ISSN 2079-004X(Print), ISSN 2786–7587(Online)., №2(10),,2024

УДК 621.77.07 DOI: 10.20998/2079-004X.2024.2(10).07

CHUKHLIB V., VOLK W., LECHNER P., SCANDOLA L., GUBSKYI S., BIBA M., SCHUKRAFT J.

COMPARATIVE ANALYSIS OF THE SHAPE CHANGE WHEN A PRODUCT IS PRODUCED BY FREE-FORM BENDING

The paper presents a comparative analysis of the shape change of a rod when it is deformed in a moving die using the Abaqus and Qform software packages. The approaches to determining the shape of a profile formed by a moving die are analyzed. Methods for analyzing the shape change when a product is obtained by free-form bending, based on predicting the volumetric unevenness of metal deformation in the processes of pressure treatment and determining the product curvature, are considered. For the process of modeling the bending of a product in a moving die, a rod was selected, as well as an algorithm for moving the moving die and feeding the rod. As a result of the simulation, it was found that the resulting product models in these software systems are identical in geometry. Based on the methods of analyzing the shape change when a product is obtained by free-form bending, we analyzed the uneven distribution of deformation parameters and determined the curvature of the workpiece during deformation. It was found that a significant deformation irregularity is observed in the workpiece, which is caused by the chosen scheme of deformation. Proposed approaches for further research.

Keywords: free-fom bending, metal forming, finite element method (FEM), modelling, deformation.

ЧУХІБ В. Л., VOLK W., LECHNER P., SCANDOLA L., ГУБСЬКИЙ С. О., БІБА М. В., SCHUKRAFT J.

ПОРІВНЯЛЬНИЙ АНАЛІЗ ФОРМОЗМІНИ ПРИ ОТРИМАННІ ВИРОБУ ВІЛЬНИМ ЗГИНАННЯМ

У статті проведено порівняльний аналіз формозміни прутка при деформуванні його в рухомій матриці із застосуванням програмних комплексів Abaqus та Qform. Проведено аналіз підходів до визначення форми профілю, що утворюється за допомогою рухомої матриці. Розглянуто методи аналізу формозміни при отриманні виробу вільним згинанням, що базуються на прогнозуванні об'ємної нерівномірності деформації металу в процесах обробки тиском та визначення викривлення виробу. Для процесу моделювання гнуття виробу в рухомій матриці був обраний пруток, алгоритм руху рухомої матриці та подачі прутка. В результаті моделювання встановлено, що отримані моделі виробу в даних програмних комплексах однакові за своєю геометрією. Базуючись на методах аналізу формозміни при отриманні виробу вільним згинанням був проведений аналіз нерівномірності розподілу параметрів деформування та визначення викривлення заготовки в процесі деформації. Встановлено, що в заготовці спостерігається значна нерівномірність деформації, яка зумовлена обраною схемою формозміни. Запропоновані підходи до подальших досліджень.

Ключові слова: вільне гнуття, обробка металів тиском, метод кінцевих елементів (МКЕ), моделювання, деформація.

1. Introduction. Various approaches to the manufacture of parts and products by bending are being actively developed. The typical technological process of manufacturing a profile with gradual edge deformation in stands has been further developed in the production of bent profiles with variable cross-section in width and height [1], while the possibility of using it to manufacture high-strength steel profiles is being considered [2]. The process of pipe bending in pipe bending devices [3] has been developed in the use of a movable die, which allows the manufacture of products of various 3D geometries [4].

Manufacturing elements by bending rods and tubes using a moving die is a modern technology in metal forming. This approach makes it possible to produce parts of complex 3D geometry without replacing bending tools. Products made using this method are in demand in the automotive, energy, chemical, aerospace, and other industries [5].

The manufacture of the required elements by bending rods and pipes using a moving die is based on the kinematically controlled process of continuously feeding a pipe or rod into a moving die that performs rotational and/or translational movements [6].

Paper [7] developed a finite-element analysis model for simulating the technology of bending in a moving die, and presented a theoretical model for determining the control data of a bending die. The modeling results were compared with the experimental results. Similar studies were conducted in [8]. In [9, 10], a simulation approach with the construction of finite element models was proposed, which correlates well with practical results.

Controlling the geometry of a part bent in a moving die (rod, conventional and profile pipe) is a difficult task. Because the geometric error that has arisen in the deformed element (due to, for example, normalized differences in mechanical property tolerances [11]) cannot be corrected, since this element has already been formed. It is only possible to influence the next element of the part that has not yet been deformed. It is necessary to make this correction to the movement of the moving die as soon as possible to prevent rejection of the product.

In [12], an approach is proposed to control a microcontroller of a bending machine with a moving matrix based on commands coming from a neural network. This neural network is trained with a surrogate model based on simulation data that allows for backward optimization of the global geometry of the part.

2. Methods for analyzing the shape change when a product is produced by free-form bending. Based on the theoretical determination of the zone of maximum deformation irregularity in the cross-section of the resulting product and the associated longitudinal curvature, a method for predicting the volumetric irregularity of metal deformation in pressure treatment processes is used, which makes it possible to evaluate and determine rational deformation modes to obtain the required properties of products [13, 14]. To predict the volumetric unevenness of metal deformation in pressure treatment processes and, accordingly, to predict the uneven distribution of mechanical properties, a method is used according to which a point with a maximum strain value is found in each section subjected to analysis for unevenness of deformation. Then a line is drawn through the center of the section relative to it. In total, four lines are drawn across the section (including the line with the point with the maximum strain value), which are located at an angle of 45° to each other. Next, several control points (at least 6) are applied to each line symmetrically to the point with the maximum value and symmetrically to the center of the section.

To assess the uniformity of the strain distribution, which is the smallest deviation of the strain values among themselves in the section, the index of the unevenness of the deformation of the $K_н$ is calculated on the basis of the above method using the formula (1):

$$K_н = \frac{\varepsilon_i}{\varepsilon_{max}} \tag{1}$$

where ε_i - is the strain value at the control point (for example, logarithmic deformation), mm;

ε_{max} - maximum strain in cross-section, mm.

The $K_н$ index can take a value of no more than one, since it is the ratio of the strain values at the control points of the section to the maximum strain value in the section. It is necessary to take into account the fact that when the value of the index of strain irregularity of the $K_н$ takes its maximum value throughout the section, which is equal to 1, this corresponds to a uniform strain (in this case, different points of the body that have the same strain value are related to each other - that is, we have a uniform strain). The smaller the value of the strain irregularity index of the $K_н$ is from unity, the greater the strain irregularity. When some part of the metal is not subject to deformation, but falls into the section under consideration, the $K_Н$ takes its minimum value – $K_н = 0$.

To study the influence of the forming parameters on the workpiece curvature, the method of determining the product curvature is used. This method is based on comparing the absolute values of the center deviation in the control sections of the product from the center of the "main" section of the product located in the middle of the width of the deforming tool.

The coefficient that shows the degree of curvature of an element in terms of horizontal and vertical components is called the "curvature coefficient" (K_{curv}). It can take values from -1 to +1, as it is the ratio of the deviation in the current section to the maximum deviation from the product's central axis. The positive or negative sign of the indicator is determined by the displacement of the center of the control section along the axis to a positive or negative area relative to the "main" section.

The coefficient K_{curv} is calculated by the formula (2):

$$K_{curv} = \frac{h_{curv.i}}{h_{curv.max}} \tag{2}$$

where $h_{curv.i}$ - is the current value of the curvature in the section considered along the axis, mm;

$h_{curv.max}$ - maximum axial curvature of the product, mm.

3.Modeling. A 3D model of the mill with a moving die was recreated. The material of the bar is aluminum alloy AA 6603, the diameter of the bar is 42.4 mm.

The case is considered when the workpiece is fed, and the moving die performs vertical movements and rotations. The bar deformation is modeled according to a certain algorithm of the movable die movement and the bar feed rate.

The forming of the bar by means of a moving die was modeled in the Abaqus and Qform software packages.

To simulate the process of bending a rod using a moving die in Qform, the type of operation "Deformation", the type of task "3D", and the option "Unloading after operation" were selected to take into account springing. The bar blank is defined by parametric geometry, and the finite element mesh is of hexahedral type. The lubrication is mineral oil.

4. **Modeling simulation results**. As a result of modeling the deformation of a rod with a diameter of 42.4 mm (material - aluminum alloy *AA* 6603) in the Abaqus and Qform software systems, models with the same shape were obtained - Fig. 1

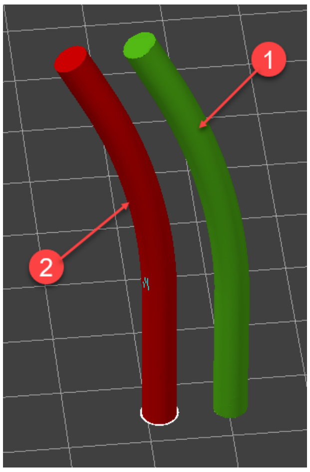

Fig. 1 - Results of modeling bar deformation in the Abaqus (1) and Qform (2) software packages

5. Analysis of deformation during free-form bending of the product. To analyze the volumetric unevenness of the distribution of deformation parameters, the final model of the product obtained after modeling the deformation of the bar using a moving matrix was divided into seven sections that are equidistant from each other - Fig. 2. Section I-I is located at the point of contact of the moving die with the workpiece, i.e., at the end of deformation. Section *VII-VII* at the beginning of deformation

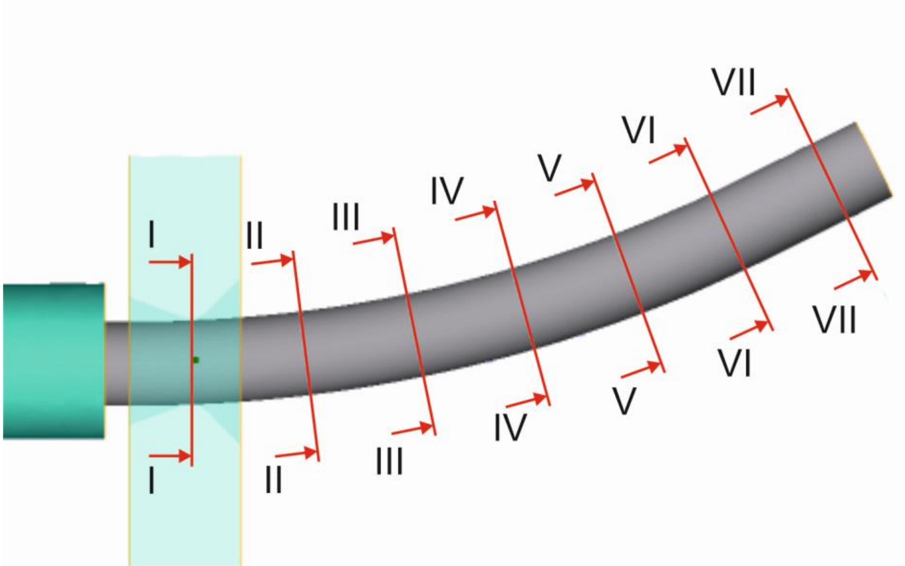

Fig. 2 - The final model of the product obtained after modeling the shape change of the rod using a moving matrix and divided into seven sections

Each section was analyzed, and the point with the maximum strain value (point 1_{max}) was determined. Then, relative to this point, four lines were drawn through the center of the section at an angle of 45° to each other (*A*, *B*, *C*, *D*). Each line was then divided into 7 control points, which were placed symmetrically to the point with the maximum value and symmetrically to the center of the section. For example, the distribution of plastic (logarithmic) strain along section *II-II* is shown in Fig. 3 (the coloring corresponds to the values of the plastic strain).

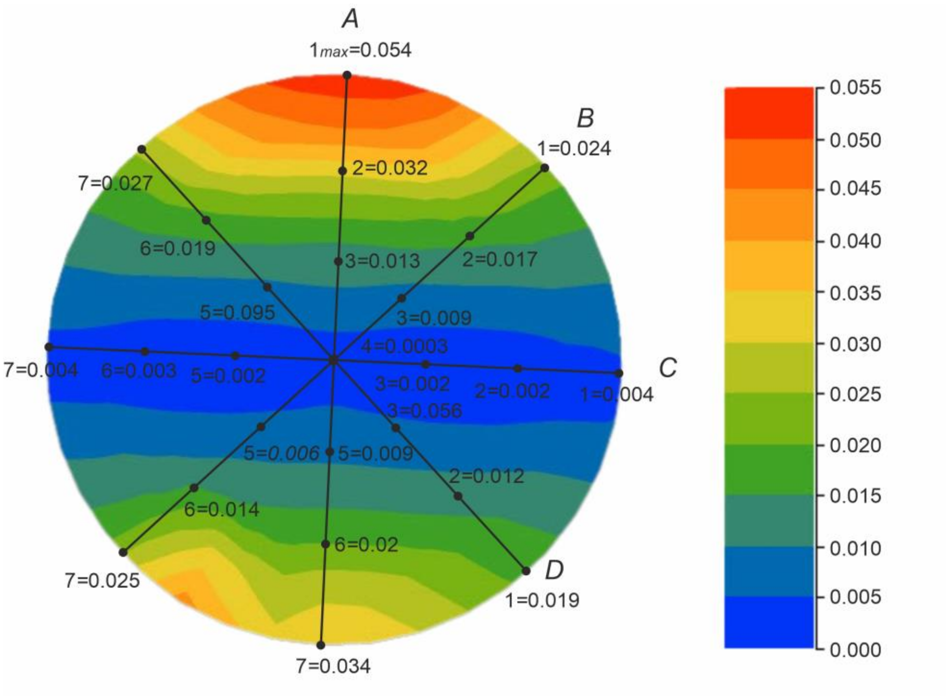

Fig. 3 - Distribution of plastic (logarithmic) strain along section *II-II*

Next, we plotted the distribution of the coefficient of unevenness of the deformation of the $K_н$ along the lines *A*, *B*, *C*, *D* for each section (e.g., section *II-II* - Fig. 4).

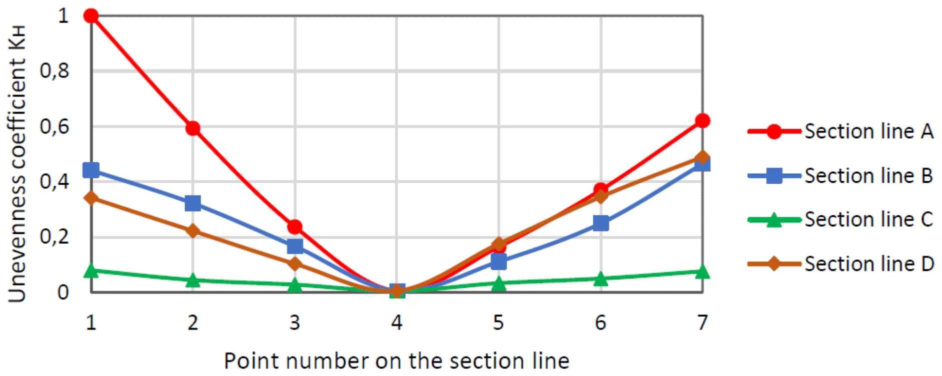

Fig. 4 - Distribution of the coefficient of unevenness of the $K_н$ deformation along the lines *A*, *B*, *C*, *D* of section *II-II*

As a result of analyzing the uneven distribution of the workpiece deformation parameters in the moving die, it was found that there is a significant deformation unevenness, as shown by the distribution of the deformation unevenness coefficient in Fig. 4. It should be noted that the minimum strain is concentrated in the entire central zone of the workpiece, and the maximum strain is only on the bending side of the workpiece surface. At the same time, the value of the unevenness coefficient $K_н$ along one of the cross-sectional lines (line *A*, Fig. 4) has a very significant difference in strain - from its maximum value on the surface $K_н$=1 to its minimum value $K_н$=0 in the center of the workpiece. This significant difference in strain distribution is due to the deformation pattern. Such a distribution of strain irregularity must be taken into account when deforming various materials, especially those that are most sensitive to significant strain irregularity and, as a result, to workpiece fracture. This can be corrected by selecting a rational deformation scheme for a particular material and the shape of the resulting product.

The curvature of the workpiece along its length was also displayed based on the K_{curv} coefficient (Fig. 5). Section *VII-VII* was chosen as the maximum curvature. The curvature in other sections was calculated relative to section *VII-VII*.

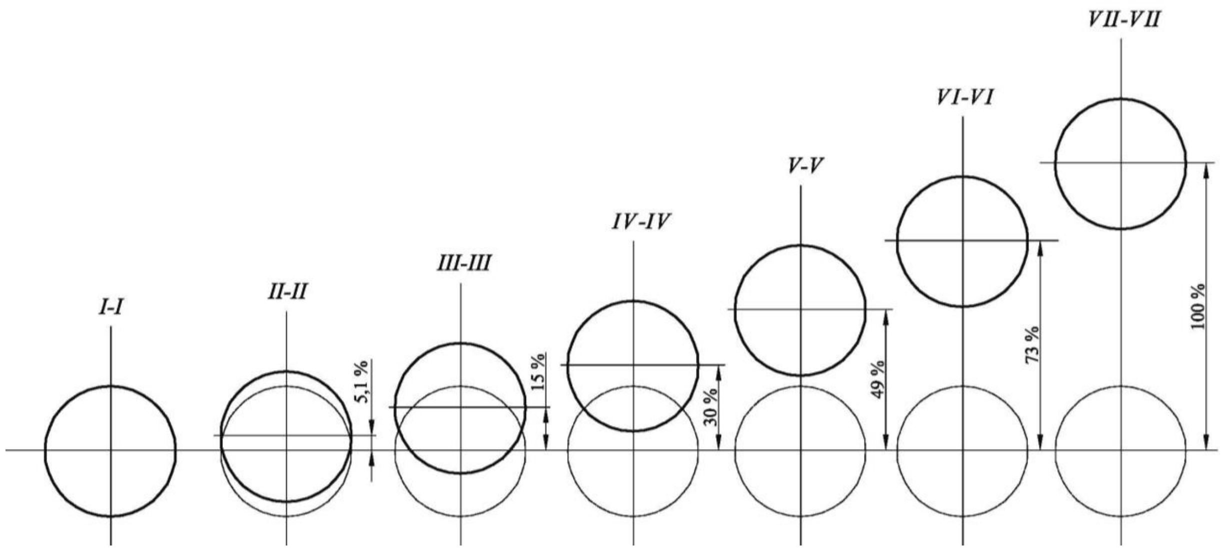

Fig. 5 - Workpiece curvature along the length

The analysis of the billet curvature during the deformation of the billet in the moving die showed that the billet remains in the same plane relative to the vertical axis during its deformation and there is no billet curvature in this direction, which corresponds to the required shape of the resulting product. In addition, the method used to analyze the billet curvature allows you to track and control the curvature of the billet in different directions relative to each of the selected axes and, if necessary, adjust the deformation mode.

Conclusions. In this work, a comparative analysis of the shape change of a rod when it is deformed in a moving matrix was carried out using the Abaqus and Qform software packages. It was found that the resulting product models in these software systems are identical in geometry.

We also analyzed the uneven distribution of deformation parameters and determined the curvature of the workpiece during deformation.

In the future, it is planned to analyze the uneven distribution of deformation parameters and determine the curvature of the pipe during deformation in a moving die. A wireless monitoring system can be used to control changes in the stress-strain state [15].

References (transliterated)

13. ***Губський С.О., Чухліб В.Л., Біба М.В.*** Моделювання формоутворення гнутого профілю зі змінним перерізом // Вісник Національного технічного університету "ХПІ". Сер. : Технології в машинобудуванні : зб. наук. пр. – Харків : НТУ "ХПІ", 2022. – № 1 (5). – С. 80-84. https://doi.org/10.20998/2079-004X.2022.1(5).11
14. ***L.-O. I. Michael Lindgren*** 3D roll-forming of hat-profile with variable depth and width / 1st International Congress on RollForming, RollFORM´09. – Bilbao, Spain, 2009.
15. ***Greg G. Miller*** Tube Forming Processes: A Comprehensive Guide // Society of Manufacturing Engineers, 2003. 385 p.
16. ***Gantner P., Bauer H., Harrison D.K., Anjali K.M. De Silva*** Free-Bending - a new bending technique in the hydroforming process chain. // J. Mater. Process. Technol. 167 (2–3), 2005.- p 302–308. https://doi.org/10.1016/j.jmatprotec.2005.05.052
17. ***Maier D., Stebner S., Ismail A., Dölz M., Lohmann B., Münstermann S., Volk W.*** The influence of freeform bending process parameters on residual stresses for steel tubes // Advances in Industrial and Manufacturing Engineering, 2021. Volume 2 (100047). https://doi.org/10.1016/j.aime.2021.100047
18. ***Gantner P., Harrison D. K., De Silva A. K., Bauer H.*** The Development of a Simulation Model and the Determination of the Die Control Data for the Free-Bending Technique // Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2007. Volume 221, Issue 2. – pp 163 – 171. https://doi.org/10.1243/09544054JEM642
19. ***Murata M., Aoki Y.*** Analysis of circular tube bending by MOS bending method // T. Altan Editor, Advanced Technology of Plasticity I, 1996. – pp 505–508.
20. ***Li P., Wang L., Li M.*** lexible-bending of profiles and tubes of continuous varying radii // The International Journal of Advanced Manufacturing Technology, 2017, volume 88. – pp 1669–1675. https://doi.org/10.1007/s00170-016-8885-9
21. ***Beulich N., Craighero P., Volk W.*** FEA Simulation of Free-Bending – a Preforming Step in the Hydroforming Process Chain //. J. Phys. Conf. 896, 12063, 2017. https://doi.org/10.1088/1742-6596/896/1/012063
22. ***Werner M., Majer D., Scandola L., Volk W.*** Motion profile calculation for freeform bending with moveable die based on tool parameters // Proceedings of the 24th International Conference on Material Forming. Ed. by ULi`ege Library, 2021. https://doi.org/ 10.25518/esaform21.1879
23. H***agenah H., Vipavc D., Plettke R., Merklein M.*** Numerical Model of Tube Freeform Bending by Three-Roll-Push-Bending // 2nd International Conference on Engineering Optimization. Lisbon, 2010.
24. ***Lechner P., Scandola L., Maier M., Hartmann C., Lieb M.*** Data-Based Global Control of the Part's Geometry During Free-Form Bending // International Conference on the Technology of Plasticity ICTP 2023: Proceedings of the 14th International Conference on the Technology of Plasticity - Current Trends in the Technology of Plasticity, 2023. – pp 36–47.
25. ***Чухліб В. Л., Клемешов Є. С., Гринкевич В. О., Дия Х.*** Дослідження впливу параметрів процесу попереднього осаджування на нерівномірність розподілення деформацій в металі при протягуванні заготовок з титанового сплаву // Вісник НТУ «КПІ». 2016. №1 (76). С. 147–155.
26. ***Чухліб В. Л., Клемешов Є. С., Гринкевич В. О., Дия Х.*** Дослідження напружено-деформованого стану при протяжці титанового сплаву з метою оптимізації параметрів кування // Вісник НТУ «ХПЇ». 2015. №24. С. 159–166.
27. ***Sergienko N., Hubskyi S., Pavlova N., Turchyn O., Hasiuk O., Židek K.*** (2023). Obstacle-Resistant Wireless Strain Gauge Complex for Automated Monitoring of the Steel Structures Condition. In: Balog, M., Iakovets, A., Hrehova, S. (eds) EAI International Conference on Automation and Control in Theory and Practice . EAI ARTEP 2023. EAI/Springer Innovations in Communication and Computing. Springer, Cham, 2023 https://doi.org/10.1007/978-3-031-31967-9_2

Поступила (received) 10.12.2023

Chukhlib Vitaliy – Doctor of Engineering Sciences, Professor, Head of the Department of Computer Modeling and Integrated Forming Technologies, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine; ORCID: http://orcid.org/0000-0001-6176-0917; mob.: (095) 792-55-92; e-mail: profdnepro@gmail.com.

Volk Wolfram – prof. Dr.-Ing., Ordinarius, Technical University of Munich, Chair of Metal Forming and Casting (utg).

Lechner Philipp – Assistant Professor, University of Augsburg, Professorship of Data-driven Materials Processing (DDMP).

Scandola Lorenzo – Research Associate, Technical University of Munich, Chair of Metal Forming and Casting (utg).

Hubskyi Serhii – PhD, Associate Professor at the Department of Computer Modeling and Integrated Forming Technologies, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine; ORCID: http://orcid.org/0000-0001-7797-9139; mob.: (066) 219-20-50; e-mail: gubskiyso@gmail.com.

Biba Mykola – PhD, Head of MICAS Simulations Ltd; Oxford, United Kingdom; e-mail: nick@qform.com.

Schukraft Joél – Dr.-Ing., University of Augsburg, group leader "Processes" Hybrid Composite Materials.