Research on the New Process of Separating Hollow Work-Piece by Eccentric Torsion Cutting for Stamping

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This work aims to conduct theoretical and experimental studies on the energy and force parameters of the separation process, as well as the geometric accuracy of the separated tubular workpiece using the "eccentric twisting" method. A mathematical model of a device with a "crank-circular" mechanism for cutting pipes by "eccentric twisting" has been developed. The technological process of cutting pipes by "eccentric twisting" was simulated using the DEFORM-3D software package. The results of experimental studies are in good agreement with the theoretical data calculated using the proposed mathematical model and the specialized program DEFORM-3D. The maximum differences between the cutting torque values obtained theoretically and experimentally do not exceed 6%. For the industrial implementation of research results, a design of an installation with a wedge-hinged drive with a concave wedge in combination with a "crank-circular" mechanism for separating pipes by the «eccentric torsion» scheme is proposed.

Key words: *separation, eccentricity, torsion, slider, connecting rod, crank, work-piece, force, moment, quality, wedge, hinge.*

1. INTRODUCTION

In contemporary market conditions, enhancing the competitiveness of machine-building products is of paramount importance for their successful implemen–ation to consumers. One way to achieve this is to opti–ize 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 work–ieces that meet the production conditions of a particular machine-building enterprise is crucial in achieving these objectives. A well-chosen workpiece enables the reduc–ion of tolerances, resulting in a lower volume of subse–uent 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 promi–sing 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 repla–cement 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 defor–mation schemes for separating rolled products is the

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"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 sle–eve knives, the separation plane is divided into two zo–nes: a zone of pure twisting and a zone of displa–cement of the separated parts along the arc. The specific pro–portion of these zones depends on the value of the eccen–tricity e. When e = 0, there is pure twisting. When $0 < e < r$, there is "eccentric twisting". When $e \geq r$, there is cut–ting 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.

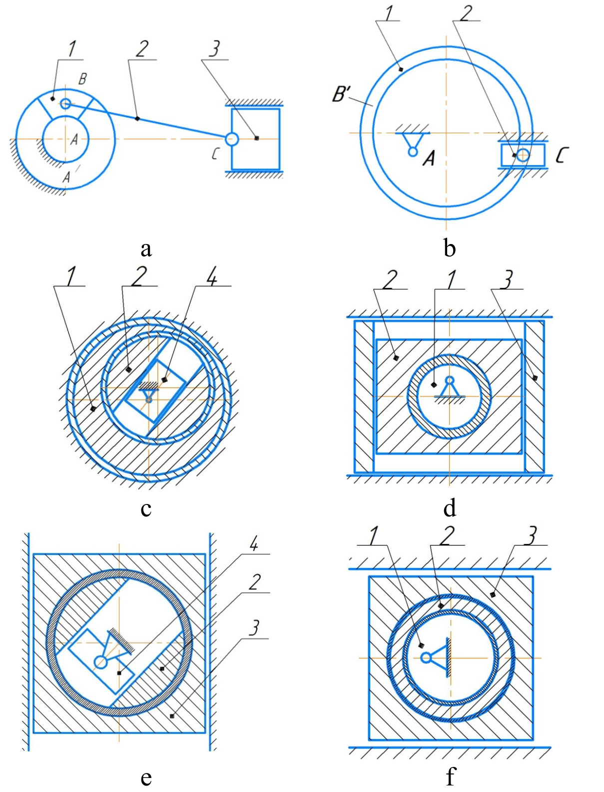


Figure 1. Structural diagrams of mechanisms

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.

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 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 [21].

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].

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 2 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 peri–meter 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 fun–damental 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.

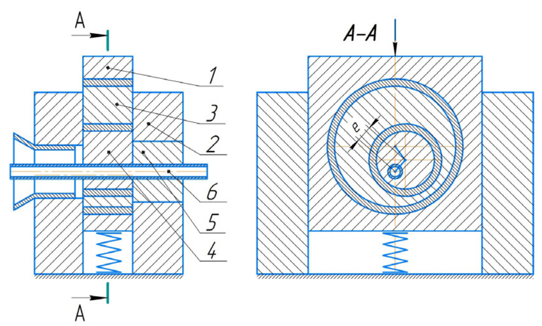


Figure 2. Schematic diagram of the device's construction principle

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 posi–tion, 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 rotates by an angle that depends on the mechanical properties of the material being cut (up to 180º). After knife 4 completes a full revolution of 360º, the axes of the cutting knife-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 mechanism parts 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.

$$\left.\begin{aligned}
&\sum M_A(F_i)_2 = 0 : R_{23x}\cdot(y_A - y_B) -\\
&- R_{23y}\cdot(x_A - x_B) + M_{21\mathrm{T}} + M_{23\mathrm{T}} = 0;\\
&\sum M_B(F_i)_3 = 0 : M_{32\mathrm{T}} + M_{30} = 0;\\
&\sum (F_{ix})_3 = 0 : R_{30x} - R_{23x} = 0;\\
&\sum (F_{iy})_3 = 0 : -R_{23y} + F_3 + F_{\mathrm{T}} = 0;\\
&\sum (F_{ix})_2 = 0 : R_{21x} + R_{23x} = 0;\\
&\sum (F_{iy})_2 = 0 : R_{21y} + R_{23y} = 0,
\end{aligned}\right\} \quad (1)$$

where R_{21x}, R_{21y}, R_{23x}, R_{23y} – are the reactions in the hinges;

R_{30x} – is the reaction in the translational pair;

F_T – is the force of friction in the translational pair;

F_3 – is the force applied to the slider;

M_{21T}, M_{23T}, M_{32T} – are the moments of friction in the rotational pair, which can be represented in the follo–wing dependencies:

$$\left.\begin{aligned}
&M_{21\mathrm{T}} = -\sqrt{R_{21x}^2 + R_{21y}^2}\cdot f_A \cdot r_A \cdot Sign(\varphi_2^{/} - \varphi_1^{/});\\
&M_{23\mathrm{T}} = -\sqrt{R_{23x}^2 + R_{23y}^2}\cdot f_B \cdot r_B \cdot Sign(\varphi_2^{/});\\
&M_{32\mathrm{T}} = -M_{23\mathrm{T}};\\
&M_{12T} = -M_{21\mathrm{T}};\\
&F_{\mathrm{T}} = -\left|R_{30x}\cdot f_n\right|\cdot Sign(x_3^{/}),
\end{aligned}\right\} \quad (2)$$

where r_A, r_B – are the radii of the joints;

f_A, f_B, f_n – are the friction coefficients;

$\varphi_1^{/}$, $\varphi_2^{/}$ – are first-order transfer functions.

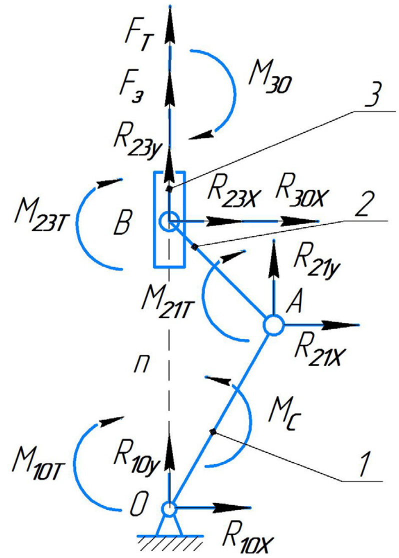


Figure 3. Mechanism diagram with applied forces and reactions in kinematic pairs

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 kine–matic analysis of the mechanism has been developed in the procedures outlined earlier. The Newton method was employed to solve the nonlinear system of equa–tions (1), and (2).

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

$$\left.\begin{aligned}
&\sum (F_{ix})_1 = 0 : -R_{21x} + R_{10x} = 0;\\
&\sum (F_{iy})_1 = 0 : -R_{21y} + R_{10y} = 0;\\
&\sum M_O(F_i)_1 = 0 : M_{10\mathrm{T}} + M_C + M_{12\mathrm{T}} +\\
&+ R_{21x}\cdot(y_O - y_A) - R_{21y}\cdot(x_O - x_A) = 0.
\end{aligned}\right\} \quad (3)$$

where M_c – the moment of resistance;

R_{10x}, R_{10y}, – reactions at the hinge;

M_{10T} – the moment of friction in the rotational pair, which can be represented by the following dependence:

$$M_{10\mathrm{T}} = -\sqrt{R_{10x}^2 + R_{10y}^2}\cdot f_O \cdot r_O \cdot Sign(\varphi_1^{/}), \quad (4)$$

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.

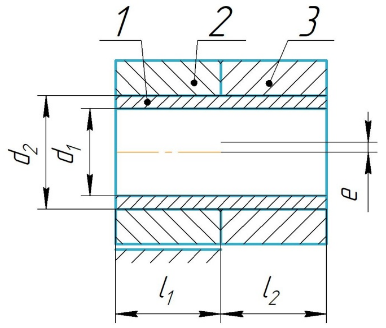


Figure 4. The design diagram of the process of cutting off a measured tubular workpiece

The material of the tubular workpiece is steel C 22-ISO. The parameters of the workpiece are as follows: inner diameter – d_1 = 12 mm, outer diameter – d_2 = 16 mm. Width of cutting knives-bushings: $l_1 = l_2$ = 30 mm. The magnitude of the eccentricity is e = 3 mm.

The mechanical properties of the material of the workpieces are presented in Table 1.

Table 1. Mechanical properties of the workpiece material

Parameters	$\sigma_{0,2}, MPa$	σ_B, MPa	δ,%	ψ,%
Steel C22	245	412	21	55

To simulate the cutting process, the following parameters were set:

- failure criterion – Normalized C&L;
- type – Lagrangian incremental;
- mesh – 40000;
- movement of the knives – rotation;
- angular velocity of the moving knife – 3 rad/s;
- friction-shear – 0,7;
- temperature – 20ºC.

The calculation results are presented in Fig. 5.

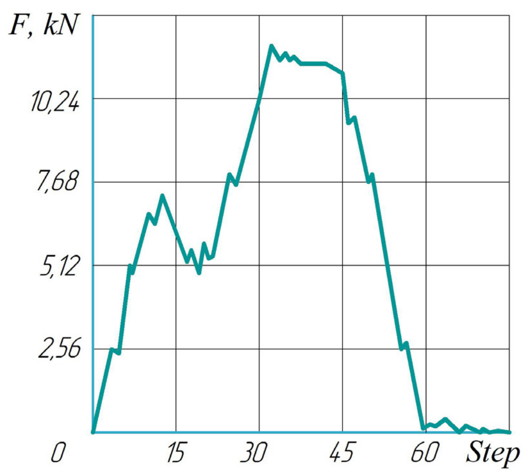


Figure 5. Graph of the change in the cutting force during the separation of a tubular workpiece

4. EXPERIMENTAL STUDY OF THE PROCESS OF CUTTING TUBULAR BLANKS

To verify the results of the theoretical calculations, ex–perimental studies of pipe separation using the “eccen–tric 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 inser–ted 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 $\delta = 2mm$).

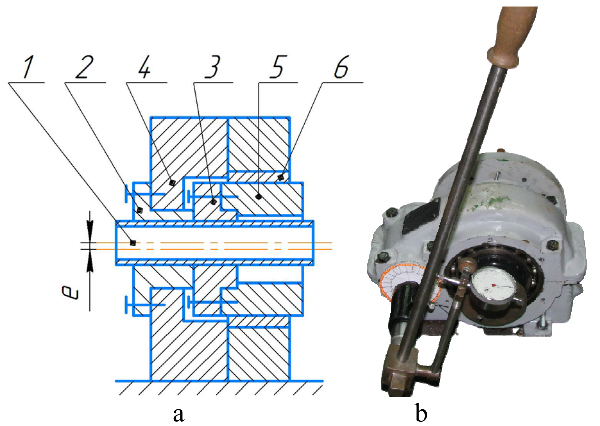


Figure 6. Design (a) and photo (b) of the experimental setup

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 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 $F_{\max} \cong 11{,}6\,kN$. Therefore, the cutting torque of the tubular blank can be calculated as:

$$M_{omp} \cong F_{\max} \cdot (d/2 + e) \cong 11600 \cdot (16/2 + 3) = 127600\,N \cdot mm.$$

The results of the calculations (formula (3)) are presented in the form of a graph showing the change in resistance moment M_c with the angle of rotation of the knife φ for blanks made of steel C22 (Fig. 7) – curve 1. The experimental dependence $M_c = f(\varphi)$ is also presented in Fig. 7 – curve 2.

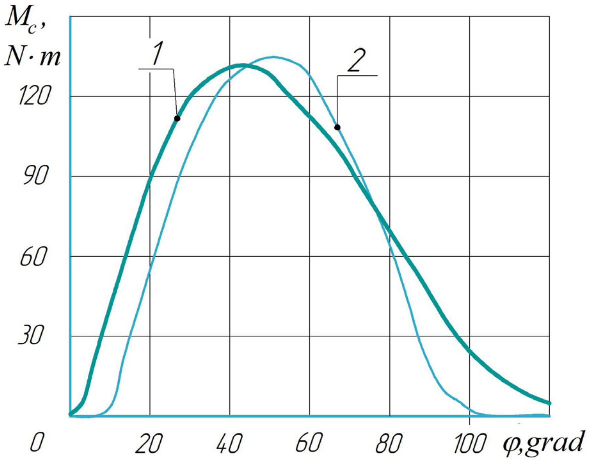
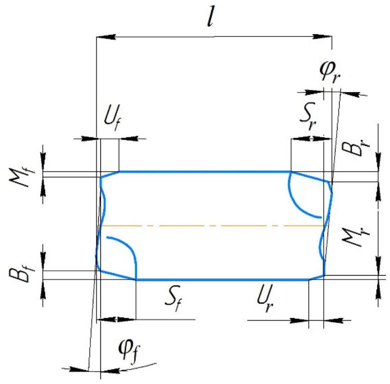


Figure 7. Dependence of the moment on the movable blade-bushing on the angle of rotation of the blade



***φ* – angle of work-pieces end; *M*, *U* – cross and longitudinal dimensions of the tightening; *B*, *S* – cross and longitudinal dimensions of the knife marks; *f*, *r* – indexes indicating front and rear ends**

Figure 8. Basic dimensions for evaluating the work-piece shape distortion [32]

The obtained results of experimental studies are satisfactorily consistent with the theoretical data calculated using both the proposed mathematical model and the specialized DEFORM 3D program. The discrepancy between the maximum values moment M_c, obtained theoretically and experimentally, does not exceed 6%. The theoretical results were slightly underestimated, which is associated with the need for a more correct account of friction in rotating pairs. The shift of curve 2 to the right is due to the selection of gaps between the tool and the workpiece. The measurement of geometric parameters characterizing the geometric accuracy of the cut blanks was carried out by direct measurement using a universal measuring instrument according to a known measurement scheme [32] (Fig. 8).

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.

Figure 9. Image of cut steel pipe work-piece made of steel C22 [32]

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 2. Indicators of geometric accuracy of work-pieces

Material	Deviation magnitude									
	$\varphi,^0$		$u = U/d$		$s = S/d$		$m = M/d$		$b = B/d$	
	φ_f	φ_r	U_f	U_r	S_f	S_r	M_f	M_r	B_f	B_r
Steel C22	2,00	1,00	0,02	0,01	0,05	0,03	0,01	0,01	0,06	0,04

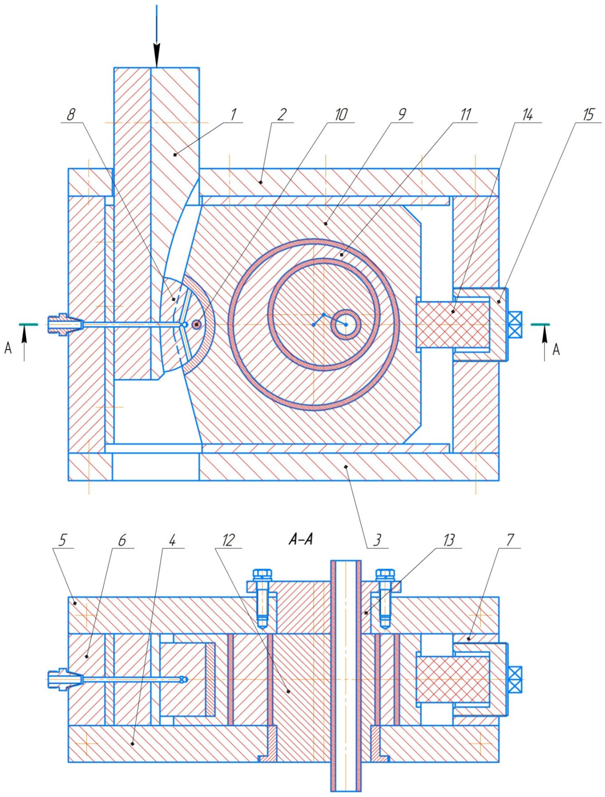


Figure 10. Device for cutting pipes

The proposed installation design uses incorporates a compact crank-connecting rod mechanism in combination with a frame slider. The developed area of support for the connecting rod in the slider reduces the specific forces in this support and contributes to damping oscillations, contributing to the damping of oscillations. This, coupled with a small deformation zone, results in high dynamic stability and eliminates rocking on the foundation [33].

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.

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

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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 „ексцентричног увијања“. Развијен је математички модел уређаја са „кружно-кружним” механизмом за сечење цеви „ексцентричним увијањем”. Техно–лошки процес сечења цеви „ексцентричним уви–јањем“ симулиран је коришћењем софтверског пакета ДЕФОРМ-3Д. Резултати експерименталних студија су у доброј сагласности са теоријским подацима израчунатим коришћењем предложеног математичког модела и специјализованог програма ДЕФОРМ-3Д. Максималне разлике између вредн–ости момента резања добијених теоријски и експе–риментално не прелазе 6%. За индустријску импле–ментацију резултата истраживања, предлаже се пројекат инсталације са клинастим погоном са кон–кавним клином у комбинацији са „кружно-круж–ним“ механизмом за одвајање цеви по шеми „ексцентричне торзије“.