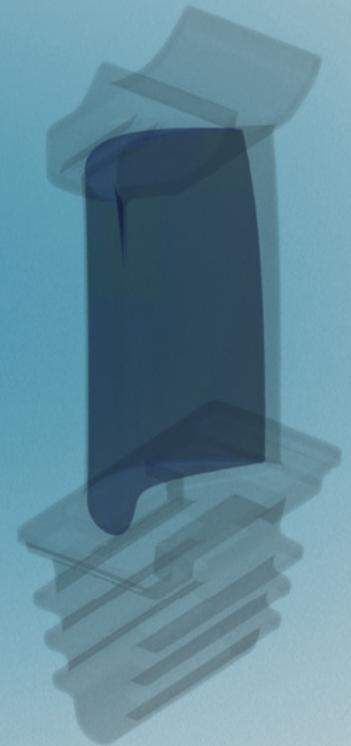# LATTICE OPTIMIZATION AND PROCESS SIMULATION OF A TURBINE BLADE

Additive manufacturing offers the ability to build lightweight components designed through topology optimization, incorporating lattice structures to provide conformal cooling. Lattices are repeated arrangements of unit cells. The numerous shapes and sizes available for unit cells have led to a breakthrough in the production of more robust lightweight materials and structures. In the modern manufacturing world, lattice structures are being used for internal support, reducing the amount of material or improving the strength- to-weight ratio. Medical implants, automotive and aerospace and defense components are a few major applications which have directly benefitted from lattice structures. To further improve the efficiency of these lattice structures, they can be optimized for the required in-service loading conditions.

In this paper, a turbine blade geometry was used to demonstrate different steps related to lattice generation, lattice sizing, and process simulation. A cavity was created inside the turbine blade and an internal lattice was generated. During the process of lattice generation, an Abaqus INP file with beam elements representing the lattice was automatically generated. A combination of tetrahedrons and beams represented the complete turbine blade. Appropriate in- service loading conditions were applied on the turbine blade model and a beam sizing optimization was setup. This generated a sized lattice that corresponded to the stresses that were generated in the turbine blade, as a result of in-service loads. Through some basic Python scripting, the optimization results were converted to a format that enabled the import of the sized lattice into the **3D**EXPERIENCE Platform.

Once the sized lattice was generated, additive manufacturing process simulations were performed on the geometry. The turbine blade was positioned on the build tray at 450. Appropriate supports and scan path strategies were implemented to complete build setup of the turbine blade. Using the previously generated scan path, a thermal-mechanical process simulation was executed on the geometry.
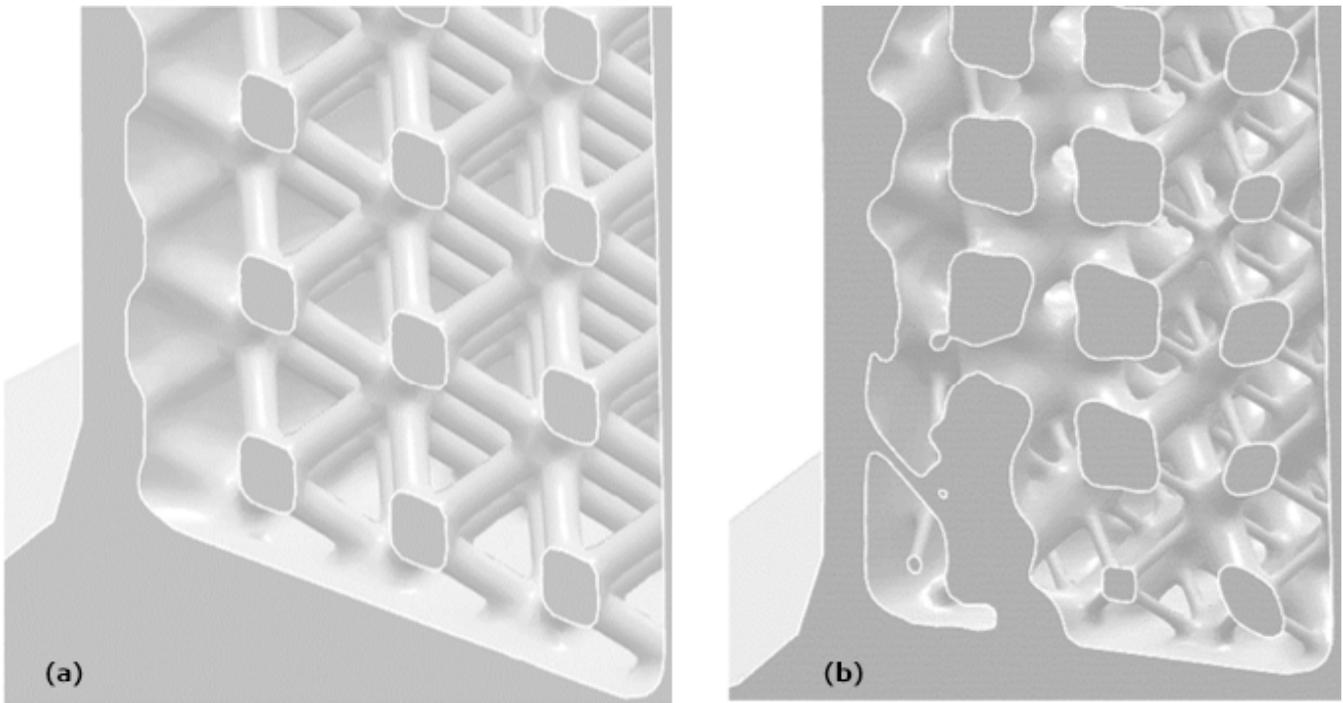
Figure 1: Internal Lattice of a Turbine blade; (a) before sizing, (b) after sizing.

INTRODUCTION

Over the years, additive manufacturing (AM) made its way to becoming one of the revolutionary next generation technologies in the manufacturing industry. The technology has improved to such an extent that parts are now being manufactured for production, and are used in aircraft, automobiles, dental implants etc.

In the past few years, certain processes, such as metal powder bed processes, have gained popularity for their remarkable freedom to create light weight, organic, and intricately shaped parts in industrial graded materials. In the Powder Bed Fusion Additive Manufacturing process, parts are produced in a layer-by-layer fashion by spreading powder on a metal bed and fusing it with laser or electron beam, turning CAD files directly into finished products or near net shape components, without the need for expensive tooling or fixtures. It is a viable option for the manufacturing of pressure blades for aero engine and power turbines.

In AM, the goal from both the consumer as well as the manufacturer's point of view is to design lightweight and innovative parts, which yield the same performance rating as parts manufactured using traditional methods, without compromising structural integrity. One way to achieve such a structure is through topology optimization. Although this technology opens up a new world of possibilities to redesigning existing components, the end application of the part will determine if the design is going to be suitable or not. In the case of a turbine blade, the designs are mostly based on industry standards that dictate the functioning of the blade. Hence, there is very little scope for changing the overall exterior design. The other way to optimize such a design is by creating a cavity of the inner core and filling it with a lattice structure. By creating
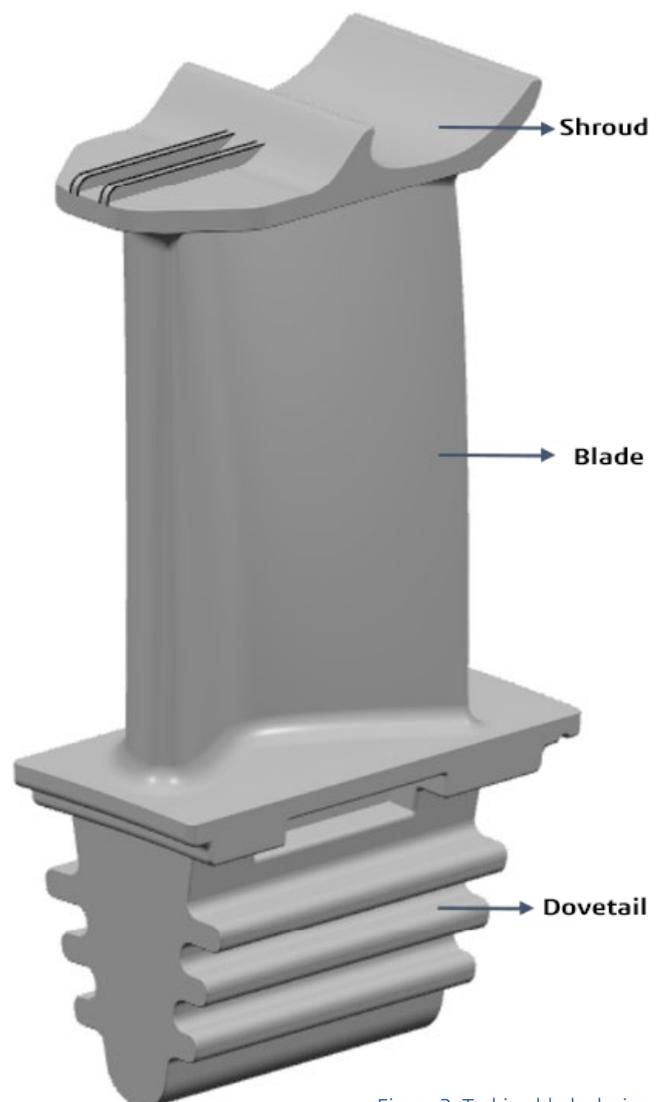

Figure 2: Turbine blade design.

a lattice, the overall design will be lighter compared to the original design. Since there is no topological change to the existing exterior surfaces, the same design will be suitable for the intended application. To further enhance the design, the diameters of the lattice beams can be optimized depending on the different in-service loads acting on the geometry, to yield an optimized internal lattice core.

LATTICE GENERATION

The Part Design app on the **3D**EXPERIENCE Platform was used for generating the internal lattice structure. The first operation in generating the lattice structure was to create the internal cavity. The external surfaces of the turbine blade were offset by 1 mm internally. The offset surfaces were used as a bounding box to remove material thereby creating the internal cavity (see Figure 3). Since the geometry of the turbine blade is complex, a user defined cavity was created. The lattice tool can automatically create an internal cavity as well.

Once the internal cavity was created, the lattice generation tool automatically captured the user defined cavity. A pre-defined star pattern was chosen as the unit cell shape for the lattice structure. The beams of the lattice were 4 mm long and 0.4 mm in radius (see Figure 4).

During the lattice generation process, an Abaqus input file containing all the beam nodal and element connectivity, along with beam profile and beam section properties was simultaneously created. The beam model was used downstream for simulations and for lattice optimization (see Figure 5).

MODEL AND SIMULATION SETUP

The Mechanical Scenario app on the **3D**EXPERIENCE Platform was used to generate the model and the simulation of the turbine blade. The model setup consisted of combining the beam mesh and the mesh of the rest of the turbine blade. The turbine blade was meshed with 1 mm linear tetrahedral elements. Once the mesh was created, individual node sets were created for the beam mesh and the solid tetrahedron mesh. Figure 6 shows the mesh statistics for the finite element model.

The material model of Cobalt Chromium alloy (Co-Cr) was applied to the geometry. A solid section property was created for the turbine blade. The material model consisted of temperature dependent properties which were used downstream in process simulations.
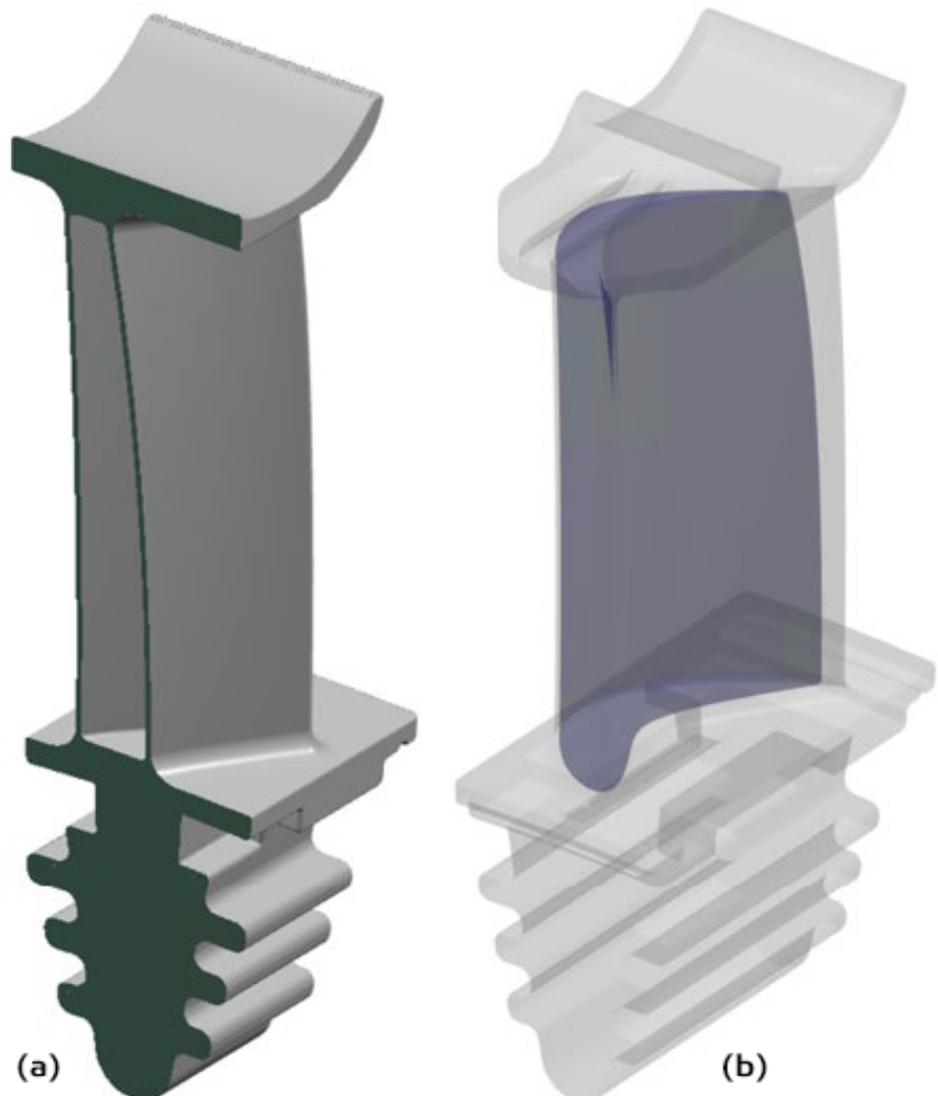

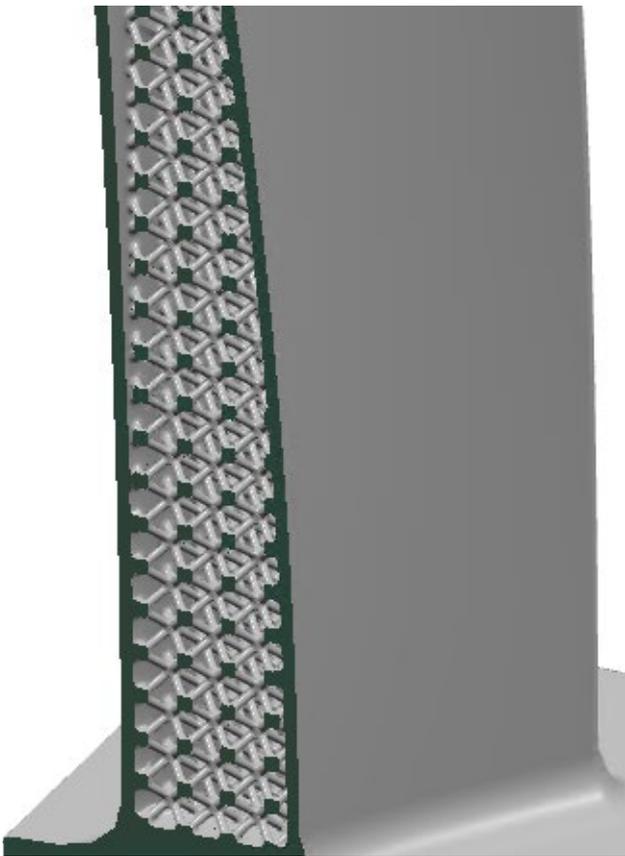Figure 3: (a) Turbine Blade cross section; (b) Turbine blade internal cavity.

(a)

(b)

Figure 4: Cross section of the turbine blade showing uniform internal lattice.

A tie constraint was defined between the two node based surfaces and a position tolerance was specified to tie only the nodes that are in proximity with one another. This ensured that there was mesh connectivity and the in-service loads would be translated throughout the structure when applied. This completed the model setup (see Figure 7).

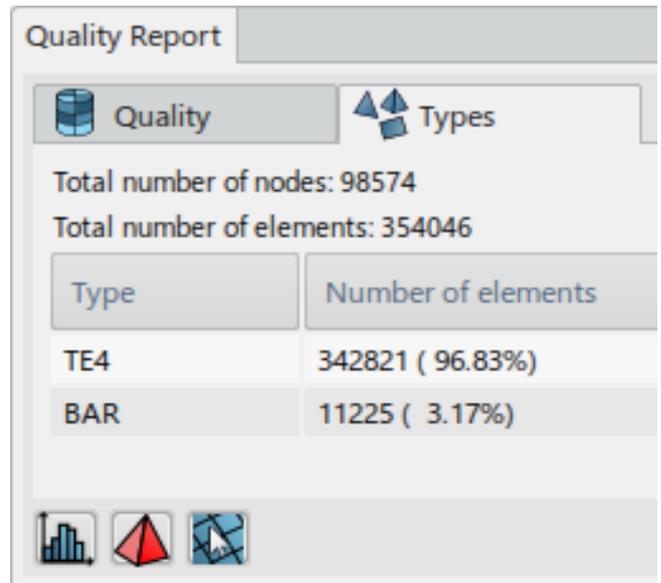Figure 5:   Beam mesh with 3D rendering.

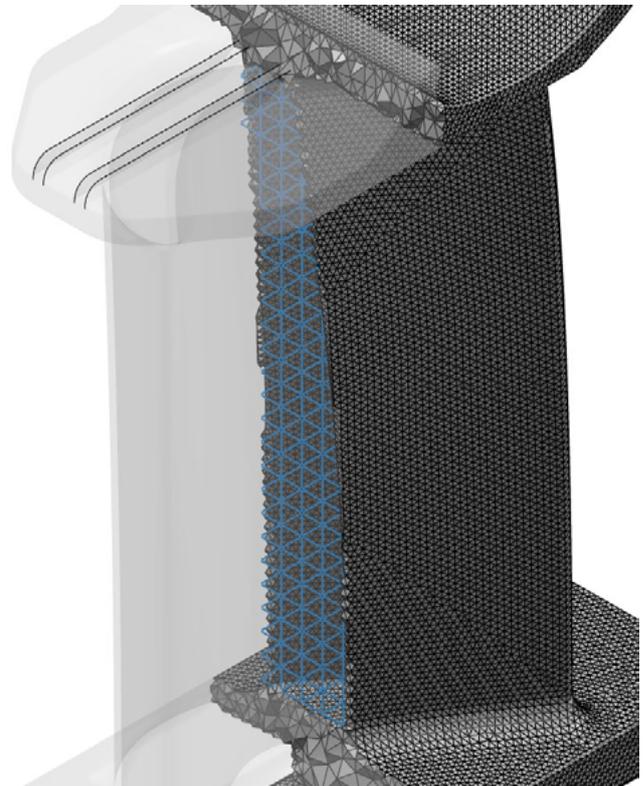Figure 6: Mesh diagnostics for the turbine blade and lattice structure mesh.

Figure 7:   Tetrahedron mesh of the turbine blade tied with the beam elements of the internal lattice structure.

A static simulation was then generated using the previously created finite element model. The boundary condition was to fix the turbine blade at the dovetail region, in order to prevent rigid body motions when in-service loads were applied. The in-service loads consisted of a pressure force applied between the leading edge and the trailing edge of the turbine blade. This mimics either a fluid at high pressure or compressed gas impacting the turbine blade with a certain force. In addition, since the turbine blade is in constant rotational motion, a centrifugal force was applied to the entire turbine blade (see Figure 8).
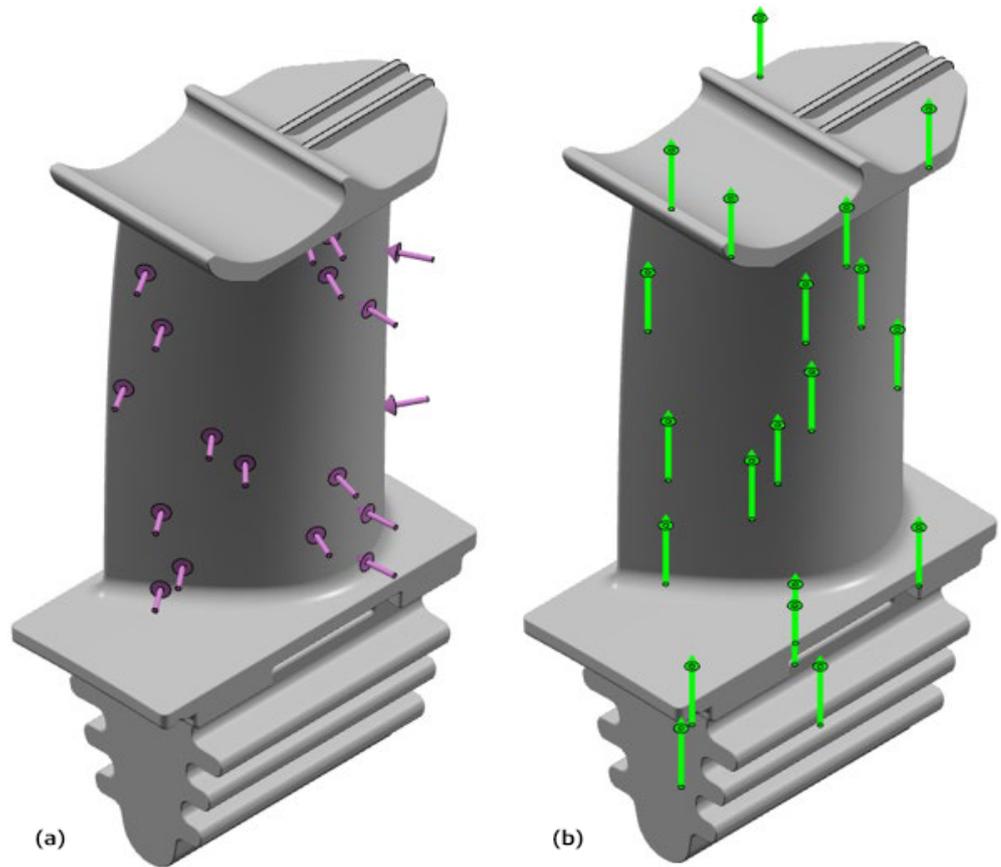
Figure 8: (a) Pressure in-service load; (b) Centrifugal force in-service load.

(a) **(b)**

The results of the simulation indicated that more stresses were induced near the region of the dovetail where it was fixed. The images are shown below. Upon creating a view cut and also applying a deformation scale factor of 250, it was clear that the beams and the turbine blade were connected and there are no disconnected regions. This implied that the loads were translated throughout the model when applied (see Figure 9).

LATTICE SIZING OPTIMIZATION WORKFLOW

The lattice generated in **3D**EXPERIENCE was optimized using Tosca Structure sizing capability. The optimization was conducted in the **3D**EXPERIENCE platform using the Process Composer application. The Process Composer workflow used a **3D**EXPERIENCE utility adapter to generate an Abaqus input file from the previously created static simulation.
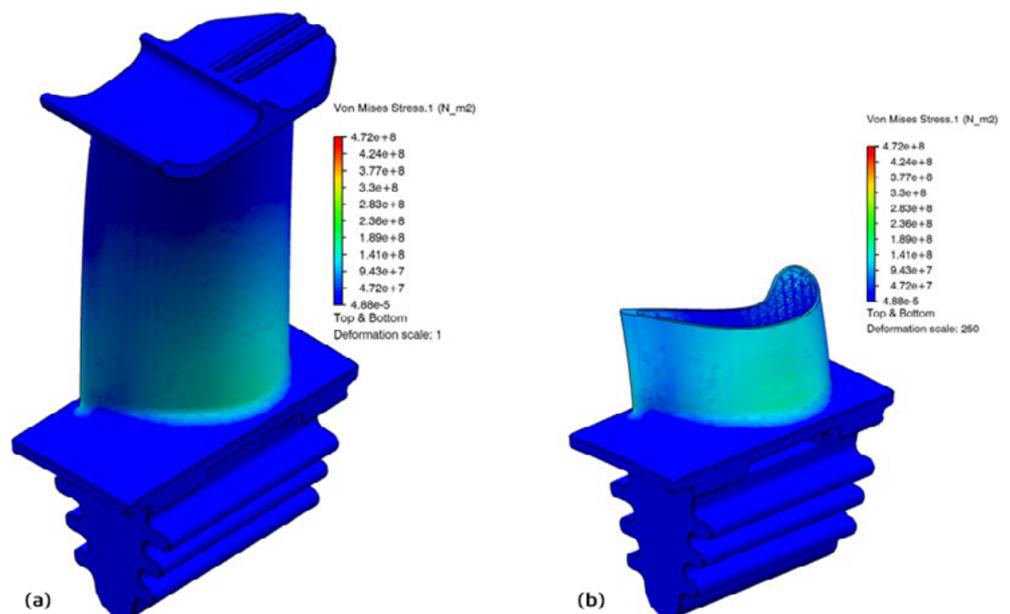

Figure 9: (a) Von mises stress contour plot (b) Von mises contour plot with deformation scale factor and view cut.
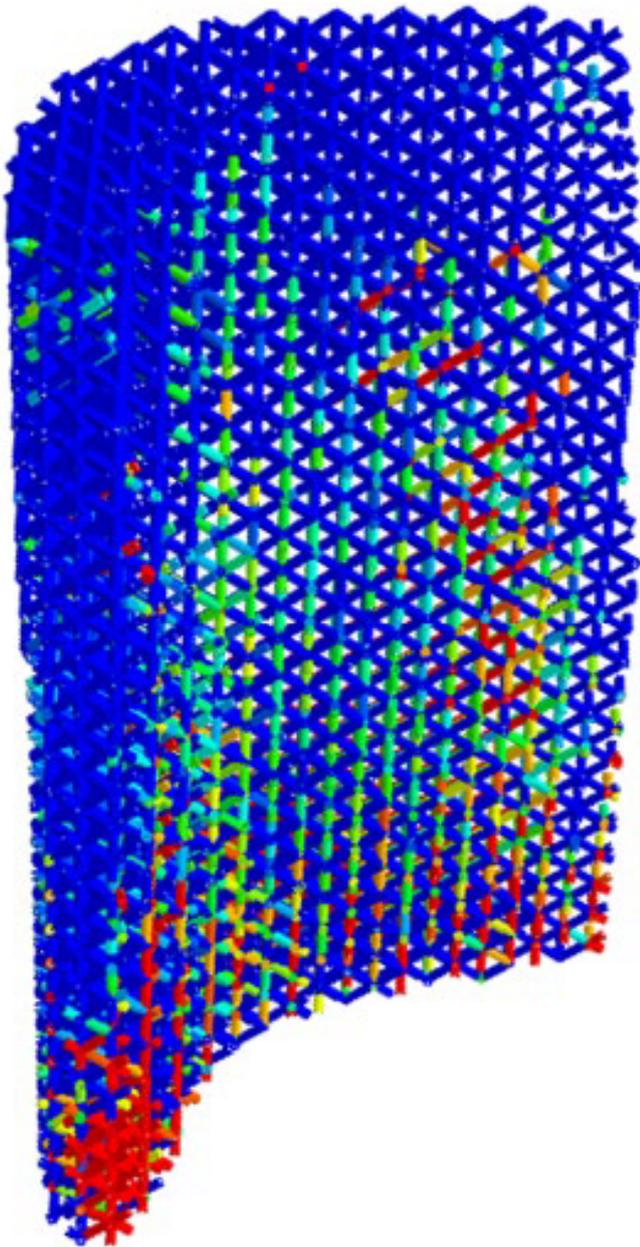
(a) **(b)**

Figure 10: Beam sizing optimization results indicating thicker beams near the dovetail.

This input file was used in the sizing optimization via the OS Command adapter that launched the optimizer.

The optimization was executed using the Tosca Structure sizing module, to optimize the beam radii in the model. The beam radii in this optimization were allowed to vary in the range of 0.2 mm through 0.8 mm. The initial beam radius was 0.4 mm for all the elements in the model. These bounds were chosen based on the critical feature size that can be printed using an additive manufacturing machine. The optimization was set to redistribute the existing weight to maximize the stiffness of the structure. The optimization considered the nonlinear effects such as material and geometric nonlinearity defined in the simulation. The optimization completed in 27 design cycles and created the results as shown below in Figure 10.

After the optimization, the result was converted to a lattice format using a Python script. Once the Python script step was complete, the resulting file obtained was accessible by the lattice generation tool. This file was imported into the **3DEXPERIENCE** Platform using the Upload tool in the Process Composer workflow. The overall process composer workflow is illustrated in Figure 11.

The original un-optimized lattice with uniform beam radii was replaced with the optimized lattice for downstream Additive Manufacturing process simulation, as shown in Figure 12.

PROCESS PLANNING SETUP

With the creation of a turbine blade design with an internal optimized lattice structure, as discussed earlier, the only feasible method to manufacture this part is through additive manufacturing. For this example, Powder Bed Fabrication-Additive Manufacturing (PBF-AM) process is selected. In this process, intricate and organic shaped parts are manufactured directly from CAD in a layer-by-layer fashion, spreading powder on a metal bed and fusing it through a laser beam.
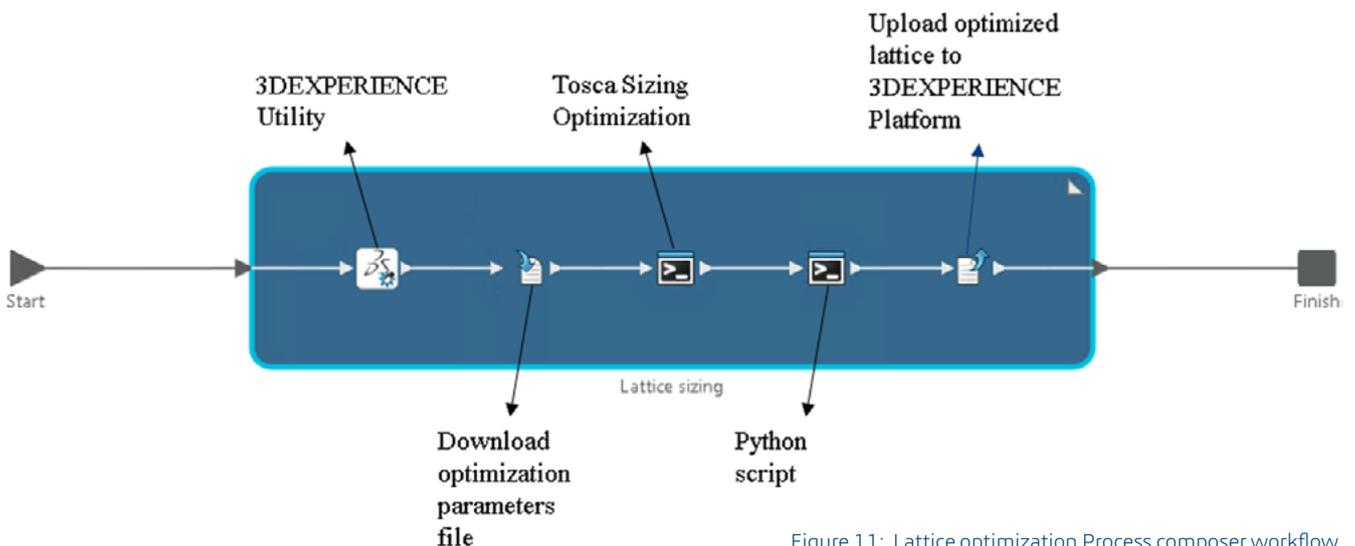

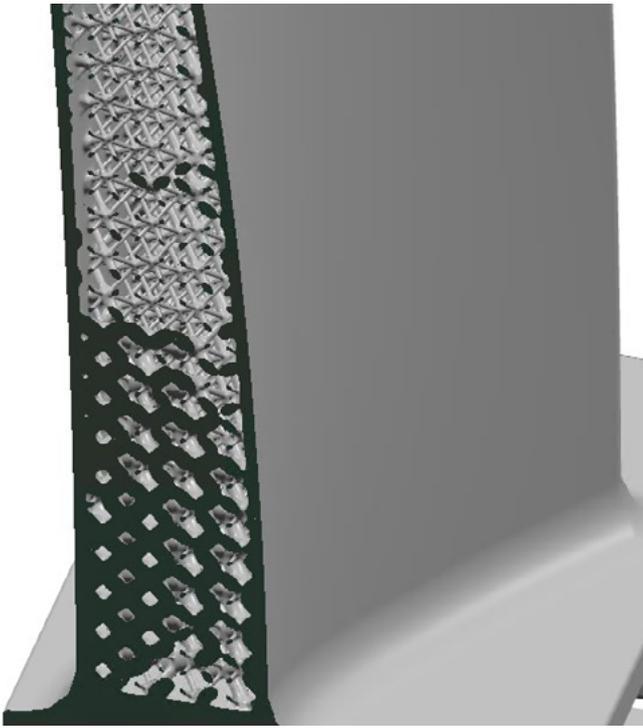Figure 11: Lattice optimization Process composer workflow.

Figure 12: Cross section of the turbine blade showing non-uniform lattice structure after beam sizing.

Figure 13: Turbine blade with both primary and secondary supports.

One of the critical aspects of manufacturing any part is to choose the right build orientation. This can result in minimizing the amount of support material that is required, and can also result in minimizing the contact area of the part on the build tray. Sometimes, one can avoid excessive support material at the design stage of the part, by performing topology optimization to come up with an organic design. In addition, manufacturing constraints to reduce overhanging surfaces can also be included to come up with a design that will require few supports. In this case, the turbine blade was mounted on the build tray at 450 to minimize the amount of support material required to manufacture the part.

The next important aspect is to choose the right support structure strategy. It is important to understand that support structures are important for a successful build. Support structures can be designed as either primary and/or secondary supports. Primary supports are those which are designed in the CAD environment along with the component design, and planned as sacrificial structures, that will be removed once the build is finished. Secondary supports are those that are generated in machine build preparation software. In Figure 13, the turbine blade is mounted on the build tray at 450 and has a combination of primary and secondary supports. The primary supports were imported since they are designed as a separate part. The secondary supports, in this case, were imported as well.
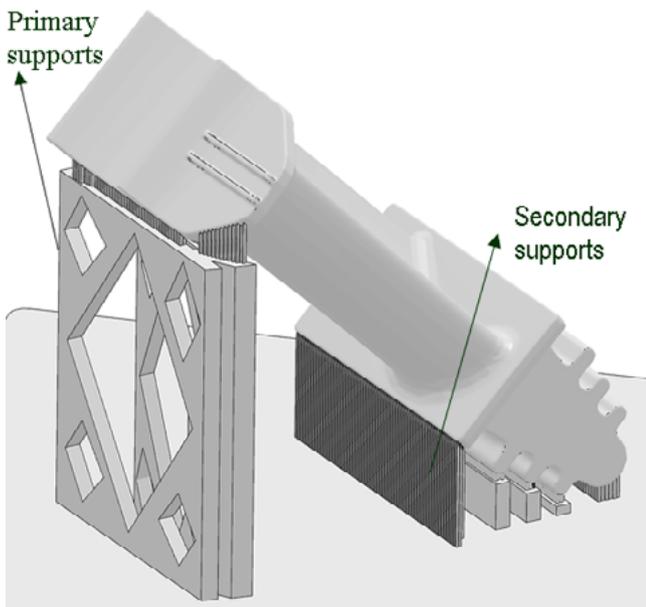
The third aspect is choosing the scan path strategy. The right scan path strategy can minimize the residual stresses in the manufactured part. Slicing and scan paths are generated based on process parameters like laser power, hatch angle, scan speed, layer thickness with stripes scanning strategy etc. Table 1 shows the parameters that were used to generate the scan path.

The scan path information can then either be sent directly to the printer via a Virtual Machine or neutral file formats, or in this case, it is used as input for process simulations. The process planning setup was completed using the Powderbed Fabrication application on the **3DEXPERIENCE** Platform.

Sr. No.	Parameter	Values
1	Laser power	170W
2	Layer thickness	60µm
3	Angle of rotation between slices	670
4	Stripe width	5mm
5	Hatching distance	140µm
6	Build tray dimension	248x248x33mm
7	Recoating time	8sec
8	Build tray temperature	1700C

Table 1: Parameters used to generate scan path for the turbine blade and supports.

VIRTUAL PRINTING SETUP

Following the build setup, the next step is to simulate the manufacturing process of the turbine blade. The process simulation is executed using a general purpose process simulation framework, which supports different types of thermal mechanical additive manufacturing processes, using data generated in the process planning stage.

In this simulation framework, finite elements are activated in a progressive fashion during the analysis in a computationally efficient manner. During the simulation, any element could be completely or partially filled with material, or empty. The solver precisely keeps track of this evolution, monitoring mass inventory and distribution to account for the addition of material during printing. The moving heat flux module was also developed to handle single/multiple moving heat sources of different shapes. Element external facets are computed as material is being activated and this allows for a very precise assessment of cooling, regardless of the finite element discretization.

Radiation and convection can be modelled on a continuously evolving surface that reflects the current shape of the part at any given point in the build.

Once scan path and slicing information were generated, a sequentially coupled thermal mechanical analysis was set up on the same platform using the simulation framework to predict build stability, temperatures, residual stresses and distortions. The primary supports were meshed using 8-noded, 6-noded and 4-noded elements (Figure 14) and the turbine blade was meshed with 8- noded, 6-noded,

5-noded, and 4-noded elements based on the hexahedral-dominant meshing algorithm on the **3D**EXPERIENCE platform (Figure 15).

The virtual printing simulation setup was done using the Additive Manufacturing Scenario app on the **3D**EXPERIENCE Platform. Tie connections were created between supports and part and between supports and build tray. Cobalt-Chromium (Co-Cr) alloy was used to simulate this build.

Initial temperatures were defined for powder and build tray. Material addition and moving heat flux was defined using this framework with earlier mentioned parameters. The generated tool paths in the format of time, location and field data were used to derive the material/element activation and heat addition. The external facets of elements were computed as material was being activated and this allowed for a very precise assessment of cooling, regardless of the finite element discretization. Emissivity and film coefficients were defined to model radiation and convection on the continuously evolving surfaces, according to material activation.

Build plate temperature was kept constant at 1700C and was clamped for the static simulation, to prevent rigid body motions. Temperature history from the heat transfer analysis was mapped to the subsequent static analysis to compute stresses and distortions. These results are discussed in next section.

Figure 14: (a) Primary and secondary supports meshed with tetrahedral elements (b) Mesh diagnostics of all primary and secondary supports.
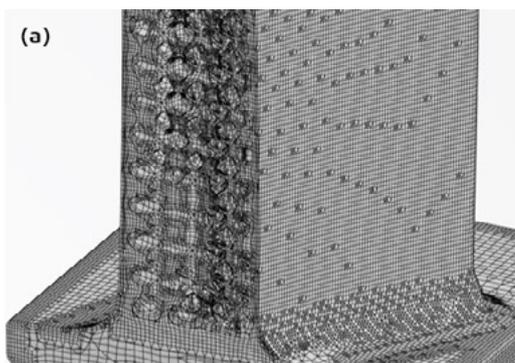
Figure 15: (a) View cut to show the hex-dominant mesh of the turbine blade (b) Mesh diagnostics of the turbine blade mesh.

RESULTS

The image below (Figure 16 (a), (b)) shows residual stresses and distortions in the build setup after manufacturing. It is observed that there is higher distortion near the region of the primary support. This indicates that more supports are required around that region to reduce distortion of the shroud. In addition, the stresses on the part and the supports are uniformly distributed, which suggests that there are no regions of high stress concentrations that may cause build failure.
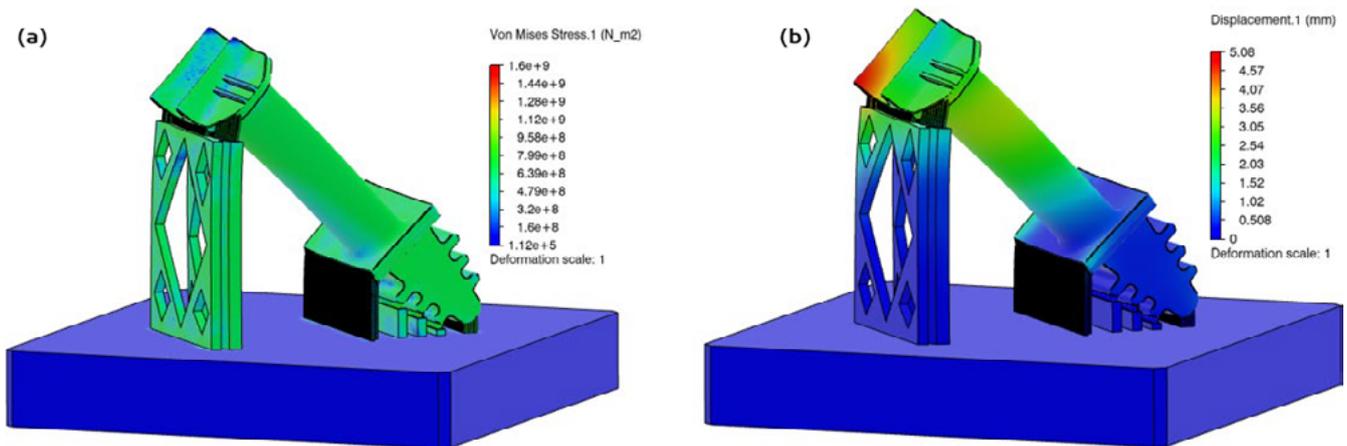

Figure 16: (a) Stress contour plot
(b) Distortion contour plot

CONCLUSION

In this paper, the workflow to generate an internal optimized lattice structure of a turbine blade and to virtually print the optimized turbine blade using Powder Bed Fusion Additive Manufacturing (PBF-AM) technology was presented. The internal lattice of the turbine blade was optimized based on in-service loads applied in a static simulation. The optimized turbine blade was positioned on the build tray and appropriate primary and secondary supports were defined. Standard scan path parameter values were chosen to define the energy distribution during the build. Part positioning, supports, and the previously generated scan path were used in the virtual printing simulation to yield stresses and distortions on the part.

Future work includes the following:

- Generate lattice structures with different unit cell patterns and varying parameters, optimize them and study the effect of stresses during in- service loading

- Using different internal lattice structures and different support structure strategies to understand the combined effect on residual stresses and distortions

- To include operating temperature conditions and how it affects residual stresses

- To study the effect of lattice structures on turbine blade cooling

- To generate a lattice that is not only optimized for performance, but also for print

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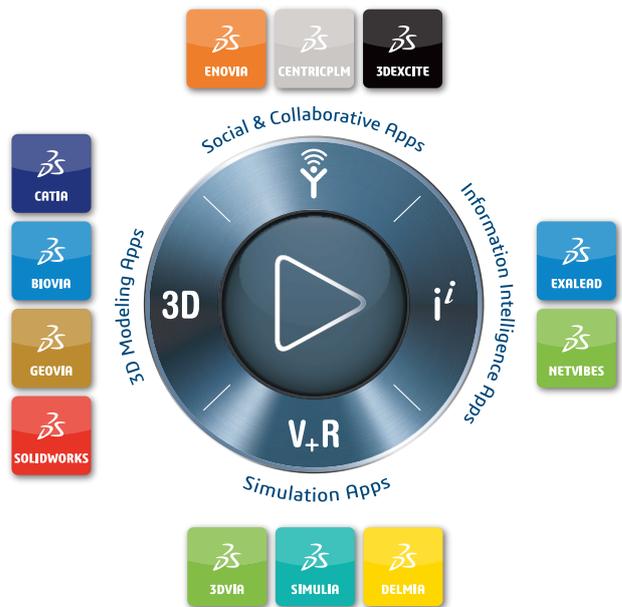
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