

NUMERICAL SIMULATION AND EXPERIMENTAL INVESTIGATION OF EQUAL-CHANNEL ANGULAR PRESSING OF POROUS POWDER BILLETS

Full Prof., Dr. Tech. Science Ryabicheva L., Ph.D Usatyuk D., Dyadichev A.
Department of Material Science – Volodymyr Dahl East Ukrainian National University, Lugansk, Ukraine
ryabic@gmail.com

Abstract: The theoretical and experimental study of stress-strain state and density distribution into the billet at equal-channel angular pressing has been conducted. It has shown clearly that deformation zone takes a substantial volume with dramatic non-uniformity of stress-strain state after the first pass of equal-channel angular pressing at the backpressure of 90 MPa. The presence of turbulence zone that ensures structure fragmentation of material has established by microhardness indentation. A possibility of production of high-density billets after the second pass at the backpressure of 150 MPa with high mechanical properties and more uniform stress-strain state, free of loosening and cracks has presented.

KEYWORDS: BILLET, STRESS, DEFORMATION, BACKPRESSURE, DENSITY, MICROHARDNESS, TURBULENCE ZONE.

1. Introduction

Different methods of severe plastic deformation, including equal-channel angular pressing (ECAP), are effective production techniques for materials with prescribed properties. It allows production of high-density powder materials with fine-grained structure, as a result of which their properties are changing qualitatively. Computer modelling of ECAP of various porosity powder billets without backpressure have observed in papers [1, 2]. Evolution of densification and deformation zones depending on physical and mechanical properties of material and deforming conditions has shown clearly. A part of sample moving onto a free surface does not compact properly and its density remains the same with initial billet at deforming without backpressure. It has established [3] that it is possible to obtain ultimate density of powder billets of high initial porosity by ECAP with backpressure.

The purpose of this work is further theoretical and experimental study of densification and plastic forming of porous powder billets after one and two ECAP passes with backpressure.

2. Mathematical model

Mathematical modelling of ECAP has been conducted using the fundamentals of plasticity theory of porous bodies where the plastic potential is described as a function of stress tensor components with the smooth, convex and closed surface corresponding to it into the stress space [4, 5]. This potential may be presented in the following way:

$$(1) \quad F = \frac{\tau^2}{\varphi} + (1+m)^2 \frac{\left(p + \frac{m}{m+1} \bar{\rho} \sigma_s \sqrt{\psi}\right)^2}{\psi} - \bar{\rho} \sigma_s,$$

where $p = \frac{1}{3} \sigma_{ij} \delta_{ij}$ - is the hydrostatic pressure;

$\tau = \sqrt{(\sigma_{ij} - p \delta_{ij})(\sigma_{ij} - p \delta_{ij})}$ - is the intensity of shear stresses;

$\varphi = (1-\theta)^2$, $\psi = \frac{2(1-\theta)^2}{3\theta}$ - are functions of porosity θ ;

$\bar{\rho} = 1 - \theta$ - is the relative density.

m - is the parameter characterizing the degree of imperfection of the contacts in the powder preparation and defining different resistance of a porous body during its testing in tension and compression.

The rate of volume change as a result of plastic deformation may be expressed as follows [5]:

$$(2) \quad e \sim \frac{2(1+m)^2}{\psi} p + \frac{2m(1+m)\sigma_0}{\sqrt{\psi}},$$

where σ_0 - is the flow stress of hard phase, which is a function of accumulated deformation ω and is determined by a hardening curve of powder material at uniaxial tension.

A flow stress of hard phase may be expressed as the function $\sigma = \sigma_0 + K\omega^{0.5}$, where K - is the hardening coefficient. It was assumed that $K/\sigma_0 = 0.5$ during numerical simulation.

The rate of accumulating deformation in hard phase of porous body was determined on the basis of postulate of uniqueness of the dissipation function formulated by Skorokhod V.V. [6]:

$$(3) \quad \omega = \sqrt{1-\theta} \left(\frac{m}{1+m} \sqrt{\psi} e + \frac{\sqrt{(1+m)^2 \gamma^2 + e^2 \psi}}{1+m} \right),$$

where γ - is the shape changing rate.

The value of accumulated deformation ω is renewed by solving of the following differential equation [5]:

$$(4) \quad \frac{d\omega}{dt} = W,$$

where W - is the equivalent strain rate defined as follows [5]:

$$(5) \quad W = \frac{1}{\sqrt{1-\theta}} \sqrt{\psi e^2 + \varphi \gamma^2}.$$

A finite element method presented as a series of procedures was implemented for determination of distributions of stress and strain intensity, as well as density. The first procedure is a triangulation of a plastic deformed body or transition from a continuum billet to its finite element counterpart. Such simulation requires implementation of extremal requirement for the functional [5]:

$$(6) \quad J(v_i(x)) = \int_{\Omega} D(e_{ij}(V_i)) d\Omega + \int_{\partial\Omega_p} p_i v_i d(\partial\Omega),$$

where $D(e_{ij}(V_i))$ - is the dissipative function;

p_i - is the stress vector on the surface of investigated billet;

v_i - is the velocity vector on the surface of investigated billet.

The first integral in the functional (6) is the total rate of energy dissipation, the second integral is the power of external stresses.

The dissipation function $D(e_{ij}(V_i))$ of plastically deforming porous body is described by the following expression [5]:

$$(7) \quad D(e_{ij}(V_i)) = \frac{\sqrt{\gamma^2 \varphi + e^2 \psi}}{\sqrt{1-\theta}} \tau_s + \frac{p_0 e}{\sqrt{1-\theta}},$$

where

$$(8) \quad V_i = v(x), \quad e_{ij} = \frac{1}{2} \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right), \quad p_0 = -\sqrt{\frac{2}{3}} \tau_s \sqrt{\psi} \frac{m}{1+m},$$

τ_s - is the shear yield stress.

The dependences (1) - (8) were used for finite element analysis of ECAP of prismatic-shaped copper porous powder billet with section 15x15 mm, 59 mm in length, initial porosity 42% at temperature 20°C by using of QForm 5.1.3 program. The molybdenum disulfide is used as lubrication material. The viscoplastic material model was implemented for the billet: modulus of elasticity is 124000 MPa, Poisson's ratio 0.35, initial yield stress 100 MPa. The Levanov's exponential friction law was implemented for modelling of friction. Parts of die tool were presented as elastoplastic bodies at isothermal conditions [4, 7, 8].

The essential advantage of the QForm 5.1.3 program is special simulation algorithm for deformation of sintered porous powder billets with initial porosity up to 30%. This algorithm ensures simultaneous calculation of the stress-strain state and distribution of density by the volume of billet for each step of deformation process. The initial data preparation procedure includes operations that are very similar to compact materials with adding of one variable for relative density [8].

Another substantial advantage of the Qform 5.1.3 is fully automatic generation of initial adopted finite element mesh with regular automatic remeshing during simulation process. At the same time the automatic remeshing algorithm allows finite element simulation of forming operations of porous billets with substantial non-uniformity of stress-strain state, because it generates finer mesh in areas of high solution gradients and surface curvature [8].

Finite element modelling of different extrusion schemes performed by authors of papers [1-3, 9-11] has shown clearly possibilities of simulation of metal forming operations for billets with higher initial porosity by the results of mechanical testing of samples with given initial porosity and following multiplying of calculated relative density values by the coefficient of correction that is a quotient of real value of relative density of the billet divided by minimum permissible value for solver of the Qform 5.1.3 that is equal to 0.7 [8, 9].

Thereby, modelling included the following stages: construction of solid model of ECAP, development of mathematical model of deformed porous powder material by the results of uniaxial compression tests of samples with 42% initial porosity, generation of initial adopted finite element mesh from quadratic elements, determination of initial and boundaries conditions, solving of governing equations system, analysis of simulation results [8, 11].

In such case, the density of billet for each deformation step may be determined by the following expression [12]:

$$(9) \quad \rho_i = \frac{\rho_p \cdot h_k}{h_k + (s_i - s_{i-1})},$$

where ρ_p - is the pycnometric density of powder material;

h_k - is the final height of the billet;

s_i - is the displacement of punch at the end of i deformation step;

s_{i-1} - is the displacement of punch at the beginning of i deformation step.

Therefore, average density of the billet may be calculated by the formula [8, 13, 14]:

$$(10) \quad \rho_{ave} = \frac{n}{i=1} \rho_i,$$

where n - is the number of deformation steps.

The increment of relative density for the finite element j on i deformation step, while accounting of expressions (9) and (10), is determined in the following way:

$$(11) \quad \Delta \bar{\rho}_{ij} = \frac{v_{ji}}{v_{ji} - v_{ji-1}},$$

where v_{ji} - is the volume of the finite element j at the end of i deformation step;

v_{ji-1} - is the volume of the finite element j at the beginning of i deformation step.

Consequently, the relative density value for the finite element j on i deformation step was calculated by the following expression:

$$(12) \quad \bar{\rho}_{ij} = \bar{\rho}_{ij} + \Delta \bar{\rho}_{ij}.$$

The average value of relative density of porous powder billet on deformation step i during simulation of density distribution for set of finite elements into the volume of billet:

$$(13) \quad \bar{\rho}_i = \sum_{j=1}^N \bar{\rho}_{ij},$$

where N - is the number of finite elements into the volume of billet.

The limitation on initial value of relative density set in program-solver may be overcome by implementing the coefficient of correction as follows:

$$(14) \quad k_\rho = \frac{\bar{\rho}_{init}^{real}}{\bar{\rho}_{init}},$$

where $\bar{\rho}_{init}^{real}$ - is the initial value of relative density of porous powder billet;

$\bar{\rho}_{init}$ - is the minimum permissible value, limited by the solver.

A precision of simulation of porous powder billets compaction and other forming operations for production of powder parts is defined mostly by the discreteness of finite element discretization the volume of billet and may be increased while decreasing of characteristic dimension of finite element [13, 14].

3. Experimental investigation

The experimental investigation of ECAP has been conducted for verifying of simulation results. Prismatic-shaped with section 15x15 mm, 59 mm in length, initial porosity 42% obtained from electrolytic copper powder PMS-1 GOST 4960-75 by double-action pressing on the hydraulic press PD-476 (force 1600 kN). Sintering was carried out into synthesis gas medium (the gas composition is 72% H₂, 21% CO, 5.5% CO₂, 1.5% H₂O) in a stepwise mode. ECAP performed by the scheme presented on fig. 1 on the same hydraulic press.

The coordinate grid with the cell 3x3 mm was patterned on the billet before ECAP. The compacting pressure during the first pass was 890 MPa and 1330 MPa for the second pass. The value of backpressure assumed 90 MPa for the first pass and 150 MPa for the second pass.

Distributions of stress-strain parameters by sections 1, 2 and 3 (fig. 2) after the first and second passes are presented on fig. 3. The section 1 is from backpressure side and section 3 under the punch.

Simulation of ECAP has shown that stress-strain state after the first pass is characterized by substantial non-uniformity (fig. 3, a). Increasing of the intensity of stress has been observed in section 1 from bottom face to upper face with maximal value of 257 MPa into the deformation zone. It decreases dramatically on the upper face of billet. The same character of variation of stress intensity has been observed in the section 2 with a bit higher value into the deformation zone. The second deformation zone is formed under the punch in section 3 under the influence of friction forces similarly to closed-die upsetting: the intensity of stress has grown from the bottom to upper face. At the same time the intensity of stress under the punch was equal to 198 MPa.

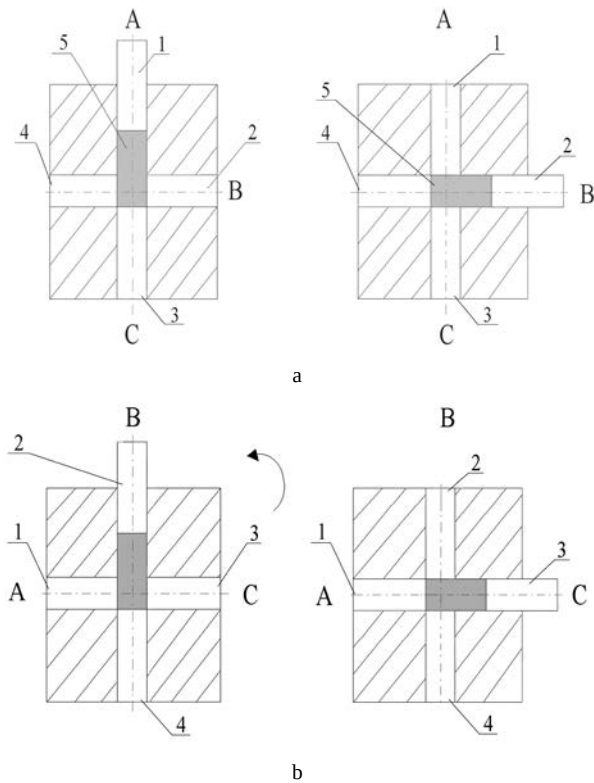


Fig. 1 Scheme of equal-channel angular pressing: *a* – is the first pass; *b* – is the second pass.

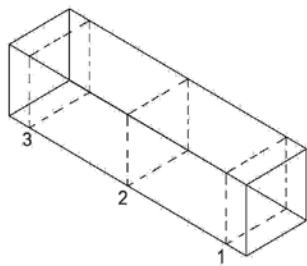


Fig. 2 Sections of the billet.

The second pass has been performed after rotation of the billet: section 1 was placed under the punch; section 3 – from the backpressure side, explanation remained the same. Decreasing the intensity of stress has been observed in section 1 from the bottom face to upper face. The deformation zone with maximal intensity of stress remained in section 2, but its size is smaller due to hardening of hard phase obtained during the first pass. Diminishing of stress intensity in section 3 under the punch has been observed (fig. 3, a).

Changing the intensity of deformation indicates that deformation zone almost fills the central part of billet, scoping the volume from the punch to backpressure side. In such case intensity of deformation grows to maximum value into the deformation zone and on the corner part of the upper face. The volume of the deformation zone after the second pass decreased, densification was minimal, deformation of powder particles has happened. Obviously, the volume changing rate of billet is lower than forming rate.

Experimentally verified distribution of deformation intensity is presented on fig. 4. The character and value of deformation intensity is similar to the picture obtained by numerical simulation. Loosening has appeared on upper face of the billet in section 1 that indicating of insufficient backpressure value. The billet has no loosening and cracks after the second pass while increasing of backpressure up to 150 MPa. The coordinate grid was substantially distorted. Formation of vortex has observed into the deformation zone that indicates intensity of high angle boundaries formation [7].

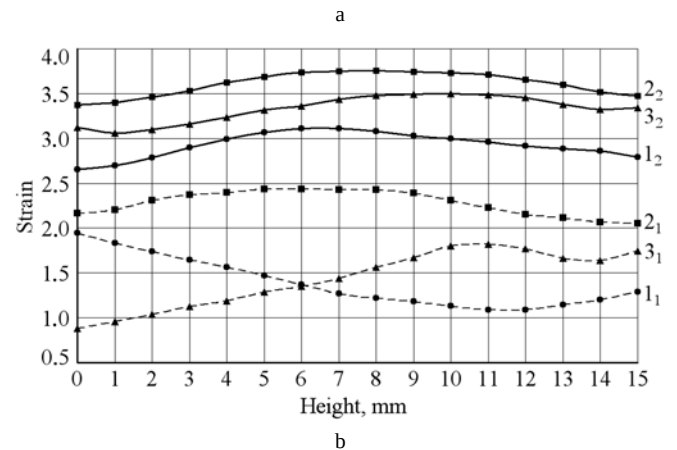
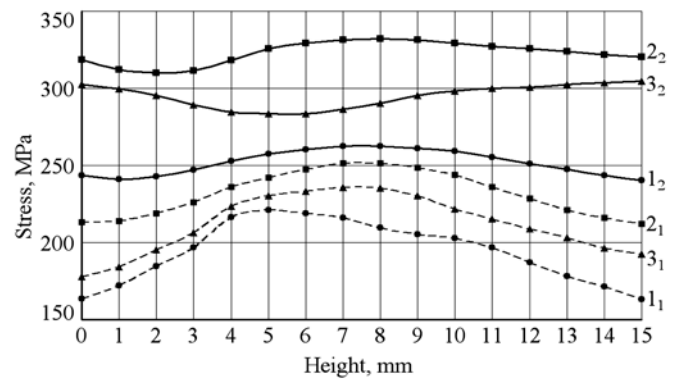


Fig. 3 Distribution of the intensity of stress – *a* and deformation – *b* in sections 1, 2 and 3, obtained by numerical simulation: $1_1, 2_1, 3_1$ – after the first pass; $1_2, 2_2, 3_2$ – after the second pass.

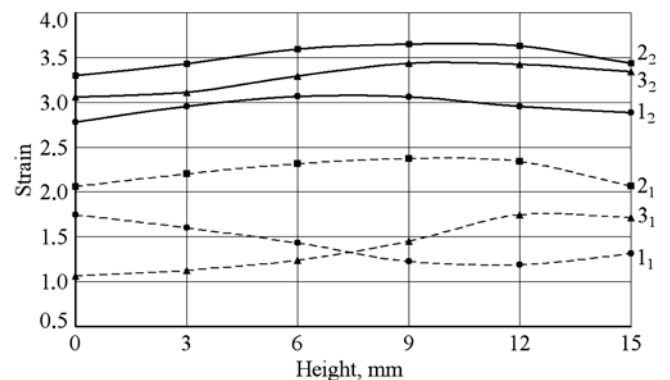


Fig. 4 Distribution of the deformation intensity by the sections 1, 2 and 3 (experimental): $1_1, 2_1, 3_1$ – after the first pass; $1_2, 2_2, 3_2$ – after the second pass.

Microhardness variation has been investigated by longitudinal section of the sample after the first and second passes for experimental estimation of stress state. A non-monotonic distribution of microhardness after the first pass has been observed. The microhardness level is growing by section of billet from outer faces to the centre while growing the intensity of deformation. The highest microhardness value 714 MPa that is corresponding to maximal intensity of deformation has been measured into the deformation zone. The microhardness into zone from backpressure side was 480 MPa at deformation intensity 1.2 that is connected with development of loosening. Growing of microhardness has been observed after the second pass and variation of its values between the outer surface and centre of the billet drops substantially while increasing of accumulated deformation. The highest microhardness of 780 MPa was measured after the second pass into the deformation zone where formation of vortex field, connected with transversal flow of material in the plane normal to the deformation axis, has been observed. The highest intensity of deformation after the second pass was equal to 4.0, corresponding to main

microhardness growth into the middle zone and zone under the punch.

Distributions of relative density lengthwise of billets are presented on fig. 5. It has established that after the first pass of ECAP it is possible to distinguish three zones into the volume of billet: 1 – is the loosening zone appeared from the backpressure side; 2 – is the middle zone of maximal density; 3 – is the zone under the punch.

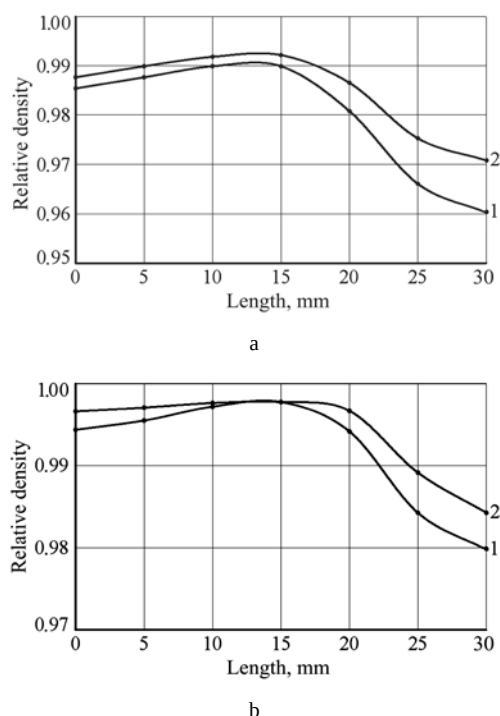


Fig. 5 Density distributions lengthwise of billets after ECAP: a – after the first pass; b – after the second pass: 1 – is the experimental dependence; 2 – is the dependence plotted by the results of numerical simulation.

The length of each zone was approximately 10 mm after the first pass, while depth of damage layer from the backpressure side was 0.4 mm.

The inhomogeneous distribution of relative density after the first pass is stipulated by non-uniformity of stress-strain state and effect of friction forces. The relative density that is almost equal to 1 has been observed after the second pass into zones 2 and 3 while decreasing from the backpressure side.

The relative error of determination of relative density by a finite element method with implementation of expressions (11) - (14) was 1.4-2.5 % that is quite sufficient for practical purposes.

4. Conclusions

Theoretical investigation and finite element simulation using the QForm 5.1.3 program verified by the results of laboratory experiments have shown clearly that density obtained into the volume of porous powder billet after the first pass of ECAP at the backpressure of 90 MPa was lower than density of compact material. The deformation zone fills large volume, scoping of three zones distinguished into the billet, at substantial non-uniformity of stress-strain state. The high-density billet with more uniform stress-strain state, free of loosening and cracks has been obtained after the second pass of ECAP at the backpressure of 150 MPa while contracting a size of the deformation zone. The presence of turbulence zone that ensures structure fragmentation and promotes to production of billets of powder materials with ultrafine-grained structure and high mechanical properties has been established by microhardness indentation.

5. References

1. Maydanyuk A. Equal-channel angular extrusion of porous billets: computer simulation and experimental study, The International congress and exhibition EURO PM 2010 proceedings, October 10-14, 2010, Florence, Vol. 3, pp. 1206–1212 (Maydanyuk, A., M. Shtern, G. Bagluck, L. Ryabicheva).
2. Maydanyuk A.P. Evolution of density distribution at equal-channel angular pressing of porous billets, Herald of the Volodymyr Dahl East Ukrainian National University, 2008, Issue 3, Vol. 2, pp. 213–216 (Maydanyuk, A.P., L.A. Ryabicheva, M.B. Shtern, G.A. Bagluck).
3. Ryabicheva L.A. Deformation behavior of porous powder billet during equal-channel angular pressing, Herald of the National Technical University «Kharkiv Polytechnical Institute», 2010, pp. 42–50 (Ryabicheva, L.A., V.V. Smolyak).
4. Favrot N. Modeling Sintering Deformations Occurring After Cold Compaction, Qualitative Methods for the Mechanics of Compaction, Proceedings of the International Workshop on Modeling of Metal Powder Forming Process, Grenoble, France, 21-23 July 1997, pp. 133 – 147 (Favrot, N., J. Besson, C. Colin, F. Delannay, Y. Bienvenu).
5. Shtern M.B. Phenomenological theories of powders pressing. Kiev, Naukova dumka, 1982. – 140 p (Shtern, M.B., G.G. Serdjuk, L.A. Maksimenko).
6. Skorokhod V.V. The rheological basics of sintering theory, Kyiv, Naukova Dumka, 1972. – 152 p (Skorokhod, V.V.).
7. Beygelzimer Ya.E. Some considerations concerning severe plastic deformations based on their similarity with vorticity, High Pressure Physics and Technics, 2008, Vol. 18, No 4, pp. 77–86 (Beygelzimer, Ya.E.).
8. Biba N. Material Forming Simulation Environment based on QForm3D Software System, Metal Forming 2008: Proceedings of the 12th International Conference on Metal Forming / Ed. by M.Pietrzyk et.al., Verlag Stahleisen GmbH., Poland, Krakow, 2008 (Biba, N., S. Stebunov).
9. Ryabicheva L.A Modeling of evolution of the deformation zone for different extrusion schemes, Herald of the Moscow State University of Mechanical Engineering «MAMI», 2013, No. 1(15), pp. 120-124 (Ryabicheva, L.A, D.A. Usatyuk).
10. Ryabicheva L. Computer modeling of radial-direct extrusion of complex-shaped details // Journal of Computer and Information Technology, 2012. Vol. 2, No. 1, pp. 91–101 (Ryabicheva, L., D. Usatyuk, N. Beloshitskij).
11. Ryabicheva L. Computer Modelling of Radial-Direct Extrusion of Porous Powder Billets. Computational and Numerical Simulations: The book, INTECH Open Access Publisher, Croatia, 2014, Ch. 6, pp. 119–137 (Ryabicheva, L., D. Usatyuk), <http://dx.doi.org/10.5772/57142>.
12. Bragina I.Y. The study of the pressure effect on the compression of ZrO₂ powder with heating by electric current // Materials working by pressure, 2013, No. 3 (36), pp. 145–149.
13. Ryabicheva L. Mathematical Modelling of Structure Formation of Discrete Materials // Numerical Simulations, Applications, Examples and Theory: The book, INTECH Open Access Publisher, Croatia, 2011, pp. 377–400 (Ryabicheva, L., D. Usatyuk), <http://dx.doi.org/10.5772/13193>.
14. Wagoner R.H. Metal Forming Analysis. Cambridge University Press, 2001. – 376 p (Wagoner, R.H., J.L. Chenot).