DOI: 10.21062/mft.2023.044 http://www.journalmt.com

Volume Change Measurements Using 2D DIC System

Barbora Kotlánová (0009-0003-7990-8619), Jakub Javořík (0000-0002-0204-5240), Milan Žaludek (0000-0002-7281-1940), Raphael Olabanji Ogunleye (0000-0001-9856-520X)
Department of Production Engineering, Faculty of Technology, Tomas Bata University in Zlín. Vavrečkova 5669, 76001 Zlín. Czech Republic. E-mail: b_kotlanova@utb.cz

The presented study focuses on measuring volume changes in elastomeric materials using digital image correlation (DIC), specifically the 2D DIC universal system and the 2D DIC video-extensometer directly implemented to the universal testing machine. Optical measurement methods were applied in two-dimensional (2D) configurations during the mechanical testing of dumbbell-shaped test specimens under uniaxial tension. The measured data were used to determine the dependencies of the bulk modulus and Poisson's ratio on the strain. The dependencies obtained by both methods correspond to the model behavior of rubber-like materials. Compared to the 2D DIC implemented video-extensometer, the 2D DIC universal system provides a tool for measuring transverse and longitudinal strain, and a wide range of post-processing options, including change of the input parameters, settings, or calculation relations.

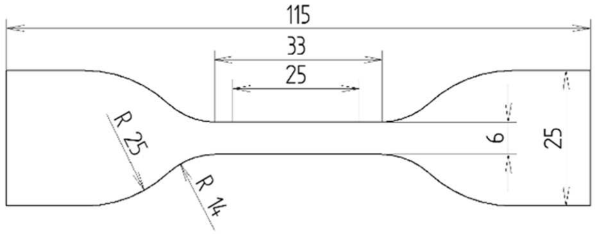
Keywords: Elastomer, DIC, Volume Change, Bulk Modulus, Poisson's ratio

1 Introduction

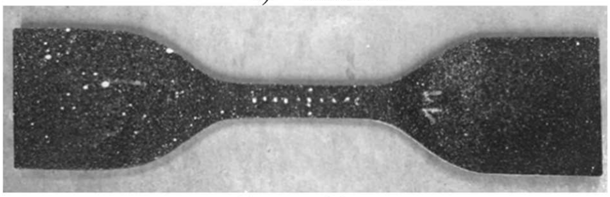
Elastomers are polymeric hyperelastic materials widely used in engineering applications. Most deformations of elastomers are considered by a change in shape, and the change in volume is minor. The potential for volume changes in materials is characterised by Poisson's ratio, which is the relation of transverse strain to longitudinal strain under tensile loading. Poisson's ratio reaches values close to 0.5; therefore, elastomers are assumed incompressible or nearly incompressible [1,2] because volume changes are often insignificant and neglected in specific applications. Changes in volume can occur due to various phenomena in the measured materials. The magnitude of volume changes in elastomeric materials is determined by the material composition of the rubber compound (type of rubber, shape and size of fillers, degree of vulcanisation, and manufacturing technology) and vary with the type of stress and operating temperature. Thus, measuring, observing, and quantifying them is necessary to determine the material constants of elastomers. Digital Image Correlation (DIC), the non-contact optical measurement method, is a suitable tool for this purpose [3,4]. The DIC method scans a speckle pattern on the surface of the measured sample and determines the displacement and deformation of individual points by comparing reference and deformed images [6,7,8]. DIC measurements are performed using either one or more cameras. 3D DIC refers to the configuration in which two or more cameras are used for spatial recording. When using a single camera (2D DIC), planar strain fields are recorded, which is sufficient for laboratory testing of flat test specimens. 2D DIC methods also include the use of video extensometers implemented as part of the possible equipment directly on the test machines. The characterization of Poisson's ratio of engineering elastomers can be done in different modes of loading [9,10]. A frequently investigated area is the measurement of the mechanical behaviour of elastomers under creep and cyclic loading [4,5], which indicates long-term load aspects. Regarding short-term uniaxial static loading, few research have been performed using the DIC measurement method. The presented study aims on using the digital image correlation (DIC) method for measuring volume changes in elastomeric materials. The main result of the research is the description of the dependencies of the bulk modulus on the strain when using two different measurement methods for uniaxial tensile loading. The results of both methods are compared with each other.

2 Materials and methods

The dumbbell-shaped test specimens were used for measurements and cut from sheets of the NR and SBR compound (thickness 2 mm) with dimensions corresponding to the standard ISO 37 (Fig. 1a). A continuous speckle pattern (Fig. 1b) with the specified measurement area (dotted cross with side lengths of 20 and 5 mm) was applied to the test specimens. This pattern is used for the software setup and is directly involved in the measurement.



a) dimensions



b) speckle pattern

Fig. 1 *The dumbbell-shaped test specimen used for measurements*

The measurements of uniaxial strain were performed on a universal testing machine. The applied crosshead speed of the testing machine is 200 mm/min according to the standard ISO 37. A setup of DIC equipment Mercury RT (Fig. 2) containing a mono camera recording device and relevant software was connected to the universal testing machine. A DIC video-extensometer TRViewX directly implemented on a universal testing machine was also used.

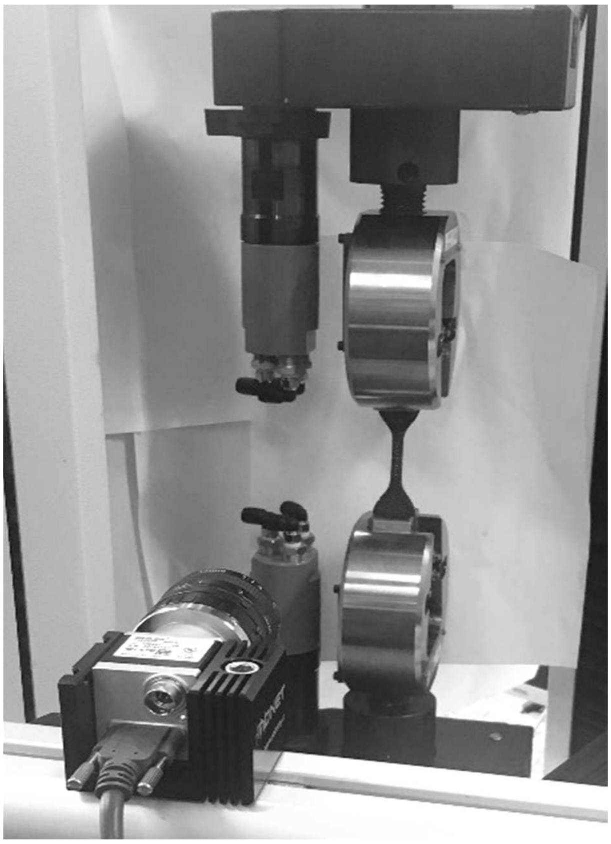


Fig. 2 *Experimental setup of the 2D DIC universal system Mercury RT*

The deformations of test specimens were investigated in the range of 0 to 100%. The transverse and longitudinal strain required to find Poisson's ratio were measured on the cross-specified region (Fig. 1b). These measurements were further used to calculate the variables using the equations below.

Poisson's ratio ν [-] defines the relation between the transverse strain ε_y (reduction) and the longitudinal strain ε_x (elongation in the direction of loading) under tensile loading.

$$\nu = -\frac{\varepsilon_y}{\varepsilon_x} \tag{1}$$

The bulk modulus K can be determined from the relationship between the stress σ [MPa] and the relative volume change θ [-].

$$K = \frac{\sigma}{\theta} \tag{2}$$

With knowledge of the strain values, the relative volume change θ can be obtained using the following equation.

$$\theta = \left(1 + \varepsilon_y\right)^2 \cdot (1 + \varepsilon_x) - 1 \tag{3}$$

3 Results

3.1 2D DIC universal system

Fig. 3 shows the dependence of the bulk modulus on the strain with fitting curve for the 2D DIC universal system measurements. The coefficient of determination R is also indicated. As can be seen in the figure, the measured data at low strains are widely scattered as the displacement values here are at the limit of the resolution of the DIC device.

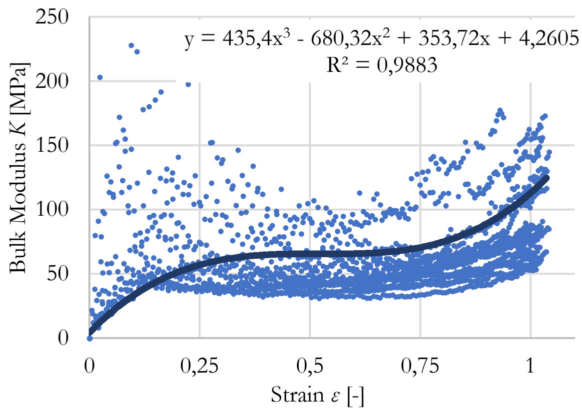


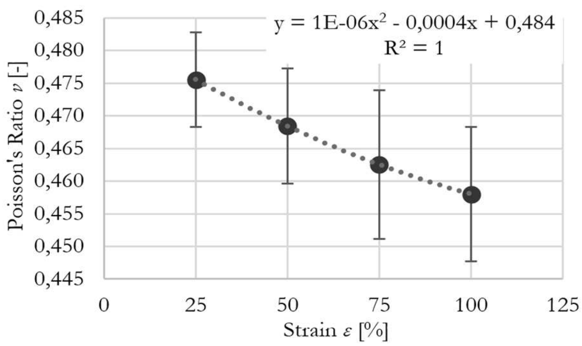
Fig. 3 *The dependence of the bulk modulus K on the strain ε*

According to the results of this measurement, the average values of Poisson's ratio and the bulk modulus and their statistical variables (standard deviation, minimum, maximum, medium) at strain values of 25%, 50%, 75%, and 100% were determined and displayed in Tab. 1.

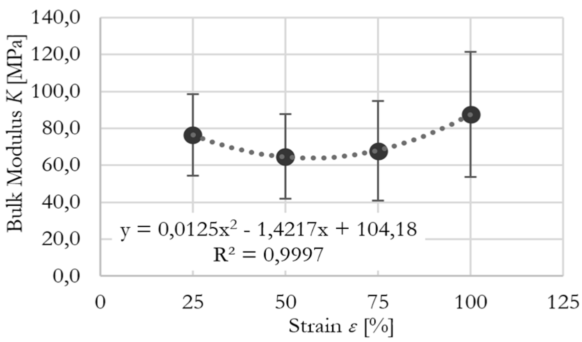
Tab. 1 *The average values of Poisson's ratio and the bulk modulus*

2D DIC			ν [-]		
ε [%]	Average	Deviation	Min	Med	Max
25	0.476	0.007	0.464	0.477	0.485
50	0.468	0.009	0.457	0.466	0.483
75	0.463	0.011	0.450	0.459	0.482
100	0.458	0.010	0.444	0.457	0.472
2D DIC			**K [MPa]**		
ε [%]	Average	Deviation	Min	Med	Max
25	76.4	21.9	50.8	75.1	106.1
50	64.7	22.9	40.9	58.5	107.2
75	67.9	27.0	41.6	61.2	129.5
100	87.5	34.0	49.2	83.1	141.2

The obtained data (Tab. 1) are graphically presented in Fig. 4a) and b). The dependence shown in Fig. 4b) corresponds to the diagram in Fig. 3 – the bulk modulus increases between 80 % and 100 % of the strain.



a) The dependence of Poisson's ratio v on the strain ε



b) The dependence of the bulk modulus K on the strain ε

Fig. 4 *The average values of Poisson's ratio and the bulk modulus and their statistical variables*

3.2 2D DIC implemented video-extensometer

The diagram for the values of the bulk modulus depending on the strain for the 2D DIC implemented video-extensometer measurements with fitting curve and the coefficient of determination R is shown in Fig. 5. This method reveals more scattered data at low strain compared to the 2D DIC universal system method, and as can be seen in the figure, data between 0 and 0.1 strain had to be filtered out due to their indistinguishability.

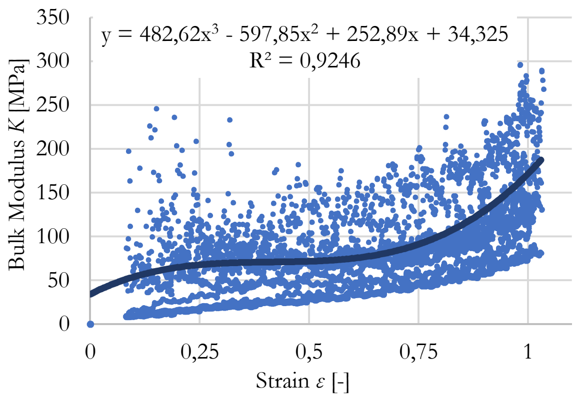


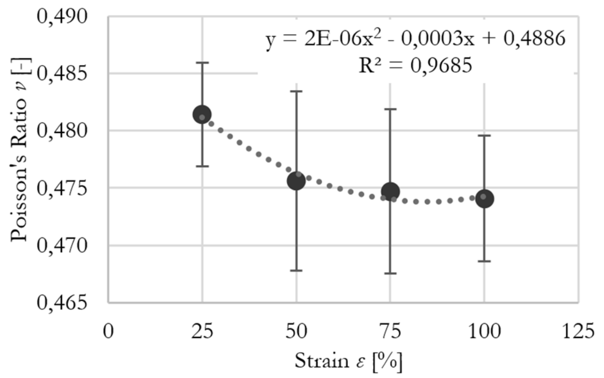
Fig. 5 *The dependence of the bulk modulus K on the strain ε*

The measured values were used to calculate the average values and their statistical variables for the bulk modulus and Poisson's ratio at strain values of 25%, 50%, 75%, and 100%. And these calculated values are displayed in Tab. 2.

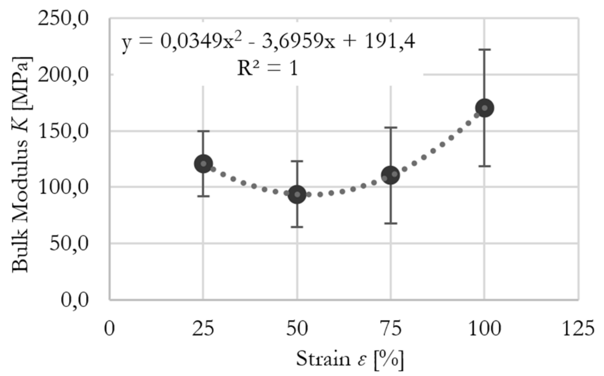
Tab. 2 *The average values of Poisson's ratio and the bulk modulus*

Vid.-ex.			ν [-]		
ε [%]	Average	Deviation	Min	Med	Max
25	0.481	0.005	0.474	0.480	0.487
50	0.476	0.008	0.467	0.477	0.485
75	0.475	0.007	0.465	0.473	0.485
100	0.474	0.005	0.468	0.472	0.483
Vid.-ex.			**K [MPa]**		
ε [%]	Average	Deviation	Min	Med	Max
25	120.8	29.1	86.9	114.8	158.7
50	93.6	29.2	66.1	89.4	135.9
75	110.4	42.6	72.4	96.1	201.4
100	170.3	51.9	130.8	146.1	269.6

The following is the dependence of the average Poisson's ratio values on the strain (Fig. 6a). The obtained points do not follow the expected trend (Fig. 5), but the regression model is slightly increasing in the region between 80% and 100% of the strain. However, the increasing trend of the average values in this area of the strain can be seen in the diagram of the dependence of the average values of the bulk modulus at selected values of the strain (Fig. 6 b).



a) The dependence of Poisson's ratio ν on the strain ε



b) The dependence of the bulk modulus K on the strain ε

Fig. 6 *The average values of Poisson's ratio and the bulk modulus and their statistical variables*

4 Discussion

The volume changes in elastomeric materials can be characterized by the change of Poisson's ratio and the bulk modulus depending on the strain. The dependencies can be observed and measured, for example, using camera scanning methods. This study compares two measurement methods (the 2D DIC universal system; the 2D DIC implemented video extensometer) based on the measured results and the device setup capabilities. The fitting curves of the dependence of the bulk modulus on strain for the 2D DIC universal system and the 2D DIC implemented video-extensometer are displayed together in Fig. 7. The use of the universal measurement device (2D DIC) seems to be more suitable compared to the implemented system on the machine (video-extensometer). The main advantage of the DIC technology over conventional video-extensometer measurement is the versatility of the device, post-processing of the data and the possibility of modifying or repeating the measurements after the test. The settings of the input measured parameters can be changed or adjusted on the already evaluated camera recording of the test specimens. Furthermore, equations and diagrams not included in the original measurement (or in the different form) can be changed, modified, or created without the requirement to repeat the experimental measurement physically. However, the 2D DIC universal system experiences difficulties detecting the transverse strain of very elongated dumbbells at high deformations. Both measurement methods are performed in the plane (2D); therefore, it is necessary to position the camera perpendicular to the test specimen. Otherwise, the results may become distorted. Production processes and procedures can be improved and accelerated by providing the measurement method that allows reliable results to be obtained relatively in-time. The DIC method can also be used in the 3D DIC configuration, i.e., using two or more cameras. This method provides spatial deformation data, and the results are less sensitive to the exact placement of the test specimen in front of the cameras. Therefore, future research in the field of DIC methodology can be oriented to compare 2D and 3D DIC methods.

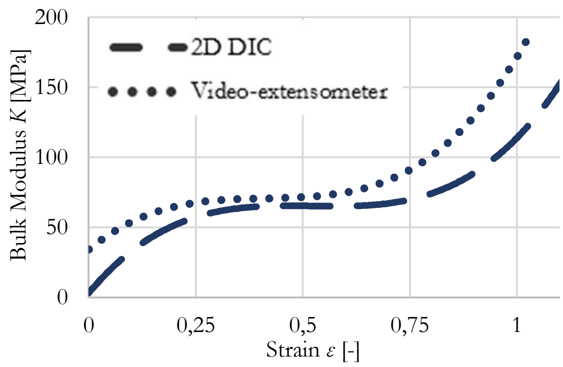


Fig. 7 *The dependence of the bulk modulus K on the strain ε for 2D DIC and video-extensometer measurements*

5 Conclusion

Methods for measuring volume changes in elastomeric materials under uniaxial tensile loading have been studied in this research. Two DIC methods were used to measure the deformation – the 2D DIC universal system and the 2D DIC implemented video-extensometer. The 2D DIC universal system measurement method was considered to be more suitable due to the in-time accurate measurement of transverse and longitudinal strain essential to determine Poisson's ratio and the bulk modulus. This method may be a potential and alternative candidate for determining the Poisson's ratio of elastomers and the resulting characteristics because the estimated Poisson's ratios were close to the reported values obtained using other experimental techniques. Further research on this issue is necessary, and the authors of this article currently plan to continue investigating this area.

Acknowledgement

This article was written with the support of the project IGA/FT/2023/004 TBU in Zlin.

References

[1] LE CAM, J. B., TOUSSAINT, E. (2009). Cyclic volume changes in rubber. In: *Mechanics of Materials*, Vol. 41, No. 7, pp. 898-901. Elsevier. ISSN 0167-6636.

[2] DE CREVOISIER, J. et al. (2012). Volume changes in a filled elastomer studied via digital image correlation. In: *Polymer Testing*, Vol. 31, No. 5, pp. 663-670. Elsevier. ISSN 0142-9418.

[3] CANDAU, N. et al. (2016). On the use of a four-cameras stereovision system to characterize large 3D deformation in elastomers. In: *Polymer Testing*, Vol. 56, pp. 314-320. Elsevier. ISSN 0142-9418.

[4] FARFÁN-CABRERA, L. I. et al. (2017). Determination of creep compliance, recovery and Poisson's ratio of elastomers by means of digital image correlation (DIC). In: *Polymer Testing*, Vol. 59, pp. 245-252. Elsevier. ISSN 0142-9418.

[5] SOTOMAYOR-DEL-MORAL, J. A. et al. (2022). Characterization of Viscoelastic Poisson's Ratio of Engineering Elastomers via DIC-Based Creep. In: *Polymers*, Vol. 14, No. 9, pp. 1837 MDPI. ISSN 2073-4360.

[6] SCHREIER, H., ORTEAU, J.J., SUTTON, M. A. (2009). Image Correlation for Shape, Motion and Deformation Measurements. *Springer US*. ISBN 978-0- 387-78746-6.

[7] SUTTON, M., REU, P. L. (2017). International Digital Imaging Correlation Society: Proceedings of the First Annual Conference. *Springer International Publishing*. ISBN 978-3-319-84651-4.

[8] International Digital Image Correlation Society, JONES, E.M.C. and IADICOLA, M.A. (2018). A Good Practices Guide for Digital Image Correlation.

[9] ILSENG, A., SKALLERUD, B. H., CLAUSEN, A. H. (2017). An experimental and numerical study on the volume change of particle-filled elastomers in various loading modes. In: *Mechanics of Materials*, Vol. 106, pp. 44-57. Elsevier. ISSN 0167-6636.

[10] LE CAM J. B. (2010). A REVIEW OF VOLUME CHANGES IN RUBBERS: THE EFFECT OF STRETCHING. In: *Rubber Chemistry and Technology*, Vol. 83, No. 3, pp. 247–269. American Chemical Society Rubber Division. United States. ISSN 0035-9475.

[11] CHEVALIER, L. et al. (2001). Digital image correlation used to analyze the multiaxial behavior of rubber-like materials. In. *European Journal of Mechanics - A/Solids*, Vol. 20, No. 2, pp. 169-187. Elsevier BV. ISSN 0997-7538.

[12] SUTTON, M. A. et al. (2008). The effect of out-of-plane motion on 2D and 3D digital image correlation measurements. In: *Optics and Lasers in Engineering*, Vol. 46, No. 10, pp. 746-757. Elsevier. ISSN 0143-8166.

[13] CHRISTENSEN, R. G., HOEVE, C. A. J. (1970) Comparison between theoretical and experimental values of the volume changes accompanying rubber extension. In: *Journal of Polymer Science Part A-1: Polymer Chemistry*, Vol. 8, No. 6, pp. 1503-1512. John Wiley & Sons, Inc. ISSN 1099-0518.

[14] GOEBEL, J. C., TOBOLSKY, A. V. (1971) Volume Change Accompanying Rubber Extension. In: *Rubber Chemistry and Technology*, Vol. 44, No. 5, pp. 1391–1394. American Chemical Society Rubber Division, United States. ISSN 0035-9475.

[15] PENN, R. (1970) Volume changes accompanying the extension of rubber. In: *Transactions of the Society of Rheology*, Vol. 14, No. 4, pp. 509–517. The Society of Rheology. ISSN 0038-0032.

[16] SCHREIER, H.W., BRAASCH, J. R., SUTTON, M. A. (2000). Systematic errors in digital image correlation caused by intensity interpolation. In: *Optical Engineering*, Vol. 39, No. 11, pp. 2915-2921. SPIE. ISSN 0091-3286.

[17] VAŠINA, M., PÖSCHL, M., ZÁADRAPA, P. (2021). Influence of Rubber Composition on Mechanical Properties. In: *Manufacturing Technology*, Vol. 21, No. 2, pp. 261-269. ISSN 1213-2489.

[18] GOH, C. P., RATNAM, M.M., ISMAIL, H. (2016). Large In-plane Deformation Mapping and Determination of Young's Modulus of Rubber Using Scanner-Based Digital Image Correlation. In: *Experimental Techniques*, Vol. 40, pp. 1117–1127. Springer Nature. ISSN 0732-8818.

[19] SOBOTKA, J., SOLFRONK, P., KORECEK, D. (2020). Influence of Stress State on the Yield Strength of Aluminium Alloy. In: *Manufacturing Technology*, Vol. 20, No. 1, pp. 92-97. ISSN 1213-2489.

[20] PAN, B. et al. (2009). Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review. In: *Measurement Science and Technology*, Vol. 20, No. 6, pp. 1-17. IOP Publishing. ISSN 0957-0233.

[21] KUGLER, H. P., STACER, R.G., STEIMLE, C. (1990). Direct Measurement of Poisson's Ratio in Elastomers. In: *Rubber Chemistry and Technology*, Vol. 63, No. 4, pp. 473–487. American Chemical Society Rubber Division, United States. ISSN 0035-9475.

[22] KOREČEK, D., SOLFRONK, P., SOBOTKA, J. (2022). Analysis of the Dual-phase Steel DP500 Stress-strain Characteristics During the Plane Shear Test. In: *Manufacturing Technology*, Vol. 22, No. 1, pp. 34-38. ISSN 1213-2489.

[23] FARFÁN-CABRERA, L.I., PASCUAL-FRANCISCO, J.B. (2022). An Experimental Methodological Approach for Obtaining Viscoelastic Poisson's Ratio of Elastomers from Creep Strain DIC-Based Measurements. In: *Experimental Mechanics*, Vol. 62, pp. 287–297. Springer. ISSN 0014-4851.

[24] SEDLAK, J. et al. (2022). Determination of Mechanical Properties of Plastic Components Made by 3D Printing. In: *Manufacturing Technology*, Vol. 22, No. 6, pp. 733-746. ISSN 1213-2489.

[25] GOH, C.P. et al. (2017). Single-step scanner-based digital image correlation (SB-DIC) method for large deformation mapping in rubber. In: *Optics and Lasers in Engineering*, Vol. 88, pp. 167-177. Elsevier ISSN 0143-8166.