MACHINE BUILDING AND MACHINE SCIENCE
МАШИНОСТРОЕНИЕ И МАШИНОВЕДЕНИЕ

УДК 621.771.014 https://doi.org/10.23947/1992-5980-2018-18-3-289-299

Experimental study on power parameters of "rolling - ECA-pressing" combined process*

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Экспериментальное исследование энергосиловых параметров совмещенного процесса «прокатка — равноканальное угловое прессование»***

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Introduction. Power parameters of the "rolling − equal-channel angular pressing" (ECA) combined process are studied. The work objective is to determine forces of rolling and pressing in the deformation by the combined method.

Materials and Methods. The die strength calculation and the experiment on deformation of AISI 6063 aluminum samples were carried out. During the experiment, the force values were recorded using a strain-gauge station.

Research Results. The strength analysis results show that this die design is suitable for creating an experimental stand of the "rolling − ECA-pressing" combined process, since the calculated safety margin is sufficient to implement the pressing under extreme conditions. The rolling forces at all stages of the deformation exceed the corresponding pressing forces, which is a necessary condition for the combined process.

Discussion and Conclusions. The obtained results can be used in the design of experimental stands that implement the investigated combined process. Herewith, the given strain-gauge method for studying strength characteristics is suitable for the case of calibrated rolls.

Keywords: combined process, rolling, equal channel angular pressing, force, strength analysis, tensometry.

Введение. Статья посвящена исследованию энергосиловых параметров совмещенного процесса «прокатка — равноканальное угловое прессование (РКУ)». Цель работы — определение возникающих усилий прокатки и прессования при деформировании совмещенным способом.

Материалы и методы. Был проведен прочностной расчет матрицы и эксперимент по деформированию образцов из алюминия марки AISI 6063. В ходе опытов значения усилий фиксировались с помощью тензометрической станции.

Результаты исследования. Результаты прочностного анализа позволяют утверждать, что данная конструкция матрицы пригодна для создания экспериментальной установки совмещенного процесса «прокатка — РКУ-прессование», поскольку рассчитанного запаса прочности вполне достаточно для реализации прессования на предельных условиях. Усилия прокатки на всех этапах деформирования превышают соответствующие усилия прессования, что является необходимым условием совмещенного процесса.

Обсуждение и заключения. Полученные результаты могут быть использованы при проектировании экспериментальных установок, реализующих исследуемый совмещенный процесс. При этом тензометрический метод исследования прочностных характеристик пригоден и при использовании калиброванных валков.

Ключевые слова: совмещенный процесс, прокатка, равноканальное угловое прессование, усилие, прочностной анализ, тензометрия.

* The research is done within the frame of the independent R&D.
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*** Работа выполнена в рамках инициативной НИР.

For citation: A.B. Naizabekov, et al. Experimental study on power parameters of "rolling - ECA-pressing" combined process. Vestnik of DSTU, 2018, vol. 18, no.3, pp. 289–299. https://doi.org/10.23947/1992-5980-2018-18-3-289-299

Образец для цитирования: Экспериментальное исследование энергосиловых параметров совмещенного процесса «прокатка – равноканальное угловое прессование» / А. Б. Найзабеков [и др.] // Вестник Дон. гос. техн. ун-та. — 2018. — Т. 18, № 3. — С. 289–299. https://doi.org/10.23947/1992-5980-2018-18-3-289-299

Introduction. Improvement of the deformable metal quality is one of the major tasks when creating a new metal forming process (MFP) or improving the known one. No matter which type (rolling or blacksmithing) the process belongs to, it is recommended to apply a deformation scheme implementing a pure shear. In this case, a minimum amount of energy is expended on the metal deformation; maximum and uniform workpiece processing through the section is performed; and internal defects are closed.

Over the past two decades, forming techniques have been actively developed. They enable to obtain ultrafine-textured blanks. Their analysis shows that they are based on the principles of implementation of shear or alternating deformations. Processes that are a combination of these principles are worthy of special mention. These processes allow for the implementation of an unconventional forming operation which is called "severe plastic deformation" (SPD). SPD implements such methods as torsion under high pressure [1-3], equal-channel angular (ECA) pressing [4-8], screw extrusion [9-12] and others. Special attention should be given to an echelon ECA-die (or ECA-die with parallel channels) [13-14]. It enables to realize a shear deformation when the workpiece passes through its channels and concurrently two alternating deformation zones, provided that the input and output channels are codirectional. In comparison with the usual angular die, the echelon ECA-die is energy-saving, since it allows for implementing a greater degree of deformation in one pass with the equal force.

The MFP methods discussed above belong to the discrete press forming techniques. These technologies for the molded articles production have a number of shortcomings. The principle ones are due to:

- press operation discreteness (discontinuity);
- occurrence of reactive frictional forces on the metal-to-container contact.

Thus, due to uneven deformation and high energy intensity of the press operation, the length of the pressed products is limited, and their quality is reduced. The application of the continuous pressing scheme enables to eliminate these drawbacks. This method differs fundamentally from the previous ones in that active friction forces are used to deform and extrude the workpiece through the die hole. The length of the workpiece is thus not limited.

In recent years, the so-called "combined" MFP processes, which are a combination of two or more deformation processes, are being developed.

Crucially, the most important feature of the combined MFP process is that shortcomings of the components of individual processes are often reduced or completely eliminated under its implementation.

Besides, more and more attention has been recently paid to the energy-saving technologies based on the use of active friction forces for deformation.

The authors of the study have developed a combined technique of rolling and pressing in an equal-channel echelon die, which, in comparison to the conventional pressing in an equal-channel echelon die, removes the limitations on the dimensions of the initial blanks [15]. It seems to be one of the most advanced and understudied on the practical level rolling and pressing processes, and it in many ways surpasses the known forming methods. The principle of this straining method is as follows. The workpiece, pre-heated up to the temperature of the deformation onset, is fed to the cast rolls. The first pair of rolls, due to the contact friction forces, bites the workpiece and pushes it on exit through the channels of an equal-channel echelon die. After the workpiece completely leaves the die channels, it is bitten by the second pair of rolls, which completely pull the workpiece out of the die also by contact friction forces. Thus, in this case, pressing the workpieces is provided by the friction contact forces that arise on the surface of the metal-to-rotating rollers contact. Previously, various studies of this combined process have been carried out – both theoretical [16-19] and laboratory ones (on a single-roll machine) [20-23].

This paper presents the results of the power analysis performed during the development of a pilot plant with two pairs of rolls (Fig. 1).

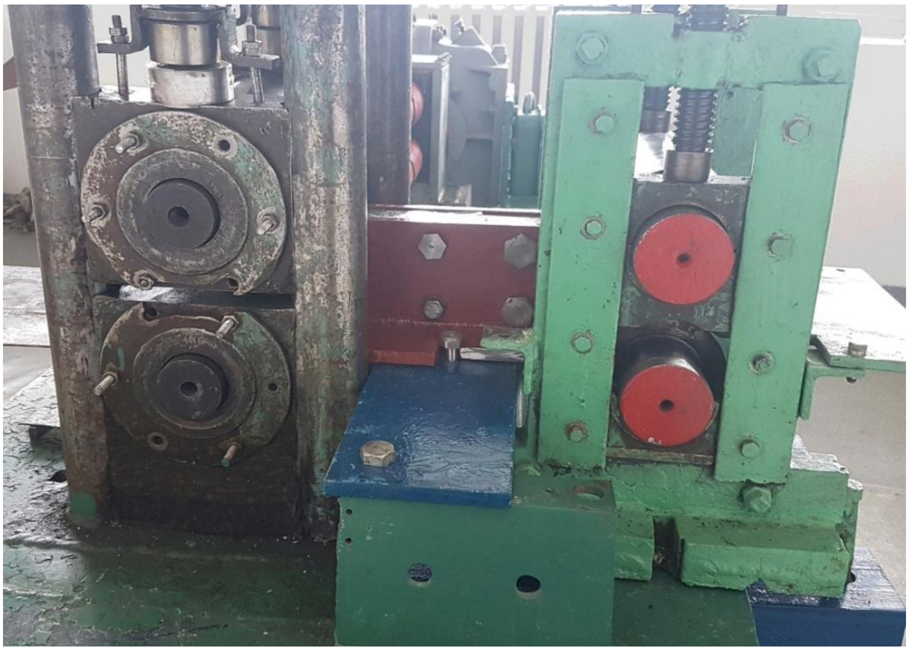


Fig. 1. Pilot plant for "rolling – ECA-pressing" combined process implementation

Strength analysis of the ECA-die. When implementing the combined process of the "rolling – ECA-pressing", a pilot plant created on the basis of the laboratory rolling mills DUO-200 and DUO-250 was used. Their power characteristics enable to cold-form aluminum and copper alloys.

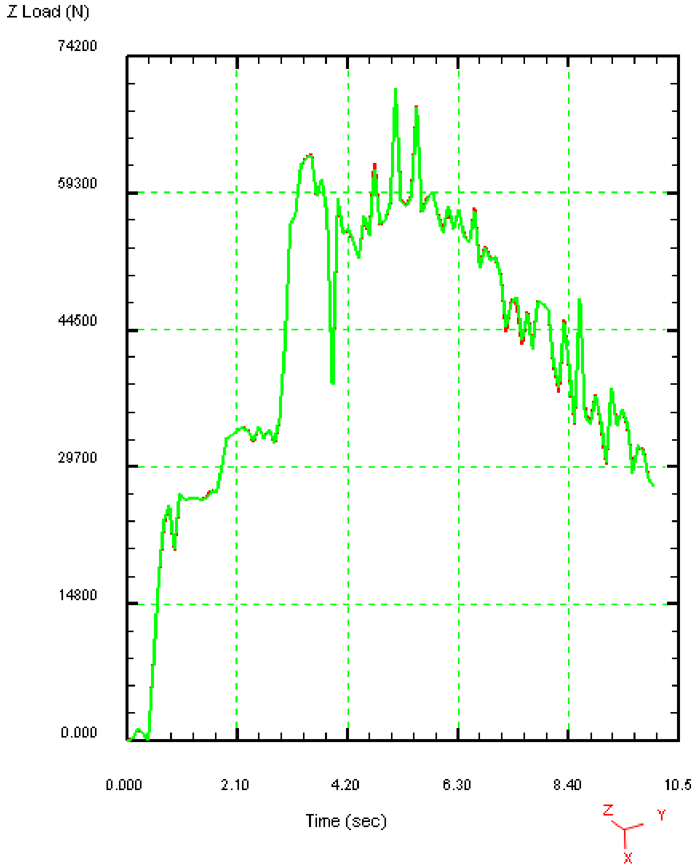
When designing a new technology of deformation at the pilot stage, strength analysis is essential. It enables to determine the tool durability and rigidity, and to estimate its strength margin which will give information on its service life. Theoretical studies of the "rolling – ECA-pressing" combined process were performed using computer simulation in the DEFORM program. As a result, it was established [17, 18] that the most loaded part is the pressing die. This is explained by the fact that the most rigid straining conditions occur in the joint mouth zone. Thuswise, a strength analysis was carried out to test the selected die design validity. For this purpose, a model of a joint die mouth with 150 degree angle represented in [20], was constructed.

When implementing the combined process, it is appropriate to select the workpiece width in such a way that under forming in the die, the metal does not contact with its sidewalls. This will significantly reduce the die total back force. However, one cannot completely exclude such a case. Thus, an ECA-pressing model, in which the workpiece height and width correspond to the height and width of the die mouth, was created in the DEFORM software. This case of deformation is limiting and is almost impracticable. Therefore, if the die is hard enough, it will be suited for a combined process, the conditions of which are much "softer". In particular, the workpiece height and width is somewhat less than the height and width of the die mouth, which is a necessary condition for the metal passage through the mouth.

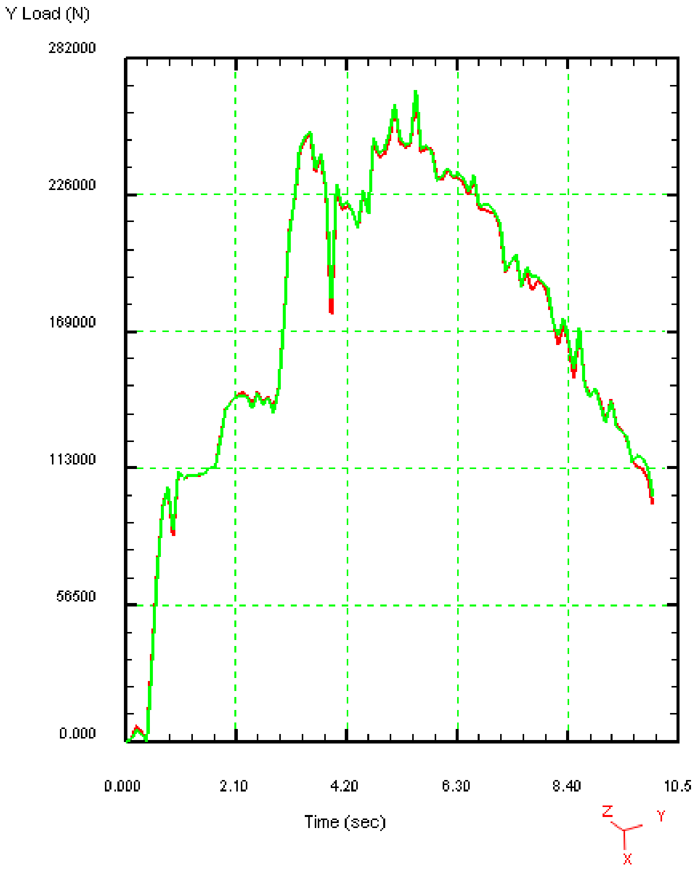
The initial blank dimensions are 10 × 40 × 90 mm. The conditions and assumptions used in modeling:

- initial material is isotropic, it does not have any stress or strain;
- workpiece is divided into 24,000 finite elements, average length of the element edge is 1.5 mm;
- initial temperature of the workpiece is 700 °C, besides, strain warming-up, and heat transfer from workpiece to tool and into the environment are considered;
- instrument is taken as an absolutely rigid body;
- dummy blank is taken as elastoplastic;
- workpiece material is AISI 1045, corresponding to steel 45;
- friction factor at the workpiece-die contact is 0.1;
- punch speed is 10 mm / sec.

As a result of the calculation, the deformation force on all die elements was determined to find the most strained structural members. The greatest forces occur in the direction of the normal stresses action (Fig. 2).



a)



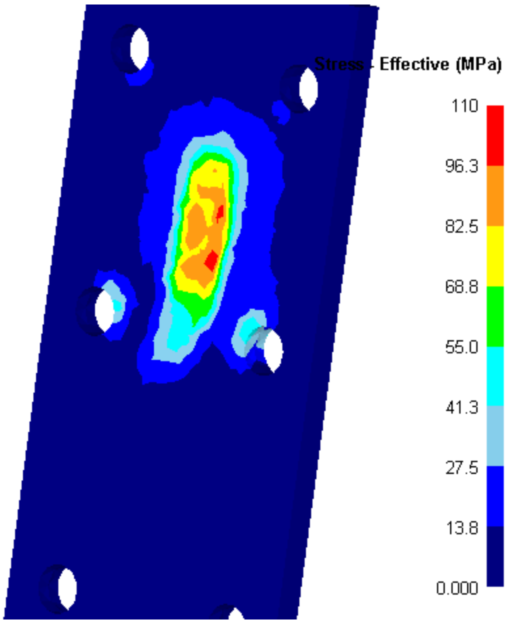
b)

Fig. 2. ECA-pressing force curves for sidewalls (*a*) and central segments (*b*)

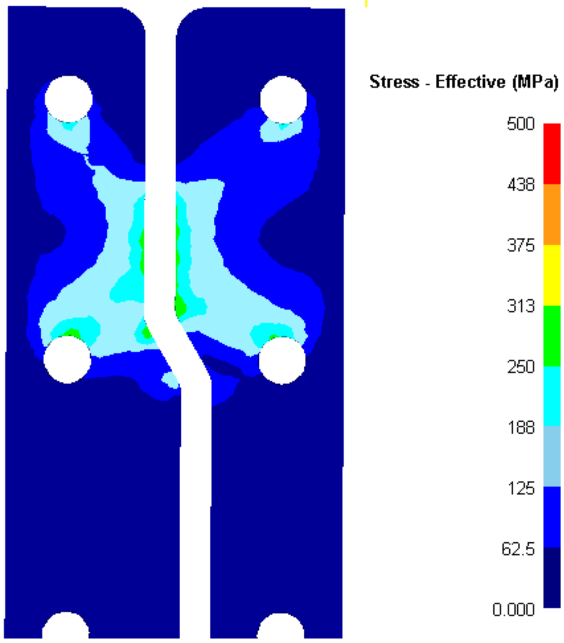
Fig. 2 shows that the most strained die elements are the central segments. At deformation, the force up to 260 kN occurs on them, while it does not exceed 75 kN on the sidewalls. Based on these data, the stress analysis of the tool was carried out in the DEFORM program using a dedicated module. This analysis approach implies that absolutely rigid model elements become elastic bodies taking stress. Interpolation of operating forces on the tool is carried out from the workpiece. Then, fixation points are defined so that the elastic bodies do not scatter under the action of forces. In our case, the fixation points are ring openings for holding elements. In addition, in this calculation, it is required to specify the tool material. 5XB2C instrument steel was used to make the die. It is used for manufacturing:

- complex dies operating with high impact loads,
- knives for cold metal cutting,
- thread-rolling dies,
- punches and swaging dies for cold operation.

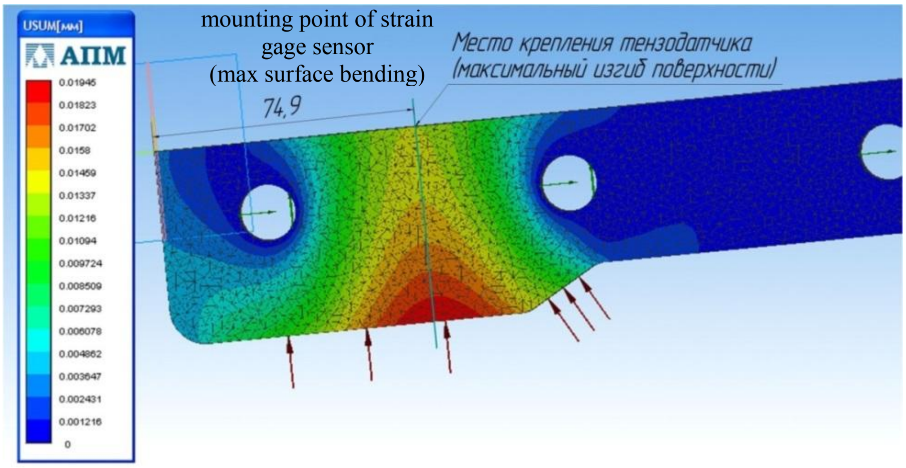
As a result, the following data were obtained (Fig. 3).



a)



b)



c)

Fig. 3. Strength analysis results: stress on sidewalls (*a*); tension in central segments (*b*); linear displacement (*c*)

Fig. 3 shows that the most loaded zones in the central segments are surface areas near the die mouth joints and arc zones around the first two pairs of openings. Here, voltage up to 250 MPa occurs.

In the areas between openings, the voltage is within 125 ÷ 150 MPa (see Fig. 3, *a*).

On the sidewalls, peak voltage occurs in the contact zone with the deformable metal, and it is equal to 95 ÷ 100 MPa (see Fig. 3, *b*).

The results of calculating the linear displacements of structural elements under the action of elastic deformation were considered [24] in the specialized calculation APM library to study the structure rigidity. The investigation of elastic deformation shows its greatest value in the surface region near the die mouth joints. Two facts should be mentioned. The first: operating stresses on all die elements are much lower than the 5ХВ2С steel yield limit. The second: peak value of linear displacement reaches 0.019 mm (Fig. 3, c), which is negligible and allows us to speak about the increased rigidity of the proposed structure. In light of this, we can conclude that this matrix design is suitable for creating a pilot plant of the "rolling – ECA-pressing" combined process, since the estimated safety margin is sufficient for ECA-pressing implementation under extreme conditions.

Laboratory experiments to study forcing. As a result of the strength analysis, the location of the strain gage sensors in the matrix was determined for measuring the deformation force. The mounting spots are at a distance of 75 mm from the leading edge of the central segment where peak linear displacements occur.

The following equipment was used to measure the emerging deformation forces:

- ZET-017-T8 strain-gauge station ("ETSM" CJSC, Russia);
- force sensors with TKFO1-2-200 strain gages ("ETSM" CJSC, Russia);
- laptop computer to control the strain gage and to record the signal.

The strain-gauge station manufactured by "ETSM" CJSC (Moscow) is designed to measure power and other parameters on several channels with a time resolution of writeenable up to 20 kHz [25].

On investigating the power parameters of the "rolling – ECA-pressing" combined process, it is planned to study the deformation forces at the stages of rolling and molding in dies. This calls for installation of strain gauges on the die and on the measuring cells of the roll mill. The principle of tensometry is that during the deformation process, the rolling and pressing forces affect the rolls and the die. As a result, the rolls and the die are bent. Strain gages attached to the die and measuring cells are deformed along with them. Their electrical resistance value changes. The strain-gauge station records this variation and, according with the results of the predetermined calibration of the sensors, converts it automatically into the force pattern.

For the predetermined calibration of the strain gages, the die central segment and measuring cell were tested by compression on the MI-40KU hydraulic torsion-tensile machine. Usage of a torsion-stretching machine enables to develop considerable forces (35-40 kN). Herewith, their values are fixed accurately and reliably. The change in the onloading stress-strain state causes deformation and a linear resistance variation of the strain gages. The principle of calibration is in the construction of the circuit electrical voltage – applied force relationship. This dependence always has a strictly linear character.

To perform the calibration, the elements under study were sequentially loaded in increments of 5 kN in the zero – 35 kN range. The corresponding values of the circuit voltage on-load and after unloading were fixed. In order to increase the accuracy, three passes were performed over the specified range – up-down-up (42 measurements). As a result, for each element, the "force – displacement" relationship was obtained ("displacement" corresponds to the value of the upper striker travel). The calibration test data were statistically processed, and the linear regression equations that connect the force applied to the tool (P_i, H) and the voltage (U_i, mV) in the circuit were obtained from them.

The equation for measuring the rolling force is as follows:

$$P_i = -4852{,}7U_i + 23538.$$

The coefficient of determination R^2 = 0.998. The standard measurement error based on the results of 42 tests was less than 0.2%.

The equation for measuring the pressing force is as follows:

$$P_i = -4120{,}2U_i + 21609.$$

The determination factor R^2= 0,997. The standard measurement error based on the results of 42 tests was less than 0.3%.

The data obtained were entered on the program of registration and processing of measurements of the ZET-017-T8 strain-gauge station. This enabled to record the signal as a schedule of effort.

After the calibration operations, the die with the strain gage was placed on the pilot plant (Fig. 4).

Fig. 4. Force measurement under "rolling – ECA-pressing" combined process"

Here, on the measuring cells of the first stand, strain gages were also installed to measure the rolling force which was performed only on the first stand. This is a key parameter according to the process concept. When implementing the combined process, the rolling force should exceed the resulting pressing force.

The basic material used was 6063aluminum alloy (analog of AD31aluminum deformable alloy) at room temperature. Its chemistry and mechanical behavior are given in Table 1.

Table 1

Chemistry and mechanical characteristics of 6063aluminum alloy

Weight content of elements, %								
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other
0.2–0.6	0.35	0.1	0.1	0.45–0.9	0.1	0.1	0.1	0.15

Mechanical properties at 20 °C			
Tensile stress, MPa	Yield stress, MPa	Hardness, HB	Stretching, %
90	48	25	20

Blanks of equal size (15 × 25 × 450 mm) were rolled with the thickness of 9 mm in the first stand. In the second stand, the roller gap was 7 mm. The blank length was selected so that its lead end was bit by the second pair of rolls, whereas the back end was being still rolled in the first stand (Fig. 5).

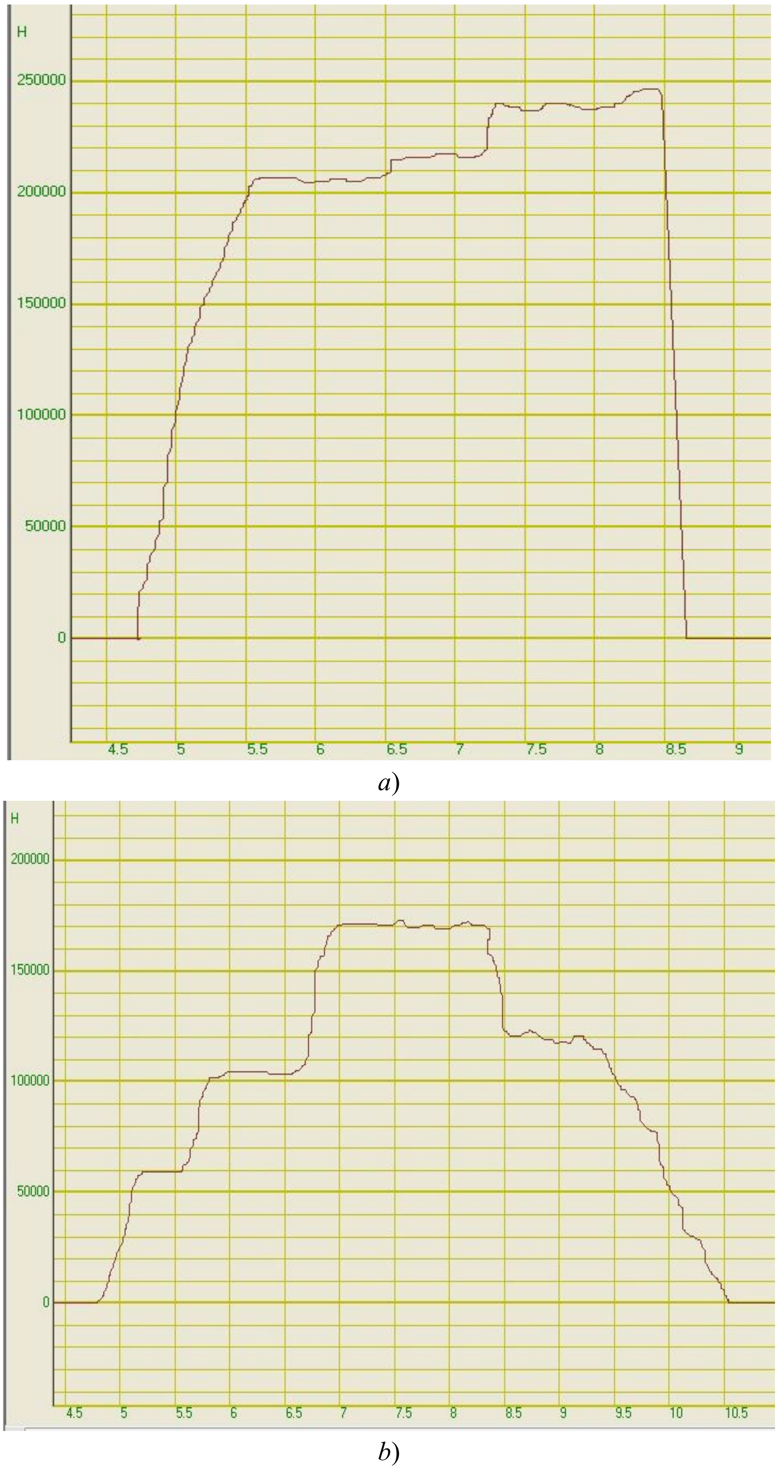


Fig. 5. Force variation under deformation of 6063aluminum alloy: rolling in the first stand (*a*); pressing in the die (*b*)

The force measurement data are presented in Table 2.

Table 2

Force measurement results

	1st stage	2nd stage	3rd stage
Rolling step, kN	205	217	242
Pressing step, kN	59	104	172
Difference (friction margin), %	247	108	40

The difference between the values of the rolling and pressing forces was also determined. In this case, this difference characterizes the level of active friction force margin:

$$\Delta = (\frac{P_{ПРОК}}{P_{ПРЕСС}} - 1) \cdot 100\% ,$$

where $P_{ПРОК}$ is rolling force in the first stand; $P_{ПРЕСС}$ is back force in the die.

A comparative analysis of the values of the arising forces has shown that the rolling forces at all three stages exceed the values of the corresponding pressing forces. Thus, the necessary condition for implementing the combined process is satisfied. Herewith, the active friction forces margin in the first stand with the advancing of the blank along the die mouths reduces dramatically.

Conclusions. The study results indicate that the die strength margin is quite sufficient for the ECA-pressing implementation under the limiting conditions. It should also be mentioned that the rolling forces at all stages of deformation exceed the pressing forces, and thus, the necessary condition for implementing the combined process is satisfied. At this, the active friction forces margin in the first stand with the advancing of the blank along the die mouths reduces dramatically.

The results obtained can be used for designing the experimental facilities that implement the combined process of interest. The stain-gauge analysis of strength characteristics is also suitable for the calibrated rolls.

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Received 09.02 .2018
Submitted 10.02.2018
Scheduled in the issue 21.06.2018

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