Topology optimization of the tool holder produced with additive manufacturing

M Stepanek, K Raz, Z Chval
University of West Bohemia, Regional Technological Institute, Univerzitni 8, 306 14 Pilsen, Czech Republic

stepanem@rti.zcu.cz, zdchval@rti.zcu.cz, kraz@rti.zcu.cz

Abstract. This paper deals with the topology optimizations of tool holder where three different mass targets were required. The holder was loaded with 499 N. Weight reduction of the tool holder placed in tool turret can positively affect the bearing durability. Easier manipulation with the holder is one of the results. In the process of the topological optimization manufacturing constraints, such as overhang prevention, self-supporting and material spreading were defined for needs of Direct Metal Laser Sintering production technology. Structural analyses of three obtained geometries were simulated for evaluation of the stiffness in three main directions of the tool holder. Finally, the weight and the stiffness of each individual geometry was compared and prepared for manufacturing.

1. Introduction
During the last decades, substantial changes have appeared in an approach to obtain desired geometry in manufacturing. In some cases, traditional subtractive manufacturing is substituted with a completely opposite approach where the material is deposited, united together to create 3D geometry. In general, we talk about additive manufacturing (AM). Additive manufacturing includes many technologies differing of used material (polymers, metals, ceramic, etc.), in the dimension of created geometries accuracy, and required properties [1]. Topology optimization could offer to design construction with desired properties. Topology optimization has experienced rapid development in the past decades and the AM offered the opportunity to design more freedom geometry in a shorter time [2], [3].

2. Design assumptions, dimension, load, manufacturing limits
From the very beginning, it was known, in which testing manufactory the tool holder would be tested after printing. Therefore printed holder is needed to be compatible comparable and similar in outer dimension to the tool holder which is commonly used in the testing manufactory. [4]

2.1. Dimensions
Tool holders made by company EWS are widely used in the testing manufactory. Tool holder EWS 17.4040LDCTXTF was chosen in this article. The dimensions and geometry of the EWS tool holder are shown in Table 1 Loading forces. The main dimensions which must be complied are diameter 40 mm for a tool, height 152 mm, width 76 mm, and length 116 mm [5]. According to those dimensions a scenery body was created.
2.2. Manufacturing limitation

Topological optimized tool holder is going to be produced with Direct Metal Laser Sintering technology (DMLS). Overhang prevention is one of the most important limitations. Every face where the angle between that and the platform (build surface) smaller than 45° must be supported. Despite the ability and accuracy of DMLS too tiny features would be avoided. More details about the overhang issues are mentioned in chapter 5.

2.3. Load

Specific coordinate system was established in this article. The coordinate system is related to the main direction during machining and its scheme could be found in Figure 4 and force components of resultant 499 N are shown in Table 1.

| Load in horizontal-axial direct. (N) | Load in horizontal-radial direct. (N) | Load in vertical-radial direct. (N) |
|--------------------------------------|--------------------------------------|-----------------------------------|
| 450                                  | 200                                  | 80                                |

**Table 1** Loading forces

3. Topology optimization

Software Siemens NX was used for modelling and for the topology optimization. A couple years ago the topology optimization was integrated into a modelling environment. This Integrated Topology Optimization is also known as Generative Design.

3.1. Analysis model

The analysis model is composed of three solid bodies. In Figure 2 design space is colored pink and its dimension was discussed in 2.1. Grey cylinders were defined as scenery bodies. The smaller cylinders are there instead of the holes for a set of screws. The hole for the tool is represented with a bigger
cylinder. Clamping geared rod is not included in the analysis model, because it is not needed for topology optimization.

![Figure 2 Analysis model](image)

### 3.2. Design Constraints

The software allows the setup of different Design Constraints (DC) Planar Symmetry, Extrude Along Vector, Material Spreading, Overhang Prevention, Self-Supporting, etc. Usage of the constraints is dependent on manufacture technology therefore are sometimes called Manufacturing Constraints. Overhang Prevention, Self-Supporting, and Material Spreading are the most important ones for the purpose of DMSL [8]. Overhang prevention and self-supporting constraints are used to solve issues such as the ones shown in Figure 10. The Material Spreading is set in percentages; 30% tends to hollow out solid regions, 60% tends to cause thin walled structures and 100% tends to spread into strut like structures [9]. The final geometry is not only influenced by the constraints used but also by the order of the constraints. Several analyses were conducted to investigate influence of the constraints on the final geometry. Some of the results could be seen in Figure 3 [10]. The constraints which were used in final analysis in the same order: Planar Symmetry, Overhang Prevention, Self-Supporting and Material Spreading set up from 60 to 73%.
3.3. Load and constraints definition

Loads were defined according to Figure 4.
The loads were applied on the planar face on the end of the cylinder representing tool (brown face in Figure 2). Face of the holder which is in contact with a turret (green face in Figure 2) was fixed.

3.4. Material properties
Topologically optimized tool holder was going to be made of Maraging Steel MS (1.2709) its properties are given in Table 2 [6]. Material properties differing in direction were averaged. The value of Poisson’s ratio was 0.288 [7].
Table 2 Material properties of MS1

3.5. Results of the topology optimization
The three topology optimizations that were done differed in targeted mass. All three designs marked v.10, v.11, v.12 were evaluated and compared with each other and their geometry is shown in Figure 5-7.

![Figure 5 Design v.10](image-url)
4. Valuation of results of the topology optimization
There were no exact specifications of values of stiffness, maximal deformation, frequencies, etc. Therefore an evaluative criteria had to be specified. For evaluation the mass and stiffness of each of the three geometries were compared.

4.1. Structural analyze
Four structural analyses were done (3 optimized geometries and original geometry of EWS tool holder. A nominal force of 1000 N was applied to the model in each of the main directions according to Table 1 Loading forces. Then stiffness in each main direction could be determined. The stiffness is linear depended to load so that nominal force could be different to real load 499 N. The definition of the analysed model is shown in Figure 8. The geometry was meshed with 3D tetrahedral elements. Material properties were set as in topology optimization 3.4. The cylinder substituted tool was not used in the structural analysis. The load was applied to 1D mesh of rigid elements type RGB2 and through it was applied to cylindrical face of hole for tool as is shown in the next figure.
All analysis results are presented in the following Table 3.

**Table 3 Results of stiffness and weights**

|          | Horizontal radial stiffness (N/mm) | Horizontal-axial stiffness (N/mm) | Vertical-radial stiffness (N/mm) | Weight (Kg) |
|----------|-----------------------------------|-----------------------------------|---------------------------------|-------------|
|          | (%)                               | (%)                               | (%)                             | (%)         |
| **Orig.**| 190009                            | 0                                 | 407082                          | 9,1         |
| **v.10** | 41139                             | -78,3                             | 106683                          | 3,8         |
| **v.11** | 85067                             | -55,2                             | 204431                          | 4,9         |
| **v.12** | 14410,3                           | -24,2                             | 333448                          | 7,0         |
5. Direct Metal Laser Sintering

DMLS creates the desired geometry layer-by-layer (LbL) by repetitive sintering of metal powder. From the powder feed compartment more powder than is needed for one layer is prepared. The powder is equally distributed on the previous finished layer by a ceramic or metal recoater in a specific height [11]. In the case of EOS M290 it is 40 µm. The rest of the powder is stored in a powder overflow compartment. Manufactured component is connected to the build platform through supports. The supports are used for holding the component above the platform and it leads a large amount of heat away from the built component. Because the component is built LbL it is unevenly heated. The position and amount of support influences accuracy and quality of built component surfaces. Every overhanging face where the angle between the face and platform is less than 45° must be supported. The layer being currently built needs to be united with the previous one. If the angle is too small, quality of the surface gets worse and even could be separated. Influence of overhang on quality of the surface is shown in Figure 10 [12].
6. Conclusion
Topologically optimized tool holder mounted to a turret was designed. Three different results of topology optimization were analysed and for those stiffness and weight were compared. Properties of each design are easily seen in Figure 11.

![Figure 11 Stiffness and weight of original and optimized design](image)

**Figure 10** Defects of overhanging surfaces [13]
Based on the properties, design v.11 was chosen for its sufficient stiffness and mass. Further investigation will be done, and this article could be used as methodology for optimization of tool holder with specified desired properties for example natural frequency.

![Printed tool holder v.11](image)

**Figure 12** Printed tool holder v.11

7. **Acknowledgments**

This paper has been prepared under project ‘Research of additive technologies for future usage in mechanical engineering - RTI plus’, CZ.02.1.01/0.0/0.0/18_069/0010040 of the Pre-application research for ITI of the Ministry of Education of the Czech Republic aimed at supporting research, development and education.

**References**

[1] THOMPSON, Mary Kathryn, et al. Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. CIRP annals, 2016, 65.2: 737-760.

[2] LIU, Jikai, et al. Current and future trends in topology optimization for additive manufacturing. Structural and Multidisciplinary Optimization, 2018, 57.6: 2457-2483.

[3] DENG, Shiguang; SURESH, Krishnan. Multi-constrained topology optimization via the topological sensitivity. *Structural and Multidisciplinary Optimization*, 2015, 51.5: 987-1001.

[4] VLAH, Daria; ŽAVBI, Roman; VUKAŠINOVIĆ, Nikola. Evaluation of topology optimization and generative design tools as support for conceptual design. In: Proceedings of the Design Society: DESIGN Conference. Cambridge University Press, 2020. p. 451-460.

[5] FILIZ, S., et al. An improved tool–holder model for RCSA tool-point frequency response prediction. *Precision Engineering*, 2009, 33.1: 26-36.

[6] MONKOVA, Katarina, et al. Study of 3D printing direction and effects of heat treatment on mechanical properties of MS1 maraging steel. *Archive of Applied Mechanics*, 2019, 89.5: 791-804.
[7] ÖZER, Gökhan; KARAASLAN, Ahmet. A Study on the Effects of Different Heat-Treatment Parameters on Microstructure–Mechanical Properties and Corrosion Behavior of Maraging Steel Produced by Direct Metal Laser Sintering. steel research international, 2020, 91.10: 2000195.

[8] ZHOU, Ming, et al. Progress in topology optimization with manufacturing constraints. In: 9th AIAA/ISSMO Symposium on multidisciplinary analysis and optimization. 2002. p. 5614.

[9] VATANABE, Sandro L., et al. Topology optimization with manufacturing constraints: A unified projection-based approach. Advances in Engineering Software, 2016, 100: 97-112.

[10] MHAPSEKAR, Kunal; MCCONAHA, Matthew; ANAND, Sam. Additive manufacturing constraints in topology optimization for improved manufacturability. Journal of Manufacturing Science and Engineering, 2018, 140.5.

[11] DELGADO, Jordi; CIURANA, Joaquim; RODRÍGUEZ, Ciro A. Influence of process parameters on part quality and mechanical properties for DMLS and SLM with iron-based materials. The International Journal of Advanced Manufacturing Technology, 2012, 60.5-8: 601-610.

[12] PATTERSON, Albert E.; MESSIMER, Sherri L.; FARRINGTON, Phillip A. Overhanging features and the SLM/DMLS residual stresses problem: Review and future research need. Technologies, 2017, 5.2: 15.

[13] Less support is a good thing—when 3D printing. In: The Additive Report [online]. Elgin (IL): The FABRICATOR, 2019 [cit. 2020-06-19]. Available: thefabricator.com/additivereport/article/additive/less-support-is-a-good-thingwhen-3d-printing