ORIGINAL ARTICLE

Designing and researching of the equipment for cutting by breaking of rolled stock

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Abstract

The aim of the work is designing of the new schemes of cut-to-length workpieces of rolled stock and equipment for their implementation. A special construction of the equipment for cutting by breaking of rolled stock has been designed. The energy accumulated into hydro press at the expense of elastic deformation of the machine frame and the drive is used for effective work, namely, application of stress concentrator for cutting by breaking the next workpiece. Mathematical model for indentation of the wedge tool with different form has been designed. Dependences for calculation of energy-power parameters of the process of stress concentrator application have been found. Experimental studies of indentation of the wedge-shaped tool with different forms into the sample confirmed the adequacy of the proposed mathematical models. Calculating errors within 5–10% is related to the need for a more correct choice of the value of sliding friction coefficients. Calculations for steel C 20 (0.2% of the carbon) with triangular stress concentrator show that the amount of accumulated energy of elastic deformation of the machine frame and the drive of hydraulic press will be enough for application of the effective stress concentrator for cutting by breaking the next workpiece (taking into account the bluntness of the cutting edges of the wedge knife).

Nomenclature

x_0	Traverse stroke of the hydraulic press
H	Cutting stroke (indentation depth)
l_1	Load application shoulder during breaking of the rolling according to the console scheme
l	Length of the cut workpiece
x_i, y_i	Coordinates of the corresponding singular points: A, B, C, D, E, N, K
A_{ENK}	Triangle area defining the volume of the displaced metal
L_{ij}	Lengths of the respective segments: NA, NB, BA, CB, CA, DA
α	Half-angle of the top of a double-sided wedge knife
ϕ	Angle at the top of the centered mesh
γ	Angle of approach of the DA characteristics to the contact surface of the deforming tool
Θ	Angle of approach of the leg L_{DE} to the horizon
K	Shear yield strength
τ	Tangential contact stresses
k	Number of the next cycle of solution iterative procedure
A_L	Changing step of the segment length
$signY_{E_{расч}}$	Sign function corresponding to the sign of the calculated geometric coordinate of the point E
σ_{ADE}	Mean stress in the ADE region
σ_{AO}	Pressure along the contact line AO

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σ_{xE}, σ_{yE}	Normal stresses
F_i	Indentation force of the tool
μ	Coefficient of plastic friction
R	Radius of the workpiece
L_i	Half-width of the area indentation
σ_T	Yield strength
σ_B	Tensile strength
HB	Brinell's hardness
$\delta\%$	Elongation
$\gamma\%$	Relative narrowing
h	Height of the wedge, cone and pyramid
B, L	Width and length of the wedge base
D	Diameter of the cone base
S	Side of the pyramid base

1 Literature review

Mechanical engineering plays the leading role in the social and economic development and is considered a foundation of the industry [1]. A great contribution to the finished cost of engineering production is made by the efficiency of blank production [2]. More than ten different methods of preforming by means of cutting of the rolled stock into cut-to-length workpieces are used [3]. The choice of the way of preforming is connected with the concrete technical and economic cost calculation of the completed part, which is done for the given volume of the annual output, subject to other production conditions. The most perspective methods of the cutting of the rolled stock into cut-to-length workpieces among the known ones are the following waste-free methods: cutting by shear and cutting by breaking [4].

The task of the improvement of techniques and equipment used in blank production is actually.

Scientists have made a great contribution to the present development of the theory, methods, and equipment for cutting of the rolled stock [5, 6].

One of the main problems of equipment used for cutting processes is its work under conditions of abrupt load reset at the moment of workpiece breaking. This effect leads to the press frame destruction and layup of the foundation and is accompanied by hydraulic impact initiation in the hydraulic system of the press, which is connected with cavitation [7]. It leads to choose the high-power equipment. Therefore, the power of the equipment used for cutting processes has low capacity factor: press equipment with the force less than 2 MN is used no more than 60–80% of rated capacity; with the force less than 4 MN is used no more than 40–60% of rated capacity; and with the force more than 4MN is used less than 40% of rated capacity [8].

Problem-solving technique for such tasks is considered in the papers [9–11], and quantitative evaluation of

indentation force of smooth wedge knife without external friction of its contact surface is given there [12, 13]. In the papers [14, 15], the authors concede the surface flatness stability of deformed workpiece, thus neglecting the volume of displaced metal. A numerical interpretation of the slip-line method allows to increase the accuracy and to extend the number of current tasks.

Designing new schemes for cutting of the rolled stock and creating new efficient, versatile, and quick-set devices, which are simple in use and service, may solve this task. It is especially actually for short-run and large-scale mixed workpieces production, when the use of high-cost equipment.

2 Proposed concept of equipment

The aim of the work is designing of new schemes for cutting of the rolled stock into cut-to length workpieces as well as equipment for their implementation.

In this work, it is proposed to use the energy, accumulated in the machine at the expense of elastic deformation of the press frame and the drive, for stress concentrator application. To implement this idea, a structural scheme of the stamp used for cutting of the rolled stock by bending has been designed (Fig. 1).

The stamp consists of frame, actuating cylinder 1, breaker 3, and knife 4 which are fixed to the moving beam 2. Under the force action of cylinder drive 1, moving beam 2 moves downwards, making the clamping (by means of the elastic element 5) and cutting by breaking of the rolled stock 6 with the stress concentrator, which is preliminary applied on the separate plane on the arm l_1.

An abrupt reset of the force takes place at the moment of rolled stock cutting. The system "cylinder 1, moving beam 2, breaker 3, knife 4" becomes dynamically unbalanced. The moving beam gathers speed on the stroke x_0, and knife 4 applies the stress concentrator on the rolled stock 6, at the expense of wedge indentation into metal at the depth of H, for cutting by breaking the next workpiece with the length l. The indentation of the knife with shape of wedge leads to localize a maximal deformation under apex of the wedge. It allows to increase a strength and decrease a plasticity (by means hardening of material) in the stress concentrator [16, 17].

The energy accumulated in the machine at the expense of elastic deformation of the frame and the drive is used for effective work, namely, application of stress concentrator for cutting by breaking during bending of the next workpiece. The stress concentrator, in this method, is the induced main macro-crack. The macro-crack may be of maximum size; this meets the optimal requirements demanded for the process of cold breaking by bending. So, two operations are combined in one working cycle, breaking by bending and stress

Fig. 1 Cutting by breaking of the rolled stock in the stamp
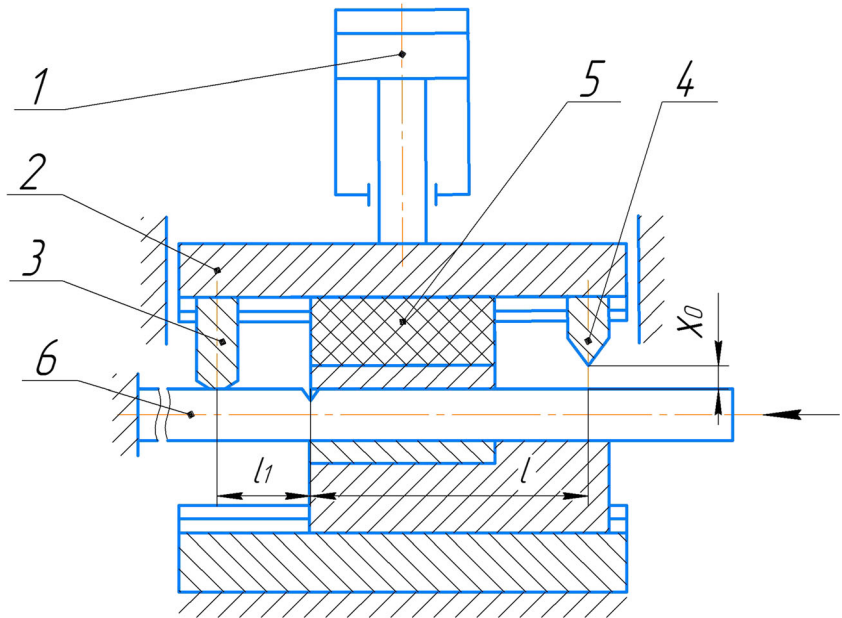
concentrator application in the place of the next workpiece cutting, which leads to productivity improvement of the process. The equipment of static action works in dynamic mode and provides a higher speed of stress concentrator application, which leads to higher quality of the cut workpieces.

Mathematical simulation of stress-strain state of metal, when applying the stress concentrator with wedge shape based on a slipline method need to receive. This method is notable for its informativity and allows to consider a two-dimensional plastic deformation.

3 Theoretical investigation

Design diagram of one-half of deformation zone (Fig. 1) used in this case is shown in Fig. 2.

Besides, designing the field of features in the physical plane (Fig. 2a) and, at the same time, in the plane of hodograph (Fig. 2b) was carried out by means of numerical determination of geometric coordinates of total sum of singular points A, B, C, D, E towards the axes x, y, which derive from the wedge-edge of the knife.

Having designated the depth of knife indentation as H, geometric ratio determining coordinates of auxiliary points N and K belonging to the initial workpiece surface was put down:

$$x_N = H \cdot \text{tg}\alpha; \quad y_N = H \tag{1}$$

$$x_K = 0; \quad y_K = H, \tag{2}$$

where α is the semi-angle by the apex of the double-sided wedge.

Taking this into consideration, the area of the triangle ENK, which defines the volume of displaced metal, can be determined as:

$$A_{ENK} = x_N \cdot \frac{y_K}{2} = \frac{H^2 \cdot \text{tg}\alpha}{2}. \tag{3}$$

Having set the segment length NA beforehand, geometric coordinates of the singular point A were determined:

$$x_A = x_N + L_{NA} \cdot \sin\alpha, \, y_A = y_N + L_{NA} \cdot \cos\alpha. \tag{4}$$

Having accepted the surface of displaced metal AB as rectilinear and taking into account the fact that the height of the triangle BAN is $(y_A - y_N)$ and its area should correspond to the area of the triangle EKN, the length of the segment NB was determined:

$$L_{NB} = \frac{2 \cdot A_{ENK}}{(y_A - y_N)} \tag{5}$$

At the same time, geometric coordinates of the point B were determined:

$$x_B = x_N + L_{NB}, \quad y_B = H \tag{6}$$

According to the slip-line features, the angle characteristics of 45° right triangle BAC are $\angle BCA = \frac{\pi}{2}$, $\angle CBA = \angle CAB = \frac{\pi}{4}$, and hypotenuse length BA corresponds to the equality:

$$L_{BA} = \sqrt{(x_B - x_A)^2 + (y_A - y_B)^2} \tag{7}$$

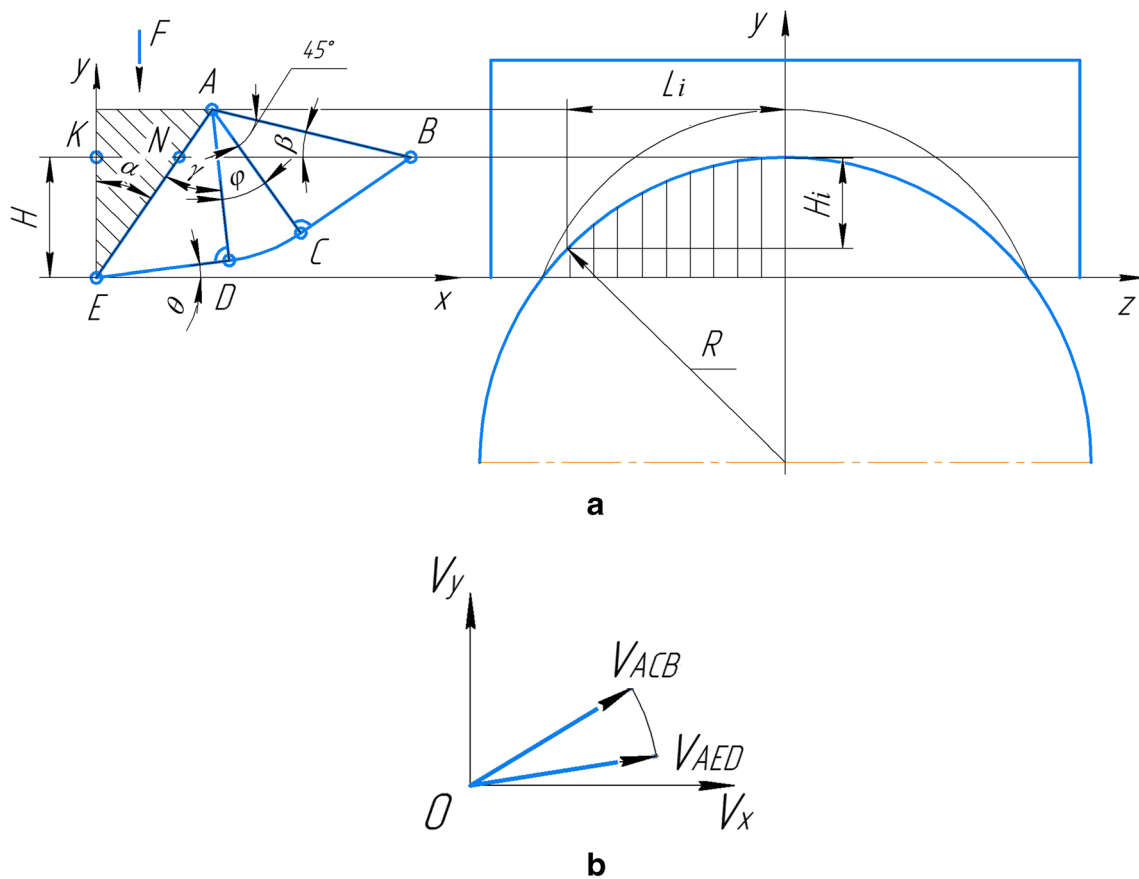Then, the lengths of the sides CB and CA may be represented as:

Fig. 2 Design diagram of slip-line fields by indentation of solid double-sided wedge knife into rolled stock

$$L_{CB} = L_{CA} = \frac{L_{BA}}{\sqrt{2}}. \tag{8}$$

Hence, the hypotenuse approach angle BA to the horizontal equals to:

$$\beta = \text{arctg} \frac{(y_A - y_B)}{(x_B - x_A)} \tag{9}$$

Geometric coordinates of the singular point C will be:

$$x_C = x_B - L_{CB} \cdot \cos \left[\frac{\pi}{4} - \text{arctg} \left(\frac{y_A - y_B}{x_B - x_A} \right) \right];$$
$$y_C = y_B - L_{CB} \cdot \sin \left[\frac{\pi}{4} - \text{arctg} \left(\frac{y_A - y_B}{x_B - x_A} \right) \right]. \tag{10}$$

In the most common case, the field of characteristics in the physical plane, by solid wedge knife indentation (Fig. 2a), represents the solution of the fourth boundary value problem of the statically determined plane metal flow, which is characterized by the presence of the singular point A, where characteristics CA and DA form a centered semicircle with the angle ϕ. Taking into account $L_{DA} = L_{CA}$, and declivity angle of the characteristic DA towards the vertical equals $(\gamma - \alpha)$, where $\gamma = 0, 5 \cdot \arccos(\tau/K)$ is the approach angle of the characteristic DA to the contact surface

of the deforming tool, which is determined by the ratio of the tangential contact stress τ and the deformed metal resistance to the shift K, geometric coordinates of the singular point D will be:

$$x_D = x_A + L_{DA} \cdot \sin(\gamma - \alpha); \quad y_D = y_A - L_{DA} \cdot \cos(\gamma - \alpha) \tag{11}$$

At last, having expressed the cathetus length $L_{DE} = L_{DA} \cdot \text{tg}\gamma$ from the right triangle ADE and having determined its hypotenuse approach angle to the horizontal $\Theta = \frac{\pi}{2} - \alpha - \left(\frac{\pi}{2} - \gamma \right) = (\gamma - \alpha)$, calculating coordinates (i.e., corresponding to the given value of the segment length L_{NA}) of the singular point E may be represented as equality:

$$x_{E_{cal}} = x_D - L_{DE} \cdot \cos(\gamma - \alpha); \quad y_{E_{cal}} = y_D - L_{DE} \cdot \sin(\gamma - \alpha), \tag{12}$$

where the calculating values $x_{E_{cal}}$, $y_{E_{cal}}$, according to the approved design diagram (Fig. 2a) should correspond to the origin of coordinates, i.e., should equal 0.

Fulfillment of the given condition in turn may be provided on the basis of organization of additional iterative procedure for determining the required segment length NA using the method of purposeful search:

$$L_{NA}(k + 1) = L_{NA} \cdot k + A_L \cdot \text{sign} Y_{E_{cal}} \cdot k, \tag{13}$$

where k is an ordinal number of the next cycle of iterative procedure of the solution, A_L is a change step of the segment length NA, and $\mathrm{sign}Y_{E_{cal}}$ is a sign function, corresponding to the sign of calculating geometric coordinate of the point E.

By the fulfillment of the condition $Y_{E_{cal}} \cong 0$, a required load angle characteristic ϕ was determined as:

$$\phi = \mathrm{arctg}\left(\frac{x_C - x_A}{y_A - y_c}\right) - \mathrm{arctg}\left(\frac{x_D - x_A}{y_A - y_D}\right). \tag{14}$$

The mean stresses in the ADE zone and the pressure along the contact line AE are constant and equal to (Fig. 3):

$$\sigma_{ADE} = K \cdot (1 + 2 \cdot \phi);$$
$$\sigma_{AO} = 2 \cdot K \cdot (1 + \phi). \tag{15}$$

At the same time, normal tension σ_{xE}, σ_{yE} and modified up to 1 value width of force F_x, F_y, according to the slip-line features, are (Fig. 3):

$$\sigma_{xE} = \sigma_E - K \cdot \sin 2\Theta; \tag{16}$$

$$\sigma_{yE} = \sigma_E + K \cdot \sin 2\Theta; \tag{17}$$

$$F_x = \sigma_{xE} \cdot y_A - \tau \cdot x_A; \tag{18}$$

$$F_y = \sigma_{yE} \cdot x_A + \tau \cdot y_A, \tag{19}$$

where $K = \frac{\sigma_1 - \sigma_3}{2}$ is the shear yield stress according to Tresca yield criterion and $\mu = \frac{\tau}{2 \cdot K}$ is the coefficient of plastic friction.

With a glance at the symmetry of loading conditions, the total force of wedge upsetting if there is a square or rectangular workpiece with the width b and i time point of depth H_i will be:

$$F_i = 2F_{yi} \cdot b. \tag{20}$$

In case of circular cross-section workpiece, the pattern is changing and requires additional numerical solution by means of division into elementary width sections, i.e., along axis z.
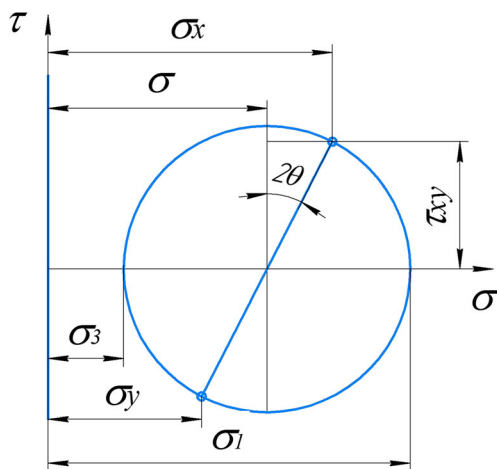

Fig. 3 Mohr circle

At the same time, similar to the deformation center of the rolling process, the half-width of the indentation area L_i into the i time moment, i.e., by the known indentation depth in the middle of the workpiece H_{ci}, may be determined from the statement (Fig. 2a):

$$L_i^2 = R^2 - (R - H_{ci})^2 = 2RH_{ci} - H_{ci}^2, \tag{21}$$

whence

$$L_i = \sqrt{2RH_{ci} - H_{ci}^2} \tag{22}$$

With a glance at the known value L_i and the given value of subdivisions quantity KRj, subdivision step will equal to $\Delta z_i = \frac{L_i}{KRj}$, and coordinate of each certain j of the value towards the axis z, which derives in the workpiece center, will equal to:

$$z_{ij} = \Delta z_i \cdot j \tag{23}$$

Indentation depth in j section H_{ij} will correspond to:

$$H_{ij} = R - \sqrt{R^2 - z_{ij}^2} \tag{24}$$

Depending on this and according to the algorithm examined above, the force F_{ij} can be determined, and the total value of the indentation force will be:

$$F_i = 2\left[F_{ci} \cdot \Delta z_i + \sum_{j=2}^{KRj-2} \frac{F_{ij} + F_{i(j-1)}}{2} \Delta z_i + F_{i(KRj-1)} \cdot \frac{\Delta z_i}{2}\right], \tag{25}$$

where F_{ci} is the indentation force for the average cross-section corresponding to the depth H_{ci}.

Mathematical models for indentation of the tools of other forms, the cone and the pyramid, were additionally designed similarly to the given one.

4 Experimental investigation

To evaluate adequacy of the proposed mathematical models and values of the energy-power parameters, necessary for application of the effective stress concentrator, experimental study of the indentation of wedge tool of various shapes into rolled stock was carried out.

For conducting the experiment, the equipment has been designed. Its construction is shown in Fig. 3. It consists of the frame (1), the slider (2), which is set on the frame and though reciprocating motion is possible, and the wedge (3) which is fixed inside. Sample (4), which is placed on the support (5), is in the grooves of the frame. Pressure capsule (6) is placed in the recess hole of the slider (2). Sliding

Table 1 Mechanical properties of the samples materials

Grade	σ_Y (MPa)	σ_T (MPa)	HB	$\delta\%$	$\gamma\%$
C20	287	471	131	30	63
AlCuMg1	264	392	129	10	16

member (8) is rigidly fixed to the pressure capsule by means of the lever (7); reciprocating motion is possible along the guide (9) of the resistor (10) with the wire diameter of 0.08 mm.

Cylindrical samples with diameter of 16 mm were used during the experiment. Mechanical properties of the samples are shown in the Table 1.

Data concerning the tool form and dimensions are given in the Table 2.

Foil resistance strain gauges, included according to the bridge circuit, were used during the experiment. Pressure capsule gauging was carried out on hydraulic press by static loading at the operating range up to 30 кN. PC with the special module SDI-ADC16-32 was used as the recording system, which allows to measure 16 differential channels with galvanic separation from computer electric circuits.

Two parallel channels for designing dependence (force F and H stroke) were used during the experiment. Input signal was digitized by 16-bit AD converter with the frequency up to 100 kHz and amplification possibility in the range 1–1000. Registration and measurement of the results processing were done by means of developed software.

Sampling of comparative data of the experiment outcome and theoretical calculations, which were done according to the known mathematical models, is represented as curves $F = f(H)$ (Fig. 4).

Calculation analysis shows the results divergence between theoretical calculations and experimental data to be in average 5–10% for the different materials when indentation using tools of different form. The error is related to the fact that material hardening in the process of deformation is not taken into account in mathematical model.

Calculations allow to evaluate the work value necessary for stress concentrator application and workpiece separation, e.g., for steel C20 samples.
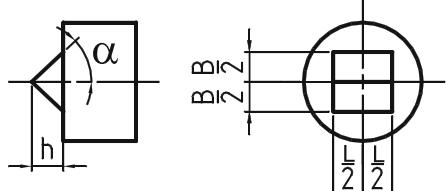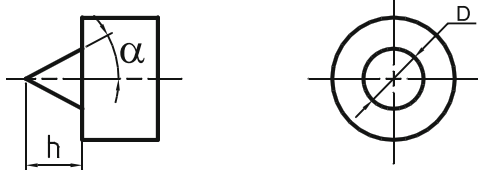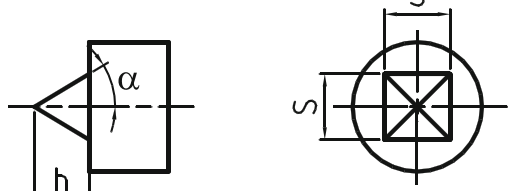
Maximum value of plastic deformation and decrease of impact ductility are provided by triangular cut. Therefore, such shape was taken as the basis.

5 Discussion of obtained results

Analysis of performed calculations shows that the results divergence between theoretical calculations and experimental data is on average 5–10% for samples from different materials by indentation of the tools with different shape.
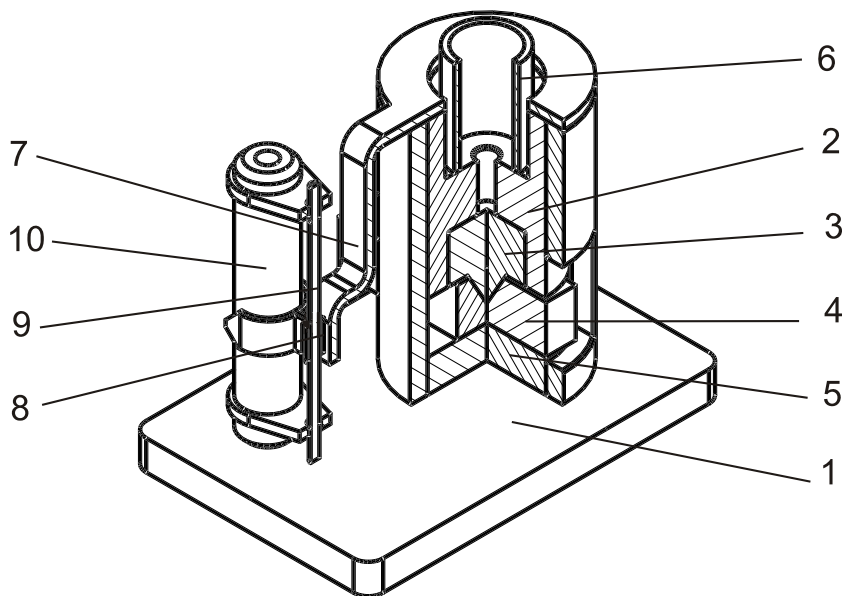
Values of the force, obtained by calculation way, were less than forces, measured during experiment when the tools with a cone (Fig. 5a) and a wedge (Fig. 5c) were indented into the workpieces (steel C20). This can be explained by the fact that

Table 2 Form and dimensions of the wedge-shaped knife

Form	Draft	Dimensions, mm
Wedge		$h = 7\,mm$; $\alpha = 43°$; $B = 13\,mm$; $L = 13\,mm$
Cone		$h = 12\,mm$; $\alpha = 28°$; $D = 13\,mm$
Pyramid		$h = 11\,mm$; $\alpha = 31°$; $S = 13\,mm$

Fig. 4 Construction scheme of the experimental equipment

the mathematical model does not take into account the hardening of the material during cold plastic deformation.

The calculated values of the indentation force were higher than the data obtained experimentally (Fig. 5b) when the tool with a pyramid shape was indented into the workpieces (alloy AlCuMg1). This is due to the fact that it is necessary more accurately to take into account the value of the friction coefficient.

Mathematical models of the tool indentation for various shapes, wedge, cone, and pyramid, are implemented using the slip-line field method. Experimental studies of the indentation of wedge-shaped tools for various shapes into the rolled stock were carried out under static loading. The obtained data can help to predict the results of the stress concentrator formation with the use of the energy in the press due to the elastic deformation of the frame and drive. The magnitude of the work required to form the stress concentrator was evaluated for samples of steel C20.

The decrease of toughness is ensured a notch with a triangular shape, as has been confirmed in work [4]. Therefore, this concentrator's shape is accepted as a basis. Method of the breaking by bending leads to cracking from sharp of the stress concentrator to opposite side of the workpiece. Therefore, the stress concentrator, formatted around the entire perimeter of the destroyed section, does not have special advantages over one-sided.

Taking into account the recommendations on the dependence of the depth of the stress concentrator (10–20%) of the size of the workpiece cross-section, the value of the effective stress concentrator was $H = 3$ mm.

Thus, in accordance with the schedule (Fig. 5c), the work of the formation in a stress concentrator to a sample with diameter equal to 16 mm is 54 J. It is a good result from the point of view of practical realization of technology and

equipment using energy accumulated in the press due to elastic deformation of the frame and drive.
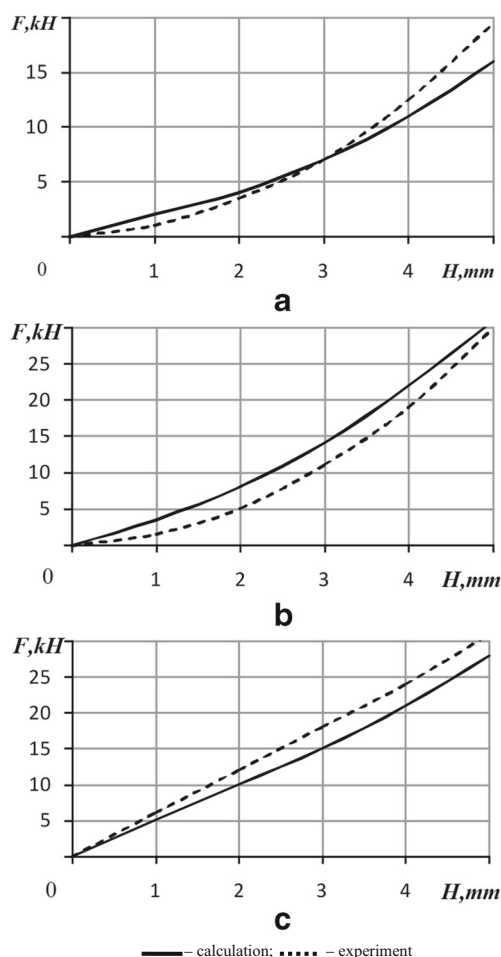
Fig. 5 Curve change of the implementation forces after the tool stroke $F = f(H)$ by inserting cone into steel sample C20 (**a**), pyramid into alloy AlCuMg1 (**b**), and wedge into steel sample C20 (**c**)

6 Conclusions

1. The equipment for breaking high-quality rolled stocks by bending has been developed. The advantage of the proposed design is that the energy accumulated in the press due to the elastic deformation of the frame and the drive is spent on useful work—formation of the stress concentrator for breaking by bending of the next workpiece. Thus, in one cycle of the equipment work are combined two operations, breaking by bending and formation of the stress concentrator in the separation plane of the next workpiece, which increases the productivity of the process. The equipment works in dynamic mode and provides an increase velocity formation of the stress concentrator, which improves the quality of separated workpieces.

2. Mathematical models of the indentation process of a wedge tool of various shapes have been developed. Dependencies for calculating of the energy-power parameters for formation process of the stress concentrator have been established. Mathematical models consider the effect of free surface taking into account the volume of the displaced metal.

3. Conducted experimental studies on the indentation of wedge-shaped tools of various shapes into the sample confirmed the adequacy of the proposed mathematical models. The calculation error within 5–10% is explained by necessary of more correct choice of the value of the friction coefficients.

4. By indentation of tool in the form of a cone (Fig. 5a) and a wedge (Fig. 5c), the force obtained by calculation was expected to be less than the force measured during the experiment. This can be explained by the fact that the mathematical model does not take into account the hardening of the material in the area of deformation. By embedding the pyramid in a sample made of AlCuMg 16 alloy (Fig. 5b), the calculated values of the embedding force were higher than the values obtained experimentally, that is due to the need to more accurately account for the value of the coefficient of friction.

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