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Producing of elongated forgings with sharpened end by rupture with local heating of the workpiece method

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Abstract
The finite element simulation of changing the stress-strained state parameters and simulation of the indices of the plasticity reserve usage at the new technology of producing of elongated parts with sharpened end by the longitudinal rupture and local heating of a workpiece was done. The comparison of the indices of the plasticity reserve usage was made with the application of various methods. A research of macrostructure and technology approbation in industrial conditions confirmed satisfying technological heredity of products that produced by considered method.
Keywords: FORGINGS WITH SHARPENED END, LONGITUDINAL RUPTURE OF WORKPIECE, LOCAL HEATING, STRESS-STRAIN STATE, PLASTICITY RESERVE USAGE, MACROSTRUCTURE AND TECHNOLOGICAL HEREDITY

Introduction

A wide commodity cluster for production of the hand tools, projectile tools, chisels, cape chisels, bolt chisels, groove-cutting chisels, harrow tooth etc. belong to the forgings with an elongated axle. The production technology of such forgings is diverse and depends upon the configuration of a product, presence of thickenings and ledges.

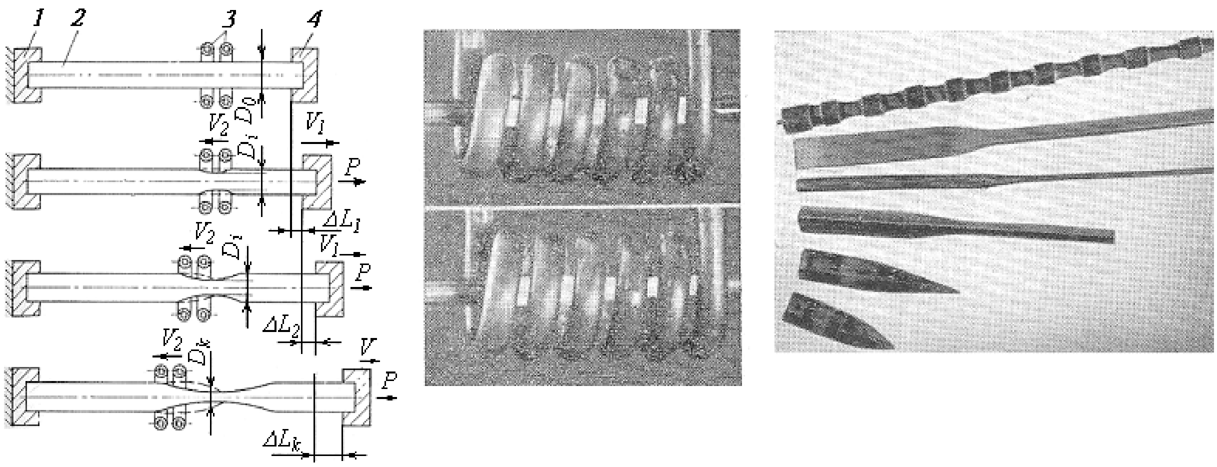
The analysis of recent publications and problem statement

The production of elongated forgings with sharpened end on the roll-forging machine often relates to a waste formation and the necessity of bringing of trimming operations [1]. Receiving of elongated forgings with sharpened end is possible with extrusion [2] and forming by closed die technique, at the same time using resource-demanding and self-correcting dies, which operate in difficult conditions. The tool of simplified shape is used for forging on radial-forging [4, 5] or radial-pressing [6] machines. However, except the complex kinematics, these devices are characterized by their expensiveness and orientation on massive products of large-scale production.

The new original method of production of elongated forgings with sharpened end, according to utility models [7–9], is straining with workpiece rupture. At the same time the two parts, whose sharpening is formed in a necking place, are produced from the one long-boled (twin) workpiece. The principles of the controllable tearing are successfully used in rolling technology [10]. However, the application of straining with the workpiece rupture for shaping of forgings without dies demands a complex of experimental and theoretical studies and knowledge accumulation that is necessary for production engineering of parts with required working qualities.

Among the main backgrounds of elongated products shaping without dies, axial tension at super plasticity rate should be pointed out [11], with the help of which not only the sharpened forgings, but deformed sections (periodical profiles) workpieces (fig. 1) can be produced.

The existing ways of mechanical testing of samples for straining according to the State Standard (GOST) 1497-84, being performed on standardized testing machine, also include rupture of a workpiece with sharpening on the reduced neck. The problems of learning the stress-strain analysis and partially changing of neck form while straining were paid much attention to in studies [12–14]. In the thesis [15] empirical description of concavity radius of the divided workpiece with forming profile in a necking place was suggested. Consequently, studies in this field continue developing hitherto.



a b c

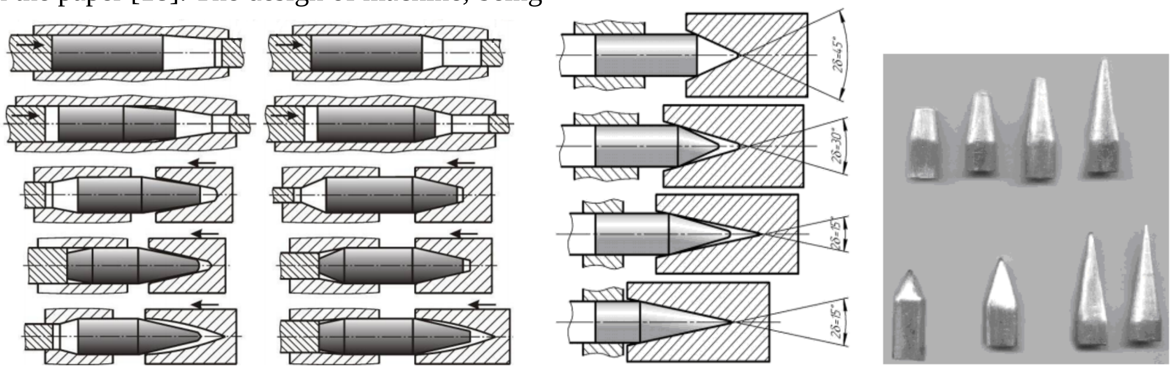
Figure 1. Shape forming in superplasticity mode [11]: a – scheme of process; b – workpiece in the inductor; c – typical parts; 1 and 4 – fixed and movable clamp of straining press; 2 – workpiece; 3 – inductor

Configurations of the product after stretching to break a standard form chisels, tooth harrow (fig. 2). Thus, analyzed profiling method can serve as a final or intermediate operation similar to broach or fullering. Applying this operation is a profitable alternative for multistage die forming of sharpened rod taper pieces (fig. 3), suggested in studies [16, 17], with obvious reduction of number of technological transitions and formation of spade part geometry.

a b

Figure 2. A harrow tooth (a) and a spade chisel (b)

Zonal heating is applied in a place of rupture to control the form changing process, while prerequisites for supplying straining machines with heating devices have been existing for a long time, which was pointed out in the paper [18]. The design of machine, being intended to involve differential heating and tempering of sharpening after splitting of a workpiece, was suggested by authors [9] for accomplishing profiling of workpieces without dies by straining with rupture method.



a b c

Figure 3. The multistage technology of rods upsetting [17] with sharpened end (a and b) and forgings (c)

A research of geometrical macroindices of energy-power characteristics deformation of straining with rupture process of round and square section depending on the length of the heating zone in a splitting place was conducted in studies [19, 20]. Criterion analysis showed significant energy advantages of the method from the point of view of compared work spent with the deformation of final form changing. The proposed calculated dependences for determining the length of the heated area and the length of the working stroke of the machine until the rupture of the workpiece form the basis for designing technological processes of pneumatic hammers chisels production for breaking the lining of metallurgical tankages [20, 21].

The peculiarity of the part forming is the localization of deformation in the zone of sharpening. Despite the well-known postulate that the hot deformation contributes to "healing" of microcracks, that may occur in the areas of tensile stresses, a study of stress-strained state in the area of rupture and forecasting technological heredity in narrow parts of the piece, where the maximum loads occur during operation, is of particular interest.

The purpose of the work

The purpose of this work is to study stress-strained state, the indices of the plasticity reserve usage and the metallographic analysis of the sharpened part of the elongated parts, acquired with longitudinal rupture of a workpiece, to measure their technological heredity.

Materials of research

As is well known the length of the local heating area affects such parameters as the amount of the working stroke until the rupture of workpieces, the maximum force of tensile deformation, dimensions and geometric configuration of the pointed section characteristics. Proceeding from finite size of the forging "Chisel" with length of the stub sharpened section l_k = 32 mm, diameter d = 26 mm, material – steel 60C2A (C 0.58–0.63%, Si 1.6–2.0%, Mn 0.6–0.9%, S ≤0.025%, P ≤0.025%) in technological process of production by straining with rupture of twin workpiece with diameter ∅26 mm and 500 mm at length (fig. 4) based on the elaborated method of calculation [20, 21] was designed. At that the temperature of heated central part of twin workpiece is 1100 °C. The length of the heating area ($l_н$) and the amount of working stroke (Δl), providing the rupture of workpiece, was calculated as

$l_н = \alpha \cdot l_k + \beta \cdot d = 1.292 \cdot 32 + 0.083 \cdot 26 = 43$ mm; (1)

$\Delta l \geq \alpha^{/} \cdot l_н + \beta^{/} \cdot d = 1.5125 \cdot 32 + 0.7329 \cdot 26 = 67.5$ mm, (2)

where α = 1.292, β = 0.083 и $\alpha^{/}$ = 1.513, $\beta^{/}$ = 0.733 – coefficient for the heated steel workpieces [21].

The Measurement of the stress-strained state and the indices of the plasticity reserve usage were appraised by finite-element simulation process of deformation in axial-symmetric parts with the help of iterative resolvent Abaqus/Standart. The workpiece was presented as central heated deformable strengthenable zone and cold rigid areas, contacting the seizing body of tearing press (fig. 4). For the straining process simulation on the flanks of workpiece boundary conditions were determined, providing their movement among the axle of the workpiece in the opposite directions with the 0.5 mm/s speed, and that corresponds to the deformation rate.

At approximation of the workpiece model by a net of final elements were used four-nodal axial-symmetric quadratic finite elements with reduced integration scheme and degeneracy control, size of which was 0,5 mm. Strengthening of material at given temperature and deformation rate were considered according to directory database [22].

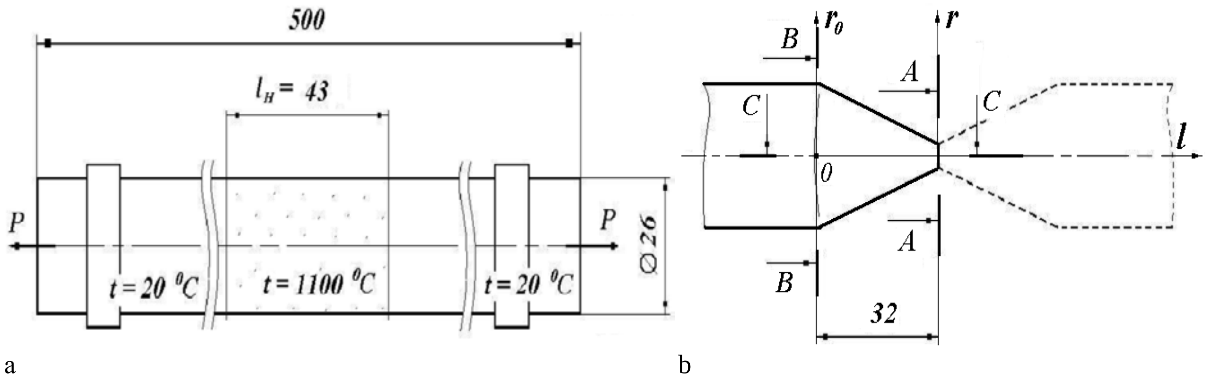


Figure 4. Scheme for the model of dividing a workpiece for "chisel" forging production before deformation (a) and at the moment of rupture (b)

Proceeding from the set in the simulation process values of the principal stresses (σ_1, σ_2, σ_3), strain tensor components ($\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{xz}$) and strain intensity ($\sigma_i$) in volume of the deformed part of the workpiece next characteristics were determined [23, 24]:

- Nadai-Lode indicator:

$$\nu_\sigma = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}; \quad (3)$$

- Strained state coefficient:

$$k_\sigma = \sigma_{av.} / T, \quad (4)$$

where $T = \sigma_i / \sqrt{3}$ – intensity of tangential stress;

$\sigma_{av.} = (\sigma_x + \sigma_y + \sigma_z)/3$ – hydrostatic stress.

In the process of the neck formation strained state of deformed part transforms from linear to voluminous. That is why complex of the indices of the plasticity reserve usage (Ψ) was tested [23, 24]:

- according to V.L. Kolmohorov:

$$\Psi_1 = \frac{\Lambda}{\Lambda_p} < 1 \quad \text{or} \quad \Psi_1 = \int_0^\tau \frac{H(\tau)}{\Lambda_p[k_\sigma(\tau)]} d\tau < 1, \quad (5)$$

where τ – deformation time;

$H = \xi_i \cdot \sqrt{3}$ – the intensity of shear strain rates, here ξ_i – intensity of deformation;

$\Lambda = \int_0^\tau H d\tau = \sqrt{3} \cdot e_i$ – the rate of shear deformation, here for marking the intensity of information e_i is used;

$\Lambda_p = \sqrt{3} \cdot e_p$ – ultimate shear deformation rate, when destruction starts, while $e_p = \ln(l_p / l_0)$, where l_0 and l_p – length of workpieces before and after the rupture by results of tearing testing in required deformation conditions;

- according to G.D. Del V.A. Ogorodnikov and V.G. Nakhaychuk:

$$\Psi_2 = \int_0^{e_i} n \frac{e_i^{n-1} de_i}{e_p(\eta)^n} < 1, \qquad (6)$$

where $n = 1 + 0.2 arctg(d\eta / de_i)$ and $\eta = 3\sigma_{av.} / \sigma_i = (\sigma_1 + \sigma_2 + \sigma_3) / \sigma_i$;

- considering the third invariant of strain tensor in a form of:

$$\Psi_3 = \int_0^{e_i} (1+f) \frac{e_i^f de_i}{e_p(\eta, \nu_\sigma)^{1+f}}, \qquad (7)$$

where $f = 0.2 arctg\left(\frac{d\eta}{de_i} + \frac{d\chi}{de_i} \right)$, here

$\chi = \sqrt[3]{\sigma_1 \sigma_2 \sigma_3} / \sigma_i$;

$e_p(\eta, \nu_\sigma) = 1{,}85(0.41\nu_\sigma - 0.51\eta)$;

- considering voluminous stress-strained state with nonlinear principle of damage

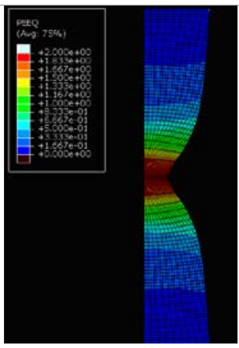
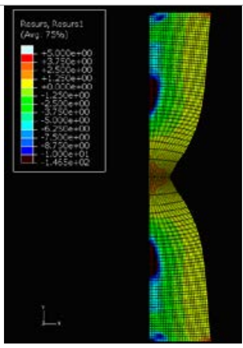
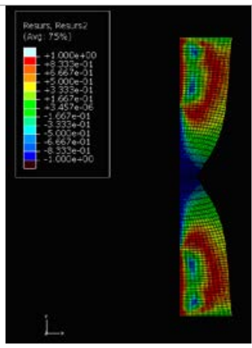
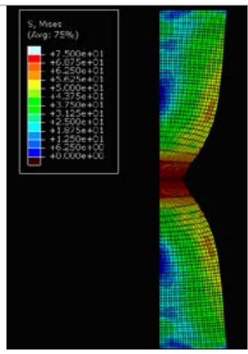
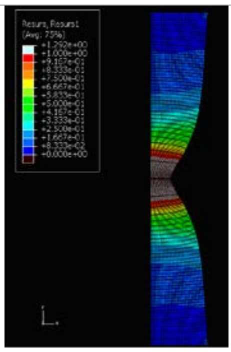
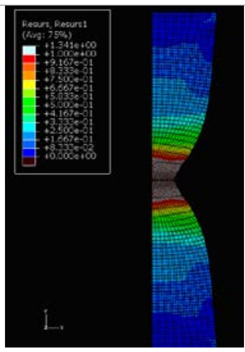
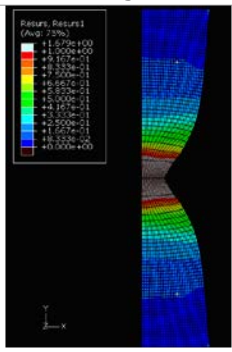
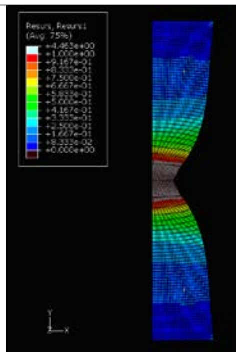
$$\Psi_4 = \int_0^{e_i} n \frac{e_i^{n-1} de_i}{e_p(\eta, \nu_\sigma)^n}, \qquad (8)$$

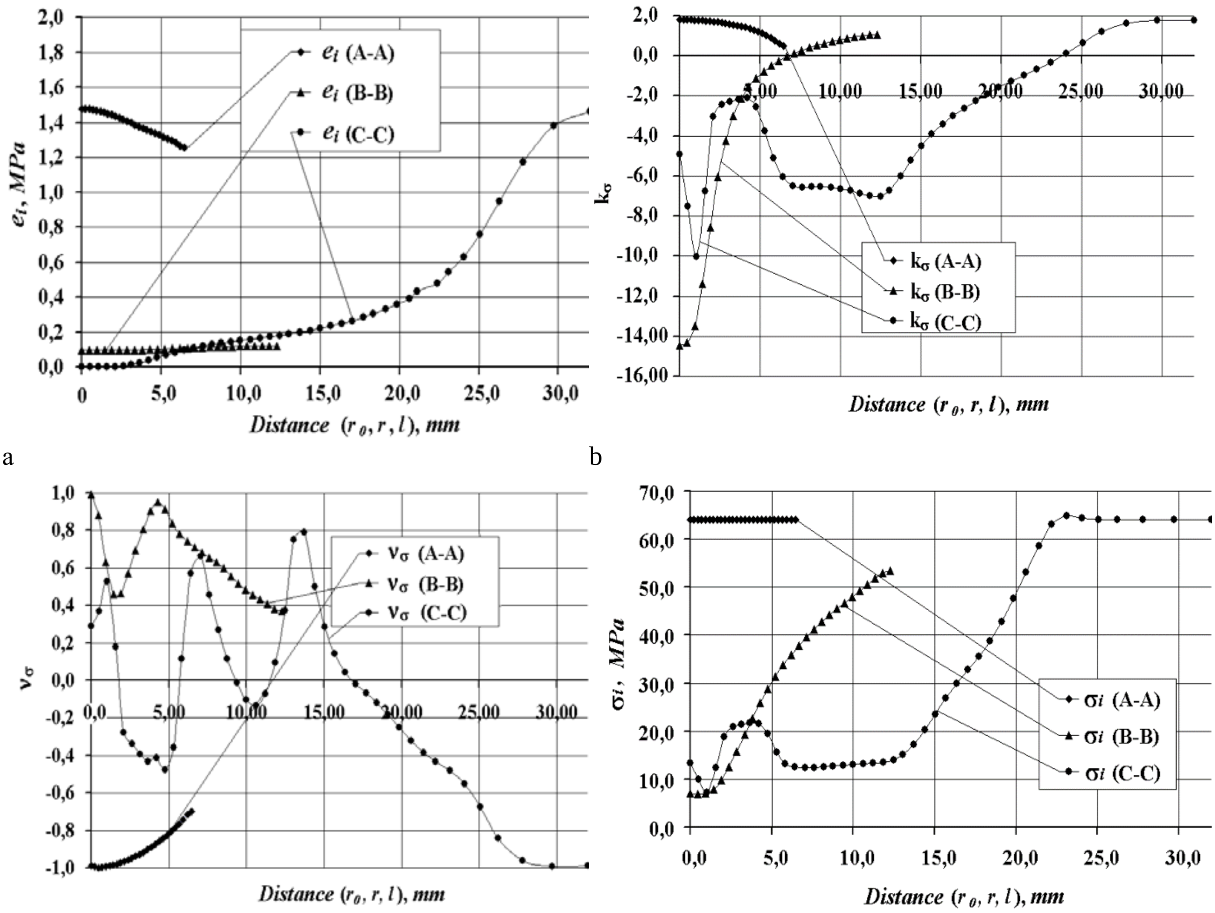
where $n = 1 + a\frac{d\eta}{de_i} - b\frac{d\nu_\sigma}{de_i}$; a = 0.06, b = 0.037.

To determine fields of parameterization (k_σ, ν_σ, Ψ_1, Ψ_2, Ψ_3 и Ψ_4) in the volume of workpiece software, developed with usage of Python interpreter, built in the Abaqus system, was used. The simulation results are presented by a video files (amplification *.avi), when recorded fields of the studied parameters for rupture phase are shown in a table 1.

Furthermore, on fig. 5 one can see the graphs of stress-strained state indices distribution in sections A–A, B–B and C–C workpiece (fig. 4, b), namely strain intensity (fig. 5, a), coefficient of the strained state, defined according to equation (4) (fig. 5, b), Nadai-Lode index, calculated by the equation (3) (fig. 5, c), and intensity of strains (fig. 5, b). Absolute increase of stress-strained state indices is observed in plastic zone with approaching to axle of the workpiece among the cross-section and the splitting place. Thus, the zone of maximal operational stress is the most complete.

Table 1 Results of stress-strained state and the indices of the plasticity reserve usage simulation on tearing a workpiece phase

e_i	k_σ	ν_σ	σ_i
			
Ψ_1	Ψ_2	Ψ_3	Ψ_4
			



a b

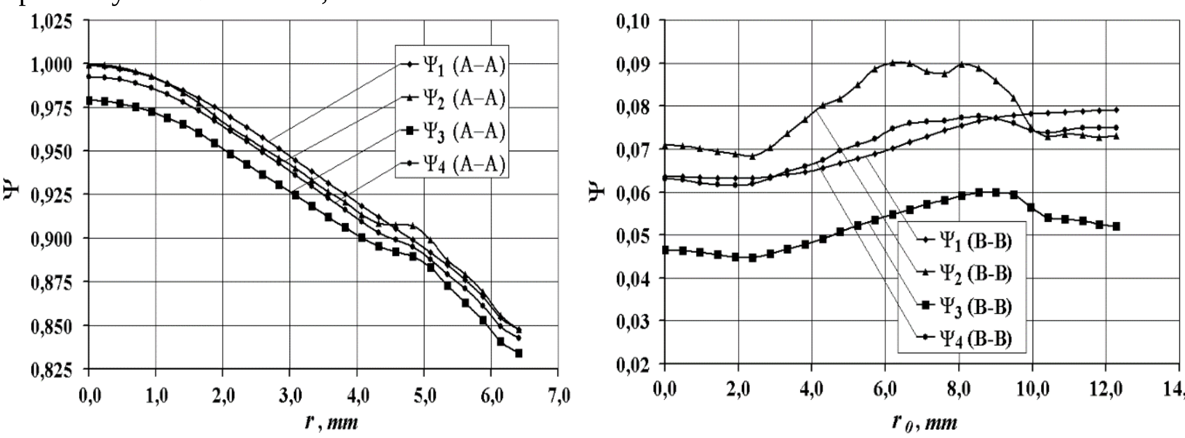
c d

Figure 5. Stress-strained state indices on the cross-section of a workpiece:

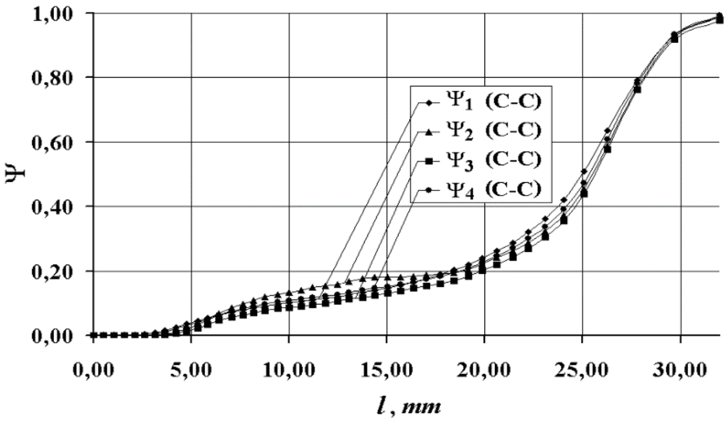
a – allocation e_i; b – allocation k_σ;

c – allocation ν_σ; d – allocation σ_i

In the fig. 6 one can observe the comparison of the usage of plasticity reserve indices distribution, defined by the equations (5), (6), (7) and (8). Acquired graphical dependences are close in quality and quantity. Naturally, in a place of rupture there is depletion of plasticity stock. However, at the distance of 5 mm from the cross-section A–A at length (which corresponds to the size of technological stock for sharpening the end) the indices of the plasticity reserve usage are on the rate ≅ 0.7, which is quite satisfying even for the cold plastic deformation conditions.



a b



c

Figure 6. the indices of the plasticity reserve usage distribution in the cross-sections of the workpiece: a – cross-section A–A; b – cross-section B–B; c – cross-section C–C

To evaluate the technological heredity of the metal of the forgings produced by straining with rupture method, analysis of macrostructure was done. Parts with formed sharpening are shown in fig. 7, a. After making the experimental researches several forgings divided, having various length of the heated area, were selected, including forgings produced with the suggested chisel production technology. After the macrosection production, the workpieces were subjected to the chemical etching by 20% water solution HNO_3, the texture was revealed by taking sulfur print (Bauman method). Additionally, metallographic examinations were carried out on the workpieces for forgings “Harrow tooth” of square cross section, (fig. 7, b) divided in conditions of different length of the heating zone (according to the results [20]). Considering that the applied workpieces “Harrow tooth” had the reverse side sharpening technology, an opportunity to compare macrostructure of the sharpened part appears.

a

b

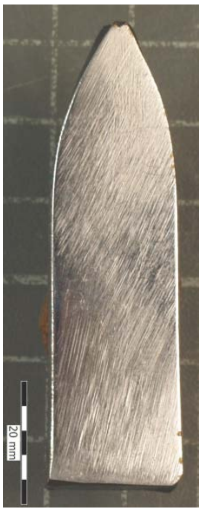
Figure 7. Workpieces of circular cross-section («Chisel») (a) and of square cross-section («Harrow tooth») (b), divided, having various length of the heated area

The results of the research are shown in table 2, where sections N 1–3 are made of workpieces with initial circular cross-section (“Chisel”, steel grade 60C2A – C 0.58–0.63%, Si 1.6–2.0%, Mn 0.6–0.9%, S ≤0.025%, P ≤0.025%), and sections N 4 и N 5 of square cross-section (“Harrow tooth”, steel grade 55Г – C 0.52–0.6%, Si 0.17–0.37%, Mn 0.7–1.0%, Cr ≤0.25%). Discovered macrostructure of longitudinal templates is quite satisfying and is characterized by well observed texture in the sharpening formation zone. Fibers are elongated in direction of the effect of working load. It was established that sharpening acquired with traditional technology has cross-cut fibers, that fact indicates their production by mechanical (by grinding) methods. Obviously sharpening formation by plastic deformation is more preferable.

In the zone of the sharpened end of the workpiece N 3 and in zones of welding clamps of workpieces N 4 and N 5 heat-affected zones were revealed in a way of darkening. Sulfur printings of all the samples have even dispensing of dotted segregate of medium colouring power. After etching there were no defects of macrostructure revealed.

As a rule, processes of hot deformation are accompanied by dynamic recrystallization with restoration of mechanical properties of steel, and texture formation improves the strength indices in direction of fiber elongation. Accordingly, the most of the parts, produced by the hot deformation, are brought into production and successfully operated after being produced by containing elements of violating the integrity of product technologies (flash trimming of forgings, mechanical processing stock and lap removal etc.).

Table 2. The results of metallographic studies

№	1	2	3	4	5
I. Exterior view of section					
II. Section after chemical etching					

III. The sulfur Baumann printing					

Conclusions

The mechanism of the stress-strained state development of the sharpened end formation in production of "Chisel" forgings by methods of longitudinal rupture with differentiated heating was determined. It was revealed that the indices of the plasticity reserve usage, calculated by various methods, are close in quality and in quantity. The approbation of the technology in industrial conditions (of PJSC "ILYICH IRON AND STEEL WORKS OF MARIUPOL") and the evaluation of macrostructure indicators for "Chisel" forging and "Harrow tooth" forging operation confirmed satisfying technological heredity of products, produced by straining with rupture of a workpiece method.

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