Possibilities of Application of Virtual Prototyping and 3D Printing Methods in Practice

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Abstract. The present contribution describes 3D printing of a part and related engineering design techniques which are used for virtual prototyping. Using these advanced techniques, one can cut the consumption of material in the production of machine parts by reducing the parts' weight while respecting the applied loads. In this investigation, the techniques were applied to a drop weight tower jaw for high-speed tensile testing. The weight of the jaw is a significant factor in the test, particularly for ductile specimens. As part of this investigation, these parts were topology optimized. The resulting design was adjusted to make the part's shape suitable for building by DED (Direct Energy Deposition). The part was then fabricated from titanium in InssTek MX600 additive-manufacturing machine. 3D printing made it possible to fully exploit the potential of topology optimization and minimize the need for subsequent machining.

Keywords: Topology optimization · DED · Tosca · FEM

1 Introduction

Today's requirements for minimizing material usage in production are becoming ever stricter. 3D printing technology promises to meet these requirements. It is developing rapidly and offers ways to manufacture parts, namely in job-lot production, which could not be produced by other techniques. It finds use in prototyping because a 3D-printed part is much cheaper than a cast part, for instance.

3D printing, in fact, provides an answer to topology optimization, which has not been applied widely until recently. Topology optimization involves the removal of the largest possible amount of material to obtain a part with an optimum layout of the material. The outcome of topology optimization is an organic shape that requires the least material to support the applied load. Many of those shapes are impossible to manufacture using conventional methods, such as casting and welding, because of these methods' limited capability to create cavities. There are virtually no such limitations in 3D printing. However, the manufacturable shapes are dictated by the chosen 3D printing method.

Despite these advantages, it remains difficult to identify new industrial applications for the combined process of topology optimization and 3D printing, mainly because of

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the limited availability and time-consuming nature of the printing process. This paper presents one possible application.

Conventionally manufactured drop a tower holder had an effect on the tensile calculation due to large weight. As the lower jaw hangs with the sample for ductile material, which results in constant preload. Due to this, the tensile calculation results have to accept with some error percentage. It is very important to reduce the weight of the structure by deducting the unnecessary material by topology optimization. Thus optimized part would enhance the tensile test calculation accuracy, and the optimized part should be able to sustain for impact load during application. The aim of this work was to find a way how to decrease the weight of the functional part used for the drop weight tower machine and then produce this part using AM.

2 Materials and Methods

2.1 Topology Optimization

Topology optimization (TO) of solid structures refers to the internal member configuration of a structure indicating the regions where holes will be located, the amount of the holes, their shapes, and the connectivity of the domain. TO is a mathematical method that determines the material placed in a given domain to achieve the desired functionality for a given set of loads and constraints while optimizing for certain qualities such as minimal material usage or uniform stress distribution. Guided by gradient computation or non-gradient algorithms, TO builds on repeated analysis and design update steps. TO was introduced in 1988 in a seminal paper by Bendsøe and Kikuchi, and since it has developed immensely in many different directions. The general form of a TO problem to find the material distribution that minimizes an objective function $\boldsymbol{F}$, subject to volume constraint $g_0 \leq 0$, and possibly other constraints $g_i \leq 0$, $i = 1,\ldots$, n, can be written as:

$$min: \boldsymbol{F} = F(\boldsymbol{u}(\rho), \rho) = \int_0^{\varphi} f(\boldsymbol{u}(\rho), \rho) dV \tag{1}$$

$$subject\ to: \begin{cases} g_0(\rho) = \int_0^{\varphi} \rho dV - V_0 \leq 0 \\ g_j(\boldsymbol{u}(\rho), \rho) \leq 0\ with\, j = 1, \ldots, n \\ \rho(\boldsymbol{x}) = 0\ or\ 1\ \forall x \in \varphi \end{cases} \tag{2}$$

The density variable $\rho(\boldsymbol{x})$ describes the material distribution, and it can be either 0 (void) or 1 (solid) at any point in the design domain φ. Linear or non-linear state equations are satisfied by the state field $\boldsymbol{u}$. V represents the volume of the structure.

The design optimization process is performed using the topology optimization method in Abaqus/Tosca Structure 2018 (Dassault Systèmes Simulia Corp, Johnston, RI, USA), and the workflow of the computational design optimization is presented in Fig. 1.

The objective function used is to minimize design response values of strain energy. The density update strategy used in Abaqus is normal, and the initial density used the optimization product default.

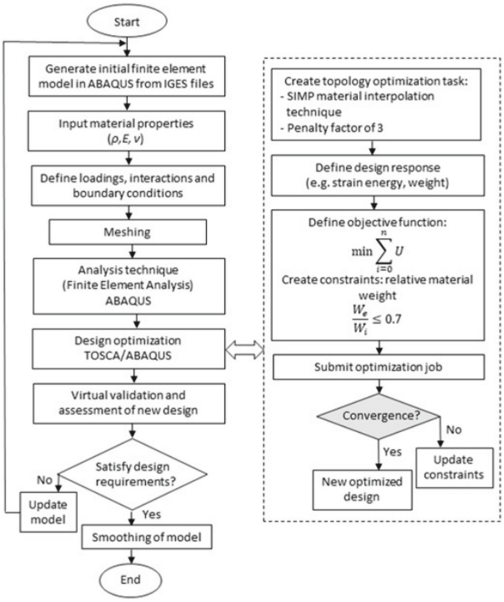

Fig. 1. Computational design optimization workflow using Abaqus/Tosca. [1]

2.2 3D Printing

DED (Direct Energy Deposition) is one of the metal additive manufacturing processes to fuse powder/wire material using focused thermal energy. The laser is used to deliver focused thermal energy that generates a melt pool. The powder is supplied at a controlled rate to the melt pool, and it solidifies as the laser head travels along a path dictated by the scanning strategy. The moving laser source thus creates a track of deposited material. The scanning movement of the laser head in two dimensions produces the deposited layer. Adding the material layer by layer leads to a 3D solid structure. The movement of the heat source and the associated rapid cooling critically correlate with the part's quality and structural integrity.

The experiment was carried out with InssTek MX-600 metallic deposition system (InssTek, Daejeon, South Korea) with a 2 kW ytterbium fiber laser configured for the DED technique. Figure 2a shows the InssTek MX-600 system. Figure 2b depicts the interior of the build chamber. The powder was kept in a feeder mounted at the top of the machine. The deposition head contains a laser source and has a multi-axis movement capability. Powder and argon gas flow coaxially through the deposition nozzle head to the laser path. The baseplate holder mounted at the bottom of the machine can travel along multiple axes. [2].

The laser beam diameter is 0.8 mm. The powder feeder is a gravity-based type with controlled gas pressure and a rotating wheel. The powder was fed at a constant feed rate of 3 g/min. Argon gas with a constant pressure of 2 bar was used as the shielding gas to protect the weld pool. The shielding gas consumption was 10 l/min, and that of the

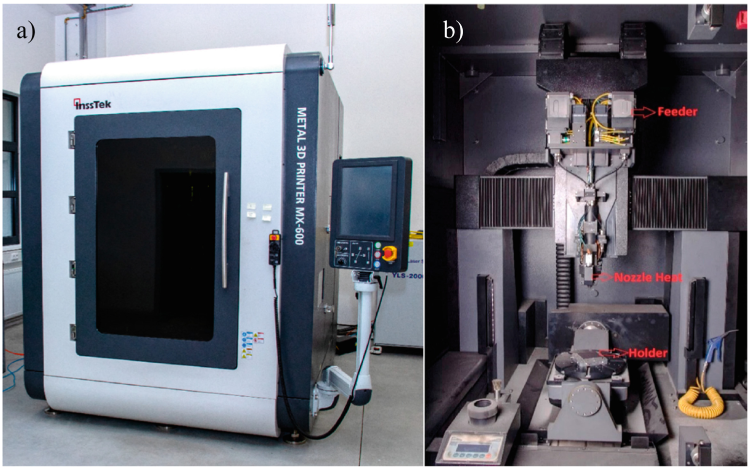

Fig. 2. InssTek MX600 3D printer. [2]

powder carrier gas was 2.5 l/min. The spacing between the tracks was 0.5 mm (hatching distance). The velocity of the laser head was 14 mm/s. [2].

The equipment has four hoppers connected to the nozzle head. By combining materials from these hoppers, one can produce parts of virtually any chemical composition.

The build space (Fig. 3) dimensions are 450 × 600 × 380 (X × Y × Z axis) mm. The control system can handle a 5-axis (or 3 + 2-axis) arrangement with which almost any shape can be produced.

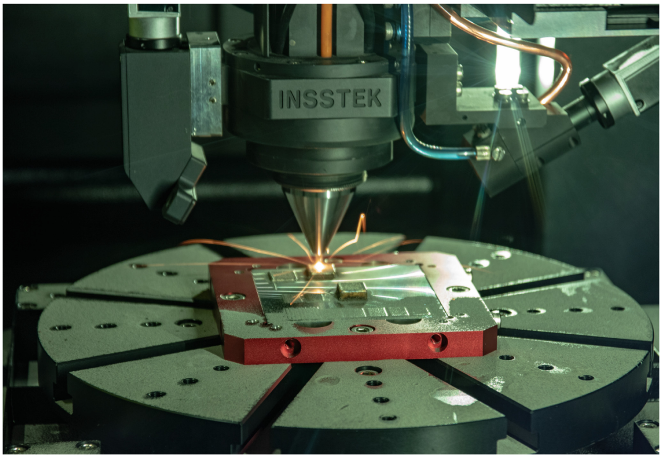

Fig. 3. Printer build space.

Fig. 4. Tensile test configuration.

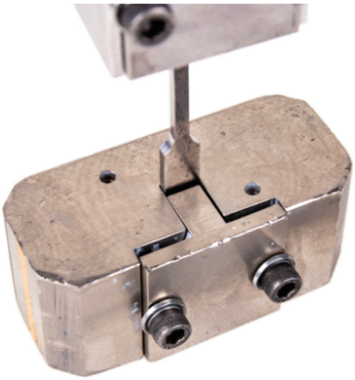

Fig. 5. Elements to be optimized.

2.3 Experiment

The method was used to modify the design of a lower jaw assembly for high-speed tensile testing in a drop weight tower (Fig. 4). The lower jaw has an appreciable impact on the measurement, particularly with ductile or small specimens.

2.4 Numerical Simulations

Numerical calculations were carried out using Abaqus/Tosca software and its basic function to “minimize design response values of strain energy”. Using this function, the minimum volume of the part for a particular load is sought. The lower jaw assembly (Fig. 5) comprises the actual jaw, a backplate and connecting screws.

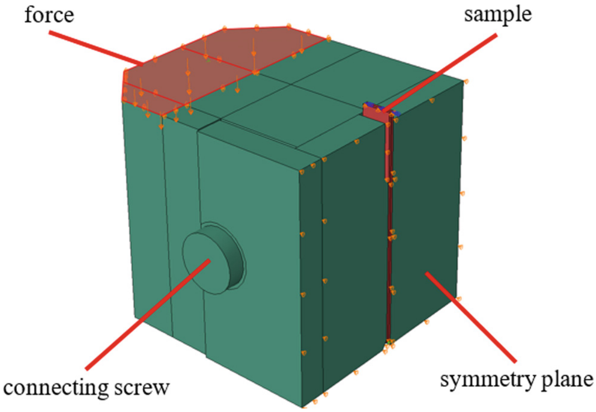

Fig. 6. Boundary conditions.

Figure 6 shows the boundary conditions. For this purpose, a model was developed that comprised one half of the assembly and a portion of the test specimen. The figure shows the symmetry plane, the point of application of the test force and the specimen which is inserted in the plane of cut.

The specification for topology optimization includes definitions of functional surfaces or volumes that should be excluded from the optimization algorithm. Basically, these locked surfaces include those on which boundary conditions are applied.

Screws themselves and their adjacent regions were also excluded from topology optimization. The size of these regions was governed by the screw head size, much like in calculations of stiffness of pre-stressed joints.

For the specification, the base surface of the backplate had to be selected. The reason is that the backplate has several flat surfaces on which it could rest during 3D printing. They would require the use of supports which might make the production difficult. The natural base surface of the jaw is its upper surface to which the test force is applied.

The setting “minimize design response values of strain energy” involved two variables, the first one being strain energy which is minimized using the “condition based optimization” algorithm, and the other is volume, where the target is 25% of the initial volume. The maximum number of iterations was set at 50.

3 Results and Discussion

3.1 Topology Optimization

The following images show the result of topology optimization after smoothing. Figure 7 shows the entire optimized jaw assembly. Figure 8. and Fig. 9 show the separate optimized parts (the jaw alone and the backplate).

Machining allowances were added to the model prior to actual printing. Thanks to the parts’ orientation with respect to the building direction, the only regions where the material had to be added were contact surfaces. It is important to deposit material without support in DED. DED technique does not build the structure with support. Whereas

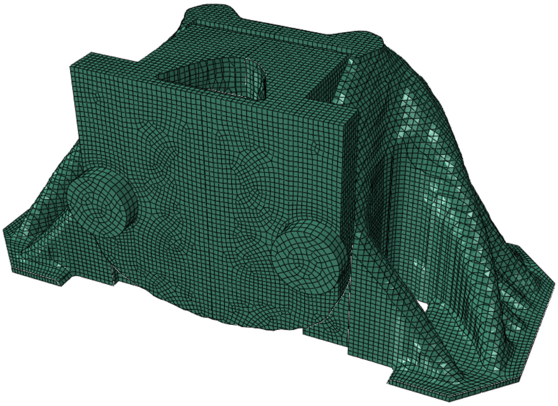

Fig. 7. The result of the calculation – assembly.

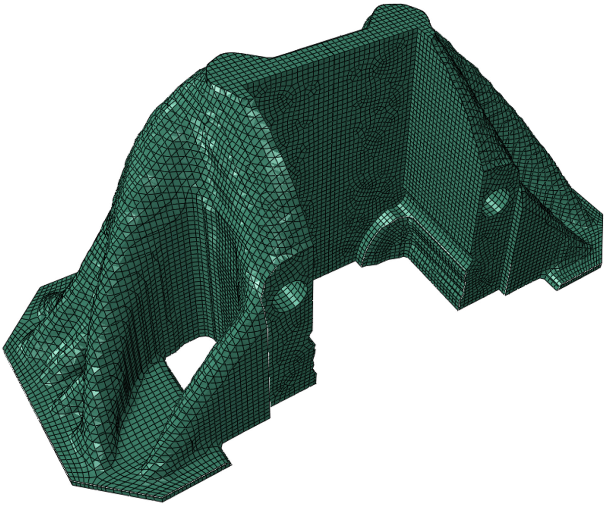

Fig. 8. The result of the calculation – jaw.

Selective Laser Melting (SLM) accommodate supporting structure during deposition of overhanging parts. Guanghui et al. deposited the topology optimized aerospace bracket rotating model about 20 °C to reduce the number of support structures [3]. Holes for screws were removed from the model because the holes will be drilled during the finishing of the contact surfaces.

3.2 Final Product

The models were converted to machine instructions for the InssTek MX600 3D printer. The material was Ti6Al4V titanium alloy. The process parameters were adopted from earlier research work, e.g. [4, 5] and [6]. These papers present the analyses and optimum 3D printing parameters for various materials.

Figure 10 and Fig. 11 show the 3D-printed builds on build platforms for the jaw and the backplate. The backplate build included a test slug for checking the build quality.

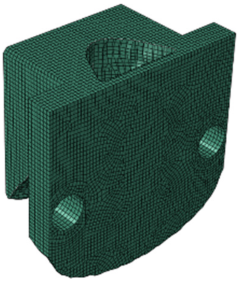

Fig. 9. The result of the calculation – backplate.

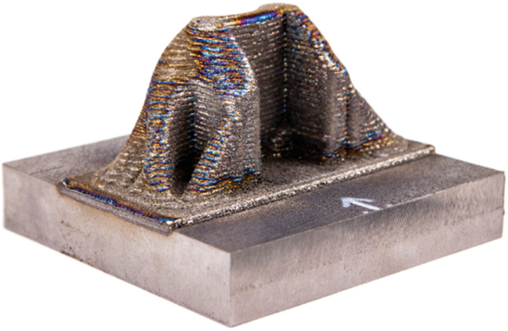

Fig. 10. Printed part – jaw.

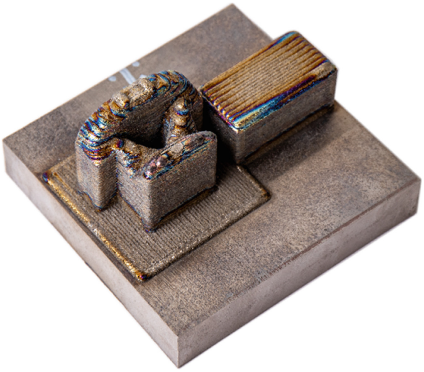

Fig. 11. Printed part – backplate.

Fig. 12. Final product.

Prior to machining, the parts were heat-treated to improve their quality, relieve internal stresses and homogenize the material of the build. The heat treatment involved annealing in a vacuum furnace at 750 °C using the following sequence:

- Heating at 200 °C/hour;
- Holding for 90 min;
- Slow cooling in the furnace to 100 °C.

After the builds had been cut away from the build platforms, they were machined in a 5-axis milling centre. The contact surfaces were machined to the required precision. Figure 12 shows the lower jaw assembly prepared for testing.

4 Conclusions

The ever more widely available metal 3D printing technology is predominantly deployed in prototyping and repairs of worn surfaces. Its application in ordinary production is prevented by long printing times and the associated high costs.

3D printing of new parts is advantageous in job-lot production and for topology-optimized parts, which are often impossible to manufacture by conventional techniques due to their intricate shapes. Yet, it is difficult to find suitable candidates, mainly because of today's heavily standardized production, where it is difficult to introduce novel solutions.

The part chosen for this investigation was suitable for topology optimization and subsequent 3D printing. It was a lower jaw assembly for high-speed tensile testing in a drop weight tower. The size and momentum of this jaw affect the testing process, mainly with small or ductile specimens.

Conventional approaches to adjusting the weight of this part were found to deliver no additional improvement. The existing jaw is made of titanium and weighs 587.59 g. Topology optimization and 3D printing of a new titanium part have led to a weight of 238.82 g, which amounts to a reduction of 59.4%.

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