1. INTRODUCTION

In contemporary market conditions, enhancing the competitiveness of machine-building products is of paramount importance for their successful implementation to consumers. One way to achieve this is to optimize the use of workpieces, employ economical methods of forming, and utilize mechanical processing to reduce metal consumption, minimize waste, and prevent metal losses [1-5].

The selection of the method for obtaining workpieces that meet the production conditions of a particular machine-building enterprise is crucial in achieving these objectives. A well-chosen workpiece enables the reduction of tolerances, resulting in a lower volume of subsequent processing, lower labor intensity, and lower production costs [6, 7].

Cutting pipes into standard workpieces is one of the most prevalent operations in machine-building production. Thus, improving the methods of pipe cutting enables cost reduction of the finished product and is a critical task.

2. LITERATURE REVIEW AND PROBLEM STATEMENT

Currently, there are numerous methods of cutting pipes, each characterized by a set of technical and economic indicators and having a rational range of applications.

Based on the metal waste factor, all known methods of pipe cutting can be divided into three groups: waste, methods, including cutting on disk saws, milling-cutting machines, lathes, power saws, etc.; waste methods with irreversible waste, including cutting with abrasive, friction tools, gas cutting, plasma, laser, etc.; and wasteless methods, including cutting by shift, cold breaking by bending, cutting with wedge-shaped disk knives [8-16].

Wasteless cutting methods are the most promising in terms of productivity and waste reduction.

Cutting by shearing is the most effective and promising method for obtaining cut-to-length workpieces in terms of productivity and waste reduction. For instance, the amount of work done by 7-8 saws in cutting pipes can be completed in one shearing stamp. The replacement of pipe cutting on metal-cutting machines with shearing in stamps ensures a savings of 5-40% of metal, depending on the length of the work-pieces [17].

The method of cutting by shearing in stamps with mandrel blades and the introduction of blade guides into the pipe hole have not found wide application due to the formation of burrs and protrusions on the ends of the workpiece [17].

One of the methods for improving the quality of pipe cutting is the sequential two-axis shift in horizontal and vertical directions. However, this negatively affects the productivity of the separation process [18].

A method of two-stage cutting has been developed for cutting thin-walled pipes [19]. This method involves pre-compressing the pipe in the cutting zone onto a flat oval within the limits of elastic deformation, subsequent cutting of sections coaxial with the major axis of the resulting oval using a forked flat punch (knife), and final cutting of the pipe using a knife moving in a transverse direction. The disadvantage of this method is its complexity in implementation.

One of the promising combined mechanical deformation schemes for separating rolled products is the...
“eccentric twisting” cutting scheme using sleeve knives (a type of not fully enclosed cutting scheme) [20]. In the “eccentric twisting” cutting process, the cut workpiece rotates in a circular motion around an axis that is displaced from the tube axis by a certain distance, called eccentricity, which does not exceed the radius of the rolled product \( r \). This cutting method is a combined process that incorporates the advantages of both shear and twist cutting processes.

In the “eccentric twisting” cutting process using sleeve knives, the separation plane is divided into two zones: a zone of pure twisting and a zone of displacement of the separated parts along the arc. The specific proportion of these zones depends on the value of the eccentricity \( e \). When \( e = 0 \), there is pure twisting. When \( 0 < e < r \), there is “eccentric twisting”. When \( e \geq r \), there is cutting along the arc. And when \( e = \infty \), there is cutting equal to the translational movements of the separated parts.

The objective of this study is to conduct theoretical and experimental research on the energy and force parameters of the separation process, as well as the geometric accuracy of tube blanks separated by the “eccentric twisting” method.

To achieve the required kinematics of the knife movement in the “eccentric twisting” cutting process, possible design schemes of mechanisms were analyzed (see Fig. 1). The following designations are used: 1 – crank; 2 – connecting rod; 3 – slider; 4 – guide.

To provide multiple relative displacements of the cut-off part of the workpiece in several radial directions, a sinusoidal mechanism (see Fig 1, d) can be used, in which the crank 1 in the form of an eccentric is placed inside the connecting rod 2, which, in turn, is located inside the slider 3 [24].

For these purposes, a tangential mechanism (see Fig. 1, e) can be used – a type of cam mechanism in which the cam 4 is placed inside the connecting rod 2, which, in turn, is located inside the hinge installed inside the slider 3 [24].

The article [21-23] presents two variants of the constructive design of the crank-slider mechanisms that provide the required kinematics of the cutting tool motion during the tube cutting process (see Fig. 1, c).

To perform “eccentric twisting” cutting, a compact crank-shaft mechanism in combination with a circular slider - a “crank-circular mechanism” (see Fig. 1, f) can be used, where the crank is located inside the connecting rod and the connecting rod 2 is inside the slider 3 [24].

The most promising cutting scheme among the ones considered is the scheme of cutting pipes by “eccentric twisting” using the crank-circular mechanism (see Fig. 1, f) [24-26]. In this case, it is advisable to use a wedge-joint mechanism with a concave wedge as the main actuator of the press [21].

Thus, this article proposes a new approach to shear pipe cutting, when the pipe is cut along the entire perimeter through the use of a crank-circular mechanism in combination with a wedge-joint mechanism with a concave wedge. This technology and the equipment for its implementation exhibit all the signs of novelty. It has significant advantages compared to known solutions including the reduction of power of separation, ensuring the quality of separated workpieces, and increasing the reliability of equipment operation.

3. MATHEMATICAL MODELING OF PIPE CUTTING PROCESS

To implement the cutting scheme (see Fig. 1, f), a fundamental design of the device is proposed (see Fig. 2).

The main elements of the device include are: a movable 1 and a fixed 2 slide; a circular disc 3, located in the movable slide 1 with cutting blade-bushings 4, 5 eccentrically inserted.

Figure 1. Structural diagrams of mechanisms

In the crank-slider mechanism (see Fig. 1, a) [21-23], a circular groove \( A \) is made in which the crank 1 is placed in the form of an insert \( B \), which can be a cutting tool (knife, roller).

In the mechanism (see Fig. 1, b) [21-23], the crank is designed as an eccentric with a circular groove \( B' \) that interacts with the combined assembly of “connecting rod + hinge C”. This design scheme of the mechanism also allows for achieving the desired trajectory of the cutting tool along the perimeter of the tube.

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Figure 2. Schematic diagram of the device’s construction principle
The magnitude of the eccentricity corresponds to the length of the connecting rod. The cutting blade-bushing 4 is installed eccentrically relative to its axis of rotation, with the eccentricity magnitude corresponding to the radius of the crankshaft. The eccentricity magnitude corresponds to the radius of the crankshaft. In turn, the billet is placed in the cavity of the blades with an eccentricity \( e < r \).

The device operates as follows: in the initial position, the cutting knives-bushings 4 and 5 are coaxially aligned. The pipe 6 is inserted into the cavity of these bushings until it stops. Under the force from the press, the movable slider 1 moves down along the guides. The pipe becomes wedged in the knives 4 and 5, causing plastic penetration of the knives, which results in tangential displacement of the parts of the pipe and the concentration of stresses. When the frictional forces on the surfaces of the cutting knife 4, the circular washer 3, and the pipe 6 exceed a certain threshold, the cutting knife 4 begins to rotate around its axis and carries the cut part of the pipe, causing it to twist in the cutting plane and leading to the final separation of the pipe 6.

The cutting process ends when the cutting knife-bushing 4 completes a full revolution of 360º, the axes of the cutting knife 4, the circular washer 3, and the pipe 6 align again. The cutting knives-bushings 4 and 5 align again.

A mathematical model has been developed for a device designed to cut pipes using “eccentric twisting” (see Fig. 3). The forces of gravity and inertia of the device designed to cut pipes using “eccentric twisting” were neglected. The force calculation began with the consideration of the structural group 2-3. The system of equilibrium equations is presented below, including the friction forces in the translational pair and the friction moments in the rotational pair.

\[
\begin{align*}
\sum M_x(F_x) &= 0: R_{21}, (y_x - y_2) - R_{23}, (x_x - x_3) + M_{21x} + M_{23x} = 0; \\
\sum M_y(F_y) &= 0: M_{21y} + M_{23y} = 0; \\
\sum F_x &= 0: R_{21x} - R_{23x} = 0; \\
\sum F_y &= 0: R_{21y} + F_x + F_y = 0; \\
\sum F_z &= 0: R_{21z} + R_{23z} = 0; \\
\sum (F_n) &= 0: R_{21n} + R_{23n} = 0,
\end{align*}
\]

where \( R_{21x}, R_{21y}, R_{21z}, R_{23x}, R_{23y}, R_{23z} \) – are the reactions in the hinges; \( R_{21n} \) – is the reaction at the hinge; \( F_T \) – is the force of friction in the translational pair; \( F_1 \) – is the force applied to the slider; \( M_{21x}, M_{23x}, M_{23y} \) – are the moments of friction in the rotational pair, which can be represented in the following dependences:

\[
\begin{align*}
M_{21x} &= -\sqrt{R_{21x}^2 + R_{21z}^2} \cdot f_x \cdot r_x \cdot \text{Sign}(\phi_2 - \phi_1); \\
M_{23x} &= -\sqrt{R_{23x}^2 + R_{23z}^2} \cdot f_x \cdot r_x \cdot \text{Sign}(\phi_2); \\
M_{23y} &= -M_{21y}; \\
M_{12z} &= -M_{21z}; \\
F_1 &= -[R_{21} \cdot f_x] \cdot \text{Sign}(x_1),
\end{align*}
\]

where \( r_x, r_y \) – are the radii of the joints; \( f_x, f_y, f_z \) – are the friction coefficients; \( \phi_1, \phi_2 \) – are first-order transfer functions.

As a result of solving the system of equations (1) with consideration of (2), reactions in kinematic pairs, forces, and moments of friction can be determined. To determine the sign of friction forces and moments, it is necessary to know the first-order transfer functions of all links. To determine them, a methodology for kinematic analysis of the mechanism has been developed in the procedures outlined earlier. The Newton method was employed to solve the nonlinear system of equations (1), and (2).

Knowing the reactions \( R_{21x}, R_{21y}, R_{21z} \), the resistance moment from the work-piece was determined using the equilibrium condition of link 1:

\[
\begin{align*}
\sum (F_n)_1 &= 0: -R_{21x} + R_{23x} = 0; \\
\sum (F_y)_1 &= 0: -R_{21y} + R_{23y} = 0; \\
\sum M_x(F_x)_1 &= 0: R_{21x} + M_{21x} + M_{23x} + \\
&+ R_{21y} \cdot (y_2 - y_1) - R_{23y} \cdot (x_3 - x_2) = 0.
\end{align*}
\]

where \( M_c \) – the moment of resistance; \( R_{10x}, R_{10y}, R_{10z} \) – reactions at the hinge; \( M_{10x} \) – the moment of friction in the rotational pair, which can be represented by the following dependence:

\[
\begin{align*}
M_{10x} &= -\sqrt{R_{10x}^2 + R_{10z}^2} \cdot f_0 \cdot r_0 \cdot \text{Sign}(\phi_1),
\end{align*}
\]

where \( r_0 \) – is the radius of the hinge; \( f_0 \) – is the coefficient of friction.

The developed mathematical model was verified by simulating the technological process of cutting pipes using the “eccentric twisting” method, based on the previously discussed diagram (see Fig. 2), using the DEFORM-3D software package [27-30].

The design diagram of the process of cutting off a measured tubular workpiece is shown in Fig. 4.
4. EXPERIMENTAL STUDY OF THE PROCESS OF CUTTING TUBULAR BLANKS

To verify the results of the theoretical calculations, experimental studies of pipe separation using the "eccentric twisting" method were conducted. The setup (Fig. 6) works as follows. The pipe to be divided (1) is fed into the slot between knives (2 and 3) until it reaches the stop (not shown). The stationary knife (2) is fixed to the stamp body (4), while the movable knife (3) is fixed to the shaft (5). The shaft rotates on bearings (6). At the same time, the axis of rotation of the shaft (5) is shifted relative to the axes of rotation of the knives (2, 3) by the eccentricity value $e$. When the drive is turned on, the movable knife (3) rotates around its axis. At the initial stage of cutting, the pipe (1) is wedged between knives (2 and 3). Then, there is a plastic penetration of the cutting edges of knives (2 and 3) into the tubular blank (1), with simultaneous twisting of the cut part of the blank in the plane of separation until failure.

During the experiment, a tubular workpiece is inserted into the cavity between the movable and fixed knife bushings until it comes to a stop. Upon activation of the drive, the movable knife rotates around its axis. At the initial stage of cutting, the workpiece becomes jammed between the knives. Subsequently, there is a plastic embedding of the cutting edges of the knives into the workpiece, and twisting of the cut part in the plane of division until it fractures. After the movable knife completes a full rotation around the axis of the cutting knives, the knives realign with each other, and the cycle of operation repeats.

The gear ratio of the reducer is $U=4.3$. In the experiment, tubular samples with the following dimensions were used: an outer diameter of 16 mm and a length of 200 mm. The material of the samples was steel C 22 (wall thickness $\delta = 2\text{mm}$).

An opening was drilled in both the movable and stationary knives, in one pass, to accommodate the tubular blank, whose axis is offset from the knife rotation axes by a distance of $e = 3\text{mm}$.

The force parameters of the separation process were measured using a single-handed dynamiter with an indicator head, which was calibrated in advance [31].

5. DISCUSSION OF RESEARCH RESULTS

The analysis of the results of mathematical modeling (see Fig. 5, a) shows that the calculated maximum force for cutting the pipe was $F_{max} \approx 11.6 \text{kN}$. Therefore, the cutting torque of the tubular blank can be calculated as:

$$M_{comp} \approx F_{max} \cdot (d/2 + e) \approx 11600 \cdot (16/2 + 3) = 127600 \text{N} \cdot \text{mm}.$$
The resistance moment $M_c$ with the angle of rotation of the knife $\phi$ for blanks made of steel C22 (Fig. 7) – curve 1. The experimental dependence $M_c = f(\phi)$ is also presented in Fig. 7 – curve 2.

The measurements in Table 2 show the relative average distortions of the geometric shape of tubular blanks obtained through 'eccentric twisting' cutting. The cut tubular blanks display satisfactory geometric accuracy, as seen in the photo in Fig. 9.

6. PRACTICAL IMPLEMENTATION OF THE OBTAINED RESULTS

For industrial implementation of the research results, we propose a device design illustrated in Fig. 10. It comprises a housing containing a plate: upper (2), lower (3), front (4), rear (5), cross left (6), and cross right (7), fastened with bolts and dowels. The device is powered by a wedge-joint mechanism with a concave wedge, consisting of a reciprocating wedge (1) with a concave profile and a joint (8). The joint contacts the wedge along the curved surface of the radius on one side and, on the other side, along the curved surface of the radius with the reciprocating slider (9).

The joint (8) is installed to allow rolling movement in the slider (9) relative to the pin axis (10). A washer (11) is concentrically located in the slider (9). Within the washer (11), a movable bushing knife (12) is installed to allow rotational movement in sliding bearings. Adjacent to it, a stationary knife (13) is fixed to the rear plate (5). Importantly, the axes of rotation of the knives (12, 13) are displaced relative to each other by the eccentricity value 'e.' The slider (9) is spring-loaded using a polyurethane buffer (14). The pre-compression force of the buffer is adjusted by moving the nut 15. Guides are used to install the wedge (1), the joint (8), and the slider (9).

The viability of employing a wedge-joint mechanism with a concave wedge for pressure processing separation processes in machines is substantiated in [32]. The deformation force curve closely aligns with the typical technological curve for force changes during separation. This mechanism, characterized by large bearing surfaces and a small height of links in the direction of the working force, results in lower elastic deformation, enhanced press dynamics, and an increased utilization coefficient of the press in machines.

<table>
<thead>
<tr>
<th>Material</th>
<th>Deviation magnitude</th>
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<tbody>
<tr>
<td></td>
<td>$\phi,$ $\nu$</td>
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7. CONCLUSIONS

1. After analyzing literature data, the 'eccentric twisting' scheme emerged as a promising method for cutting tubular work-pieces, complemented by the 'crank-circular' mechanism as an executive design. A mathematical model for the device featuring the "crank-circular" mechanism, specifically designed for cutting tubes through “eccentric twisting”, has been developed. The technological process of tube cutting using “eccentric twisting” was modeled using the DEFORM-3D software package. Experimental studies were conducted on an original design installation to validate the results of theoretical calculations. The cut tubular work-pieces exhibit satisfactory geometric accuracy parameters.

2. The experimental results align well with the theoretical data obtained through both the proposed mathematical model and the specialized software DEFORM 3D. The disparity between the maximum values of cutting torque obtained theoretically and experimentally is within a 6% margin. The theoretical results were slightly underestimated, highlighting the necessity for a more precise consideration of friction in the rotating pairs. The shift of curve 2 to the right is attributed to the clearance between the tool and the workpiece.

3. A design for an industrial installation has been proposed to implement the research results. The design incorporates a wedge-hinged drive with a concave wedge coupled with a "crank-circular" mechanism for dividing pipes using the “eccentric twisting” scheme. The wedge-hinged mechanism with a concave wedge has large supporting surfaces and a small height of links in the direction of the working force. This design choice ensures reduced elastic deformation and enhanced machine dynamics, leading to an increased coefficient of utilization for forging-press equipment. Simultaneously, the developed support area for the connecting rod within the slide of the crank-circular mechanism diminishes specific forces in this support, contributing to vibration damping. This, combined with a small deformation zone, results in high dynamic stability and eliminates rocking on the foundation.

4. The upcoming research will focus on investigating the cutting process under increased loading rates.

REFERENCE


ИСТРАЖИВАЊЕ О НОВОМ ПРОЦЕСУ ОДВАЈАЊА ШУПЉЕГ РАДНОГ КОМАДА ЕКСЦЕНТРИЧНИМ ТОРЗИЈСКИМ СЕЧЕЊЕМ ЗА ШТАНЦАЊЕ

С.Г. Карнаух, О.Е. Марков, А.А. Лисенко

Овај рад има за циљ да спроведе теоријска и експериментална истраживања параметара енергије и силе процеса сепарације, као и геометријске тачности одвојеног цевастог обратка методом „екскенцентричног увијања“. Развијен је математички модел уређаја са „кржно-кружним“ механизmom за сечење цеви „екскенцентричним увијањем“. Технологијски процес сечења цеви „екскенцентричним увијањем“ симулиран је коришћењем софтверског пакета ДЕФОРМ-3Д. Резултати експерименталних студија су у добријо сагласности са теоријским подацима израчунатим коришћењем предложеног математичког модела и специјализованог програма ДЕФОРМ-3Д. Максималне разлике између вредности момента резања добијених теоријски и експериментално не прелазе 6%. За индустријску имплементацију резултата истраживања, предложе се пројекат инсталације са клинастим погоном са конковним клином у комбинацији са „кружно-кружним“ механизmom за одвајање цеви по шеми „екскенцентричне торзије“.