Topological Optimization of a Component Made by the FDM Method

Jana Dvorakova
Institute of Technology and Automobile Transport, Mendel University in Brno, Brno, Czech Republic
Email: xdvora15@mendelu.cz

Karel Dvorak
Department of Technical Studies, College of Polytechnics, Jihlava, Czech Republic
Email: karel.dvorak@vspj.cz

***Abstract*— To increase the efficiency of technical preparation for the production of components produced by additive technologies, the importance of simulation and optimization processes is growing already in the phase of the design solution. The article aims to introduce the method and demonstrate the process of component optimization, based on the application of the results of simulation methods verification. The available technology is a method of applying molten polymer-based material in layers - FDM (Fused Deposition Modeling). It is possible to produce a part of a rather complex shape in this way. An attribute of the method is the relatively low strength, given by the characteristics of the material used in connection with the production method. To achieve good functional properties of the component, topological optimization can be applied in its design and preparation of production technology. Topological optimization of a part made by the FDM method from a frequently used ABS (Akrylonitrilbutadienstyren) material is performed based on a simulation of the mechanical load of a defined component. The aim is to achieve acceptable mechanical properties and at the same time, efficient production by 3D printing. The presented procedure can be generalized and applied to components of a similar characterizer and other additive production methods. The principle of the process is the effective deployment of CAD (Computer Aided Design) and CAE (Computer Aided Engineering) tools for preprocessing the part in the design phase.**

***Index Terms*—additive manufacturing, computer aided design, computer aided engineering, fused deposition modeling, mechanical properties, topology optimization**

I. Introduction

A specific attribute of additive technology is the creation of the body structure of the part by the method of adding or transforming material. There is a broad portfolio of additive technologies according to the specifics of the material and the related production process [1]. One of the most common methods is the application of molten material by a nozzle in layers - FDM, Fused Deposition Modeling [2]. The material is usually based on a polymer or other fusible, reasonably viscous material. It is also possible to use a metal, wood or other additives, where the medium carrier is a polymeric material. The method is technologically simple and available to a wide range of users [3]. In the commercial market, there is a large offer of printers of various technological levels and related prices. It is also possible to assemble the printer in a modular form from shopping parts with a small proportion of specifically designed manufactured parts. The availability of technology offers the possibility of using 3D printing for the production of functional components of machine assemblies [4; 5]. Functional components are usually mechanically stressed by some kind of stress or a combination of stresses. The design of a mechanically stressed part consists of the analysis of loading forces and the design of a body of appropriate shape and dimensions [6]. Current design support tools are referred to as CAE, Computer Aided Engineering. The analysis of the results obtained by load simulation on a 3D digital model - a virtual prototype, provides information on the spatial distribution of stresses and deformations of a loaded part. More or less loaded places can be identified from the stress distribution. Based on the spatial distribution of the load, it is subsequently possible to optimize the distribution of the material in part by strengthening the significantly loaded places and relieving the volume with a small load. For the production of a component by conventional production processes by machining, or casting, or by forming, the relevant production technology is taken into account in the design of the shaped elements, e.g. the reachability of the shape by a tool or the shape of a mold. Additive technology - 3D printing allows shape production with minimal complexity. It is thus possible to achieve a profile with a high degree of precision in direct production without the need for programming and adjustment of the machine, or the need to produce expensive tools for casting and forming which are complex in shape. For the design of mechanically stressed components, where it is appropriate to use additive 3D printing technology, it is possible to apply the procedure of topological optimization in the design phase with a high degree of efficiency. The result of topological optimization with the

Manuscript received August 7, 2020; revised January 11, 2021.

doi: 10.18178/ijmerr.10.2.67-71

use of computer support is a digital body of general planar shape in the appropriate scale. The body generated in this way can be used directly as a starting point for the preparation of production technology by 3D printing. The text presents the procedure of optimization of a mechanically loaded body - a lever for force transmission. The results of body optimization research are applicable to the design of components of a similar nature. The research is applied to a body produced by the FDM method. An identical optimization procedure is feasible for the design of components for which the production of one of the other additive methods is assumed, e.g. the DMLS method for printing metal components. For the design of the final shape, the possibility of postprocessing the part is taken into account to achieve higher accuracy of selected structural elements.

II. Virtual Prototype Preparation

A. Primary CAD Model

The general principle of CAD data preparation is identical to the rules and recommendations for the creation of digital models - virtual prototypes. The result is a mathematically accurate parametric or nonparametric digital model. To assume topological optimization, it is advantageous to create and identify in the structure model structural elements that are key to defining boundary conditions, bearings and loads. The procedures presented in the text are entirely implemented via the CAx (Computer Aided technologies) tool Siemens NX. The Modeling module is used to create the model. CAE – FEM (Finite Element Method) analysis of the initial model is performed using the Simcenter tool [7]. Subsequent topological optimization is realized through the implemented simulation module Frustum TopoOpt. Siemens NX is a robust CAx application, including modeling, display, simulation and technology modules. Due to the above properties, it is suitable not only for industrial use but also for research purposes. The test samples are printed on an Ultimaker 3 printer. The preparation of print postprocessors is performed in the Cura tool. For the research of optimization procedures, a model of an angled lever for the transmission and change of the direction of force is proposed. It is primarily a component of the rudder control system of a light drone. CAD data of the primary model are used for calculation by the finite element method, where the starting point is the shape and dimensions determined by the digital model. Boundary conditions represent loading forces in the bearing of the lever arms and a pivotal attachment at the point of rotation of the lever. The primary model is shown in Fig. 1. For the finite element calculation, a network on a solid body is defined, to which the properties of the ABS material are assigned, especially Young's modulus, characterizing the deformation of the part under a given load. The definition of the FEM network, load and storage are shown in Fig. 2. The identical material is then used to define the material characteristics for topological optimization.

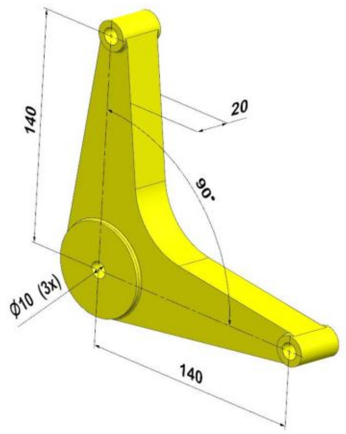

Figure 1. CAD data of primary product with mandatory dimensions.

Figure 2. CAE data of primary product with loads and constraints

B. Simulation Results

The simulation is performed primarily to analyze the stress distribution in the volume of the part at a defined load. The Von-Mises reduced stress method is chosen for evaluation, providing general results for assessing the functional behavior of the loaded part. Initial physical and mechanical characteristics of the component according to Fig. 1 made of ABS material are listed in Table I.

TABLE I. Parameters of Primary Cad Part

Material	ABS
Material density	1050 kg/m^3
Modulus of Elasticity	2000 MPa
Volume	225x10^{-6} m^3
Mass	0.2363 kg

The component is loaded according to the diagram in Fig. 3 with a force of 500 N. The system is in static equilibrium. The force of 500 N is sufficient to derive the force within the function of the device fulfilling the given purpose. This is the force required to transfer the force to the control element. Practical applications can be transformed into several equivalent mechanical applications [8]. The simulation results are shown by visualization in Fig. 4, Fig. 5 and numerically in Table II.

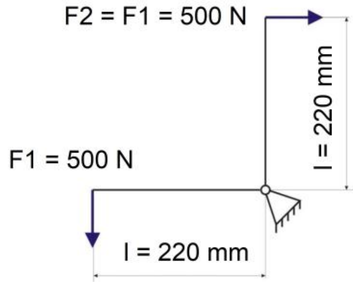

Figure 3. Load and Constraint scheme

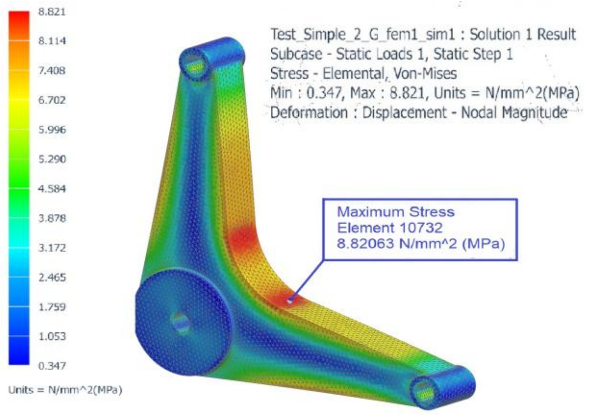

Figure 4. Stress result

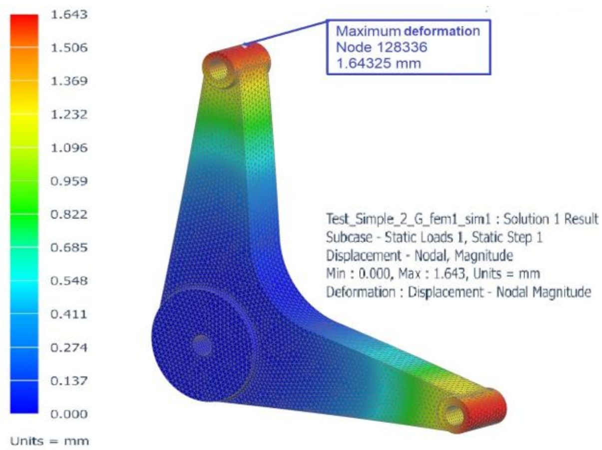

Figure 5. Deformation result

C. *Topology Optimization Results*

The default parameters for topological optimization are to define the space available for placing the part in the assembly and to specify strict structural elements to ensure functional properties. Space is limited by a solid body. Strict construction elements in the example shown are a hole for mounting rods and a hole for mounting using a pin, ensuring the rotation of the lever. At the same time, the limiting body is determined. The loading of the holes at the place of attachment of the lever and the definition of the rotary bearing is identical, with the boundary conditions for the simulation of the exact lever according to the previous chapter. The geometry of the initial simulation is shown in Fig. 6.

The dark green area represents the space for generating the optimized body and is based on the spatial definition of the assembly. The light green area represents a space constraint. The purple body informatively shows the original design of the component according to the previous chapter. The generated, topologically optimized body is shown in Fig. 7.

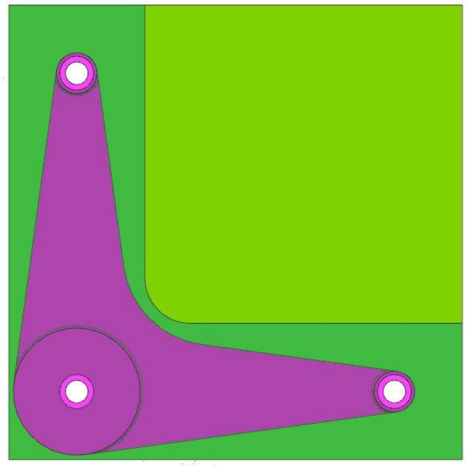

Figure 6. Stress result

Figure 7. Topology optimization body

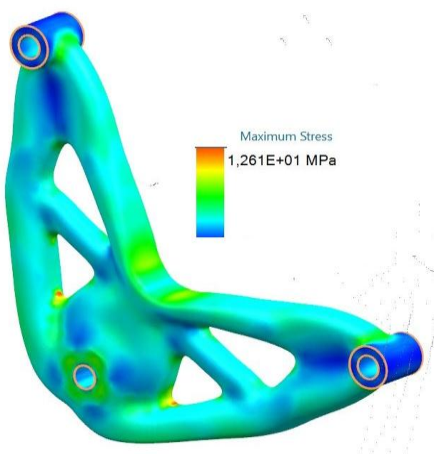

Figure 8. Topology optimization body

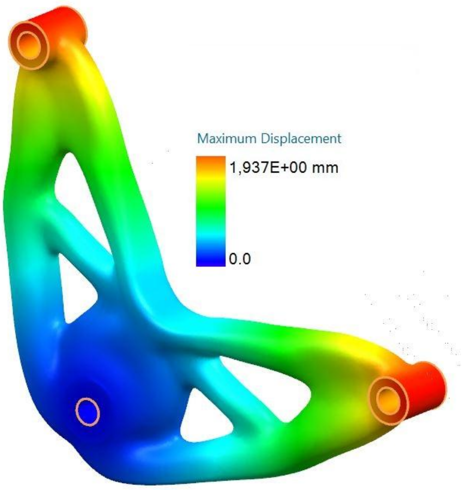

Figure 9. Topology optimization body

In addition to reducing the volume and associated weight [9; 10], the local stress level is also optimized. An illustration of the stress distribution in the volume of the optimized component is shown in Fig. 8. Deformation is demonstrated in Fig. 9.

The characteristics of the optimized body are in Table II.

TABLE II. PARAMETERS OF OPTIMIZED PART

Material	ABS
Material density	1050 kg/m^3
Modulus of Elasticity	2000 MPa
Volume	225x10^{-6} m^3
Mass	0.1895 kg

The weight of the optimized body is 19.8% less than the original when reducing the stress in the most stressed parts of the volume. Topological optimization leads to a reduction in the required volume and a related reduction in the stressed cross-sections in the entire body, which leads to a more significant overall deformation of the loaded part by 15%. In case of non-acceptance of this value, while maintaining the strength, it is possible to tighten the optimization conditions at the place of the most significant deformation, or the body as a whole. The highest stress in the stressed cross-section decreased by 85%, which is a significant increase in safety with an overall reduction in volume and weight due to optimization.

D. Topology Optimization Application

The stated results on the sample body can be applied in equivalent or similar applications of the design of a structural solution of a stressed part, in which the perspective of production is one of the additive technologies. Standard applications of FDM products are polymer-based components that have lower strength characteristics rather than products of identical materials made by machining from molded or cast blanks. At the same time, thermoplastic polymeric materials generally have lower strength characteristics compared to other, mostly metallic, materials. The simplicity of achieving the desired shape with defined component properties using the FDM method expands the portfolio of production technologies of organizations and individuals and complements the technological security of the production process. The advantage of FDM methods is an easy technological preparation of production technology with the subsequent production process.

III. CONCLUSION

The use of topological optimization expands the potential of the common use of industrial tools for modeling and simulation [11, 12]. The application of the topology-optimization module enables to obtain the initial digital optimized data for the preparation of 3D printing by FDM technologies on originally proposed models with relatively simple steps. The use of the resulting data is not limited to additive FDM technology, and it can be used for several other technologies, such as DMLS (Direct Metal Laser Sintering), SLS (Selective Laser Sintering), SLA (Stereolithography), etc. The optimized body is characterized by significantly free shapes, representing free formed surfaces. In addition to 3D printing, achieving precise shape is only possible with multiple NC (Numerical Control) machining. Compared to 3D printing, it is a significantly more expensive production method, with high demands on the technologies used, which is ineffective, especially for polymer components.

The resulting digital body does not have to be only the starting point for the subsequent production process. Analytical use for semi-manual optimization of primary design solutions may be advantageous. The optimized shape is a guide for the application of shape accessories based on standard and non-standard shape elements.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The author Jan Dvorakova created the text and structure of the work, including a search of information sources and evaluated the results of simulations and analyzes. The author Karel Dvorak created a CAD model of the starting product, performs a CAE simulation and topological optimization, including a description and graphical interpretations of the results. Both authors had approved the final version.

ACKNOWLEDGMENT

This research was supported by the College of Polytechnics, Jihlava, Czech Republic, under Grant „Research of parameters for topological optimization of 3D printed components“.

REFERENCES

[1] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, D. Hui, “Additive manufacturing (3D printing): A review of materials, methods, applications and challenges," *Composites Part B: Engineering*, vol. 143, pp. 172-196, 2018.

[2] H. Yu, H. Hong, S. Cao, and R. Ahmad, "Topology optimization for multipatch fused deposition modeling 3D printing," *Applied Sciences*, vol. 10, no. 3, Feb. 2020.

[3] J. M. Mercado-Colmenero, M. A. Rubio-Paramio, M. D. la Rubia-Garcia, et al. "A numerical and experimental study of the compression uniaxial properties of PLA manufactured with FDM technology based on product specifications," *The International Journal of Advanced Manufacturing Technology*, vol. 103, pp. 1893–1909 August 2019.

[4] R. Rezaie, M. Badrossamay, A. Ghaie et al. "Topology optimization for fused deposition modeling process," presented at the Conference: *17th CIRP Conference on Electro Physical and Chemical Machining (ISEM)*, Leuven, Apr. 2013, Procedia CIRP vol. 6, pp. 521-526, Published: 2013.

[5] D. J. Alejandrino, R. S. Concepcion II, S. C. Lauguico, R. R. Tobias, L. Venancio, D. Macasaet, A. A. Bandala, and E. P. Dadios, "A machine learning approach of lattice infill pattern for increasing material efficiency in additive manufacturing processes," *International Journal of Mechanical Engineering and Robotics Research*, vol. 9, no. 9, pp. 1253-1263, September 2020.

[6] C. Grandvallet, F. Vignat, F. Pourroy, G. Prudhomme, and N. Béraud, "An approach to model additive manufacturing process rules," *International Journal of Mechanical Engineering and Robotics Research*, vol. 7, no. 1, pp. 9-15, January 2018.

[7] M. Drajewicz, P. Cichosz, and S. Rudy, "Coupled numerical simulations of the SIMCENTER 3D for casting equipment made of grey cast iron," *International Journal of Mechanical Engineering and Robotics Research*, vol. 9, no. 10, pp. 1360-1364, October 2020.

[8] J. A. Gopsill, J. Shindler, B. J. Hicks, "Using finite element analysis to influence the infill design of fused deposition modelled parts," (2018) *Progress in Additive Manufacturing*, vol. 3, no. 3, pp. 145-163. https://link-springer-com.ezproxy.lib.cas.cz/journal/40964

[9] B. Nicolas, C. Olivier, R. Mickael, and R. Simon, "A design methodology for additive manufacturing applied to fused deposition modeling process," *Mechanics and Industry*, vol. 20, no. 6, Article Number: 608

[10] H. Rezayat, J. R. Bell, A. J. Plotkowski, S. S. Babu, "Multi-solution nature of topology optimization and its application in design for additive manufacturing," *Rapid Prototyping Journal*, vol. 25, no. 9, pp. 1475-1481, Special Issue: SI, Oct. 2019.

[11] L. R. Toleos, Jr., N. J. A. B. D. Luna, M. C. E. Manuel, J. M. R. Chua, E. M. A. Sangalang, and P. C. So, "Feasibility study for Fused Deposition Modeling (FDM) 3D-printed propellers for unmanned aerial vehicles," *International Journal of Mechanical Engineering and Robotics Research*, vol. 9, no. 4, pp. 548-558, April 2020.

[12] K. Dvořák, L. Zárybnická, "Influence of the 3D model and technological parameters on the mechanical properties of fused deposition modeling 3D products," *International Journal of Mechanical Engineering and Robotics Research*, vol. 7, no. 4, pp. 415-421, 2018.

Jana Dvorakova obtained her M.Sc. degree at the Faculty of International Relations at the University of Economics in Prague in 2000, her B.Sc. degree at the Faculty of Mechanical Engineering at the Brno University of Technology in 2017.
She worked as a trainer, assistant of the Board of Directors and as a technician in Skoda Auto Mlada Boleslav, Czech Republic, as the assistant of the company management in Hettich Zdar nad Sazavou, Czech Republic where she was responsible for project management of various projects. Now she works at the College of Polytechnics Jihlava. She specializes in testing mechanical properties of 3D printed samples. In parallel she studies doctoral degree at Mendel University in Brno.

Karel Dvorak obtained his M.Sc. degree in aircraft operations from Czech Technical University in Prague in 2003, his B.Sc. degree in engineering pedagogy from Masaryk Institute in Prague in 2004, and his Ph.D. degree in modeling and simulation in engineering education from the University of Hradec Kralove in 2014.
He worked as a Designer and CAx/PLM Consultant for R&D departments, for example, Donaldson Engine, AxiomTech, FEI Czech Republic, and Thermo Fisher Scientific. In parallel, he has worked as a Teacher of computer-aided design, computer-aided engineering, and product lifecycle management in Secondary Engineering School Zdar nad Sazavou and College of Polytechnics Jihlava. He specializes in advanced modeling methods and preprocessing and postprocessing of CAD models related to rapid prototyping.