DOI: 10.5604/01.3001.0016.0289
Volume 112 • Issue 1 • May 2022
Journal of Achievements in Materials and Manufacturing Engineering
International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Topology optimization of a 3D part virtually printed by FDM

I. Antar [a,*], M. Othmani [b], Kh. Zarbane [a], M. El Oumami [a], Z. Beidouri [a]
[a] Laboratory of Advanced Research on Industrial and Logistic Engineering, National Higher School of Electricity and Mechanics, Hassan II University of Casablanca, B.P. 8118 Oasis, Casablanca, Morocco
[b] Laboratory of Control and Mechanical Characterization of Materials and Structures, National Higher School of Electricity and Mechanics, Hassan II University of Casablanca, B.P. 8118 Oasis, Casablanca, Morocco
* Corresponding e-mail address: intissar.antar@ensem.ac.ma
ORCID identifier: https://orcid.org/0000-0002-6906-7030 (I.A.)

ABSTRACT

Purpose: This research work aims to exhibit the possibility to topologically optimize a mesostructured part printed virtually by FDM taking into account the manufacturing parameters.

Design/methodology/approach: The topology optimization of a 3D part printed by FDM was carried out using the software ABAQUS. On the other hand, a numerical approach using a script based on G-code file has been achieved to create a virtual model. Then, it was optimized according to the Solid Isotropic Material with Penalization (SIMP) method, which minimizing the strain energy was the objective function and the volume fraction of 30% was the constraint.

Findings: The final topological optimization design of the virtual model is approximately similar to the homogeneous part. Furthermore, the strain energy of the virtual model is less than the homogeneous part. However, the virtually 3D optimized part volume is higher than the homogeneous one.

Research limitations/implications: In this study, we have limited our study on one layer owing to reduce the simulation time. Moreover, the time required to optimize the virtual model is inordinate. The ensuing study, we will optimize a multiple layer of the mesostructure.

Practical implications: Our study provides a powerful method to optimize with accurately a mesostructure taken into consideration the manufacturing setting.

Originality/value: In this paper, we have studied through an original approach the potential of topology optimization of a 3D part virtually printed by FDM. By means of our approach, we were able to optimize topologically the 3D parts printed by FDM taking into account the manufacturing parameters.

Keywords: Topology optimization, Fused deposition modelling, Virtually 3D printed part, SIMP

Reference to this paper should be given in the following way:

I. Antar, M. Othmani, Kh. Zarbane, M. El Oumami, Z. Beidouri, Topology optimization of a 3D part virtually printed by FDM, Journal of Achievements in Materials and Manufacturing Engineering 112/1 (2022) 25-32. DOI: https://doi.org/10.5604/01.3001.0016.0289

ANALYSIS AND MODELLING

1. Introduction

Additive Manufacturing (AM), commonly known as 3D printing is a technology for creating three-dimensional objects from a digital (or numerical) file. It is defined by the joint ISO/ASTM 52900:2015 terminology standard to be the "process of joining materials to make parts from 3D model data, usually layer upon layer, unlike the subtractive manufacturing and formative manufacturing methodologies" [1].

This technology allows printing the complex geometries which cannot be printed with the classic subtractive processes. AM technologies have been categorized in seven families: Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DLMS), Fused Deposition Modelling (FDM), material jetting, binder jetting, Directed Energy Deposition (DED) and sheet lamination [2]. Amongst these technologies, FDM is one of the most popular used methods due to it simple to use, low cost and environment-friendly [3].

Hence, this technology has several applications in many different areas, such as medical, automobile and aerospace [4].

Topology Optimization (TO) is an advanced structural design method. It strives to seek in the design space, the optimal distribution of material representing the structure on the basis of a set of loads [5]. The first paper on topology optimization was published over a century ago by the versatile Australian inventor Michelle (1904) who derived optimality criteria for the least weight layout of trusses [6]. Since the landmark paper of Bendsøe and Kikuchi [7] has been presented, various topology optimization methods have been extensively developed after, such as the density approach: solid isotropic material with penalization (SIMP) [8] and rational approximation of material properties (RAMP) [9], evolutionary approach structural optimization (ESO) which considered as a hard-kill method [10] and level set method (LSM) [11,12].

L-bracket is one of the two well-known test examples in topology optimization. It used by several authors to study the stress constraint problem due to its geometric singularity. Holmberg [13] has developed and evaluated first a method to avoid stress constrained topology optimization. His method has been verified numerically on L-shaped beam and MMB-beam. Then, Zhang et al. [14] presented a method to perform stress-based topology optimization with discrete geometric components. Chu et al. [15] proposed a method based on adaptive volume constraint and stress penalty, and through the numerical example using L-bracket, lightweight structure that meets the stress constraint can be obtained and its compliance is simultaneously optimized. Likewise, Fan et al. [16] developed the BESO method for compliance minimization structure subject to both constraints on volume fraction and maximum von Mises stress. To validate their method, L and double L -bracket are used.

On the other hand, L-bracket is also used to compare between the different topology optimization techniques such as Yago et al. [17], which presented the comparison between the well-known methods of topology optimization: SIMP, BESO, VARTOP and level set method. Through this comparison, the VARTOP and SIMP approaches provide topology layouts with a higher quality than other methods.

Combination of TO and AM provide to the industry the possibility of producing structures with high performance and light weight in less time and cost in contrast to the traditional manufacturing methods. In this work, we propose a method for optimizing the L-bracket virtually printed by FDM. Through a script developed in "Python" then integrated in "Abaqus Standard" the digital model has been created similar to the physical one, this process is called "virtual 3D printing." This method takes into consideration during the optimization of model the following parameter printing: layer thickness, raster angle, infill density and number of perimeters.

The remainder of this paper is organized as follows. In section 2, presents topology optimization of L-bracket using SIMP method. Section 3 is devoted to the methodology and numerical set up of the virtual 3D printing model. In order to verify the validity of this approach, section 4 presents a comparison between the optimization of the virtually 3D printed L-Bracket and the homogeneous one. This comparison is based on the optimal design results, volume fraction and the strain energy value. Finally, a conclusion is drawn in section 5.

2. Topology optimization using SIMP method

2.1. Mathematical formulation

SIMP so-called "power-law approach" [18] is one of the most popular mathematical methods and commonly used in topology optimization. It consists of finding the optimal distribution of a material in a given space, which the objective function is minimizing the compliance or maximizing the stiffness under a volume fraction constraint [15,16]. The general equation can be stated as:

$$\min c(x) = U^T K U = \sum_{e=1}^{N} (x_e)^P \, u_e^T K_e u_e \qquad (1)$$

$$\text{s.t.} \begin{cases} \frac{V(x)}{V_0} = \text{Volfrac} \\ KU = F \\ 0 < x_{min} < 1 \end{cases} \qquad (2)$$

where U and F are the global displacement and force vector, K is the global stiffness matrix, u_e and K_e are the element displacement vector and stiffness matrix, respectively. x_{min} is a vector of minimum relative densities (non-zero to avoid singularity). N is the number of elements used to discretize the design domain, p is the penalization power. This parameter penalizes intermediate densities. V(x) and V_0 is the material volume and design domain volume. Volfrac prescribes the volume fraction [19].

2.2. Topology optimization via ABAQUS

L-bracket is a popular test and benchmark problem in topology optimization. It can be a stand for a device, while the corners are due to spacing from other devices or the shape of the actual device itself. Therefore, industrial applications were used by this sort of design domain. That shape is optimized topologically as a printed part with behaviour law of the ABS filament regardless of the manufacturing parameters.

The SIMP method using ABAQUS finite element analysis with Tosca, a linear and isotropic solid element type is applied to the 3D L-bracket. The properties of the model are illustrated in Figure 1 and Table.1 summarizes the parameters for topology optimization of the part.

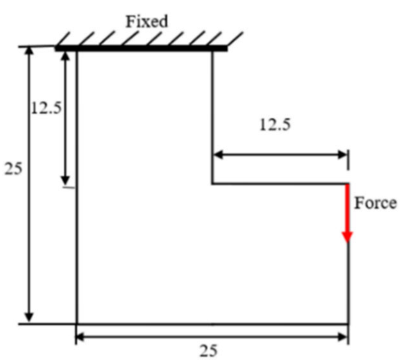

Fig. 1. Geometry and boundary condition for the L-bracket

Table.1.
Design parameters for topology optimization of L-bracket

Properties	Values
Young's Modulus	2200 MPa
Poisson's ratio	0.33
Force	4 N
SIMP factor	3
Filter radius	1.1
Volume fraction	0.3
Thickness	0.2 mm

Linear 3D tetrahedral elements were made in mesh type, the domain is discretized by 324,000 elements and the material used is ABS. Then optimized topologically the homogeneous part, according to two variables, was used2 The first was to minimize the compliance or strain energy and the second was the constraint of volume, which represents the volume we desire to maintain and it is set at the value of 30%. The domain is discretized by 324,000 elements.

Asus computer with INTEL Core i5 CPU 2.2 GHz and 4 GB of RAM is used here. The time consumed for optimizing one layer is 15 min. The final topological optimization design is shown in Figure 2. And the distribution of the von Mises stress σ_{VM}^{H} in the homogeneous optimal design is presented in Figure 3. We also mention that the optimization problem is solved by the method Optimality Criteria (OC) approach [20].

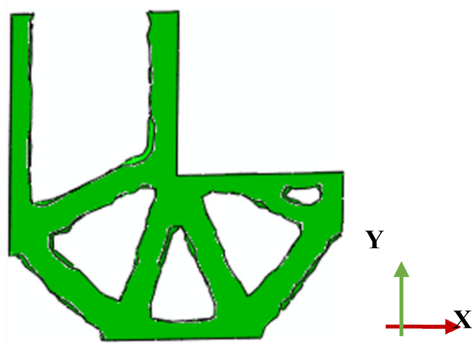

Fig. 2. Optimal design for L-bracket

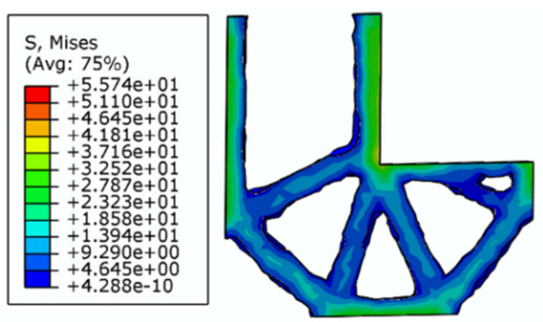

Fig. 3. Distribution of von Mises stress σ_{VM}^{H} in the homogeneous L-bracket

During the optimization process, the convergence of the strain energy is obtained in less than 25 iterations and the preserved volume fraction of solid material is 30% as it appears in Figure 4. the initial stain energy is 33.5 J.

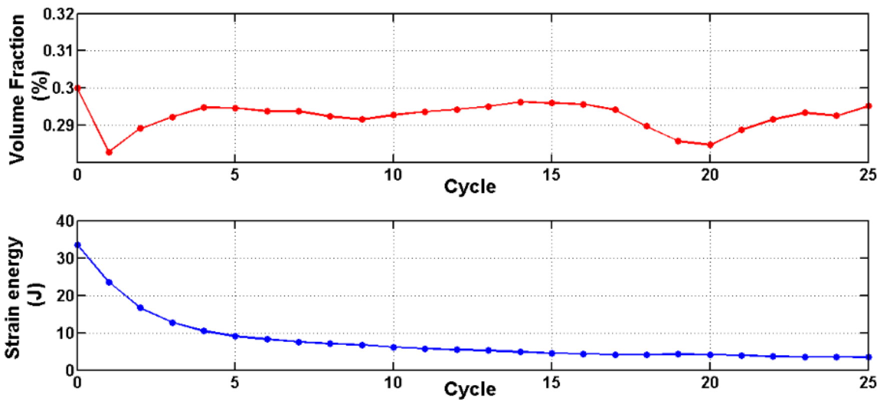

Fig. 4. Evolution histories of the values of volume fraction and objective function throughout the iterations of the homogeneous L-bracket topology optimization

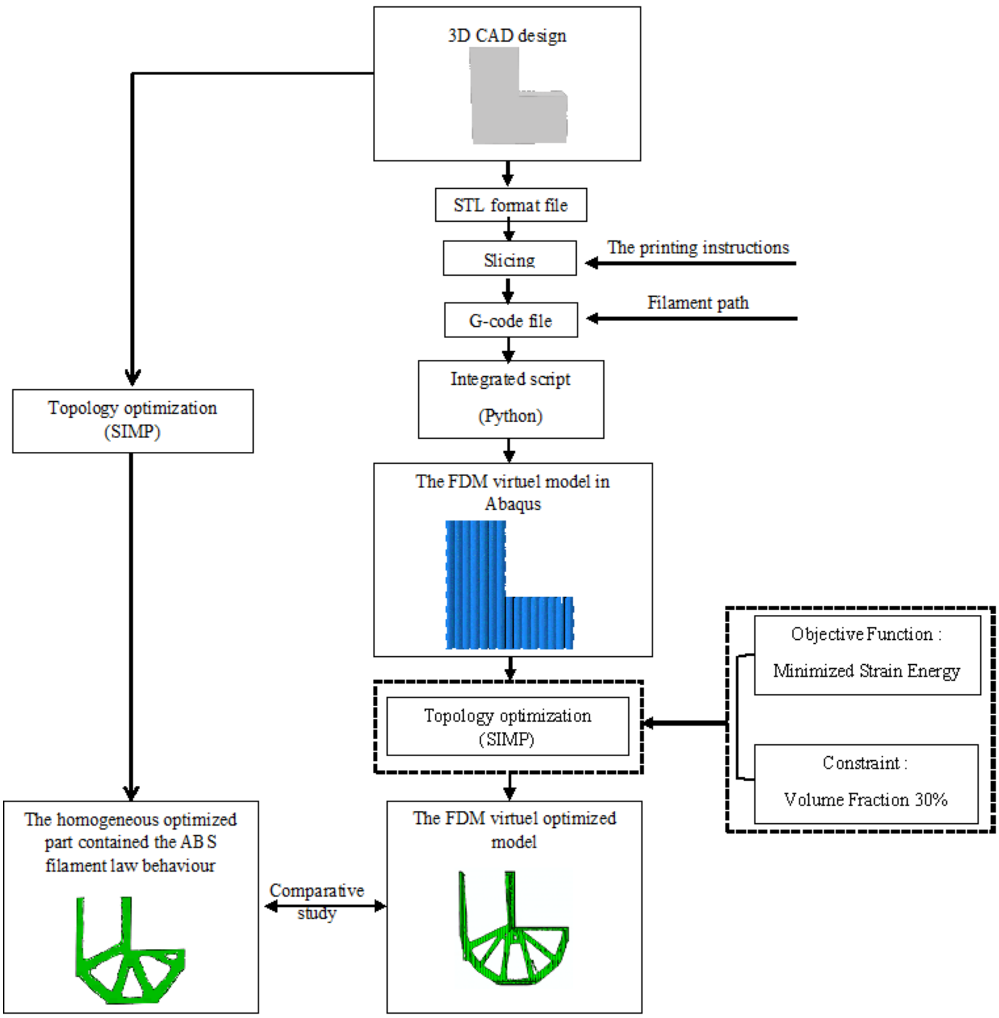

Fig. 5. Scheme of the proposed approach

3. Methodology and numerical model setup

In order to optimize topologically the 3D printing L-bracket, taking into consideration the manufacturing parameters, a virtual model has been created through a script integrated in Abaqus Standard. It is a programming language integrated in Abaqus Standard the way that it executes the G-code extracted from 'Slic3r' then draws the toolpath and the raster section [21]. The virtual model submitted the same boundary conditions on the homogeneous L-bracket optimized above in section 2.

3.1. Geometry description

After creating 3D L-bracket by the CAD software and saved in STL (Stereo Lithography) format, we extract the G-code in order to reproduce the mesostructure which is containing the printing and filament settings (Tab. 2). Then a script in "Python" based on the G-code file has been developed and integrated in the "Abaqus Standard." At the end of the script generation, the virtual model has been obtained.

Table 2.
Printing setting of L-bracket

Parameters	Values
Layer thickness	0.2 mm
Raster angle	90 degree
Infill pattern	aligned
Infill density	99%
First layer printing speed	30
Print speed of other layers	150
Number of perimeters	1
Temperature	230°C

Finally, we optimized topologically the virtual 3D printing model. The Figure 5 shows the process that was followed.

3.2. Numerical setup

When the part generation is completed, we introduced the elastic constants of the ABS filament [21]. Independent instance type is selected in the 'Assembly' module, and tie type interaction contact is created between the contour and infill aiming to stick the filament between them to determine which part of the surface of the model comes into contact during the deformation. The digital model was submitted the similar boundary conditions (load and DOF) to the homogeneous part stated above (Fig. 6). Linear 3D tetrahedral elements are used for meshing the virtual model. The design domain is discretized by 59,829 elements.

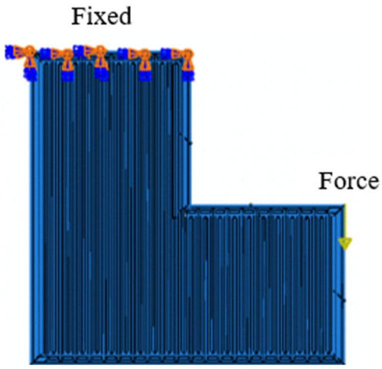

Fig. 6. Virtual L-bracket manufactured by FDM process with boundary conditions

For optimizing the digital model, a topology optimization type was defined in the 'Optimization task' module, under 'Advance' tab, we selected SIMP method in material interpolation technique. Then, we determine the value of the penalty factor [5]. Furthermore, strain energy (presented the compliance on the part) and volume is selected as the variables of topology optimization that used for the objective function that will be minimized and the constraint. The target of the optimization is minimizing the strain energy as per the volume fraction values, for that simulation. The preserved volume of the geometry is 30% of the initial volume to retain the toughness in accordance with its geometric dimension. In the end, we picked out 25 iterations in the optimization process. The parameters necessary for topology optimization are presented below in Table 3.

Table 3.
Design parameters for topology optimization of L-bracket

Properties	Values
Young's Modulus	2200 MPa
Poisson's ratio	0.33
Force	4 N
SIMP factor	3
Filter radius	0.3
Volume fraction	0.3

3.3. Result

The final topological optimization design is illustrated in Figure 7 and the distribution of the von Mises stress σ_{VM}^{V} in the optimal design is presented in Figure 8. The time consumed for the optimization of the virtual model is 58 min.

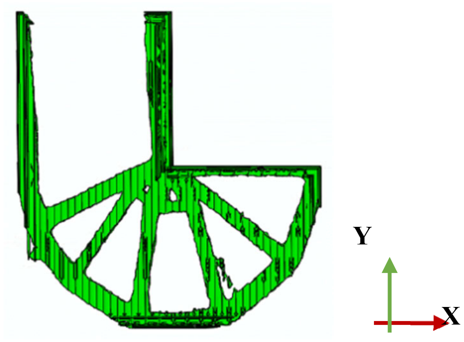

Fig. 7. Optimal design for the virtual L-bracket

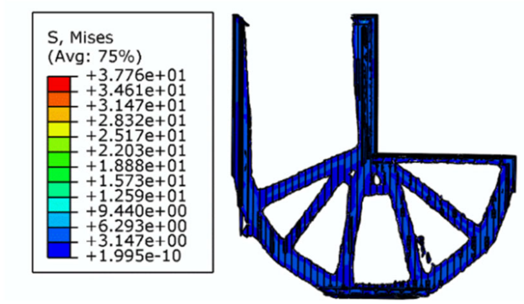

Fig. 8. Distribution of von Mises stress σ_{VM}^{V}n the virtual L-bracket

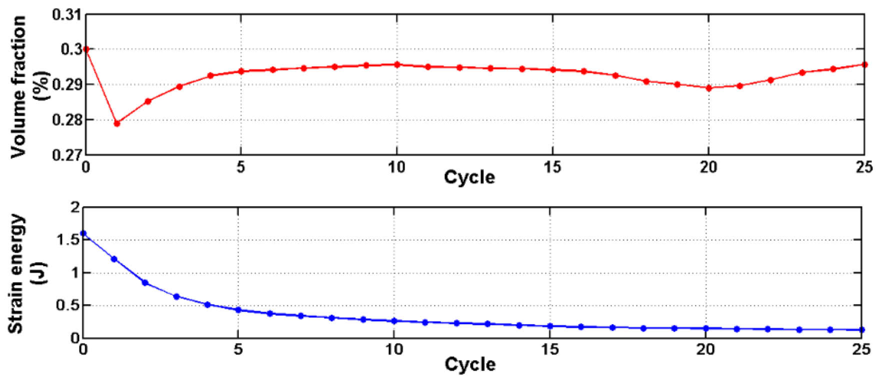

Fig. 9. Evolution histories of the values of volume fraction and objective function throughout the iterations of the virtual L-bracket topology optimization

The volume fraction of the virtual model is 30% and the objective function has decreased throughout the iterations as noticed from Figure 9. That proved the successful topology optimization of the virtual L-bracket, taking into account the 3D printing parameters stated above. The initial strain energy for 0.3 volume fraction is 1.59 J.

4. Comparison and discussion

In this section, a comparison between two methods to optimize a part manufactured by FDM is accomplished. The results can be compared in term of the optimal topology, volume fraction and the objective function value. Both simulations use the same initial design and the same boundary conditions.

By comparison of the results obtained in the L-bracket shown in Figure 10, it can be observed that the overall design of the structure of the two methods is similar, except some regions (contoured regions) due to the higher percentage of the volume fraction that will be reduced while the optimization of the virtual filament.

Regarding the volume fraction, although two parts are identical in the dimensions geometric, the optimized part volume of the virtual model is superior to the homogeneous part (Tab. 4). That refers to the frailness of the virtual model compared with homogeneous one. The mesostructure of the virtual model needed more matter (or volume) to preserve its toughness in contrast to the homogeneous model that needed less matter.

Table.4.
Values of the volume during the optimization process of the 2 parts

Type part	Initial volume, cm^3	Optimized part volume, cm^3	Volume fraction 30%, cm^3
Homogeneous part	93.75	65.62	28.125
Virtual model	131.17	91.8	39.351

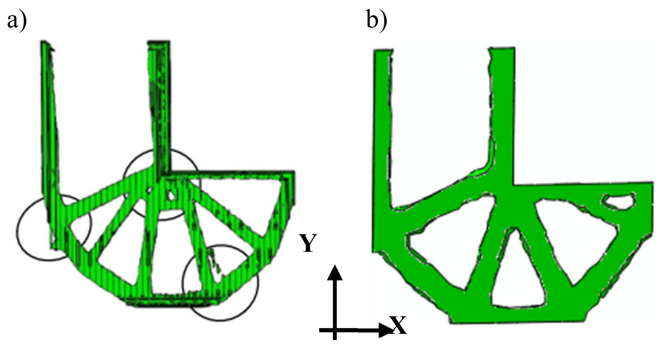

Fig. 10. Comparison of the resulted shape: a) virtual model, b) homogeneous part

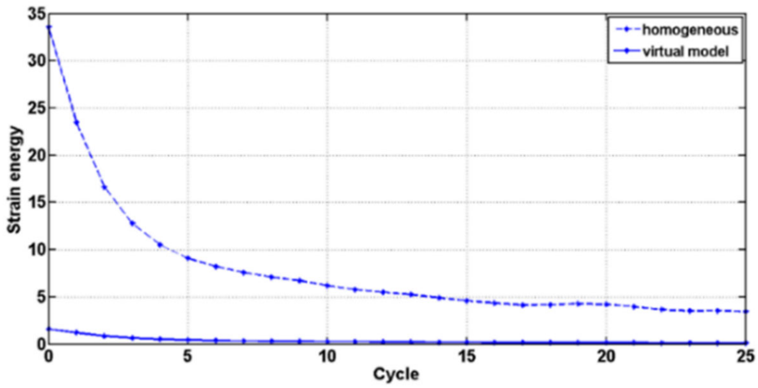

Fig. 11. Comparison of strain energy values of the homogeneous and virtual model at 25 cycles

The curves presented in Figure 11 prescribed the evolution of strain energy throughout 25 iterations to both parts, the homogeneous and the virtual L-bracket. It appears that both curves were decreased versus cycles that demonstrated the successful optimization of the two parts. The final strain energy of the homogeneous L-bracket is 3.43 J and the virtual L-bracket is 0.12 J. However, the difference between the values of the strain energy caused by the porosity existing in the virtual model, which explains the higher value of the conserved volume of the virtual model.

5. Conclusions

The present work aims at studying through a numerical approach the potential of optimizing topologically a 3D printed part taking into account its manufacturing parameters. After presenting the mathematical formulation, we carried out a numerical approach to optimize a virtual model which represents the mesostructure obtained by FDM process. This virtual model was created via a script that we developed in "Python" based on the G-code file and integrated in "Abaqus Standard". It was then topologically optimized according to the SIMP method which minimization of compliance is the objective function and the constraint is the volume fraction of 30%. A comparative study has been achieved according to the topological shape results, volume fraction value and strain energy values of two methods, either for the homogeneous optimized part fabricated by the ABS, or the optimized mesostructure of the virtually 3D printed part. The results of the optimal design for 3D L-bracket are, in general, identical except some regions. Furthermore, the final volume of the optimized parts demonstrates that the homogeneous part is lighter than the virtual one. Nevertheless, the discrepancy in the volume fraction and the strain energy value of both models is owing to the porosity existing in the virtual model. This study is a preliminary work aimed at optimizing the support structure while printing the model.

References

[1] D.L. Bourell, Perspectives on additive manufacturing, Annual Review of Materials Research 46 (2016) 1-18. DOI: https://doi.org/10.1146/annurev-matsci-070115-031606

[2] ISO/ASTM 52900. Additive Manufacturing-General Principles-Terminology, 2015.

[3] S. Jiang, G. Liao, D. Xu, F. Liu, W. Li, Y. Cheng, Z. Li, G. Xu, Mechanical properties analysis of polyetherimide parts fabricated by fused deposition modeling, High Performance Polymers 31/1 (2019) 97-106. DOI: https://doi.org/10.1177/0954008317752822

[4] J. Plocher, A. Panesar, Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures, Materials and Design 183 (2019) 108164. DOI: https://doi.org/10.1016/j.matdes.2019.108164

[5] M.P. Bendsøe, O. Sigmund, Topology optimization. Theory, Methods, and Applications, Springer Science & Business Media, Berlin, 2013.

[6] G.I. Rozvany, A critical review of established methods of structural topology optimization, Structural and Multidisciplinary Optimization 37/3 (2009) 217-237. DOI: https://doi.org/10.1007/s00158-007-0217-0

[7] M.P. Bendsøe, N. Kikuchi, Generating optimal topologies in structural design using a homogenization method, Computer Methods in Applied Mechanics and Engineering 71/2 (1988) 197-224. DOI: https://doi.org/10.1016/0045-7825(88)90086-2

[8] G. Rozvany, The SIMP method in topology optimization-theoretical background, advantages and new applications, Proceedings of the 8th Symposium on Multidisciplinary Analysis and Optimization, Long Beach, USA, 2000, Paper No. AIAA 2000-4738. DOI: https://doi.org/10.2514/6.2000-4738

[9] M. Stolpe, K. Svanberg, An alternative interpolation scheme for minimum compliance topology optimization, Structural and Multidisciplinary Optimization 22/2 (2001) 116-124. DOI: https://doi.org/10.1007/s001580100129

[10] Y.M. Xie, G.P. Steven, Evolutionary structural optimization for dynamic problems, Computers and Structures 58/6 (1996) 1067-1073. DOI: https://doi.org/10.1016/0045-7949(95)00235-9

[11] M.Y. Wang, X. Wang, D. Guo, A level set method for structural topology optimization, Computer Methods in Applied Mechanics and Engineering 192/1-2 (2003) 227-246. DOI: https://doi.org/10.1016/S0045-7825(02)00559-5

[12] G. Allaire, F. Jouve, A.M. Toader, Structural optimization using sensitivity analysis and a level-set method, Journal of Computational Physics 194/1 (2004) 363-393. DOI: https://doi.org/10.1016/j.jcp.2003.09.032

[13] E. Holmberg, B. Torstenfelt, A. Klarbring, Stress constrained topology optimization, Structural and Multidisciplinary Optimization 48/1 (2013) 33-47. DOI: https://doi.org/10.1007/s00158-012-0880-7

[14] S. Zhang, A.L. Gain, J.A. Norato, Stress-based topology optimization with discrete geometric components, Computer Methods in Applied Mechanics and Engineering 325 (2017) 1-21. DOI: https://doi.org/10.1016/j.cma.2017.06.025

[15] S. Chu, L. Gao, M. Xiao, Z. Luo, H. Li, X. Gui, A new method based on adaptive volume constraint and stress penalty for stress-constrained topology optimization, Structural and Multidisciplinary Optimization 57/3 (2018) 1163-1185. DOI: https://doi.org/10.1007/s00158-017-1803-4

[16] Z. Fan, L. Xia, W. Lai, Q. Xia, T. Shi, Evolutionary topology optimization of continuum structures with stress constraints, Structural and Multidisciplinary Optimization 59/2 (2019) 647-658. DOI: https://doi.org/10.1007/s00158-018-2090-4

[17] D. Yago, J. Cante, O. Lloberas-Valls, J. Oliver, Topology optimization methods for 3D structural problems: a comparative study, Archives of Computational Methods in Engineering (2021) 1-44 (online first). DOI: https://doi.org/10.1007/s11831-021-09626-2

[18] O. Sigmund, K. Maute, Topology optimization approaches: a comparative review, Structural and Multidisciplinary Optimization 48/6 (2013) 1031-1055. DOI: https://doi.org/10.1007/s00158-013-0978-6

[19] O. Sigmund, A 99 line topology optimization code written in MATLAB, Structural and Multidisciplinary Optimization 21/2 (2001) 120-127. DOI: https://doi.org/10.1007/s001580050176

[20] W. Prager, Optimality criteria in structural design, Proceedings of the National Academy of Sciences PNAS 61/3 (1968) 794-796. DOI: https://doi.org/10.1073/pnas.61.3.794

[21] M. Othmani, Kh. Zarbane, A. Chouaf, Enhanced mesostructural modeling and prediction of the mechanical behaviour of acrylonitrile butadiene styrene parts manufactured by fused deposition modeling, International Review of Mechanical Engineering 14/4 (2020) 243-252. DOI: https://doi.org/10.15866/ireme.v14i4.17736