Mechatronic Systems 2

Applications in Material Handling Processes and Robotics

Edited by
Leonid Polishchuk
Orken Mamyrbayev
Konrad Gromaszek

ROUTLEDGE

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Edited by

Leonid Polishchuk
Vinnytsia National Technical University, Vinnytsia, Ukraine

Orken Mamyrbayev
Institute of Information and Computational Technologies CS MES RK, Almaty, Kazakhstan

Konrad Gromaszek
Lublin University of Technology, Lublin, Poland

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Konrad Gromaszek was born in Poland in 1978. He was professor of the Lublin University of Technology at the Faculty of Electrical Engineering and Computer Sciences. After obtaining a doctorate in December 2006, he was employed at the Department of Electronics and Information Technology. In 2019, he obtained DSc degree and now works as a university professor.

In the years 2007–2008, he was the manager of the FP6 project, related to the development of the Regional Innovation Strategy for the Lubelskie Voivodeship. He participated in a total of about 15 courses and training in data management and processing. He has received two awards from the Rector of the Lublin University of Technology (second and third degree). Konrad Gromaszek is the author and coauthor of over 53 publications (including three monographs, two manuals, and scripts). He was the tutor of 89 diploma theses. He tries to combine research and teaching with organizational activities. He participated in the preparation of applications for seven research projects and was the contractor in four. He is also active in non-university projects as an expert. He belongs to the following organizations: IEEE, Polish Association of Measurements for Automation and Robotics (POLSPAR), Polish Society of Theoretical and Applied Electrical Engineering (PTETiS), Polish Information Technology Society (PTI), and Lubelskie Towarzystwo Naukowe (LTN).

Orken Mamyrbayev was born in Kazakhstan, 1979. He was Deputy General Director in science and head of the laboratory of computer engineering of intelligent systems at the Institute of Information and Computational Technologies. In 2014, he obtained his Ph.D. in Information Systems at the Kazakh National Technical University named after K. I. Satbayev and was Associate Professor in 2019 at the Institute of Information and Computational Technologies. He is a member of the dissertation council "Information Systems" at L.N. Gumilyov Eurasian National University in the specialties Computer Sciences and Information Systems. His main research field of activity is related to machine learning, deep learning, and speech technologies. In total, he has published more than five books, over 120 papers, and authored several patents and copyright certificates for an intellectual property object in software. Currently, he manages two scientific projects: the development of an end-to-end automatic speech recognition system for agglutinative languages and information model and software tools for the system of automatic search and analysis of multilingual illegal web content based on the ontological approach.

Leonid Polishchuk was born in Ukraine in 1954. He is the Head of the Department of Industrial Engineering at Vinnitsia National Technical University, Ukraine. Leonid is Doctor of Technical Sciences, professor, academician at the Ukraine Academy of Hoisting-and-Transport Sciences, member of the editorial board of two scientific and technical publications in Ukraine, and member of the specialized scientific council for the defense of doctoral dissertations. In 1994, he defended his thesis "Dynamic Load of the Mechanical System of the Belt Conveyor with the Built-in Drive" in the concentration of "Dynamics, Strength of Machines, Devices and Equipment". In 2017, he defended the specialized council doctoral thesis "Dynamics of Drive System and Boom Construction of Belt Conveyors on Mobile Machinery" in the concentration of "Dynamics and Strengths of Machines." The scientific focus is the dynamics of drive systems with devices and control systems with variable operating modes and diagnostics of metal structures of hoisting-and-transport and technological machines. He has more than 200 scientific publications of which two are monographs, 123 are of scientific and 18 are of educational and methodological nature, 8 are of scientific nature in publications such as Scopus and WoS, and 33 are patents.

List of contributors

I. Aftanaziv, Descriptive Geometry and Engineering Graphics Department, Institute of Applied Mathematics and Basic Sciences, National University "Lvivska Polytechnica", Lviv, Ukraine

I. Aliiev, Automation of Mechanical Engineering and Information Technologies, Processing of Metal Forming Department, Donbass State Engineering Academy, Kramatorsk, Ukraine

L. Aliieva, Automation of Mechanical Engineering and Information Technologies Processing of Metal Forming Department, Donbass State Engineering Academy, Kramatorsk, Ukraine

Y. Amirgaliyev, Institute of Information and Computational Technologies CS MES RK, Almaty, Kazakhstan

S. Amirgaliyeva, Institute of Information and Computational Technologies CS MES RK, Almaty, Kazakhstan, IT Department, Academy of Logistics & Transport, Almaty, Kazakhstan

A. I. Andrukhiv, Transport Technologies Department, Lviv Polytechnic National University, Lviv, Ukraine

R. Argat, Mechanical Engineering Technology Department, Institute of Mechanics and Transport, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

T. Arkhipova, Department of Material Resistance and Applied Mechanics, Vinnytsia National Technical University, Vinnytsia, Ukraine

D. Baitussupov, IT Department, Academy of Logistics & Transport, Almaty, Kazakhstan

V. Bandura, Agricultural Engineering and Technical Service Department, Vinnytsia National Agrarian University, Vinnytsia, Ukraine

Y. Basova, Processing of Metal Forming Department, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine

G. Borankulova, Faculty of Information Technology, Automation and Telecommunications, M. Kh. Dulaty Taraz Regional University, Taraz, Kazakhstan

I. Bubnovska, Electrical Systems, Technologies and Automation in Agriculture Department, Vinnytsia National Agrarian University, Vinnytsia, Ukraine

R. Budyak, Machine-Tractor Fleet Operation and Maintenance Department, Vinnytsia National Agrarian University, Vinnytsia, Ukraine

A. Chernish, Mechanical Engineering Technology Department, Institute of Mechanics and Transport, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

V. Chukhlib, Processing of Metal Forming Department, Kharkiv Polytechnic Institute, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine

Y. Danylchenko, Machine Design Department, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine

O. Dedov, Machines and Equipment of Technological Processes Department, Kyiv National University of Construction and Architecture, Kyiv, Ukraine

O. Deribo, Machine-Building Technology and Automation Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

O. Diachenko, Machines and Equipment of Technological Processes Department, Kyiv National University of Construction and Architecture, Kyiv, Ukraine

M. Dmytriiev, Industrial Engineering Department, Vinnitsia National Technical University, Vinnytsia, Ukraine

V. Dragobetskii, Mechanical Engineering Technology Department, Institute of Mechanics and Transport, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

P. Droździel, Faculty of Mechanical Engineering, Lublin University of Technology, Lublin, Poland

Z. Dusaniuk, Machine-Building Technology and Automation Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

G. Duskazaev, IT Department, Academy of Logistics & Transport, Almaty, Kazakhstan

P. Golubkov, Automation of Technological Processes and Robotic Systems Department, Odessa National Academy of Food Technologies, Odessa, Ukraine

K. Gromaszek, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, Lublin, Poland

R. Grudetskyi Automation and Computer-Integrated Technologies Department, Lutsk National Technical University, Lutsk, Ukraine

S. Gubskyi, Processing of Metal Forming Department, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine

P. Harchuk, Automation and Computer-Integrated Technologies Department, Lutsk National Technical University, Lutsk, Ukraine

V. F. Hraniak, Theoretical Electrical Engineering and Electrical Measurements Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

O. Hrushko, Material Resistance and Applied Mechanics Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

B. Imanbek, Faculty of Information Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan

R. Iskovych-Lototsky, Industrial Engineering Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

Y. Ivanchuk, Computer Science Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

M. Junisbekov, Automation and Telecommunications, M. Kh. Dulaty Taraz Regional University, Taraz, Kazakhstan

M. Kalimoldayev, Institute of Information and Computational Technologies CS MES RK, Almaty, Kazakhstan

V. Kaliuzhnyi, Aircraft Production Technologies Department, National Technical University of Ukraine 'Igor Sikorsky Kyiv Polytechnic Institute', Kyiv, Ukraine

A. Kalizhanova, Institute of Information and Computational Technologies CS MES RK, Almaty, Kazakhstan, Faculty of Information Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan

P. Kisała, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, Lublin, Poland

Y. Klemeshov, Metal Forming Department, Z. I. Nekrasov Iron & Steel Institute of NAS of Ukraine, Kyiv, Ukraine

T. R. Klotchko, Devices Production Department, National Technical University of Ukraine "Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine

P. Komada, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, Lublin, Poland

A. Kotyra, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, Lublin, Poland

I. Koval, Integration of Education with Enterprises Department, National University "Lvivska Polytechnica", Lviv, Ukraine

K. Koval, Integration of Education with Enterprises Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

O. O. Koval, Industrial Engineering Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

M. Kovalchuk, Higher Mathematics Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

A. Kozbakova, Institute of Information and Computational Technologies CS MES RK, Almaty, Kazakhstan, Faculty of Engineering and IT, Almaty Technological University, Almaty, Kazakhstan

M. Kozhamberdiyeva, Faculty of Information Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan

V. Kraievskyi, Higher Mathematics Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

V. V. Kukharchuk, Theoretical Electrical Engineering and Electrical Measurements Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

Y. Kulakova, Institute of Automation and Information Technologies, Satbayev University, Almaty, Kazakhstan

V. Levchenko, Automation of Mechanical Engineering and Information Technologies, Processing of Metal Forming Department, Donbass State Engineering Academy, Kramatorsk, Ukraine

O. Mamyrbaev, Institute of Information and Computational Technologies CS MES RK, Almaty, Kazakhstan

V. Matviichuk, Electrical Systems, Technologies and Automation in Agriculture Department, Vinnytsia National Agrarian University, Vinnytsia, Ukraine

M. O. Mokliuk, Department of Material Resistance and Applied Mechanics, Vinnytsia State Pedagogical University named after M. Kotsiubynsky, Vinnytsia, Ukraine

T. Molodetska, Industrial Engineering Department, Vinnitsia National Technical University, Vinnitsia, Ukraine

D. Moloshtan, Mechanical Engineering Technology Department, Institute of Mechanics and Transport, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

O. Mozghovyi, Physics and Methods of Teaching Physics, Astronomy Department, Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, Vinnytsia, Ukraine

M. Mussabekov, IT Department, Academy of Logistics & Transport, Almaty, Kazakhstan

O. Mykhalevych, Higher Mathematics Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

V. Mykhalevych, Higher Mathematics Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

O. Naumova, Mechanical Engineering Technology Department, Institute of Mechanics and Transport, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

I. Nazarenko, Machines and Equipment of Technological Processes Department, Kyiv National University of Construction and Architecture, Kyiv, Ukraine

Y. Nemyrovskyi, Exploitation and Repairing Machine Department, Central Ukrainian National Technical University, Kirovohrad, Ukraine

K. Nurseitova, Department of Information Technology, D. Serikbayev East Kazakhstan State Technical University, Ust-Kamenogorsk, Kazakhstan

G. Ogorodnichuk, Industrial Engineering Department, Vinnytsia National Agrarian University, Vinnytsia, Ukraine

V. Ogorodnikov, Department of Material Resistance and Applied Mechanics, Vinnytsia National Technical University, Vinnytsia, Ukraine

A. Okun, Processing of Metal Forming Department, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine

Z. Omiotek, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, Lublin, Poland

A. Oralbekova, IT Department, Kazakh University Ways of Communications, Almaty, Kazakhstan

S. Orazalieva, Faculty of Engineering and IT, Almaty Technological University, Almaty, Kazakhstan

A. Ormanbekova, Faculty of Information Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan

S. Pavlov, Biomedical Engineering Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

A. Petryshyn, Machine Design Department, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine

O. Polischuk, Safety of Life and Security Pedagogy Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

N. Posvyatenko, Manufacturing, Repair and Materials Engineering Department, National Transport University, Kyiv, Ukraine

E. Posviatenko, Manufacturing, Repair and Materials Engineering Department, National Transport University, Kyiv, Ukraine

R. Puzyr, Mechanical Engineering Technology Department, Institute of Mechanics and Transport, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

S. Rakhmetullina, East Kazakhstan State Technical University named after D.Serikbayev, Ust-Kamenogorsk, Kazakhstan

S. Repinskyi, Machine-Building Technology and Automation Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

M. Ruchynskyi, Machines and Equipment of Technological Processes Department, Kyiv National University of Construction and Architecture, Kyiv, Ukraine

V. Rutkevych, Machinery and Equipment of Agricultural Production Department, Vinnytsia National Agrarian University, Vinnytsia, Ukraine

V. Savulyak, Industrial Engineering Department, Vinnitsia National Technical University, Vinnytsia, Ukraine

A. P. Senyk, Transport Technologies Department, Lviv Polytechnic National University, Lviv, Ukraine

O. Serdiuk, Machine-Building Technology and Automation Department, Vinnytsia National Technical University, Vinnytsia, Ukraine,

I. Sevostyanov, Technological Processes and Equipment of Processing and Food Production Department, Vinnytsia National Agrarian University, Vinnytsia, Ukraine

A. Shapoval, Mechanical Engineering Technology Department, Institute of Mechanics and Transport, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

S. Shargorodsky, Machinery and Equipment of Agricultural Production Department, Vinnitsia National Technical University, Vinnitsia, Ukraine

V. Shenfeld, Industrial Engineering Department, Vinnitsia National Technical University, Vinnitsia, Ukraine

I. Shepelenko, Exploitation and Repairing Machine Department, Central Ukrainian National Technical University, Kirovohrad, Ukraine

L. Shevchuk, Descriptive Geometry and Engineering Graphics Department, Institute of Applied Mathematics and Basic Sciences, National University "Lvivska Polytechnica", Lviv, Ukraine

S. Shlyk, Mechanical Engineering Technology Department, Institute of Mechanics and Transport, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

A. Shortanbayeva, Faculty of Information Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan

V. I. Skytsiouk, Devices Production Department, National Technical University of Ukraine "Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine

A. Slabkyi, Industrial Engineering Department, Lutsk National Technical University, Lutsk, Ukraine

S. Smailova, Department of Information Technology, D. Serikbayev East Kazakhstan State Technical University, Ust-Kamenogorsk, Kazakhstan

A. Smolarz, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, Lublin, Poland

D. Somov, Automation and Computer-Integrated Technologies Department, Lutsk National Technical University, Lutsk, Ukraine

B. I. Sokil, Engineering Mechanics Department, Hetman Petro Sahaidachnyi National Army Academy, Lviv, Ukraine

M. B. Sokil, Transport Technologies Department, Lviv Polytechnic National University, Lviv, Ukraine, D. Somov, Automation and Computer-Integrated Technologies Department, Lutsk National Technical University, Lutsk, Ukraine

L. Strutynska, Descriptive Geometry and Engineering Graphics Department, Institute of Applied Mathematics and Basic Sciences, National University "Lvivska Polytechnica", Lviv, Ukraine

S. Strutynskyi, Applied Hydroaeromechanics and Mechanotronics Department, Igor Sikorsky Kyiv Politechnic Institute, Kyiv, Ukraine

A. Sviderskyi, Machines and Equipment of Technological Processes Department, Kyiv National University of Construction and Architecture, Kyiv, Ukraine

I. Svidrak, Descriptive Geometry and Engineering Graphics Department, Institute of Applied Mathematics and Basic Sciences, National University "Lvivska Polytechnica", Lviv, Ukraine

V. Sychuk, Automation and Computer-Integrated Technologies Department, Lutsk National Technical University, Lutsk, Ukraine

V. Tikhenko, Metal-Cutting Machines, Metrology and Certification Department, Odessa National Politechnical University, Odessa, Ukraine

A. Toigozhinova, IT Department, Academy of Logistics and Transport, Almaty, Kazakhstan

Y. Tsekhanov, Department of Engineering and Computer Graphics, Voronezh State Technical University, Voronezh, Russia

A. Tuleshov, Institute of mechanics and engineering science CS MES RK, Almaty, Kazakhstan

Y. Turgynbekov, Faculty of Information Technology, Automation and Telecommunications, M. Kh. Dulaty Taraz Regional University, Taraz, Kazakhstan

V. Turych, Industrial Engineering Department, Vinnytsia National Agrarian University, Vinnytsia, Ukraine

V. M. Tverdomed, Faculty of Infrastructure and Railway Rolling Stock, State University of Infrastructure and Technology, Kyiv, Ukraine

G. S. Tymchyk, Devices Production Department, National Technical University of Ukraine "Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine

S. Tymchyk, Biomedical Engineering Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

R. Vakylenko, Mechanical Engineering Technology Department, Institute of Mechanics and Transport, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

N. Veselovska, Machinery and Equipment of Agricultural Production Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

I. Vishtak, Material Resistance and Applied Mechanics Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

N. Weselowska, Industrial Engineering Department, Vinnytsia National Agrarian University, Vinnytsia, Ukraine

W. Wójcik, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, Lublin, Poland

V. Yehorov, Automation of Technological Processes and Robotic Systems Department, Odessa National Academy of Food Technologies, Odessa, Ukraine

B. Yeraliyeva, Faculty of Information Technology, Automation and Telecommunications, M. Kh. Dulaty Taraz Regional University, Taraz, Kazakhstan

G. Yerkeldessova, IT Department, Academy of Logistics & Transport, Almaty, Kazakhstan

G. Yusupova, Department of IT, Turan University, Almaty, Kazachstan

O. Zabolotnyi, Automation and Computer-Integrated Technologies Department, Lutsk National Technical University, Lutsk, Ukraine

V. Zagoryanskii, Mechanical Engineering Technology Department, Institute of Mechanics and Transport, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine

U. Zhunissova, Department of IT, Astana Medical University, Nur-Sultan City, Kazakhstan

S. Zlepko, Biomedical Engineering Department, Vinnytsia National Technical University, Vinnytsia, Ukraine

I. Zozulyak, Technological Processes and Equipment of Processing and Food Production Department, Vinnytsia National Agrarian University, Vinnytsia, Ukraine

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Chapter 10

Tensor models of accumulation of damage in material billets during roll forging process in several stages

V. Matviichuk, I. Bubnovska, V. Mykhalevych, M. Kovalchuk, W. Wójcik, A. Tuleshov, S. Smailova, and B. Imanbek

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10.1 INTRODUCTION

The development of cold rolling forging processes is hindered by the lack of information on the mechanics of forming curvilinear blanks, the stress–strain state, and the materials' deformability (Kukhar 2018).

As a result of the study of the mechanics of forming blanks during roll forging, we have come up with a method for manufacturing curvilinear blanks by two-stage roll forging. In the suggested method, in the first stage, roll forging is performed on a flat roll body, and in the second stage, roll forging of the billet is performed in gauges of cylinder rolls. In this case, in the second stage, the billet is rotated by 90°, and rolling forging is then performed in gauges of cylinder rolls.

In the process of manufacture of curvilinear blanks by cold roll forging, the matter of evaluating fractures of the billet material becomes particularly relevant. The limiting degree of compression and the mechanical characteristics of the material of the products depend on this. It is clear that at different stages of rolling forging, the stress–strain state of the particles of the billet material varies and is not monotone, which causes additional difficulties in the process of fracture evaluation of the billet material.

The aim of the research is to develop models of fracture evaluation of the billet material for cold roll forging in schemes in two or more stages.

10.2 ANALYSIS

To evaluate fractures of the billet material in roll forging, it is necessary to choose an approach to the calculation of equivalent plastic strain at the fracture point. Judging by the hundreds and most likely thousands of papers on this topic, the number of which increases annually, the most widely used approach is based on the damage summation

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theory. So, the preface to the proceedings of the forum on the forming technology notes: “A more widely used approach is the identification of fracture strains in the function of stress triaxiality as proposed by Johnson and Cook. This in combination to damage evolution approaches is better able to model the experimental outcomes” (Hora 2018).

It is enough to point out that almost all of the reports submitted to this forum use said approach to model the fracture. However, within the framework of this approach, a large number of damage summation models have been proposed. An idea of these models can be obtained from earlier works (Cockcroft 1968; Rice 1969). In the works (Del 1978; Rene 1976), the more complicated principle of summing damages is substantiated. The authors (Oh 1979), along with the stress triaxiality, discuss the use of invariant indexes in the form of the ratio of principal stresses. Clift et al. (1990) considered a simplified model. A comparative analysis of various fracture models is carried out periodically, for example (Bao 2004b; Golling 2017). Some key features of fracture models for sheet materials are considered in (Bai 2008; Bao 2004a, 2005). In (Gese 2007; Hooputra 2004), revolutionary proposals were made to account for the type of fracture for sheet materials. In (Del 1975a; Ogorodnikov 2018a), a fracture criterion was developed, which takes into account additional features of the strain trajectory, and also some of its properties are investigated. In (Grushko 2012; Mikhalevich 1994), results were obtained justifying the use of new fracture models. These models relate primarily to the initially isotropic body or to equivalent plastic strain at the fracture point. One more important feature of these models is the scalar description for damage particulates.

Models based on the tensor description of the material particulate damage were proposed in (Del 1983; Ilyushin 1967; Mikhalevich 1996). However, over the past decades, the use of tensor models is clearly inferior to the popularity of scalar models. For example, in (Hooputra 2004), the tensor model is mentioned but not discussed.

Scalar fracture models for an initial anisotropic body in the framework of the approach under consideration were proposed in (Ilyushin 1967; Park 2018; Yoon 2017). The paper (Basak 2019; Mikhalevich 1993) is one of the few in which a tensor model was constructed for an initially anisotropic body (Polishchuk 2016a, 2016b, 2018).

10.3 RESULTS OF THE STUDY

By means of experimental and analytical studies and the use of simulation modeling in the DEFORM 3D software package, it was found that for particles of the material on the free surface of the billet, for which the stress triaxiality changes from $\eta = 1$ at the first stage to $\eta = -1$ at the end of roll forging, at the second and third stages, a linear law is valid for the strain path (Kozlov 2019; Ogorodnikov 2018b; Polishchuk 2019):

$$\bar{\varepsilon} = -k \cdot \eta + b, \quad k, b > 0 \tag{10.1}$$

where: $\bar{\varepsilon}$ – equivalent plastic strain; and η – stress triaxiality:

$$\eta = \frac{3 \cdot \sigma_m}{\sigma_v} \tag{10.2}$$

where: σ_m – hydrostatic stress; and σ_v – equivalent stress (von Mises).

Equation (10.1) can be represented as:

$$\eta = \frac{\bar{\varepsilon} - \bar{\varepsilon}_0}{\bar{\varepsilon}_1 - \bar{\varepsilon}_0} \tag{10.3}$$

where: $\bar{\varepsilon}_0, \bar{\varepsilon}_1$ – values of the equivalent plastic strain on the path strain at $\eta = 0$ and $\eta = 1$.

Those particles of material that, in the first stage, were deformed under "hard" stress–strain state schemes, in the second stage, will be in "soft" conditions of deformation. In this case, there is non-monotonic deformation. Therefore, to evaluate the fracture of a material, it is necessary to use models that take into account the directional nature of damage accumulation and their dependence on the type of stress state. Such models are tensor models.

Despite the simplicity of relation (1), an attempt to apply a tensor model to describe the process of changing the material's stress–strain state, which leads to the specified strain path, showed the need to adopt a number of assumptions to obtain unambiguous results (Dragobetskii 2015; Ogorodnikov 2004, 2018c).

Let us suggest a deformation model of certain particulates in the billet material in the form of a deformation process within four separate stages. For this case, using a tensor-linear model, we obtain:

$$\psi_{ij}\left((\bar{\varepsilon})_k\right) = n \cdot \sum_{k=1}^{4} \int_{(\bar{\varepsilon})_{k-1}}^{(\bar{\varepsilon})_k} \frac{\bar{\varepsilon}^{n-1}}{\bar{\varepsilon}_{fs}^{n}\left[\eta(\bar{\varepsilon})\right]} \cdot \beta_{ij}(\bar{\varepsilon}) \cdot d\bar{\varepsilon} \tag{10.4}$$

where: $\bar{\varepsilon}_{fs}(\eta)$ – curve of the limit equivalent plastic strain to fracture under stationary deformation; $(\bar{\varepsilon})_{k-1}, (\bar{\varepsilon})_k$ – equivalent plastic strain, respectively, at the beginning and the end of the k-th deformation stage ($(\bar{\varepsilon})_0 = 0, (\bar{\varepsilon})_k < \bar{\varepsilon}_f$); and β_{ij} – directional tensor for increment strain:

$$\beta_{ij} = \sqrt{\frac{2}{3}} \cdot \frac{d\varepsilon_{ij}}{d\bar{\varepsilon}} \tag{10.5}$$

where: $d\varepsilon_{ij}$ – strain increment tensor; $d\bar{\varepsilon}$ – plastic strain increment intensity; and $n > 0$ – material constant.

In the future, we assume that the properties of the material of the billet will be described by the defining relations of flow theory (Del 1975b; Vorobyov 2017; Kukharchuk 2017a):

$$d\varepsilon_{ij} = \frac{3}{2} \cdot \frac{\bar{\varepsilon}}{\sigma_u} \cdot s_{ij} = \frac{3}{2} \cdot \frac{\bar{\varepsilon}}{\sigma_u} \cdot \left(\sigma_{ij} - \delta_{ij} \cdot \sigma\right) \tag{10.6}$$

where: σ_{ij}, s_{ij} – stress tensor and stress deviator, respectively; and δ_{ij} – Kronecker symbol:

$$\delta_{ij} = \begin{cases} 1, i = j, \\ 0, i \neq j. \end{cases} \tag{10.7}$$

In this case, both the directional tensor for increment strain and the directional tensors for the stress coincide:

$$\beta_{ij} = \sqrt{\frac{2}{3}} \cdot \frac{d\varepsilon_{ij}}{d\bar{\varepsilon}} \tag{10.8}$$

For particles of the billet material that belonged to the free surface of the billet in the deformation process in the first stage, each of the four stages is considered separately (Table 10.1).

Table 10.1 Dependencies of the directional tensor for increment strain under various types of stress state

Stage (k)	*Stress-state*	*Directional tensor for increment strain* $\left(\beta_{ij}^{(k)}\right)$	
1	Uniaxial tension	$\begin{bmatrix} \frac{\sqrt{6}}{3} & 0 & 0 \\ 0 & -\frac{\sqrt{6}}{6} & 0 \\ 0 & 0 & -\frac{\sqrt{6}}{6} \end{bmatrix}, \eta = 1$	(10.11)
2	Uniaxial tension + torsion	$\begin{bmatrix} \frac{\sqrt{6}}{3} \cdot \eta(\bar{\varepsilon}) & \sqrt{1-\eta^2(\bar{\varepsilon})} & 0 \\ \sqrt{1-\eta^2(\bar{\varepsilon})} & -\frac{\sqrt{6}}{6} \cdot \eta(\bar{\varepsilon}) & 0 \\ 0 & 0 & -\frac{\sqrt{6}}{6} \cdot \eta(\bar{\varepsilon}) \end{bmatrix}, 0 \le \eta < 1$	(10.12)
3	Uniaxial compression + torsion	$\begin{bmatrix} \frac{\sqrt{6}}{6} \cdot \eta(\bar{\varepsilon}) & \sqrt{1-\eta^2(\bar{\varepsilon})} & 0 \\ \sqrt{1-\eta^2(\bar{\varepsilon})} & -\frac{\sqrt{6}}{6} \cdot \eta(\bar{\varepsilon}) & 0 \\ 0 & 0 & -\frac{\sqrt{6}}{6} \cdot \eta(\bar{\varepsilon}) \end{bmatrix}, -1 \le \eta < 0$	(10.13)
4	Uniaxial compression+ hydrostatic compression	$\begin{bmatrix} -\frac{\sqrt{6}}{3} & 0 & 0 \\ 0 & \frac{\sqrt{6}}{6} & 0 \\ 0 & 0 & \frac{\sqrt{6}}{6} \end{bmatrix}, \eta < -1$	(10.14)

In accordance with the representation (10.1), (10.4), (10.9) for the first stage (Kukharchuk 2017b):

$$\psi_{ij}(\bar{\varepsilon})=\left(\frac{\bar{\varepsilon}}{\varepsilon_t^*}\right)^n\cdot\beta_{ij}^{(1)},\quad 0\le\bar{\varepsilon}\le -k+b<\varepsilon_p^* \tag{10.9}$$

where: $\varepsilon_t^*=\bar{\varepsilon}_{fs}(\eta=1)$ – equivalent plastic strain to fracture under tension.

By analogy, for the second and third stages, we obtain:

$$\psi_{ij}(\bar{\varepsilon})=\left(\frac{b-k}{\varepsilon_t^*}\right)^n\cdot\beta_{ij}^{(1)}+n\cdot\int\limits_{b-k}^{\bar{\varepsilon}}\frac{\bar{\varepsilon}^{n-1}}{\varepsilon_{fs}^n\left[\eta(\bar{\varepsilon})\right]}\cdot\beta_{ij}^{(2)}(\bar{\varepsilon})\cdot d\bar{\varepsilon},\quad b-k\le\bar{\varepsilon}\le k+b \tag{10.10}$$

The curve of the limit equivalent plastic strain to fracture under stationary deformation is represented by the well-known expression:

$$\bar{\varepsilon}_{fs}(\eta)=\varepsilon_s^*\cdot\left(\frac{\varepsilon_t^*}{\varepsilon_c^*}\right)^{\frac{\eta}{2}}\cdot\left(\frac{\varepsilon_t^*\cdot\varepsilon_c^*}{\left(\varepsilon_s^*\right)^2}\right)^{\frac{\eta^2}{2}} \tag{10.15}$$

where: $\varepsilon_s^*=\bar{\varepsilon}_{fs}(\eta=0)$ – equivalent plastic strain to fracture in shear; $\varepsilon_c^*=\bar{\varepsilon}_{fs}(\eta=-1)$ – equivalent plastic strain to fracture in compression.

As a measure function of damage, the second invariant of the damage deviator was adopted:

$$\psi=\psi_{ij}\cdot\psi_{ij},\quad 0\le\psi\le 1 \tag{10.16}$$

In the initial state $\psi(\bar{\varepsilon}=0)=0$, and the achievement of the limit state is determined by the condition:

$$\psi\left(\bar{\varepsilon}=\bar{\varepsilon}_f\right)=1 \tag{10.17}$$

where: $\bar{\varepsilon}_f$ – equivalent plastic strain to fracture under conditions an arbitrary process of deformation (η = const or $\eta\neq$const; if η = const $\Rightarrow\bar{\varepsilon}_f\equiv\bar{\varepsilon}_{fs}$).

The simulation of damage accumulation was carried out in the environment of the Maple computer mathematics system using a program developed by us. The results of the calculations of the values under study, depending on the stress triaxiality, are presented in Figure 10.1.

The simulation results demonstrate that regardless of the value of the nonlinearity index for the summation of damages n, the damage accumulation rate begins to decrease at $\eta<-0.3$.

For the range of values $n=1\div 1.5$, there is a maximum value for the damage accumulation curves when approaching the stressed compression state.

This is a very important, at least theoretical, result. Since after reaching the maximum value, the damage begins to decrease against a monotonous increase in the equivalent plastic strain.

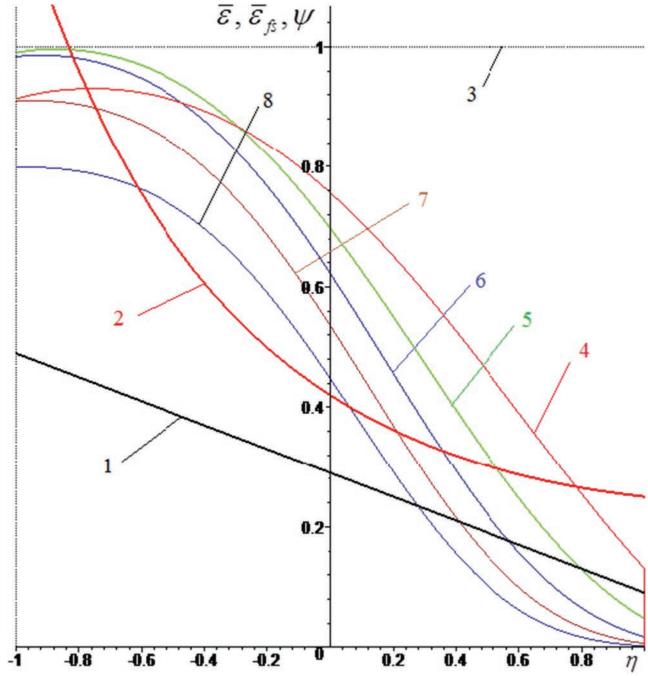

Figure 10.1 Strain path (1 – (1), $k = 0.2$, $b = 0.29$); the curve of the limit equivalent plastic strain to fracture under stationary deformation for steel EP866 ($\varepsilon_t^* = 0.25$, $\varepsilon_s^* = 0.42$, $\varepsilon_c^* = 1.25$) (2 – (15)); 3 – damage intensity limit; 4÷8 – damage accumulation in stages 2, 3 – (10), (16): 4 – $n = 1$; 5 – $n = 1.5$; 6 – $n = 2$; 7 – $n = 2.5$; 8 – $n = 3$.

A similar result in a somewhat different form was discovered earlier in processes accompanied by a discrete change in the direction of plastic strain increment. It is under the given conditions that the indicated effect was experimentally discovered and theoretically described in the papers of Dell (1983). A more detailed theoretical and experimental study of certain aspects of this phenomenon is represented in the papers of V. Mykhalevych and V. Matviichuk (Mikhalevich 1993, 1994).

In this case, the effect under study was found in the processes with continuous changes in the directions of the principal strain increments. The numerical values of this effect are so minor that they do not go beyond the limits of the experimental data scattering. This makes it impossible for us to experimentally substantiate or argue against the discovered theoretical effect. On the other hand, a more detailed theoretical study of this effect may lead to confirming conditions under which it will manifest itself to a greater degree, which, in turn, will create the necessary prerequisites for experimental research.

The graphs in Figure 10.1 clarify that the calculated damage value at the end of the first stage monotonously decreases with an increase in the nonlinearity index of damage summation $n \in [1{:}3]$. As for the calculated damage value at the end of the third stage, here we get the non-monotonic dependence presented in Figure 10.2.

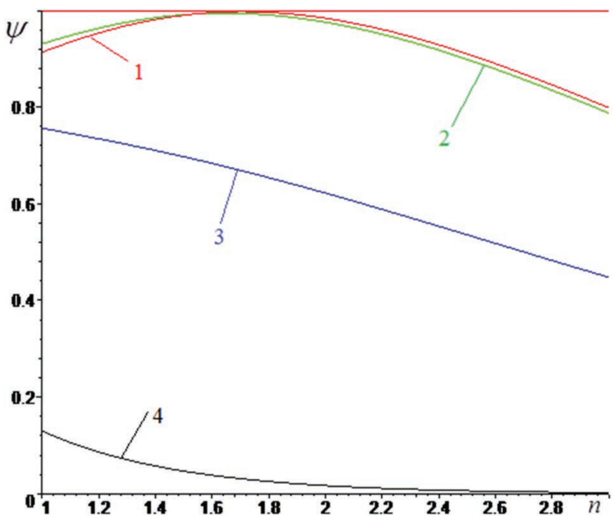

Figure 10.2 Damage at a given point of the deformation path (4) depending on the value of the nonlinearity parameter of damage summation: 1 – $\bar{\varepsilon}$ = 0.49; 2 – $\bar{\varepsilon}$ = 0.44; 3 – $\bar{\varepsilon}$ = 0.29; 4 – $\bar{\varepsilon}$ = 0.09.

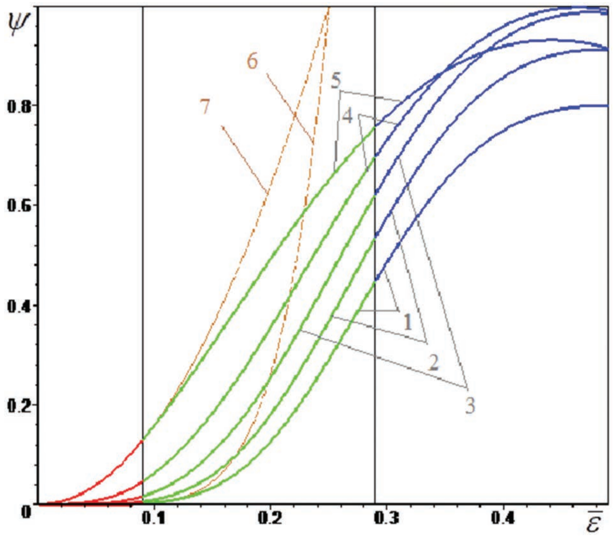

Figure 10.3 Damage at a given point of the deformation path (4) depending on the value of the nonlinearity parameter of damage summation: 1 – $\bar{\varepsilon}$ = 0.49; 2 – $\bar{\varepsilon}$ = 0.44; 3 – $\bar{\varepsilon}$ = 0.29; 4 – $\bar{\varepsilon}$ = 0.09.

Curves 6 and 7 in Figure 10.3 reflect the pattern of damage accumulation to fracture under tension. As can be seen with $n \geq 1$ and the constant stress state, we get an avalanche accumulation of damage, which is consistent with the classical physical concepts of scattered fracture.

At the same time, by changing the stress state in the process of deformation, the accumulation of damage can be accelerated or slowed down. In this case, the "softening" of the stress state from uniaxial tension to shear reduces the rate of damage accumulation, as can be seen from the curves in Figure 10.3, related to the second stage of the process. Further "softening" of the stress state "shear + compression" – "compression" further slows down the accumulation of damages up to the already noted effect of their partial "healing."

Calculations were carried out for the curve of the limit equivalent plastic strain to fracture at stationary deformation, which is the case for steel EP866. In Figure 10.3, the behavioral regularities of damage accumulation are presented depending on the equivalent plastic strain (Wojcik 1997, 2010).

10.4 CONCLUSIONS

For the first two stages of the deformation trajectory under study, according to the tensor theory of damage accumulation, the most rigorous prediction of limiting deformations corresponds to the linear principle of damage accumulation. An increase in the parameter n, which characterizes the degree of the nonlinear nature of damage accumulation, corresponds to a decrease in the damage accumulation rate. The third stage is characterized by a significant decrease in the rate of damage accumulation and the not monotonic nature of depending on the calculated limit values in the index n. For the first time, the effect of partial "healing" of damage in the processes with continuous changes in the directions of the principal strain increments was theoretically discovered.

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