J. KESSLER, K. SEMRÁD, K. DRAGANOVÁ, P. KAŠPER

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APPLICATION AND MECHANICAL PROPERTIES OF THERMOPLASTIC POLYMERS FOR THE ADDITIVE MANUFACTURING OF TRANSPORTATION SYSTEMS

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The gradual integration of the additive manufacturing into the common practice involves more complex requirements for the used materials. Although the additive manufacturing was mainly used for the rapid-prototyping purposes, with the development of the high-performance thermoplastic materials, the produced components can be applied not only in the laboratory conditions, but also in the real operation. Therefore, it is necessary to consider also the environmental influences that can significantly shorten the component lifetime. This article presents the 3D printing process for the selected thermoplastic polymers and the experimental verification of the strength analysis of the universal sensor holder together with the quantitative and qualitative comparison of their mechanical properties.

Keywords: thermoplastic polymers, mechanical stress analysis, numerical analysis, additive manufacturing, transportation system

INTRODUCTION

Thermoplastic materials used for additive manufacturing have been recently developed rapidly in terms of their mechanical resistance [1]. This makes it possible to use the 3D printing of the thermoplastics not only for the prototyping purposes [2] but also for the direct manufacturing of components for operation in the practice [3, 4]. However, when the specific material for a given application is chosen, it is also necessary to consider that considering the exterior applications, the material will be exposed to the environmental influences that can affect the mechanical properties significantly [5, 6]. In addition to the thermal stability, it has to be resistant also to the UV radiation. Several thermoplastics for the additive manufacturing meet these requirements. Moreover, it is also necessary to consider their processing demands and to ensure the most efficient utilization of the material.

For this reason, this article presents the generative design module of the CAD/CAM/CAE Creo software from the PTC company, as a progressive tool for the topological optimization, in the direct application to the construction of the universal sensor holder.

GENERATIVE DESIGN

For the design of the universal sensor holder, a generative design was chosen mainly to increase the efficiency of the utilization of the material with regard to the achieving the lowest possible weight of the final component. To achieve this goal, the methodology based on the artificial intelligence was used, the resulting design of which is as close as possible to the natural evolution. However, the generative design is a tool for the optimization [7] of an already created model. The basic requirement for the creation of a model of the universal sensor holder was a joint attachment to the construction of a machine or the whole system, such for example a conveyor belt, a UAS (Unmanned Aerial System), or a monitoring system [6]. It is also necessary to ensure the possibility of the sensor replacement without the need to the re-adjustment of its position. These conditions are fulfilled by the ball pin which can be easily adjusted and also fixed. The requirement for the universality is met by the platform to which the sensor can be attached. The model together with its subsequent optimization applying the generative design was performed in the PTC Creo 7.0 software. The original model of the sensor holder before the optimization is shown in Figure 1.

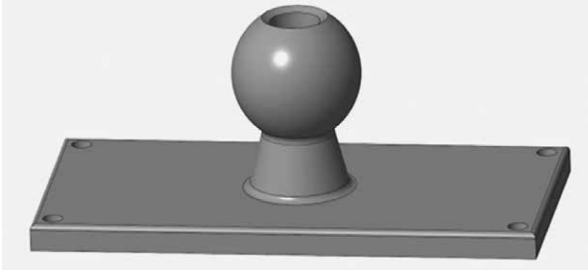

Figure 1 Initial design of the universal sensor holder

J. Kessler, K. Semrád, K. Draganová, P. Kašper, Faculty of Aeronautics, Technical University of Kosice, Kosice, Slovakia
Corresponding author: karol.semrad@tuke.sk

For the generative design creation, it is necessary to define several boundary conditions. These boundary conditions include not only the definition of constraints, loads and materials as in the case of conventional numerical analysis, but in this case, it is also necessary to determine the boundary conditions for the optimization process on the basis of the static load analysis results. For this analysis, it is necessary to define the overall goal of the optimization, i.e., in our case, the required value of the weight saving in the percentual form of the total volume. It is also necessary to define the volumes, to which the boundary conditions will be applied and the volumes to be optimized. This distribution is shown in Figure 2. On the platform part of the model marked with the number 1, the boundary conditions of the static analysis including the magnitude of the loading force, constraints and the material properties can be set. These were already defined in the modeling phase and therefore there is no necessity to define them again, but if necessary, they can be subsequently changed. The part of the model marked with the number 2 will be optimized. The last part of the model, marked with the number 3, is a protective volume, the resulting optimized shape of which cannot be modified [8].

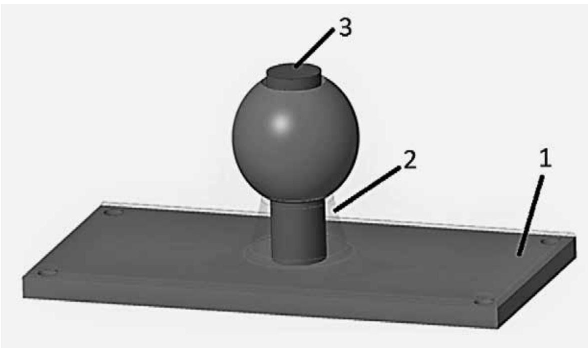

Figure 2 Definition of the optimalization volumes

During the optimization process using the generative design module in the Creo 7.0 software, it is also possible to choose a manufacturing method as one of the boundary conditions of the simulation. The optimization process will therefore consider not only the weight reduction requirements but also the production possibilities of the FDM (Fused Deposition Modeling) technology. However, it is necessary to choose the surface of the model, which will be placed on the printing pad during the printing process. In our case, the choice is obvious, as it is necessary to choose a surface that will be flat and have sufficient external dimensions to ensure the high quality of the first layer. Moreover, it is possible to set for example the maximum overhang angle that can be reliably printed using the selected 3D printer (45°) without the necessity to use the support structures. It is also necessary to adjust the minimum size of the particular elements so that they can be reliably printed. This parameter was set to the value, which was three times larger in comparison to the diameter of the used nozzle (1,2 mm). The resulting value of the material savings is 17,8 % from the initial model weight.

NUMERICAL ANALYSIS

The generative design module involves the solver for the static analysis, which represents the input for the optimization itself. This simulation uses the same solver as the Creo-Simulate module, but some of its features are not available in the 7.0 version. The Simulate module in the Structure Mode is determined directly for the structural analyses. In this software, it is necessary to apply the boundary conditions of the simulation to the resulting model from the generative design module and to create a mesh of the finite elements for the FEM (Finite Element Method) analysis.

During the static simulation of this model, the 3D Tetra, Brick and Wedge elements [9] were used to create the mesh for the simulation purposes. The resulting mesh was generated and optimized automatically to achieve the high-quality computational model. The critical areas were subsequently adjusted manually to achieve the further improvement and stability of the calculation model in the critical areas with the highest concentration of the mechanical stress. In these areas, it is necessary to increase the density of the used elements.

The value of the force load for this simulation was set to 60 N. This load, in the case of the mounting of the sensor holder for example on the conveyor structure, corresponds to the unprofessional attempt to replace the damaged sensor. Considering the placement of the sensor holder on the UAVs (Unmanned Aerial Vehicles), the sensor holder can withstand a hard landing or a minor collision. Due to the symmetrical shape of the model, it is necessary to apply the load only to one side. Thanks to this simplification, it is possible to reduce the total time required for the numerical calculation without affecting the accuracy of the performed analysis. Figure 3 and Figure 4 show the results of the static analysis of the optimized model. From the obtained results it can be seen that the mechanical stress with the maximum concentration is in the top part connecting the pin to the body of the sensor holder. The maximum value of the mechanical stress in this point is 38,23 MPa. Figure 4 shows the deformation caused by the simulated load of 60 N. The maximum value of the deformation is achieved in the point of the application of the given load and is equal to 2,995 mm. The numerical analysis was performed for several materials. The resulting values of the mechanical stresses were identical, but the strain values corresponding to the deformation of the component were for various materials different. From the comparison of the analyses results shown in Tab. 1 it can be concluded that the most suitable material from the compared materials in terms of the mechanical properties is the ASA material.

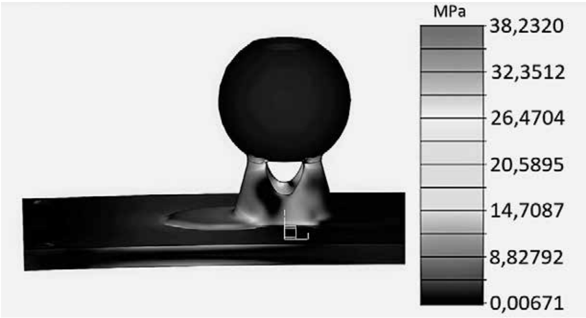

Figure 3 Mechanical stress in the optimized sensor holder

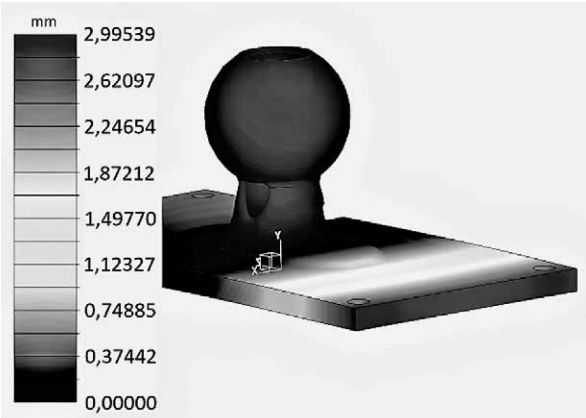

Figure 4 Deformation of the optimized sensor holder made from the ASA material

Table 1. **Comparison of mechanical properties**

Material	Density / g·cm^{-3}	Tensile Strenght / MPa	Flexural Strength / MPa
PET-G	1,27	50	69
ASA	1,11	49,5	75,5

3D PRINTING SIMULATION

Before the 3D printing process, it is necessary to prepare the G-code according to which the given component will be created. In addition to the coordinates defining the movements of the 3D printer print head, the G-code also involves temperatures for the processing of the thermoplastic material chosen for the manufacturing process. The result of this procedure is shown in Figure 5. The most important parameter is the temperature of the print head, at which the processed material melts. This value is 240 °C for the PET-G material and 260 °C for the ASA material and has a significant effect on the resulting mechanical properties of the printing process. If the temperature is insufficient, a poor-quality connection will occur between the layers and the resulting mechanical properties of the component will be influenced significantly. In the extreme case, it will be possible to separate the individual layers in the hands. On the other side, if the print head is overheated to the too high temperature, there is a risk of the overflow during the formation of the individual layers. The manufacturer of the material always specifies the so-called working window, in which the correct tem-

Figure 5 Simulation of the 3D printing process

perature has to be set. The particular temperatures may vary due to different sensors, etc. The most convenient temperature can be determined experimentally by the tensile test.

EXPERIMENTAL MEASUREMENTS AND RESULTS

To verify the mechanical properties of the given component, it is necessary to perform the experimental measurement during which the applied load will be the same as during the numerical analysis. Figure 6 and Figure 7 show the results of the experimental measurement of the designed universal sensor holder samples. In Figure 6 can be seen the comparison of the selected

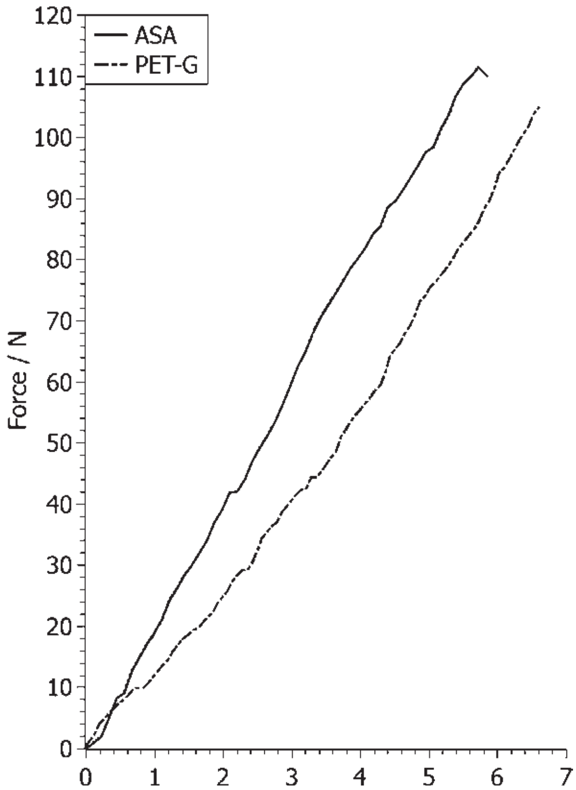

Figure 6 Dependence of the material deformation on the applied force

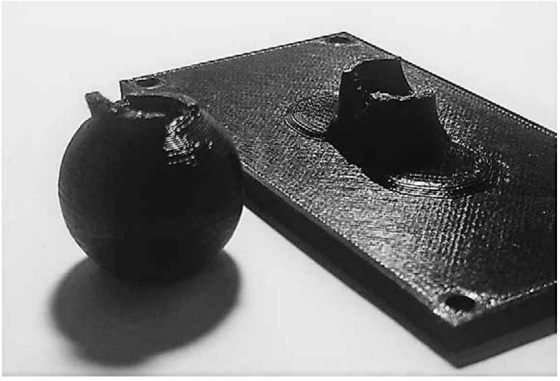

Figure 7 Sample of the damaged sensor holder after mechanical tests

ASA material with the PET-G prototyping material. As expected, the ASA material had better mechanical properties comparing to the PET-G material. The maximum obtained value of the mechanical load reached 111,2 N in the case of the ASA material and 104 N in the case of the PET-G material. The maximum deformation value was 5,85 mm for the ASA and 6,59 mm for the PET-G material. It can be seen that the experimental measurement confirmed the results obtained during the numerical analysis. Considering the value of the applied load of 60 N, the value of the deformation was 2,96 mm. This value corresponds to the static analysis results and confirms the quality of the methodology and of the created model.

Figure 7 shows the broken sample after the mechanical test. The fracture location corresponds to the area determined by the static analysis. It is only shifted slightly lower.

CONCLUSIONS

Due to its mechanical properties and the demands put on its processing, the ASA material was evaluated as the most suitable for its application in the role of the universal sensor holder. The experimental measurement showed that the performed numerical analyses and simulations corresponds to the experimental measurement. The material damage occurred approximately in the area determined by the numerical simulation. The final analyses of the damaged component showed that the component was manufactured without the internal defects. The damage occurred at a value that was almost two times higher in comparison to the values obtained during the simulations of the mechanical stress and deformations. There was also a non-negligible saving of the material applying the generative design optimization. The value of the savings exceeds 17 % of the initial model weight, which also has the influence on the reduction of the energetical requirements for the manufacturing process of the component.

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Note: The English Language translation was done by Assoc. Prof. Ing. Katarína Draganová, PhD., ING-PAED IGIP, Technical University of Kosice, Slovakia