UDC 621.73

Experimental research of distribution of strains and stresses in work-piece at different modes of stretch-forging with rotation in combined dies

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Abstract
The characteristics of the stress-strain state in work-pieces are investigated by the experimental method of coordinate grid during new intensive modes of a stretch-forging in combined dies. Lows of influences of modes with the fixed reduction at increase of angle of rotation at common aggravation of compressing of metal layers in a cross-section have been detected. The modes of stretch-forging with the fixed angles of rotation and increasing of reduction leads to the growth of intensity of a strain on a cross-section with the best compressing of metal layers of a medial zone.

Keywords: FORGING OF SHAFTS, STRETCH-FORGING, COMBINED DIES, COORDINATE GRID, STRESS-STRAIN STATE, COMPACTING WORK OF METAL LAYERS

Introduction

Increasing of the longitudinal size of the work-piece at stretch-forging is produced by compression of its cross-section by different working tools: flat die, convex die, cut-out die, combined dies. The calibers of the traditional cut-out and combined dies for forging of shafts with round cross-sectional have a rhombic or radius(round) profile. Currently there is an active development of innovative ways of forging, which can intensify the compacting work of internal layers of the ingot at low coefficients of total reduction of cross-section [1]. The bulk of these methods are sent to creation of macroshift of material of work-piece in the deformation zone by complication of form of dies for the intermediate forging and combining of tools. From this point of view an actual scientific and practice task is development of the energy-saving modes of deformation of work-pieces at stretch-forging with the use of the traditional combined dies due to realization of methods of intensive strains and achievement of high degree of compacting work of metal layers for providing of production of metal forgings shafts with the required operating properties.

Analysis of the last researches and literature

In the work [2] the process of forging of ingots by profiled dies with receiving of three-beam or four-beam billet is offered. The further stretch-forging with macroshifts from profiled work-piece is demands of tool change and is conducted of a cooling of metal of a semi-product. Technological realization of the method [3] assumes of forging of billet in the beginning by the flat dies and then it’s rotation in round of longitudinal axis in dies with round cut-out without increase in length of a shaft. The article [4] in which conditions of a change of the sizes of work-piece and an emergence of macroshifts are analysed is devoted to researching of a stretch-forging of ingots by profiled dies. It is obvious that achievement of positive influence of macroshifts effect on indicators of quality of forgings due to complication or increase in quantity of sets of the working tool is economically justified only during forging of ingots from the high-alloyed expensive brands of steel.

In the work [5] probes of modes of a stretch-forging of billets in the combined dies with a rotation of work-piece in round of longitudinal axis in relation to conditions of forge and press shop of the LLC “Metinvest – the Mariupol Mechanical-repair Plant” enterprise that organized on the basis of maintenance shops of PJSC "Iyich Iron and Steel Works of Mariupol" are begun. A stress-strain condition of shaft forgings during working was investigated by finite-element modeling. The development of scientifically reasonable recommendations about a choice of rational modes of forging by such tool demands of experimental research of influence of sizes of upset reduction and angles of rotation of billet round of longitudinal axis on compacting work of material of a forging-part and geometrical characteristics of a cross-section.

Object of research and statement of tasks

The aim of this research is experimental studying a stress-strain state at various modes of a stretch-forging of cylindrical billets with rotation in round a longitudinal axis in the combined dies.

For achievement of the specified aim the tasks are set: to develop the methodological approaches for definition of the strain condition of work-pieces in relation to processes of forging of shaft by a stretch-forging in the combined dies; to establish of influence of stretch-forging modes on distribution of strains and stresses in a cross-section of the zone of deformation of work-pieces; to determine the best values of upset reduction and angles of a rotation of work-piece round a longitudinal axis for achievement of high-quality compacting work of metal layers of billet by a cross-section in the deformation zone at stretch-forging.

Materials of research

The six samples with a diameter D_0 = 50 mm and length $L_0 = 100$ mm were made from antimonial lead (*CCy* brand) for performance of experimental research. The samples were made by pressing in the form of two halves of semicircular cross-section, and coordinate grid with a step s = 3 mm was put on the inner part of one of halves. The soldering by Wood's alloy was carried out (fig. 1, a) for receiving of continuous samples which marked on one of ends by signs "0", "1", "2", "3", "5", "8" (fig. 1, b), and the marking for the performance of rotation of work-piece a round of longitudinal axis on the fixed corners $\Delta\varphi$ = 30°, 60° и 90° was put at other end (fig. 1, c).

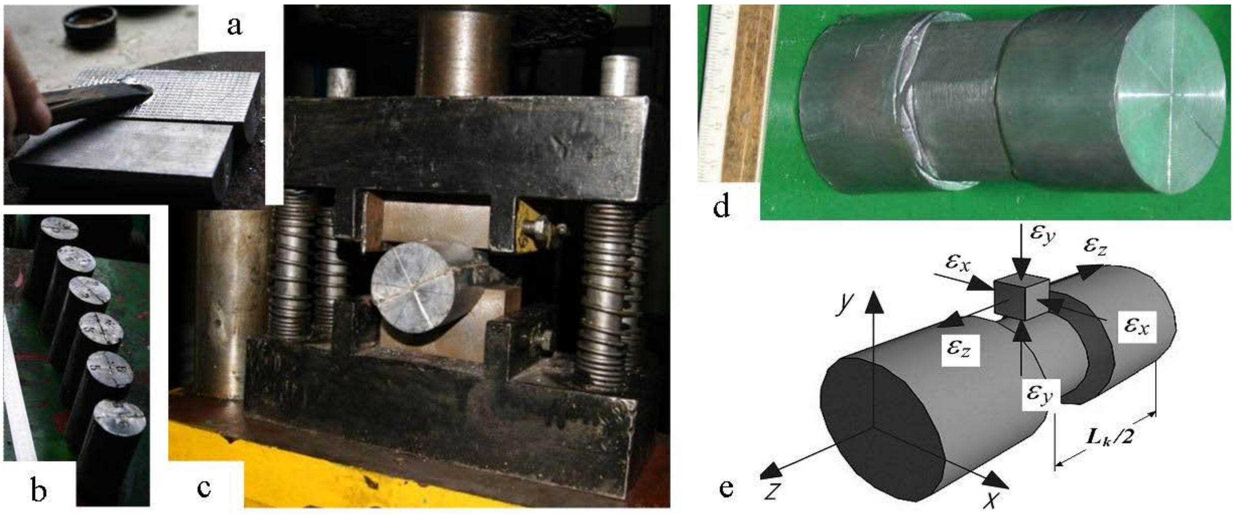
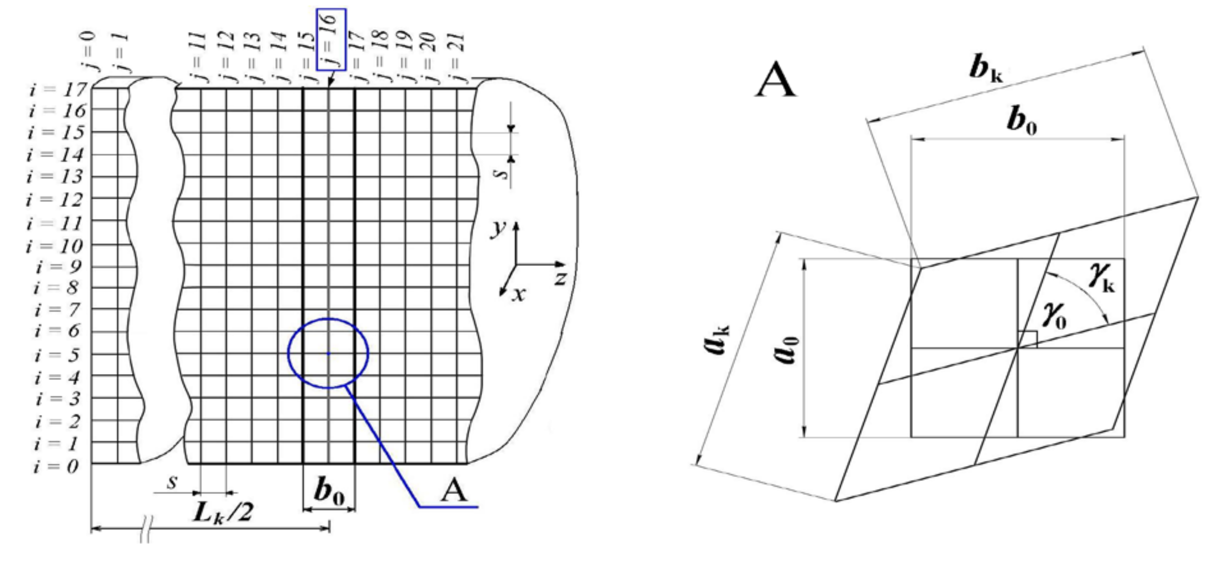


Figure 1 Preparation and forging of experimental samples: a – soldering by Wood's alloy of samples with coordinate grid;b – marking on the ends of soldered samples;c – forging of sample with marks in combined dies; d – sample after forging mode; e – mechanical scheme of strains

The model of cut-out anvils were made for laboratory experiments in scale 1:10 to the size of a productive nature: width B_m = 30 mm, the radius of the notch in the lower anvil R_m = 30 mm. The material of anvils is steel 45 (0.45% Carbon). These anvils were fixed in a stamp block (Fig. 1, c), mounted on a universal testing machine (0.2 MN), and carried out the deformation of lead samples (Fig. 1, d) with the entire width of the anvil in the middle of the length of the work-piece (which corresponds to the amount of feed ΔL = 30 mm, the relative feed rate $\psi = \Delta L / B_m$ = 1.0). So, the influence of hard and not deformed ends at modes of stretch-forgings was also taken into account (Fig. 1, d and e), which receives the stretch in the longitudinal direction due to making compressions (Fig. 1, e). In real conditions it is necessary to remove the work-piece along the front of feed with relative feed $\psi \le 1.0$ and hold running along the diameter, having the given values of upsetting and angles of rotation for the implementation of the next step of stretch forging.

The samples were divided into two groups to study the effect of influence of stretch forging modes on the controlled indicators, each of which was assigned rotation angle $\Delta\varphi$, value of reduction (upsetting) Δd and quantity of reduction till to full rotation of the work-piece to 360°. In the first group of samples ("0", "1" , "2") varying of the rotation angle φ was performed at a fixed value of reduction Δd = 5 mm: a sample "0" – $\Delta\varphi$ = 30°, n = 12; a sample "1" – $\Delta\varphi$ = 60°, n = 6; a sample "2" – $\Delta\varphi$ = 90°, n = 4. In the second group of samples ("3", "5", "8") varying with the value of reduction Δd was performed at a fixed tilting of rotation angle $\Delta\varphi$ = 60°: a sample "3" – Δd = 5 mm, n = 6; a sample "5" – Δd = 6.6 mm, n = 6; a sample "8" – Δd = 9 mm, n = 6. Thus, the study was carried out at relative reduction: $\varepsilon_d = \Delta d / D_0$ = 0.1; 0.132 and 0.18.

To investigate the stress-strain state as a basis, the experimental method of grids was chosen [6]. The vertical line was determined before the soldering of the samples j = 16 (Fig. 2, a), which is at a distance $L_0 / 2$ (then $L_k / 2$) from the end of the sample. Along this line initial height (a_{0_i}) and the width (b_{0_i}) of each i cell of the grid was measured. A feature of measurements was that the base rate of the cells of the grid took the width $b_0 = 2s$ and height $a_0 = 2s$ with the presence of an orthogonal basis in the form of two crossing lines in the middle of the cells (Fig. 2, b). This facilitates the measurement of the central angle of cell shift γ_{k_i} of the grid relatively to the initial angle γ_0 = 90°, as well as finale size a_{k_i} and b_{k_i} (see Fig. 2, b) after forging and desoldering of the samples. Accordingly, the deformation refers to the center of the cell with the cross of lines in the middle, the material was considered isotropic. Measurements were performed using microscope (model: BMI-10) and according to scanned images of the grid.



a b

Figure 2 Measurement scheme of the grid: a – the numbering of cells at length and height; b – the cell is before and after forging

The forging with rotation involves the conversion of the original round cross-section of the work-piece into a round section of a forging-part, so the stress-strain state of the material in the area of deformation can be taken as axisymmetric. The components of strains in elementary cells were calculated as

$$\varepsilon_{y_i} = ln\frac{a_{k_i}}{a_{0_i}}; \quad \varepsilon_{x_i} = \varepsilon_{y_i};$$

$$\varepsilon_{z_i} = ln\frac{b_{k_i} \cdot sin\gamma_{k_i}}{b_{0_i} \cdot sin\gamma_{0_i}} \quad (1)$$

Components responsible for the shift:

$$\bar{\gamma}_{yz_i} = \left(\varepsilon_{y_i} - \varepsilon_{z_i}\right) \cdot ctg\gamma_{k_i} \cdot \frac{1}{exp\left(\varepsilon_{y_i} - \varepsilon_{z_i}\right) - 1};$$

$$\bar{\gamma}_{xy_i} = \bar{\gamma}_{xz_i} = 0 \quad (2)$$

Accordingly, the intensity of strains for the accepted conditions:

$$e_{i_i} = \frac{\sqrt{2}}{3}\sqrt{2\left(\varepsilon_{y_i} - \varepsilon_{z_i}\right)^2 + \frac{3}{2}\bar{\gamma}^2_{xz_i}} \quad (3)$$

According to the hypothesis of a unique curve, we have unique functional relationship between the intensities of stresses σ_i and intensity of strains e_i for given conditions of thermo-mechanical deformation of material: $\sigma_i = f\left(e_i\right)$.

The similarity of kinematics of deformation of work-pieces from different materials was allowed. Then the quantity of the deformation along the height of semi-finished item depends on the type of curve of hardening. The dependence for antimonide lead *CCy* was determined after the tests (coefficient of determination $R^2 = 0.9997$):

$$\sigma_{i(CCy)} = -1987.8e_i^4 + 2664.6e_i^3 - 1354.4e_i^2 + 303.53e - 0.0108 \quad (4)$$

The approximation of hardening curve of the steel *12ХНМФА* (C 0.09-0.16% , Cr 0.6-0.9% , Ni 1,0-1,4%, Mo 0.15-0.3% , V 0.1-0.2%) at the temperature $t = 1100°$ C and velocity of deformation ξ = 10 c^{-1} [7] gives the following relationship ($R^2 = 0.9838$):

$$\sigma_{i(12XHM\Phi A)} = -811.41e_i^4 + 1544.1e_i^3 - 1191.3e_i^2 + 462.69e + 50.904 \quad (5)$$

The conditions of deformation were taken monotone, so the coefficients of hardness of the scheme of stress and strain state (according to G.A. Smirnov-Aliaev [8]) were considered:

$$(\eta_\sigma)_i = \frac{\sigma_{x_i} + \sigma_{y_i} + \sigma_{z_i}}{\sigma_{i_i}};$$

$$(\eta_e)_i = \frac{\varepsilon_{x_i} + \varepsilon_{y_i} + \varepsilon_{z_i}}{e_{i_i}}$$

$$\eta_i = (\eta_\sigma)_i = (\eta_e)_i \quad (6)$$

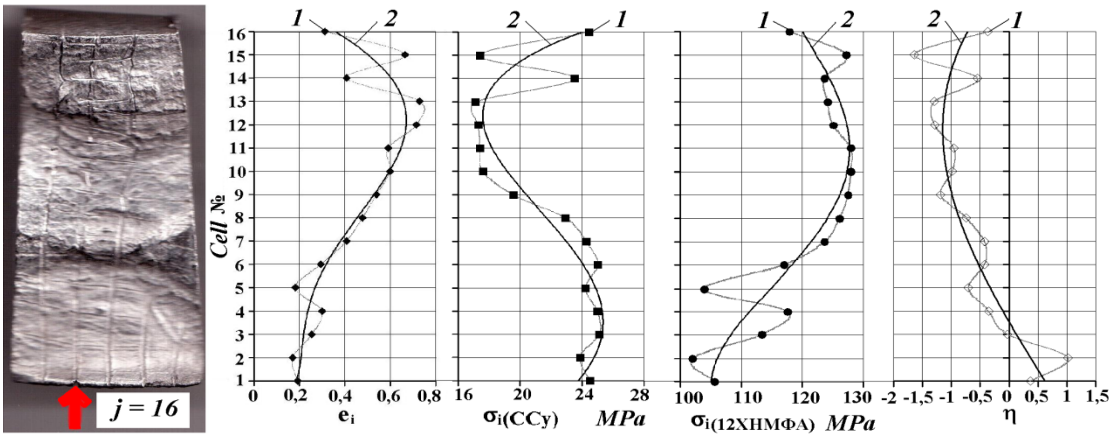
where $\sigma_{x_i}, \sigma_{y_i}, \sigma_{z_i}$ и $\varepsilon_{x_i}, \varepsilon_{y_i}, \varepsilon_{z_i}$ – the components of stress and strain for i-cell.

For axisymmetric deformation the coefficient of hardness of the scheme of stress-strain state was calculated as

$$\eta_i = \frac{2\varepsilon_{y_i} + \varepsilon_{z_i}}{e_{i_i}} \quad (7)$$

The results of processing of experimental data are shown in Fig. 3 and Fig. 4.

The increasing of the angle of rotation of the work-piece at a fixed relative reduction ($\varepsilon_d = 0.1$) is accompanied by a decrease of the average values of the intensities of strains e_i in the deformation zone, deterioration in compacting work of metal layers (see Fig. 3). The moving of values of the coefficients of hardness of stress-strain state η in the middle of the height of the cross-section in a hard area also confirms the ability of appearance here of stretching stresses at angles of rotation $\Delta\varphi = 60°$ and $90°$, despite the fact that the maximum values of parameter e_i are not in the central area of the work-piece.



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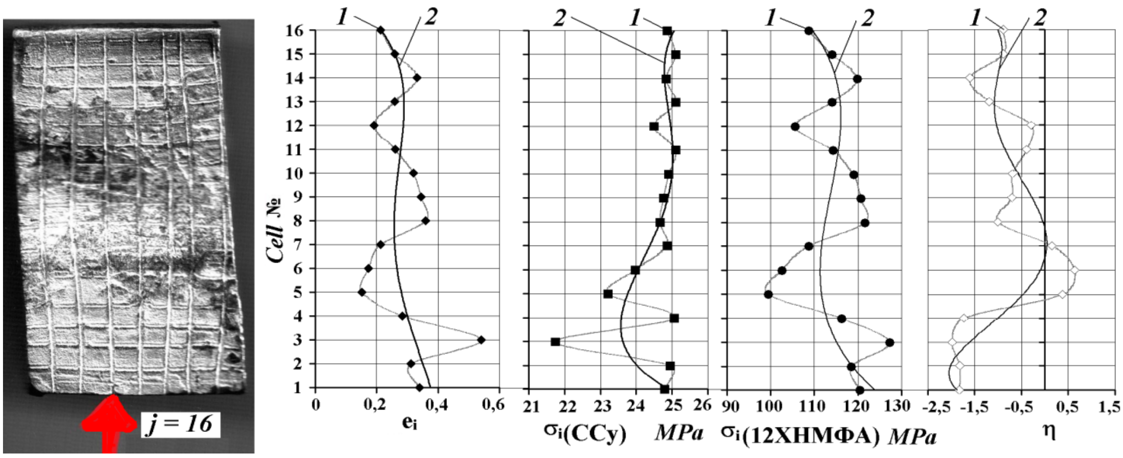
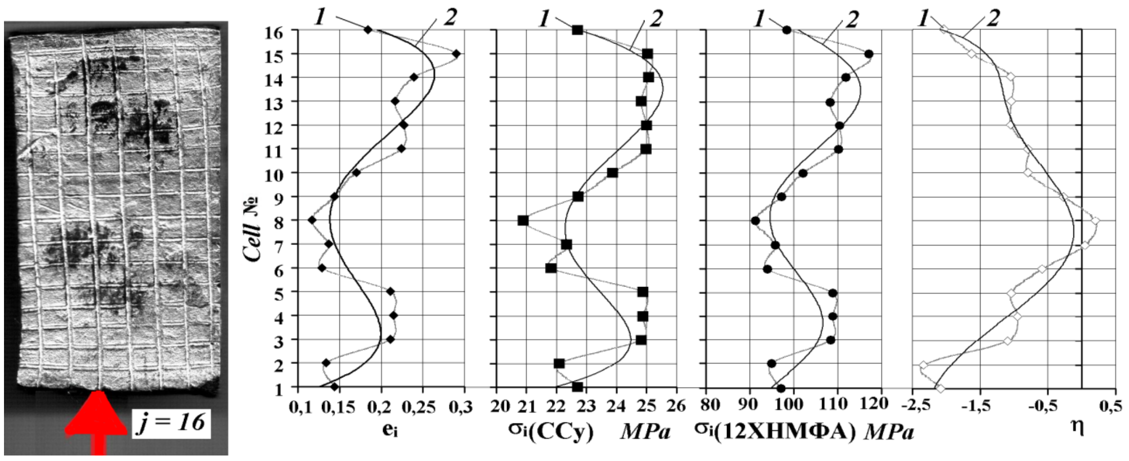
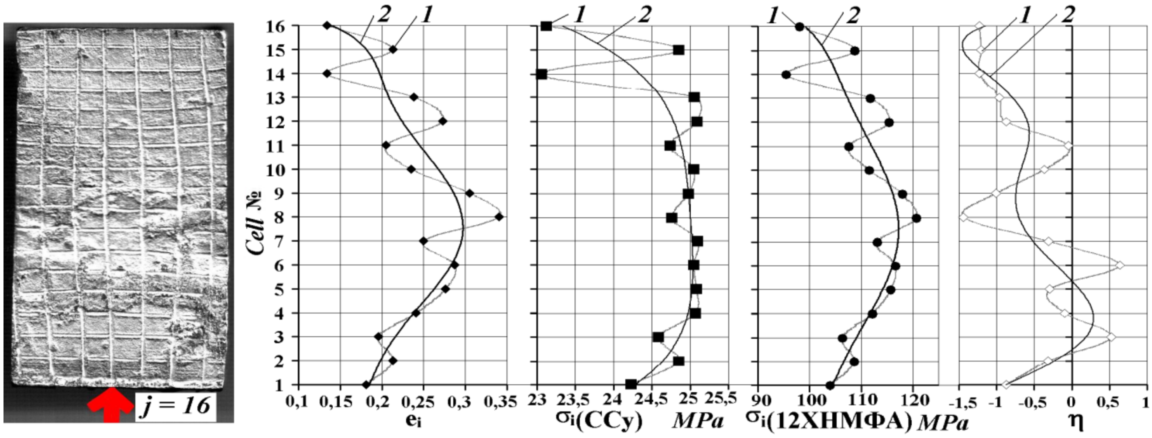


b



c

Figure 3 Graphs of the distribution of intensity of strains e_i, intensity of stress for lead CCy ($\sigma_{i(CCy)}$) and steel 12ХНМФА ($\sigma_{i(12XHM\Phi A)}$) billets, and coefficients of hardness of scheme of stress-strain state η at height: a – sample "0" ($\varepsilon_d = 0.1$; $\Delta\varphi = 30°$); b – sample "1" ($\varepsilon_d = 0.1$; $\Delta\varphi = 60°$); c – sample "2" ($\varepsilon_d = 0.1$; $\Delta\varphi = 90°$); 1 – experimental points, 2 – data approximation



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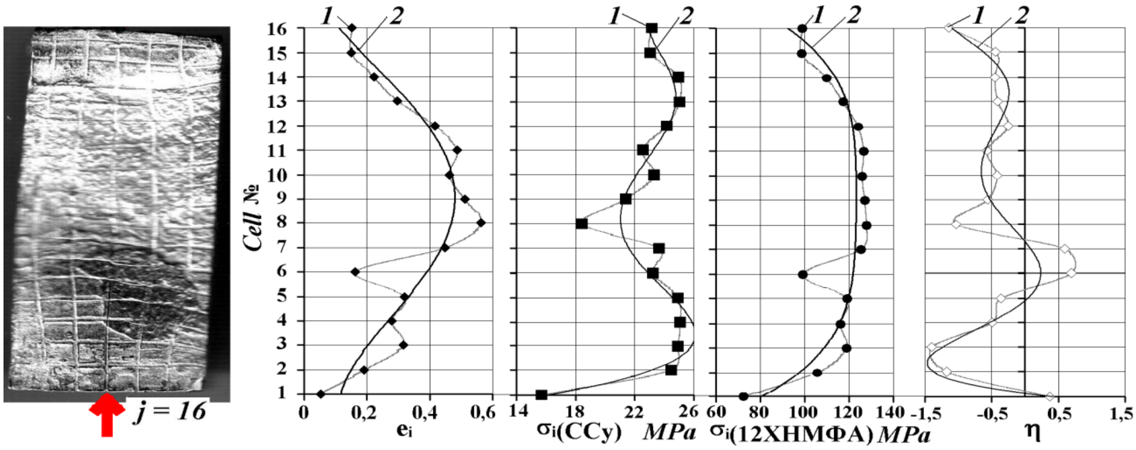

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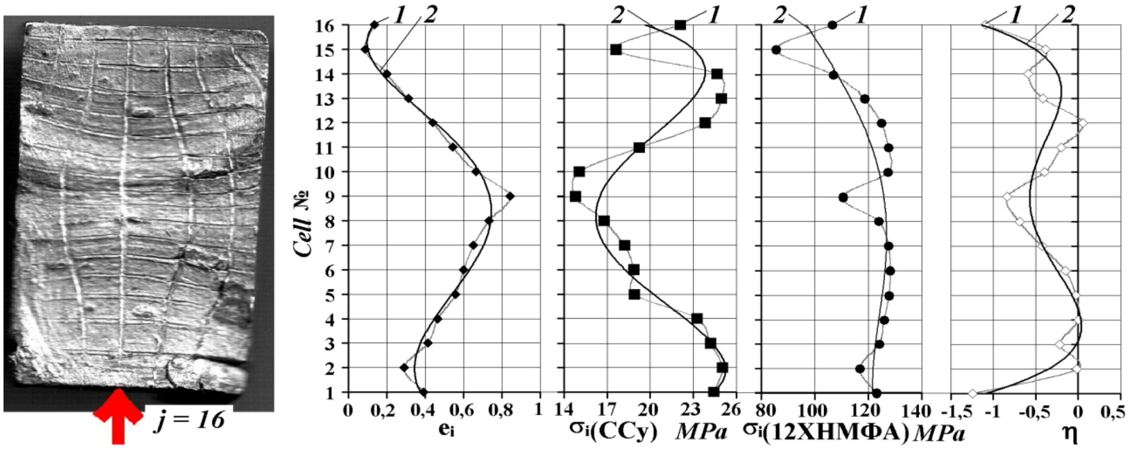

c

Figure 4 Graphs of the distribution of intensity of strains e_i, intensity of stress for lead CCy ($\sigma_{i(CCy)}$) and steel 12ХНМФА ($\sigma_{i(12XHM\Phi A)}$) billets, and coefficients of scheme of stress-strain state η at height: a – sample "3" ($\Delta\varphi$ = 60°; ε_d = 0.1); b – sample "5" ($\Delta\varphi$ = 60°; ε_d = 0.132); c – sample "8" ($\Delta\varphi$ = 60°; ε_d = 0.18); 1 – experimental points, 2 – data approximation

At different values of reduction and angle of rotation $\Delta\varphi$ = 60° the maximum of intensities of strains e_i is observed at middle of height of the samples (see Fig. 4), increases with a rise of values of upsetting ε_d. Growth of reduction values also leads to fewer of layers of metal of billet which are located in a hard area, and the average value of coefficients of harness of stress-strain state η belongs to a soft area. The qualitative difference between the stress intensity values σ_i for the same deformation modes of work-pieces from different materials connected with different mechanism of their hardening under given thermo-mechanical conditions of deformation.

Conclusions

The technique of experimental determination of the influence of the modes of the stretch forging on the distribution of the strains and stresses in a cross-section of the work-piece, which takes into account the mechanical and kinematics conditions of its deformation with rotation in combined anvils, is developed. The fact that in fixed reductions (upsetting) the increasing of the angle of rotation of the work-piece around the longitudinal axis allow to reducing an average value of intensity of deformation along the cross-section with increasing of a share of stretching deformation on the midpoint of the height of the work-piece was found. At fixed values of the angle of rotation the increasing of reduction (upsetting) leads to rising of all-average intensity of strains with a maximum in the middle of the height of the deformation zone and reduction of dispersion of values of the coefficients of hardness of scheme of stress-strain state. The best results from the point of view of achieving a qualitative compacting works of the metal on the cross-section of deformation zone showed the modes with the angle of rotation $\Delta\varphi$ = 60° and relative reduction ε_d = 0.18.

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