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ANALYSIS OF SPECIMEN PLASTIC FLOW FEATURES DURING SEVERE PLASTIC DEFORMATION

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Abstract. In the present work the numerical modeling results for the following severe plastic deformation processes: equal channel angular pressing, T-shaped pressing, cruciform pressing and 2D forging are presented. Two criteria - regularity of strain intensity distribution and rigidity coefficient of stressed state – were used for comparative analysis. Experimental research of severe plastic deformation processes was carried out.

1. INTRODUCTION

At the present time research of structure formation features in metals during large plastic deformations is of academic and practical interest that opens significant prospects for ultra-fine grain and nano-structured materials creation [1]. Novel pressure treatment processes appeared with basic purpose of deformation accumulation in workpieces without considerable form change that allows to accumulate significant plastic deformations in workpieces after multiple repeat of the process [1-5]. To describe such processes they use a definition of severe plastic deformation (SPD).

The purpose of this paper was to compare SPD methods that could be potentially used to obtain ultra-fine grain and nanostructured materials industrially. The analysis was carried out by computer simulation methods and experimental investigation.

Among the great amount of SPD methods the simplest ones for realization are: ECAP [1], modified method of uniform pressing (T-ECAP) [2,3], Cross-ECAP of long-length specimens and 2D forging (Fig. 1).

ECAP scheme is performed in Fig.1a. A metal billet is pressed though a die containing two channels, equal in cross-section, intersecting at angle Φ. During pressing, the billet undergoes severe shear deformation but retains the same cross-sectional geometry so that it is possible to repeat pressings for a number of passes, each one refining grain size.

T-ECAP was performed with the help of special tool where side extrusion of material is occurred in two mutually antithetic directions (Fig. 1b). During completion phase of the process material cannot flow freely to the sides and has to fill all the die volume. Thus initial workpiece form remains till the next pressing cycle.

To perform Cross-ECAP process material should freely deform to both sides with top-down movement of punches at one time (Fig. 1c). This process allows to increase the length of workpiece compared to T-ECAP. To simplify the process realization a floating die can be used.

2D forging is widely used in industry at present. The process of 2D forging is put into practice with the help of multiaxial deformation module MAX-Strain Gleeble System 3800.

Since the basic principle of processes considered is strain accumulation, one of the criterion for method comparison is a factor of accumulated de-

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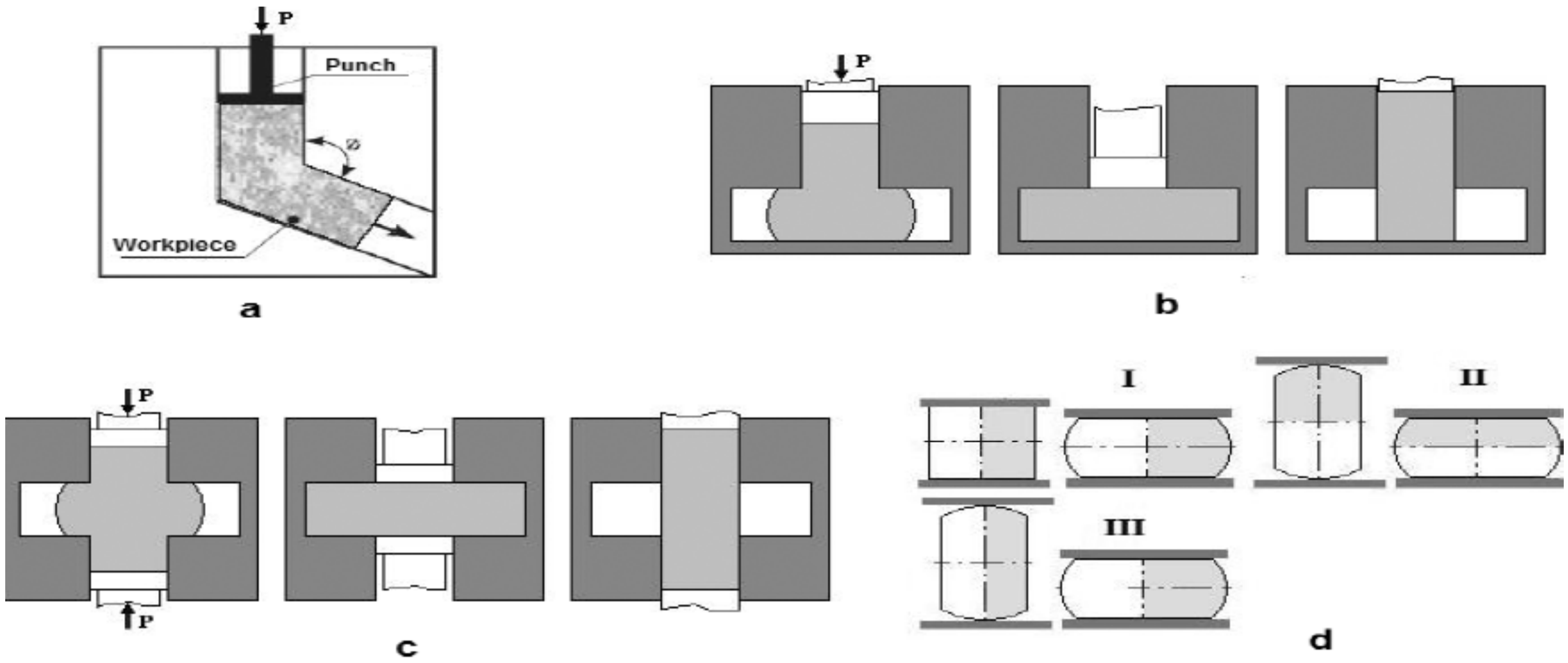

Fig. 1. Analyzed SPD process scheme: a) ECAP; b) T-ECAP; c) Cross-ECAP; d) 2D forging.

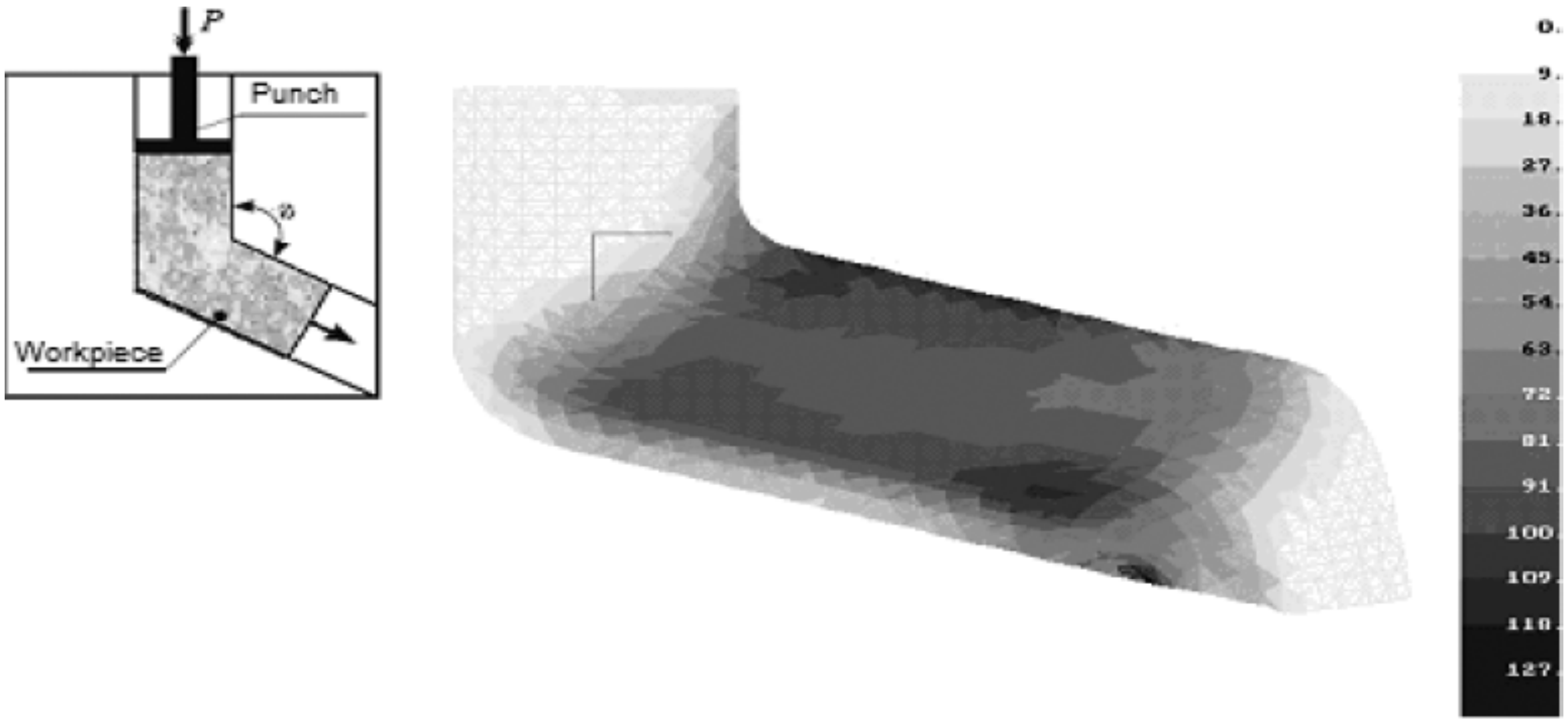

Fig. 2. Distribution of accumulated strain intensity along the longitudinal section of the workpiece after one pass of ECAP.

formation regularity value in metal. It is known that plastic deformation is accompanied by material plasticity decrease [4,5]. At that metal defect accumulation in the processes being analyzed depends on accumulated deformation value, stress state type in different workpiece parts and also its forming line during multiple process repeat. For this reason another important criterion for such processes is stress state stiffness coefficient $k = \sigma_0/\sigma_i$, i.e. ratio of hydrostatical pressure value to stress intensity value.

2. FINITE ELEMENT MODELING

Mathematical modeling of the processes chosen was realized by finite element method. The following model approximations were assumed: material model – elastoplastic solid, deformation model – plain deformation. Friction conditions in contact zones of the material and deforming tool in all four cases were described by friction coefficient $\mu = 0,2$. It is also supposed that all the processes considered were carried out at room temperature. Commercial aluminum was taken as model material.

In the work [6] the influence of die geometry and friction conditions on strain distribution regularity during ECAP was described and some recommendations of its realization were given. Basing on research results ECAP simulation was made for one-turn channel with the following geometry: intersecting angle between inlet and outlet channel part $\Phi = 105°$; outer coupling radius $R = 10$ mm, inner coupling radius $r = 5$ mm and width of channel straight portion $b = 20$ mm. Fig. 2 shows distribution fields of accumulated strain intensity along the longitudinal section of the workpiece after one pass of ECAP and Fig. 3 shows results of numerical solution of T-ECAP task. Initially the workpiece had a ratio of height to width as 2:1. After one pressing pass strain degree of the workpiece was $\varepsilon = 50\%$.

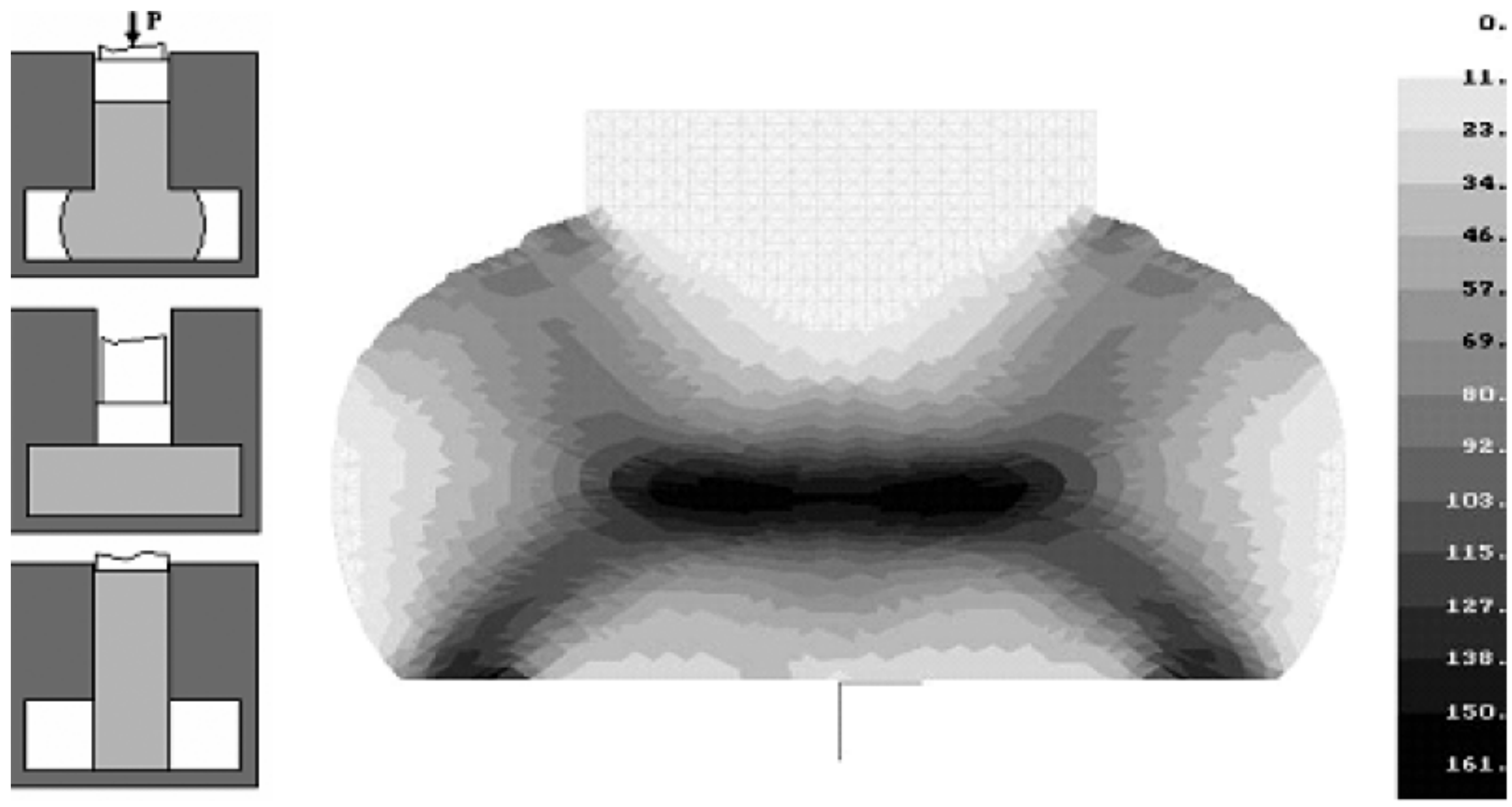

Fig. 3. Distribution of accumulated strain intensity along the longitudinal section of the workpiece after one pass of T-ECAP.

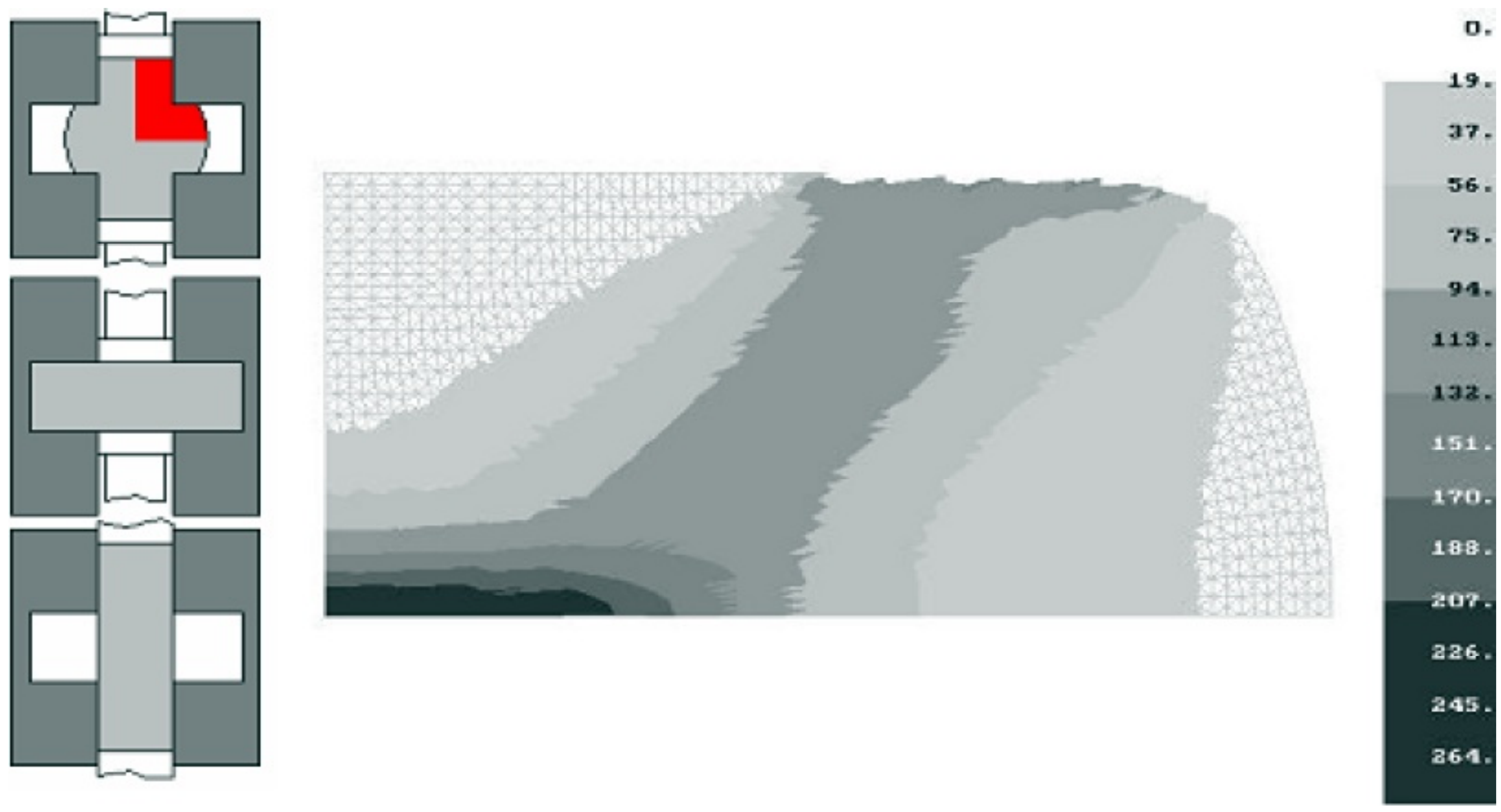

Fig. 4. Distribution of accumulated strain intensity along the longitudinal section of the workpiece after one pass for Cross-ECAP.

For Cross-ECAP simulation in view of workpiece symmetry the calculation was made for ¼ part. Fig. 4 shows distribution fields of accumulated strain intensity along the longitudinal section of the workpiece after one pass of Cross-ECAP.

2D forging process was investigated for ½ part in view of workpiece symmetry. Numerical analysis of 2D forging process was carried out for 3 stages. At the first stage the billet was deformed between striking edges along one axis with strain degree ε = 20%. Then the workpiece turns 90° anticlockwise and it's deformed along another axis: ε = 40%. At the third stage the workpiece turns 90° clockwise and it's deformed again with strain degree ε = 40%. Fig. 5 shows the shape of ½ workpiece part after 3 deformation stages and also distribution of accumulated strain intensity in the cross-section.

Having analyzed distribution fields of accumulated strain intensity in material received for all the processes being investigated it appears that ECAP has the most regularity by this criterion (Fig. 2). For the rest processes the zone of the most intense plastic deformations is located in the center and goes to its corners. As a result there are weakly worked areas in the workpiece (under the punch and on the side free surfaces) (Figs. 3-5). At that the increase of forming cycle numbers doesn't allow to get rid of such irregularity, and finally this may essentially result in complete product properties.

It's known that with negative values of hydrostatic pressure (k<0) material plasticity is essentially higher that with positive values of this pressure (k>0). Therefore the most dangerous from the viewpoint of

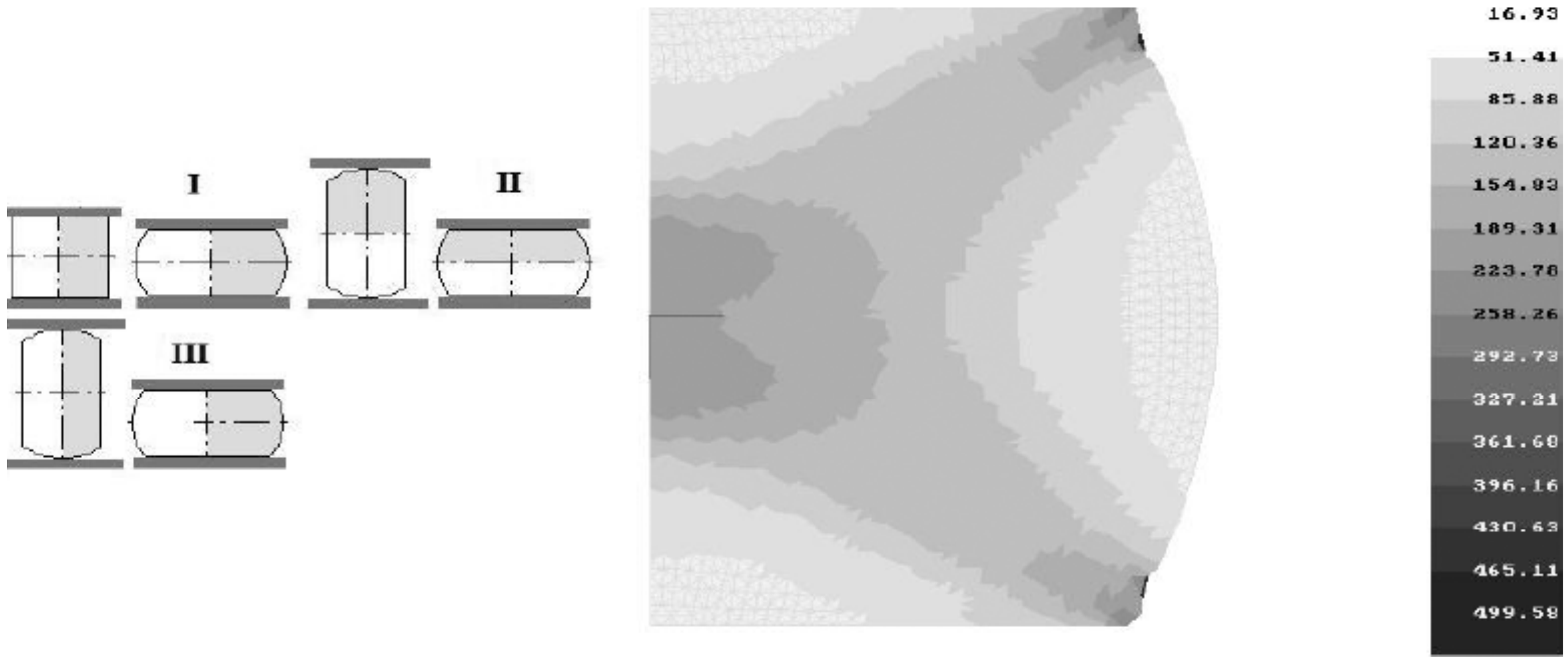

Fig. 5. Distribution of accumulated strain intensity along the workpiece cross-section after three deformation passes of 2D forging.

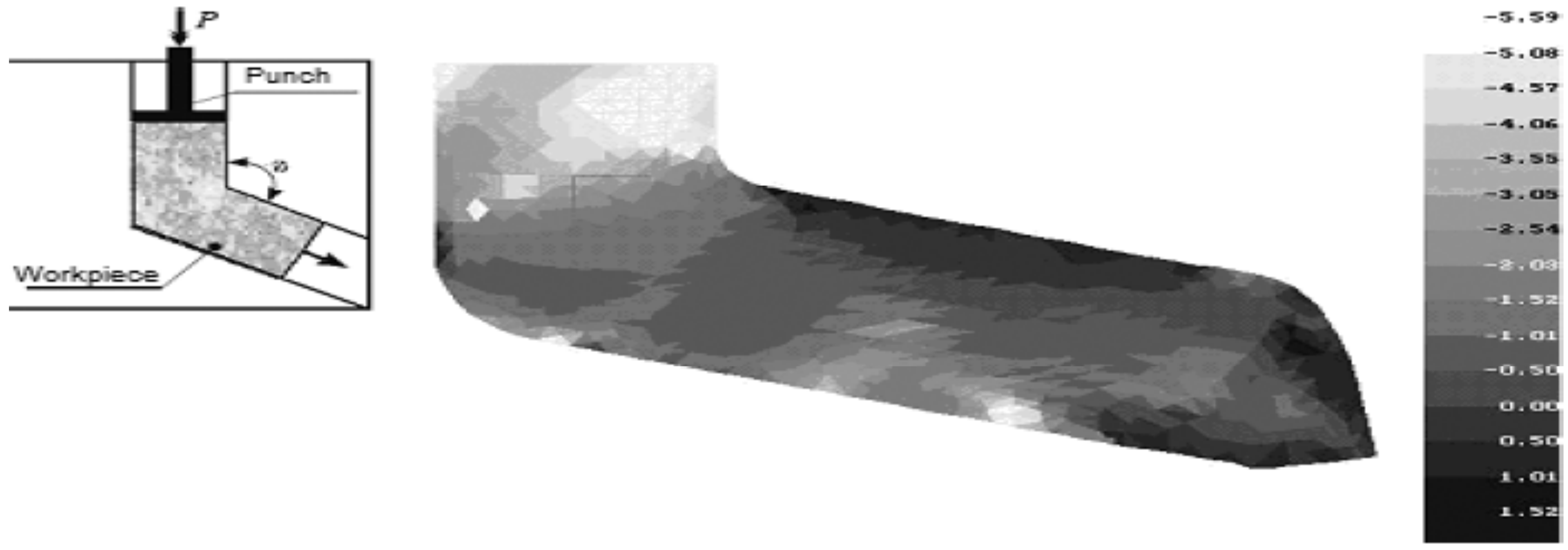

Fig. 6. Distribution of stress state stiffness coefficient k along the longitudinal section of the workpiece after one pass for ECAP.

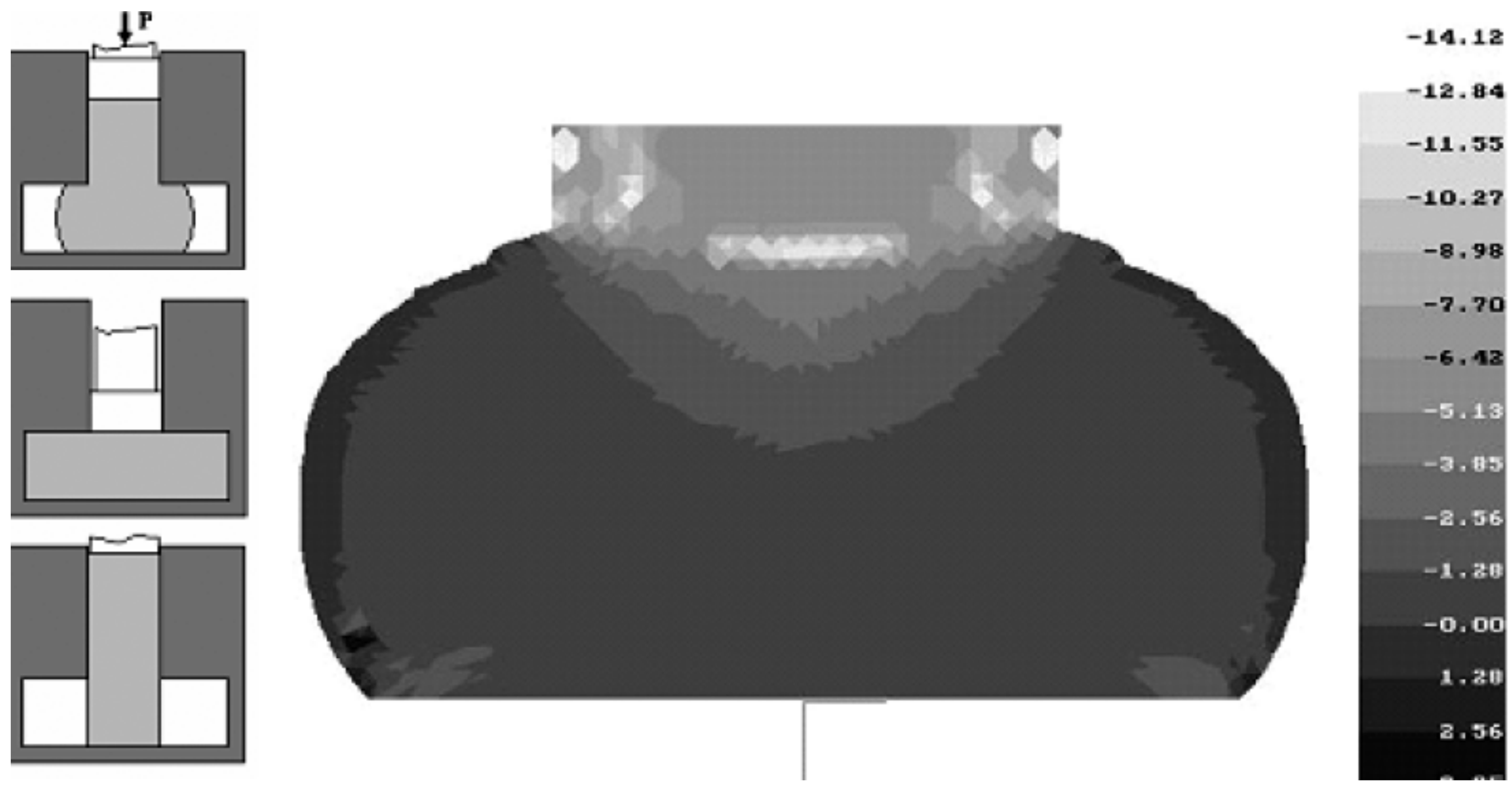

Fig. 7. Distribution of stress state stiffness coefficient *k* along the longitudinal section of the workpiece after one pass for T-ECAP.

microcrack formation and growth zones of the processed material are those characterized by positive values of stress state stiffness coefficient k.

Figs. 6-10 show distribution of stress state stiffness coefficient *k* for all the processes analyzed.

ECAP process is characterized by formation in the workpiece of a zone joining the upper side of channel outlet where coefficient *k* value is more than zero (k_{min}=1.525). This zero crossing is explained by nonmonotonicity of deformation process along the outer channel side: hydrostatic stresses change sign when getting through deformation zone. In the inlet channel material layers near the inner side undergo compression, in the outlet channel – ten-

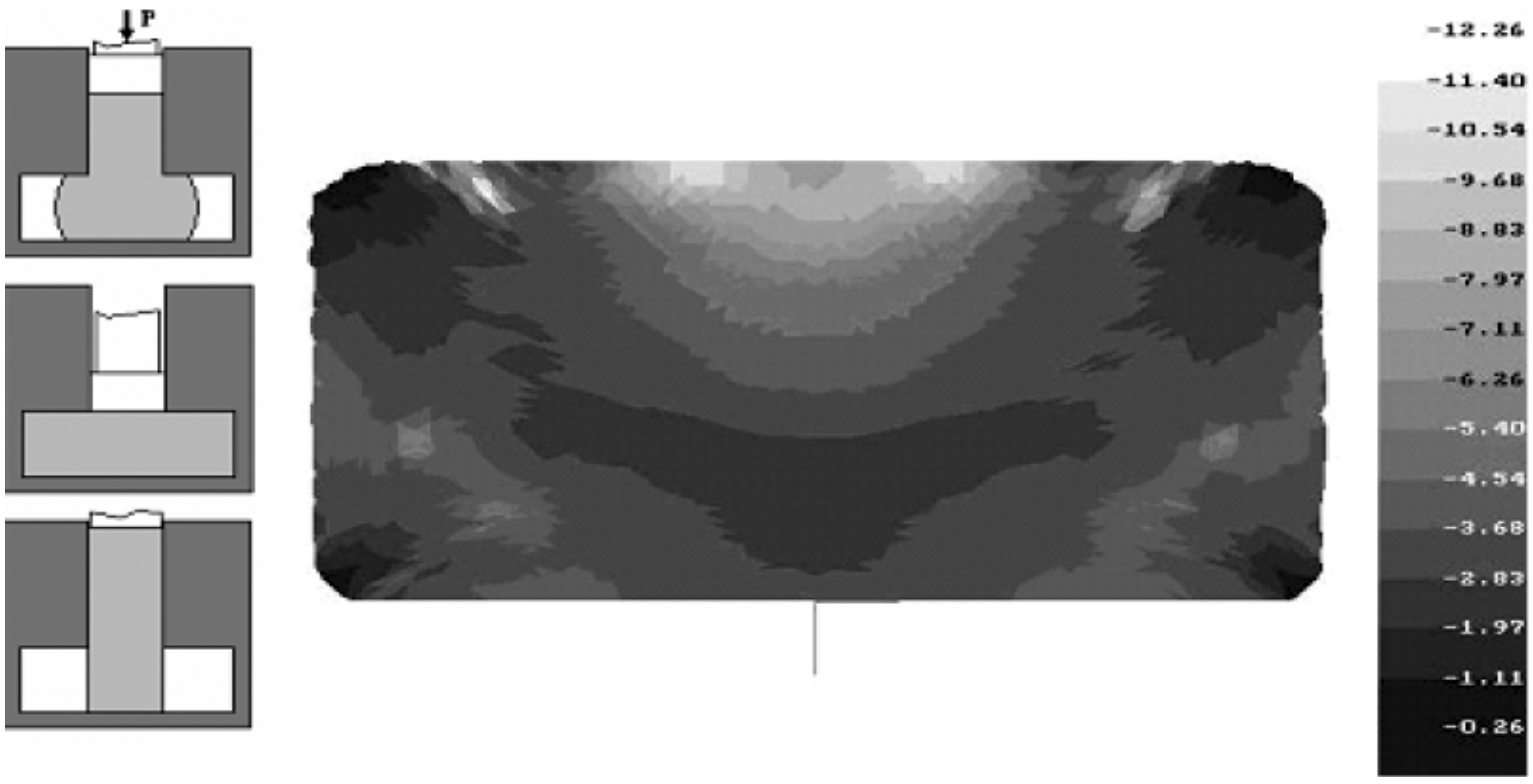

Fig. 8. Distribution of stress state stiffness coefficient *k* along the longitudinal section of the workpiece after one pass for T-ECAP with lateral support.

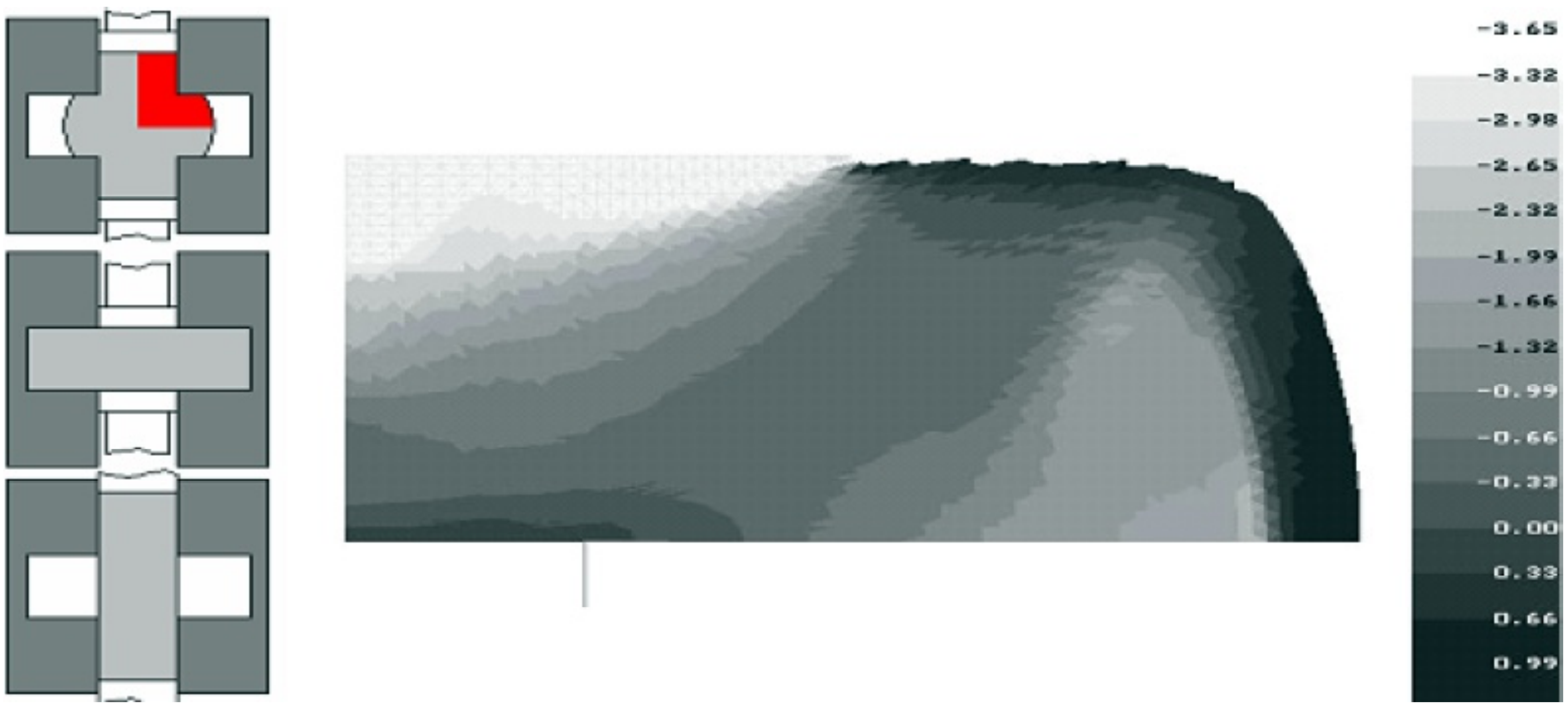

Fig. 9. Distribution of stress state stiffness coefficient *k* along the longitudinal section of the workpiece after one pass for Cross-ECAP without lateral support.

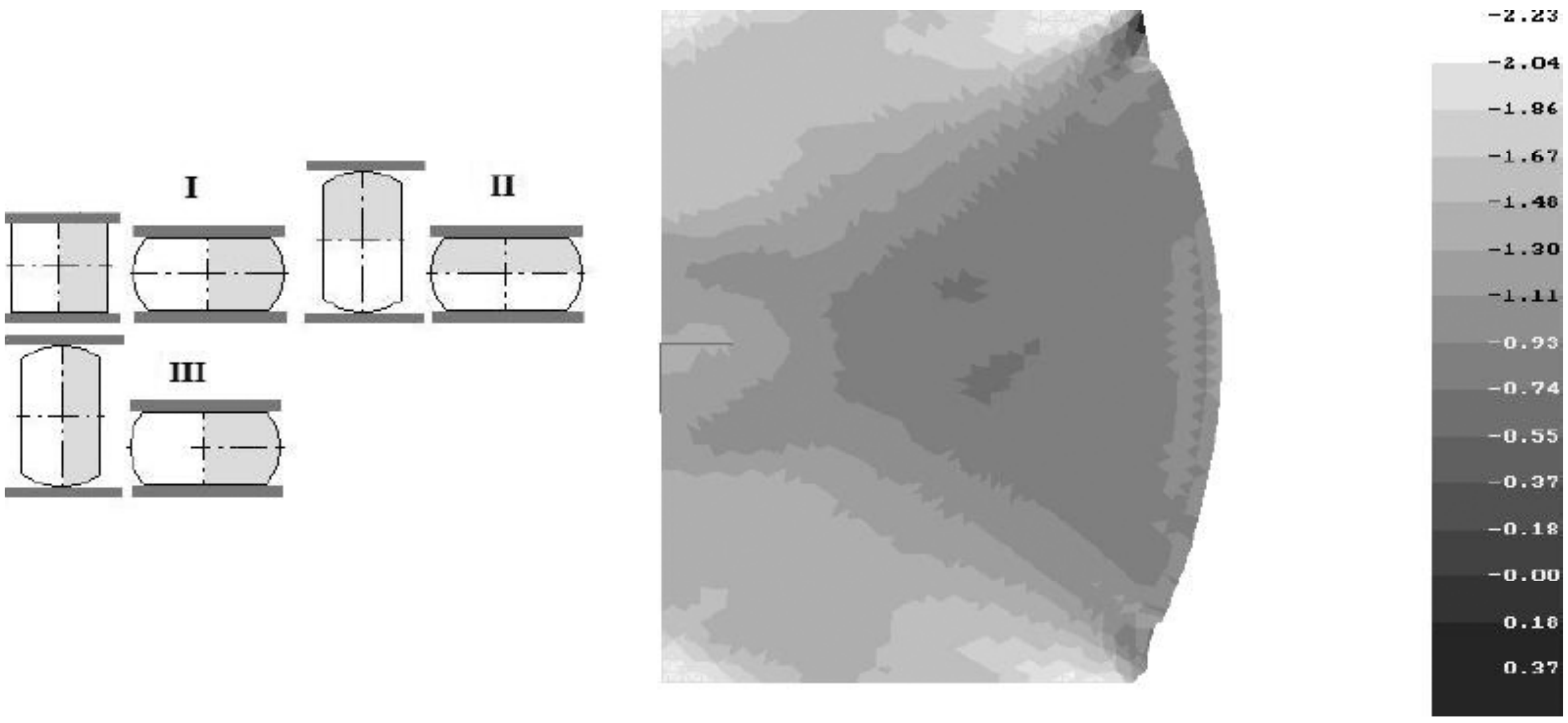

Fig. 10. Distribution of stress state stiffness coefficient *k* along the cross-section of the workpiece after three passes for 2D forging.

sile. In case when low-plastic material is treated tensile stresses occurred can result in discontinuity flaw on its surface.

During T-ECAP coefficient k has positive values at lateral edges of the workpiece (Fig. 7). At the end of the process a free workpiece surface rests on

Fig. 11. The shape of the billet after ECAP process (a) and distribution of accumulated strain intensity for experimental mesh of finite elements (b).

Fig. 12. Appearance of a camera with a sample and striking edges of MAXStrain module.

the lateral side of a die. As a result there appears a lateral support and coefficient k has negative value as shown in the Fig. 8. During Cross-ECAP the similar picture is observed. Besides in central zone of the workpiece coefficient *k* has also positive value that can result in cracks and discontinuity flows appearance in these zones.

During 2D forging coefficient *k* has positive values in the corners of the workpiece that can result in cracks and discontinuity flows appearance in these zones.

3. EXPERIMENTAL RESEARCH OF SPD PROCESSES

3.1. ECAP

Basing on numerical modeling of ECAP process an experimental tool was made [6]. For experimental research of metal flow regime during pressing a method of coordinate scale was used. Aluminum workpieces consisted of two parts with sizes 10x20x65 mm. On the inner side of each part there was a scale made by a laser marker. This scale absolutely corresponded to the finite element mesh used for ECAP process modeling. Fig.11a shows the billet with deformed scale after ECAP. Using special digital handling the experimental scale was transferred into computer file. Then its processing was carried out by FEM methodology with form function use.

Fig. 11b shows distribution of accumulated strain intensity for experimental mesh of finite elements around the deformation zone. Comparing Fig. 2 with Fig.11a one can see that numerical simulation results well agree with experiment. Slight difference in accumulated strain values is caused by varying friction conditions.

3.2. Physical modeling of 2D forging process on GLEEBLE SYSTEM 3800 complex

GLEEBLE SYSTEM 3800 complex is used to simulate deformation processes in metallurgical and machinery technologies. GLEEBLE SYSTEMS are available in several modules, each with a wide variety of available options and configurations.

Multiaxial deformation module is designed for validation through elaboration of technologies to obtain ultra-fine grain materials by plastic deformation methods. Deformation is carried out between two striking edges.

The main difference of this module is possible interchange of deformation in mutually perpendicular transversal to axis directions by 90°-turn of the workpiece relative to longitudinal axis clockwise or anticlockwise. The workpiece is turned together with gripping devices. Rotation speed allows to deform with minimal pause of about 0.5 sec. Appearance of a camera with a sample in the initial state and striking edges for repeated train is shown in Fig. 12.

MAXStrain module operation aspect during biaxial deformation is assignment of striking edge movement value, i.e. reduction in thickness value of a workpiece test portion. It's possible to define

Fig.13. Metal flows on test portion edge of the workpiece after several cycles.

deformation value during the process after each strike only by indirect method, i.e. by calculation subject to plane deformation scheme is being kept on (axial deformation in workpiece is absent).

Test portion length along the longitudinal axis according to producer's requirements should be about 2mm more than striking edge width. Therefore each strike forces some metal out of deformation zone that results in metal flows on the sides of this zone (Fig. 13).

Experimental research was carried out on MAXStrain module at room temperature with commercial aluminum as a test material. Deformation of workpieces was made at 3 stages. Initial workpiece with cross section of 11x11mm was deformed to the one with cross section of 9x9mm, then to the one of 7.4x7.4mm and finally to the one of 6x6mm. Each stage consisted of 60 cycles (one cycle has 2 strikes and a turn). Fig. 14 shows experimental results of MAXStrain module operation.

On the figure one can see metal hardening when passing from one stage to another. At the same time there is deformation force decrease during each stage. It is explained by material reduction in deformation zone (see Fig. 13). As indicated in the picture during experiment for each stage it can be enough to make 10 cycles.

After 2D forging and mechanical operation the workpieces were tensile tested with further macro-

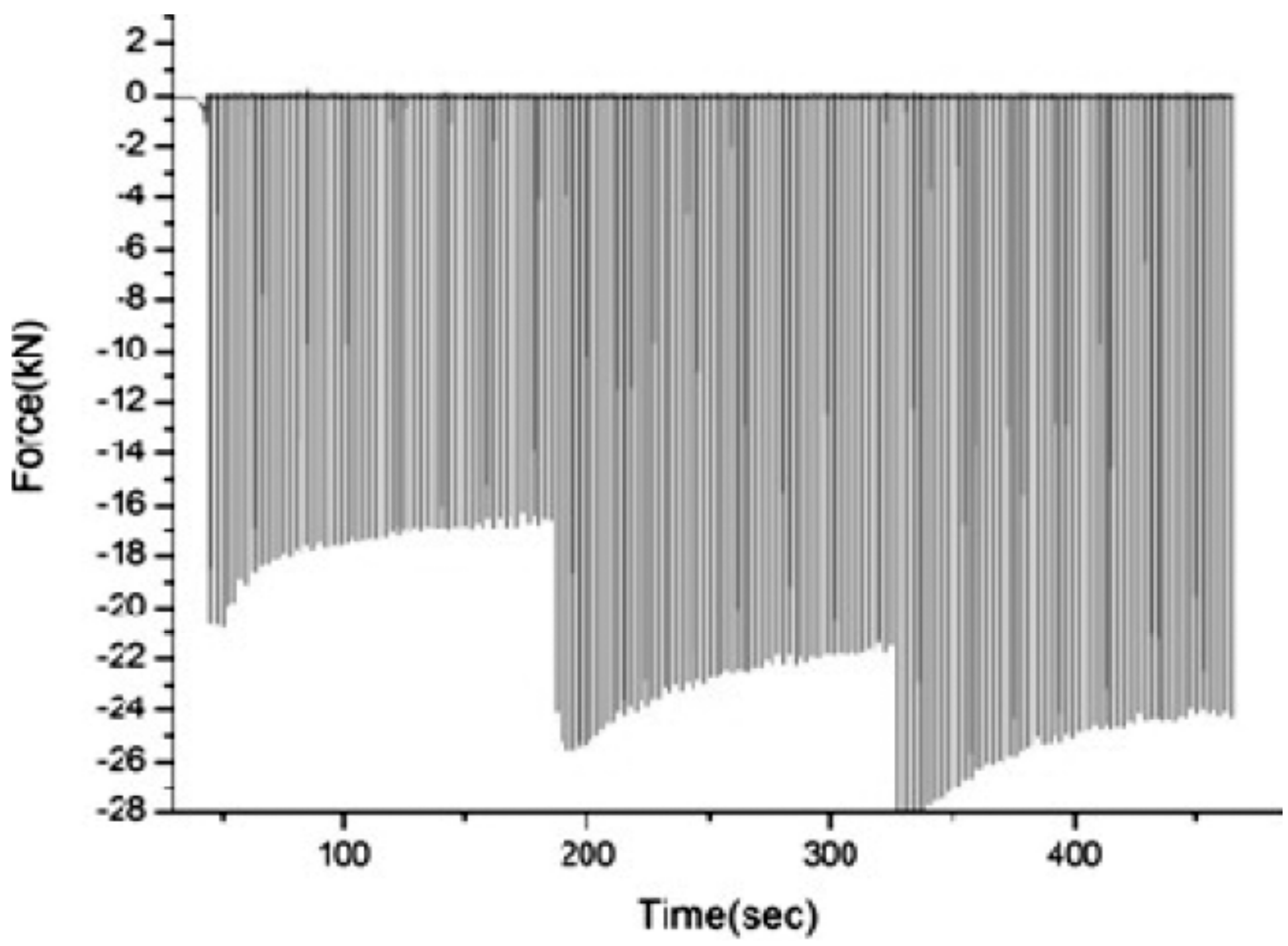

Fig. 14. Deformation force dependence on working time of MAXStrain module.

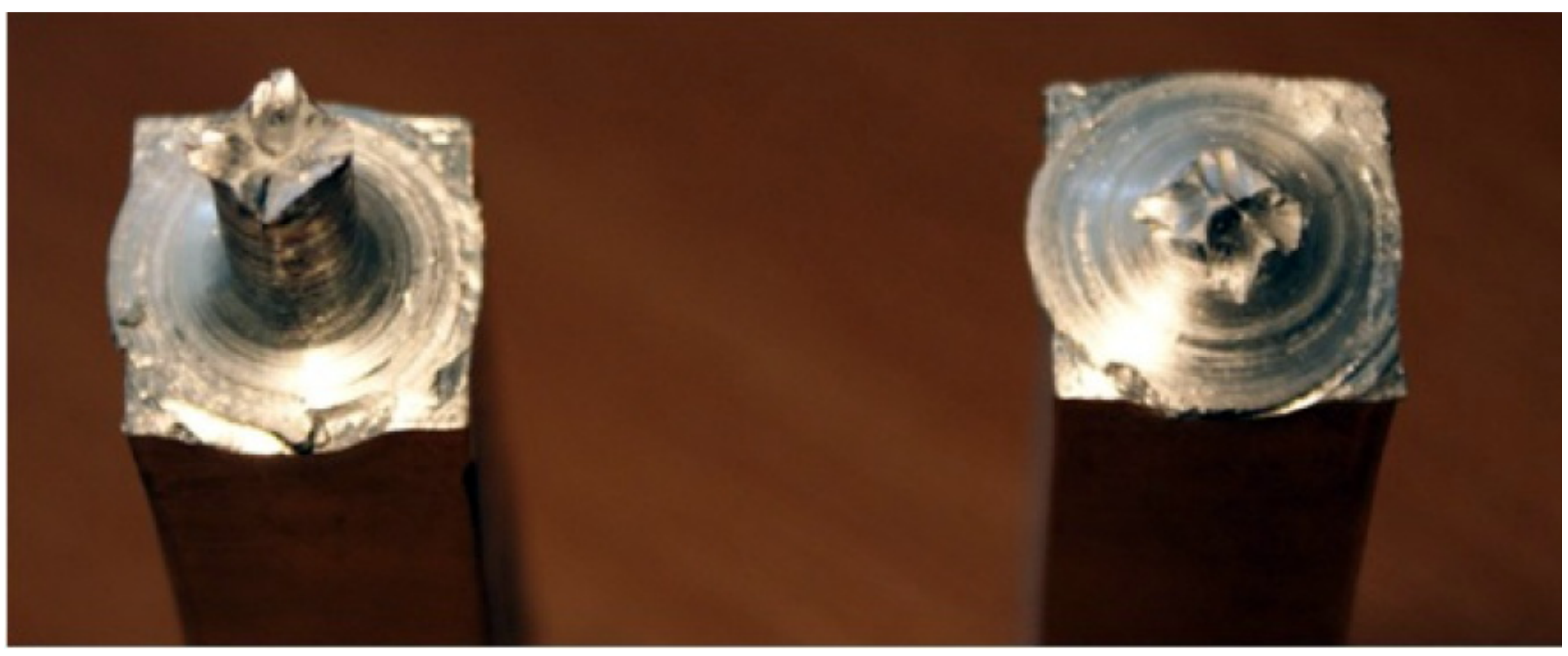

Fig. 15. Appearance of broken workpiece.

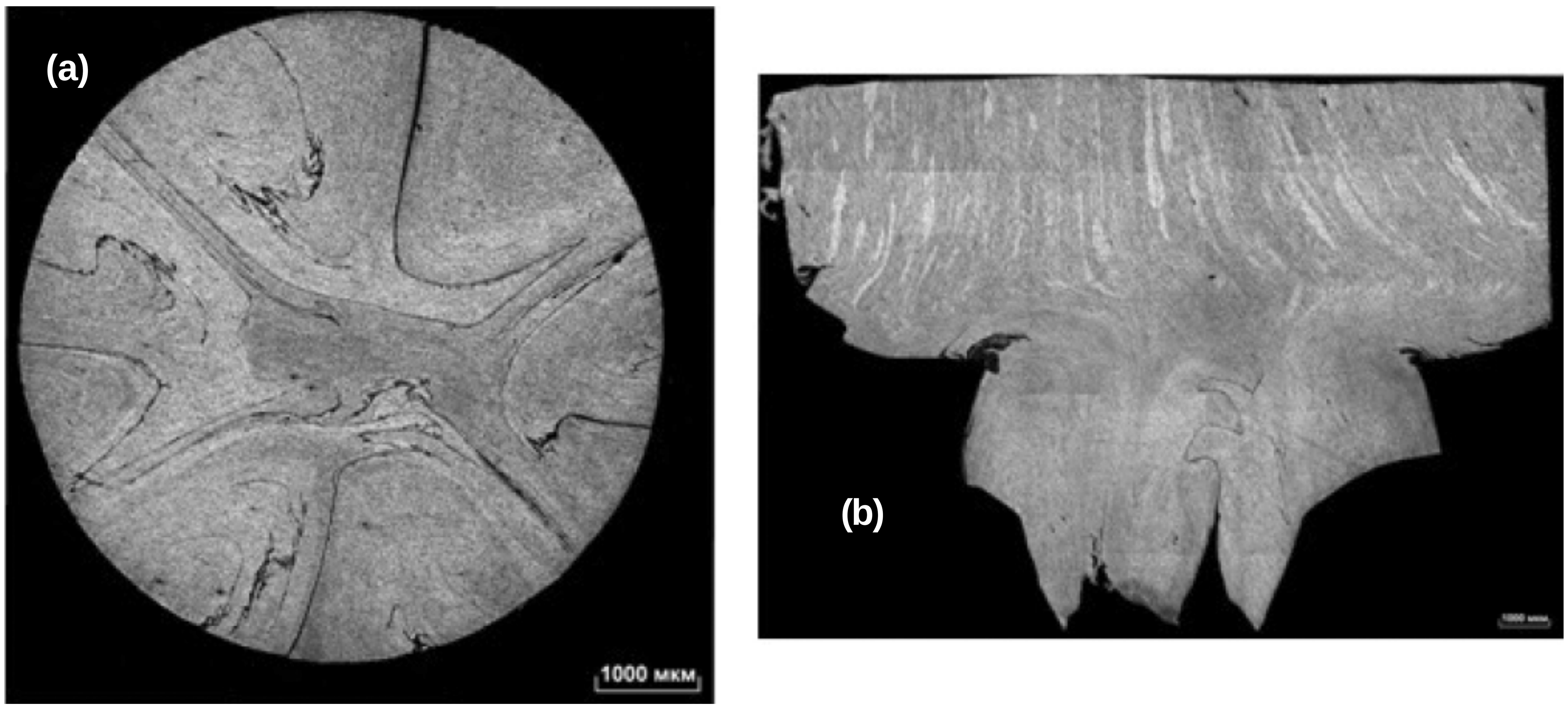

Fig. 16. Structure of test workpiece: a) cross section, b) longitudinal section.

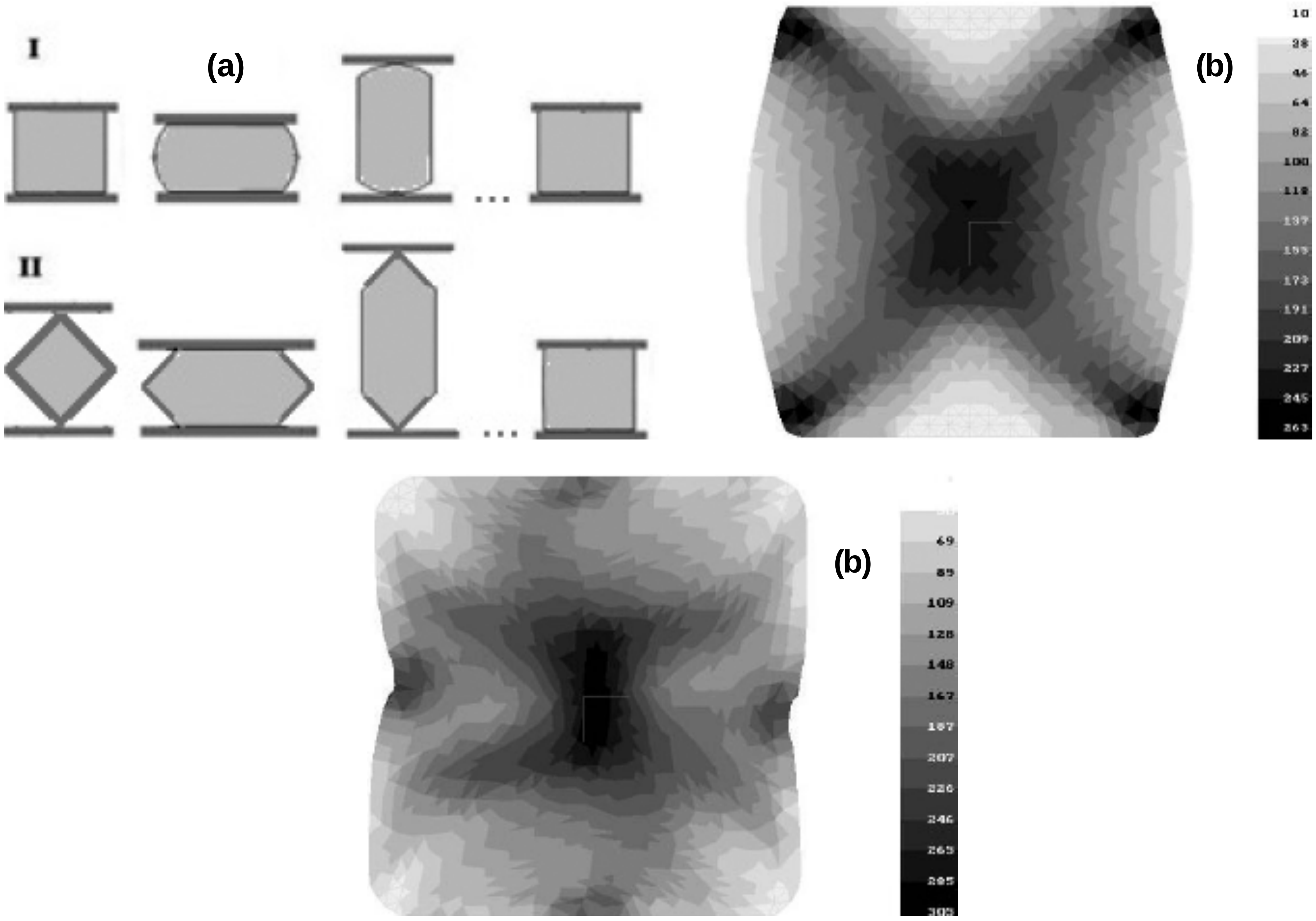

Fig.17. Improved 2D forging: scheme of the process (a), distribution of accumulated strain intensity after 1st (b) and 2nd (c) stages.

structure analyses. Tensile testing was performed on testing machine by Zwick/Roell company.

After severe plastic deformation in 2D forging mode tensile strength of aluminum increased 5 times, but at the same time there is a considerable plasticity decrease. Workpiece breaking is of fragile nature (Fig. 15).

Fig. 16 distinctly shows plastic flow lines and brittle cracks that appeared due to deformation irregularity. In spite of the fact it's relatively easy to put this SPD method into practice, it has one very significant disadvantage – high accumulated deformation distribution irregularity in the cross-section (Fig. 5). Intensive material flow takes place mainly in diagonal making a forging cross, at that accumulated deformation value in these zones can exceed several times a value of average cross-section deformation.

To reduce this irregularity one can offer the following deformation scheme: after deformation cycle made by traditional regime a single deformation force is applied that changes a cross-section form to the square. Then the workpiece is turned around 45° as it is shown in Fig. 17 and the process is going on.

Such turn can be carried out easily enough by changing of the workpiece in the part where it is fixed in the gripping device.

As the results of this process modeling show, after turn and the first two crimping a deformation irregularity along the cross-section reduces (Fig. 17c). One can suppose that deformation cycle amount increase will result in irregularity decrease.

3.3. T-ECAP and Cross-ECAP

The results of numerical modeling of T-ECAP and Cross-ECAP showed high irregularity of deformation distribution along the workpiece cross-section. Since it's impossible to change deformation scheme for these processes it was decided not to carry out experimental research.

4. CONCLUSIONS

On the results of computational modeling and experimental research of SPD processes considered the following conclusions can be made:

SPD methods that can be potentially used to obtain ultra-fine grain and nanostructured materials industrially were compared. For this two criteria were used: accumulated strain regularity value in the workpiece and stress state stiffness coefficient;

ECAP process was shown to have the most accumulated strain regularity value in the workpiece. Numerical simulation results well agree with experiment. For other processes investigated a considerable strain distribution irregularity was established;

Distribution fields of stress state stiffness coefficient along the longitudinal section of the workpiece were graphed. In the processed material zones with most possible cracks formation were revealed;

With joint impact of both criteria the most effective process is ECAP. To reduce zones of possible cracks formation in processed material it's necessary to use extra hydrostatic pressure;

2D forging experiments carried out on GLEEBLE SYSTEM 3800 revealed two serious problems coming out during realization of this process:

Fixation of workpieces doesn't provide for the necessary stiffness of system along longitudinal axis of workpiece. Therefore during transverse contraction there are some longitudinal deformations that accumulate with each deformation cycle. This fact is proved by metal flows out of deformation zone. At that maximal axial deformations are observed at initial deformation cycles as it follows from the diagram of deformation force change at cycles.

During physical modeling of 2D forging there is a significant strain irregularity in the workpiece (a forging cross is formed) that accumulates with each deformation cycle and as a consequence structure irregularity and its properties is observed. One of the possible options to reduce this irregularity is 45° turn of workpieces after each cycle. In this case typical distribution of strain intensity will keep at new cycles but accumulated strain irregularity will decrease. Such deformation scheme can be realized either with use of special construction or with eight-faced workpieces.

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