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Prediction of Residual Stresses using FEM before 3D printing by Selective Laser Melting of Stainless Steel AISI 316L

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Abstract. This paper deals with experimental analysis of stress prediction and simulation before 3D printing by Selective Laser Melting method (SLM) and subsequent separation of printed sample from substrate (building board) in Simulation Additive (MSC Software) and Additive Manufacturing Simulation (ANSYS). Practical verification of the simulation was performed on a 3D printed topologically optimized part made of 316L steel (DIN 1.4404). The paper summarizes new knowledge in the field of stress analysis and simulation of 3D printing metallic alloys. The paper also summarizes current trends in the area of simulation software for additive production and reflects their weaknesses and strengths not only with regard to their use in science and research, but also in practice.

Introduction

3D printing (additive manufacturing - AM) of precise metal models includes three technological phases: pre-process (simulation, prediction and data preparation), process (3D printing) and post-process (heat treatment, support removal, machining, etc.). These processes largely affect the reduction or even elimination of stresses and deformations, reducing scrap and manufacturing costs. Selective Laser Melting (SLM) belongs to the Powder Bed Fusion (PBF) additive manufacturing technology, whose principle consists in melting or sintering atomized metal powder by laser. The SLM method is characterized by a thermal process taking place in the so-called melt pool, where the metal powder melts [1]. Due to the local heat input, the printed part does not cool homogeneously, and thus thermal gradients are created, which generally lead to thermal stresses around the melt pool [2]. Heat transfer in the SLM process has a great influence on the final mechanical properties of the print. To obtain a fully dense component without pores, it is necessary to completely melt the metallic particles of the powder. Therefore, it is advisable to use a high laser power, but this brings negative thermal effects, such as a balling effect and internal stress [3] causing distortion of the part or crack.

Several researchers have already researched distortion prediction [4, 5], most of them based on simulation of a model for welding using the FE method. This simulation method consists in the application of a mathematically modeled heat source to the thermomechanical FEA model [4]. This method has been mainly applied in a process where the input material is powder or additional wire. However, these simulations are very limited when the geometry of the part is complex. Chiumenti et al. [5] performed a fully-coupled thermo-mechanical numerical simulation including phase-change phenomena defined in terms of both latent heat release and shrinkage effects. Thus, they formulated a new activation methodology for simulating layer deposition. This method was followed by Lundbäck et al. [6], when it was successfully tested to simulate the deposition of individual layers. In addition, they have improved it by calibrating the inflow and heat input, to predict the correct temperature and distortion. They compared the results experimentally. Hussein et al. [7] developed a 3D FE model for the prediction of melt pool size and temperature gradients that are affected by the scan speed parameter during single layer deposition, this model is valid only for AISI 316L material. He concluded that higher speeds cause a smaller melt pool size in the width and depth parameters, but the pool length parameter is higher. Another conclusion of the publication was that the highest temperature gradients were reached with the first layer and then rapidly decreased with each subsequent layer (at all scan speeds tested). Zhang et al. [8] used a 3D FE model to investigate the dependence of temperature gradients on laser power and scanning speeds. It has been shown that high laser power and low scanning speed lead to significant heat input and high maximum temperature in the SLM process. However, these simulation approaches require high PC performance and a lot of computational time. To speed up simulations, some researchers have begun to use the inherent strain approach, which is commonly used in the field of welding for large components. Keller et al. [9] used the inherent strain approach on a macro scale and successfully managed to significantly reduce the computation times of the simulations, however, the question arises how accurate these simulations are because they have not been experimentally verified. A similar approach based on FE and inherent strain was developed by the team around Afazov et al. [10], when they succeeded in simulating an industrial model of an impeller blade on a macro scale. The data obtained from the simulation were successfully experimentally verified with a high degree of accuracy. Song et al. [11] pointed out in their publication an important fact that needs to be taken into account when designing the simulation, namely that for accurate simulation it is necessary to take into account the surrounding powder around the printed part, when heat is transferred to the surrounding powder.

This study focuses on the prediction and evaluation of deformations using two solutions by ANSYS Additive Suite and MSC Simufact. In both cases, a 3D non-linear finite element model based on thermo-mechanical fields was used. Furthermore, simulations and predictions of temperature distribution and thermal stress were performed. The aim and motivation of this article is to realistically verify and compare the results of advanced commercial software, even experimentally.

Methods

Both ANSYS Additive Suite (AAS) and MSC Simufact work on the principle of Finite Element (FE) simulation and are directly designed for SLM technology. The primary task of these software is to avoid unnecessary cost and time and improve product quality. These tools allow, thanks to the prediction of stresses and deformations in the AM process, to choose the optimal design and orientation of the part in the build chamber. Another function is compensation and distortion prediction, which allows the part to be pre-deformed. Both simulation programs use a layered discretization with voxel elements (cube with a defined edge length). AAS even offers layered tetrahedral elements for better adaptation to the shape of the part. In the AAS program, it is recommended to set 10-20 times the actual height of the print layer for layer simulation [12]. For MSC Simufact, the manual recommends setting the voxel size to 1.8 mm, according to the literature [13] it is clear that the smaller the voxel size is set, the longer the simulation time takes. In general, the simulation procedure can be described by a flowchart, see Fig. 1.

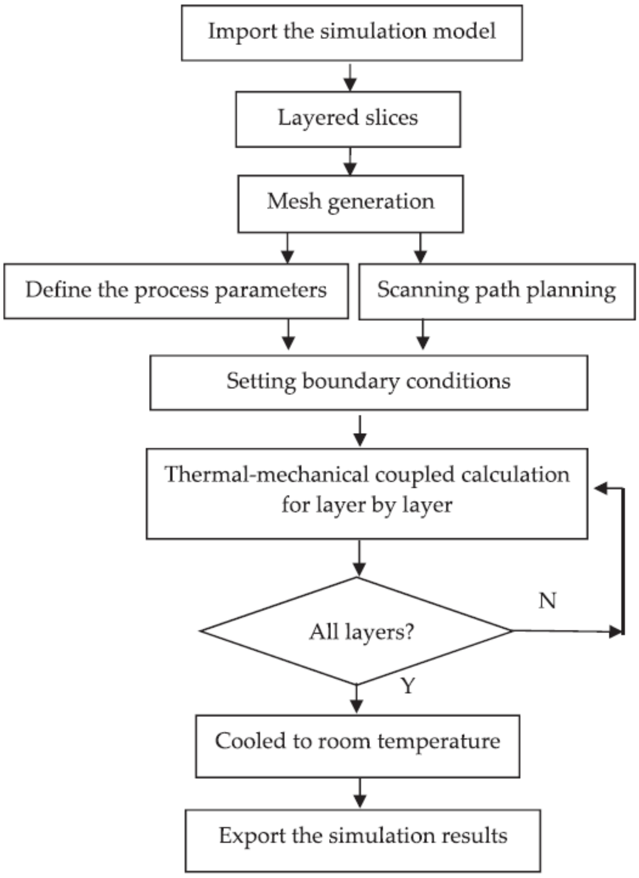


Fig. 1: Flowchart of simulation model [14]

Simulation approach

ANSYS Additive Suite. AAS is fully adapted for work in the ANSYS Workbench environment. The component is first completely meshed to individual layers of either voxel or tetrahedral elements. Each FE layer represents a number of real metal powder layers, assuming thermal continuity of the next layer. The program does not take into account a moving heat source, for example, when the thermal gradient in the build direction dominates over the thermal gradient in the plane due to its effect on residual deformations. Unlike MSC Simufact, AAS requires more input parameters. To simulate the process, it is necessary to specify the basic properties of the material, which are temperature dependent, or inherent strain calibration is also possible. However, the first approach was considered in this study. These parameters include elastic modulus, orthotropic thermal conductivity, Poisson's ratio, density, elastic bilinear curves of plastic stress and strain, coefficient of thermal expansion, and specific heat capacity up to the melting point of the material. In this study, the material properties for AISI 316L (AM), which is predefined in ASS, were set for the simulation. Other process parameters necessary for print simulation are given in Table 1. Meshed was also build plate with hexahedral element.

For this study was used ANSYS Inc. ANSYS Mechanical Workbench, version 2020R1.

Table 1: Process parameter for input data AAS

Parameter	Value
Element size	0.75 mm
Method	Cartesian
Hatch Spacing	0.13 mm

Scan Speed	650 mm/s
Preheat Temperature	22 °C
Layer thickness	50 µm
Scan strategy	Meander

MSC Simufact. MSC Simufact is a program developed specifically for Power Bed Fusion Additive Manufacturing simulations. Selective Laser Melting (SLM), Electron Beam Melting (EBM), Laser Beam Melting (LBM) and Direct Metal Laser Sintering (DMLS) methods can be analyzed. One of the advantages of the software is the coverage of the simulation of the whole AM process, such as printing simulation, support cutting, heat treatment, Hot Isostatic Pressing (HIP) and of course the evaluation of residual stresses and distortions. Simufact offers only a hexahedral element for voxel mesh. After creating the voxel mesh, a volumetric mesh structure is created, which provides a 3D network, then a surface mesh is generated. Voxel and surface mesh complement each other and thus guarantees coverage of the entire part. Since the program offers work with inherent strain, it is necessary to calibrate using cantilever, when a set of cantilever was first printed on the printer in various positions, these were then cut lengthwise, thus activating residual stresses and entering the measured values into software. Material curves and constants have already been predefined for the AISI 316L material as well as for AAS by the manufacturer. The only necessary input from the user is the input of the machine type (for setting the working space), layer thickness, the direction of cutting the part from the printing pad and the voxel size.

For this study was used MSC Software Inc. Simufact version 2019. Main considered parameters in the simulation are stated in Tab.2.

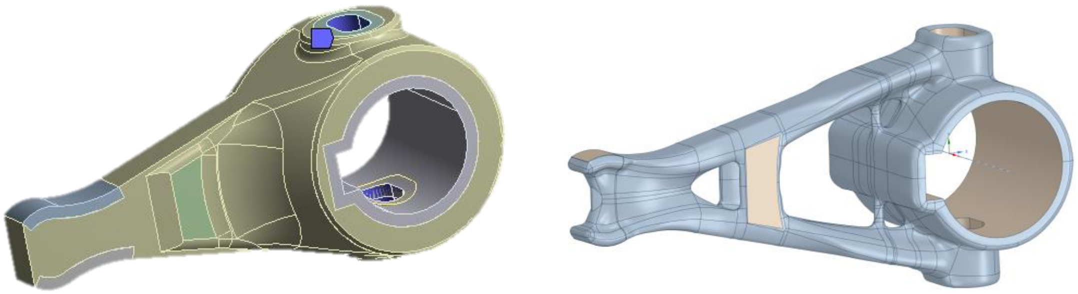
Table 2: Process parameter for input data MSC Simufact

Parameter	Value
Element size	1 mm
Method	Inherent Strains
Hatch Spacing	0.11 mm
Scan Speed	650 mm/s
Preheat Temperature	Ambient
Layer thickness	50 µm
Scan strategy	Meander

Test geometry. For evaluation and validation purposes, was chose a practical component called the Shifting thumb, which is used in the gearbox of trucks. The original shape was topologically optimized for maximum use of the 3D printing potential, see Fig. 2.

Topology optimization has become a powerful area since its algorithms can be applied in many design problems in different physical disciplines such as solid mechanics, fluid dynamics, as well as thermal dynamics. Using topology optimization methods and related algorithms, a designer can generate innovative design ideas especially in engineering fields. Instead of using trial and error methods in designing engineering products, designers use different topology optimization methods to generate conceptual designs.

In topology optimization, it is usually done by creating a geometry that only considers the constraints of the part ranging from supports to the vacant area that the body can move around within the assembly. However, since that part has almost no space within the assembly, the original geometry has been considered in this study with a slight modification for simplicity of calculations and some fitment issues, where the radius at the tip of the thumb was not perfectly matching when attaching it into the main assembly. ANSYS Discovery Live software was used for topological optimization. Final reduction of volume was 63%. The verification of design has been performed in ANSYS Workbench leading to 214.2MPa of Von Mises stress (232.3MPa in ANSYS Discovery Live) what is comparable with 221.5MPa obtained for the original design. Young’s modulus E=195GPa and Poisson’s ratio ν=0.3 were used in the simulations.



(a) (b)

Fig. 2 Original geometry of main shifting thumb (a); Topologicaly smoothed shifting thumb (b)

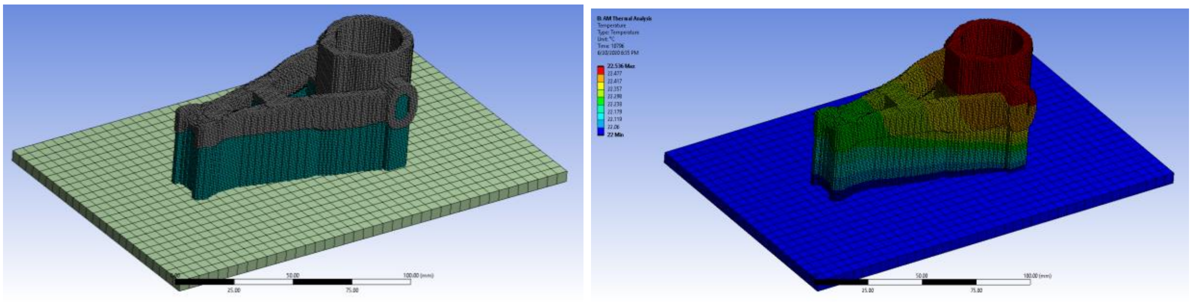
SLM printer RenAM400. A Renishaw AM400 3D printer was used to manufacture and test the part. It is a device for 3D printing of metal parts from the English industrial company Renishaw. This is an improved version of the AM250 printer. The AM400 features an improved optics control system, redesigned inert gas flow, a window protection system and a 400 W optical system with a fiber laser with a wavelength of 1070 nm, which provides a beam with a diameter of 70 μm at the melting point. Argon, which has a higher atomic number than nitrogen, was used to make the experimental sample, displacing more oxygen in the printing chamber and keeping the oxygen level below 500 ppm.

Digital Image Correlation. Testing was performed using Digital Image Correlation (DIC) which is an optical method. Mercury®RT system provided by Sobriety company was used to capture displacement field. The optical contrast coating was created on the printed part (generally known as pattern). The main goal was to investigate the deformation of the part after support removal and subsequent comparison with the deformation predicted by FEM.

The software used in DIC measurement is Mercury RT which is capable of three-dimensional measurements. Two high accuracy cameras (2x2.3Mpx@40Hz) where fixed in front of the investigated part during the cutting process. The cameras record the deformation of the part once the cutting process has begun. With the capabilities of the software deformation contours were gained for comparison with the numerical prediction.

Results and discussion

Total displacement simulation in AAS. The software offers an orientation map feature where it simulates all possible angles and calculate build time, distortion tendency, and supports. After the selection of the appropriate orientation the model then undergoes an additive manufacturing thermal analysis to simulate the printing process and predict structural defects such as deformation due to shrinkage during cooling time. Using ANSYS Additive Manufacturing Wizard, the following project setup would automatically generate. AM thermal analysis meshing is displayed in Fig. 3a, also AM thermal analysis results are shown in Fig. 3b which confirms that the effective thermal stress proportionally related to the increase of layer height from bed surface.



(**a**) (**b**)

Fig. 3: AM meshing for thermal analysis (a); thermal analysis results (b)

After thermal analysis, structural AM analysis was performed. From the nature of using Cartesian mesh, we can get an unacceptable result. Therefore, a subsequent finite element analysis (submodeling) is required to obtain finer and more accurate results by selecting finer mesh. Such process was performed with suppressed base plate and ignored nonlinear effect as well as initial strain. After obtaining the evaluation of the simulated printing process in Fig. 4, theoretical results are then verified by performing the printing process and perform a deformation test during cutting the part from its base plate. Maximum displacement is about 0.83 mm. The largest deviation from the original shape is shown on the "nose" of the part. Here the greatest deformation occurs due to the fact that the coarser part does not deform and the rest bends due to thermal stress and also the corners of the part act as stress concentrators.

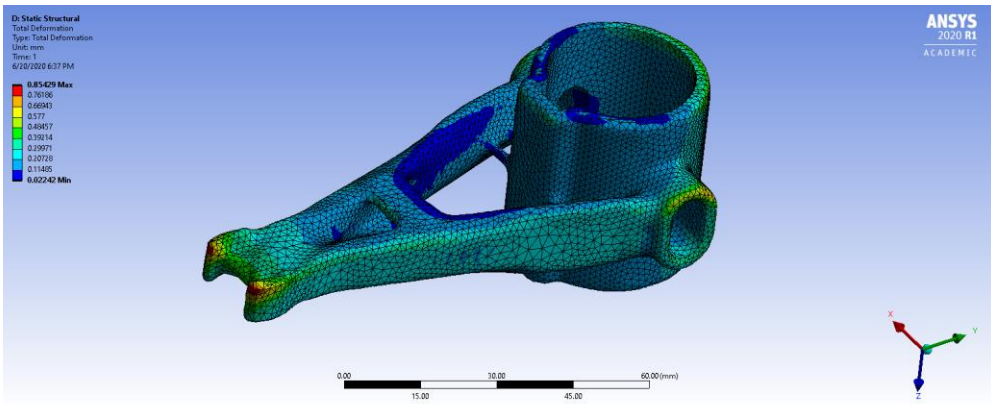
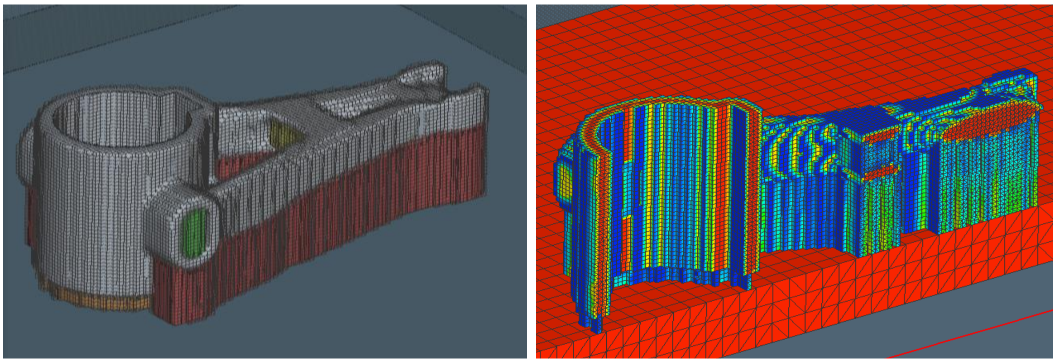


Fig. 4: Standalone structural analysis by ASS

Total displacement simulation in MSC Simufact. Performing a simulation in the Simufact program consists of eight steps. After importing the geometry, support elements are generated or imported. In the third step, the manufacturing parameters are defined, see Table 2. By selecting the AM printer, the dimensions of the working environment are automatically set, then the distance of the Z-axis direction is manually set. In the fourth step, a surface and voxel mesh are formed, see Fig. 5a. The surface mesh is set to 2 mm by default for each analysis. Surface mesh is the type of mesh that is transferred to the shifting thumb part after the voxel mesh. The voxel element size was set to 1 mm. Voxel mesh then directly analyzes the deformations, see Fig. 5b. The main reason for creating the surface and voxel mesh is to bring the part as close as possible to the actual shape. The fifth step analyzes the results and shows a preview, in the sixth step the results are graphically displayed, which are used to calculate the pre-deformed model and can be further analysed. The penultimate step consists in removing the supporting elements and in the last step the cutting of the part from the build plate is realized.



(a) (b)

Fig. 5: Voxel and Surface mesh (a); Voxel mesh analysis (b)

In this study, the layer height was set to 0.05 mm and the inherent strains ε_{xx} = -0.0036, ε_{yy} = -0.0036, ε_{zz} = -0.03 at distribution uniform. These values were determined by calibration using a reference structure for the equipment used. From the results of the simulation with the printing plate, a total displacement in the range of 0.6-0.7 mm was obtained. The surface deformation deviation was 0.58 mm and, as with the ASS software, the largest deformation on the "nose" of the component was evaluated, see Fig. 6.

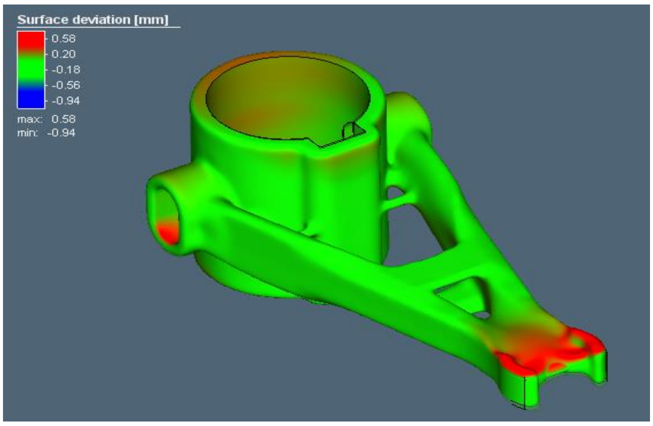
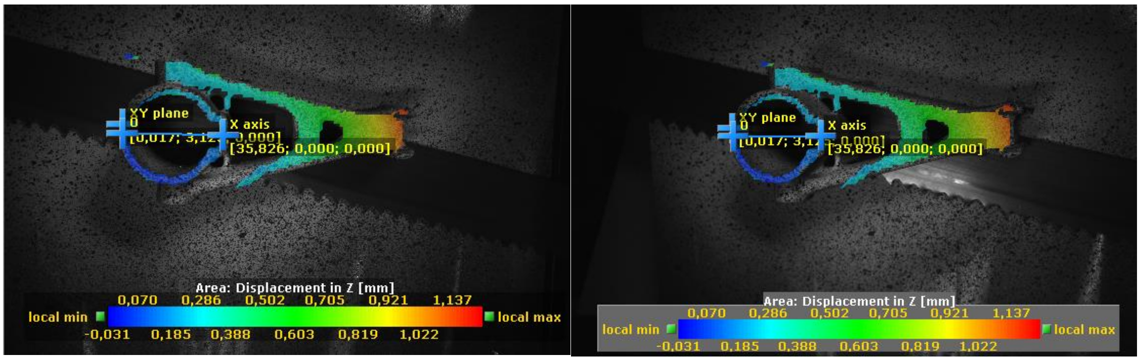


Fig. 6: Standalone structural analysis by MSC Simufact

Validation of the results. The part was printed on RENISHAW AM400 machine using Stainless Steel AISI 316L as a print material. After the completion of printing process, excess powder material was then safely removed for recycling into future jobs. Then, the printed part goes through cutting from base plate process which was investigated to observe if any deformation occurs in the printed part.

Testing was performed using Digital Image Correlation (DIC). It is observed in Fig. 7, that the resulting deformation is a slightly higher than the simulated deformation in Fig. 4 and Fig. 6. There are many factors that might have a role in such difference. For instance, computational tools have different approaches and input parameters and that might result in different values. Also, the factor that can be easily pointed out is the material properties that were implemented into the simulation process where ANSYS and MSC material library was the source of the material properties assigned. Material properties of the printed part differ from the material properties available in the library. Even more, meshing of the bodies might have a significant impact since the calculations where constrained to limited number of elements to run the calculations Moreover, heating due to slicing could be a factor for additional deformation of the part.

Cutting from the base plate was realized on saw blade and the maximum displacement was measured to 1.137 mm.



(**a**) (**b**)

Fig. 7: Maximum displacement on the left camera (a) and on the right camera (b)

Conclusions

Simulations play an important role in the additive manufacturing process as well as in welding. Thanks to them, we are able to virtually design and verify the entire process. This saves material and costs. We are able to eliminate the trial-and-error method, and, in addition, we can benefit from benefits such as pre-defining the shape, which straightens into the desired shape due to residual stresses. Simulations unlock the potential of AM technology.

This study summarized new knowledge in the field of stress analysis and simulation of 3D printing metallic alloys. The paper also summarizes current trends in the area of two commercial simulation software ANSYS AAS and MSC Simufact. A real component was selected, which underwent topological optimization and subsequently simulations were performed in both programs. For both SW, the default setting of material properties supplied by the manufacturer of the SW was used (it was not the same for both simulations). The part was also experimentally printed using the SLM method to verify the development of deformations during removal from the set plate. Thanks to the performed simulations and real verifications, several conclusions were drawn:

- All performed simulations provide a great basis for the prediction of stresses and strains. Both programs showed very similar deviation values.
- When comparing the simulation with real measurements, a deviation of ± 0.5 mm is achieved. However, the DIC measurement could be affected by the heating of the material at the cutting point, which probably caused the part to deflect towards the cameras, which corresponds to the fact that the measured maximum displacement is larger than in the simulations. The actual shape of the part will be verified by scanning for a possible magazine article.
- Generated support elements in both software can be successfully used instead of generated supports in slicer software.

Further research could compare other software as well as focus on multiple scanning strategies and the use of multiple different print settings.

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