completing the soil tillage process at the end of the run. Between *AD* and *EC* are represented line segments, which characterize the projections of trajectories on the soil surface of other points on the edge in the soil. Arrows on the line segments indicate the direction of their movement. The furrow *AECD* is formed due to the passage of all points on the disc edge in the soil.

The line segments *AD* and *EC* and others, located between them, are equal, parallel and inclined from the travel direction at an angle γ, determined from the expression:

$$\gamma = \mathrm{arctg}[\lambda.\sin\alpha/(\lambda.\cos\beta - 1)], \quad (1)$$

where λ –kinematic parameter, $\lambda = V_0/V$;

V_0 – peripheral speed of the disc tillage tool;

V – forward speed of the machine;

β – disc angle.

In Figure 3 the theoretical and experimental dependences of the effect of the kinematic parameter λ and the disc angle β on the angle γ are presented. Their analysis shows that an increase in the parameter λ the angle γ increases continuously.

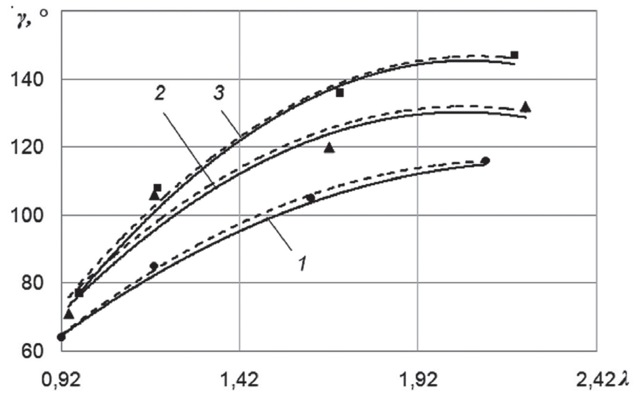


Fig. 3. Effect of the kinematic parameter λ and disc angle β on the angle γ

- - - - - – theory; ———— – experiment

1 – β = 40°; 2 – β = 30°;3 – β = 20°

The intensity of growth is dependent on the disc angle β. When the disc angle is 40°, at $\lambda = 0.92$ the angle $\gamma = 64°$. With an increase in λ to 2.11 the angle γ increases to 116°, i.e. the growth is 81%. When the disc angle equals to 20°, at $\lambda = 0.97$ the angle γ was 77°. The change of λ to 2.19 resulted in an increase in the angle γ to 147°. In this case, the growth of the angle γ was 91%.

The value of the angle γ depends on the disc angle β. A larger disc angle β corresponds to the lower value of the angle γ. The indicated difference rises with an increase in the kinematic parameter λ. For example, when $\beta = 40°$ and $\lambda = 0.92$ the angle γ was equaled to 64°. At the disc angle 20° and $\lambda = 0.97$ this angle was 77°, i.e. more than 13°. With an increase in λ to 2.11-2.19 for these disc angles the angle γ was equaled to 116° and 147° respectively. In the latter case, the difference of the angles γ is 31°.

The cross-section of furrow *mtn* (Figure 2) is a part of an ellipse. Its semi-major axis is equaled to the radius of the disc R, and the semi-minor axis is $R \cdot \sin\beta$. The furrow is characterized by the depth h and width B. Profiles of the cross-sections of furrow depend on configurations of the contour line of the disc edge and the tilt angle of the disc.

The furrow is partially covered by the soil volume and crop residues, passed through the tillage tool after the operation of the conical disc with the ring working surface.

Furrow formation by the disc tillage tool with the separated cutting blades inclined to the plane of rotation

In Figure 4a top view of the furrow formed by the one cutting blade from penetration till the completion of the lifting is illustrated. The white arrow with a replication number of test shows the forward direction of travel of the tillage tool. Line segments *AE'* and *DC'* are the sides of the furrow *AE'C'D*. They have an angle of inclination from the direction of travel.

In Figure 4b a schematic view of this furrow from the top side in the form of parallelogram *AE'C'D* is shown. Here the line segments *AE'* and *DC'*, as in Figure 4, a, are the sides of the furrow. They are parallel to each other, equal and inclined from the travel direction of machine at an angle ξ. The angle ξ is determined by the following formula:

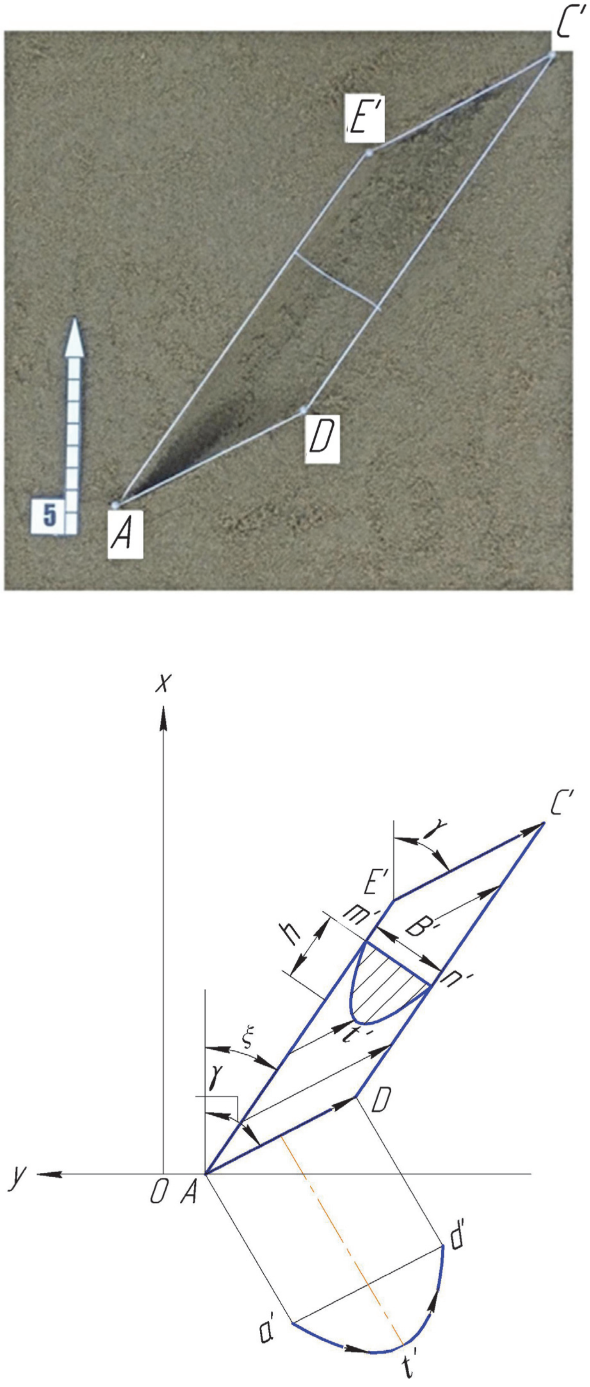
$$\xi = \text{arctg}[b.\cos\beta/(\pm b.\sin\beta + \theta \,.\, R/\lambda)], \qquad (2)$$

where b – the length of the cutting blade of the disc tillage tool;

θ – the central angle, covering the one cutting blade of the disc tillage tool.

In Figure 5 the theoretical and experimental dependences of the effect of the kinematic parameter λ and the disc angle β on the angle ξ are shown.

With the increase in the parameter λ increases the angle ξ. At the beginning period when $\lambda = 0.92$-1.19 this growth is very intense. At that time for $\beta = 40°$ λ is increased by 1.4 times, and for $\beta = 20°$ it is increased by 1.6 times. Then, when $\lambda = 1.18$-1.7 the growth of the angle ξ slows down. For the above mentioned angles, an increase was 1.18 and 1.14 times respectively. In the interval of $\lambda = 1.6$-2.2 the growth of the angle ξ is practically finished and its value becomes almost constant.



a)

b)

Fig 4. Top view to the furrow formed by the disc tillage tool with the separated cutting blades inclined to the plane of rotation
a – general view; b – schematic view

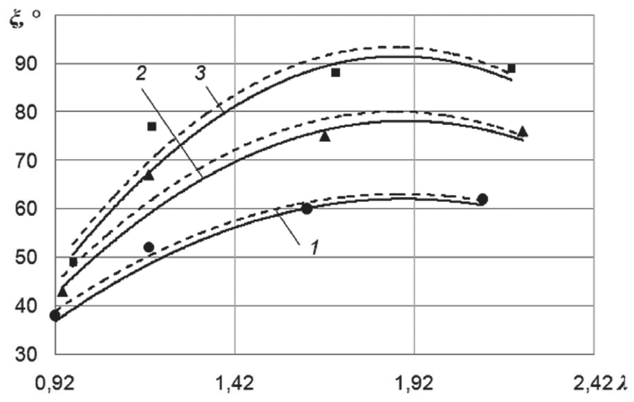


Fig. 5. Effect of the kinematic parameter λ and disc angle β on the angle ξ

– – – – – – theory; ———— – experiment
1 – β = 40°; 2 – β = 30°; 3 – β = 20°

The angle ξ depends on the disc angle β. A larger value of the disc angle β corresponds to the lower value of the angle ξ. For instance, at λ=0.92-0.97 for the disc angle β=40° the angle ξ was 36°, and for the angle β=20° was 46°. With the increase in the kinematic coefficient λ the difference of the values of the angle ξ depending on the disc angle β is increased. At λ=2.11-2.19 for the disc angle 40° the angle was equaled to 61°, whereas for the disc angle 20° was 86°. In this case, the difference was 25° and at λ=0.92-0.97 it was only 10°.

The length of the furrow sides *AE'* and *DC'* is determined by the following formula:

$$L_{AB'} = \rho.\cos\beta / \sin\xi, \qquad (3)$$

where ρ – working width of the disc tillage tool.

During the soil tillage cutting blades of the disc cyclically, alternately penetrated into the soil and lifted out from it. We consider the operation of a one blade. On its edge we select a point, which begins the soil tillage. It is penetrated into the soil and lifted out from it along the curvilinear trajectory *a'f'd'*. (Figure 4a). Its configuration and parameters are identical to the trajectory *afd*, along which are moved in the soil the points on the edge of the disc tillage tools with the plain concave and conical ring working surfaces. Here, along the curve *a'f'* also occurs the penetration of the point on the blade edge into the soil, and along the curve *f'd'* occurs the lifting. Each point on the edge moves in the soil along such trajectory. Trajectories start at the line *AE'* and end along the line *DC'*. The trajectory projections on the soil surface (horizontal plane) are segments of the straight lines. The line segment *AD* is the trajectory projection of the front point on the blade edge, which starts to deform the soil. The line segment *E'C'* is the projection on the horizontal plane of the trajectory in the soil of the end point on the blade edge, completing the soil tillage process. Between *AD* and *E'C'* are represented the line segments, which are the projections of trajectories of other points on the blade edge in the soil. Arrows on the line segments indicate the direction of their motion. The furrow *AECD* is formed after the pass of all points on the blade edge in the soil.

Thus, points on the edge of all three types of the disc tillage tools move in the soil along exactly the same trajectories.

The line segments *AD* and *E'C'* are equal, parallel and inclined from the travel direction at an angle γ, determined from the expression (1). This indicates that the angles γ for all three types of the disc tillage tools are equaled.

The cross-section of furrow *m't'n'* (Figure 4b) is a part of an ellipse. Its semi-major axis is equaled to the radius of the disc *R*, and the semi-minor axis is equaled to $R\cdot\sin\beta\cdot\sin(\gamma-\xi)/\sin\gamma$. The furrow depth, as the first two disc tillage tools, is equaled to *h*, and the width is *B'*.

Discussion

We combine schemes of furrows, shown in Figures 2 and 4, on the line segment *AD* (Figure 6). From Figure 5 follows that

$$AD = AM/\cos(90° - \gamma) = B/\sin\gamma.$$

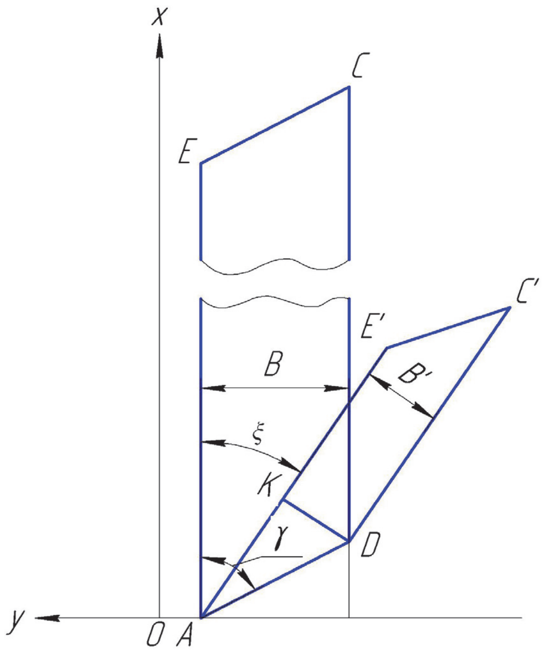


Fig. 6. The scheme for determining the width of furrow formed by the cutting blade inclined to the plane of rotation of the disc tillage tool

The furrow width *B'*, which is formed by the disc tillage tool with the cutting blades inclined the plane of rotation, is determined by the expression:

$B' = KD = AD.sin\ (\gamma - \xi)$.

Taking into consideration the previous formula

$$B' = (B.sin\ (\gamma - \xi))/\ sin\ \gamma. \quad (4)$$

Taking into account that $sin(\gamma - \xi)/sin\gamma < 1$, it can be considered that $B' < B$.

Thus, at the same tillage depth the cutting blade inclined to the plane of rotation of the disc tillage tool forms the furrow with the smaller width than the disc tillage tools with the solid and ring working surfaces.

Conclusions

1. Disc tillage tools with the plain concave and conical ring working surfaces form a continuous furrow, parallel to the travel direction, along the length of the cultivated land run. The contour line of the cross-section of furrow is part of an ellipse.

2. The cutting blades of the disc tillage tool mounted obliquely to the plane of rotation form the furrows within the working width of the tillage tool. These furrows are narrower and inclined from the travel direction. The contour line of the cross-section of furrow is part of the ellipse.

3. Points on the edges of all three types of the disc tillage tools are moved in the soil along exactly the same trajectories.

4. Dependences of the effects of the disc angle, kinematic coefficient and operating widths of the blades on the parameters of the furrows formed by the disc tillage tool with the cutting blades inclined to the plane of rotation are revealed.

5. Based on the obtained data the parameters of the tillage tool can be selected which provide the optimal furrow formation. Due to this the smoothness of the furrow bottom and weed destroying will be increased, i.e. the quality of the soil tillage process will be improved.

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