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Analysis of the Deflection of Aluminum Profiles for Special Applications Using FEM

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Abstract

The study presents a numerical analysis and experimental verification of deflection of the elements of the band that forms the superstructure of a medium-sized fire-fighting and rescue vehicle. The conducted tests were aimed at the selection of the FEM numerical model enabling the identification of the strain of the structure and the determination of the state of deformation under operational loads. The numerical tool used for the analysis was the Ansys software. Based on the conducted tests, it was possible to identify the key areas of the band in which the occurrence of the highest loads is predicted. The use of a numerical solution allows for determining the safe performance level of the designed element before putting it into production. It allows, among other things, to estimate the maximum deflection of a cross-section of a given length loaded perpendicularly and parallel to the direction of extrusion. The cases analyzed in the work are important from the point of view of their application in the construction of a medium rescue and firefighting vehicle.

Keywords: FEM, Deflection, Safety margin, Anodizing, Aluminum alloys

1. Introduction

Due to their properties, such as high corrosion resistance and good plasticity, Al 6xxx series aluminium alloys with the addition of magnesium and silicon are used in various industries, including automotive, shipbuilding, and electronics. In the automotive industry, aluminium profiles are used to build structural elements (frames, superstructures and body parts). One of the main advantages of using aluminium alloys is their small specific gravity, as a result of which their application in specific cases is aimed at reducing the weight of a given element or the entire structure. The use of aluminium alloys to produce aluminium frames significantly reduces the weight of the vehicle, which allows for shortening the braking distance and reduce exhaust emissions [1, 2].

Predicting the behaviour of the material during operation is not a simple task, because possible hidden defects in the material should be also considered. One of the predominant types of damage that occurs during metal shaping is ductile cracking caused by void nucleation, growth, and coalescence. Therefore, it is important to anticipate the crack initiation in a given material already during the plastic working process.

The literature on the subject offers an analysis of the phenomenon through the use of appropriately selected models: mechanics of continuous damage, porous mechanics of a solid, cohesive and phenomenological models [3–6]. Among the models mentioned above, phenomenological models are the most widely used. Although they do not explain the cracking mechanism, they are very easy to implement in computer software for analysing plastic working of metals. These models assume that ductile cracking is the result of a change in energy caused by the accumulation of plastic deformations. Cracking occurs when the damage function reaches a critical value. Critical damage is determined experimentally, usually using tensile testing. Literature review shows that the problem of determining the deflection curve for various types of materials can be found in [7-12], which presents the theoretical model and the design solution of the device determining the modulus of elasticity by bending the material (sample test), instead of using the tensile testing. Whereas the problem of critical damage to materials deformed in hot and hot forming processes is addressed by research conducted by Kim et al. [8], who performed tensile testing of flat alloy AZ31 samples (in the temperature range 50–250°C) in order to determine the critical damage, using the failure criterion formulated as a function of the Zener-Hollomon parameter. Kim and Lee [9] performed tensile testing on flat samples in the temperature range of 100–300°C and determined critical damage using the ductile cracking criteria formulated by Cockcroft-Latham, Brozzo et al., and Ayada et al. Using the Freudenthal criterion, Jia et al. [10] performed upsetting testing to determine the critical damage for alloy AZ31B generated in the temperature range of 250–450°C and the strain rate of 0.01–10 s^{-1}. Liu et al. [11] used the criterion based on the Bonor damage model in the tests of samples made of the X12 steel deformed in the temperature range of 950–1150°C and with the application of the strain rate of 0.1–5 s^{-1}. Whereas Pater et al. [12] estimated the level of critical damage of the C45 steel subjected to deformation in the temperature range 950–1150°C. Zhu et al. [13] investigated crack initiation during hot compression of titanium alloy Ti40 subjected to forming in the temperature range 850–1100°C with the use of the Oh fracture criterion.

In the case of the applicability analysis of structural aluminium profiles, the use of the deflection curve method is very important as it allows to determine the critical points of the structure under development. Unit weight and good plasticity are the features that allow the production of aluminum profiles with complex shapes at significantly lower production costs, compared to steel profiles. The problem of protecting aluminium profiles against chemical or mechanical factors is solved by using the anodising process [3-5]. This process consists in creating a coating on the aluminium surface, which increases resistance to various external factors, such as acid rain, sea water or UV radiation. It is also an effective way to delay the aging of aluminium. The use of anodising significantly improves the aesthetic value of aluminum products. When designing structures made of aluminium profiles, it should be noted that aluminium structures have lower strength and stiffness compared to structures made of steel profiles [6, 14-16]. Therefore, in order to predict the occurrence of unfavourable events during operation, such as torsion of the structure, excessive deflection of the structure, permanent deformation or cracks, it is necessary to carry out a detailed analysis, including deflection curve analysis.

In order to determine whether a given profile meets the safety conditions, computer software based on the finite element method can be used in the initial phase of designing the structure. The use of this type of solution to determine the strength indicators of aluminium profiles allows for shortening the time needed to introduce structural changes at the stage of designing ready-made application solutions. Application of the finite element method for determining the strength of structures made of aluminium alloys is the subject of studies conducted in many scientific and research centres [17-21]. Based on the analysis of results of the conducted tests, it is possible to determine, among others, the influence of the surface and shape of the so-called material recesses that reduce the load on the rigidity of a specific structure. Due to the growing demand for the application of aluminium profiles, this is invariably justified.

In the study, numerical and experimental tests were carried out to determine the deflection curve of the elements of the band forming the superstructure of a medium rescue and fire-fighting vehicle. The adopted concept of building a rescue and fire-fighting vehicle made of Al alloys allows for the possibility of a quick replacement of parts of the superstructure in the event of any damage. However, the new design solution requires a thorough analysis of the load condition of the superstructure element during operation in dynamic conditions.

2. Purpose and scope of the study

The purpose of the study was to assess the strength and rigidity of the design solution for the superstructure of a medium rescue and fire-fighting vehicle based on numerical tests and experimental verification of the obtained results. The deflection curve analysis was performed for two section widths. The studied cases are important from the point of view of their application in the construction of a medium rescue and fire-fighting vehicle. Figure 1. shows the layout of the manufactured band made of the sections shown in Figure 2.

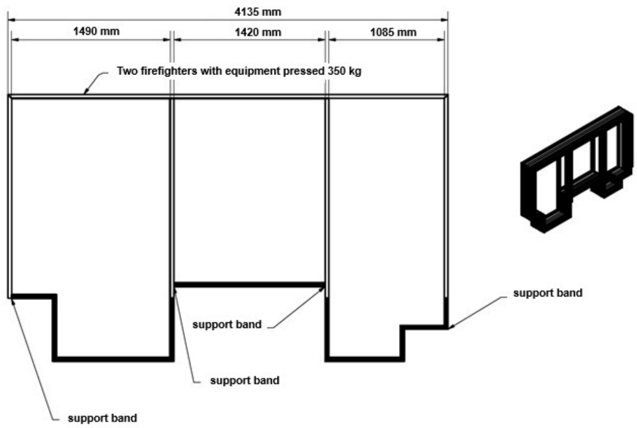

Fig. 1. Layout of the band of the superstructure

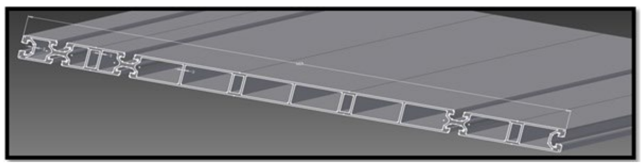

Fig. 2. Cross-section of the section

In the analysed case, according to the application assumptions, the longest unsupported structural fragment in the front compartment of the superstructure will have a length of 1,490 mm. When planning the construction of the superstructure, a maximum load of 350 kg was assumed.

3. Conditions for numerical tests

In the study, deflection curve analysis was performed using ANSYS Software Solutions, which enables solving complex engineering problems, thus allowing for making quick and accurate decisions during the design process. The tests presented in the article were carried out using the Mechanical Structural module, which uses the finite element method (FEM), allowing for the correct definition of the boundary conditions of the model. The main advantage of the finite element method is the ability to obtain results for complex shapes for which it is impossible to perform analytical calculations. This way, the process of searching for the optimal solution can be automated, which enables to quickly test a large number of virtual prototypes, which is why the ANSYS software is widely used in many industries.
The first stage of the analysis was the discretisation of the examined area. A mesh was generated with 26,658 nodes and 14,552 elements (Fig. 3).

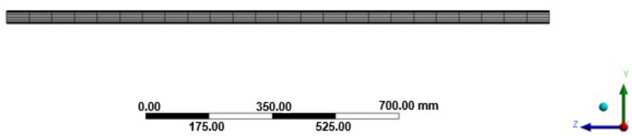

Fig. 3. Longitudinal cross-section of the section with an overlaid numerical modelling mesh

The following initial conditions were adopted for the strength deflection curve analysis of the tested section:
- linear load 350 kg,
- duration of unloading 1 h,
- support distance 1,500 mm,
- the opposite surfaces of the section were immobilised (Fig. 4).

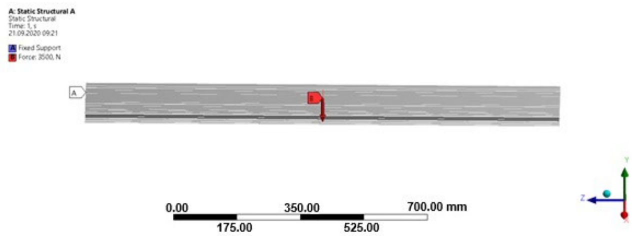

Fig. 4. Boundary conditions for numerical modelling

3.1. Analysis of the obtained test results

A support was applied over a distance of 1,500 mm, while the assumed pressure of 350 kg was applied over the entire width of the section, in the middle of the length adopted for the analysis, as shown in Fig. 4. The obtained results of the numerical tests are presented in Fig. 5÷7.

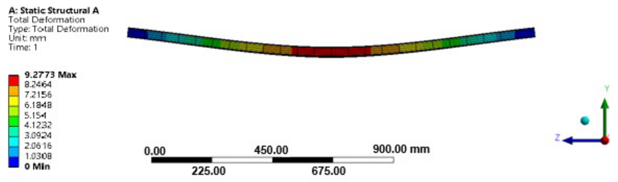

Fig. 5. Distribution of deformation on the longitudinal cross-section under the assumed load

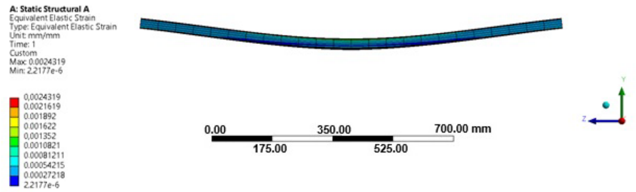

Fig. 6. Distribution of equivalent elastic strain on the longitudinal cross-section under the assumed load

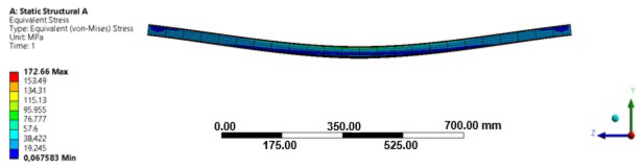

Fig. 7. Distribution of equivalent stress on the longitudinal cross-section under the assumed load

To extend the scope of the study, a numerical analysis was also carried out for a smaller profile cross-section with a length of 1,500 mm, as shown in Fig. 8÷10.

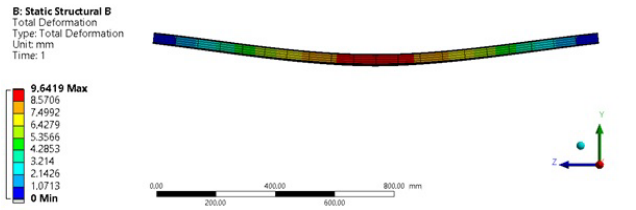

Fig. 8. Distribution of deformation on the longitudinal cross-section under the assumed load

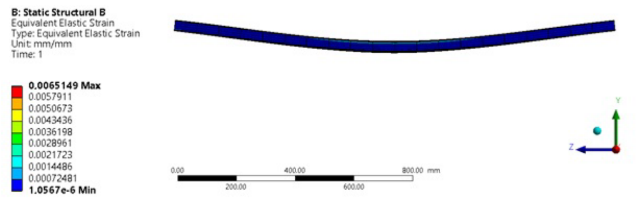

Fig. 9. Distribution of equivalent elastic strain on the longitudinal cross-section under the assumed load

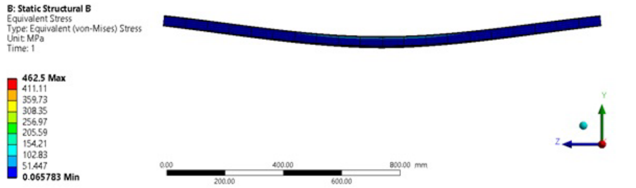

Fig. 10. Distribution of equivalent stress on the longitudinal cross-section under the assumed load

Based on the obtained test results, it can be concluded that the maximum deflection of a section with a length of 1,500 mm in both analysed cases is about 9 mm. It should be noted that for the analysed sections, the assumed load is linear, while the induced deformation is within the elastic range. After unloading, the sections return to their original shape.

The section load was also tested parallel to the tensile direction over a length of 500 mm (Fig. 11). The generated mesh of finite elements consisted of 42,262 nodes and 8,778 elements.

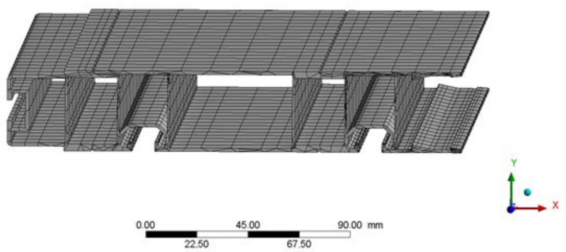

Fig. 11. Longitudinal cross-section of a section with an overlaid numerical modelling mesh

The section load tests were also carried out parallel to the tensile direction over a length of 500 mm for the following conditions:

- linear pressure 350 kg,
- unloading duration 1 h,
- support distance 1,500 mm,
- the opposite surfaces of the section were immobilised (Fig. 12).

The obtained results of the numerical tests are presented in Figures 13÷15.

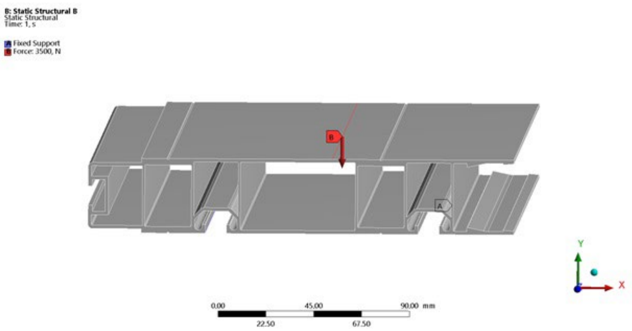

Fig. 12. Boundary conditions adopted during numerical modelling

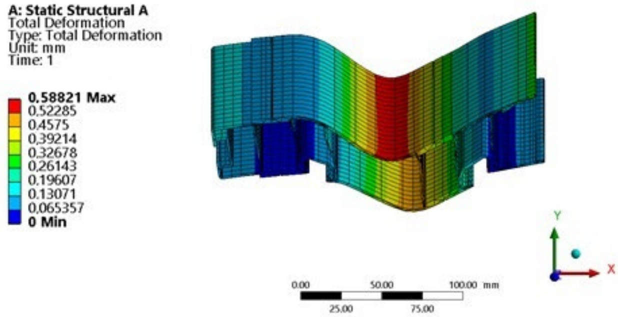

Fig. 13. Distribution of deformation on the cross-section of the section under the assumed load

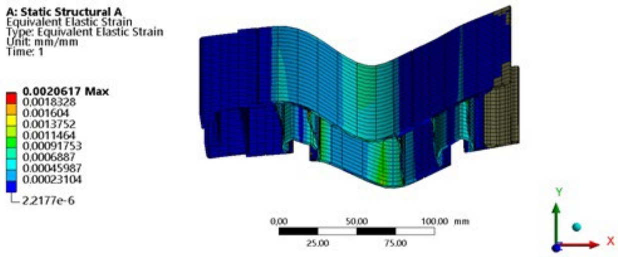

Fig. 14. Distribution of equivalent elastic strain on the cross-section of the section, under the assumed load

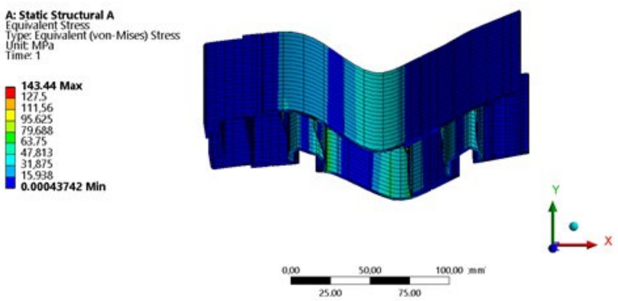

Fig. 15. Distribution of equivalent stress on the cross-section of the section under the assumed load

Based on the obtained test results, it can be concluded that the maximum deflection in the cross-section of the section is about 0.6 mm. Deformation of the analysed sections caused by a linear load is within the range of elastic deformation. After unloading, the sections return to their original shape. The maximum stress at the point of load application was 143 MPa, and the deformation was 0.002.

3.2. Verification of experimental numerical tests

To determine the correctness of the obtained results of numerical tests, experimental tests were carried out, including a bending test of a panel consisting of two profiles made of the 6xxx series aluminium alloy without an anodised layer, and connected longitudinally with elastic elements.

The purpose of the study was to determine the range of elastic deformation and the value of the maximum bending moment. The flat profile bending test was performed at the temperature of 24°C with the crosshead speed of 10 mm/min. The structure load diagram is shown in Fig. 16.

The obtained test results are presented on the crosshead force-displacement plot (Fig. 17). Figure 18 shows the degree of panel deformation after the test.

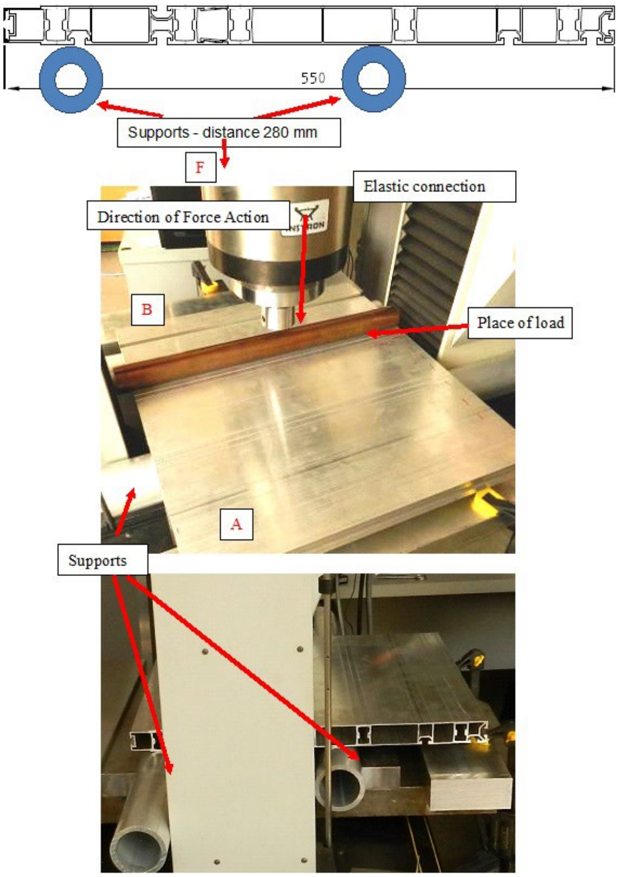

Fig. 16. Sample setting on a testing machine

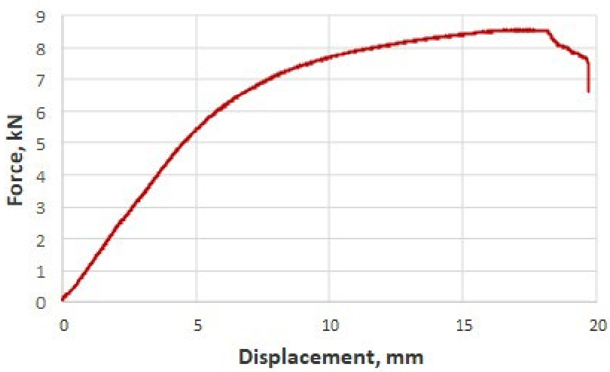

Fig. 17. Force-displacement plot for a flat profile

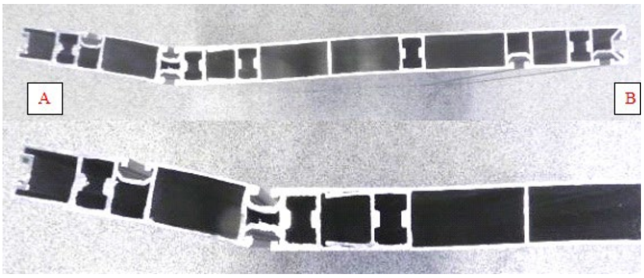

Fig. 18. Panel after the bending test with profiles A and B marked

During the bending test, permanent deformation of the sections took place under the force greater than 8 kN, which is a value significantly exceeding the assumed values of operational pressures.

4. Conclusions

Based on the analysis of the conducted numerical tests and their experimental verification, the following final conclusions were formulated:

- the use of the Ansys software based on the finite element method for modelling the load condition of the superstructure element during operation in dynamic conditions is the right choice,
- the maximum deflection of the section with a length of 1,500 mm, loaded perpendicular to the extrusion direction, is about 9 mm, and is within the range of elastic deformations,
- the maximum deflection of a section loaded parallel to the tensile direction is about 0.6 mm and is also within the range of elastic deformations,
- experimental verification of the numerical tests confirmed that the adopted initial assumptions and the applied numerical solutions were correct,
- the use of numerical modelling for deflection curve analysis when designing aluminium profiles reduces the cost of manufacturing finished products.

References

[1] Miller, W.S., Zhuang, L., Bottema, J., Wittebrood, A.J., De Smet, P., Haszler, A. & Vieregge, A. (2000). Recent development in aluminium alloys for the automotive industry. *Materials Science and Engineering: A*. 280, 1, 37-49. https://doi.org/10.1016/S0921-5093(99)00653-X.

[2] Fridlyander, N., Sister, V.G., Grushko, O.E., Berstenev, V.V., Sheveleva, L.M. & Ivanova, L.A. (2002). Aluminum alloys: promising materials in the automotive industry. *Metal Science and Heat Treatment*. 44, 365-370. https://doi.org/10.1023/A:1021901715578.

[3] Nowak, M. (2020). Hard anodic oxide coatings on aluminum and its alloys. *Stal, Metale & Nowe Technologie.* 1-2, 136-141. (in Polish).

[4] Sheasby, P. G., Pinner, R., & Wernick, S. (2001). *The surface treatment and finishing of aluminium and its alloys* (Vol. 1, p. 231). Materials Park, OH: ASM International.

[5] Gwóźdź, M. (2007). Design problems of modern aluminum structures. *Czasopismo Techniczne*. 4-A, 281-286. (in Polish).

[6] Kossakowski, P. (2014). Aluminum facades. *Przegląd Budowlany*. 2, 39-43. (in Polish).

[7] Pater, Z., Tomczak, J., Bulzak, T., Knapinski, M., Sawicki, S. & Laber, K. (2021). Determination of the critical damage for 100Cr6 steel under hot forming conditions. *Engineering Failure Analysis*. 128, 105588, 1-17. https://doi.org/10.1016/j.engfailanal.2021.105588.

[8] Kim, W.J., Kim, H.K., Kim, W.Y. & Han, S.W. (2008) Temperature and strain rate effect incorporated failure criteria for sheet forming of magnesium alloys. *Materials Science and Engineering: A.* 488(1-2), 468-474. https://doi.org/10.1016/j.msea.2007.11.077.

[9] Kim, S.W. & Lee, Y.S. (2014). Comparative study on failure prediction in warm forming processes of Mg alloy sheet by the FEM and ductile fracture criteria. *Metallurgical and Materials Transactions B*. 45B, 445-453. https://doi.org/10.1007/s11663-013-9886-9.

[10] Jia, W., Ma, L., Le, Q., Zhi, C. & Liu, P., (2019). Deformation and fracture behaviours of AZ31B Mg alloy at elevated temperature under uniaxial compression. *Journal of Alloys and Compounds.* 783, 863-876. https://doi.org/10.1016/j.jallcom.2018.12.260.

[11] Liu, J., Chen, X., Du, K., Zhou, X, Xiang, N. & Osaka, A. (2020). A modified Bonara damage model for temperature and strain rate-dependent materials in hot forging process. *Engineering Fracture Mechanics.* 235, 107107. https://doi.org/10.1016/j.engfracmech.2020.107107.

[12] Pater, Z., Tomczak, J. & Bulzak, T. (2020). Establishment of a new hybrid fracture criterion for cross wedge rolling. *International Journal of Mechanical Sciences.* 167, 105274. https://doi.org/10.1016/j.ijmecsci.2019.105274.

[13] Zhu, Y., Zeng, W., Zhang, F., Zhao, Y., Zhang, X. & Wang, K. (2012). A new methodology for prediction of fracture initiation in hot compression of Ti40 titanium alloy. *Materials Science and Engineering: A*. A553, 112-118. https://doi.org/10.1016/j.msea.2012.05.100.

[14] Kissel, J.R. & Ferry, R.L. (2002). *Aluminium Structures: A Guide to Their Specifications and Design (2nd ed.)*. John Wiley & Sons, New York.

[15] Mazzolani, F.M. & Mandara, A. (2002). Modern trends in the use of special metals for the improvement of historical and monumental structures. *Engineering Structures.* 24(7), 843-856. https://doi.org/10.1016/S0141-0296(02)00023-8.

[16] Kossakowski, P. (2013). Aluminum – an ecological material. *Przegląd Budowlany*. 10, 36-41. (in Polish).

[17] Lonkwic, P., Usydus, I. & Tofil, A. (2018). Application of the numerical method to determine the deflection of an irregularly shaped aluminum profile. *Obróbka metalu, Materiały Eksplatacyjne, Metrologia, Jakość*. 3, 38-42. (in Polish).

[18] Dębski, H., Koszałka, G. & Ferdynus, M. (2012). Application of fem in the analysis of the structure of a trailer supporting frame with variable operation parameters. *Eksploatacja i Niezawodność – Maintenance and Reliability*. 14 (2), 107-114.

[19] Kawałek, A., Bajor, T., Kwapisz, M., Sawicki, S. & Borowski, J. (2021). Numerical modeling of the extrusion process of aluminum alloy 6XXX series section. *Journal of Chemical Technology and Metallurgy*. 56(2), 375-381.

[20] Bajor, T., Kwapisz, M., Krakowiak, M. & Jurczak, H. (2021). The analysis of the extrusion process of al 6005 alloy section. *Journal of Chemical Technology and Metallurgy.* 56, 3, 637-642.

[21] Kawałek, A., Rapalska-Nowakowska, J., Dyja, H. & Koczurkiewicz, B. (2013). Physical and numerical modelling of heat treatment the precipitation-hardening complex-phase steel (CP). *Metalurgija*. 52(1), 23-26.